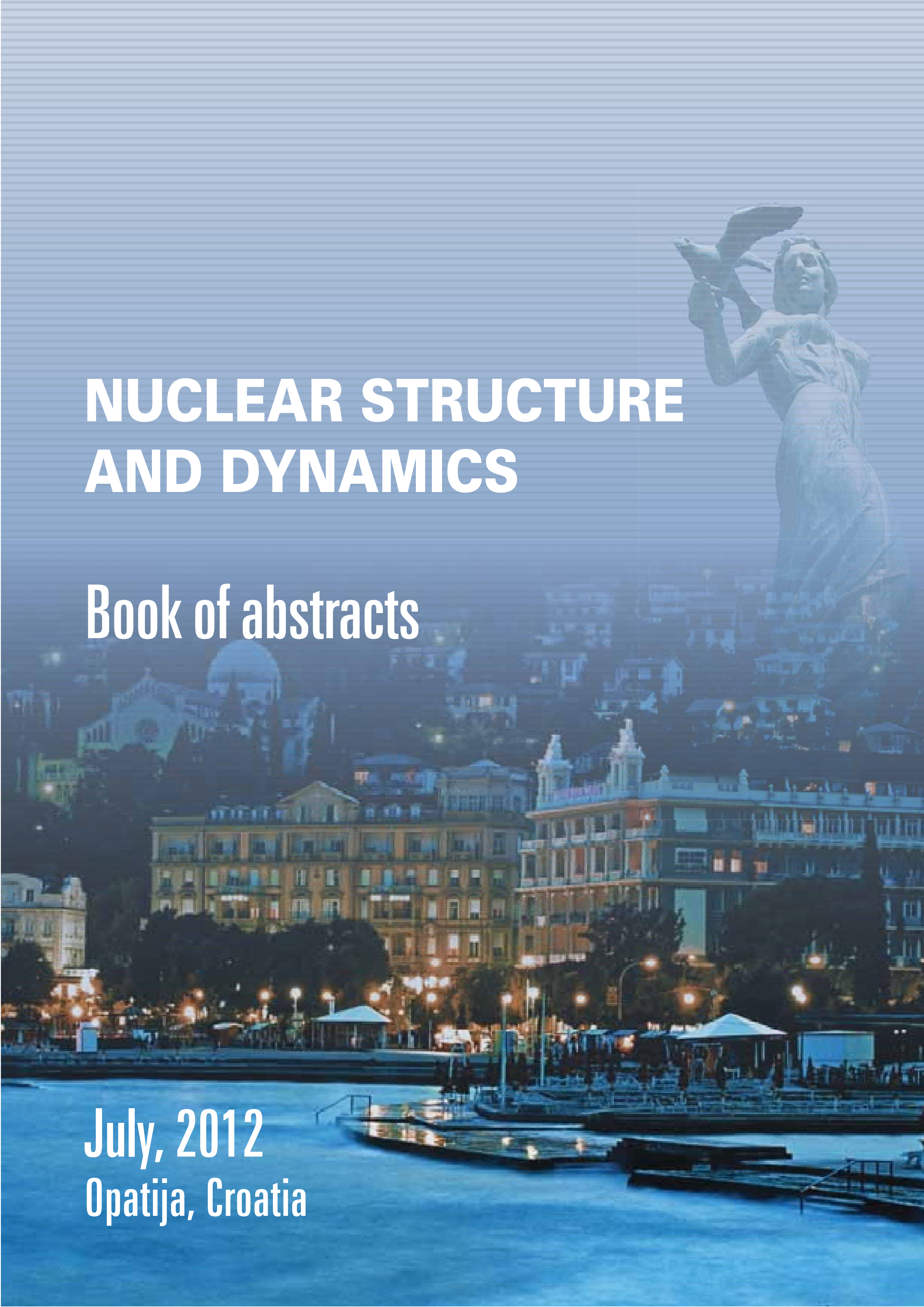

NUCLEAR STRUCTURE AND DYNAMICS

Book of abstracts

July, 2012

Opatija, Croatia

Preface

We have the pleasure to welcome you to the International Conference: "Nuclear Structure and Dynamics". Taking place in the historic resort town of Opatija, the meeting is hosted by the Physics Department of the University of Zagreb and the Ruđer Bošković Institute.

Following the success of the first "Nuclear Structure and Dynamics" conference, held in Dubrovnik in 2009, this meeting will provide a broad discussion forum on recent experimental and theoretical advances in the physics of nuclear structure and reactions. The main focus will be on the following topics:

- Nuclear structure and reactions far from stability
- Collective phenomena and symmetries
- Reaction dynamics of light and heavy ions
- Sub- and near-barrier reactions
- Ab initio calculations, cluster models, and shell-model
- Nuclear energy density functionals
- Nuclear astrophysics
- Fundamental symmetries and interactions

This booklet contains the abstracts of contributions which will be presented at the Conference, either as invited and contributed talks, or oral poster presentations. A large number of received abstracts demonstrates a considerable interest in attending this meeting. Unfortunately, not all contributions could be included in the final program.

We wish all the participants and their accompanying persons a pleasant stay in the beautiful town of Opatija, and hope that you will find the Conference stimulating and rewarding in many ways. Finally, we thank the organizing institutions, our sponsors for financial support, and all people who helped in the organization of this conference.

Suzana Szilner and Dario Vretenar

Conference Organization

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Physics Department of the University of Zagreb, Croatia

Ruđer Bošković Institute Zagreb, Croatia

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Abstracts

Observation of breakup transfer process for the bound states of ^{16}O populated from $^{12}C(^{6}Li,d)$ reaction at 20 MeV

S. Adhikari[1], C. Basu[1], P. Sugathan[2], A. Jhinghan[2], K. S. Golda[2],
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The $^{12}C(^{6}Li,d)^{16}O^{*}$ is an interesting reaction from the view point of both nuclear astrophysics [1] and nuclear physics [2]. Though the reaction has been studied over a large energy range in the last three decades, the availability of sophisticated reaction models in recent times can help us to understand this reaction in a much better way. The reaction has been generally studied by a measurement and analysis of the deuteron angular distributions populating discrete states of ^{16}O. In the past, most of the physical interpretations of the data were made either in terms of an alpha transfer process or in terms of compound nuclear emissions populating discrete states of the residual nucleus. The contribution of the alpha transfer mechanism is thought to be significant due to the loosely bound α+d substructure of the ^{6}Li projectile and this is usually estimated from the Finite-Range DWBA (FR-DWBA) theory. However, there may be another significant alpha transfer process that can follow after the breakup of the loosely bound projectile. This process of alpha transfer can be named breakup transfer and has been ignored in all previous studies except one in 2003 [3]. In [3] however, breakup transfer alone was not found to be an important reaction even in the forward angular zone.

In this work we measure deuteron angular distributions emitted from $^{12}C(^{6}Li,d)^{16}O^{*}$ at 20 MeV. In our experiment, several discrete states were populated out of which seven states were found to be strong. We show in figure 1 the angular distribution for the population of the ground state of ^{16}O as a representative case. This state being a natural parity (0^{+}) state can be populated by both alpha transfer and compound nuclear mechanism. The Hauser-Feshbach calculation is shown by dotted lines. The compound nuclear calculations clearly fail to reproduce the shape and magnitude of the observed data. The direct alpha transfer component is calculated in the framework of the FR-DWBA theory using the code FRESCO v2.9 [4]. The calculations (dashed lines) grossly underpredict the data. A more physical mechanism of alpha transfer is that following the breakup of the projectile is evaluated using the Continuum discretized Coupled channel-coupled reaction channel (CDCC-CRC) theory using FRESCO. The CDCC-CRC calculations (solid line) describe the data in a much better way than the other two calculations. Since we are interested in predicting the gross features of the reaction no attempt was made to adjust the parameters to obtain a better fit of the experimental angular distributions. The general feature of the reaction mechanism when all the states of ^{16}O are analyzed will be discussed. We are grateful to Prof. Ian Thompson for helpful discussions regarding the calculations with FRESCO.

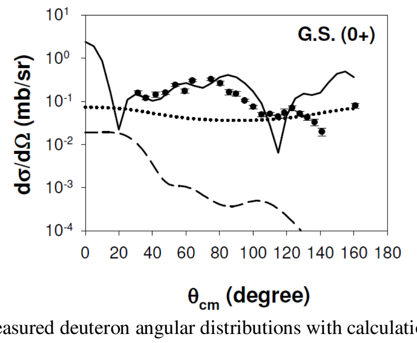

Fig. 1. Comparison of measured deuteron angular distributions with calculations (solid, dashed, dotted). For details please see text.

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Probing neutron pair transfer with Borromean isotopes of Helium

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Light neutron-rich radioactive nuclei, with their extended and therefore dilute matter distributions provide a unique opportunity to study both the complexity and simplicity of an aggregate of quantum particles. The role of pairing correlations in nuclear structure is well established. It is of great interest to get experimental information on their dynamical aspects. Nucleon transfer reactions, particularly on heavy targets, are an important tool for such studies. The loosely bound valence neutrons in Borromean nuclei like ^{6,8}He and ^{11}Li, whose binding arises essentially from pairing correlations, provide a unique laboratory for investigating the role of neutron correlations in the dynamics of dilute nuclear systems.
Recent developments in reaccelerated beams and the associated improvement in experimental techniques have now made measurements of pair and single neutron transfer reactions involving short-lived nuclei far from the valley of stability possible. We will present an overview of experimental challenges and the progress made in the deconvolution of one- and two- neutron transfer cross sections with such beams. In particular we will discuss studies involving both online and offline techniques, with beams of ^{6,8}He in the vicinity of the Coulomb barrier, on targets with A > 50. The talk will highlight a "non standard" way of obtaining the first limits on the ratio of σ_{2n}/σ_{1n}, involving ^{8}He.

Potential Barrier of Strongly Deformed Nuclei

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In this study, the potential barrier of two strongly deformed, arbitrarily oriented, axially symmetric heavy nuclei has been presented. The nucleus-nucleus potential has been considered as summation of the Woods-Saxon potential, Coulomb and spin-orbit interaction. The influence of the deformed surface diffuseness in potential barrier has been obtained. Calculations have been extended to cover quadrupole and hexadecapole deformation. This type of potential can be used to determine alpha disintegration, fusion and fission reactions probability.

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Lifetime Measurements of Excited States in the N=80 isotone, ^{138}Ce.

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This work reports on the utilisation of gamma-ray coincidences between germanium and lanthanum bromide $LaBr_3$:(Ce) scintillation detectors for the determination of electromagnetic transition rates in the pico to nanosecond regime. The technique utilises the high-quality full-energy peak resolution of the $LaBr_3$(Ce) detectors [1] coupled with their excellent timing responses in order to study discrete energy gamma-ray cascades from nuclei populated using the ^{130}Te(^{12}C, 4n)^{138}Ce fusion-evaporation reaction at beam energy of 56 MeV. The beam was provided by the Tandem van de Graaff accelerator at Bucharest, Romania [2]. The target consisted of a 1 mg/cm^2 thick enriched ^{130}Te foil on a 20 mg/cm^2 thick ^{208}Pb backing to stop the recoiling nuclei. Extracted Lifetimes for excited states in the N=80 isotone, ^{138}Ce will be presented and reduced transition probabilities have been calculated for the electromagnetic decays from these states and compared with productions of shell model calculations.

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Shape coexistence and charge radii in the lead region studied by in-source laser spectroscopy at RILIS-ISOLDE

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On behalf of a CERN-KU Leuven-Paisley-Gatchina-Oulu-Orsay-Mainz-Bratislava-Brussels collaboration

The competition between spherical and deformed nuclear shapes at low energy gives rise to shape coexistence in the region of the neutron-deficient lead isotopes with Z~82 and N~104 [1]. In order to determine to which extend the ground and/or isomeric states of those isotopes are affected by this phenomenon, a large campaign of investigation of changes in the mean-square charge radii is on-going at ISOLDE. Using the high-sensitivity of the in-source laser spectroscopy technique, which combines the ISOLDE-RILIS lasers with the Windmill alpha-decay spectroscopy setup, it has been possible to study very exotic isotopes of lead [2-3] and polonium [4-6], down to N=100 and N=107 respectively, and, more recently, thallium down to N=99, see Figure.

In this contribution, we will review the systematics of charge radii in the long chains of lead and polonium isotopes and also present the first, preliminary results of the 2011 experimental campaign on thallium isotopes.

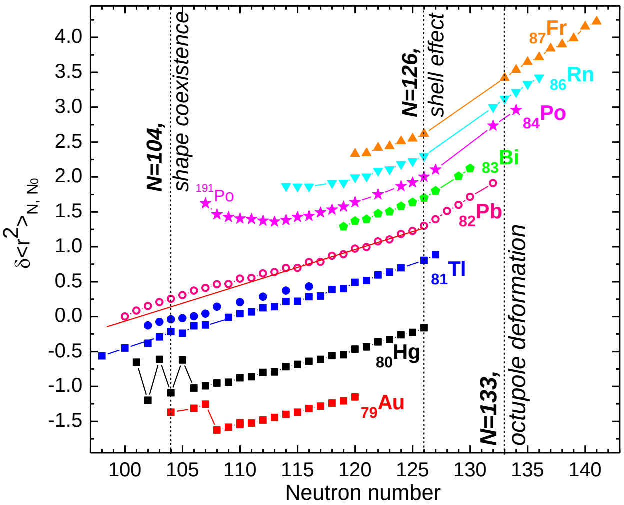

Figure. Charge radii for Au-Fr isotopes (courtesy A. Barzakh). For the sake of clarity the data for different elements are shifted relative to each other by a vertical off-set.

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SPES: the INFN radioactive beam facility for nuclear physics

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The SPES project at Laboratori di Legnaro of INFN (Italy) is concentrating on the production of neutron-rich radioactive nuclei for nuclear physics experiment, by the Uranium fission at a rate of 10^{13} fission/s . The emphasis to neutron-rich isotopes is justified by the fact that this vast territory has been little explored. The Radioactive Ion Beam (RIB) will be produced by ISOL technique using the proton induced fission on a Direct Target of UCx.

The most critical element of the SPES project is the Multi-Foil Direct Target. Up to day the proposed target represents an innovation in term of capability to sustain the primary beam power.

During the talk will be presented the status of the project, financed by INFN, and in the construction phase at Legnaro. In particular developments related the target and the ion-source activities using the surface ion source, plasma ion source, laser ion source techniques it will be reported. Finally test e results on handling of the target system it will be shown.

Dynamical approach to heavy-ion induced fission using actinide target nuclei at energies around the Coulomb barrier

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In order to success the synthesis of superheavy elements, it is indispensable to clarify the fusion-fission mechanism, which is included a role of the nuclear structure of colliding nuclei and the deformation of them in the fusion process. For this purpose, a large amount of experimental data is available, including the mass and total kinetic energy distribution of fission fragments, excitation function of each cross section, mass-angle distributions and so on. Using such experimental data, we verify of the model and establish a reliable model to describe the fusion-fission process.

We analyzed the experimental data using the unified model which can treat all reaction processes in heavy- and superheavy mass regions [1]. It takes into account the time evolution from the diabatic potential to the adiabatic potential. We then perform a trajectory calculation on the time-dependent unified potential energy surface using the Langevin equation [2].

To describe heavy-ion fusion reactions around the Coulomb barrier with an actinide target nucleus, we propose a model which combines the coupled-channels approach and a fluctuation-dissipation model for dynamical calculations. Fusion-fission, quasi-fission and deep quasi-fission are separated as different Langevin trajectories on the potential energy surface.

Using the new model, we calculate the capture and fusion cross sections in the reaction ^{34,36}S+^{238}U and ^{30}Si+^{238}U and compare the experimental data [3]. We calculate mass distribution of fission fragments (MDFF) and discuss the fusion-fission and quasi-fission events in MDFF. Also, we analyze the mass-angle distribution of fission fragments, which gives the reaction time scales [4]. Using our model, we discuss the reaction mechanism in the reaction ^{30}Si,^{31}P,^{36}S,^{40}Ar +^{238}U, ^{64}Ni,^{48}Ti,^{34}S+^{184}W at several incident energies. Such discussion is very important to understand the dynamical process.

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Antikaons in extended relativistic mean field study of neutron stars

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A neutron star (NS), as the name implies, is mostly composed of neutrons and a small fraction of protons. However this picture changes with increasing density (i.e. from crust to core of the NS) as other exotic particles like hyperons, kaons, pions and quarks can exist [1,2]. The study of NS properties has gained momentum recently due to several new observations [3,4], identification of several links with finite nuclear properties [5,6], and the development of sophisticated theoretical descriptions [6–9]. The recent versions of extended relativistic mean field (RMF) models could explain the finite nuclei throughout the nuclear chart as well as the NS without any change in the Lagrangian or its parameters [8]. In this work, employing such a model [9], we discuss the role of higher order couplings in conjunction with antikaon (K^-, $\bar{K}^0$) condensation on the neutron star properties. We discuss the onset of condensation of K^- and $\bar{K}^0$ which highly depend not only upon strength of kaon optical potential but also upon the new couplings of the RMF models. Presence of antikaons leads to a softer equation of state and yield a neutron star with a symmetric and electron-deficient core. We show that these effects strongly influence the mass-radius relation as well as the composition of NS. We also show that the recently [4] observed 1.97 solar mass NS can be explained in three ways: (i) A stiffer EoS with both antikaons, (ii) a relatively softer EoS with K^- and (iii) a softer EoS without antikaons. We demonstrate that a precise observation of the radius of such a massive NS could be useful in determining the presence of exotic cores and also to validate the corresponding models.

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Quasi-free knockout reactions with high-energy radioactive beams*

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The measurement of proton-induced reactions in complete kinematics will be an important part of the physics program at the future R^3B (Reactions with Relativistic Radioactive Beams) experiment at FAIR. In particular the quasi-free knockout processes of the type (p,2p), (p,pn), (p,pa) will be used to investigate the single-particle and cluster structure of neutron-proton asymmetric nuclei and the role of nucleon-nucleon correlations in nuclei.

At the present LAND/R3B setup we have performed experiments using a prototype installation for the detection of high-energy protons and neutrons in (p,2p) and (p,pn) reactions, respectively. Recoil protons have been detected with an array of Si-Strip detectors and the 4-p NaI spectrometer "Crystal Ball". Measurements have been performed with a ^{12}C beam as a benchmark as well as with the proton-dripline nucleus ^{17}Ne. For comparison, breakup of ^{17}Ne induced by a carbon target has been studied as well in complete kinematics. For ^{12}C, proton knockout from different single-particle states has been identified including knockout from the 0s state by reconstructing the excitation-energy spectrum of ^{11}B utilizing g spectroscopy and the invariant-mass method. In case of proton knockout from ^{17}Ne, the excitation energy of the unbound ^{16}F clearly shows contributions from halo and core knockout. From the analysis of the momentum distributions and cross sections the occupancies for the s and p configurations in the ^{17}Ne ground state have been determined. Examples for knockout reactions populating unbound states beyond the neutron dripline will be discussed as well.

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Light ion transfer reactions with the Helios spectrometer[1]

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Light-ion induced transfer and inelastic scattering reactions on stable or long-lived targets have been used extensively to study the structure of nuclei near the line of beta stability, and much of the detailed information on the single-particle structure of nuclei has been derived from such studies. Recently, however, a substantial expansion of the range of isotopes, for which this nuclear structure information can be obtained, has presented itself by using radioactive beams in inverse kinematics reactions. Such beams are now available at a number of facilities around the world, including the in-flight production method and CARIBU facility at ATLAS [1,2] and more are coming on line in the near future.

Using inverse kinematics in conventional detector arrangements used to measure the energy and emission angle of the ejectile does, however, carry a significant penalty in terms of Q-value resolution [3], which may limit the applicability of this method. The HELIOS spectrometer, which has been used since August 2008 at ATLAS, circumvents many of the problems associated with inverse kinematics [4, 5]. In this talk I will discuss the principle of the spectrometer as well as some of main physics results that have been obtained to date in nuclei ranging from ^{13}B to ^{137}Xe using both stable and radioactive beams [6-9].

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Nuclear stopping at intermediate energies - experiment versus theory

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Owing to an enhanced interplay of the one-body and the two-body phenomena around the Fermi energy the study of heavy-ion collisions (HIC) below 100A MeV is of a particular interest. In this energy range the nuclear matter stopping power has recently been investigated in the central nucleus-nucleus collisions for the mass symmetric systems [1]. An important degree of transparency of nuclear medium has been revealed. The observed transparency is in line with our earlier simulation result by the semiclassical Landau-Vlasov transport model [2]. By using this dynamical model of HIC we study the nuclear stopping for the same reactions and energies as in the above mentioned experimental work. The stopping observables are the ratio of particle transversal and longitudinal energy R_E as well as linear momentum R_p on the same way as in the experiment. We investigate the impact on these observables of the choice of both the nuclear mean field (both of the stiffness of nuclear equation-of-state and of the interaction non-locality) and of the parameterization used and the strength of the residual nucleon-nucleon (NN) interaction.

For the local potential we take the Zamick parameterizations of the Skyrme interaction: the soft one characterized by the incompressibility modulus $K_\infty = 200$ MeV and the stiff potential with $K_\infty = 380$ MeV. The momentum-dependent interaction is represented by two parameterizations of the Gogny force with the same and the best recommended degree of non-locality: the soft force G1-D1 ($K_\infty = 228$ MeV, $m^*/m = 0.67$) and the stiff G3 one ($K_\infty = 360$ MeV, $m^*/m = 0.68$). The NN cross section is varied either by multiplying by a constant factor the empirical on energy and isospin dependent free nucleon cross section [3] or by varying the NN cross section parameterization: (i) constant or phenomenological which besides energy and isospin accounts for (ii) the NN cross section modification due to a local change of density [4, 5] as well as due to (iii) its dependence on angle [5, 6].

The momentum dependence of the interaction turns out to play a decisive role, the soft G1-D1 interaction providing a much closer agreement with the experimental results than the stiff G3 one. Either soft or stiff local potential predict by far too much stopping. The agreement of the soft G1-D1 interaction with the R_E and R_p experimental results, in particular above about 50A MeV, is improved when the density dependent NN cross section is used.

In conclusion, the new outstanding experimental findings below 100A MeV offer a unique opportunity to pin down the essential characteristics of nuclear interaction as well as to clarify the role played by the nuclear medium in modifying the NN scattering in the energy range studied.

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Properties of the alpha cluster states of ^{212}Po from elastic scattering of alpha particles from ^{208}Pb

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The alpha clustering structure of light nuclei such as ^{12}C, ^{16}O, ^{18}O, ^{28}Si etc. are rather well known. However, the alpha clustering in heavy nucleus was first proposed for ^{212}Po from theoretical calculations relatively recently [1]. The first experimental evidence of this proposition was obtained from a very recent study of ^{208}Pb(^{18}O,^{14}C) alpha transfer measurements [2]. In this work we measure the α+^{208}Pb elastic scattering to obtain a α+^{208}Pb potential to describe both elastic scattering and the properties alpha cluster states in ^{212}Po. This two body cluster core picture is appropriate as both the components are closed shell nuclei. The measurements are performed at higher energy and analyzed in terms of the phenomenological and microscopic model for elastic scattering.
The experiment was carried out at the K130 VECC Cyclotron, Kolkata facility using the alpha beam at energies 40, 43, 46, 49 and 52 MeV. A 900 μg/cm^2 self supporting target was used whose thickness was determined from alpha particle energy loss from a Thorium alpha source and also from Rutherford scattering of the beam. Silicon ΔE-E telescopes were setup for particle identification and measurement of the angular distributions.
The analysis of the elastic scattering data was carried out satisfactorily using microscopic real potentials (Paris and Reid soft core). In a recent work [3] it has been proposed that a SW+SW^{3}potential form-factor closely imitates that of the folded microscopic potential. The elastic scattering calculation with this potential is shown in figure 1. The dependence of the calculation on the variation of the shape and strength of W by keeping the real potential fixed is also shown. The measurement of extreme backward angle data would therefore be necessary to confirm the value of the imaginary potential. The properties of the alpha cluster states can be calculated using this α+^{208}Pb potential.

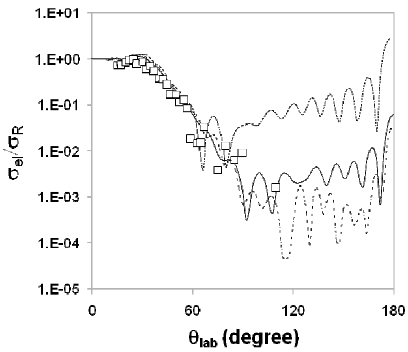

Fig. 1. The sensitivity of the elastic scattering angular distribution calculations on the imaginary part of the optical potential. The dashed-dotted and dotted lines show calculations with a SW potential of strength 30 and 10 MeV respectively. The solid lines are for a SW^2 potential with strength 30 MeV.

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Particle-number fluctuations and neutron-proton pairing effects on proton and neutron radii of even-even $N \simeq Z$ nuclei

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The particle-number fluctuation effect on the root-mean-square (rms) proton (r_p) and neutron (r_n) radii of even-even $N \simeq Z$ nuclei is studied in the isovector neutron-proton (np) pairing case. An expression of the proton and neutron quadratic radius is established using an exact particle-number projection method [1-3]. This expression does generalize the one used in the pairing between like-particles case [4-5].
The quantities r_p and r_n are then calculated for some even-even nuclei such as $0 \leq (N - Z) \leq 4$ within the framework of a Woods-Saxon model. The results are compared to experimental data as well as the results obtained when one considers only the pairing between like-particles. As a first step, the np pairing effect is studied by evaluating the relative discrepancies between the results including or not the np pairing correlations, before or after projection. It is shown that the average value of these quantities, calculated over all the considered nuclei, is roughly the same in both situations, for the proton and neutron radii. However, the np pairing effect varies as a function of $(N - Z)$ and is clearly more important when $N = Z$. As a second step, the projection effect is studied by evaluating the relative discrepancies between the results before and after projection, in the pairing between like-particles case, as well as in the np pairing case. It is shown that the average value of these quantities, calculated over all considered nuclei is also roughly the same in both situations. However, the projection effect also varies as a function of $(N - Z)$ and is more important in $N = Z$ nuclei. Moreover, the projection effect is more important than the np pairing one for the proton system whereas it is less important for the neutron system.

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Heavy Ion Collisions and the Pre-Equilibrium Exciton Model*

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The possibility of extension the pre-equilibrium exciton model to be applicable to the heavy-ion collisons can be dated to early eightieths [1–4]. The main problem was the initial exciton number. Starting originally from systematics obtained by analyses of reactions through a simple derivation iunderlying the basic physical arguments up to simple formulae replacing the empirically found trends [5–6].

The other emerging problem specific for heavy-ion reactions is the size of computation, which — fortunately — does not appear to be any substantial obstacle today, and some calculations within this model were successfully done [4, 7, 8]

Heavy-ion reactions typically involve large angular momenta, which strongly influence the particle and γ emission. The lack of a corresponding variable in the exciton model applied to heavy ions was a significant handicap. The main idea of a possibility to overcome this gap and perform spin-dependent calculations has been published some years ago [9].

The last problem included in the contribution is the emission of light particles (clusters). The Iwamoto-Harada model [10, 11], which is essentially a statistical formulation of pickup, has been extended to be suitable to describe α-particles [12] and to include also knock-out reactions [13]. Finally, we employed possibility to minimize the mathematical formalism as for the angular momenta for the cluster emission [14].

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Extending Mass Measurements and Laser Spectroscopy to the Heaviest Elements*

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The investigation of superheavy elements (SHE) on the way towards the island of stability is at the forefront of research on exotic nuclides. Such elements are of great interest for nuclear physics, atomic physics, and chemistry. While nuclear shell effects are the reason for their very existence, relativistic effects have a strong influence on their electronic shell structure that is studied by atomic physics and chemistry.

At the GSI in Darmstadt, Germany, a full suite of instruments is available for studies in all of these research areas with the recoil separators SHIP and TASCA, the Penning trap mass spectrometer SHIPTRAP, the TASISPec decay spectroscopy detector system, and many more. This worldwide unique combination together with the UNILAC accelerator provides excellent conditions for various experimental studies on SHE.

Among the recent highlights are the first direct mass measurements of nobelium and lawrencium isotopes performed with SHIPTRAP. The accurate mass values obtained give access to nuclear binding energies and allow the mapping of the deformed subshell closure at N=152.

In addition, experiments on the laser resonance ionization of nobelium and lawrencium are being prepared. Extending this powerful technique to elements above fermium will provide first experimental data on atomic levels and information on nuclear spins, moments, and charge radii independent of a particular nuclear model.

This contribution will discuss the latest results and the future plans of the mass measurement and laser spectroscopy programs.

