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ELEMENTARY PARTICLES AND FIELDS
Experiment

Kaon, Pion, and Proton Associated Photofission of Bi Nuclei*

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Abstract—The first measurement of proton, pion, and kaon associated fission of Bi nuclei has been performed in a photon energy range $1.45 < E_\gamma < 1.55$ GeV. The fission probabilities are compared with an inclusive fission probabilities obtained with photons, protons and pions. The fission probability of Bi nuclei in coincidence with kaons is 0.18 ± 0.06 which is ~3 times larger than the proton and pion associated fission probabilities and ~2 times larger than inclusive ones. The kaon associated excess fission events are explained in terms of bound Λ residual states and their weak nonmesonic decays.

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1. INTRODUCTION

The excitation of nuclei by electromagnetic probes such as real photons (γ quanta) or virtual photons (inelastic electron scattering) offers attractive features for the study of nuclear and hypernuclear phenomena over a broad range of excitation energies. In the GeV energy region the gamma—nucleus reaction has been currently explored in the framework of a two-step interaction model [1–3]. In this approach, firstly a rapid intra-nuclear cascade (INC) develops through binary intra-nuclear collisions. During the second stage of the reaction, the excited residual nucleus slowly reaches its final state through a competition between the fission and the particle-evaporation process. The two-step picture clearly assumes that

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fission is a relatively slow process which samples the target residues only after they have lost a large fraction of their excitation energy. Therefore, the fission of a heavy nuclear system provides an excellent tool for studying the later stages of a complex, high-energy nuclear reaction. Coulomb energy systematics give a clear indication for the binary fission process, while fragment angular correlations and mass and energy distributions can be used to estimate average quantities such as linear momentum transfer and mean mass and excitation energy of the fissioning system. The use of nuclear fission as a filter for reaction mechanisms of low-to-intermediate energy nucleus—nucleus collision has been widely exploited over the past [4]. The nuclear fission as an inelastic reaction tag has been used in the total absorption cross-section measurement experiments carried out by real and virtual photons on uranium isotopes. The delayed fission allows to study the production of heavy Λ hypernuclei and their subsequent weak decay, initiated by the electromagnetic [5] or hadronic (antiproton [6] and proton [7]) probe. In these experiments a recoil distance technique [8] was used to separate prompt and, associated with Λ-hypernuclei weak decay, delayed fission events, without any strangeness production tag, i.e. without any coincidence with associated kaon production due to negligibly small expected coincidence rates.

Nuclear reactions including a strangeness degree of freedom, such as $(\gamma,\ K^+)$ leave a strangeness quantum number $S = -1$ in a nucleus converting a nucleon (N) into a hyperon (Λ or Σ). The Λ-producing $(\gamma,\ K^+)$ reactions are believed to be complementary to $(K^-,\ \pi^-)$ and $(\pi^+,\ K^+)$. The mean-free paths of both the γ and K^+ in the nuclear medium are relatively long compared to those of $\pi^\pm$ and K^-. This feature makes it possible to probe behavior of Λ in the nuclear interior with less distortion and offers an important opportunity to study the production and decay of hypernuclear states and quasi-free (QF) hyperon production. The QF produced hyperons can be finally captured and form hot, compound hypernuclei. From the old emulsion experiments [9] it is known that the QF hyperon capture rates for K^- absorption at rest are $(8 \pm 2)\%$ from C, N, O and $(58 \pm 15)\%$ from Ag, Br.

The photon-induced fission of preactinide nuclei in coincidence with an associated kaon was proposed to be used as a tool for the study of heavy hypernuclei and other exotics [10], and to measure directly the lifetime of heavy hypernuclei associated with nonmesonic decay of Λ hyperon in the nuclear environment [11, 12].

This experiment is the first measurement of (γ, pf), $(\gamma, \pi^+ f)$, and $(\gamma, K^+ f)$ reactions on ^{209}Bi nuclei using electromagnetic probes. We describe the experiment, analyzing procedures, and present the fission probabilities in coincidence with forward ($\theta \leq 14^\circ$) produced protons, pions, and kaons. The kaon associated fission events are explained in terms of QF Λ production, formation of bound Λ-residuals states, and their weak nonmesonic decays.

