Quasiparticle-phonon coupling in relativistic framework: shell structure of Z=120 isotopes

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Degrees of freedom relevant for a description of nuclear dynamics at ~1-50 MeV excitation energies: single-particle & collective (vibrational); coupling

Approach: covariant energy density functional (CEDF) theory extended by many-body correlations (Nuclear field theory)

Towards spectroscopic accuracy:
Nuclear structure properties
- Nuclear single-particle structure
- Gross and fine structure of nuclear excited states: (dipole)

Unknown region of the nuclear chart:
Shell structure and alpha decay properties of Z=120 isotopes

Separation of scales is useful, but there are important effects at the borders:
Coupling of the degrees of freedom = overlap of scales
Dynamics of medium-mass and heavy nuclei at ~1-50 MeV excitation energies: single particles & vibrations

NpNh:

3p3h excitations: iterative PVC

2p2h excitations: Particle-Vibration Coupling (PVC)

1p1h excitations: Quasiparticle Random Phase Approximation (QRPA)

Ground state: Relativistic Mean Field (RMF)

\[ (J^\pi,T) = (0^+,0) \quad (J^\pi,T) = (1^-,0) \quad (J^\pi,T) = (1^-,1) \]
First step beyond relativistic mean field: quasiparticles coupled to vibrations

One-body Green’s function in N-body system (Lehmann):

\[ G(\xi, \xi'; \varepsilon) = \sum_n \frac{(\Psi(\xi))_{n0} (\Psi^{\dagger}(\xi'))_{n0}}{\varepsilon - (E^{(N+1)}_n - E^{(N)}_0) + i\delta} + \]

\[ + \sum_m (\Psi^{\dagger}(\xi'))_{0m} (\Psi(\xi))_{m0} \frac{1}{\varepsilon + (E^{(N-1)}_m - E^{(N)}_0) - i\delta}, \]

\[ (\Psi^{\dagger}(\xi))_{n0} = \langle \Phi^{(N+1)}_n | \Psi^{\dagger}(\xi) | \Phi^{(N)}_0 \rangle, \]

\[ (\Psi(\xi))_{n0} = \langle \Phi^{(N-1)}_n | \Psi(\xi) | \Phi^{(N)}_0 \rangle, \]

One-body Green’s function in N-body system (Lehmann):

\[ (\varepsilon - \mathcal{H}_{RB} - \Sigma^{(e)}(\varepsilon)) \varepsilon G(\varepsilon) = 1 \]

Doubled quasiparticle space:

\[ \eta = \pm 1 \]

\[ \Sigma_{k_1 k_2}^{(e)\eta_1 \eta_2}(\varepsilon) = \sum_{\eta=\pm 1} \sum_{k, \mu} \gamma^{\eta_1 \eta_2 \eta \eta_2^*}_{\mu; k_1 k} \gamma_{\mu; k_2 k} \]

\[ G^{(e)\eta}_{\varepsilon k}(\varepsilon) = \sum_{\nu, \eta'} \frac{\tilde{S}_{\eta'(\nu)}}{\varepsilon - \eta \eta' E^{(\nu)}_k} \]
Quasiparticle-vibration coupling: Pairing correlations of the superfluid type + coupling to phonons

Near Fermi energy (FE)

Mean field: Free Q

Q+phonons

Far from Fermi energy

Spectroscopic factors $S_k^{(v)}$

Level schemes

Spectroscopic factors in $^{119,121}$Sn:

<table>
<thead>
<tr>
<th>(nlj)</th>
<th>$S^\text{th}$</th>
<th>$S^\text{exp}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2d$_{5/2}$</td>
<td>0.32</td>
<td>0.43</td>
</tr>
<tr>
<td>1g$_{7/2}$</td>
<td>0.40</td>
<td>0.60</td>
</tr>
<tr>
<td>2d$_{3/2}$</td>
<td>0.53</td>
<td>0.45</td>
</tr>
<tr>
<td>3s$_{1/2}$</td>
<td>0.43</td>
<td>0.32</td>
</tr>
<tr>
<td>1h$_{11/2}$</td>
<td>0.58</td>
<td>0.49</td>
</tr>
<tr>
<td>2f$_{7/2}$</td>
<td>0.31</td>
<td>0.35</td>
</tr>
<tr>
<td>3p$_{3/2}$</td>
<td>0.58</td>
<td>0.54</td>
</tr>
</tbody>
</table>
Excited states: nuclear response function

Functional derivative of the nucleon self-energy

\[ i \frac{\delta}{\delta G} \delta G = i \frac{\delta \Sigma}{\delta G} = \]

\[ R = A + A (V + \Phi) R \]