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Dynamical effects in proton breakup from exotic nuclei

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We study dynamical effects in proton breakup from a weakly bound state in an exotic nucleus on a heavy target. The Coulomb interactions between the proton and the core and between the proton and the target are treated to all orders, including also the full multipole expansion of the Coulomb potential. The dynamics of proton nuclear and Coulomb breakup is compared to that of an equivalent neutron of higher binding energy in order to elucidate the differences with the well-understood neutron breakup mechanism. A number of experimentally measurable observables such as parallel momentum distributions, proton angular distributions, and total breakup cross sections are calculated. With respect to nuclear breakup it is found that a proton behaves exactly as a neutron of higher binding energy. The extra effective energy is caused by the combined core-target Coulomb barrier. In Coulomb breakup we distinguish the effect of the core- target Coulomb potential (called the recoil effect), with respect to which the proton behaves, again, as a more bound neutron, from the direct proton-target Coulomb potential. The latter gives cross sections about an order of magnitude larger than the recoil term. The two effects give rise to complicated interferences in the parallel momentum distributions. They are instead easily separable in the proton angular distributions, which are therefore suggested as a very useful observable for future experimental studies.

$^3He+^4He$ astrophysical factor study using activation method

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Abstract

In 1998, the $S_{34}(0)$ data difference between direct capture and activation methods [1] and its importance for the Standard Solar Model was the reason for a new experimental quest to understand the discrepancy. New results solved this issue, but introduced a new situation to clarify: $S_{34}(E)$ variations for old and new data at higher energies, an important factor in the theory models used for extrapolations to the Gamow window for this reaction, didn't look the same. Theorists' models for the old data shared the same fate as the experimental data: each $S_{34}(E)$ curve variation was far from the other and gave a different $S_{34}(0)$. That's why theorists asked for new experimental data in 0.3 - 3.0 MeV CM energy region. Very recently, one new theory approach could reproduce the new experimental data [2] but there is still a lot of controvercy on this issue.

We started this project with the main goal to clarify the situation for the energy range 1.2-3.0MeV CM. We used the activation method only, as the new data proved that direct capture and activation results have no reason to differ. A new gas cell target with thin window was designed and constructed at ATOMKI based on Monte Carlo simulations for the optimization of the gas cell dimensions. The preliminary tests and the experiment, for several energies, were run using the ATOMKI cyclotron and Van de Graaff accelerators. ^4He beam was de-focused and covered a large area on the surface of the window. Monte Carlo calculations and experimental data were analysed to check for the efficiency variation of the Ge detector due to a big area spread for the ^7Be. We present our work and results for the S_{34}.

Keywords: direct capture, low energy, solar neutrino

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Low-Lying Dipole Strength in Exotic Neutron-Rich and Neutron-Deficient Nuclei

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The pioneering results on the appearance of low-lying dipole (PDR) strength in unstable Sn isotopes [1] have stimulated both theoretical and experimental investigations on this phenomenon in exotic nuclei. Starting from the interpretation of Sn-results with respect to the symmetry energy parameters of the equation-of-state (EOS) of neutron matter [2], a vivid discussion about the correlation of low-lying dipole strength to key parameters of the EOS and, thus, the neutron-skin thickness is ongoing [3,4,5].

On the experimental side, the amount of data still is rather scarce. Here, we report about recent results obtained with the LAND-R^{3}B setup at GSI in Darmstadt, in which the Coulomb excitation of unstable nuclei at relativistic beam energies has been investigated in inverse kinematics. The experiment provides a kinematically complete measurement of all decay particles.

Energy-differential cross sections will be presented for ^{68}Ni from the one-neutron and two-neutron decay channels and interpreted in terms of giant dipole resonance (GDR) and PDR strength. The findings are compared to a complementary measurement on ^{68}Ni using photon scattering [6].

Following theoretical predictions for the appearance of PDR strength in neutron-deficient nuclei [7,8], the Coulomb excitation of ^{32}Ar and ^{34}Ar was studied using our experimental technique. Both integral and energy-differential cross sections for the one-proton and two-proton decay channels indicate a strong increase of low-lying strength in ^{32}Ar in comparison to ^{34}Ar.

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0 and 1 ħω Shell Model Description of the Phosphor Isotopes with A= 30 to 35

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The USD shell model interaction [1,2] has been very successful to describe the properties of positive parity states in sd nuclei. We have developed in Strasbourg a new interaction called PSDPF [3,4] with the aim to extend the shell model description to negative parity states throughout the sd shell. As an example, we show in Fig.1 a comparison experiment versus theory of the negative-parity states with $J^\pi = 2^-$ to 5^- members of the multiplet with dominant neutron configuration $\upsilon(d^{-1}_{3/2}f^{1}_{7/2})$ in the N = 20 isotones ^{40}Ca, ^{38}Ar, ^{36}S and ^{34}Si. In this conference, we will present results of the Phosphor isotopic chain with A = 30 (N=15) to 35 (N=20). Calculated energy spectra and electromagnetic properties will be compared to experimental results for 0ħω and intruder 1ħω states up to excitation energies of several MeV. One of our goals is also to establish for each isotope up to what excitation energy the 0p-0h and 1p-1h description remains appropriate and does not require more complex np-nh excitations.

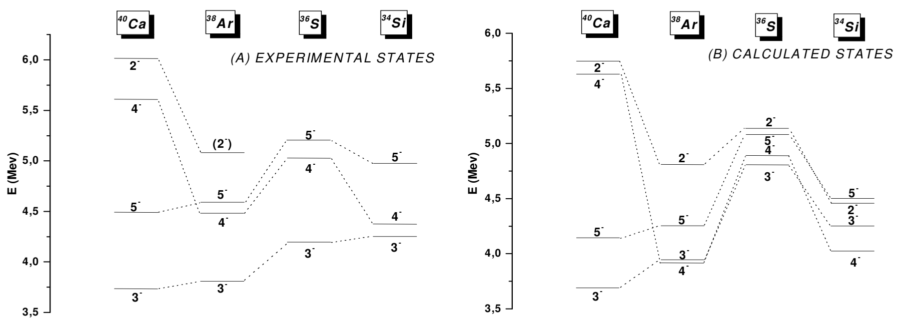

Fig. 1. The negative-parity states with $J^\pi = 2^-$ to 5^- members of the multiplet with dominant configuration $\upsilon(d^{-1}_{3/2}f^{1}_{7/2})$ in the N = 20 isotones ^{40}Ca, ^{38}Ar, ^{36}S and ^{34}Si: comparison between the experimental (A) and calculated (B) with PSDPFB excitation energy spectra.

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Population of high-spin states following fragmentation

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Projectile fragmentation of heavy atomic nuclei at relativistic velocities remains a fairly recent tool in experimental nuclear physics. Interest in fragmentation reactions is in part due to the ability to produce short-lived 'exotic' n-rich and n-deficient nuclei located far from the valley of stability. Using a ^{208}Pb fragmentation beam a recent study [1] uncovered a wealth of spectroscopic data for n-rich nuclei from Ta to Tl close to the N=126 major neutron shell closure. The current study focuses on the dynamics of fragmentation reactions, specifically the population of excited states relative to the total production of nuclei during the reaction. This is often directly determined by measuring the 'isomeric ratio' (R), the number of observed (γ-)decays from a particular metastable excited state relative to the total number of identified nuclei. R has been determined experimentally for over 20 (mainly yrast) isomeric states including five high-spin isomers with I >19 ħ in ^{211}Po, $^{211-213}$At and ^{214}Rn produced using a 1 GeV.A ^{238}U fragmentation beam at GSI Darmstadt (Germany).

Fragmentation has previously been described by a two-step process of 'abrasion' and 'ablation' [2]. A simple theoretical formula [3] is used to predict the probability of producing excited states of angular momentum I (ħ) in a given nucleus following the reaction. By integrating this function between I_m (spin of the populated isomeric state) and all states with I > I_m one obtains an estimate of R to compare with experiment. The assumption that all states populated above the isomeric state of interest eventually decay through it is known as the sharp-cutoff model. Fig. 1 compares the experimental isomeric ratio (R_{exp}) and the theoretical value (R_{th}) as a function of spin I (ħ) for isomeric states examined in the current study. The predicted population of isomeric states with I < ~15 ħ is generally overestimated, not an unexpected consequence of the assumption made by the sharp-cutoff model. However, the population of states with I > ~19 ħ is clearly underestimated. Similar patterns for high-spin states are apparent in the work of Podolyák [4] and AM Denis Bacelar [5].

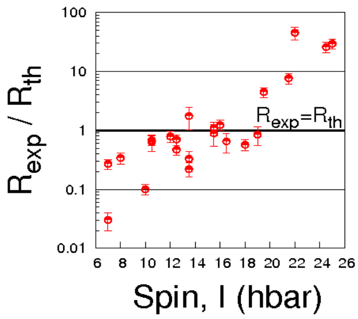

Fig. 1. Comparison of experimental and theoretical isomeric ratios determined for nuclei in this study.

Given the low probabilities of populating such high-spin states in the sharp-cutoff model the discrepancy between experiment and theory remains unexplained. Experimental data will be presented in the context of previous measurements of isomeric ratios in A ~ 200 nuclei produced via ^{208}Pb and ^{238}U fragmentation beams. More improved models of fragmentation (notably the ABRABLA [2] and INC [6] codes) will be employed to better understand the observed phenomena. It is hoped the current study will ultimately be of great interest to future experiments utilizing isomer spectroscopy. With the population of high-spin states greater than previously expected, the resulting increase in isomeric beam yields can be harnessed in a range of experiments.

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Fine structure of alpha decay of trans-lead nuclei – an intriguing nuclear structure paradigm

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The calculation of absolute values of alpha-decay rates is a problem that is not fully solved yet, especially when the transitions to excited nuclear states of the daughter nuclei are concerned (the so-called fine structure of the alpha decay). We re-examine the systematics of the experimental quantities concerning the alpha decay towards the 2^+, 4^+ and 6^+ states of the ground state band in daugther nuclei heavier than lead, in comparison with predictions of the most recent theoretical calculations. Both the experimental branching ratios (BR) and hindrance factors (HF) are considered. The BR are purely experimental quantities, while the HF, defined as the ratio between the reduced widths of the state and that of the ground state, are model-dependent quantities as they contain the barrier penetrabilities in the two channels, evaluated with a certain model.

The BR to excited states, relative to the g.s. to g.s. transition, as well as certain HF evaluations are examined both as a function of the mass number and of the valence correlation scheme parameter P of Casten ($P=N_pN_n/(N_p+N_n)$, where $N_p(N_n)$ are the number of active protons(neutrons) with respect to the nearest closed shell). The P-representation is useful because it allows a correlation with the evolution of the collectivity, distinguishes between isobars, and leads to rather smooth trajectories for the HF values. The relative BR ratios ($B_{r,gs}/B_{r,x}$, where *"x"* denotes an excited state) and the HF show similar evolutions, and the following systematic trends have been observed. For the 2^+ state: while for the "vibrational" nuclei (P-values below about 4.0) different theoretical calculations reproduce rather well the experimental values, for the "rotational" nuclei (P larger than about 4.0) the experimental data show a practically exponential increase with P, which is not reproduced by any of the theoretical approaches. For the 4^+ state, measured mostly in the "rotational nuclei": both the relative BR and HF show a striking behavior, with a pronounced maximum around P=7.5. This is rather unexpected, as all nuclei with P > 6.0 are usually considered good rigid rotors (the ratio between the energies of their 4^+ and 2^+ states is rather high, above 3.27). For the 6^+ state: the same quantities evolve practically out of phase with those of the 4^+ state (they decrease between $P \approx 4.0$ and $P \approx 8.0$). These behaviors of the 4^+ and 6^+ states are not described by the theoretical calculations.

The evolution of different nuclear structure quantities of these nuclei (moment of inertia, R(4/2) ratio, quadrupole and hexadecapole deformation) has been examined, in trying to find some correlations with the variations observed for the alpha-decay fine structure quantities. For the 2^+ state, a good correlation has been observed between the exponential increase of HF and the increase of the nuclear rigidity (nuclei with higher P are closer to a rigid rotor); a more adequate treatment of the properties of the involved states could improve the theoretical predictions (one should note that only in the coupled channel calculations of Delion *et al.,* Phys. Rev. C75(2008)054301, the structure of the excited states was explicitely taken into account, but within the rigid rotor model). As for the striking behavior of the 4^+ state, no correlation has been found, leaving the observed behavior in the region of the "good rotor" nuclei as a very intriguing phenomenon.

Correlations in structure between masses and spectroscopic observables *

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Collective effects in nuclei can often be understood by considering how many valence particles, i.e. total number of valence protons and neutrons, the nucleus has. Within the last years, ideas such as N_pN_n and P-factor schemes [1] have been successful in correlating properties such as $R_{4/2}$ which is the energy ratio between the first excited 4^+ state and the 2^+ state. In this talk, studies of the sensitivity of calculated collective contributions for deformed nuclei to separation energies will be discussed as well as how both experimental separation energies and the first excited 2^+ states show correlated changes as a function of N will be presented. Finally, enhanced collective effects [2-4] will be investigated in terms of correlations of masses and spectroscopic observables including some results using the IBA.

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Nuclear rainbow in the $^{16}O + {}^{27}Al$ system: The role of couplings at energies far above the barrier

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The $^{16}O + {}^{27}Al$ elastic and inelastic angular distributions have been measured in a broad angular range (13° < θ < 52°) at 100 MeV incident energy at INFN-LNS (Italy). The use of the MAGNEX large acceptance magnetic spectrometer [1] and of the ray-reconstruction analysis technique has been crucial in order to provide, in the same experiment, high-resolution energy spectra and cross-section measurements distributed over more than seven orders of magnitude, down to hundreds of nb/sr [2]. The data analysis shown in Fig. 1 confirms a rainbow formation as predicted by parameter-free Coupled Channel calculations obtained with the parameter free double folding Sao Paulo optical potential [3]. It also reveals the crucial role of inelastic couplings in the rainbow formation for heavy systems even at energies far above the Coulomb barrier. This behavior is also observed at higher bombarding energy as revealed by a preliminary analysis of a very recent experiment performed at INFN-LNS at 280 MeV. This feature, well known in atomic/molecular scattering, is experimentally found for the first time in Nuclear Physics [4].

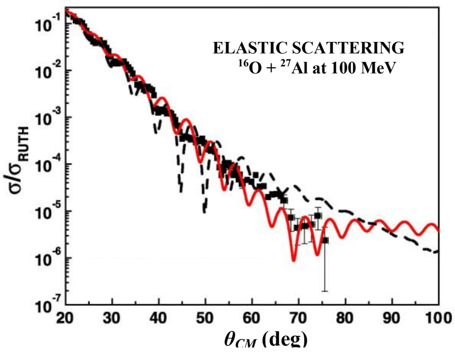

Fig. 1. Experimental angular distributions for the elastic scattering, as compared with the corresponding theoretical Coupled-Channel predictions (solid lines) and from Optical Model calculations without couplings (dashed line).

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Improved Local and Global Nuclear Mass Relations

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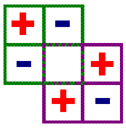
At NSD09 we showed illustrated improved Garvey-Kelson like local mass relations. One of these demonstrated a vanishing model error for heavier even-even isotopes. That is to say, the error in estimating atomic masses could be entirely accounted for by the declared experimental error in measurement.

Encouraging though this result may have been, it is not always a useful method, because frequently the unknown masses of interest lie towards the drip-lines where neighboring masses too are unknown. In this paper we show new local relations which from which generic global equations, using point functions can be derived. These new global relations are more accurate than the Garvey/Kelson and Janecke/Masson equivalents. Evidence will be presented showing that extrapolation to unknown mass regions is more reliable.

	Local Relation		Global Relation (2120 isotopes)		
	Diagram	Model Error kev	Number of Parameters	Terms satisfying Local Relation	Model Error kev
GKT	 **Classical Garvey Kelson transverse local relation**	216	509	***$f_Z(Z)$, $f_N(N)$, $f_A(N+Z)$*** **Janecke / Masson formula**	329
New	-1 +2 -1 +2 -4 +2 -1 +2 -1	82	513	*$f_Z(Z)$, $f_N(N)$, $Nf_{NZ}(Z)$, $Zf_{ZN}(N)$, odd*	174

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A microscopic particle-vibration coupling model applied to single-particle states and giant resonances

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Recently, we have developed a self-consistent particle-vibration coupling model (PVC) which is based on the use of a Skyrme-type effective interaction and does not introduce any other free parameter. In this contribution, we will survey the applications of this model to various physics cases. We start from the calculation of the single-particle strength fragmentation in magic nuclei (both stable and neutron-rich): at present, we have at our disposal a version of the model that also takes proper care of the continuum, and we can discuss advantages and drawbacks of this implementation. We then discuss the spreading width and the decay of giant resonances, by using the two examples of the Giant Quadrupole Resonance (GQR) in ^{208}Pb with its γ-decay partial widths as well, and the Gamow-Teller Resonance in few nuclei with its astrophysical implications. We conclude by a critical analysis of the open questions, the main one being how to account at the same time for the coupling with collective vibrations and with the background of non-collective states. Hints from the many-body Hedin's equations will be highlighted.

Microscopic description of reactions involving exotic nuclei

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Elastic scattering and breakup reactions represent efficient tools to investigate the structure of exotic nuclei. The main issue for theory is to determine their spectroscopic properties from the measured cross sections. The Continuum Discretized Coupled Channel (CDCC) method [1] (at energies around the Coulomb barrier) and the eikonal method (at high energies) are widely used in reaction theories. Both approaches rely on projectile wave functions as accurate as possible.

On the other hand the spectroscopy of light nuclei is well described by microscopic cluster models [2]. In this approach the wave functions are completely antisymmetrized, and the model only relies on a nucleon-nucleon interactions. Many applications have been performed in recent years for the description of light exotic nuclei, such as ^{6}He, ^{8}B or ^{11}Li [3].

The next step is to combine these microscopic wave functions with a reaction theory. This opens many possibilities for reactions around the Coulomb barrier. Not only elastic scattering can be studied, but also inelastic scattering or breakup reactions. One of the main advantages of the approach is that, in contrast with traditional models which require nucleus-target optical potentials, it only depends on a nucleon-target potential, which is in general well known. We present preliminary results on the ^{7}Li+^{59}Co elastic and inelastic scattering, where ^{7}Li is described by an α+^{3}H cluster structure . Theoretical predictions are compared with experimental data at energies around the Coulomb barrier [4].

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Quantum partner-dance of two interacting ^{12}C nuclei fuels stellar carbon burning*

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Using time-dependent wave-packet dynamics within a nuclear molecular picture, which is an innovative model of fusion, an alternative approach to a quantitative understanding of the ^{12}C + ^{12}C sub-Coulomb fusion resonances is introduced. Various molecular resonances are predicted near the Gamow peak energy (1.5 MeV)- that is, the stellar energy with the highest ^{12}C + ^{12}C fusion rate. These are caused by the dance-like movements of the ^{12}C nuclei symmetry axis in the dinuclear system, which are closely correlated to fusion. This generates fusion resonances which seem to correspond well with the experimental results. Therefore, the present approach might be a more suitable tool for expanding the cross section predictions towards lower energies than the commonly used potential model approximation. The results are also important for understanding X-ray superburst ignition on accreting neutron stars, which is likely triggered by a high rate of carbon burning.

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New nonrelativistic energy density functionals for low-energy nuclear phenomena*

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Methods based on nuclear energy density functional (EDFs) have already become the standard tool in describing nuclear ground states and low-energy excited states [1, 2]. In the present contribution, I will focus on recent developments related to the quest for new-generation functionals that might provide us with increased precision of global description of nuclear data and link low-energy phenomena to ab-initio properties of nuclear matter and nuclear interactions. The main line of generalizations will be in expansions of EDFs in series of higher-order corrections related to derivatives of densities and fields [3]. I will also discuss generalizations of momentum-dependent interactions, like the Skyrme force, to higher orders [4] and derivations of quasilocal higher-order functionals from nonlocal ones [5]. Finally, I will present ideas related to introducing new functionals based on regularized zero-range forces [6].

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Recent Penning trap mass measurement results of neutron rich nuclei

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Several on-line Penning trap facilities provide high-precision atomic masses of short-lived nuclei. On neutron rich side of the nuclide chart these data is commonly used either for understanding nuclear structure or for astrophysical r-process. Typically mass precision of about 10 keV is reached.
In this contribution I'll summarize the most recent atomic mass measurements of neutron rich nuclei measured with Penning traps. These include, for instance, masses near ^{132}Sn and around ^{100}Zr subshell closure.

Results from the experimental campaign of the AGATA Demonstrator at LNL

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The expected experimental conditions at the planned future facilities for radioactive ion beams and for high-intensity stable beams are extremely challenging, requiring unprecedented levels of efficiency and sensitivity, which cannot be reached with the conventional 4π arrays of Compton-suppressed high-purity germanium detectors. The approach pursued in the past few years implies covering the full 4π solid angle with germanium detectors only, and maximising the photopeak efficiency and the peak-to-total ratio through the identification of the interaction points of the photons within the germanium crystals and a software reconstruction of the trajectories of the individual photons. These processes are generally known as *pulse shape analysis* and *γ-ray tracking*. Arguably, the major advantage with respect to the present generation arrays is the excellent spectra quality provided up to relativistic beam velocities, where the Doppler broadening correction is dominated by the position resolution within the individual crystals rather than by the finite opening angle of the detectors.
Presently, two projects aim to build an array based on the techniques of pulse shape analysis and γ-ray tracking: AGATA in Europe and GRETA in the United States. Both instruments are expected to play a major role in the future nuclear structure studies at the very limits of nuclear stability.
This contribution will focus on the AGATA project. A subset of the whole array, known as the AGATA Demonstrator Array, has operated since 2009 until the end of 2011 at the Laboratori Nazionali di Legnaro, where it was installed at the target position of the magnetic spectrometer PRISMA. Following the commissioning runs in 2009, the AGATA Demonstrator has been exploited in a two-years experimental campaign. A total of 20 PAC-approved measurements were performed, plus 3 in-beam tests, for a grand total of 148 days of beam time. Given the possibilities offered by the coupling with the PRISMA magnetic spectrometer, the campaign has focused mainly on the study of moderately neutron-rich nuclei populated via multinucleon transfer or deep inelastic reactions. However, the proton-rich side of the nuclides chart has been explored as well by using other complementary devices such as the TRACE silicon detectors or the scintillators of HELENA and HECTOR. The analysis of all of the performed experiments is still in progress and the preliminary results of a few selected of them will be presented.

*on behalf of the AGATA and PRISMA Collaborations

Skyrmions*

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The Skyrme model provides a soliton description of atomic nuclei. Nuclei can be modeled by quantising certain degrees of freedoms of Skyrmions, the solutions of the Skyrme theory. In the past, this has served to describe the properties of nucleons as well as the rotational spectra of some small nuclei. More recently, α-particle clustering has been observed in the Skyrme model, and it predicts interesting structures for nuclei of baryon number B divisible by four, such as 8, 12, 16, 24, 32.

A promising approach to find some Skyrmions with intermediate baryon numbers is to remove single nucleons from Skyrmions made from α-particles. By means of quantising the resulting solutions, spectra of nuclei with 31 baryons could be modeled. More insight into the interactions of two α-particles has been gained recently [1], and it seems now possible to find vibrational spectra, for example of Sulphur-32.

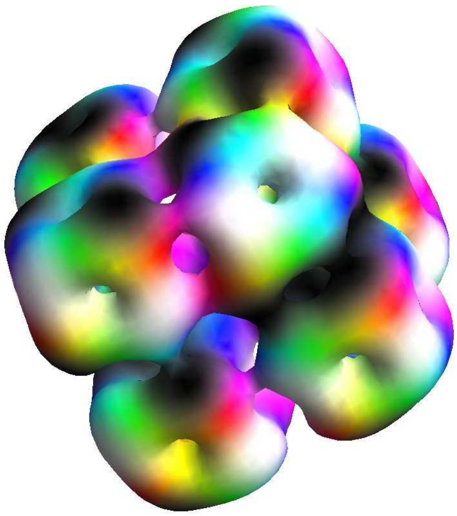

FIG. 1: Removing one baryon from the cubic $B = 32$ Skyrmion we obtain a $B = 31$ Skyrmion. The missing baryon can be seen here as a distorted corner in what looks otherwise like an approximate cube.

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Collisions Induced by Halo and Weakly Bound Nuclei Around the Coulomb Barrier: Recent Results at INFN-LNS Catania.

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The study of collisions around the Coulomb barrier induced by halo and/or weakly bound nuclei has been object of many publications in the last years. In fact, it has been shown that the peculiar structure of such nuclei, which have very low break-up thresholds and also an extended matter distribution in the case of the nuclear halo, can strongly affect the reaction mechanisms around the Coulomb barrier (see e.g. [1,2,3] and references therein). One expects that direct processes like breakup or transfer are favored by the low breakup thresholds and by the cluster or halo structure of such nuclei. Due to the low breakup threshold coupling effects to the continuum are expected to play an important role on fusion and elastic scattering, and a complete description of such processes requires complex CDCC calculations. Recent experimental results on the above topic obtained by our group in Catania will be summarized and discussed.

Almost all elastic scattering and direct reaction data with halo nuclei around the barrier, published in the literature, concerns reactions induced by ^{6}He. Therefore data with different halo nuclei are needed. We recently measured elastic scattering and transfer+breakup angular distributions for ^{11}Be+^{64}Zn, observing a strong suppression of elastic scattering and, correspondingly, a strong enhancement of total reaction cross section. The data, together with the Optical Model fits and CDCC calculations, will be presented and discussed.

In the study of collisions induced by halo nuclei around the barrier, controversial conclusions concerning the presence or not of possible enhancement effects of the fusion cross sections have been reached by different authors. We recently extended to lower energies our previous [5] comparison of fusion excitation functions for the systems ^{6,4}He+^{64}Zn. An enhancement of fusion cross section for the ^{6}He induced collision when compared with the one induced by ^{4}He has been observed and its possible origin will be discussed.

The study of collisions induced by stable weakly bound nuclei, which do not have halo structure, has also a considerable interest, and we recently measured elastic scattering angular distributions and total fusion cross sections at several energies around the barrier for the systems ^{6,7}Li+^{64}Zn. The energy dependence of the optical potential has been extracted from the optical model analysis of the elastic A.D. , and no usual threshold anomaly was observed. A comparison of the experimental relative yields of different heavy residues with the predictions of CASCADE suggests that complete fusion dominates at energies above the barrier whereas incomplete fusion or transfer are dominant in the subbarrier region.

The conclusions of our studies will be compared with the ones of different authors to see if clear systematic behaviors appear in the various aspect of the discussed topic and to understand which type of new experimental data would be helpful for a better understanding of this subject.

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Applications of In-Medium Chiral Dynamics to Nuclear Structure

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A relativistic nuclear energy density functional has been developed in the last years, guided by the most important feature connecting chiral dynamics and the symmetry breaking pattern of low-energy QCD: long- and intermediate-range interactions generated by one-and two-pion exchange. We performed several calculations for ground-state properties [1] and excited-state properties [2] (at the same quality level of the best phenomenological relativistic mean-field models). The model has been furhter extended to describe single Λ-hypernuclei [3].
In this talk we are going to show an important extension to our original energy functional, in which the *particle-particle* channel is constrained by chiral dynamics (two-body forces at N^3LO order and three-body forces at N^2LO) [4].
Possible extensions to higher partial waves and isospin dependence will be discussed.

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Present status on the search for Neutrinoless Double Beta Decay

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Following the recent results on the measurement of the neutrino oscillation parameters, the determination of the mass presents itself as one of the most interesting challenges in neutrino physics. Different approaches exist but the most popular and most widely explored is the neutrinoless double beta decay ($0\nu\beta\beta$).
The neutrinoless double beta decay process can be mediated by light massive Majorana neutrinos and can potentially be observed in isotopes where the double beta decay with neutrinos ($2\nu\beta\beta$) occurs, and has already been observed in several isotopes. Unlike the decay with neutrinos, where a part of the decay energy is carried by the neutrinos resulting in a continuous β spectrum, in $0\nu\beta\beta$ decay, the whole of the decay energy is carried out in the electrons, resulting in the observation mono-energetic peak at the decay endpoint. Its observation would imply violation of the leptonic number on the neutrino sector and would potentially shed light into the neutrino mass, as the half-life of this decay would depend on the effective mass of the electron neutrino.
Several experiments are currently aiming to observe this decay mode, exploring a wide range of the possible isotopes, and explore several different technologies. At present a claim upon the observation of $0\nu\beta\beta$ decay on the ^{76}Ge isotope has been performed by a subgroup of the Heidelberg-Moscow experiment, whose verification is now the primary aim of the new generation of experiments. Presently several experiments are being developed to observe this process with several different isotopes, some of which are already taking data with the potential to test the existing claim.
In this talk a review of the status on the search for neutrinoless double beta decay will be given, with particular emphasis on the presently running experiments. A review of the detection approaches and isotopes used in current and future experiments will be given, along with an explanation of the different limiting backgrounds and uncertainties, and a comment on the aimed sensitivities of each experiment.