2. EXPERIMENTAL SETUP

The first attempt of the E02-17 experiment was performed at Jefferson Laboratory by using partially the setup of the E01-011 (HKS) experiment in Hall C [13, 14]. It consists (Fig. 1) of two major parts: magnetic spectrometer-HKS with the front splitter magnet, for detection of forward produced protons, pions, and kaons and fission fragment detector (FFD) [15] for detection of fission recoils. The scattered electrons were not tagged in this experiment.

The electron beam pipe was terminated before the E01-011 splitter magnet, and the FFD was inserted in the gap in between the beam exit window and the entrance vacuum window of the splitter magnet. Target for this experiment was mounted in the center of the FFD. The incident electrons have to pass through the stainless steel foil vacuum window for the terminated beam pipe, ~20 cm air, and the 250 μm thick Al window for FFD with a Cu foil (0.7 mm thick, 5% of the radiation length) mounted on it. Therefore intensive real photons with wide energy range were produced from these materials and incident to the tilted thin Bi target foil together with the beam electrons. The primary beam electrons, scattered electrons, and forward produced particles, e.g., protons, pions, positrons, and kaons exited the FFD through a 250 μm Al window. The positive particles from primary reaction were detected by the following HKS spectrometer and the associated fission fragments by FFD. The goal of the experiment E02-17 was to measure the lifetime of the heavy hypernuclei produced on Bi target in the $(e, K^+ f)$ reaction and we spent a few days of beam time for basic performance study of the FFD. However, during this short running time it was possible to take proper data with FFD to determine for the first time the proton, pion, and kaon associated fission rates in electron—photon interactions with ^{209}Bi nuclei.

3. THE PROTON, PION, AND KAON ASSOCIATED FISSION EXPERIMENT: ANALYSIS AND RESULTS

In this experiment, the incident electrons with energy of 1.853 GeV and photons with wide range of energy bombarded the ^{209}Bi target located in the

