IN-BEAM γ-RAY ANGULAR DISTRIBUTION AND LIFETIME MEASUREMENTS — EXPERIENCE FROM RISING AND PERSPECTIVES AT FAIR*

P. Bednarczyk, J. Grębosz, M. Kmiecik, A. Maj
W. Męczyński, S. Myalski, J. Styczeń

H. Niewodniczański Institute of Nuclear Physics PAN
Radzikowskiego 152, 31-342 Kraków, Poland

C. Domingo-Pardo, P. Doornenbal, J. Gerl
M. Górska, H.J. Wollersheim

GSI, Planckstrasse 1, 64291 Darmstadt, Germany

J. Jolie, P. Reiter

Institut für Kernphysik, Universität zu Köln
Zülpicher Strasse 77, 50937 Köln, Germany

A. Bracco, F. Camera

University of Milano and INFN, via Celoria 16, 20133 Milano, Italy

(Received January 14, 2010)

RISING experiments delivered important knowledge on difficulties in performing prompt in-beam γ-ray spectroscopy measurements, caused by the use of very fast radioactive beams. The obtained results pointed out possible ways to suppress the overwhelming γ-ray background that should be considered in setting up new facilities planned at GSI and FAIR. In the course of the RISING campaign, the spectroscopy methods: γ-ray angular distribution and lifetime measurements useful in deducing $B(\mathrm{E2})$ transition rates were developed. They can be effectively applied in experiments with the new generation γ-ray detector array AGATA.

PACS numbers: 21.10.Tg, 23.20.En, 29.30.Kv, 29.38.De

* Presented at the XXXI Mazurian Lakes Conference on Physics, Piaski, Poland, August 30–September 6, 2009.

1. Introduction

In-beam nuclear structure studies by means of γ-ray spectroscopy will be the aim of HISPEC/NUSTAR Collaboration at FAIR [1]. The HISPEC forerunner experiment — PRESPEC, is currently being prepared at GSI.

At FAIR, radioactive ion beams (RIB) will be produced in fragmentation of relativistic heavy ions delivered by the SIS synchrotrons. Fragments with a sufficiently long half-life $T_{1/2} \geq 100$ ns, will be selected by the fragment separator Super-FRS and slowed down to intermediate kinetic energies of 50–150 A MeV. The radioactive projectiles impinging on a secondary reaction target placed at the Super-FRS focal plane will be used to induce nuclear reactions: multi-nucleon transfer, fragmentation or Coulomb excitation. The emitted nuclear radiation: γ-rays, particles and fragments will be registered by a complex set of detectors surrounding the experimental area. The HISPEC campaign will be a follow up of a series of successful measurements performed at GSI with the RISING setup [2]. RISING has delivered not only new and valuable nuclear structure results [3], but was an important source of unique knowledge concerning the experimental technology, as it operated at relatively high beam energies with respect to the similar facilities available worldwide. The experience gained at RISING contributed to better understanding of the origin of an excessive prompt γ-ray background and its effective reduction. It allowed for developing in-beam spectroscopy methods to be used at the newly designed setups as γ-ray angular distribution and lifetime measurements.

2. Prompt γ-ray background at intermediate RIB energies

In the RISING setup, γ-ray detectors were positioned around the secondary target in the FRS focal plane. The setup originally consisted of an array of 15 HPGe clusters of EUROBALL placed around the beam axis at forward angles and a set of 8 large volume BaF_2 HECTOR detectors mounted at backward angles. Before hitting the target, beams of radioactive fragments selected by FRS passed through a series of energy degraders, beam monitoring detectors and slits. Scattered projectiles and reaction products were identified and stopped in a position sensitive $\Delta E - E$ telescope, which for the reason of very limited space was mounted just behind the EUROBALL array. Particles and electromagnetic radiation emitted in collisions of the fast fragments with the surrounding matter caused an excessive background seen in the γ-ray detectors. Fig. 1(A) demonstrates a typical prompt γ-spectrum measured in the Ge clusters in the reaction of scattering ^{54}Cr fragments on a gold target at 100 A MeV kinetic energy. In the spectrum, on top of the dominant smooth background, one sees a group of Doppler broadened γ-lines characteristic for the inelastic scattering of fast neutrons