Challenges to understanding the structure of light nuclei

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In certain classes of nuclear states, nucleons condense into sub-units or clusters. This phenomenon has been shown to be most pronounced close to the associated cluster decay threshold. Perhaps the most famous of these is the Hoyle-state in 12C. This talk will examine a range of cluster states from those composed entirely of alpha-particles to cluster states in neutron-rich nuclei where valence neutrons play a role very similar to electrons in covalent molecules – they are exchanged between the centres/cores.
The structure of 12C has remained something of an enigma, especially the 7.65 MeV, Hoyle-state. It is almost universally accepted to possess a cluster structure, but the very nature of which remains to be fixed. Part of the fascination with the state is its influence on the synthesis of carbon in stars. One step forward to the understanding of the structure would be the discovery of a 2+ collective excitation. As yet the evidence is sparse. We will present our most recent measurements performed at the iThemba LABs and Notre Dame, in which we have made a search for this excitation and the associated 4+ state. The results of these results will be discussed in the context of other measurements.
As noted, the Hoyle-state is believed to have a pronounced 3 alpha cluster structure. What happens if valence neutrons are added is an intriguing question. It has been found that in systems composed of two-alpha particles and valence neutrons that the neutrons are exchanged between the alpha-cores in a manner which is similar to the exchange of electrons in covalent atomic molecules. Such structures are found, for example, in the nuclei 9Be and 10Be and due to their similarity with their atomic cousins have been called “nuclear molecules”.
We have investigated the resonant scattering of 10Be on 4He in an attempt to populate molecular type resonances in 14C, which are composed of three alpha-particles and two valence neutrons. These measurements were performed at ORNL with a helium gas target populating resonances from the decay threshold to an excitation energy of above 20 MeV. Similarly measurements have been performed on 7Be+4He and 9Be+4He. The latest results from the on-going analysis will be presented.

Recent progress in nuclear astrophysics

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Nuclear astrophysics is an exciting collaborative research area where nuclear physicists, astrophysical modelers and observational astronomers work together to understand the structure and evolution of astrophysical objects. These can range from stars where the nuclear reactions occur under conditions of hydrostatic stability and often involve reactions between stable nuclei, to objects such as novae, x-ray bursters and supernovae where the reactions occur in explosive conditions and often involve unstable, short-lived nuclei. As the range of nuclei available as radioactive nuclei from new facilities increases and the quality and intensity of the beams improves, more of the key reactions which determine the development of these unique explosive objects can be studied.

The study of the key reactions involved in stars generally involves measuring very small cross sections at low energies and this brings particular challenges. Different, but equally challenging, are the measurements of explosive environment reactions with low intensity radioactive beams. Other reaction processes such as the s- and r- and p-processes require measurements of neutron capture or gamma absorption. New experimental approaches have had to be developed to meet these unique challenges. In many cases the beams required for the direct measurements are not available, or the cross sections are too low for present experimental approaches. In these situations we have to revert to calculating the reaction rates using models or knowledge of the structure of the interacting nuclei. This in turn may involve using indirect techniques to determine this information from other reaction measurements.

In this talk I will review the main nucleosynthesis processes and the astrophysical sites where they occur, as well as presenting some recent results on the key reactions involved in novae and AGB stars.

Electron Screening in Nickel

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Due to Coulomb repulsion the cross section for charged particle induced nuclear reaction drops rapidly with decreasing beam energy and as a consequence at energies far below the Coulomb barrier, the reaction rate becomes very low. For nuclear reactions studied in the laboratory, the target nuclei and projectiles are usually in the form of neutral atoms or molecules and ions, respectively. The electron clouds surrounding the interacting nuclides act as a screening potential. In order to account for this effect, electrons can be thought of as effectively lowering the Coulomb barrier by a constant and energy-independent energy increment U_e, the screening potential. The increment of impact energy leads to a higher cross section for screened nuclei than would be the case for bare ones.

Experimental studies of low-energy fusion reactions involving light nuclides [1-5] have shown the expected exponential enhancement of the cross section at low energies, which for the metals were much larger than could be accounted for from the adiabatic limit. In addition, an increase of the screening potential proportional to proton number *Z* of the target was observed in Be and V targets [5-6]. The discrepancy between measured U_e and the adiabatic limit is presently not completely understood.

In order to further investigate electron screening phenomenon we studied proton induced nuclear reactions over an energy range from 1.35 to 3.08 MeV for different environments: Ni metal and NiO insulator. The measurements were based on observation of the γ-ray yields of ^{59,61,63,64,65}Cu and ^{58,60,62}Ni produced in the reactions: ^{58}Ni(p,γ)^{59}Cu, ^{60}Ni(p,γ)^{61}Cu, ^{62}Ni(p,γ)^{63}Cu, ^{64}Ni(p,γ)^{65}Cu and ^{58}Ni(p,p'γ)^{58}Ni, ^{60}Ni(p,p'γ)^{60}Ni, ^{62}Ni(p,p'γ)^{62}Ni, ^{64}Ni(p,nγ)^{64}Cu using high purity natural Ni and NiO targets. In a very similar (p,n) reaction in vanadium which has only three protons less than nickel, an electron screening potential of $U_D=27\pm9$ keV was measured (U_D is the difference between screening potentials in metal and insulator targets). Due to the prediction [6] of the linear dependence of U_D on target *Z*, we expected U_D in Ni to be around 30 keV. However, our preliminary experimental results give $U_D=48\pm14$ keV. Although the large error bars still allow U_D to be the same in Ni and V, our screening potential for Ni is actually the highest screening potential ever measured.

Also, we have observed the decay of ^{61}Cu produced in the reaction ^{60}Ni(p,γ), (decay by $\beta^+$and electron capture) in order to find possible decay rate perturbation by a change in atomic electrons and found a difference in half-life of about 1% for metallic compared to oxide environment, respectively. However, the difference in β^+/EC branching ratio is larger.

The present preliminary results show that the metal surrounding clearly affects the fusion reactions at low energy and that it also affects the decay rate. It also points to a conclusion that electron screening dependence on Z is not simply linear but that it depends on the environment in a more complicated way.

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Low-lying dipole response in the stable ^{40,48}Ca nuclei with the second random-phase approximation

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The Skyrme-second random-phase approximation is used to analyze the low-energy dipole excitations for the stable isotopes ^{40}Ca and ^{48}Ca. For the latter a significant amount of strength is found experimentally [1,2] which is not well described within RPA models. The presence of a neutron skin in the nucleus ^{48}Ca would suggest the interpretation of the low-lying response in terms of a pygmy excitation. The inclusion and the coupling of 2 particle-2 hole configurations in the second random-phase approximation [3] lead to an appreciable dipole response at low energies for the neutron-rich nucleus ^{48}Ca. The composition of the excitation modes (content of 1 particle-1 hole and 2 particle-2 hole configurations), their transition densities and their collectivity are analyzed. This analysis indicates that these excitations cannot be clearly interpreted in terms of oscillations of the neutron skin against the core. In fact, only the most collective peak exhibits features usually associated to pygmy resonances while for the other states different properties are found. This suggests that the ^{48}Ca nucleus is still too light to present clear signatures of an oscillation of the neutron skin against the internal core and that individual degrees of freedom are still dominant in the description of the dipole low-energy spectrum as for lighter nuclei.

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Brueckner – Hartree-Fock Based Optical Potential for p-A Scattering Involving Exotic Nuclei

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Conventionally, the proton distribution in nuclei can be reliably determined through the electron scattering, while the corresponding neutron distribution is extracted only indirectly. The proton-nucleus scattering provides a useful tool to determine either the parameters entering in the assumed shape of the neutron distribution or test the reliability of the theoretically calculated neutron distributions. The Bethe - Brueckner Hartree-Fock (BBHF) based optical potential used in the calculation of the experimental observables (e.g. differential cross section, polarization) of the nucleon – nucleus scattering requires as input (1) the nucleon – nucleon (NN) interaction and (2) the nucleon distributions in target nuclei. Various local realistic inter-nucleon (NN) potentials like local Hamada-Johnston (HJ), Reid93, Urbana av14, Argonne av18 along with several model nucleon density distributions are employed in generating the nucleon optical potential. We study the sensitivity of the calculated physical observables on the NN interaction and density distributions used. For illustration, some results of the representative cases including the nuclei having a halo structure, will be presented and discussed.

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Concealed configuration mixing and shape coexistence in the platinum nuclei

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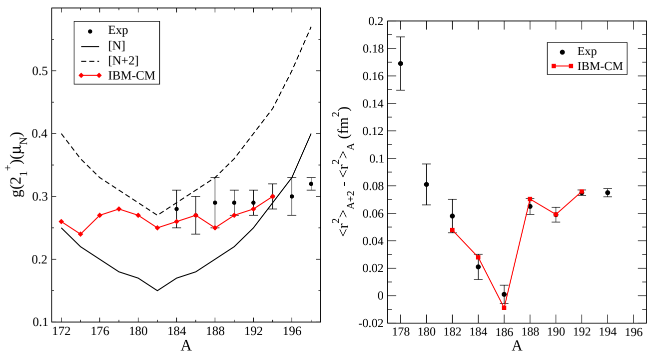
Shape coexistence has been observed in many mass regions throughout the nuclear chart and turns out to be realized in more nuclei than anticipated a few decades ago [1]. A particularly well-documented example of shape coexistence is the Pb region where ample experimental evidence for shape coexisting bands has been accumulated for the Pb (Z=82) and Hg (Z=80). For these nuclei the existence of intruder configurations is self-evident after a careful view of the energy level systematic, where the intruder energies show a clear parabolic behavior.
The case of Pt, as well as Po isotopes, although in the Pb region, is particularly intriguing because the parabolic characteristic of the energy systematic is lost. In this work we investigate the role of configuration mixing in the Pt region using the framework of the Interacting Boson Model (IBM). For this chain of isotopes the nature of the ground state changes smoothly, being spherical around mass $A \sim 174$ and $A \sim 192$ and deformed around the mid-shell $N = 104$ region. We start our study with a detailed study of excitation energies and $B(E2)$ transition probabilities to accurately fix the IBM Hamiltonian and $E2$ transition operator [2]. We prove that those observables are not valid to discriminate about the necessity or not of using intruder configuration in the description of Pt nuclei. We next present our calculations using IBM with configuration mixing for gyromagnetic factors (see left side of the figure), α-decay hindrance factors, and isotope shifts (see right side of the figure). It will become evident the necessity of incorporating intruder configurations to obtain an accurate description of the latter properties [3].
The study of the Pt nuclei is interesting because it demonstrates that calculations of a very different nature can give rise to a good description of a number of properties. In this respect, the use of the configuration mixing is quite illuminating as it consistently describes an as large set of observables as possible.



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Recent Experimental Results with Uranium Fragments at the Present FRS

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New experimental results were obtained with relativistic exotic nuclei produced via uranium projectile fragmentation and fission at the present in-flight separator FRS at GSI. More than 57 neutron-rich isotopes have been discovered in the element range from Nd to Ac. Most of these isotopes have been identified for the first time directly with the FRS and there production cross section have been measured and compared to theoretical predictions. In other experimental campaigns the fragments were separated in flight and injected into the storage-cooler ring ESR for accurate mass- and lifetime measurements. New mass values have been measured for 33 different nuclides circulating in the ESR. In the preparatory phase for the new large-acceptance in-flight separator (Super-FRS) at FAIR pioneering experiments with the combination of a cryogenic gas stopping cell and the multi-reflexion time-of-flight spectrometer have been performed. First results of this novel experimental setup will be presented.

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Deeply-bound Nucleon Removal and Transfer from Light Exotic Nuclei.

The distribution of spectroscopic strength in nuclei can be extracted from direct-reaction cross section measurements, assuming a proper modelling of the reaction mechanism. Direct transfer or knockout reactions in inverse kinematics, at low and intermediate energies respectively, are essential tools to study the shell structure of unstable nuclei.

Recently, a compilation of one-nucleon removal at intermediate energies from sd-shell exotic nuclei showed that the measured cross sections of knocking out a deeply-bound nucleon (namely a neutron in ^{32}Ar, ^{28}Ar and ^{24}Si) are about four times smaller than predictions from state-of-the-art calculations [1]. On the other hand, at low energy, a study of the (p,d) neutron transfer on the proton-rich ^{34}Ar and on the neutron-rich ^{42}Ar provides experimental spectroscopic factors in agreement to within 20% with large-basis shell model calculations [2]. These findings which are in agreement with a previous systematic study of transfer reactions [3] are inconsistent with the trend observed in knockout. Therefore, it is suggested that these two probes lead systematically to different spectroscopic factors. The origin of this difference has to be understood.

To further investigate this question, we performed one-nucleon removal on ^{14}O and ^{16}C at the NSCL at 53 and 75 MeV/nucleon respectively. Both have a large difference of proton and neutron separation energies, of about 20 MeV, similar to the cases where a strong discrepancy between knockout measurements and theoretical cross section predictions were observed. Moreover, in order to have a complete description of a same proton-rich nucleus both in knockout and transfer, we also studied ^{14}O via the one-nucleon transfer reactions ^{14}O(d,t)^{13}O and ^{14}O(d,^{3}He)^{13}N at 18 MeV/nucleon at GANIL. The results of both experiments will be presented and compared.

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^{12}C+^{16}O: properties of sub-barrier resonances γ-decay

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The investigation of resonant behaviour in excitation functions of light and medium mass systems at low energy (until few MeV per nucleons) is one of the most exciting topics in nuclear physics since 1960's. Today quasi-molecular resonances are well established and understood. Our experimental programme is focused on the properties of those resonances decay. Following Bohr's hypothesis of the compound nucleus, the decay should be independent of the entrance channel. However if the number of open channels is small this hypothesis becomes less pertinent and the subsequent decay starts to be more dependent of the entrance channel. Through selection rules and structural effects, the resonance will feed specific states.

Our recent experiments deal with the electromagnetic decay of the resonance. One of the best way to test this electromagnetic decay is to use the the radiative capture reaction in which the resonance decay solely by γ-ray emissions. Radiative capture of light particles, *e.g.* n, p or α, is a well known process especially in the nucleosynthesis process in stellar environment. Between light heavy ions, *e.g.* ^{12}C+^{12}C or ^{12}C+^{16}O, this reaction channel have been studied in the 80's [1,2] and present sharp resonances around the Coulomb barrier. Due to experimental limitations, it was not possible to observe the complete resonance decay patterns. We performed new radiative capture measurement in ^{12}C+^{16}O using γ-recoil techniques in order to suppress the overwhelming γ-flux coming from the fusion-evaporation channels. Using the high efficiency γ-array (BGO) coupled to the very rejective 0°-spectrometer DRAGON of the TRIUMF laboratory (Vancouver, Canada) in order to select the ^{28}Si, we performed a series of experiments at several resonant energies.

Previous studies done in our group by Lebhertz *et al.* [3] on this system have shown that above the Coulomb barrier ($V_B \sim 7.8$ MeV) resonances can be described by mixture of two spins. In order to shed light on doorway states in the γ-decay of ^{28}Si, we recently performed measurement below the Coulomb barrier. Both explored energies correspond to resonant structures: one narrow in the radiative capture cross section to the 2^+_1 [2] at $E_{c.m.} = 7.2$ MeV and the other one, broad, at $E_{c.m.} = 6.6$ MeV, observed in the fusion cross section by Christensen *et al.* [4] and Cujec *et al.* [5]. At the lowest energy, located $\sim 15\%$ below the barrier, a strong feeding of $T = 1$ states around 10 MeV arises. Monte-Carlo simulations performed display the particular importance of the 1^+, $T = 1$ at 11.446 MeV. Electron scattering experiments [6] demonstrate that this state concentrates a large part of the M1 isovector strength in good agreement with shell model calculations.

Tentative attribution of resonance spins will be presented together with comparison with our previous ^{12}C+^{16}O experiment [3] and with neighbouring system ^{12}C+^{12}C in which the importance of $T = 1$ states has also been demonstrated [8].

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Unusual states in light nuclei

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Light nuclei are the interesting objects. The properties of light nuclei can change drastically with adding or removal a single nucleon. Only in the region of light nuclei, species beyond both borders of nuclear stability are known, and the nuclei with the highest N/Z ratio are investigated. Additionally *ab initio* calculations could be made for nuclei in this region. These calculations provide for reliable criterion for selection of the most interesting findings.

Recent developments in the experimental technique and analysis [1-5] presented a group of the unusual levels in light nuclei; some of them were in the nuclei beyond the stability borders. The single particle or the cluster structure of the levels in question is a conventional issue of the “old” models; only the extreme pure character of the structure seems unusual. However, the understanding of the structure observed at the neutron rich border of stability should overstep the limits of the present knowledge.

I’ll consider the most interesting observations using mainly Ref.s [1-5], and perspectives for future experiments.

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The r-process nucleosynthesis: nuclear and astrophysics challenges

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About half of the nuclei heavier than iron observed in nature are produced by the so-called rapid neutron capture process, or r-process, of nucleosynthesis. The identification of the astrophysics site and the specific conditions in which the r-process takes place remains, however, one of the still-unsolved mysteries of modern astrophysics. Another underlying difficulty associated with our understanding of the r-process concerns the uncertainties in the predictions of nuclear properties for the few thousands exotic neutron-rich nuclei involved and for which essentially no experimental data exist.
The present contribution emphasizes some important future challenges faced by nuclear physics in this problem, particularly in the determination of the nuclear structure properties of exotic neutron-rich nuclei as well as their radiative neutron capture rates and their fission probabilities. These quantities are particularly relevant to determine the composition of the matter resulting from the r-process. Both the astrophysics and the nuclear physics difficulties are critically reviewed with a special attention paid to the r-process taking place during the decompression of neutron star matter or within the neutrino-driven wind of type II supernovae.

Anomalous behaviour of DSSSDs*

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Double Sided Silicon Strip Detectors (DSSSDs) are often used in nuclear physics experiments in a wide energy range. According to the previous experiments, when a particle hits the interstrip region of these detectors, different effects may occur. Anomalous response can be due to the inhomogeneous electric field in the region, lost charge in dead layers and to different ionization profiles that detected ions may have. Charge sharing, pulse height deficits and inverse polarity pulses on adjacent strips can influence the measured charge [1, 2, 3]. In order to undestand this behaviour and improve DSSSD use, an experiment was performed at the scanning proton microbeam of the Ruđer Bošković Institute (RBI) using low proton microbeam currents ($\sim fA$) and two DSSSDs (thickness 72 μm and 1000 μm). The response of these detectors is studied as a function of the beam position, at different beam energies (0.8, 1.7, 3, 6 MeV) and bias voltages. Results show that the detector area, where full charge is collected, is not constant with respect to the ion penetration depths. Moreover the behaviour of the charge collection in the interstrip region shows strong and complex dependence with the amplitude of the inverse polarity pulses. Mechanisms behaviour and implications by using DSSSD in nuclear physics experiments will be presented.

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DSA lifetime measurements of ^{124}Cs in the context of time-reversal symmetry

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Symmetry considerations dominate modern quantum physics from theoretical as well as experimental standpoint. Time-reversal is one of the fundamental symmetry incorporated in the description of the atomic nucleus. The possibility of time reversal symmetry breaking appears in the Cabibbo-Kobayashi-Maskawa matrix of the standard model, however, it is not associated with low energy nuclear excitations where time-reversal invariance rules the quantum description of the strong interaction. Even if the time-reversal is fundamentally conserved, there is a possibility of its spontaneous breakdown.

A hypothesis of the chiral symmetry breaking opened a new opportunity for the study of spontaneous time-reversal symmetry breaking in an atomic nucleus. The occurence of chirality has been found in ^{126,128}Cs nuclei [1,2] for which specific electromagnetic selection rules have been found in Doppler Shift Attenuation experiments. Here, recent DSA measurements in the ^{124}Cs nucleus will be presented. The ^{124}Cs nucleus was produced in the ^{114}Cd(^{14}N,4n)^{124}Cs reaction at Heavy Ion Laboratory of the University of Warsaw. The obtained results agree with basic expectations deduced from the chiral symmetry breaking. A connection between the chirality phenomenon and the time-reversal symmetry will be discussed and a possibility of using chiral doublets for studies of fundamental time reversal symmetry will be proposed.

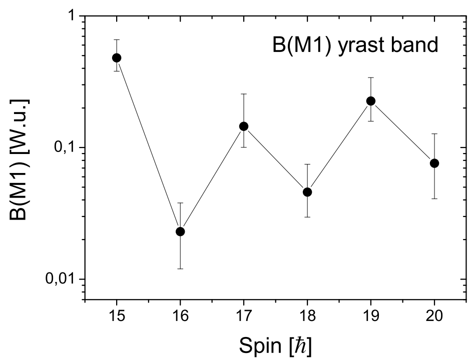

FIG. 1: M1 gamma-selection rules resulting from spontaneous time reversal symmetry breaking in ^{124}Cs.

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Finite-size instabilities in nuclear energy density functionals

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In view of the next generation of radioactive ion beam facilities that will allow to probe the properties of very exotic nuclei, there has been a major theoretical effort to refine and extend nuclear energy density functionals (EDF) for atomic nuclei. These more involved EDFs often contain strong derivative terms that may lead to finite-size instabilities when their coupling constants exceed certain limits. The determination of these limits is a delicate problem. Some of the instabilities can be studied with linear response theory for infinite nuclear matter, as demonstrated by Lesinski et al. [1], whereas others - thus far - are only observed in studies of finite nuclei. The latter studies require the solution of the mean-field equations in the most general possible way, that is, with symmetry-breaking and not cutting the instabilities artificially through the use of a finite-size basis.

A consistent understanding of these instabilities is of the utmost importance for the development of future nuclear EDFs. Indeed, when the finite-size instabilities are related to the so-called time-odd terms of the EDF that only contribute when time-reversal invariance is broken [2,3], they cannot be detected when the coupling constants in the EDF are adjusted because fitting protocols focus on the ground-state properties of even-even nuclei, hence leading to unstable interactions.

In this contribution, we will present an extensive study of finite-size instabilities in atomic nuclei, probed with the very general 3D codes that have been developed within our collaboration. We will discuss several terms causing finite size instabilities, focussing in particular on the dramatic changes observed in the nuclear density and the spin density at the onset of the instability which provide an insight into the question why some finite-size instabilities cannot be observed in all methods.

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Ab Initio Calculations of Light-Ion Fusion Reactions*

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The exact treatment of nuclei starting from the constituent nucleons and the fundamental interactions among them has been a long-standing goal in nuclear physics. Above all nuclear scattering and reactions, which require the solution of the many-body quantum-mechanical problem in the continuum, represent an extraordinary theoretical as well as computational challenge for *ab initio* approaches.

I will shortly present a promising approach, the *ab initio* no-core shell model/resonating-group method (NCSM/RGM) [1,2], which complements a microscopic cluster technique with the use of two-nucleon realistic interactions, and a microscopic and consistent description of the nucleon clusters. This approach is capable of describing simultaneously both bound and scattering states in light nuclei. I will discuss applications to light nuclei binary scattering processes and fusion reactions that power stars and Earth based fusion facilities, such as the deuterium-^{3}He fusion [3] shown in Fig. 1, and outline the progress toward the treatment of three-body clusters and the inclusion of the three-nucleon force into the formalism.

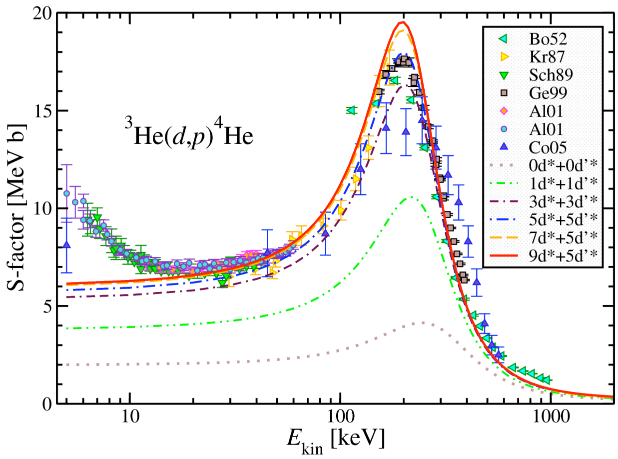

Fig. 1. Experimental astrophysical S-factor for the ^{3}He(d,p)^{4}He reaction from beam-target measurements (symbols) compared to *ab initio* NCSM/RGM calculations (lines) for bare nuclei. The calculated S-factor improves with the inclusion of the virtual breakup of the deuterium, obtained by means of excited $^3S_1$-$^3D_1$ (d*) and $^3D_2$ (d'*) deuterium pseudo-states. No electron-screening enhancement is present in the theoretical results contrary to the beam-target data.

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Competition between fusion-fission and quasifission in the reactions with heavy ions leading to the formation of Hs

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Mass and energy distributions of binary reaction products obtained in the reactions $^{22}Ne + ^{249}Cf$, $^{26}Mg + ^{248}Cm$, $^{36}S + ^{238}U$ and $^{58}Fe + ^{208}Pb$ leading to Hs isotopes have been measured. At energies below the Coulomb barrier the bimodal fission of Hs*, formed in the reaction $^{26}Mg + ^{248}Cm$, is observed. In the reaction $^{36}S + ^{238}U$, leading to the formation of a similar compound nucleus, the considerable part of the symmetric fragments arises from the quasifission process. At energies above the Coulomb barrier the symmetric fragments originate mainly from fusion-fission process for both reactions with Mg and S ions. In the case of the $^{58}Fe + ^{208}Pb$ reaction the quasifission process dominates at all measured energies.

The pre- and post-scission neutron multiplicities as a function of the fragment mass have been obtained for the reactions studied. In the case of the $^{26}Mg + ^{248}Cm$ reaction the pre-scission (M_{pre}) and post-scission (M_{post}) neutron multiplicities dependencies on fragment mass are close to the predictions of statistical model calculations. For the $^{36}S + ^{238}U$ reaction M_{pre} for the symmetric mass split is 0.5 neutron less than that for the $^{26}Mg + ^{248}Cm$ reaction and shows a parabolic mass dependence with a maximum at $A_{CN}/2$ and a decrease for asymmetric masses. It may be caused by the presence of quasifission component in the symmetric mass region for the ^{36}S ions induced reaction. In the case of the $^{58}Fe + ^{208}Pb$ reaction M_{pre} on mass dependence is parabolic. Moreover, the deviation of M_{post} from linear dependence, observed for the asymmetric mass splits, may lead to the conclusion that at least in the asymmetric quasifission process the complete dissipation of the entrance channel energy does not occur.

Studies of neutron-excess nuclei from bounds to continuum

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In light neutron-excess systems, many kinds of molecular structures are discussed from the view point of the clustering phenomena. In particular, much attention has been concentrated on Be isotopes. The molecular orbital (MO) around the ^{8}Be (=α+α) core, such as π^- and σ^+ associated with the covalent binding of atomic molecules, have been shown to give a good description for the low-lying states of these isotopes [1]. In their highly-excited states, furthermore, recent experiments revealed the existence of the interesting resonant states, which dominantly decay to the ^{6,8}He fragments [2]. In this report, we show the unified study of the exotic cluster structures of even Be isotopes (=α+α+XN, X=2,4,6,8) from bound states to continuum states.

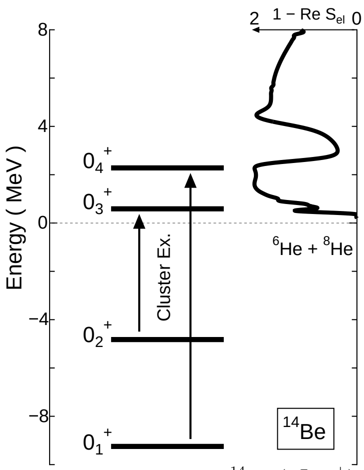

FIG. 1: Energy levels in ^{14}Be (J^π=0$^+$). The curve above the zero energy show the total reaction cross section in the collision of ^{6}He$_{g.s.}$+^{8}He$_{g.s.}$. Two arrows represent the cluster excitations from the bound states.

We applied the generalized two-center cluster model (GTCM), in which the formations of various chemical bonding structures such as covalent MOs and the atomic orbital (AO) with ^{x}He+^{y}He, can be described in a unified manner [3,4]. Due to the consistent treatment of chemical bonding structures, this model can also handle the nuclear reactions from AOs to MOs, which are observed in continuum above particle-decay thresholds [4]. An example of the application of GTCM to ^{14}Be=α+α+6N with the J^π=0$^+$ state is shown in Fig. 1.

First, we solved the bound state problem, and two energy levels are obtained (0_1^+ and 0_2^+). Next, we solved the scattering problem of ^{6}He$_{g.s}$+^{8}He$_{g.s.}$ and calculated the scattering matrix (a curve in the right side of Fig. 1). In the continuum region, we identified two resonances, 0_3^+ and 0_4^+, in the scattering matrix. These states correspond to the cluster excitation mode from the bound states, as shown in Fig. 1. Specifically, the two resonant states are generated by the excitation of two α's relative motions in the bound states. As a result of a cluster excitation, the AO structures, such as ^{6}He$_{g.s.}$+^{8}He$_{g.s.}$ and ^{6}He(2_1^+)+^{8}He$_{g.s.}$, are developed in the 0_3^+ and 0_4^+ states, respectively. We performed the similar calculations for other Be isotope ($^{8\sim16}$Be) and confirmed that, in these systems, the similar ^{6,8}He clusters such as ^{10}Be=α+^{6}He, ^{12}Be=^{6}He+^{6}He (α+^{8}He), ^{16}Be=^{8}He+^{8}He are realized in the excited states embedded in continuum. Furthermore, we extend the similar study to the heavier system, ^{28}Ne = α+^{24}O, the measurement of which is planned by employing SAMURAI at RIKEN. The possible appearance of an α cluster in ^{28}Ne will also be reported.