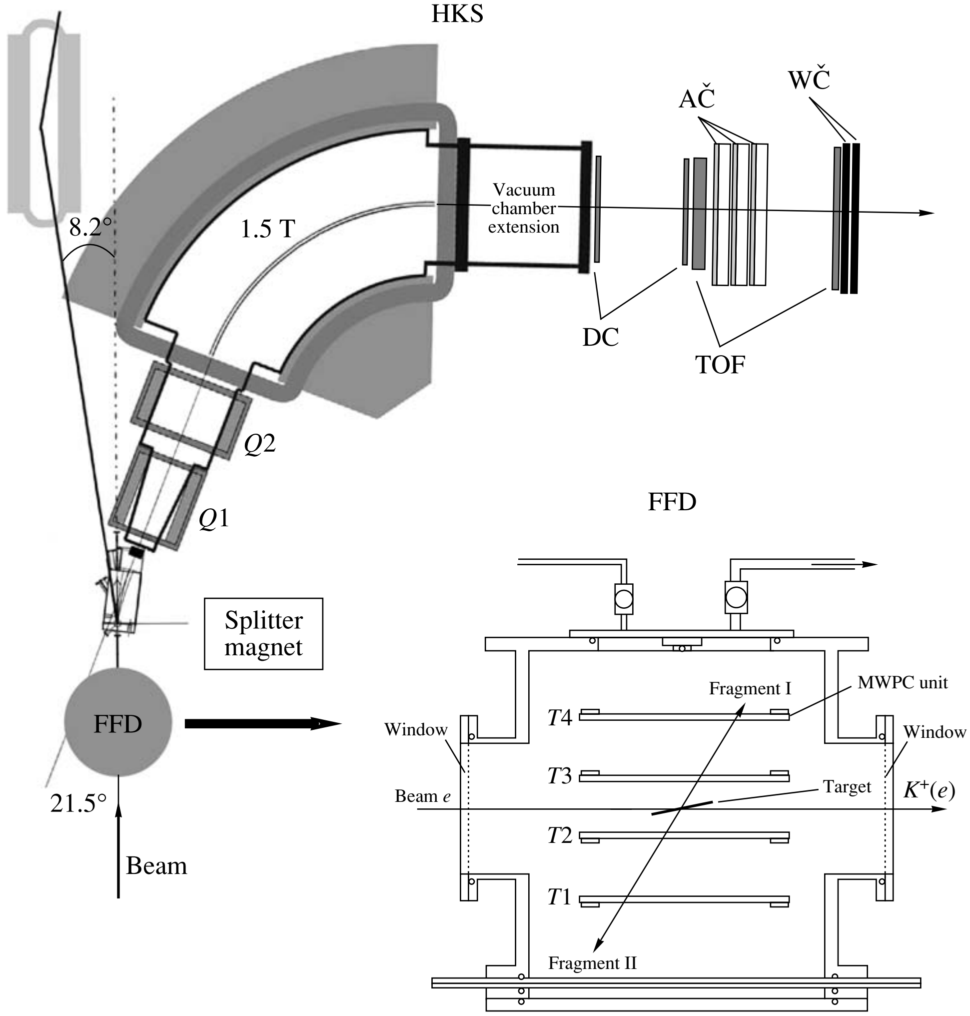

Fig. 1. Schematic of the experimental setup.

center of FFD. Noninteracted electrons and photons as well as scattered electrons and produced particles (proton, pion, kaon, etc.) exited the FFD through the exit window. The noninteracted beam electrons and photons were directed to the beam dumps and the scattered electrons to the electron spectrometer but in this experiment they were not detected. The kaon spectrometer (HKS) accepted the positive particles such as protons, pions, and kaons, produced at forward ($\theta \leq 14^\circ$) angles. These particles were separated by the particle identification system and their momentum, scattering angle, and production time (i.e. time zero) against the beam RF time structure were reconstructed.

Meanwhile in terms of the Λ-production channel the intra-nuclear cascade started in ^{209}Bi nucleus, develops to the second stage of the reaction; the excited residual nucleus reaches its final stage through a competition between the fission and the particle-evaporation processes. Fission of ^{209}Bi nucleus results in two energetic fragments with a total energy of about 150 MeV. These fragments exited the target back to back and were detected by the outer $T1$ and $T4$ planes of the FFD.

Figure 2 shows the time difference spectrum between the kaons and timing of the $T1$ plane. A coincidence gate width of about 80 ns was set by the FF trigger while the HKS trigger was timed about 30 ns behind the leading edge of the FF signal. Since the FF triggers were dominated by induced RF noise observed in this experiment, one can see two different accidental coincidence backgrounds: the RF noise accidental which is flat over the entire coincidence time gate width (see top of Fig. 2) and the accidental by real particle (kaon) and fragment which has an about 30 ns shift due to the coincidence timing setup and a cut off by the time acceptance (middle of Fig. 2). The solid lines are fitted time distributions based on Monte-Carlo simulation on the accidentals on the line shapes and widths. The bottom of Fig. 2 is the

