SPECTROSCOPY OF NEUTRON INDUCED REACTIONS WITH THE ν-BALL SPECTROMETER*

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The ν-ball is a high-efficiency hybrid spectrometer which consists of both germanium (Ge) detectors and associated anti-Compton BGO shields, coupled to lanthanum bromide ($LaBr_3$) detectors. The hybrid configuration provides a combination of both excellent energy and timing resolutions. The ν-ball geometry allows the coupling with the LICORNE directional neutron source at the ALTO facility of the IPN, Orsay. This opens the possibility to perform precise spectroscopy of neutron induced reactions and was used for two experiments during the recent experimental campaign. These two experiments are described here: 1. Spectroscopy of the neutron-rich fission fragments produced in the ^{238}U(n,f) and ^{232}Th(n,f) reactions; 2. Spectroscopy above the shape isomer in ^{238}U. The ^{238}U(n,f) and ^{232}Th(n,f) reactions produce hundreds of neutron-rich nuclei on which gamma-ray spectroscopy can be performed. The main goal of the experiment aiming to populate the shape isomer in ^{238}U is the measurement of the gamma-ray and fission decay branches as well as determination of level scheme in the super-deformed minimum. The shape isomer is populated by ^{238}U(n,n') reaction, which gives a very advantageous population cross section over other reactions. More detailed descriptions of these two ν-ball experiments will be presented here.

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1. Introduction

The ν-ball spectrometer was recently constructed at the ALTO facility of the IPN, Osray. ν-ball is a hybrid device consisting of 24 clovers and 10 coaxial Ge detectors (and associated anti-Compton BGO shields) with excellent energy resolution and up to 20 $LaBr_3$ detectors with excellent timing resolution. The main goals were to perform spectroscopy of neutron-rich nuclei and fission shape isomers as well as extract information about nuclear moments or deformations with high sensitivity using fast timing techniques. The unique possibility of coupling the ν-ball spectrometer to the LICORNE (Lithium Inverse Cinematiques ORsay NEutron source) directional neutron source at the ALTO facility [1] was exploited. This opens up the possibility for detailed spectroscopic studies of neutron induced reactions. Two experiments of this type were performed: 1. Spectroscopy of the neutron-rich fission fragments produced in the ^{238}U(n,f) and ^{232}Th(n,f) reactions [2]; 2. Spectroscopy above the shape isomer in ^{238}U [3]. The ^{238}U(n,f) and ^{232}Th(n,f) reactions give a possibility for production and study of hundreds of neutron-rich nuclei, hence many different physics cases are addressed simultaneously. The main goal of the spectroscopy above the shape isomer in ^{238}U is the measurement of population and decay of this long-lived superdeformed state in a nucleus that has a significant gamma branch to the normal deformed potential minimum. The hope is to determine the level scheme in the super-deformed minimum.

2. Coupling the ν-ball spectrometer and LICORNE neutron source

The combination of $LaBr_3$ and Ge detectors provide excellent timing and energy resolution. The measured timing resolution of $LaBr_3$ detectors was $\approx$ 250 ps and timing resolution of Ge detectors was about $\approx$ 12 ns. The Ge detectors provide in average energy resolution of 2.8 keV at 1.33 MeV energy in comparison with 2.6% at 662 keV for the $LaBr_3$. Total efficiency was simulated and confirmed by measurements to be $\approx$ 6.2% for Ge and $\approx$ 0.8% for $LaBr_3$ detectors. One of the main characteristics of the ν-ball is full digitization of all signals from detectors including BGO detectors. The FASTER digital data acquisition system was used with a total of up to 200 channels [4]. Since the BGO detectors were used without collimation, calorimetric measurement by determination of full energy deposited in the spectrometer was possible. Calorimetric measurement in combination with the determination of gamma multiplicity is a powerful tool for selection of the events coming from different processes, for example separation of fission events and beta decay. The LICORNE neutron source [1] provides intensely focused quasi-monoenergetic neutron beams produced by the inverse kinematic reaction $p(^7\text{Li},n)^7\text{Be}$. The neutron energy is constrained between 0.5 MeV and 4.0 MeV and is suitable for gamma-spectroscopy measurements of fast neutron induced reactions, particularly fission.