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Cluster and deformation in C isotopes*

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Structures of ground and excited states of C isotopes are discussed based on antisymmetrized molecular dynamics calculations.

C isotopes are fascinating nuclei where two kinds of features, shell-model and cluster ones, coexist. For instance, in ^{12}C, it has been known that shell-model aspect is important in the ground state while 3α cluster structures develop in excited states near the threshold energy. In systematic studies of C isotopes including unstable nuclei, we see a structure change of ground states along a C isotope chain. The neutron structure rapidly changes depending on a neutron number, while proton structure is rather stable because of the shell effect at $Z = 6$. As a result, a neutron-skin structure develops in neutron-rich nuclei. Another interesting feature in the structure change of ground states is deformations of proton and neutron densities. Coupling and decoupling of proton and neutron shapes are discussed in relation with $B(E2)$ values. Quenching of $E2$ transition strengths in ^{10}C, ^{16}C,^{18}C is understood by the decoupling, i.e., difference between proton and neutron shapes. The decoupling of proton and neutron shapes in terms of nuclear deformation can be regarded as decoupling of modes between a core and valence neutrons. $E1$ response shows valence neutron modes against a core, which contributes to an enhancement of low-energy $E1$ strengths (see Fig. 1).

In highly excited states near the threshold, a variety of developed cluster structures appear. One of the characteristics of C isotopes is appearance of three-center cluster structures. As well known, a typical example is the second 0^+ state of ^{12}C, which is regarded as a α gas state composed by weakly interacting three α particles. In contrast to such a non-geometric 3α structure, a triangle structure and a linear-chain one of three α clusters have been other attractive topics in C isotopes. Cluster structures of excited states in C isotopes are discussed in this paper.

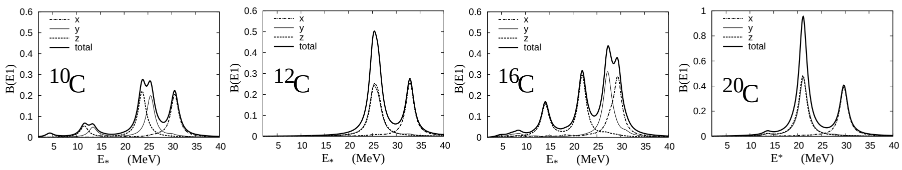

FIG. 1: $E1$ transition strengths (e^2fm^2/MeV) as functions of excitation energy of C isotopes calculated with the time-dependent AMD method [1]. The smoothing parameter is chosen to be $\Gamma = 2$ MeV. The total strengths are shown by the thick solid lines. Thin dash-dotted, solid, and dotted lines are the contribution for the x,y, and z-directions, respectively.

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How atomic nuclei cluster

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Nucleonic matter displays a quantum liquid structure, but in some cases finite nuclei behave like molecules composed of clusters of protons and neutrons. Clustering is a recurrent feature in light nuclei, from beryllium to nickel. For instance, in ^{12}C the Hoyle state, crucial for stellar nucleosynthesis, can be described as a nuclear molecule consisting of three alpha-particles. The mechanism of cluster formation, however, has not yet been fully understood. The origin of clustering can be traced back to the depth of the confining nuclear potential. By employing the theoretical framework of energy density functionals that encompasses both cluster and quantum liquid-drop aspects of nuclei, it is shown that the depth of the potential determines the energy spacings between single-nucleon orbitals, the localization of the corresponding wave functions and, therefore, the degree of nucleonic density clustering [1]. Relativistic functionals, in particular, are characterized by deep single-nucleon potentials. When compared to non-relativistic functionals that yield similar ground-state properties (binding energy, deformation, radii), they predict the occurrence of much more pronounced cluster structures. More generally, clustering is considered as a transitional phenomenon between crystalline and quantum liquid phases of fermionic systems.

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Properties of quasifission in heavy ion induced reactions

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In reactions with heavy ions complete fusion and quasifission are competing processes. The relative contribution of quasifission to the capture cross section becomes dominant for superheavy composite systems and compound nucleus formation is hindered by the quasifission process. The balance between the two processes strongly depends on the entrance channel properties, such as mass-asymmetry, deformation of interacting nuclei, collision energy and the Coulomb factor Z_1Z_2.

It is known that in superheavy composite systems quasifission mainly leads to the formation of asymmetric fragments with mass asymmetry ~0.4. This type of quasifission process, so-called asymmetric quasifission, is characterized by asymmetric angular distributions in the center-of-mass system and thus fast reaction times (~10^{-21} s). The total kinetic energy for these fragments is observed to be higher than that for CN-fission and hence this process is colder than CN-fission. Due to this reason shell effects in quasifission are more pronounced.

Generally, in heavy-ion induced reactions the formation of quasifission fragments is connected with the strong influence of the nuclear shell at Z = 82 and N = 126 (doubly magic lead). In fact, for the $^{48}Ca + {}^{238}U$ reaction the maximum yield corresponds to fragments with masses 208 u. However, in reactions with lighter projectiles on an uranium target, the asymmetric quasifission peak shifts toward more symmetric masses. By contrast, for the heavier projectile ^{64}Ni the maximum yield of quasifission fragments corresponds to the heavy mass 215 u. This trend may be due to the fact that in the formation of the asymmetric quasifission component also the closed shell in light fragment at Z = 28 and N = 50 could be effective together with the shells Z = 82 and N = 126 and could lead to the shift of the asymmetric QF peak.

Neutron-skin thickness from the study of the giant dipole resonance

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Recent progress in development of radioactive beams has made it possible to study the structure of nuclei far from stability. An important issue is the size of the neutron skin of unstable neutron-rich nuclei, because this qualitative feature of nuclei may provide fundamental nuclear structure information. There is a renewed interest for measuring precisely the thickness of the neutron skin, because it makes possible to constrain the symmetry-energy term of the nuclear equation of state. The precise knowledge of the symmetry energy is essential not only for describing the structure of neutron-rich nuclei, but also for describing of the properties of the neutron-rich matter in nuclear astrophysics. In this work we are suggesting a new precise method for measuring the neutron-skin thickness in both stable and radioactive beams.

The nuclear symmetry energy plays a central role in a variety of nuclear phenomena. It determines to a large extent the equation of state (EoS) and the proton fraction of neutron stars, the neutron skin in heavy nuclei, it enters as an input in the analysis of heavy ion reactions, etc. Furnstahl demonstrated that there exists an almost linear empirical correlation between theoretical predictions for the symmetry energy of the EoS in terms of various mean-field approaches and the neutron skin. This observation has contributed to a renewed interest in an accurate determination of the neutron skin in neutron-rich nuclei.

Giant resonances can also be used for this purpose. In one of our previous works on inelastic alpha scattering, excitation of the isovector giant dipole resonance was used to extract the neutron-skin thickness of nuclei. The cross section of this process depends strongly on ΔR_{pn}. Another tool, we used earlier, for studying the neutron-skin thickness is the excitation of the isovector spin giant dipole resonance (IVSGDR). The L=1 strength of the IVSGDR is sensitive to the neutron-skin thickness. The energy difference of the Gamow-Teller (GTR) resonance and the isobaric analogue state (IAS) depends strongly on ΔR_{pn}. Vretenar et al., suggested a new method for determing the ΔR_{pn} by measuring the energy of the GTR. The nuclear symmetry energy and neutron skins were also derived recently from the strength of the pygmy dipole resonances showing the importance of the giant resonances in this field. In my talk I am going to review a few different experimental methods, which could be used also in radioactive beams.

In our recent experiment the antianalog of the giant dipole resonance (AGDR) has been excited in the ^{124}Sn(p,n) reaction performed in inverse kinematics using ^{124}Sn beam with an energy of 600 MeV/A. The energy and angle of the neutrons were measured with a novel low-energy neutron time-of flight array (LENA). The excitation energy has been reconstructed from the energy of the γ-decay to the isobaric analogue state measured with large (3.5"x 8") $LaBr_3$ detectors in coincidence with the ejected neutrons. The energy of the γ-rays differs considerably from the energy of the GDR and turned out to be very sensitive to the neutron-skin thickness (ΔR_{pn}). Our calculations performed with state of the art self-consistent random phase approximation (RPA), based on the framework of relativistic energy density functionals supports also such strong ΔR_{pn} sensitivity of the energy of the AGDR. By comparing the theoretical results calculated as a function of ΔR_{pn} and the measured energy of the AGDR, the ΔR_{pn} value was deduced to be 0.26 $\pm$ 0.02 fm, which agrees nicely with the previous results. The energy of the AGDR measured previously for ^{208}Pb was used also to determine the ΔR_{pn} for ^{208}Pb. In this way a very precise $\Delta R_{pn} = 0.22 \pm 0.02$ neutron skin thickness has been obtained for ^{208}Pb. The present method offers new possibilities for measuring the neutron-skin thicknesses also in rare isotope beams.

Dynamics of Hypernuclear Nonmesonic Weak Decay *

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The Λ-hypernuclei are mainly produced by the (K^-, p^-) and the (p^+, K^+) reactions and most of them disintegrate via the nonmesonic weak decay (NMWD) $\Lambda N \rightarrow nN$ $(N = p, n)$, where the mass is changed by 176 MeV, and the strangeness by $\Delta\mathsf{S} = -1$. As such, the NMWD may be seen as the most intensive modification of an elementary particle within the nuclear matter, and offers the best opportunity to scrutinize the strangeness-changing force between hadrons. On the other hand, the hypernuclear physics leads to the extension of the radioactivity domain to three dimensions $(\mathsf{N}, \mathsf{Z}, \mathsf{S})$, which, because of the additional binding due to the Λ-hyperon, modifies the neutron drip line, and is even richer in elements than the ordinary (N, Z) domain. (For instance, while the one-neutron separation energy in ^{20}C is 1.01 MeV, it is 1.63 MeV in $^{21}_{\Lambda}$C, and $^{6}_{\Lambda}$He is bound while ^{5}He is unbound.) This glue attribute of hypernuclei has motivated a recent proposal to produce neutron rich Λ-hypernuclei at J-PARC, including $^{9}_{\Lambda}$He. Thus, the ΛN interaction is closely related to the inquiry on the existence of strange quark matter and its fragments, strange stars (analogues of neutron stars). This makes that the NMWD can be also relevant for astrophysics and cosmology.

The NMWD spectra induced by one bound nucleon in $^{4}_{\Lambda}$H, $^{4}_{\Lambda}$He, $^{5}_{\Lambda}$He, $^{7}_{\Lambda}$Li, $^{9}_{\Lambda}$Be, $^{11}_{\Lambda}$B, $^{12}_{\Lambda}$C, $^{13}_{\Lambda}$C, $^{15}_{\Lambda}$N and $^{16}_{\Lambda}$O are evaluated by employing the simple independent-particle shell-model as nuclear structure framework, while the dynamics is described by the soft $\pi + K$ one-meson-exchange model proposed in [1]. The comparison is done with recent measurements done at BNL [2], KEK [3], and FINUDA [4] of: 1) single-nucleon spectra, as a function of its kinetic energy E_N, and 2) coincidence nN spectra as a function of: i) the sum of kinetic energies $E_n + E_N \equiv E_{nN}$, ii) the opening angle θ_{nN}, and iii) the center of mass momentum $P_{nN} = |\mathbf{P}_{nN} = \mathbf{p}_n + \mathbf{p}_N|$. The issue of the weak decay induced by two bound nucleons, as well as the effect of final state interactions, are also addressed. Emphasis is put on very light s-shell systems.

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Scissors Mode Resonances Built on Excited Levels in Gd Nuclei Studied from Neutron Capture in Resonance Region

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Two complementary experiments with highly segmented 4π BaF_2 detector systems were performed to get unique information on photon strength in stable Gd nuclei. Spectra of γ rays following neutron capture at isolated resonances were measured with the DANCE detector at the Los Alamos LANSCE spallation neutron source [1,2]. Average resonance capture spectra were obtained from experiment using the detector system installed at pulsed neutron beam produced via the ^{7}Li(p,n)^{7}Be reaction at Forschungszentrum Karlsruhe [3]. An analysis of the accumulated capture γ-ray spectra within the extreme statistical model [4] leads to an inescapable conclusion that scissors mode resonances are built not only on the *ground-state*, but also on *excited levels* in all product nuclei studied. The results on summed $B(M1)\uparrow$ strength and energy of the scissors mode are compared with systematics of scissors mode parameters for the *ground-state* transitions deduced from nuclear resonance fluorescence measurements on even-even deformed nuclei. A specific feature of our experiments is getting the information on scissors mode resonances of odd nuclei, for which the nuclear resonance fluorescence provides only limited information.

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E1 vorticity and its manifestation in ^{124}Sn

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Last years the E1 pygmy resonance (E1PR) was a subject of intensive investigations, both in experiment (see e.g. [1,2,3]) and theory (e.g.[4,5]). Different properties of the E1PR were analyzed: isospin structure from (α,α') and (γ,γ') reactions [1], splitting and gross-structure of the E1PR [3], influence of the complex configurations [1,4], relation to the isoscalar and dominant isovector E1 resonances [1] etc. In this contribution, the vorticity of the states in the E1PR region is studied, using the method proposed in [6]. The method follows the concept of vorticity proposed by Raventhall and Wambach [7] and allows to treat the vortex, toroidal and compression modes on the same theoretical footing beyond the long wave approximation [6]. The vorticity multipole operator is related by a simple way to the toroidal, compression and standard electric multipole operators.

In the present study, the E1 strength functions of these operators are analyzed in ^{124}Sn (in connection to the new data [1]) and some deformed nuclei. The Skyrme self-consistent separable RPA approach is applied, which was earlier widely used for investigation of electric [8] and M1 [9] giant resonances. The effect of complex configurations is partly taken into account by the energy-dependent Lorentz averaging ("double folding") approach [10]. Both convection and magnetization nuclear currents are involved. It is shown that, like in the previous study for ^{208}Pb [6], the vortex E1 and toroidal E1 nodes are dominated by the convection nuclear current in the isoscalar (T=0) channel and by magnetization nuclear current in the isovector (T=1) channel. The compression mode is fully convective in both channels. The effect of deformation in the vortex, toroidal, and compression modes is discussed in detail.

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Density-dependent Covariant Energy Density Functionals

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The framework of relativistic nuclear energy density functionals has been applied very successfully to the description of a variety of nuclear structure phenomena at and far away from the stability line.
Here, we use the DD-ME2 energy density functional, which characterized by an exact density dependence of the meson nucleon coupling, to study fission barriers in actinides and superheavy nuclei, and giant resonances. The role of pion is also discussed.

Gamma spectroscopy of calcium nuclei around doubly magic ^{48}Ca using heavy-ion transfer reactions

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The gamma decay of neutron-rich nuclei around ^{48}Ca was measured at Legnaro National Laboratory with the PRISMA-CLARA setup, using the multi-nucleon transfer reaction ^{48}Ca on ^{64}Ni at 282 MeV. The existence of a large spin alignment allows to use angular distributions and polarizations of gamma-rays to firmly establish, for the first time, spin and parities of excited states in several nuclei. The nature of the states is investigated by lifetime measurements with the Differential Plunger Technique, in comparison with shell model and particle-vibration coupling calculations. The ±1 neutron transfer channels (^{47}Ca and ^{49}Ca) are investigated in parallel. Evidence is found for particle-vibration coupled states based on the 3^- phonon of ^{48}Ca. They are among the few fully established examples of particle-vibration coupling in nuclei with mass A<100, showing the robustness of nuclear collectivity in rather light systems. Perspectives for similar type of studies around the ^{64,66}Ni and ^{132}Sn cores will be also discussed.

The work evidences the multifaceted nature of particle-core coupling interactions and demonstrates the feasibility of complete in-beam gamma-spectroscopy with heavy-ion transfer reactions, providing a method that can be further exploited in the future with heavy targets and radioactive beams.

Radioactive Ion Beams in Brasil (RIBRAS)-Recent results*

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The Radioactive Ion Beams in Brasil (RIBRAS) system is installed [1,2] next to the 8UD Pelletron Tandem of the Nuclear Physics laboratory of the University of Sao Paulo. It consists of two superconducting solenoids with maximum magnetic field of B = 6.5 T. Light radioactive ion beams are produced through transfer reactions, using solid or gaseous production targets of Be, LiF, ^{3}He etc. The solenoids make a magnetic rigidity selection and the use of the two solenoids with a degrader between them allows the production of quite pure secondary beams. Beams of ^{6}He, ^{8}Li, ^{7}Be, ^{10}Be, ^{8}B, ^{12}B are currently produced and used to study elastic, inelastic, and transfer reactions on a variety of light, medium mass and heavy secondary targets. The data are analyzed, using most of the time, the Sao Paulo potential (SPP) [3] and compared to optical model and continuum discretized coupled-channels (CDCC) calculations.

Some examples of reactions recently studied are H(^{8}Li,^{4}He)^{5}He, H(^{8}Li,H)^{8}Li using thick CH_2 targets to measure their excitation functions. The transfer reaction ^{12}C(^{8}Li,^{4}He)^{16}N, leading to well defined excited states of ^{16}N, through the transfer of ^{4}H or the sequential decay ^{3}H+n, is being studied through the coincident detection of neutrons.

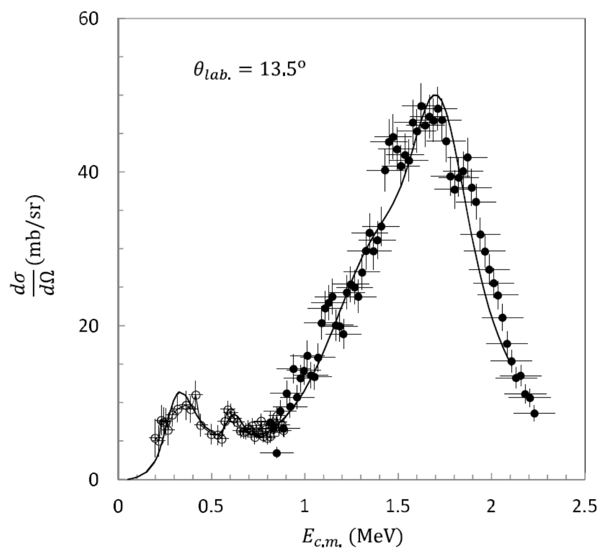

Fig. 1. The 8Li(p,α)5He differential cross section with the R-matrix fit (solid line).

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Order and chaos across a first-order quantum phase transition in nuclei*

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Quantum phase transitions (QPTs) are qualitative changes in the properties of a physical system induced by a variation of parameters λ in the quantum Hamiltonian $\hat{H}(\lambda)$. Such ground-state transformations have become a topic of great interest in different branches of physics [1], and are manifested empirically in nuclei as transitions between different shapes [2]. The competing interactions in the Hamiltonian that drive these transitions, can affect dramatically the nature of the dynamics and, in some cases, lead to the emergence of quantum chaos. This effect has been observed in quantum optics models of atoms interacting with a radiation field [3], where the onset of chaos is triggered by continuous QPTs. In this case, the underlying mean-field (Landau) potential $V(\lambda)$ has a single minimum which evolves continuously into another minimum. The situation is more complex for discontinuous (first-order) QPTs. Here $V(\lambda)$ develops multiple minima that coexist in a range of λ values and cross at the critical point, $\lambda = \lambda_c$. Hamiltonians describing such QPTs are often non-integrable and involve a mixed phase space in which regular and chaotic motion coexist. In the present contribution, we portray characteristic features of this mixed form of dynamics, in relation to first-order QPTs in nuclei [4,5].

We present a comprehensive analysis of the evolution of order and chaos across a generic first-order QPT between spherical and deformed quadrupole shapes, employing the interacting boson model of nuclei. The intrinsic part of the Hamiltonian determines the Landau potential with corresponding minima separated by a high barrier. Its classical analysis reveals a change in the system from an anharmonic oscillator- and Hénon Heiles- type of dynamics on the spherical side, into a pronounced regular dynamics on the deformed side of the transition. In spite of the abrupt structural changes taking place, the dynamics inside the coexistence region exhibits a very simple pattern. It is robustly regular and confined to the deformed region, and is well-separated from the chaotic behavior ascribed to the spherical region. The coexistence of regular and chaotic motion persists in a broad energy range throughout the coexistence region and is absent outside it. This simple pattern manifests itself also in the quantum analysis, based on Peres spectral lattices, disclosing regular rotational bands in the deformed region, which persist to energies well above the barrier and retain their identity amidst a complicated environment. Kinetic terms in the collective part of the Hamiltonian involving rotations in the orientation (Euler angles) and triaxiality (γ) variables, preserve the ordered band-structure, while collective rotations in the deformation (β) variable can disrupt it by mixing regular and irregular states.

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Energy density functional description of nuclear low-lying spectrum and shape transition

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The Covariant Energy Density Functional (CEDF) theory has achieved great success in the description of nuclear structure over almost the whole nuclide chart, from relatively light systems to superheavy nuclei, and from the valley of β stability to the particle drip lines. In general, the framework based on the static nuclear mean field approximation can only describe ground-state properties. Excitation spectra and electromagnetic transition probabilities can only be calculated by including correlations beyond the static mean field through the restoration of broken symmetries and configuration mixing of symmetry-breaking product states. One effective approach is to construct a collective Bohr Hamiltonian with deformation dependent parameters determined from microscopic self-consistent mean-field calculations. The entire dynamics of the collective Hamiltonian is governed by by the choice of a particular microscopic nuclear energy density functional. The main parts, i.e. local term (collective potential) and second derivative term (kinetic energy parts) in the configuration mixing have been taken into account in the approach, and can provide great description of low-energy excitation structure. Due to the less computation tasks, this approach can be used over almost the whole nuclide chart [1].

Recently, we have constructed the microscopic collective Hamiltonian based on the triaxial covariant energy density functional [2] and applied it to several interesting topics:

- Microscopic description of the nuclear quantum phase transition and order parameter [3–5];
- Fission barrier and super-deformed band in ^{240}Pu [6];
- Shape evolution and shape coexistence in $N = 28$ isotones [7];
- Shape evolution including octupole degree of freedom [8];
- Extend the model to include the time-odd field fully self-consistently and investigate the effect of it on the collective inertia parameters and spectra.

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Local covariant density functional constrained by the relativistic Hartree-Fock theory

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Nuclear density functional theory (DFT) is one of the promising universal theories to describe both ground-state and excited state properties of nuclei throughout the nuclear chart. Its covariant version (CDFT) is based on density functionals which take into account the Lorentz symmetry in a self-consistent way. It has received wide attention due to its successful description of a large variety of nuclear phenomena.

The CDFT in the Hartree level includes only local potentials, thus the theoretical framework is relatively simple and the computational cost is less. However, a few common diseases are found in the widely used relativistic Hartree (RH) functionals in literatures, such as the properties of effective mass of nucleon and its isospin splitting, spin-isospin resonances, tensor effects and nuclear shell structure evolutions, etc. In contrast, the success of the CDFT in the Hartree-Fock level has been demonstrated on the above issues [1–5]. However, since the relativistic Hartree-Fock (RHF) theory introduces non-local potentials beyond the Kohn-Sham scheme, its theoretical framework is much more complicated and the computational cost is heavy.

In the present work, a new local nuclear covariant density functional constrained by the density-dependent RHF theory is proposed. The isoscalar and isovector channels of nucleon-nucleon couplings are determined via the zero-range reduction and Fierz transformation. With this RHF equivalent functional, the neutron-proton Dirac mass splitting in asymmetry nuclear matter as well as the nuclear charge-exchange excitations can thus be naturally reproduced. This retains the advantages of existing RH functionals, and cures a couple of problems in the isovector properties.

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Low-lying isomeric state in ^{80}Ga from the β^- decay of ^{80}Zn *

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The β^- decay spectroscopy of ^{80}Zn was performed at the ISOLDE facility at CERN as part of systematic ultra-fast timing studies of neutron rich Zn nuclei. The RILIS ion source and cooled quartz transfer line between the target and ion source were used in order to produce almost pure beam of neutron rich Zn isotopes.
We report here results of the β gated γ-ray singles and $\gamma - \gamma$ coincidence measurements. A new level scheme was constructed for ^{80}Ga which is significantly different from the one reported in [1]. The main goal of our research was to identify properties and excitation energies of the two β^- decaying states in ^{80}Ga. The new level scheme contains 21 energy levels up to 2800 keV. Importantly, we have identified a new low-lying state at 22.4 keV. Properties of the level scheme suggest that the ground state has spin $J = 6$ and the first excited state has spin $J = 3$. The spin assignments are in agreement with laser spectroscopy values measured in [2]. Our work provides the first evidence for the $J = 6$ being the ground state.

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Large scale shell model study of nuclear spectroscopy in nuclei around ^{132}Sn

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An importance sampling iterative algorithm, developed few years ago[1] for diagonalizing large matrices, has been upgraded [2] so as to allow large scale nuclear shell model calculations in the uncoupled m-scheme [3, 4].

This new version allows to generate, for each angular momentum, a large number of eigenstates of the Hamiltonian by sampling a fraction of the basis states. It is therefore possible to offer an exhaustive description of the low energy properties of chains of isotones and isotopes.

The method was applied to the $N = 80$ isotones ranging from ^{132}Te to ^{142}Sm, Te isotopes from ^{132}Te down to ^{126}Te and Xe isotopes from ^{134}Xe to ^{130}Xe. Hamiltonian matrices of very large dimensions, up to $N \sim 3 \times 10^9$, were involved. It was possible, however, to obtain exact eigensolutions by sampling a small fraction $(1 - 5\%)$ of the basis states.

The calculations were performed using a unique set of single particle energies for all chains and a Brueckner G-matrix derived from the CD-Bonn potential. Quite rich spectra together with the strengths of the transitions among all low-lying states were produced. The spectra, the $E2$ and $M1$ transition strengths resulted to be in good agreement with the experimental data. Their comparative analysis allowed to determine the collectivity of the states, their proton-neutron (F-spin) symmetry, and their multiphonon nature. It allowed also to follow the evolution of their collectivity and symmetry properties as nuclei move away from proton or neutron shell closures.

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A multi-dimensional constrained covariant density functional theory with non-axial and reflection asymmetric deformations*

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In this talk we will present some recent results about the potential energy surface and fission barriers of nuclei in the covariant density functional theories. It is long known that the fission process of heavy and superheavy nuclei can be well described only when the most important shape degrees of freedom are suitably included. For example, the fission barriers of heavy nuclei are very sensitive to the triaxial and octupole deformations and the interplay between them. Thus it is necessary to develop a model with all of these shape degrees of freedom included self-consistently. In our recent work a multi-dimensional constrained covaraint density functional theory based on the axially symmetric harmonic oscillator basis expansion method has been developed for this purpose [1-3]. In this model the non-axial as well as the reflection asymmetric deformations are considered simultaneously. The pairing effects can be included either by the BCS approximation or the Bogoliubov transformation with zero-range or finite range seperable pairing forces.

This model has been used to investigate the fission barriers of the actinides nuclei [2]. We found that aside from the octupole deformation, the triaxiality also plays an important role upon the second fission barriers. Both the outer and the inner barriers are lowered by the triaxial deformation compared with axially symmetric results. With the inclusion of the triaxial deformation, a good agreement with the data for the outer barriers of actinide nuclei is achieved.

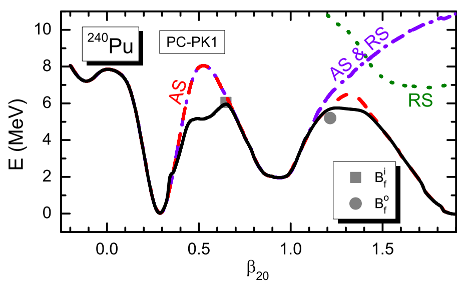

FIG. 1: Potential energy curves of ^{240}Pu with various self-consistent symmetries imposed. The empirical inner (outer) barrier height is denoted by the gray square (circle). This figure was originally published in Ref. [2]

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Identification of Triaxial Strongly Deformed Bands in ^{164}Hf*

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Significant progress has been made in the past decade in the study of nuclear triaxiality. The wobbling mode, initially predicted for even-even nuclei, has been identified in several odd-A Lu and Ta isotopes around A∼165, see, e.g., Ref. [1]. A number of theoretical investigations indicate that some Hf nuclei should be the best candidates for such studies, such as the pronounced triaxial strongly deformed (TSD) minimum at $(\varepsilon, \gamma) \approx (0.4, 24°)$ in ^{164}Hf (Fig. 1). However, TSD bands have only been observed in ^{168}Hf [2,3], which are very weak and could not be linked to known levels. Recently we have performed a Gammasphere experiment at ATLAS for ^{164}Hf. Preliminary data analysis revealed two exotic bands which have distinctive alignment pattern than the normal deformed bands (Fig. 1). The exotic bands have large initial alignments ($>20\hbar$) and do not exhibit a proton alignment at $\hbar\omega \sim 500$ keV that is seen in other normal deformed bands. These facts indicate that the high-j intruder proton orbital is already occupied at the lowest frequency in the bands, and that the bands are associated with, most likely, the predicted TSD minimum rather than the normal deformed one. The bands are stronger than the TSD bands in ^{168}Hf by an order of magnitude and cross the yrast line at spin 32, as compared to spin ∼48 in ^{168}Hf. Further results and theoretical calculations will be presented.