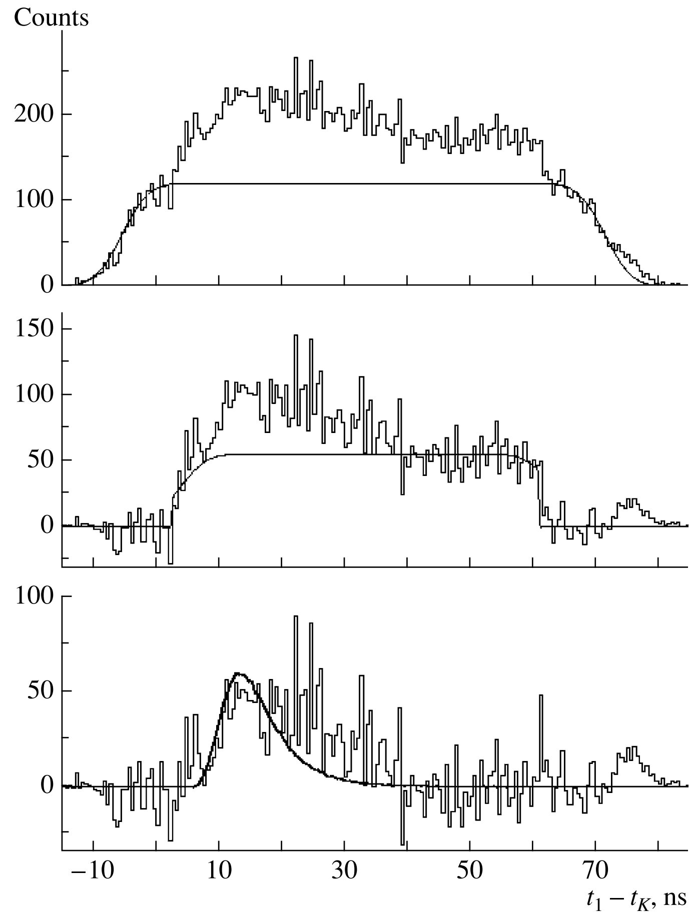

Fig. 2. Coincidence time spectrum between kaons and $T1$ plane of the FFD. t_1 is the fission time given by $T1$ plane and t_K is the kaon target time reconstructed by HKS.

time spectrum for the real (K^+ and FF) coincidence events which is distributed by a wide spread of the velocity of fission fragments. Although the quality of the spectrum was affected by the RF noise and statistics due to short running time, the real coincidence time spectrum agreed with the simulation. For the future analysis only the part of the spectrum under the fitted line was used.

By taking into account the geometrical acceptances and efficiencies of the FFD and HKS, the associated fission rates, $R_{(\gamma,pf)}$, $R_{(\gamma,\pi^+f)}$, and $R_{(\gamma,K^+f)}$, for forward (≤14°) produced protons, pions, and kaons on ^{209}Bi nuclei were determined for the first time. The rates in terms of probability are: $R_{(\gamma,pf)} = (5 \pm 4)\%$, $R_{(\gamma,\pi^+f)} = (5 \pm 3)\%$, and $R_{(\gamma,K^+f)} = (18 \pm 6)\%$, where the statical errors are given.

4. THE K^+ ASSOCIATED FISSION OF HEAVY NUCLEI

In the case of K^+ photoproduction on Bi nuclei different residual nuclei, with a charge $Z \leq 82$ and mass $A \leq 209$, can be formed. The photo-fission probability of ^{nat}Pb nuclei, which is a result of summation over many channels, is about 7% for photons in the GeV energy range [16, 17]. For some of these channels the fission probability is low, while for others can be higher than the mean value, 7%. The obtained proton and pion associated fission probabilities are, e.g., less; while the kaon associated fission probability is larger than the mean photo-fission probability of ^{nat}Pb. The K^+ photoproduction reaction is a result of summation over the following channels: $\gamma + p \to \Lambda + K^+$, $\gamma + p \to \Sigma^0 + K^+$, and $\gamma + n \to \Sigma^- + K^+$. We would like to note, that the heavier hyperon Σ, which in vacuum decays as the Λ hyperon via weak interaction, is no longer stable against the strong decay in nuclear matter. In the nuclear medium they convert to Λ particles by strangeness conserving strong decay, by the reaction $\Sigma + N \to \Lambda + N$, realizing additional ~77 MeV in the residual nuclei. Therefore, the excitation energy, E^* of the residuals, i.e. "hot" hypernuclei, is a result of remained Λ energy, K^+ rescattering, as well as rescattering or absorption of energetic nucleons from $\Sigma + N \to \Lambda + N$ reactions. It was already demonstrated by means of many-body cascade calculations that in photoproduction process with $E_\gamma \leq 1.4$ GeV [18], the residual nuclei, produced in coincidence with kaons, are hotter than those obtained by averaging the excitation energy, E^* over other channels. This is due to the fact that the kaon rest mass is about three times the pion rest mass and, due to its strangeness content, it is produced in association with a hyperon; thus the strangeness production in the γ–nucleon primary interaction leads to less available energy to excite the cascade phase and subsequent pre-equilibrium phase; as a result a moderate number of nucleons are emitted. Note that the nucleon emission is an efficient mechanism to cool down the residual hot nucleus, consequently a smaller number of ejected nucleons results in formation of the residual hot nucleus and therefore increases the fission probability of residuals.