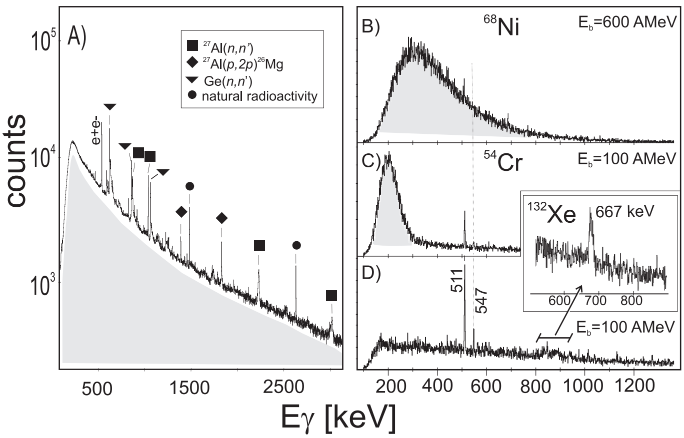

Fig. 1. (A) Prompt γ-ray spectrum measured in coincidence with RIB. There are peaks induced by fast particles (as marked) on top of the excessive background (filled area). (B), (C) Not Doppler corrected γ-ray spectra measured in coincidence with RIB scattered on a gold target. Position of the 547 keV transition from Coulomb excited ^{197}Au is indicated. The low energy atomic background is shadowed. (D) Respective γ-ray spectrum registered with the stable ^{132}Xe beam. In the inset, the 667 keV, $2^+ \rightarrow 0^+$ transition seen in the Doppler corrected spectrum.

on aluminum, the main component of the reaction chamber. Sharp ^{26}Mg transitions also visible in the spectrum, suggest occurrence of the quasi free proton scattering reaction: $^{27}\mathrm{Al}(p, 2p)^{26}\mathrm{Mg}$ induced by protons with energy $E_p > 100$ MeV, produced in the collisions. A direct interaction of particles (p, π, e) with the Ge crystals could explain a saturation of detector preamplified signals that were observed in a beam pulse, predominantly in the five clusters mounted close to the beam-line. These signals were associated with the cluster multiplicity close to the maximum fold of 7. Parallel use of digital XIA DGF cards, besides the standard analog VXI electronics, for reading out a few of the Ge detector channels allowed for filtering out these irregular signals. Inversely, the requirement of only low folds in the clusters guaranteed that properly shaped signals induced by γ-rays were accepted for the acquisition. As it was shown in [2], γ-ray measurement with HECTOR allowed to determine the origin of the registered radiation due to the very good timing properties of the BaF_2 crystals. It turned out that in addition to γ-rays from the target, strong radiation was emitted at the FRS side. On the other hand, the beam stopper was also identified as a source of huge γ-ray background. In the EUROBALL detectors, likewise in HECTOR, selection of a narrow window in the projectile-γ time spectrum, which corresponded to the target prompt γ-emission events, allowed to suppress the unwanted background radiation emitted downstream and upstream of the beam line.

At intermediate beam energies, atomic processes are the important constituents of the prompt γ-ray background. In this energy regime intense bremsstrahlung is expected to be orders of magnitude stronger than the nuclear radiation, and depending on the incident beam velocity may reach energies of several hundreds keV [2]. In Fig. 1(B), (C) and (D) are shown non Doppler corrected γ-ray spectra measured in Coulex reactions with RIB: ^{68}Ni at 600 A MeV, ^{54}Cr at 100 A MeV, and a primary ^{132}Xe beam at 100 A MeV, respectively. In all the three cases γ-rays were registered in coincidence with scattered projectiles selected by the HI detectors before and after a gold target. In the γ-spectra obtained with the fragmented beams, one notices intense low energy atomic background which in the case of the 600 A MeV ^{68}Ni beam extends to almost 1 MeV. In contrast, in the spectrum registered in the reaction with the stable ^{132}Xe projectiles such increase of the background is not observed. The excessive atomic background induced by the secondary beams may be associated with their large spatial spread that resulted in scattering on the surrounding material. Indeed, a RIB spot size was measured to be about 20 cm^2 at the target position, whereas for the stable beam it was close to 1 cm^2.

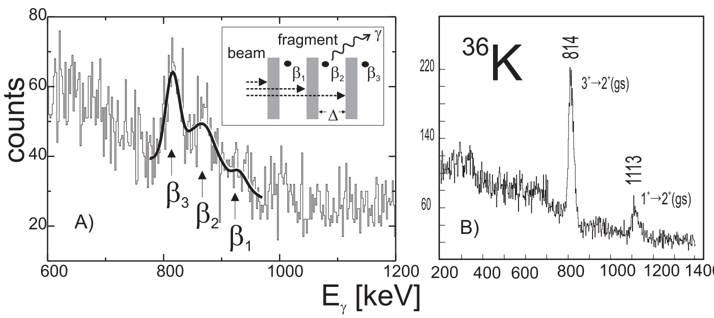

Fig. 2. (A) Splitting of the 814 keV line from ^{36}K due to γ-ray emission at the different fragment velocities: $\beta_1 = 0.53$, $\beta_2 = 0.49$ and $\beta_3 = 0.43$. The best fit to the data yielded the ^{36}K, 3^+ level lifetime of 28(6) ps. In the inset, a sketch of the plunger device. (B) The 814 keV transition in ^{36}K measured in the secondary fragmentation reaction of ^{37}Ca on a Be target.

3. Gamma-ray spectroscopy methods developed at RISING: γ-ray angular distribution and lifetime measurements

Spectroscopic investigations of exotic nuclei reveal evolution of the structure of magic nuclei. They come across new regions of nuclear deformation far from stability. Experiments performed so far at the intermediate energy RIB facilities explored these phenomena through measurements of transition energies and B(E2) rates.