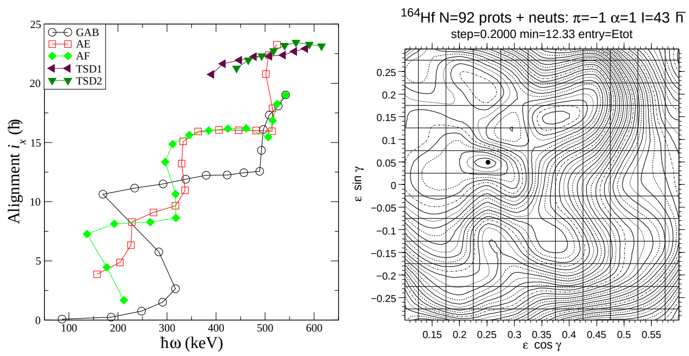

FIG. 1: Left: Aligned angular momenta of normal deformed and the two new exotic bands (TSD1 and TSD2) in ^{164}Hf. Right: Potential energy surfaces in ^{164}Hf calculated with the ULTIMATE CRANKER codes.

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Shape evolution of heated and rapidly rotating nuclei studied with GDR – status and new perspectives with the PARIS array

The study of properties of the giant dipole resonance (GDR) at high temperature and angular momentum is one of the central topics in nuclear structure as it provides insight into the behavior of nuclei under extreme conditions. Of special interest are shape changes induced by high angular momentum, particularly the predicted Jacobi (oblate to elongated prolate) and Poincare (elongated prolate to elongated octupole) shape transitions. The former one has been experimentally observed in number of nuclei up to mass 90 [1-5]. The latter is predicted [6,7] to occur at extremely very high spins in exotic neutron-rich nuclei formed in fusion-evaporation reactions induced by high-intensity radioactive beams

In the talk the available experimental results and their interpretation will be overviewed and the most recent results concerning ^{88}Mo presented. In addition the outlook of similar experiment will be discussed in the context of soon available radioactive beam facilities. Especially the concept of the novel gamma-ray calorimeter PARIS [8] will be presented and its role in such investigation will be discussed.

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Nuclear relativistic Hartree-Fock calculations with pions interacting with a scalar field

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Abstract

The effect of an interaction between the σ and π fields as well as that of the mixture of pseudoscalar (PS) and pseudovector (PV) couplings for the πN vertex on the shell structure of finite nuclei are analyzed in the framework of different nonlinear nuclear models based on the relativistic Hartree-Fock approximation (RHFA) [1]. In the case of spin-unsaturated nuclei, pions, due to their contribution to the NN tensor force, strongly influence the spin-orbit splittings, modifying the structure of the single-particle spin-orbit potentials [2, 3, 4]. For the case of a dominant πN PV-coupling, it is found that, if the σ-π interaction generates an effective pion mass increasing with the nuclear density, the unrealistic effect of pions on the shell structure can be strongly reduced, keeping, roughly, the contribution of pions to the total binding energy. The PS part of the πN coupling contributes to increase slightly the spin-orbit splittings and the binding energy of the single-particle levels.

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Role of momentum transfer in the quenching of Gamow-Teller strength*

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The Gamow-Teller (GT) resonance is a particularly interesting spin-isospin excitation in the context of nuclear astrophysics. A detailed knowledge of the GT strength is essential for the understanding of nuclear beta-decay and weak processes in stars [1]. Measurements have identified a discrepancy between the data and the model-independent Ikeda sum rule, where only around 60% of the predicted strength was observed in a number of nuclei across the whole nuclear chart. A consistent analysis of (p, n) and (n, p) reaction data from ^{90}Zr was performed recently, where a significant amount of Gamow-Teller strength was found above the resonance, an energy region previously unreachable by experimental setups [2]. The new results imply that the GT strength is quenched by approximately 10%.

The operator structure of the (p, n) probe is similar to that of the Gamow-Teller operator, but they become comparable only in the limit of vanishing momentum transfer. This condition is satisfied for zero degree scattering and small excitation energies. The extraction of the GT strength at high excitation energies is difficult due to dominating higher-multipole response, and is further complicated by the effects of momentum transfer where the main contribution comes from the isovector spin monopole (IVSM) mode. This mode, with the transition operator $r^2\boldsymbol{\sigma}\tau$, represents a collective excitation of the nucleus with quantum numbers $J^\pi = 1^+$, $L = 0$, $S = 1$ and $T = 1$. Because the distribution of the GT strength in the region of the IVSM resonance is unknown, the contribution of the IVSM mode to the $L = 0$ strength is subtracted incoherently, i.e. the interference between the Gamow-Teller and the isovector spin monopole modes is neglected.

A fully self-consistent calculation of the $L = 0$ strength in select nuclei is presented, based on a microscopic theoretical framework. Nuclear ground state is determined using the Relativistic Hartree-Bogoliubov (RHB) model with density-dependent meson-nucleon coupling constants. Transition rates are calculated within the proton-neutron relativistic quasiparticle RPA using the same interaction that was used in the RHB equations. In this way no additional parameters are introduced in the RPA calculation [3]. The behavior of the IVSM mode was examined and compared to the Gamow-Teller response. The $L = 0$ strength was calculated taking into account the interference of the two modes of excitation, and its effect on the strength distribution and the total strength was studied. Using the full $L = 0$ transition operator in the pn-RQRPA calculation to estimate the effect of finite momentum transfer, we find that the current data on the charge-exchange reactions on ^{90}Zr do not indicate a quenching with respect to the Ikeda sum rule.

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Challenges in explosive nucleosynthesis of heavy elements

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Observations of metal-poor stars show that elements with $Z \leq 52$ and $Z > 52$ are produced in two different astrophysical sites and at very early times in galactic history. Neutrino-winds from protoneutron stars in core-collapse supernova, are the preferred site for the production of elements with $Z \leq 52$. Here the nucleosynthesis is particularly sensitive to the proton-to-nucleon ratio and dynamics of the ejected material. The proton-to-nucleon ratio is determined by electron neutrino and antineutrino absorption on free neutrons and protons and is particularly sensitive to the relative spectral energy differences between both neutrino types. In this talk, I will show how a treatment of neutrino-matter interactions that is consistent with the underlying Equation of State can have an strong impact on the spectra of both neutrino types with important implications for nucleosynthesis, oscillations studies and neutrino detection on Earth.

Furthermore, I will discuss possible astrophysical sites where the nucleosynthesis of elements heavier than $Z > 52$ can take place with particular emphasis on the nuclear physics properties that can help to determine the dynamics of the astrophysical site.

^{7}Li-Induced Reactions for Fast-Timing With LaBr$_3$:Ce Detectors

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LaBr$_3$:Ce scintillators detectors boast excellent timing resolution (typically 100–300 ps depending on detector size) and good energy resolution ($\sim$2–3% at 662 keV) [1] that can be exploited for direct fast-timing measurements of nuclear lifetimes. Lifetimes in the sub-nanosecond range as short as 30 ps are accessible with LaBr$_3$:Ce detectors. In-beam fast-timing experiments have been performed using the LaBr$_3$:Ce and HPGe array at IFIN-HH, Bucharest including the use of ^{7}Li-induced reactions to populate neutron-rich nuclei close to stablity. Transfer or incomplete-fusion reactions with ^{7}Li beams at energies close to the Coulomb barrier give access to neutron-rich nuclei with stable beam and targets at low energy [2].

The ^{186}W(^{7}Li,$p\alpha$)^{188}W reaction at a beam energy of 31 MeV delivered by the 9 MV Tandem van de Graaff accelerator in Bucharest was utilised to populate low-lying states in ^{188}W. Coincidences with the HPGe detectors were used to isolate the reaction channel and the lifetime of the yrast 2^+ state at $E_x = 143$ keV [3] was measured with the LaBr$_3$:Ce detectors. Neutron-rich W isotopes are predicted to become less collective as they undergo prolate-oblate shape evolution [4] and the lifetime of the first-excited 2^+ state gives a measure of the ground state-collectivity in ^{188}W. A Sub-nanosecond half-life for the 564 keV ($7/2,9/2^-$) bandhead state was also observed through the ^{186}W(^{7}Li,$4n$)^{189}Ir fusion-evaporation channel in the same reaction [5].

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Lifetime measurement of high-lying short lived states in ^{69}As

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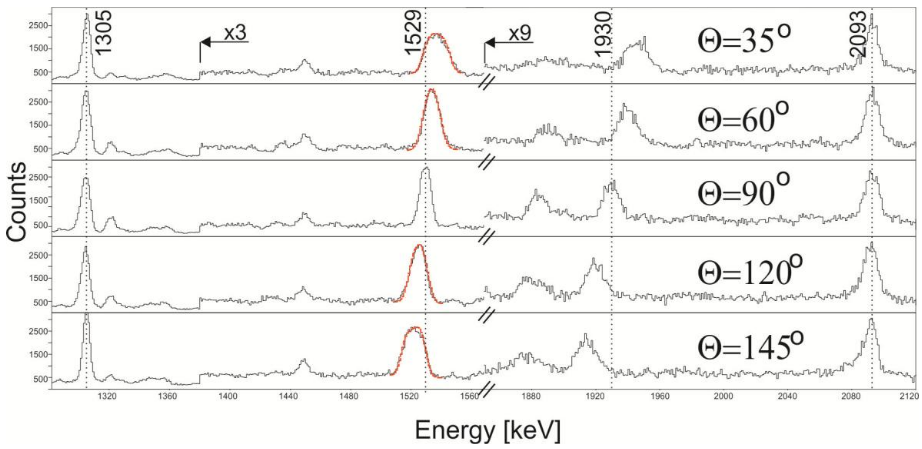
In order to investigate evolution of nuclear deformation in the vicinity of A~70 nuclei close to the N=Z line, we have performed for these nuclei a measurement of excited states lifetimes in the femtosecond range with the GASP and RFD detection system at LNL INFN. A 95-MeV ^{32}S pulsed beam from the Tandem XTU accelerator was focused on a 0.8 mg/cm^2 ^{40}Ca target. Evaporation residues were detected by the segmented Recoil Filter Detector (RFD) in coincidence with gamma rays measured with the GASP germanium detector array. The trigger condition required at least two gamma rays and recoiling nucleus in the prompt coincidence. Each segment of RFD provides information on the time of flight and the direction of every detected evaporation residuum with respect to the beam pulse signal. This setup allows to determine lifetimes of the exited states if they are comparable to or shorter than the transit time of the recoil through the target - in our case these times are in a femtosecond range.

Picture below presents the summed spectrum of gamma rays gated on the 733 keV and 1177 keV transitions in the rotational band "3" in ^{69}As. The upper panels show gamma rays detected at forward angles, Θ=35^o, 60^o, the middle panel corresponds to 90 degrees and the lowest portions show those detected at backward angles, Θ=120^o, 145^o. Event-by-event Doppler correction has been applied to the data, under the assumption that the gamma rays were emitted after the nucleus left the target. As seen in the figure, the applied correction is appropriate for the 1305 and 2093 keV transitions. But the 1529 and 1930 keV lines of band 3 are not properly corrected what indicates that the corresponding gamma rays were emitted while the recoiling nucleus was still traveling inside the target. Moreover, these transitions do not show any trace of the stopped component - such feature points to the cumulative lifetime shorter than 60 fs for the involved states. Our results offer a unique opportunity for testing predictions of various theoretical models that try to describe the electromagnetic properties of the rich variety of collective bands known in the ^{69}As nucleus.



Magnetic and Antimagnetic rotation: a microscopic description

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The self-consistent tilted axis cranking relativistic mean-field theory based on a point-coupling interaction has been established and applied to investigate systematically magnetic bands and antimagnetic rotation in a microscopic way.

For the newly observed shears bands in 60Ni, the tilted angles, deformation parameters, energy spectra, and reduced M1 and \$E2\$ transition probabilities have been studied in a fully microscopic and self-consistent way for various configurations and rotational frequencies. It is found the competition between the configurations and the transitions from the magnetic to the electric rotations have to be considered in order to reproduce the energy spectra as well as the band crossing phenomena. The tendency of the experimental electromagnetic transition ratios B(M1)/B(E2) is in a good agreement with the data, in particular, the B(M1) values decrease with increasing spin as expected for the shears mechanism, whose characteristics are discussed in detail by investigating the various contributions to the total angular momentum as well.

The same theory is also used to investigate antimagnetic rotation (AMR) for the first time in a microscopic way. Using a reliable functional, the tilted axis cranking method provides a fully self-consistent description without any adjustable parameter. The experimental spectrum as well as the B(E2) values of the recently observed AMR band in 105Cd are reproduced very well. Polarization effects play an essential role. This microscopic investigation gives a further strong hint that AMR with its two "shears-like" mechanisms is realized in specific bands in nuclei.

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Lifetime measurement of the 6.79 MeV state in ^{15}O

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An accurate determination of the lifetime of the first excited $3/2^+$ state in ^{15}O is of paramount importance in the determination of the astrophysical S-factor and the derived cross section for the ^{14}N(p,γ)^{15}O reaction, the slowest one in the CNO cycle [1]. The considered level indeed corresponds to a sub-threshold resonance of this reaction, the width of which is a crucial ingredient in the extrapolation of the cross section in the Gamow energy region. Once this cross section is known, the information of the energy production rate from the CNO cycle can be used together with the neutrino fluxes to shade light on the metallicity in the center of the Sun [2].

The results of a new direct measurement of the lifetime of the first excited $3/2^+$ state in ^{15}O are discussed. The ^{2}H(^{14}N,n)^{15}O reaction in inverse kinematics at 32 MeV beam energy (XTU Tandem, LNL) was used to populate the level of interest, which decays *via* a 6.79 MeV E1 gamma–ray transition to the ground state. Gamma rays were detected with 4 triple clusters of the AGATA Demonstrator array [3]. The energy resolution and position sensitivity of this state-of-the-art gamma spectrometer have been exploited to investigate the Doppler Shift Attenuation in the lineshape of the gamma–ray peak in the energy spectrum. This is the first time that the technique of gamma–ray tracking has been used to investigate $\approx$ fs nuclear level lifetimes. The deconvolution of the lifetime effects from the ones due to the kinematics of the emitting nuclei has been performed by means of detailed Monte Carlo simulations of the gamma emission and detection. Coupled-channel calculations for the nucleon transfer process have been used for this purpose. The comparison of the experimental and simulated data for high-energy gamma rays de-exciting $\approx 1 - 10$ fs lifetime levels will be shown, both for ^{15}O and for the known case of ^{15}N. This nucleus, produced in the same reaction process, provided a testing ground for the analysis method.

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Modeling incomplete fusion reactions

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Abstract

We would like to present a new model [1] of the dynamics of the incomplete fusion reaction. We will compare the calculated mass distributions and the alpha particle spectra to a set of experimental data.

The incomplete fusion has been of interest to the nuclear physics society since 1979 [2]. Since then a plenty of experimental and theoretical works were published (see [1,3] and references therein). Nevertheless, the models so far do not handle the dynamics of the process - the creation of a compound nucleus and a „projectile like" fragment emission. Our model describes the incomplete fusion for the cases with an α particle escape. It is based on the assumption that the incomplete fusion is a two-stage process. In the first stage the projectile breaks up into an α particle and the projectile residue during the approach towards the target. In the second stage the projectile residue fuses with the target and the α particle escapes. The model allows the spin and excitation energy of the compound nucleus to be evaluated, as well as the energy and the direction of the escaping α particle. Recently γ-ray fold distributions for the $^{51}V+^{97}Mo$ reaction at energy of 4.5 AMeV of ^{51}V [4], have been compared to the predictions of our model.

We would like to present the basics of the model as well as its software implementation – the COMPA[3] code. Working in the 'event by event' mode, it provides complete information on the reaction products: the entry state spin and energy distribution, the reaction point coordinates, the directions and the velocities of the recoil and emitted light particles. The stopping of the reaction products in the passive elements of the setup (such as support, target and backing) is taken into account. It is easy to compare the COMPA calculations with the experimental results. We will present the comparisons of simulated α particle spectra with the experimental data in ~10 AMeV region for the $^{12}C+^{160}Gd$ [2] and $^{12}C+^{51}V$ [5] as well as $^{20}Ne+^{122}Sn$ reactions, studied with the new EAGLE [6] array recently put into operation at Heavy Ion Laboratory of the University of Warsaw.

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Response function of the magnetic spectrometer Prisma for the multinucleon transfer reaction ^{40}Ar+^{208}Pb

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The revival of transfer reaction studies benefited from the construction of the new generation large solid angle spectrometers based on ion trajectory reconstruction. The coupling of these spectrometers with large γ arrays allowed us to identify in mass, nuclear charge and Q-value a particular reaction product and to investigate its excitation energy spectrum and the associated γ decay [1].

In the present work different aspects of fragment-γ coincidence studies measured with the Prisma-Clara set up in multinucleon transfer reaction ^{40}Ar+^{208}Pb [2] will be discussed. In particular, the role played by neutron-proton correlations.

Multinucleon transfer reaction ^{40}Ar+^{208}Pb was measured at $E_{\rm lab}$ = 255 MeV at Laboratori Nazionali di Legnaro, Italy. The magnetic spectrometer Prisma [3] was used to detect projectile-like particles in a large range of energy and angles, while coincident γ rays were detected on HPGe γ-array Clara [4]. Angular distributions were measured for the first time with the Prisma using three different spectrometer angular settings. A good overlap was achieved with a small misalignment at the borders of the angular acceptance due to the spectrometer response. To correct for these effects the response function of Prisma was studied via a Monte Carlo simulation [5]. The experimental differential cross sections for various transfer channels, corrected for the response of the spectrometer, will be shown and compared with semiclassical calculations (code GRAZING) [6]. Such comparison allows to determine the importance of single particle and pair degrees of freedom in transfer processes. In this context, we will discuss the role played by neutron-proton correlations which are presently attracting interest in the field, especially making use of radioactive ion beams.

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Lifetime measurements of low-lying states in ^{63}Co and ^{65}Co

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The harmonic-oscillator $N = 40$ shell closure have been shown to suddenly disappear by removing protons from the ^{68}Ni. With the $\pi f_{7/2}$ shell not fully filled, it is predicted a quadrupole deformation due to the interaction of this protons with neutrons promoted to the *sdg* shell [1]. That is the case for $N = 40$ ^{66}Fe and ^{64}Cr, where new region of deformation have been observed [1].
Neutron-rich cobalt isotopes on the other hand have one $f_{7/2}$ proton hole with respect to the spherical Ni isotopes and one proton more than the deformed Fe isotopes. While the occurrence of a low-lying state $1/2^-$ in ^{67}Co have been interpreted as a collectivity manifestation [2] driven by the $p_{3/2}$ intruder proton orbital, the trend followed by the $9/2^-$ and $11/2^-$ multiplet respect to the Ni 2^+ excitation states on the Ni cores agree with the spherical behaviour manifested by the $N = 40$ shell closure. Albeit reduced transition probabilities provides much more rich information about the collective character on this transitions. For this purpose, lifetimes for the $(11/2^-)$ excitation states in both ^{63}Co and ^{65}Co isotopes have been measured employing the Recoil-Distance-Doppler-Shift method. Experimental $B(E2)$ values are compared with large-scale shell model calculations [3], leading us to draw some conclusions on the role of the $d_{5/2}$ and $g_{9/2}$ neutron orbitals in the erosion of the $N = 40$ subshell closure.

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Reduced dispersion of transverse momentum of fragmentation products observed at 290 MeV/u

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Fragmentation process is usually used to prepare radioactive nuclear beams. The momentum distribution of fragmentation products is one of good probes to investigate the reaction mechanism. At relativistic energies, observed momentum distributions are well reproduced by an isotropic Gaussian function. The dispersion of the distribution can be understood based on the Fermi motion of removed nucleons [1]. At intermediate energies around E~100 MeV/u, the distributions becomes anisotropic and a transverse-momentum dispersion (σ_T) was larger than a longitudinal-momentum dispersion (σ_L). This behavior was discussed based on orbital deflection and the formulation proposed in [2] has been usually used to describe P_T distributions. However, there have still remained uncertainties in experimental results. There were few systematic measurements of P_T distributions and isotopes were not resolved in some measurements.

Recently, a remarkable correlation between σ_T and longitudinal momentum (P_L) has been obtained through well-organized measurements by using Ar beam at 95 MeV/u [3]. According to the results, σ_T at beam velocity agrees with σ_L as shown in Fig. 1(a), and that observed at lower P_L becomes larger than σ_L. The additional dispersion of P_T, observed in previous experiments, would be attributed to the contribution of lower P_L component.

The experimental method, used in [3], was applied to fragmentation process in higher energy. σ_T of fragmentation products, produced from Ar and Kr beams at 290 MeV/u, was obtained as a function of P_L. In contrast to the results at 95 MeV/u, σ_T is almost constant concerning P_L. This behavior implies the suppression of lower P_L component, which provides remarkable P_L dependence at 95 MeV/u. In the case of Ar beam, σ_T agrees with σ_L, like as Fig. 1(a). In the case of Kr beam, a significantly reduced σ_T, compared to σ_L, is observed as shown in Fig. 1(b).

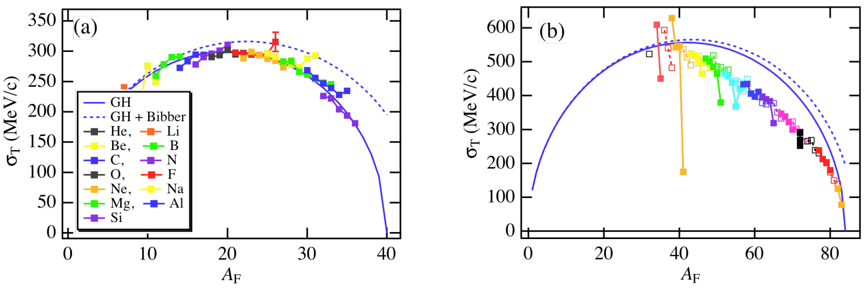

Fig. 1. σ_T as a function of fragment mass (A_F) at beam velocity. Fragments were produced through reactions (a) ^{40}Ar+^{9}Be at 95 MeV/u and (b) ^{84}Kr+^{12}C at 290 MeV/u. The blue solid lines in figures correspond to σ_L derived from observed P_L distributions.

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Fusion of $^{32}S + ^{48}Ca$ near and below the Coulomb barrier: a case where transfer couplings dominate ?

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The fusion excitation function of $^{32}S + ^{48}Ca$ has been experimentally studied in a wide energy range, from above the Coulomb barrier down to cross sections in the sub-microbarn region. The measurements were done at INFN-Laboratori Nazionali di Legnaro, using the ^{32}S beam from the XTU Tandem accelerator. The evaporation residues (ER) were separated from the beam by using the set-up based on a beam electrostatic deflector (see [1] and Refs. therein). ER angular distributions were measured at E_{lab}= 70.4, and 83.4 MeV in the range 0^0 to 8^0.

The excitation function has a smooth behavior below the barrier, with a rather flat slope (see Fig.1, left). The logarithmic slope L(E) = dln(Eσ)/dE does not reach the value expected for a constant S factor (Fig.1, center), which implies that no maximum of S vs. energy develops. However, other interesting features of the dynamics of this system can be observed. In particular, the fusion barrier distribution has an unusual shape with two peaks of similar height (Fig.1, right), lower and higher than the Akyüz-Winther (AW) barrier which is at E_{cm}= 43.4 MeV. Preliminary coupled-channels calculations have been performed using the code CCFULL [2], including the lowest 2+ and 3- states of both projectile and target, and the two-phonon quadrupole excitation of ^{32}S. The calculations employed the standard AW potential. The results (red line in Fig.1, left) clearly underpredict the sub-barrier cross sections, although the slope of the excitation function is very well reproduced, while experimental data are lower than the calculations above the barrier. The predicted barrier distribution (not shown here) is very different from experiment, in particular the high-energy peak is completely missing.

Since $^{32}S + ^{48}Ca$ has several neutron pickup transfer channels with positive Q-values, further schematic calculations have been carried out with CCFULL including also a transfer coupling simulating the +2n pickup channel. The results are shown as blue lines in the three panels of Fig.1. It is interesting to recognize that this further transfer coupling produces a fusion excitation function, a barrier distribution and a logarithmic derivative in close agreement with the data. It appears that transfer couplings push very much down in energy the threshold for hindrance, below the lowest measured energy, as recently noted for $^{40}Ca + ^{48}Ca$ [1]. More detailed analyses and calculations are anyway necessary before drawing firm conclusions.

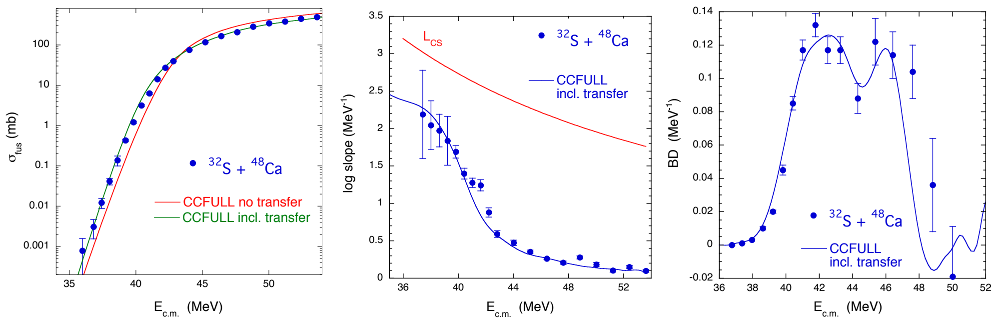

Fig. 1. (Left) Fusion excitation function of $^{32}S + ^{48}Ca$ as measured in the present experiment, and calculated by the CCFULL code (see text). (Center) Logarithmic derivative (slope) and (Right) fusion barrier distribution extracted for the same system.

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Heavy-Ion Transfer Reactions at Large Internuclear Distances

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The study of two-neutron transfer reactions represents a powerful tool to investigate correlations between nucleons in nuclei. In heavy-ion reactions many nucleon transfer channels are available, giving the possibility to compare the relative role of single particle and pair transfer modes [1]. Furthermore, below the Coulomb barrier, nucleons are transferred in a restricted excitation energy window and colliding nuclei, being at large internuclear distances, are only slightly influenced by the nuclear potential. Under these conditions the complexity of theoretical calculations diminishes and more information on pair correlations can be extracted from data [2,3].

Using the large solid angle magnetic spectrometer PRISMA, at the Laboratori Nazionali di Legnaro (LNL), a first reaction at sub-barrier energies has been performed in inverse kinematics for the closed shell system ^{96}Zr+^{40}Ca [4]. An excitation function ranging from above to well below the Coulomb barrier has been measured and transfer probabilities [5] have been extracted for the neutron transfer channels. The comparison between data and microscopic calculations shows the importance played by transitions to 0^+ excited states.

As further steps, we recently perfomed at LNL two similar experiments, both in direct and inverse kinematics, for the superfluid system ^{60}Ni+^{116}Sn where the ground state Q-values for neutron transfers are close to their optimum Q-values. In the former case, angular distributions of neutron transfer channels have been obtained, while in inverse kinematics an excitation function from above to well below the Coulomb barrier has been measured. It is therefore interesting to compare the behaviour of the transfer mechanism to the previously measured closed shell system and to the same kind of theoretical calculations.

Measurements of transfer cross sections have been obtained on the basis of an event-by-event reconstruction of the ion trajectories inside PRISMA [6], while the AGATA demonstrator has been employed to extract the transfer strength to excited states in the case of the direct kinematics reaction ^{60}Ni+^{116}Sn.

In this talk the results of these recent measurements will be presented, and a discussion will be made on the possibilities offered in the field by exploiting large solid angle spectrometers.

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Phase transitions and phase diagrams in hadronic and partonic systems

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Hadronic systems can support a variety of phases and phase transitions. I will consider here the nuclear liquid vapor phase transition and the hadronic to partonic phase transitions.

We have characterized the liquid vapor transition from a variety of experimental data. We have extracted the entire liquid vapor coexistence line up to the critical temperature. In doing so we had to correct for finite size and Coulomb effects, so that the final phase diagram is that of infinite, symmetric, uncharged nuclear matter.

I shall also discuss the hadronic to partonic phase transition in terms of the bag model. This is a first order transition with a UNIQUE temperature at which the partonic and hadronic phases can be in grand canonical equilibrium. The simple but exact thermodynamic description will be given in analytical form.

^{72}Zn(d,^{3}He)^{71}Cu transfert reaction

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The series of copper isotopes (Z=29) is of prime interest for nuclear structure. The first 5/2 level in the odd isotopes, carrying most of the f5/2 proton strength, sharply drops in energy beyond N=40 and becomes the ground state in 75Cu. The position and the strength distribution of the f7/2 spin-orbit partner is essential to understand the underlying mechanism of this effect, bent to have major implications for structure variations towards 78Ni. With this purpose in mind the 72Zn(d,3He)71Cu transfer reaction was performed at Ganil with the Must-2 particle array, giving precisely access to proton-hole states in copper. The data are currently under analysis.