3. Spectroscopy of the neutron-rich fission fragments produced in the $^{238}\text{U}(n,f)$ and $^{232}\text{Th}(n,f)$ reactions

The collection of spectroscopic information about neutron-rich nuclei is very important for many different reasons such as the nuclear structure studies (for example, testing of different theoretical models) or better understanding of astrophysical processes in which neutron-rich nuclei can be produced. Coupling of the ν-ball spectrometer with the LICORNE neutron source gave us possibility to populate and study neutron-rich nuclei. The production mechanism was fission of ^{238}U and ^{232}Th induced by the fast neutrons of incident energy around 2 MeV. The fast fission reaction provides on average higher ratios of neutrons to protons (N/Z) in the reaction products with less emitted neutrons per fission in contrast to thermal neutron-induced fission of ^{235}U,^{241}Pu and spontaneous fission of ^{248}Cm, ^{252}Cf. This is a clear advantages of these population mechanisms in comparison to ones used previously [5, 6]. Two targets of ^{238}U (81 g) and ^{232}Th (129 g) provide the possibility to perform cross checking of data. Many different physics cases will be studied. The first part of the experiment using the cylindrical shape ^{238}U target was performed in February 2018. The lithium primary beam energy was 16.4 MeV and pulsed with 400 ns period. The experiment lasted for two weeks. The second part of the experiment was performed in April 2018. The target was a conical shaped aluminum shell housing 9 samples of ^{232}Th of different diameters and thickness of 0.1 mm and an average density of 1 g/cm^3 to reduce attenuation of low-energy gamma rays. The primary lithium beam energy was 16.75 MeV, again with pulsation of 400 ns period. The measurement was three weeks duration. All data were collected in triggerless mode with all gamma ray hits in the detectors stored on disk for later offline analysis. The most important task in the data analysis is to obtain very good selectivity for the particular events of interest. The pulsed neutron beam with period of 400 ns and pulse width of 2 ns, allows separation of prompt and delayed gamma rays and gives access to time correlations. In Figs. 1 and 2, the matrices of energy *versus* time for the Ge and $LaBr_3$ detectors are presented. Another possibility to increase selectivity comes from

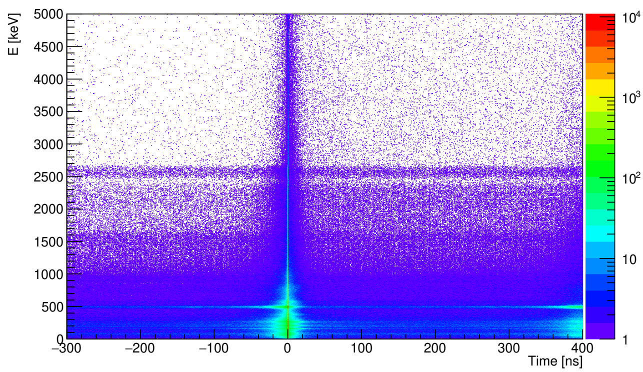

Fig. 1. Energy *versus* time for the $LaBr_3$ detectors during measurements with ^{232}Th target.