Nuclear response function \( R \): two-body propagation in the nuclear medium

Bethe-Salpeter equation (BSE) in the p-h channel

\[ V = \frac{\delta \Sigma}{\delta \rho} \]

\[ U^e = i \frac{\delta \Sigma^e}{\delta G} \]
Dipole strength in neutron-rich nuclei: importance for astrophysics

**Test case: stable nuclei**

- **120\text{Sn}**
- **116\text{Sn}**
- **90\text{Zr}**
- **88\text{Sr}**

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**Neutron-rich Sn**

- **132\text{Sn}**
- **130\text{Sn}**

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* P. Adrich, A. Klimkiewicz, M. Fallot et al., PRL 95, 132501 (2005)


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Input for
r-process nucleosynthesis:
(n,\gamma) cross sections
and reaction rates:
G. Martinez-Pinedo & Coll.
Isospin structure of the pygmy dipole resonance in $^{124}$Sn

Experiment (J. Endres, D. Savran et al.)

Theory: RQTBA

$^{124}$Sn$(\alpha, \alpha'\gamma)$

$^{124}$Sn$(\gamma, \gamma')$

Energy [keV]

Hadron vs Coulomb excitation

Transition densities

J. Endres, E. L.,..., V. Ponomarev, P. Ring et al.,
PRL 105, 212503 (2010)
Replacement of the uncorrelated propagator inside the $\Phi$ amplitude by QRPA response

Nuclear response:

$$R = A + A (V + \Phi) R$$

Poles may appear at lower energies:

'2q+phonon' response:
$$\Phi_{iji'j'}(\omega) \sim \sum_{\mu k} a_{ijk\mu}/(\omega - E_i - E_k - \Omega_\mu)$$

'2 phonon' response:
$$\Phi_{iji'j'}(\omega) \sim \sum_{\mu \nu} a_{iji'j'}/(\omega - \Omega_\nu - \Omega_\mu)$$
Fine features of dipole spectra: two-phonon effects

$2q+\text{phonon}$

$2\text{ phonon}$

$E(1^-_1) \approx E(2^+_1) + E(3^-_1)$

First two-phonon state $1^-_1$

$\text{E.L., P.Ring, V.Tselyaev, PRL 105, 02252 (2010)}$

$120\text{Sn}$

$\text{Experiment: I.Pysmenetska et al., PRC73 (2006) 017302}$
1. Vibrational 1-, 2+, 3-, 4+, 5-, 6+ spectra of the SHE Z=120 nuclei have been calculated microscopically.
2. Beyond relativistic mean field: coupling to ~100 phonons 2+, 3-, 4+, 5-, 6+ below 15 MeV.
3. Influence of many-body correlations like phonon coupling (PC) on the SHE shell structure is significant.
4. The vibrations affect very little the Z=120 shell gap supporting the earlier relativistic mean field prediction while the N=172 shell gap becomes questionable.

**Lowest collective 2+ and 3- states in $^{292}120$**

<table>
<thead>
<tr>
<th>E (2+) [MeV]</th>
<th>B(E2)$\uparrow$ [e$^2$ fm$^4$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.41</td>
<td>7.1 x 10$^4$</td>
</tr>
<tr>
<td>3.18</td>
<td>3.5 x 10$^4$</td>
</tr>
<tr>
<td>4.82</td>
<td>1.4 x 10$^4$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>E (3-) [MeV]</th>
<th>B(E3)$\uparrow$ [e$^2$ fm$^6$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.20</td>
<td>1.04 x 10$^6$</td>
</tr>
<tr>
<td>5.76</td>
<td>7.2 x 10$^5$</td>
</tr>
<tr>
<td>6.29</td>
<td>1.4 x 10$^5$</td>
</tr>
</tbody>
</table>

E. L., A.V. Afanasjev,
PRC (2011), in press
"Semi-magic" $Z = 120$ isotopes with $N = 172-184$: neutron pairing + phonon coupling

No pairing

Pairing
1. Relativistic Mean Field: spherical minima
2. Small amplitude vibrations: RQRPA
3. Very soft nuclei: large amount of low-lying collective vibrational modes (~80 phonons below 15 MeV)

Shell stabilization & vibration stabilization/destabilization (?)
**Goal:**
Constructing a **universal nuclear many-body theory** for high-precision calculations of nuclear masses and low-energy phenomena; theory with high predictive power

**Strategy** (for heavy systems):
DFT extended by relevant many-body correlations

More correlations => better agreement to data &
More definite conclusions about the quality of the underlying functional

**Methodology:**
Covariant DFT + many-body Green’s function (nuclear field theory) techniques

**Constraints**
on the form of underlying DF, its parameters, many-body coupling schemes:
high-resolution spectral data and data about drip-line nuclei
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