The probability of a compound residual hot hypernucleus formation at the end of pre-equilibrium phase of high energy ($E_\gamma \leq 1.4$ GeV) photonuclear reactions was calculated with a time-dependent Monte-Carlo Multicollisional Cascade (MCMC) approach and demonstrated that the events in which the hyperon is maintained in the nuclear medium until the end of the pre-equilibrium phase, i.e. until the "hot" hypernucleus formed, is about 50% for γ–Ni reactions [19]. It is expected that for heavy nuclei with $A \geq 200$ and forward produced kaons this probability will be close to 100%. The "hot" hypernucleus that is produced upon the completion of the INC and which has a definite value of the excitation energy E^*, definite numbers of nucleons and protons (A and Z, respectively), and definite values of the momentum P and of the angular momentum I will emit particles (p, n, d, t, and light nuclei) or undergo prompt fission. There is no experimental data or theoretical prediction about prompt fission probability $P_{\text{prompt}}(\gamma, K^+f)$ of the preactinide ($Z \leq 83$) hypernuclei produced by photons. For the 1.9 GeV proton Bi interactions, the probability of prompt fission of formed hot hypernuclei, simulated by coupled-channel Boltzmann–Uehling–Uhlenbeck (CBUU) transport calculations for the fast cascade phase, followed by Hauser–Feshbach calculations for the statistical evaporation phase [7], is $P_{\text{prompt}}(p, K^+f) = 20\%$. The same probability in the case of 1 GeV π^+–Bi interactions, simulated by using different intra-nuclear cascade model [20], gives the value $P_{\text{prompt}}(\pi^+, K^+f) = 7\%$. The main difference between pion and proton interactions is that the proton introduces a significantly higher excitation energy E^* in the compound hypernucleus; it also knocks out a larger number of nucleons from the target nucleus. In this sense the photonuclear interactions are more close to pion, than proton induced nuclear interactions, and one may expect that $P_{\text{prompt}}(\gamma, K^+f) \approx P_{\text{prompt}}(\pi^+, K^+f) = 7\%$. The remaining part (93%) of kaon production rate is associated with directly produced "cold" hypernuclei ($\sim$10%) [21] and formation of "hot" hypernuclei. The produced "hot" hypernuclei eventually evaporated nucleons (mainly neutrons) and finally formed "cold" hypernuclei with smaller neutron and proton numbers than directly produced "cold" hypernuclei. Here we assumed that the Λ-hyperon evaporation probability is small and this process can be ignored. The "cold" hypernuclei live about 200 ps until weak nonmesonic $\Lambda + N \to N + N$ reaction in nuclei then initiate the second intra-nuclear cascade, which finally develops into the evaporation/fission competition stage of the reaction. There is no prediction for delayed fission probability for these "cold" hypernuclei, formed in photonuclear reactions. For the 1.9-GeV proton–Bi reactions, this probability was simulated [7] to be equal $P_{\text{delayed}}(p, f) = 9\%$. However, for rough estimation we can assume that the delayed fission probability of "cold" residual hypernuclei formed in proton and photon–Bi interactions is the same, i.e. $P_{\text{delayed}}(\gamma, K^+f) \approx P_{\text{delayed}}(p, f) = 9\%$. Consequently, the kaon associated fission rate in photon–Bi interactions due to delayed fission of formed "cold" residual hypernuclei $R_{\text{delayed}}(\gamma, K^+f)$ is determined by a product of two probabilities: the survival probability P_s of "hot" hypernuclei against prompt fission ($P_s = 93\%$) and the probability $P_{\text{delayed}}(\gamma, K^+f)$ for fission of "cold" hypernuclei induced by a Λ-hyperon decay, $R_{\text{delayed}}(\gamma, K^+f) = P_s \times P_{\text{delayed}}(\gamma, K^+f) = 93\% \times 9\% = 8.4\%$. Finally, for the total kaon associated fission rate we expect $R(\gamma, K^+f) = R_{\text{prompt}}(\gamma, K^+f) + R_{\text{delayed}}(\gamma, K^+f) = 15.4\%$, which is in a good agreement with the obtained experimental result.