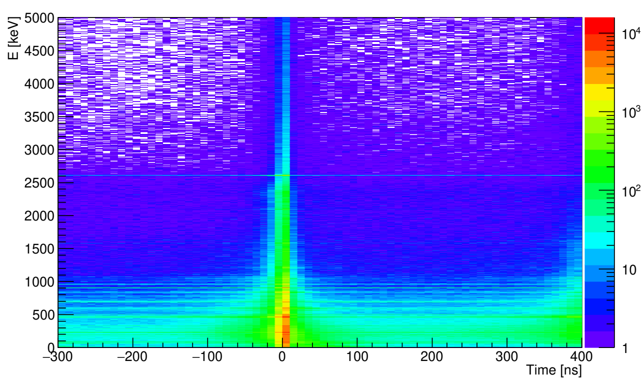

Fig. 2. Energy *versus* time for the Ge detectors during measurements with ^{232}Th target.

the fast timing of the $LaBr_3$ detectors as well as energy selection with excellent resolution of the Ge detectors. Finally, further selectivity is provided by calorimetric measurement. By analyzing sum-energy and gamma multiplicity (Fig. 3), it is possible to distinguish between events with different multiplicities and total sum energy.

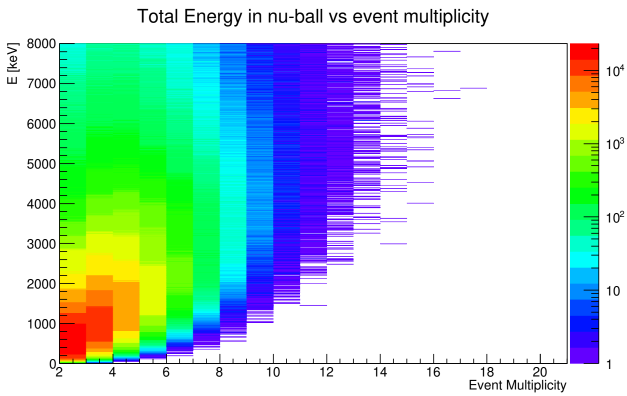

Fig. 3. Multiplicity *versus* total deposited energy in ν-ball spectrometer during activation of the ^{232}Th target.

4. Spectroscopy above the shape isomer in ^{238}U

Study of fission shape isomers can provide information about the fission barrier energy landscape as well as characteristic of super-deformed state of atomic nuclei. In this work, we decided to study the shape isomer in ^{238}U. The goal of the experiment was to obtain information about population of the fission shape isomer, its decay, branching ratio, half life and fission barrier penetrability. Study of shape isomer in ^{238}U has some advantages for experimental work. First of all, it is known that the ground state in the super deformed minimum has energy of 2.558 MeV. Also, two isomeric transitions (IT) to the normal deformed states with energy of 1878 keV and 2513 keV are identified in previous works [7, 8]. The measured half life of that IT decay is 195(30) ns [7, 8]. Decay of this state can occur through IT or isomeric fission (IF) with ratio of IT/IF = 95/5 [8]. With an incident neutron energy between 3 MeV and 5 MeV, the ratio of the prompt fission to delayed fission is $\approx 10^{-4}$ [9]. Taking into account the prompt fission cross section and the IT/IF ratio, the cross section for population of superdeformed isomeric state in ^{238}U can be expected to be ≈ 1.5 mb. Because of this high cross section, the $^{238}\mathrm{U}(n, n')$ reaction is ideal to populate the shape isomer. The LICORNE incident neutron energy was, therefore, arranged to be 3.5 MeV which will give the possibility to populate energy levels up to 1 MeV above the shape isomer in the superdeformed well. Using the ν-ball spectrometer with the LICORNE pulsed neutron beam gives the possibility first, to study IT decay of fission isomer and then, to study its population to obtain information about level scheme above the shape isomer. The experiment used the same cylindrical ^{238}U target of mass of 81 g used in the previous experiment. However, the lithium primary beam energy was higher, at 18.5 MeV. The measured LICORNE neutron energy spectrum (from TOF) is presented in Fig. 4. Data were collected over a period of approximately 6 days. Prompt and delayed gamma spectra (from 100 ns to 300 ns after beam pulse) for a part of collected data are presented in Fig. 5.