Core excitation effects in the breakup of halo nuclei*

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Breakup experiments provide useful spectroscopic information of weakly-bound exotic nuclei. The extraction of structure information from these experiments is done by comparing the data with some reaction model, such as semiclassical, adiabatic, DWBA or CDCC, among others. Typically, these methods ignore the excitations of the clusters constituents. Consequently, the breakup of a halo nucleus is described in terms of excitations of the valence particle(s) outside an inert core, thus ignoring transitions between different core states during the collision as well as admixtures of core excited components in the states of the weakly-bound nucleus. These simplifying assumptions are not expected to be accurate when the clusters are deformed. In this case, in addition to the valence excitation, the interaction with the target can induce the dynamic excitation of the core. Moreover, the core-excited admixtures are very important to describe the structure of these systems.

In this contribution, we discuss the rôle of core excitation in the scattering of halo nuclei and present new theoretical developments to account for these effects. The models are applied to several breakup reactions induced by ^{11}Be and ^{19}C and compared with available data. The calculations evidence very clearly the importance of core excitation in the scattering of halo nuclei.

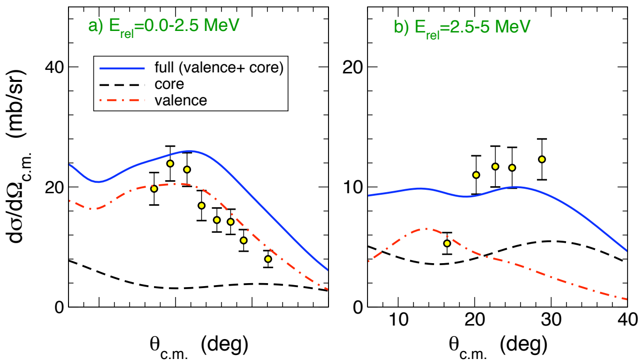

FIG. 1: Angular distribution for the breakup of ^{11}Be on protons at 63.7 MeV/nucleon for $E_{\rm rel}$=0–2.5 MeV (left panel) and $E_{\rm rel}$=2.5–5.0 MeV (right panel). The circles are the experimental data from [2]. The curves are DWBA calculations including the effect of core excitation [3]. The dot-dashed and dashed curves represent, respectively, the valence and core excitation contributions and the solid line is their coherent sum.

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Effects of Realistic Tensor Force on Nuclear Structure*

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Whereas the second-order effects of the tensor force on nuclear structure (*e.g.* on the saturation) had long been recognized, it has recently been pointed out that its first-order effects, *i.e.* effects at the mean-field (MF) level, are important particularly in systematic description of nuclear structure including nuclear far off the β-stability. However, simplified tensor force is employed in most MF studies in this line. In the Skyrme energy-density-functional (EDF) approaches a zero-range (but momentum-dependent) tensor force is assumed. Even if the function form (or the momentum expansion) is acceptable, it is not obvious how to fix its strength. Moreover, the EDF form of the Skyrme tensor force is identical to that of a part of the central force under the spherical symmetry, causing difficulty in separating out tensor force effects. These obscure how strong the tensor force effects are.

In order to describe structure of stable to unstable and relatively light to heavy nuclei based on the NN interaction, we have developed semi-realistic NN interactions [1, 2] by modifying the M3Y interaction [3] that was derived from the G-matrix. The modification has been made so that the saturation and the spin-orbit splittings could be reproduced, while the tensor channels kept unchanged. Having quite realistic tensor force, this type of interactions is suitable to investigating first-order effects of the tensor force. The tensor force plays a key role in Z- or N-dependence of the shell structure [4], and in transitions involving spin degrees-of-freedom [5]. In this presentation, it is illustrated by applying the realistic tensor force that first-order effects of the tensor force are crucial in describing several aspects of nuclear structure,

We find, in practice, the following remarkable examples which exhibit tensor-force effects. The tensor force gives significant contribution to the inversion of the $p1s_{1/2}$-$p0d_{3/2}$ levels in the Ca isotopes, the emergence of the new magic number $N = 32$ around ^{52}Ca (though not around ^{60}Ni), and the sub-magic nature of $N = 40$ around ^{68}Ni and its rapid erosion [6]. The tensor force with realistic strength is crucial in reproducing the $M1$ response in ^{208}Pb, as clarified by the HF+RPA calculation [5]. The tensor force plays a significant role also in the $E2$ strengths of the Sn isotopes, via the shell structure, as shown by the HFB+QRPA studies [7].

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Stochastic approach to correlations beyond the mean field with the Skyrme interaction

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One of the goals in the microscopic nuclear many-body theory is the ab-initio nuclear structure calculation starting with a fixed Hamiltonian. Since the strong short-range correlation in the bare NN interaction prevents a naive mean-field approach, the effective interactions were extensively developed in history of the nuclear theory. Using the effective interaction for the mean-field models, we develop a non-empirical method to treat full correlations beyond the mean field. The model space should be restricted to the one not taking account of the short-range correlations. This is done by the imaginary-time propagation method. Roughly speaking, the method consists of the following three steps. (i) *Generation and selection of Slater determinants.* Many Slater determinants are stochastically generated, then, screened by the imaginary-time propagation. (ii) *Parity and angular momentum projection.* Single-particle wave functions in each Slater determinant are represented in the three-dimensional (3D) Cartesian coordinate space without any symmetry restriction. Thus, we need to carry out the projection with respect to the full three-dimensional Euler angles. (iii) *Diagonalizing Hamiltonian in the selected space.*

Our method has some resemblance to the generator coordinate method (GCM) and the Mote Carlo shell model (MCSM). In the GCM, the generator coordinate is adopted *a priori*, under a certain physical intuition, to describe specific correlations. Our method stochastically takes into account all the important correlations. In the MCSM, basis states are stochastically generated and selected, then the diagonalization of the Hamiltonian is performed in the space spanned by those states. This concept is very similar to ours, but our method has a much wider model space and is able to describe exotic states in the spectrum very different from the ground state.

The method was tested in light $N = Z$ even-even nuclei, using the BKN interaction [1]. We will present results of our recent applications with realistic Skyrme interactions. In Fig. 1, we show an example of our calculations for ^{12}C using the SGII Skyrme interaction. The agreement with experiments is remarkable, considering the fact that there is no adjustable parameter in the calculation. Note that the second 0^+ state, which has the three α clustering, cannot be described in the shell model. We will discuss other applications and examine capability of the Skyrme density functional beyond the mean field.

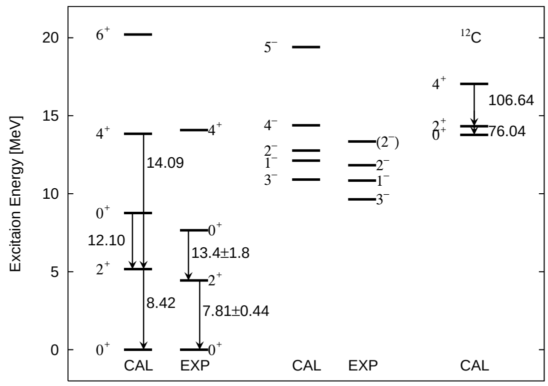

FIG. 1: Excitation spectra in ^{12}C. The numbers next to arrows indicate $B(E2)$ in units of e^{2}fm^4.

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Experimental studies of p-process nucleosynthesis*

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About 30 - 35 proton-rich stable nuclei heavier than iron are bypassed by the s and r neutron capture processes, they are referred to as p nuclei. In total, about 20.000 reactions and 2.000 nuclei are involved in the p-process reaction network, where most of them are unstable and thus not directly accessible experimentally. As experimental data is very scarce within the astrophysically relevant energy range, p-process network calculations are based almost completely on theoretical predictions stemming from the Hauser-Feshbach statistical model.

In order to improve p-process network calculations, experimentally determined nuclear physics input parameters like α + nucleus optical model potentials or γ strength functions are of crucial importance. Experiments on proton- and α-induced reactions are a dedicated approach to study these nuclear properties at astrophysically relevant energies. Due to the low interaction energies of astrophysical relevance, cross sections for ion-induced reactions are typically located in the μb range.

This talk will give an overview about p-process nucleosynthesis and different experimental techniques to study ion-induced reactions which are of relevance for the astrophysical p process:

- Activation technique using γ-ray spectroscopy of subsequent β decay of target nuclei after activation at an accelerator facility
- In-beam measurements using high resolution HPGe detector arrays
- Accelerator Mass Spectrometry

In this talk, advantages and disadvantages of the different experimental approaches will be discussed and recent results will be presented.

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Interacting boson model from energy density functionals: γ-softness and the related topics*

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Energy density functional (EDF) approach gives complete and universal description of nuclear ground-state properties, and is a good starting point for collective dynamics. We describe the γ-softness of medium-heavy and heavy nuclei from a microscopic picture. By mapping the self-consistent constrained mean-field energy surface for a wide range of the relevant non-axial nuclei onto the proton-neutron interacting boson model (IBM-2) Hamiltonian containing up to three-body boson interactions, low-lying collective spectra and transition rates are calculated [1,2].

Observables are calculated that differentiates two limiting geometrical pictures of non-axial nuclei: rigid-triaxial and γ-unstable rotor models. It is shown that neither of these pictures is realized in presumably all non-axial nuclei, and that microscopic description leads to results that are almost in between the two limits [3] (cf. Fig.1). In the IBM, such robust regularity arises naturally only when the three-body boson term is included, independently of the details of microscopic EDFs.

Some relevant topics including the isovector collective excitation of valence shells is discussed, as an extension of the EDF-to-IBM mapping procedure. Scissors 1^+ excitation and the M1 property of rare-earth nuclei are described microscopically, being rather consistently with the experiment.

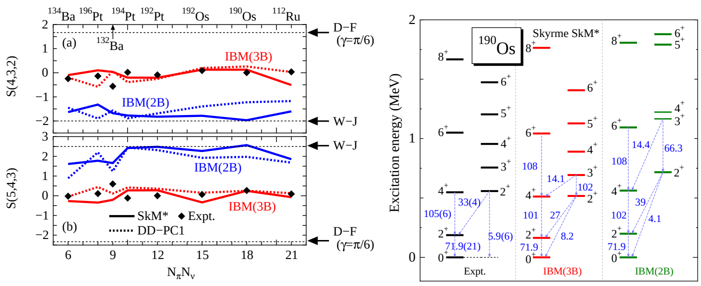

FIG. 1: (Left) Energy ratio $S(J, J-1, J-2) = [\{E(J) - E(J-1)\} - \{E(J-1) - E(J-2)\}]/E(2_1^+)$ for the quasi-γ states with (a) $J = 4_\gamma^+$ and (b) $J = 5_\gamma^+$ of typical non-axial medium-heavy nuclei, that distinguishes between the γ-unstable (W-J) and the rigid-triaxial (D-F) rotor limits. (Right) Level energy for ^{190}Os nucleus with the IBM Hamiltonian with up to three- (IBM(3B)) and two- (IBM(2B)) body terms.

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Collinear cluster tri-partition (CCT) a new kind of radioactive decay of ^{252}Cf (sf) and in (^{235}U + n) - ^{236}U*

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In a variety of experiments over the last decade (see Pyatkov*et al.*[1] and refs therein), a new type of cluster radioactivity has been observed, the "collinear cluster tri-partition", CCT. It has been observed in decays of ^{252}Cf(sf) and in the reaction ^{235}U(n,fff). The experiments are based on binary coincidences of the masses and energies of two fission fragments, independently. The total mass of the fragments, and the missing mass in binary coincidences is determined, Fig.1. One of the lighter two fragments which originate in the second step, which are originally collinear, are separated by a small angle (1) by scattering in the backing, and one fragment is blocked at the entrance grid of the ionisation chamber (see Fig.1). The relatively high yield of the CCT-effect (more than 10^{-3} per binary fission) is due to the favourable Q-values (more positive than binary), due to the formation of spherical fragment-clusters (with closed shells) like: ^{132}Sn + ^{50}Ca + ^{70}Ni. In addition it has been shown in ref.[2], that the collinear (prolate) geometry has the favoured potential energy (by 25 MeV) relative to the oblate shapes, and a large phase-space in momentum and isotopic mass is observed [3]. The decay is considered to be a sequential process. Based on this assumption we have calculated the kinetic energies [3] of the fragments. The third fragments at the center have very low kinetic energies (below 20 MeV) and probably have thus escaped detection in previous work on "true ternary fission", where in addition an oblate shape and a triangular geometry for the decay vectors has been assumed.

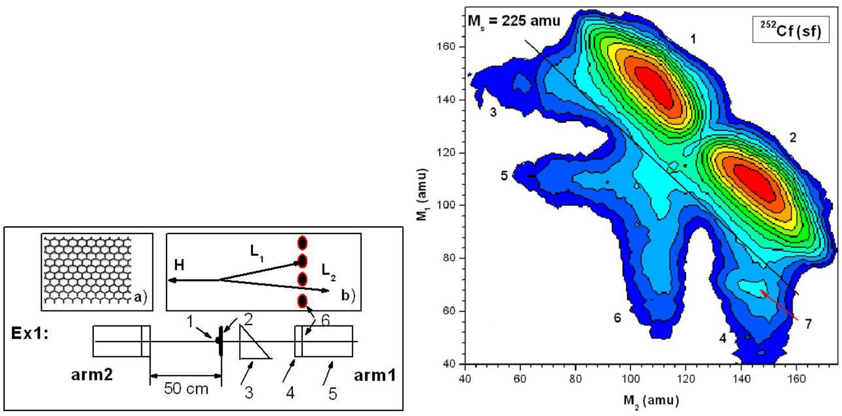

Figure 1: *Masses measured in coincidence (180 °) with two FOBOS-detectors for ^{252}Cf (sf). The arrow indicates the missing mass. Left: Scheme of the separation of two collinear fragments.*

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Beta Decay of Exotic fp-shell Nuclei with T_Z = -1 and T_Z = -2 at GANIL

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Beta-decay spectroscopy is a powerful tool to investigate the structure of nuclei far from the line of β-stability. Moreover, these studies for proton-rich nuclei can complement Charge Exchange (CE) reaction experiments carried out on the mirror stable target under the assumption of isospin symmetry. In a series of experiments at the GSI and GANIL fragmentation facilities, β^+-decay studies of T_Z = -1 and T_Z = -2 nuclei in the fp-shell have been carried out. For all of them the β^--type mirror CE reactions on T_Z = +1 and T_Z = +2 target nuclei were studied at RCNP Osaka [1,2,3].

First, at the RISING facility at GSI we measured the decay of the T_Z = -1, ^{42}Ti, ^{46}Cr, ^{50}Fe and ^{54}Ni nuclei to the self-conjugate T_Z = 0 ^{42}Sc, ^{46}V, ^{50}Mn and ^{54}Co nuclei, respectively [1,2,4]. In this experiment we were able to a) measure the β-decay half-lives with one order-of-magnitude better accuracy than in the literature, b) establish the decay schemes, c) determine the direct ground state to ground state feeding in the decay, d) measure the decay intensity to the 1^+ states populated in the daughter and hence the absolute Gamow-Teller strengths B(GT). This allowed us to compare the results with the B(GT) values measured in the corresponding CE reactions.

These results have motivated further investigations on more exotic fp-shell nuclei. Recently two β-decay experiments were carried out at the LISE3 facility at GANIL to study the structure of two nuclei, the T_Z = -2 ^{56}Zn and T_Z = -1 ^{58}Zn, for which measurements of the mirror CE reactions already exist. For the ion production we used in one experiment a ^{64}Zn beam of 79 AMeV and in the other a ^{58}Ni beam accelerated to 75 AMeV on a natural Ni target. The ions were separated by the LISE spectrometer and implanted into a DSSSD detector, surrounded by four Ge Exogam clovers for gamma detection. From the determination of the time-correlations between the heavy-ion implants and the subsequent beta or beta-gamma decays, happening in the same pixel of the DSSSD, we could extract the key spectroscopic information.

Results from the GANIL experiments will be presented, in particular the precise half-lives of ^{58}Zn and ^{56}Zn as well as other nuclei produced at the same settings. ^{58}Zn is of astrophysics interest, since it constitutes a waiting point in the rp-process. In addition, it was found that the half-life of ^{58}Zn β-decay can be well reproduced from the results of CE reaction studies on the mirror nucleus ^{58}Ni using the "merged analysis" [2,3], suggesting a good isospin symmetry in the A = 58 system.

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Perspectives of Monte-Carlo Shell Model

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I will overview perspectives of Monte Carlo Shell Model (MCSM). The MCSM methodology has been revised in recent years, so as to show the eigenvalues with high precision, aiming at substantial use of K computer . The K computer is a ten peta flops machine located in Kobe, Japan. Several techniques of extrapolation have been introduced with great success, which enables us to discuss exact eigenvalues with a small number of basis vectors from many-body Hilbert space. I will report some recent results from ab initio type MCSM calculations on light nuclei as well as usual but extremely large-scale calculations on some medium-heavy nuclei.

Microscopic investigation of structural evolution in even-even N=60 isotones

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The ground state properties of even-even N=60 isotones from the neutron-rich to the proton-rich side ($34<Z<56$) are investigated within the self-consistent Skyrme-Hartree-Fock-Bogoliubov theory in the triaxial landscape. The Skyrme energy density functional SLy4 has been considered in the particle-hole channel, while the zero range delta-interaction has been employed in the particle-particle channel [1]. In order to correctly treat the pairing correlations in the vicinity of shell closure, a particle-number projection of the wave function was carried out by the Lipkin-Nogami method [2].
The evolution of the potential energy surfaces in the (β, γ) deformation plane is presented and discussed. Moreover, quantities such as binding energies, two-proton separation energies, root-mean-square radii and quadrupole moments are investigated and compared with available experimental data and other theoretical evaluations [3-5]. The role of the triaxiality in the structure of N=60 isotones is emphasized.

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Validation of cluster structures for ^{9}Be through Coupled channel calculations*

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In a recent paper by Pandit *et al.* [1], two cluster configurations: ^{8}Be+n and ^{5}He+^{4}He of ^{9}Be have been thoroughly investigated through high precision elastic scattering data below Coulomb barrier energies on ^{208}Pb target. It was demonstrated that below Coulomb barrier only ^{8}Be+n cluster structure of ^{9}Be can able to explain the data satisfactorily. Interestingly, it was observed that the coupling effect of one neutron transfer channel remains present even at these sub-Coulomb barrier energies. Motivated by these investigations, we decided to validate these two models of ^{9}Be for other targets *viz.*, ^{28}Si [2], ^{64}Zn [3] and ^{144}Sm [4]. The available data for elastic scattering, transfer and fusion around Coulomb barrier energies have been utilised for comparison with the model calculations. Typical elastic scattering angular distribution data for ^{9}Be+ ^{144}Sm system along with the present calculations are shown in Fig. 1. The details of the calculations and results will be discussed during the conference.

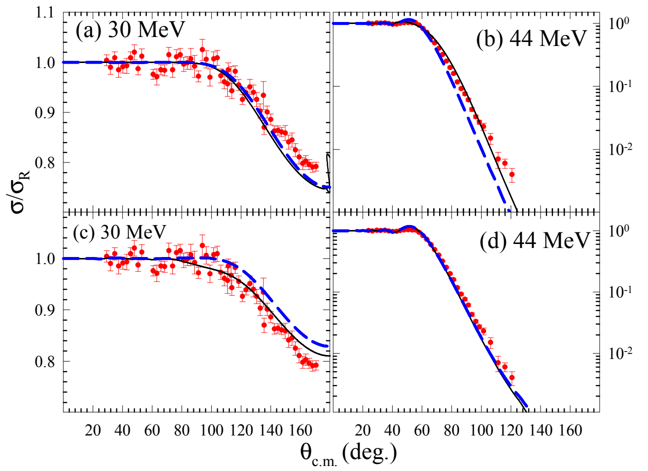

FIG. 1: Elastic scattering data for ^{9}Be+^{144}Sm [4] has been compared with two models: (a,b) ^{5}He+^{4}He and (c,d) ^{8}Be+n. Dashed and solid lines are without and with full (breakup + neutron transfer) couplings respectively.

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Studies of few-body dynamics in dripline nuclei at FLNR, JINR.*

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The nuclear driplines are nowadays achieved experimentally for the light nuclear systems and there is an important trend in the modern research with radioactive ion beams to study the systems close and even beyond the driplines. Many of these systems demonstrate unusual properties which can be attributed to different forms of irreducible few-body dynamics, like three-body nucleon haloes, true three-body decays (e.g. two-proton radioactivity as a special case), soft excitation modes, etc.

In recent years there was a successful line of studies at Flerov Laboratory of Nuclear Reactions dealing with light dripline systems. These studies were performed with ACCULINNA fragment separator, using high intensity primary beams of ^{7}Li, ^{11}B, ^{13}C, ^{15}N, ^{18}O, ^{32,34}S etc. with energy values ranging between 30 and 50 AMeV, delivered by the U- 400M cyclotron to the production target of the separator. The secondary radioactive beams with energies of about 20-30 AMeV allow us to gain new insights into the structure of neutron/proton halo nuclei through studies of one- and two-nucleon transfer or charge-exchange reactions made with hydrogen and helium targets. Such beams offer favorable conditions for the production of so far unknown particle-unstable nuclei beyond the neutron/proton drip line.

Novel results related to studies of few-body phenomena were obtained for such isotopes as ^{5}H, ^{7}H, ^{8}He, ^{10}He, ^{6}Be, ^{17}Ne, and ^{26}S. Thus, in resent studies of ^{6}Be [1] in the charge-exchange reaction ^{1}H(^{6}Li,^{6}Be)*n* the origin of the ^{6}Be negative-parity continuum was interpreted as a novel phenomenon, the isovector soft dipole mode (IVSDM) which may offer new opportunities in the nuclear structure studies. In latest studies of ^{10}He [2] (expected to be a magic one) in the ^{3}H(^{8}He, *p*) ^{10}He reaction the low-lying spectrum of ^{10}He was studied. Owing to specific angular correlations, for the first time spin-parity assignment was made for the low-lying states of ^{10}He, 0^+ g.s. at 2.1±0.2 MeV with its width ~2 MeV, 1^- (with the total energy E_T >4.5 MeV) and 2^+ (E_T >6 MeV). These new data suggest less binding energy than expected earlier and provide an evidence for the low-lying negative parity intruder state.

The major results of these studies are presented and discussed from theoretical point of view. We focus on continuum properties of three-body systems, studies of specific correlations, and practicalities of connection between theory and experiment.

Now, a new more powerful in-flight fragment separator ACCULINNA-2 at U-400M cyclotron in FLNR, JINR is planned to be built in addition to the existing separator ACCULINNA in 2010-2015. It will provide high intensity RIBs in the lowest energy range (5÷50 A MeV) which is attainable for in-flight separators thus opening new possibilities for astrophysical studies with the ACCULINNA–2 separator.

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Experimental evidence for the presence of double octupole states in ^{240}Pu*

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Octupole correlations in the actinides have attracted interest since the predictions that octupole deformation would be present in the Z∼88 and N∼134 region [1,2]. In the even-even nuclei in this region, alternating parity bands, $K^\pi=0^+_1$ and $K^\pi=0^-_1$, which are thought to indicate the presence of stable octupole deformation, have been observed. However, the question of the existence of octupole deformation is still very much open and different empirical signatures are controversial.

In the actinides mass region it was pointed out that the 0^+_2 and 0^+_3 band heads lie very close in energy, only 50-200 keV apart. Furthermore, in Ref. [4] it was suggested that the two excited bands are very different in structure. For example, the γ-ray branching ratio $B(E2;2^+_{0_i} \rightarrow 4^+_1)/B(E2;2^+_{0_i}0^+_1)$ is larger by one order of magnitude for 0^+_2 compared with the 0^+_3 band. This additional 0^+ band was interpreted by *Zamfir* and *Kusnezov* [5] in the framework of the IBA-*spdf* model as corresponding to the double octupole/dipole states. However, their interpretation is based only on the energies of the 0^+ band-head and the branching ratio of the 2^+ state. Additional experimental evidences are needed to confirm this picture by measuring other observables related to the two 0^+ bands.

In this contribution we report on a new experiment performed on the ^{240}Pu nucleus which was investigated by means of the (p,t) reaction using the Q3D spectrometer [6] and the focal plane detector [7] from Munich. Such an approach is very suitable for providing rather complete spectroscopic information for the low spin states in even-even nuclei. The comparison between experimental angular distribution and the Distorted Wave Born Approximation allowed the extraction of the relative two-neutron transition strengths. These observables can reveal important informations about the structure of different states and a special attention was given to the observation of the 0^+ states. The experimental two neutron strength for the 0^+_2 and 0^+_3 states is found in good agreement with the predictions of the IBA-*spdf* model, confirming the double octupole nature for the 0^+_2 state.

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Some exploitations of the self-consistent QRPA approach with the Gogny force

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RPA calculations with D1S Gogny force applied to spherical nuclei [1] have been extended to the QRPA treatment of axially deformed nuclei [2]. First we propose to present studies on heavy and deformed nucleus uranium 238 [3] and on low-energy dipole excitations in neon isotopes and N=16 isotones [4]. Such studies are allowed by new numerical implementation and it is now possible to undertake systematic study on spectroscopy along isotopic and isotonic chains. Then, we will compare spectroscopy of N=16, N=40 and N=50 isotones obtained with QRPA approach and with 5 dimension collective Hamiltonian (5DCH) calculations using the same D1S Gogny interaction. Evolution of the B(E2) transition probabilities in Sn isotopes will be also discussed. At the end, we will focus on the spectroscopy of Ni isotopes up to 8^+ excited states and the appearance of 0^+ excited states at low energy.

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Real-time algorithm for robust coincidence search

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In in-beam γ-ray spectroscopy experiments, we often look for coincident detection events. Among every N events detected, coincidence search is naively of principal complexity $O(N^2)$. When we limit the approximate width of the coincidence search window, the complexity can be reduced to $O(N)$, permitting the implementation of the algorithm into real-time measurements, carried out indefinitely.

We have built an algorithm to find simultaneous events between two detection channels, but it can easily be modified to work over n channels. We explain below the algorithm cycle for two channels. The algorithm works on two dynamic-sized FIFO [1] arrays that have the maximum length equal to the search window width, where timestamps of events are reported in units of AD clock cycles. Initially, both FIFO arrays are empty. We start with two list modes of measured events from which we want to compare timestamps and define the delays between them, assuming that some of the events are in coincidence. We assume the timestamps of each channel to be in ascending order. We proceed by repeatedly taking the older timestamp among the first of the remaining in each list and compare the difference between the current timestamp and all timestamps that were inserted into FIFO beforehand. At the end we are left with the array of calculated timestamp differences between the two lists. Plotting the histogram of these differences illustrates the probability distribution of delays between detected events. The peak centroid then represents the systematic delay between the the two channels of data.

The algorithm was tested in an experiment where coincidences between X and γ rays detected in two HPGe detectors were observed in the decay of ^{61}Cu. ^{61}Cu was produced in the reaction ^{60}Ni(p,γ) when we studied proton-induced nuclear reactions at an energy of 2.5 MeV for two different environments: metallic nickel and NiO insulator. ^{61}Cu decays in 61% of cases through β^+ and in 39% through EC decay [2]. Measurements were performed with a quad-channel digital spectroscopic MCA assuring the same event clock for both detectors. Comparing the entire γ ray spectrum to the coincidence γ ray spectrum we found out, that the branching γ-ray ratio for EC differs from that for β^+ decay. Comparison of branching ratios normalized to the 283 keV γ ray is given in table 1. We explain the difference by the Q value difference between β^+ and EC decay.

Table 1: Comparison of branching ratio for β^+ and EC decay to the one of only EC decay

E_γ [keV]	$b_{\beta^+ +EC}$	b_{EC}
283	1.00 (18)	1.00 (30)
656	0.89 (16)	1.36 (45)
1185.2	0.30 (6)	0.93 (46)

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Low-lying spectroscopy of a few even-even silicon isotopes investigated by means of the multiparticle-multihole Gogny energy density functional*

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A multiconfiguration microscopic method [1] has been applied with the Gogny effective interaction to the calculation of low-lying positive-parity states in even-even $^{26-32}$Si isotopes [2]. We compare the results of this approach with those of a standard method of GCM type and get insight into the predictive power of multiconfiguration methods employed with effective nucleon-nucleon force taylored to mean-field calculations. It is found that the multiconfiguration approach leads to an excellent description of the low-lying spectroscopy of ^{26}Si, ^{28}Si and ^{32}Si, but gives a systematic energy shift in ^{30}Si. A careful analysis of this phenomenon shows that this discrepancy originates from too large proton-neutron matrix elements supplied by the Gogny interaction at the level of the approximate resolution of the multiparticle-multihole configuration mixing method done in the present study. These proton-neutron matrix elements enter in the definition of both single-particle orbital energies and coupling matrix elements. Finally, a statistical analysis of highly excited configurations in ^{28}Si is performed, revealing exponential convergence in agreement with previous work in the context of the shell model approach. This latter result provides strong arguments towards an implicit treatment of highly excited configurations.