Coulomb excitation is the ideal tool to study low lying levels in the unstable long-lived nuclei. However, in the intermediate energy range, Coulex cross-section measurements may suffer from not negligible contribution of nuclear reactions that can appear at small impact parameters but are not fully controlled in the experiments. The admixture of the nuclear interaction might perturb the determination of the B(E2) probabilities estimated from the Coulex theory. RISING experiments have shown that the electromagnetic interaction along with the residual nuclear forces present in the inelastic scattering reactions accounted for the measured γ-ray angular distributions $W(\theta)$. Despite the large composite detector size and their big angular overlap, the $W(\theta)$ functions were determined by grouping individual EUROBALL detector crystals in shells at four distinct angles. Comparison of the experimental $W(\theta)$ for the target and the projectile nuclei with model calculations allowed for more precise estimation of the Coulex cross-section, thus B(E2) in some cases. More details are given in Ref. [4].

Alternatively to Coulex, in promptly-decaying exotic nuclei, excited states may be populated in secondary fragmentation reactions. In such a case, the corresponding B(E2) transition rates can be deduced from the transition energies and level lifetimes τ. At RISING, a pioneering lifetime measurement making use of a simple plunger prototype was performed. The plunger consisted of three equidistant iron plates that acted as secondary targets and degraders at the same time (*cf.* the inset in Fig. 2.(A)). The distance Δ between the plates could be adjusted according to the expected range of τ. RIB selected in FRS impinging in the plunger targets yielded to fragmentation. Gamma-radiation emitted from the secondary fragments occurred at a velocity that gradually decreased as the fragment passed through consecutive degraders. The variable γ-ray Doppler shift resulted in the γ-line splitting. The transition intensity was shared between the three peaks according to τ and Δ. In Fig. 2(A) it is shown a summed γ-ray spectrum of all Cluster detectors recorded in coincidence with the ^{37}Ca projectiles of the 200 A MeV initial energy, produced in the fragmentation of ^{48}Ca. The ^{36}K secondary fragments from the most intense 1p removal reaction channel were simultaneously selected. The three components of the 814 keV line corresponding to the $3^+ \rightarrow 2^+$ ground state transition in ^{36}K are weak but clearly seen. For comparison, Fig. 2(B) presents the same line measured in the fragmentation of the ^{37}Ca beam on a monolithic Be target. In order to extract the lifetime of the 3^+ state in ^{36}K, so far unknown, the 814 keV line shape was compared to a calculated distribution. This solution was more appropriate than a simple intensity analysis of the three peaks, since the low statistics imposed the necessity of summing data obtained for the two distances: $\Delta = 2$ mm, $\Delta = 8$ mm and all detection angles. In the model calculations, the Lorentz boosted γ-ray $W(\theta)$ function, which strongly depends on the radiation source velocity, and the γ-ray emission inside degraders were taken into account. The best fit to the data was obtained for $\tau = 28(6)$ ps. This value is comparable with the lifetime of the analogous 3^+ level at 788 keV in the ^{36}Cl mirror nucleus, which amounts to $\tau = 20(2)$ ps. More details on the lifetime data analysis will be given in a forthcoming publication.

4. Conclusion and perspectives

The results from the RISING in-beam measurements show that the excessive γ-ray background induced by fast RIB can be effectively reduced by minimization of the secondary beam spatial spread and application of an appropriate γ-ray detector shielding. On the other hand, in the new Ge detector setup planned at FAIR, application of fast signal reset preamplifiers and a digital readout electronics will be essential for selecting properly shaped signals. Moreover, a good time resolution of the electronics will play important role in filtering out the intense γ-radiation emitted outside the reaction target. These conditions will be fulfilled by the new generation Ge detector array AGATA. The use of the complete AGATA array at HISPEC and the AGATA demonstrator at PRESPEC will be advantageous in experiments aimed at γ-ray angular distribution measurements. The AGATA modularity will provide a flexible detector geometry that can be optimized for a particular experiment in order to cover the maximum angular range, thus increasing the array efficiency. Still, the array γ-ray tracking capability should allow for maintaining a very good angular resolution of the order of 1°, and to some extent by using imaging techniques, reproducing the γ-ray emission point. Already in the PRESPEC phase, the setup sensitivity is expected to be by more than 10 times greater, with respect to RISING. Therefore, the lifetime plunger measurements, will be feasible for reaction channels much weaker than those studied at RISING.

This work is supported by the Polish Ministry of Science and Higher Education Grants No: N N202 309135, N N202 109936 and N N202 240637.

REFERENCES

[1] Z. Podolyak, *Acta Phys. Pol. B* **41**, 493 (2010) this issue.
[2] H.J. Wollersheim *et al.*, *Nucl. Instrum. Methods* **A537**, 637 (2004).
[3] F. Camera, J. Gerl, *Nucl. Phys. News* **19**, 7 (2009).
[4] P. Bednarczyk *et al.*, *Acta. Phys. Pol. B* **40**, 835 (2009).