The competing processes in photon interactions with Bi nuclei at $E_\gamma = 1.5$ GeV are displayed in Fig. 3. The experimental cross section for prompt fission has been taken from [16, 17, 22]. For simplicity, we consider only the reaction $\gamma + p \to \Lambda + K^+$ as a source of Λ hyperon to estimate the delayed fission cross sections in photon–Bi interactions. The total cross section of this reaction is $\sigma(\gamma + p \to \Lambda + K^+) \approx 2\,\mu$b at $E_\gamma = 1.5$ GeV. The QF kaon production cross section on the Bi nucleus was assumed to scale as $Z_{\text{eff}}/Z = A_{\text{eff}}/A = 0.9$ [23]. The delayed fission cross section is determined as a product of three quantities: the QF kaon production cross section, the survival probability P_s of "hot" hypernuclei, and the probability $P_{\text{delayed}}(\gamma, K^+f)$ for fission of "cold" hypernuclei induced by a Λ-hyperon decay.

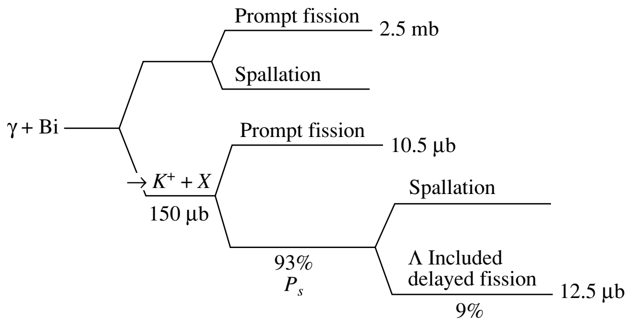

Fig. 3. Schematic representation of contributions from different competing processes in $\gamma + \text{Bi}$ interactions at $E_\gamma = 1.5$ GeV. The experimental cross section for prompt fission have been taken from [16, 17, 22]. The K^+ production cross section has been estimated taking into account only $\gamma + p \to \Lambda + K^+$ reaction.

The comparison of cross sections for delayed fission of hypernuclei and prompt fission of target nuclei in Fig. 3, shows that the K^+ detection in coincidence with fission can be used as a tag for the delayed fission associated with the weak nonmesonic decay of Λ hypernuclei with efficiency more than 50%.

5. CONCLUSION

We measured the proton, pion, and kaon associated fission rates of Bi nuclei by electromagnetic probes in the energy region of $1.45 < E_\gamma < 1.55$ GeV. The kaon associated fission probability is about 3 times larger than proton and pion associated fission probabilities and 2 times larger than the inclusive photo-fission probability. This result can be explained if the QF produced Λ hyperon is captured in Bi nuclei with a probability close to 100%. This means that hypernuclear formation probabilities in photonuclear reactions in the GeV energy range are about few percent of the total hadronic cross section, which is in agreement with the recent MCMC simulations. In this experiment, for the first time, we operated a large acceptance and windowless fission fragment detector with a target inside and intensive (∼100–500 nA) electron beam in coincidence with the forward angle magnetic spectrometer—HKS.

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