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First observation of the ground-state based rotational band in 256Rf at the border of the superheavy nuclei

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Transfermium nuclei lie at the boundary between actinides and the barely investigated region of superheavy elements (SHE). These isotopes retain fusion-evaporation cross-sections at the limits of contemporary investigation techniques [1]. These two properties therefore place them as ideal candidates for the investigation of the nuclear interaction at high masses. The use of arrays of high-purity germanium and silicon detectors in conjunction with recoiling nuclei separators provides access to the structure of these nuclei through spectroscopy techniques. These experiments are presently at the forefront of the investigation on the structure of nuclei at high masses.

Of special interest are the nuclei situated along the N=152 isotone. Deformation induces a disapearance of the degeneracy of the orbitals above the speculated superheavy nuclei spherical gap. Therefore low-J projections first close the SHE spherical gaps and come down to the vicinity of the Fermi level of transfermium nuclei, creating deformed gaps at N=152 for example. Spectroscopic measurements on these nuclei provide an important insight on the behaviour of these orbitals, necessary to understand the structure of heavier nuclei [2].

This contribution will report on the first measurement of the prompt electromagnetic transitions of ^{256}Rf and the technical achievements necessary to perform this experiment at the University of Jyväskylä. The germanium array JUROGAM II [3] was associated to the magnetic separator RITU [4] and the focal plane spectrometer GREAT [5] to identify and measure the decay of the ^{256}Rf nuclei. The detection of prompt gamma-ray transitions at high rates was allowed by the use of digital ADCs with the germanium detectors around the target position. ^{256}Rf nuclei were produced through fusion-evaporation with a beam of ^{50}Ti impinging on a target of ^{208}Pb. This beam was produced for the first time with the MIVOC method using an organometallic compound synthesized at the IPHC Strasbourg [6].

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Systematic shell-model study of isovector and isoscalar pairing in the $2p1f$ shell

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It is generally believed that $proton - neutron$ (pn) pairing is important in nuclei with roughly equal numbers of neutrons and protons [1]. The standard technique for treating these correlations is through the use of BCS or HFB approximation, generalized to include the pn pairing field in addition to the nn and pp pairing fields. Questions arise, however, as to whether these methods can adequately represent the physics of the competing modes of pair correlations, without full restoration of symmetries [2].

Important insight on pn pairing correlations has been achieved in recent years in the context of exactly-solvable models that include the various pairing modes. Analysis of the SO(8) model, for example, in which isoscalar and isovector pairing act in either a single active orbital or a series of degenerate orbitals, suggests that isospin restoration or equivalently quartet correlations are extremely important, especially at $N = Z$ [2]. A more recent study carried out for an analogous model that includes non-degenerate orbitals [3] makes possible the inclusion of deformation effects, as is critical for systems with $N \approx Z$, by treating the non-degenerate orbitals as Nilsson-like. However, it is not possible in such models to fully restore symmetries.

As a consequence, there still remain important issues concerning the role of the various pairing modes in $N \approx Z$ nuclei. In this work, we discuss a systematic study of isovector and isoscalar pairing correlations in $N \approx Z$ nuclei in the context of the nuclear shell model, whereby deformation can be readily included and symmetries exactly preserved [4].

Following a description of our model, we will report the results of selected calculations for three $N = Z$ nuclei in the $2p1f$ shell, ^{44}Ti, ^{46}V and ^{48}Cr, focusing on the role of single-particle effects in dictating how the various pairing modes compete.

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Onset of quasifission in asymmetric systems populating the compound system ^{210}Rn.

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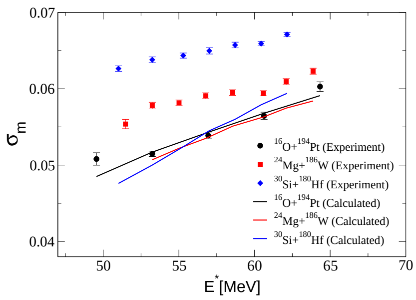
Study of onset of non-equilibrium processes such as quasifission [1,2] (QF) in less fissile systems at near barrier energies is of great research interest in the recent years. QF is a major hurdle in the formation of superheavy elements and shows strong entrance channel dependence [3,4,5]. Experimental signatures of this process include a strong reduction in evaporation residue cross section, anomalous fission fragment angular anisotropies, broadened fragment mass distributions and mass-angle correlations.

We measured the fission fragment mass-angle and mass-ratio distributions for the asymmetric reaction ^{30}Si+^{180}Hf forming the compound nucleus (CN) ^{210}Rn at energies around the Coulomb barrier. The experiment was performed at the 15UD Pelletron accelerator facility of Inter University Accelerator Centre (IUAC), New Delhi. Fragments were measured using two large area MWPC detectors and the time-difference method was used for obtaining the mass ratio distributions of the complimentary fragments [6]. The experimental energies were so chosen that the CN excitation energies were matched with two other reactions ^{16}O+^{194}Pt and ^{24}Mg+^{186}W reactions [5], forming the same CN.

Although we could not observe any mass-angle correlation in the energy range studied, the observed fragment mass-ratio widths (σ_m) were substantially larger than that of ^{16}O+^{194}Pt and ^{24}Mg+^{186}W reactions, at similar excitation energies as shown in Figure. The experimental results deviate significantly from the statistical model calculations assuming fission followed by CN formation, which indicates a strong onset of quasifission process in ^{30}Si+^{180}Hf and ^{24}Mg+^{186}W reactions. The charge product $Z_P Z_T$ of these two reactions ^{30}Si+^{180}Hf and ^{24}Mg+^{186}W are 1008 and 888, respectively, which is much less than 1600. The onset of QF in these reactions at near barrier energies clearly indicates the role of entrance channel parameters like deformation, mass asymmetry etc in the fusion-fission mechanism.



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Towards the island of stability with relativistic energy density functionals

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Relativistic energy density functionals (REDF) provide a complete and accurate, global description of nuclear structure phenomena. Modern semi-empirical functionals, adjusted to the nuclear matter equation of state and to empirical masses of deformed nuclei, are applied to studies of shapes of superheavy nuclei. The theoretical framework is tested in a comparison of predicted masses, quadrupole deformations, and potential energy barriers of actinides, with available data. The model is used in a self-consistent mean-field calculation of spherical, axial and triaxial shapes of long-lived superheavy nuclei, their alpha-decay energies and lifetimes. The effect of explicit treatment of collective correlations is analyzed in calculations that consistently use a collective Hamiltonian model based on REDFs.

^{13}C+^{4}He resonant elastic scattering on thick gas target*

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Resonant elastic scattering of ^{13}C on a thick ^{4}He target has been measured at Ruđer Bošković Institute 6 MV EN Tandem Van de Graaff accelerator facility. Reaction products from ^{13}C(^{4}He,^{4} He) were detected in a single 50×50 mm double sided silicon strip detector (1 mm thick) located at 0° in a gas volume. The gas-filled chamber has been separated from the beam-line by a 2 μm thick Havar foil. Gas pressure was monitored using absolute manometer and adjusted for the beam to stop several centimetres in front of the detector, located 42 cm from the Havar window. Beam energies of 20.0, 25.0, 30.0, 33.0 and 35.0 MeV were used with ^{4}He gas pressures of 313, 461, 591, 699 and 790 mbar, respectively.
The data analysis was performed event-by-event, assuming all detected particles were ^{4}He. Data analysis was subdivided in three steps. Firstly we calculated kinematics and energy loss [1] for elastic scattering on thick gas target and established the relationship between detected energy in the given pixel and the energy of the emitted alpha-particle, which allowed a calculation of the center-of-mass energy. Monte Carlo simulations, assuming isotropic center-of-mass angular distribution for the breakup, were used to correct a raw yield for a variation of angular acceptance of the detector. Corrected yields of different runs were checked for consistency. In the third step, we averaged the data from differet runs and normalised using Rutherford cross section. We are currently in the process of fitting R-matrix calculations to our results.
Results on ^{17}O states populated in this measurement will be presented [2].

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Effect of neutron transfer in the fusion process near and below the Coulomb barrier *

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Many theoretical and experimental studies are devoted to analysis of the fusion reactions. Reactions of sub-barrier fusion of the neutron-rich nuclei with stable nuclei are of special interest. In these reactions an increase of the fusion cross section at energies below the Coulomb barrier is observed. The processes of the rearrangement of valence neutrons with positive Q-values (that leads to a gain in the kinetic energy of the colliding nuclei) may substantially increase the sub-barrier fusion cross section.

The role of neutron transfer is investigated in the fusion process near and below the Coulomb barrier within the empirical channel coupling model (EEC model)[1,2]. In this approach the total penetrability of the fusion barrier is calculated taking into account the probabilities of transfer of a single or several neutrons (up to four neutrons), averaged over the parameterized barrier distribution function.

We will focus on the role of neutron transfers between the colliding nuclei as a mechanism that may enhance the fusion cross sections at sub-barrier energies. Different combinations (^{16,18}O + ^{116,114}Sn, ^{9,11}Li + ^{208,206}Pb, ^{4,6}He + ^{64}Zn and other) of colliding nuclei were studied. In all the cases, the sub-barrier fusion proves to be more probable for the combinations, where intermediate neutron transfer with positive Q-values is possible. The theoretical calculations show a good agreement with available experimental data. The corresponding predictions of the fusion cross section for several combinations of colliding nuclei have been made. These results may be useful in planning and data analysis of the corresponding experiments.

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MINIBALL γ-ray Spectroscopy far from Stability

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For the MINIBALL collaboration

The MINIBALL spectrometer utilizes successfully the huge variety of post-accelerated radioactive ion beams provided by REX-ISOLDE at CERN. In-beam γ-ray spectroscopy after Coulomb excitation or transfer reactions is performed with optimized setups of ancillary detectors for particle detection. An overview of the technical details of the full MINIBALL setup, including beam monitoring devices and methods to deal with beam contamination, will be presented. The physics program is covering a wide range of shell model investigations from the light sd-shell nuclei up to the Pb region. Especially the enlarged availability of exotic heavy ion beams enables unique studies of collective properties up to the actinide region. In future the HIE-ISOLDE project will provide a promising perspective for new MINIBALL experiments.

Covariant density functional theory with energy dependent self energies in nuclei.

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The concept of density functional theory in the microscopic description of quantum mechanical many-body systems is based on Hohenberg-Kohn theorem. In nuclear physics this method has been very successfully employed in the analyses of a variety of nuclear structure phenomena, not only in nuclei along the valley of β-stability, but also in exotic nuclei with extreme isospin values and close to the particle drip lines. It is based on the mean field concept connected with violation of symmetries. Although originally invented for ground states, it has been also applied for excited states for single particle excitations in closed shell systems, collective vibrations in the framework of time-dependent mean fields, and nuclear rotational bands in a rotating mean field. Of course, it is not evident from the Hohenberg-Kohn theorem that one can use for excited states same energy density functionals as for the ground states. In fact, in all these three cases one also observes serious limitations: the shell gap in the single particle spectrum of doubly closed shell nuclei is considerably too large, the random phase approximation fails to reproduce the width of the giant resonances, and the description of nuclear spectra requires a restoration of the broken symmetries.

In Coulombic systems density functional theory has been extended also for excited states in the framework of time-dependent density functional theory (TDDFT). This method is again in principle exact. However, the corresponding Kohn-Sham potential is a functional of the time-dependent energy, i.e. it depends on the full history of the time-dependent process. For practical applications one needs additional approximations. In the small amplitude limit one finds linear response theory with an energy dependent integral kernel. Going beyond the mean field approximation, an energy dependent self-energy is constructed by coupling the single particle motion to low-lying surface modes. This leads to an enhanced level density at the Fermi surface and to an induced interaction in the resulting Bethe-Salpeter equation.

We give a review on recent applications of these ideas to covariant density functional theory in nuclei, in particular the investigation of the width of giant resonances and of the coupling of low-lying dipole excitations to complex configurations.

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Dipole Polarizability and Parity Violating Asymmetry in ^{208}Pb*

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The dipole polarizability and the parity violating asymmetry at low momentum transfer in ^{208}Pb have been recently measured at RCNP (Japan) [1] and JLab (USA) [2], respectively. Both observables are intimately connected with the neutron skin thickness of the same nucleus and, more fundamentally, both are believed to be associated with the density dependence of the nuclear symmetry energy around saturation [1-4]. The impact of this basic property of the nuclear Equation of State on the dipole polarizability and the parity violating asymmetry in ^{208}Pb will be presented and discussed on the basis of a large and representative set of relativistic and non-relativistic nuclear energy density functionals. The connection between these two experimental results via the employed theoretical framework will be also discussed.

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Application of nuclear energy density functionals to lepton number violating weak processes*

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The nature of the neutrino as a Majorana or Dirac particle is still an open question. Experimental evidence of lepton-number violation weak processes such as neutrinoless double beta decay ($0\nu\beta\beta$) or double electron capture (0νECEC) would determine unambiguously the Majorana character of this elementary particle [1]. The half-lives of these processes depend on the effective neutrino mass and the nuclear matrix elements (NME) between the initial and final nuclei. Therefore, reliable calculations of the NMEs are crucial to estimate the half-lives of these decays or, in case of experimental detection, to extract the effective neutrino mass.
In this contribution we present calculations for the NMEs performed with energy density functional methods including beyond mean field effects [2,3]. In particular, we analyze the role of deformation and pairing correlations in the final values for several nuclear matrix elements of $0\nu\beta\beta$ and 0νECEC processes.

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^{25}Na and ^{25}Mg fragmentation on ^{12}C at 9.23 MeV per nucleon and AMD calculations*

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Properties of the nuclear matter at different densities and temperatures can be characterized by studying heavy-ion collisions at numerous projectile energies and with various symmetric and asymmetric mass systems and N/Z ratios for the projectile-target interacting pair. The multidetector HERACLES[1], previously operated at intermediate energies, has been adapted to study heavy-ion systems at ISAC-II (TRIUMF) energies in the 5 to 15 MeV per nucleon range. The multidetector has been recently ran with a radioactive ^{25}Na beam and a stable ^{25}Mg beam at 9.23 MeV per nucleon on a carbon target.

Many different detection devices[2] were mounted between 4.5 and 46 degrees: BaF_2 crystals and plastic scintillators in phoswich mode, CsI(Tl) scintillators in pulse shape arrangement and Si-CsI(Tl) telescopes. Energy calibration peaks have been obtained by elastic scattering on different targets of a ^{4}He-^{12}C-^{16}O cocktail beam accelerated at 6.56 MeV per nucleon. Particle identification and energy calibration of some 75 detectors have been completed and the physics analysis is underway.

Experimental energy spectra of several particles and light fragments from both beams are being compared; isotopic ratios are also analyzed. Several observables from both projectiles will be compared with the simulations based on a dynamical model, Antisymmetrized Molecular Dynamics (AMD code[3]).

The analysis is in progress. The main point is to obtain enough statistics from the simulations for the comparison of the experimental physics results to the AMD distributions based on different parameters. It will be completed so that a thorough view and interpretation will be presented at the conference

* Work supported by a grant from Natural Sciences and Engineering Council of Canada

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Highlights and future plans at RIBF

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I will introduce and review recent results on exotic nuclei at the RI Beam Factory (RIBF). Special emphasis is given to selected experiment programs that highlight studies for nuclear structure, especially for nuclei in the island-of-inversion and beyond, and neutron-rich nuclei with A~110 region. I will show future plans of new collaborations and new other devices.

The RIBF is a top world-class in-flight RIB facility, which was constructed to establish a new framework for nuclear structure, to elucidate the origin of elements, and to explore new applications with fast RIBs. The RIBF has started in operation since 2007, and for last 5 years, excellent performances of this facility have made great access to nuclei far from the stability line and have lead to exciting results via several spectroscopy methods; deformed halo nuclei such as Ne-31 [1], collective enhancement of the Ne isotopes toward the drip line [2], significantly shorter half-lives in A~110 region than predicted by a global theory [3], identification of deformed magic number N=64 in the Zr isotopes [4].

These spectroscopy works are being strengthened by a new collaboration of Euro-RIKEN Cluster Array (EURICA) for decay spectroscopy [5], and by a new setup of SAMURAI for particle unbound state spectroscopy [6]. Construction budget for rare-RI ring [7], which is dedicated to mass measurement, has been approved to accelerate mass spectroscopy for nuclear structure as well as nuclear astrophysics.

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Multipair approach to pairing in nuclei

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Pairing plays a crucial role in the description of both finite and infinite nuclear systems. BCS and projected BCS (PBCS) approaches are quite common tools to treat pairing. These theories share an important feature: they provide a description of the nuclear ground state in terms of just one collective pair. PBCS, in particular, proposes a ground state wave function that is simply a condensate of such a pair. The scenario that the exact ground state (when available) of a pairing Hamiltonian exhibits can be, however, very different from that suggested by PBCS. This is the case, for instance, of the so-called reduced-BCS or picket-fence model which describes a system of fermions occupying a set of doubly degenerate equally spaced levels and interacting via a pairing force with constant strength. The corresponding ground state is a product of collective, distinct pairs (either real or complex) irrespective of the pairing strength.

Aiming at realizing a description of the ground state of a general pairing Hamiltonian in terms of collective, distinct pairs by limiting as much as possible its computational cost, we have developed an iterative variational procedure which allows a sequential determination of the pairs through diagonalizations of the Hamiltonian in restricted model spaces. Each diagonalization is meant to generate one collective pair at a time while all the others act as spectators. All pairs are by construction real. This procedure takes inspiration from a somewhat analogous iterative approach recently proposed to search for the best description of the eigenstates of a generic Hamiltonian in terms of a selected set of physically relevant configurations [1].

Different applications of the method are provided that include comparisons with exact and PBCS results. The quantities that are examined are correlation energies, occupation numbers and pair transfer matrix elements. In a first application within the picket-fence model, the method is seen to generate the exact ground state for pairing strengths confined in a given range. Further applications of the method concern pairing in spherically symmetric mean fields and include simple exactly solvable models as well as some realistic calculations for middle-shell Sn isotopes. In the latter applications, two different ways of defining the pairs are examined: either with $J = 0$ or with no well-defined angular momentum. In spite of generating some (limited) violations of the total angular momentum, the latter choice reveals to be globally more effective leading to results that, under some circumstances, are found to be basically exact even for realistic pairing Hamiltonians.

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Alpha-like quartet correlations and proton-neutron pairing in N=Z nuclei

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It will be shown that proton-neutron pairing generates alpha-like quartet correlations in the ground state of N=Z nuclei [1]. The quartet correlations are described by a quartet condensate model (QCM) which conserves exactly the particle number and the isospin. The comparison with exactly solvable Richardson-Gaudin models and exact shell model diagonalisations indicates that QCM gives a very accurate description of pairing, much better than BCS-type models [2,3]. In the framework of QCM and shell model and using as examples N=Z nuclei with sd and pf open shells, it will be discussed how the isovector and isoscalar pairing compete with each other as well as with nuclear deformation [4,5].

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The roles of nuclear deformation and neutron transfer in sub-barrier capture process are studied within the quantum diffusion approach. The change of the deformations of colliding nuclei with neutron exchange can crucially influence the sub-barrier fusion. The comparison of the calculated capture cross section and the measured fusion cross section in various reactions at extreme sub-barrier energies gives us information about the quasifission.

Nuclear shape transitions in neutron-rich medium-mass nuclei*

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The nuclear structural evolution as a function of the number of nucleons is a subject of increasing interest in nuclear physics, which is supported by very intense activity on both theoretical and experimental sides (for a recent review, see [1]). Specially interesting are those situations where the nuclear structure suffers drastic changes between neighbor nuclides. These structural variations lead often to sudden changes of particular nuclear properties that can be used as signatures of shape transitions. This is the case of the neutron-rich isotopes with masses $A \sim 100$. We study the isotopic evolution of the ground-state nuclear shapes in various neutron-rich nuclei in this mass region, namely, Kr, Rb, Sr, Y, Zr, Nb, and Mo isotopic chains. Both even-even and odd-A nuclei are included in the analysis. For the latter we also study the systematics of their one-quasiparticle low-lying configurations. The theoretical approach is based on a selfconsistent Hartree-Fock-Bogoliubov formalism with finite range Gogny energy density functionals. We use two parametrizations, the standard D1S and the most recent D1M. The equal filling approximation is used to describe the odd-A nuclei, preserving both axial and time reversal symmetries.

Neutron separation energies, charge radii, and the spin-parity of the ground states are calculated and compared with available data. Shape-transition signatures are identified around $N = 60$ isotones as discontinuities in both charge radii isotopic shifts and spin-parities of the ground states [2]. The nuclear deformation including triaxiality and the shape coexistence inherent to this mass region are shown to play a relevant role in the understanding of the bulk and spectroscopic features of the ground and low-lying one-quasiparticle states. Comparison with the available data from laser spectroscopy [3] demonstrates the quality and robustness of the Gogny-HFB description that is able to reproduce the main features of this behavior. The signatures found are a common characteristic for nuclei in the whole mass region studied and they are robust, consistent to each other, and in agreement with experiment. We point out that the combined analysis of these observables could be used to predict unambiguously new regions where shape transitions might develop.

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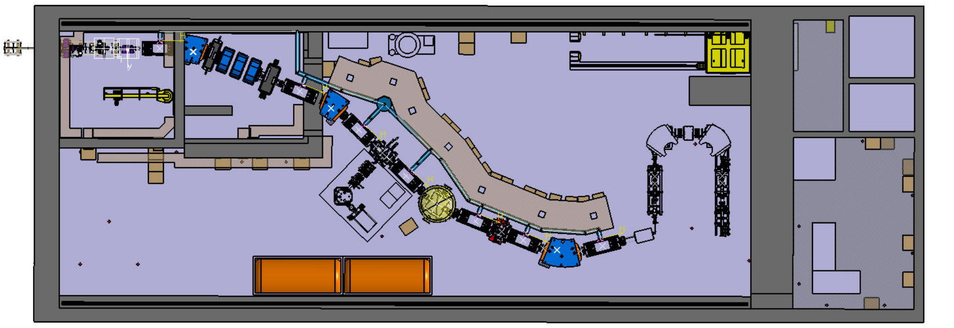
Physics avenues with the Super Separator Spectrometer at SPIRAL2

H. Savajols (GANIL) for the S^3 Collaboration

The SPIRAL2 facility, thanks to the superconducting linear accelerator LINAG, will offer unprecedented heavy ion beam intensities at energies up to 14MeV/u. This regime is ideal to explore fusion evaporation reactions that have very low cross section exit channels, in order to study these reactions as well as the reaction products, like nuclei close to the proton drip line, produced by quasi symmetric fusion reactions, heavy and super-heavy elements, produced by cold or hot fusion reactions. From the letters of intent propose by the collaboration, we will present here the physics domains that could be studied with this facility, as well as key experiments to perform reaction, spectroscopy, isomeric studies or ground states properties measurements of nuclei at the edges of the nuclear chart. More specifically we will present foreseen studies in the ^{100}Sn region and the heaviest elements.
To carry out this broad program of research beginning with the SPIRAL2 Phase 1 project we are currently designing the S^3 (Super Separator Spectrometer). It will couple a large acceptance to transmit the rare nuclei, rejection power to remove the high intensity beam from the products of interest, and mass resolution to identify these products. We will present the basics of the S^3 facility and the different experimental set-ups that will make this new physics possible.



Schematic view of the S^3 cave.

S^3 was awarded in EQUIPEX call.

Accurate Masses from a 2-3 parameter Kohn-Sham Density Functional (BCPM)

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In analogy to what is common use in atomic and molecular physics, we apply the KS-DFT approach to calculate nuclear masses. As input we take for the bulk EOS the microscopic results of Baldo et al. For a fine tune we renormalise this EOS in the range of 10^{-4} around saturation with one open parameter. For the surface we add a completely phenomenologic Hartree term using a gaussian force. The only open parameter is its range. For pairing, we take a density dependent zero range force previously adjusted to the D1S of Gogny. The spin-orbit potential is of the usual form and we also take it from the D1S Gogny force. Final results depend only weakly on the its strength. On the other hand the bulk parameter and the one of the surface term are tightly fixed to within 10^{-4} from a mass fit. The rms for masses is 1.58, better than the one with most of Skyrme and Gogny forces. Our results indicate that, once spin orbit potential and pairing is fixed within the margins of our present day knowledge, two parameters which, on one hand fine tune energy per particle of microscopically determined infinite nuclear matter and, on the other hand, a phenomenological surface energy in very tight limits (10^{-4}), suffice to fix nuclear masses to very good accuracy.

Study of low-energy spectra of the helium isotopes ^{8,9,10}He in the experiments with a tritium target

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Transfer reactions are known as one from the most reliable tools for studies of a nuclear structure near and beyond the drip-lines. Our work is dedicated to exploration of low-energy spectra of the helium isotopes ^{8,9,10}He produced in the reactions with the use of a cryogenic tritium target [1]. The ^{10}He nucleus was studied at the fragment-separator ACCULINNA (Dubna) [2] in the reaction ^{3}H(^{8}He,*p*)^{10}He at the energy of bombarding ^{8}He 21.5A MeV. Tritium in the target cell cooled down to 26 K was kept at the pressure of about 1 atm. ^{8}He emitted from ^{10}He was detected in coincidence with the proton allowing us to measure the angular distribution of ^{8}He in the center-of-mass of ^{10}He with respect to the transferred momentum vector. The measured angular correlations showed prominent interference patterns interpreted as a coherent superposition of a 0^+ ground state with a broad 1^- state having a maximum at the energy 4.5 - 6 MeV and a 2^+ state above 6 MeV. The anomalous level ordering testifies the breakdown of the $N = 8$ shell in ^{10}He.

The energy position and the width of the ^{10}He ground state (E=2.1 MeV, $\Gamma \sim 2$ MeV) are in agreement with theory predictions [3] based on the properties of the ^{9}He subsystem obtained in the neutron transfer reaction ^{2}H(^{8}He,*p*)^{9}He [4].

The reaction ^{3}H(^{6}He,*p*)^{8}He leading to the population of low-lying excited states of ^{8}He was studied at the energy of ^{6}He of about 25A MeV. This reaction, in particular, can be considered as a benchmark for the verification of results on ^{10}He. Angular distribution of ^{6}He emitted from ^{8}He at the excitation energy corresponding to the first excited state 2^+ (~ 3.7 MeV) shows a dominance of a d-wave in this energy range.

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Spectroscopic factors and ESPE from renormalized interactions

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Nuclear shell structure, and especially its evolution away from stability, is utilized to explain experimental data and justify proposed experiments with rare isotope beams. A method for extracting an effective single particle shell structure from correlated many-body observables was developed by Baranger [1], but requires complete spectroscopic information which is not accessible experimentally. Various approximations are typically employed to determine shell structure in nuclei, without consideration of the accuracy of the approximation. Furthermore, as recently shown by Duguet and Hagen [2], shell structure, as given by effective single particle energies (ESPE), is basis-independent but not observable, depending significantly on the resolution scale characterizing the Hamiltonian.

In Ref. [2], spectroscopic factors and ESPE are evaluated with the ab initio coupled cluster theory, limiting the calculations to closed-shell nuclei. With the recent development of a renormalization procedure to produce effective interactions in reduced model spaces [3], configuration interaction calculations were performed in the *sd* shell to evaluate spectroscopic properties and ESPE throughout the model space. The dependence of shell structure on the renormalization procedure is evident, and the relation between ESPE and observables, specifically the 2_1^+ excitation energy and one-nucleon separation energy gap, are evaluated. The effect on ESPE of typical experimental constraints is displayed in detail for neutron-rich oxygen isotopes. The results suggest a reconsideration of experimental methods to determine shell closures, specifically questioning the $N = 14$ gap in ^{22}O.

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Investigation of Incomplete Fusion Dynamics by Spin Distribution Measurement

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The study of complete and incomplete fusion dynamics of heavy ions has been the subject of growing interest at projectile energies above the Coulomb barrier. It has been observed that at projectile energies slightly above the Coulomb barrier both the complete fusion and incomplete fusion may be considered as dominant reaction mechanisms. In case of complete fusion, the projectile completely fuses with the target nucleus and the highly excited nuclear system decays by evaporating low energy nucleons. In the incomplete fusion, only a part of projectile fuses with the target nucleus, while remaining part moves in the forward direction [1-3]. The excited composite system decays by emission of particles and / or γ-rays. However, the experimental data on heavy ion interaction with medium mass target nucleus is scarce. In order to understand the complete and incomplete fusion dynamics, an experiment have been carried out by using Gamma Detector Array (GDA) coupled with Charged Particle Detector Array (CPDA) at Inter University Accelerator, New Delhi, India. GDA consists of 12 Compton suppressed n-type high purity germanium detectors at angles 45^0, 99^0, 153^0 with respect to the beam direction and there are 4 detectors at each of these angles. The CPDA is a group of 14 Phoswich detectors. In the CPDA scattering chamber, seven CPD were placed on top and seven on bottom of the chamber. Further experimental details are given in Ref. [4]. A self-supporting 2 mg/cm^2 thick target of ^{124}Sn (enrichment ≈97.20%) prepared with a rolling technique has been used. Spin distributions for various evaporation residues produced via complete and incomplete fusion dynamics have been measured for ^{16}O + ^{124}Sn system at projectile energy 6.3 MeV/nucleon. It is observed from the experimental results that spin distribution for the evaporation residues produced by complete fusion and incomplete fusion processes are distinctly different. These study show that the yield of incomplete fusion reaction channels are almost constant up to a maximum angular momentum and then falls unlike in complete fusion, where the yield gradually fall with spin. It is interesting to note that the spin at half yield for these evaporation residues produced through complete fusion reaction channels is found to be around $J_0 \approx 7\hbar$, while the spin at half yield for the evaporation residues detected in forward α and 2α-emitting reaction channels, associated with incomplete fusion channels comes out to be around $J_0 \approx 9\hbar$ and $J_0 \approx 12\hbar$ respectively. On the basis of above results, it can be inferred that driving input angular momentum J_0 associated with incomplete fusion products are relatively higher than complete fusion products and increases with direct $\tilde{\alpha}$-multiplicity. The observation clearly shows that lower ℓ-values do not contribute to the incomplete fusion, significantly and hence the production of 'fast' forward PLFs (associated with incomplete fusion reactions) are at relatively higher input angular momentum and hence leads to peripheral interaction.