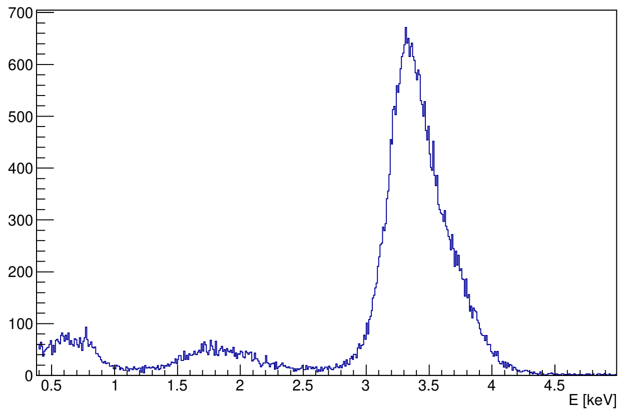

Fig. 4. Measured LICORNE neutron spectrum during the measurement of spectroscopy above the shape isomer in ^{238}U.

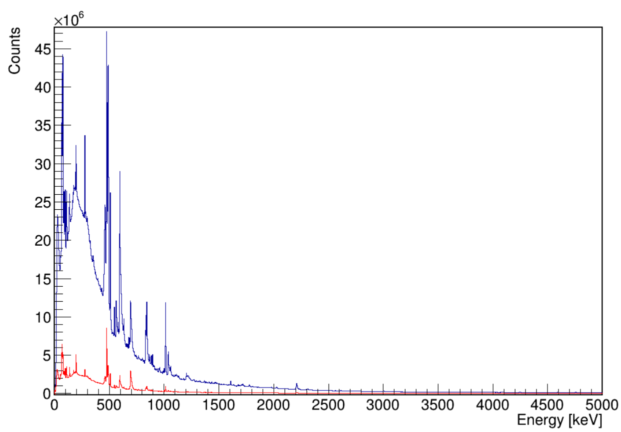

Fig. 5. (Color online) Prompt spectrum (top/blue line) and delay spectrum (bottom/red line) of Ge detectors during the measurement of spectroscopy above the shape isomer in ^{238}U.

The ability to make a selection of different events based on detected gamma multiplicity is presented in Fig. 6. No significant difference in the spectra (Fig. 6) is seen, which requires a further investigation.

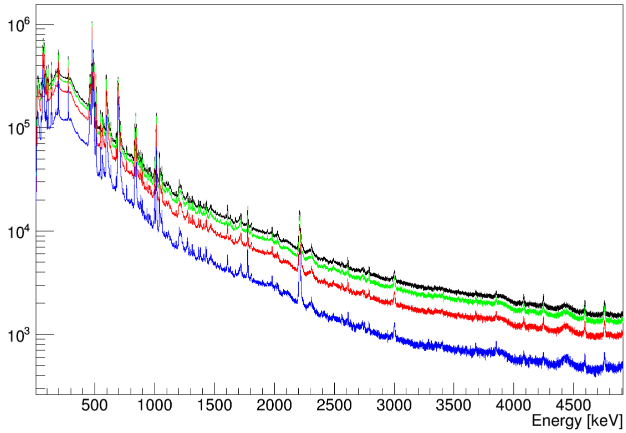

Fig. 6. (Color online) Delayed gamma spectra during the measurement of spectroscopy above the shape isomer in ^{238}U (from 100 ns to 300 ns after beam pulse) with prompt gamma multiplicity equal to or less than 1 and delay gamma multiplicity: equal or less than 1 (bottom/blue line), equal or less than 2 (second from the bottom/red line), equal or less than 3 (second from the top/green line) and equal or less than 4 (top/black line).

5. Conculusion

The coupling of the ν-ball hybrid spectrometer with the LICORNE neutron source was performed at the ALTO facility of the IPN Orsay. Two experiments concerning the gamma-ray spectroscopy of neutron-induced reactions were performed and the main ideas and experimental conditions have been described. The analysis of the collected data is in progress. New information about the structure of neutron-rich nuclei and the fission shape isomer in ^{238}U is expected.

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