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Investigations with radioactive beams at Dubna

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The new project of the in-flight fragment separator ACCULINNA-2 [1] at U-400M cyclotron in Flerov Laboratory of Nuclear Reaction, JINR is proposed as the third generation of the Dubna Radioactive Ions Beams complex, briefly DRIBs [2]. It is expected to be a more universal and powerful instrument in comparison with existing separator ACCULINNA [3]. The RIBs intensity should be increased by factor 15 (factor 6 - via angular acceptance and factor 2.5 – via more intensive primary beams of upgraded cyclotron), the beam quality greatly improved and the range of the accessible secondary radioactive beams broadened up to Z~20. The new separator will provide high intensity RIBs in the lowest and wide energy range attainable for in-flight separators, i.e. $E_{RIB} \approx 5 \div 50$ MeV/nucleons. The prime objectives of ACCULINNA-2 are to provide good energy resolution and high efficiency for correlation measurements. Extensive research program which could be carried out at this facility as from 2015 and its operating principle are foreseen.

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Fusion of calcium isotopes and of other medium-mass systems

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Studies of heavy-ion fusion dynamics in the region near and below the Coulomb barrier have been proceeding in recent years, and a large amount of experimental data has been collected, especially for medium mass systems [1] (for a recent overview on this subject see the Proceedings of the Fusion11 Conference [2]). Generally speaking, couplings to low-lying collective modes of the colliding nuclei enhance fusion cross sections close to the barrier. The behavior of the experimental excitation function at lower energies, with respect to coupled-channel (CC) calculations employing standard ion-ion potentials, is determined by the relatively smaller effects of those couplings and the intervening so-called "hindrance" phenomenon. Fusion barrier distributions and logarithmic slopes L(E) = d[ln(E)]/dE of the excitation functions are convenient representations of these effects in different energy ranges, as well as the S factor used in nuclear astrophysics. Indeed, fusion reactions between light heavy ions are very important in both hydrostatic and explosive stellar burning processes.

Recent experiments on medium-light systems (A=30-50) indicate that hindrance does show up in all cases, but exhibits varying features, depending on the structure of the two nuclei and on their neutron excess, but (apparently) not on the sign of the fusion Q value. For such systems, further interest lies in their vicinity to the lighter cases directly relevant for astrophysics. This talk will focus on the recent measurements performed at INFN-Legnaro, concerning ^{40}Ca+^{40}Ca, ^{40}Ca+^{48}Ca and ^{48}Ca+^{48}Ca, whose behaviors below the barrier offer a nice opportunity to discuss all these features fully. Representative results are shown in the figure. A comparison with near-by systems will allow to build up a detailed framework of sub-barrier heavy-ion fusion dynamics in that mass region.

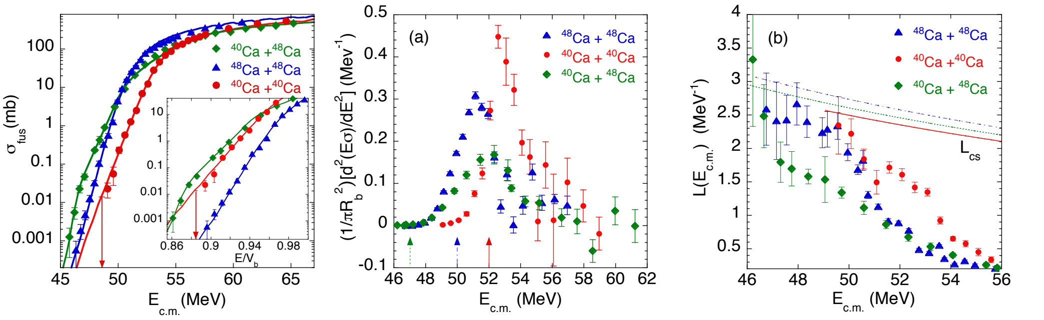

Fig. 1. Fusion excitation functions (left), barrier distributions (center) and logarithmic derivatives (right) of ^{40}Ca + ^{40}Ca, ^{40}Ca + ^{48}Ca and ^{48}Ca + ^{48}Ca (taken from Ref. [1]). Three arrows are drawn at the energy thresholds of hindrance. The lines marked L_{CS} are the slopes expected for constant S factors, and are reported for reference.

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Spin-dependent Modes in Nuclei and Nuclear Forces

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Spin-dependent modes in stable and unstable exotic nuclei are studied and important roles of tensor and three-body forces on nuclear structure and transitions are discussed. New shell model Hamiltonians, which have proper tensor components, are shown to explain shell evolutions toward drip-lines and spin-dependent properties of both stable and exotic nuclei, for example, Gamow-Teller transitions in ^{12}C and ^{14}C [1] and an anomalous M1 transition in ^{17}C [2]. The importance of the tensor interaction and the necessity of the repulsive monopole corrections in isospin T=1 channel to the microscopic two-body interactions are pointed out. The corrections are shown to lead to the proper shell evolutions in neutron-rich isotopes [2].

A new Hamiltonian with proper tensor components [2] is shown to describe well the spin-dipole transitions in ^{16}O. The ^{16}O nucleus plays an important role in producing ^{15}N by ^{16}O (ν, ν'p) ^{15}N reaction in supernova explosions. It is also contained in water, which is used as target for neutrino detections. ν-induced reactions on ^{16}O are studied by using the new Hamiltonian, and compared with conventional calculations and previous CRPA results.

Liquid Ar is an important target for the study of neutrino detections. Gamow-Teller transition strength in ^{40}Ar and ν-induced reactions on ^{40}Ar by solar neutrinos are studied based on monopole-based-universal interaction (VMU) [3], which has tensor components of $\pi + \rho$ meson exchange potential. Calculated GT strength is found to reproduce well the experimental data obtained by (p, n) reactions.

The three-body force, in particular the Fujita-Miyazawa force induced by Delta excitations, is pointed out to be responsible for the repulsive corrections among the valence neutrons [4]. The important roles of the three-body force on the energies and transitions in exotic isotopes are demonstrated [4,5]. In particular, the three-body force is shown to be important to obtain closed-shell nature for ^{48}Ca and get the concentration of the M1 strength in ^{48}Ca.

We finally discuss electron capture reactions on Ni and Co isotopes in stellar environments [6] with the use of a shell-model interaction, GXPF1J [7], which describes well the GT strength in ^{56}Ni [8], ^{58}Ni and ^{60}Ni.

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Hindered proton collectivity in the proton-rich nucleus ^{28}S: Possible magic number at $Z = 16$*

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The reduced transition probability $B(\mathrm{E2};0^+_{gs} \to 2^+_1)$ for ^{28}S was obtained experimentally using Coulomb excitation at 53 MeV/nucleon [1]. The experiment was performed using the RI Beam Factory accelerator complatx at RIKEN Nishina Center. The resultant B(E2) value 181(31) $\mathrm{e}^2\mathrm{fm}^4$ is smaller than the expectation based on empirical B(E2) systematics [2]. The proton and neutron transition matrix elements, M_p and M_n, for the $0^+_{gs} \to 2^+_1$ transition were evaluated from the B(E2) values of ^{28}S and the mirror nucleus ^{28}Mg. The double ratio $|M_n/M_p|/(N/Z)$ of the $0^+_{gs} \to 2^+_1$ transition in ^{28}S was obtained to be 1.9(2), showing the hindrance of proton collectivity relative to that of neutrons. These results indicate the emergence of the magic number $Z = 16$ in the $|T_z| = 2$ nucleus ^{28}S.

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Study of ^{24}Mg resonances relevant for carbon burning nucleosynthesis*

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Carbon-carbon burning has an important role in many stellar systems, which include super AGB stars, SN Type Ia and superbursts. Relevant energy range of cross section measurements for super AGB stars and SN Type Ia is E_{cm} = 1.5-3.3 MeV for the ^{12}C+^{12}C reaction [1]. This region of interest is far below Coulomb barrier, where measured data of cross section shows discrepancies. Therefore, new experiments or new approach are needed [2].
Thus we have studied decays of resonances in ^{24}Mg at excitations 0.5-6 MeV above the ^{12}C+^{12}C decay threshold, using the ^{12}C(^{16}O,α)^{24}Mg* reaction. This experiment has been performed at INFN-LNS, in Catania, using the Tandem accelerator and a ^{16}O beam at E = 94 MeV. The ^{24}Mg* decays into ^{12}C+^{12}C, ^{8}Be+^{16}O, α+^{20}Ne and p+^{23}Na channel. By detecting decay fragments and recoil nuclei one can extract an information about parameters of the resonances. These may provide useful data for the theortical models and for the direct cross section measurements at energies of interest.
Some preliminary results will be presented.

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Chirality in Nuclei

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In the last decade considerable experimental and theoretical effort was invested in the research of chirality in nuclei. In the pioneering work [1] it was proposed that the rotation of triaxial nuclei may give rise to pairs of identical ΔI = 1 bands with the same parity in odd-odd nuclei - the chiral doublet bands. The crucial test for the suggested nuclei as candidates to express chirality is based on precise lifetime measurements. Three lifetime experiments and theoretical approaches for the description of the experimental results will be presented in the contribution. Pairs of bands possibly due to the breaking of the chiral symmetry are investigated in ^{102}Rh, ^{134}Pr and ^{136}Pm.
Lifetimes of exited states in ^{134}Pr were measured by means of the recoil distance Doppler-shift and Doppler-shift attenuation techniques [2,3]. The possible chiral interpretation of twin bands was investigated in the two-quasiparticle triaxial rotor [1] and interacting boson-fermion-fermion models [4]. Both theoretical approaches can describe the level-scheme of ^{134}Pr. The analysis of the wave functions has shown that the possibility for the angular momenta of the proton, neutron, and core to find themselves in the favorable, almost orthogonal geometry, is present but is far from being dominant [3,5]. The structure is characterized by large β and γ fluctuations.
In a second experiment branching ratios and lifetimes in ^{136}Pm were measured by means of the plunger and DSAM techniques. The experiment was performed at LNL, using the GASP spectrometer and Cologne plunger. The reaction ^{24}Mg + ^{116}Sn at 130 MeV beam energy has been used to populate states of ^{136}Pm at moderate excitation energy and angular momentum. For the first time new results for the lifetime values in the chiral candidate bands of ^{136}Pm will be reported at the conference. Based on these results conclusion about the chiral character of the bands in ^{136}Pm will be performed.
Excited states in ^{102}Rh were populated in the fusion-evaporation reaction ^{96}Zr(^{11}B, 3n)^{102}Rh. The beam of ^{11}B, with an energy of 36 MeV, was delivered by the 15-UD Pelletron accelerator at the Inter University Accelerator Center in New Delhi. The angular correlations and the electric or magnetic character of the transitions were investigated. The obtained results were used to investigate the level-scheme of ^{102}Rh and to discover a new chiral candidate sister band. Lifetimes of the excited states of chiral candidates bands in ^{102}Rh will be reported for the first time.
The chiral interpretation of twin bands in odd-odd nuclei based on the interacting boson fermion-fermion model will be discussed. The analysis of the wave functions has shown that the possibility for angular momenta of the valence proton, neutron and core to find themselves in the favorable, almost orthogonal geometry is present, but not dominant [5]. Such behavior is found to be similar in nuclei where both the level energies and the electromagnetic decay properties display the chiral pattern, as well as in those where only the level energies of the corresponding levels in the twin bands are close together. The difference in the structure of the two types of chiral candidates nuclei can be attributed to different β and γ fluctuations, induced by the exchange boson-fermion interaction of the interacting boson fermion-fermion model. In both cases the chirality is weak and dynamic.

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Measurements of the DSSSD efficiency

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DSSSD are Si detectors segmented in strips in both faces, they are widely used in nuclear physics and for applicative purposes. Their efficiency for the full energy reconstruction is influenced by the presence of a insulating layer that separates the strips. Ionizing particles impinging on the detector in such interstrip region can generate signals of reduced amplitudes, or with an inverted polarity, reducing the overall efficiency for the full energy reconstruction. We will present a systematic study on the efficiency for full energy reconstruction for different energies using two different ions (Li and O). Moreover the effects of the applied bias will also be discussed.

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Dynamic Microscopic Theory of Fusion Using DC-TDHF*

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We discuss the recent applications of the our microscopic approach to compute fusion barriers directly from the TDHF time-evolution of the nuclear system. In this DC-TDHF approach the TDHF time-evolution takes place with no restrictions, and at certain times during the evolution the instantaneous density is used to perform a static Hartree-Fock minimization while holding the neutron and proton densities constrained to be the corresponding instantaneous TDHF densities. In essence, this provides us with the TDHF dynamical path in relation to the multi-dimensional static energy surface of the combined nuclear system. Some of the effects naturally included in the DC-TDHF calculations are: neck formation, mass exchange, internal excitations, deformation effects to all order, as well as the effect of nuclear alignment for deformed systems. The DC-TDHF theory provides a comprehensive approach to calculating fusion barriers in the mean-field limit. The theory has been applied to calculate fusion cross-sections for ^{64}Ni+^{132}Sn, ^{64}Ni+^{64}Ni, ^{16}O+^{208}Pb, ^{70}Zn + ^{208}Pb, ^{48}Ca + ^{238}U, and ^{132,124}Sn+^{96}Zr [1,2] systems, and to the study of triple-alpha system [3].

In this talk we will present further studies for light and medium mass systems as well as a new approach for the decomposition of the ion-ion potentials to the single-particle level.

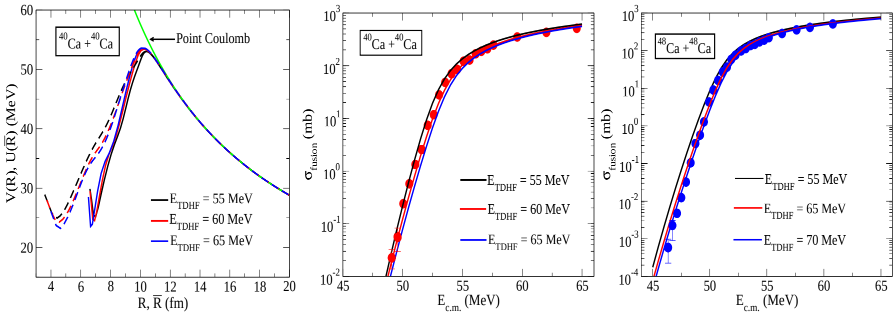

FIG. 1: Examples of fusion barriers and cross-sections calculated using the DC-TDHF approach.

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THE STUDY OF TWO NEUTRINO DOUBLE BETA DECAY BY INCLUDING FERMI CONTRIBUTIONS

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The two neutrino double beta decay of $^{128,130}Te$ isotopes to the ground state of $^{128,130}Xe$ isotopes has been calculated by including the contributions coming from the isobar analog states in the intermediate nuclei. The nuclear matrix elements have been computed by using the proton-neutron quasi-particle random phase approximation (pn-QRPA). The broken isospin invariance of the nuclear part of the total nucleus Hamiltonian has been restored for the study of the isobar analogue excitations in the intermediate nuclei. The SU(4) symmetry violation in the shell model approximation has been considered for the investigation of the Gamow-Teller states.

Table 1: Fermi and Gamow-Teller contributions to the 2νββ decay nuclear matrix element

Transitions	M_F (MeV^{-1})	M_{GT} (MeV^{-1})	M_F+M_{GT} (MeV^{-1})
$^{128}Te \rightarrow ^{128}Xe$	0.0029	0.0232	0.0261
$^{130}Te \rightarrow ^{130}Xe$	0.0022	0.0194	0.0216

Reactions induced by ^{7}Li beam and optimization of silicon detector telescope

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The quality of experimental data obtained by a standard usage of the dE-E silicon detector telescopes is highly dependent on the uniformity of the thin dE detector thicknesses [1]. On the other hand, the very arrangement is therefore suitable for studying (and compensating) the non-uniformity in dE-detector thickness.
In this contribution, an analysis of an experiment with the 52 MeV ^{7}Li beam and the ^{7}LiF, ^{6}LiF and ^{12}C targets is given, emphasizing a possible method of high-quality calibration and thin detectors (50um, Micron, 50*50mm, quadrants) uniformity study. The presented excitation spectrum shows elastic and inelastic scattering channels $^{12}C(^7Li,^7Li^*)^{12}C^*$; similar high precision spectra for a number of different reactions will be shown, and results concerning both reaction mechanism and nuclear structure given and discussed.

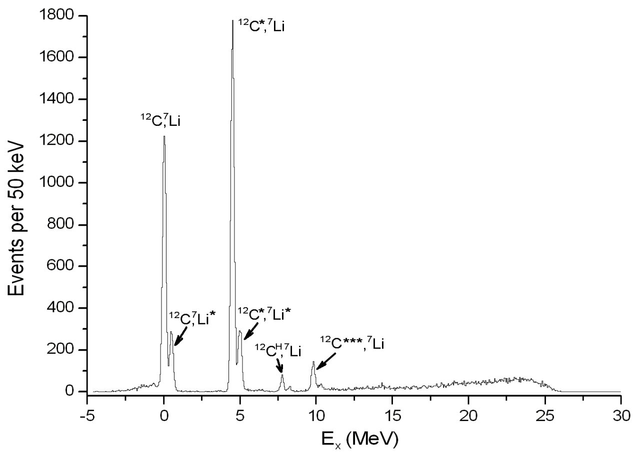

Fig. 1. Inelastic scattering of ^{7}Li beam on carbon target. ^{7}Li is detected at 20±5° scattering angle.

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Poles of the S-matrix in Woods–Saxon and Salamon–Vertse potentials.*

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For most of the phenomenological nuclear potential forms the Schrödinger equation is solved by numerical integration. The value of the S-matrix is calculated by matching the numerical solution at a finite distance to the solution of the asymptotic differential equation without nuclear potential. This amounts to assuming that the nuclear potential is zero beyond that distance. Two examples of this type of nuclear potentials are the cutoff Woods–Saxon (WS) potential and the so called Salamon–Vertse (SV) potential. The SV potential was introduced by two of us recently [1]. The advantage of the SV potential is that it goes to zero smoothly at a finite distance. It is a differentiable function everywhere, in contrast to the cutoff WS which has a jump at the cutoff radius. The trajectories of the S-matrix poles as functions of the potential strength are found to depend on the cutoff radius of the WS form [2]. Similar dependence does not appear if the SV form is used, even if its parameters are fitted to the WS form [2].

Numerical calculations performed for light and heavy nuclei show that the broad resonances are sensitive to the cutoff radius of the WS form. The bound and antibound poles however are not sensitive to the choice of the cutoff radius [3].

The migration of the antibound poles when increasing the depth of the WS and SV potentials has been also studied [3]. For zero angular momentum the first antibound pole (which belongs to a wave function with a single node at the origin) moves up along the imaginary wave number axis and becomes a bound state as the potential depth increases. The other poles with at least one extra node start as decaying and capturing resonances, and at a certain value of the depth the two resonances meet at the negative imaginary wave number axis and two new antibound poles emerge. With the depth increased the two antibound poles move in opposite directions. The one moving in the direction of the real axis becomes a bound state. The other pole remains an antibound pole.

All types of pole solutions, even the antibound states, can be included in Berggren bases and used for the description of halo nuclei in the shell model in the complex energy plane [4]. All basis vector of the Berggren basis should be normalized to unity. It is interesting to note that the normalized radial wave function of an antibound state moving to the real axis is purely imaginary. The wave function of the other antibound pole is real, like the bound state wave functions [3]. This feature is common for WS and SV potential wells. The case with centrifugal or Coulomb barrier is different because the resonances in this case meet in the origin.

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SYMMETRY ENERGY PROPERTIES IN BULK MATTER ESTIMATED FROM NEUTRON SKIN THICKNESS IN FINITE NUCLEI

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Abstract

We describe in a first part a relation between the symmetry energy coefficents in nuclear matter $c_{sym}(\rho)$ and in finite nuclei $a_{sym}(A)$. We take advantage of this relation to explore the constrains on $c_{sym}(\rho)$ provided by a large set of measurement of the neutron skin thickness in finite nuclei using antiprotonic atoms. The constrains found on the density slope of the symmetry energy at saturation are in good agreement with other estimates that use different observables in their analysis. In a second part we discuss, in a mean field approximation, the relation between the neutron radius and polarized electron scattering results in ^{208}Pb in a context similar to the one of the parity radius experiment (PREX). It is found that the high linear correlation between the parity-violating asymmetry A_{pv} (which is the quantity measured in real experiments) and the neutron skin thickness Δr_{np} is the best way to constrain this quantity in ^{208}Pb without any assumption on the neutron density profile. The present study shows that this observable A_{pv} could constrain the density slope of the symmetry energy to 10 MeV if the experimental error in its measurement is pushed to 1%.

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Lifetimes and g-factors in the A≈100 region*

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The mass $A \approx 100$ region provides a challenging testing ground to microscopic and macroscopic nuclear models. This is due to the occurrence of sub-shell closures, in the vicinity of stability that is at Z=38,40, and at N=56. Vast changes in structure take place for some isotopic chains, e.g., the Zr isotopes are near-doubly-magic at A=96 and experience a fast shape transition to deformed thereafter. Shell effects lead to extraordinary distributions of proton and neutron configurations into the wavefunctions of the lowest states [1-3]. Other chains like Ru or Pd, and as more recently found also Kr [4,5] evolve much more gradually as a result of the localized character of the sub-shell closures in play. Key data to assess the structure of these nuclei are properties of the lowest-lying states, that is energies, transition matrix elements and nuclear moments. To provide tests of models at the intersection of single-particle and collective behavior as sensitive as possible, the availability of reliable high-precision data is imperative. At WNSL, we used well-established data to develop a novel plunger method at, which allows to measure excited state lifetimes to high accuracy, simultaneous to obtaining magnetic moments [6]. Some conflicts of previous E2 data from different experiments have been lifted [7], and new questions on g-factors arise [6].

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Experiments at the interface between nuclear structure and explosive nuclear astrophysics

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The talk will explore the interface between studies of nuclear structure and nuclear reactions, and explosive nuclear astrophysics. Information on the reactions and properties of unstable nuclei are vital for understanding important astrophysical phenomena such as novae, X-ray bursters and supernovae. In many cases key astrophysical information has to be obtained by indirect approaches utilising new techniques and advanced new detector and accelerator systems. These themes will be outlined in the talk.

Formation of Superheavy Nuclei in Astrophysical *r* Process

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The astrophysical r process of nucleosynthesis is usually discussed to explain the observed abundance of heavy elements in the universe. In this process some amount of superheavy (SH) elements of the island of stability might also be produced if the fast neutron flux is sufficient to bypass the two gaps of fission instability in the upper part of the nuclear map. Strong neutron fluxes are expected to be generated by neutrino-driven proto-neutron-star winds that follow core-collapse supernova explosions [1] or by the mergers of neutron stars [2]. Estimation of relative yields of SH elements is a difficult problem that depends both on the features of neutron fluxes and on the experimentally unknown decay properties of heavy neutron-rich nuclei.

We performed a very simple estimation of the possibility of formation of SH nuclei during the astrophysical r process of neutron capture [3]. This estimation is based on the following assumptions. (i) SH nuclei are relatively short-lived. They are absent in stars initially, while the distribution of other elements is rather close to their abundance in the universe. (ii) SH nuclei may appear (and survive) in the last (rather cold) stage of the astrophysical r process when the observed abundance of heavy elements (in particular, thorium- and uranium-to-lead ratios) is also reproduced. (iii) An existing (experimental) abundance of stable nuclei may be used as an initial condition. During intensive neutron irradiation, initial thorium and uranium materials are depleted, transforming into heavier elements and going to fission, while more abundant lead and lighter stable elements enrich thorium and uranium. (iv) Unknown total neutron fluence may be adjusted in such a way that the ratios Y(Th)/Y(Pb) and Y(U)/Y(Pb) maintain their experimental values at the end of the process. Simultaneously, for a given neutron fluence, one gets the relative yield of SH elements, Y(SH)/Y(Pb).

Our estimation of the possibility of production of SH elements in the astrophysical r process (namely, the neutron-rich copernicium isotopes ^{291}Cn and ^{293}Cn) is not very explicit but also not completely pessimistic: their yield relative to lead could be about 10^{-12} if we assume initial natural abundance of all the elements (including thorium and uranium) at the beginning of the astrophysical r process. This ratio is not beyond the experimental sensitivity for a search for SH elements in nature. The question is, How long are their half-lives? In accordance with our estimations, the half-lives of most long-living copernicium isotopes, ^{291}Cn and ^{293}Cn, do not exceed several hundred years. At any rate, even this short time provides hope of finding relatively long-living SH nuclei in cosmic rays. The result turns out to be more pessimistic (i.e., lower by 8 orders of magnitude) if the initial thorium and uranium nuclei are completely burned in the s process of neutron capture before supernova explosion. Note that experimental study of the decay properties of heavy nuclei located along the beta-stability line (and to the right of it) is extremely important for a more accurate analysis of the neutron capture processes (including astrophysical ones) in the upper part of the nuclear map.

We have shown also that a macroscopic amount of long-living SH nuclei located at the island of stability might really be produced in multiple (rather "soft") nuclear explosions, if such processes could be realized technically. This goal could also be reached by using the pulsed nuclear reactors of the next generation, if their neutron fluence per pulse is increased by about 3 orders of magnitude.

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The present work aims at describing the $N=Z$ nuclei ^{96}Cd, ^{92}Pd and ^{94}Ag having their valence nucleons confined to the $1g_{9/2}$ sub-shell by means of aligned isoscalar neutron-proton pairs. A shell-model wave function analysis has been carried out for the four holes system (^{96}Cd) using different shell-model interactions and including various two-nucleon pairs. The study of the low-lying spectroscopy of the six and eight holes systems (^{92}Pd and ^{94}Ag respectively) has been performed using a mapping to the interacting boson model.

Neutron halo in deformed nuclei from a deformed Relativistic Hartree-Bogoliubov theory in continuum*

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In this talk we will present some recent results about neutron halos in deformed nuclei [1,2]. The halo phenomenon is one of the most interesting topics in modern nuclear physics. Since most open shell nuclei are deformed, the interplay between deformation and weak binding raises interesting questions. In order to give an adequate description of possible halo in a deformed nucleus, a model should be used which includes in a self-consistent way the continuum, deformation effects, large spatial distributions, and couplings among all these features. A deformed relativistic Hartree-Bogoliubov theory in continuum has been developed [1–4] for this purpose and the halo phenomenon in deformed weakly bound nuclei is investigated. These weakly bound quantum systems present interesting examples for the study of the interdependence between the deformation of the core and the particles in the halo. Magnesium and neon isotopes are studied and detailed results are presented for the deformed neutron-rich and weakly bound nuclei ^{42,44}Mg [1,2]. The cores of these two nuclei are prolate, but the halos have slightly oblate shapes. This indicates a decoupling of the halo orbitals from the deformation of the core. The generic conditions for the existence of halos in deformed nuclei and for the occurrence of this decoupling effect are discussed.

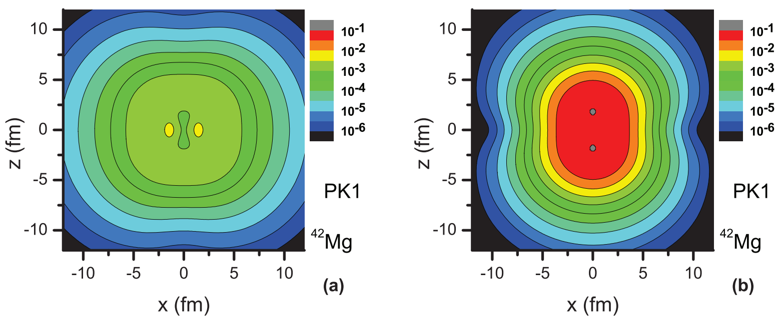

FIG. 1: Density distributions of the ground state of ^{42}Mg with the z axis as the symmetry axis: (a) the neutron halo, and (b) the neutron core. This figure was originally published in Ref. [2].

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