Vol. 51 (2020) *Acta Physica Polonica B* No 3

γ-RAY SPECTROSCOPY OF ^{85}Se PRODUCED IN ^{232}Th FISSION*

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(Received January 21, 2020)

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* Presented at the XXXVI Mazurian Lakes Conference on Physics, Piaski, Poland, September 1–7, 2019.

Excited states in the neutron-rich ^{85}Se nucleus have been studied using for the first time a fast neutron-induced fission of ^{232}Th. The experiment was performed at the ALTO facility of the IPN Orsay. Coupling of the LICORNE directional neutron source with the ν-ball high-resolution γ-ray spectrometer provided unique access to high-spin states in neutron-rich fission fragments from the ^{232}Th(n, f) reaction. A preliminary level scheme of ^{85}Se was established by the analysis of prompt γ–γ–γ coincidences. Identification of the all known yrast states in ^{85}Se is the first step towards studies of more neutron-rich Se isotopes.

DOI:10.5506/APhysPolB.51.843

1. Introduction

Nuclei in the vicinity of ^{78}Ni stand for excellent systems to probe phenomena occurring when neutron excess becomes large. Systematic investigations of neutron-rich isotopes above $Z = 28$ and $N = 50$ allow to determine changes of effective single-particle energies as valence nucleons are added to the ^{78}Ni core. Energy-level systematics of the $N = 51$ even-Z isotones show a significant decrease of the energy separation between the $1/2^+$ $(\nu\, 3s_{1/2})$ first excited state and the $5/2^+$ $(\nu\, 2d_{5/2})$ ground state from ^{91}Zr to ^{79}Ni [1]. The observed trend in the energy difference was originally interpreted as a sign of quenching of the $N = 50$ gap [1]. Later, this evolution of the $1/2^+$ energy was found to be driven by the proton occupation number affecting the character of the proton–neutron interactions [2]. To probe the evolution of other neutron single-particle states above ^{78}Ni, including the high-momentum (ℓ) orbitals $\nu\, 1g_{7/2}$ and $\nu\, 1h_{11/2}$, access to high-spin excitations of neutron-rich nuclei above $Z = 28$ and $N = 50$ is necessary.

The γ-ray spectroscopy of fission fragments is a useful tool to infer the contribution of high-ℓ orbitals from the structure of yrast levels. One of the fission reactions that produces exotic neutron-rich fragments, hence suitable to explore the ^{78}Ni region, is fast-neutron-induced fission of ^{232}Th [3]. The ^{232}Th fission yields are higher for more neutron rich isotopes than in the case of ^{238}U fission [4]. This reaction has been employed for the first time to investigate nuclear structure of neutron-rich Se isotopes. In this work, preliminary results for the $N = 51$ isotone ^{85}Se are presented.

The first information about excited states in ^{85}Se was obtained in β-decay studies of ^{85}As [5]. Spin-parity assignments of $5/2^+$ and $1/2^+$ were proposed for the ground state and first excited state of ^{85}Se, respectively. Later measurements using transfer reactions [6–8], fusion–fission reaction [9] and spontaneous fission [10] provided new spectroscopic data for ^{85}Se. So far, the location of the main $\nu\, 1g_{7/2}$ single-particle strength in ^{85}Se has not been reliably determined. For the first $7/2^+$ state, a large spectroscopic factor

$S = (0.77 \pm 0.27)$ was obtained in a one-neutron transfer reaction [8]. However, the lifetime upper limit of 3(2) ps for the $7/2^+_1$ state revealed only a minor component ($\lesssim 10\%$) in its wave function of the $(0^+ \otimes 1\,g_{7/2})$ configuration [7]. In this study, we employ a complementary method to populate high-spin states in ^{85}Se in order to determine location of states having significant component of one of the high-ℓ neutron orbitals in their wave functions.

2. Experimental method

The experiment was performed at the ALTO facility of IPN Orsay, where a dedicated kinematically focused neutron source was developed, which opened new perspectives for fast-neutron-induced fission studies. Fast directional neutrons were produced by the LICORNE source via the $p\,(^7\text{Li}, n)^7\text{Be}$ inverse reaction [11]. A primary beam of ^{7}Li produced by the tandem accelerator with average intensity of 80 nA hits the hydrogen gas target, producing cones of neutrons with an average energy of 1.7 MeV. Subsequently, those were impinged on conical ^{232}Th target (129 g, 0.984 g/cm^3) inducing fission. The time structure of the ^{7}Li beam, with 400 ns pulsing period and 2 ns pulse width, allows investigating prompt and delayed γ rays separately. Due to the pulse structure of the primary beam, time correlations can be exploited to suppress random events from β decays of fission fragments and neutron-induced background. The coupling of the LICORNE directional neutron source with a high efficiency spectrometer allows precision γ-ray spectroscopy of the most neutron-rich fission fragments to be performed. An effective beam time of 19 days was provided with fissions induced at an estimated rate of 25 kHz.

The γ rays emitted from the fission fragments were detected by the ν-ball spectrometer [12], which combines the best aspects of the different detector types. It consists of Ge detectors, including 24 clovers and 10 coaxial detectors, equipped with anti-Compton shields made of BGO, as well as $LaBr_3$(Ce) detectors — 10 coaxial- and 10 cylindrical-shaped. The FASTER digital data acquisition system [13] was used to read out signals from all detectors. The detector array covers around 70% of the full solid angle and enables angular correlation analysis using 10 different angles relative to the beam axis to be performed. To enhance the reaction mechanism selection in the offline event building process, BGO detectors will be used for calorimetry purposes, giving valuable information on the sum energy and multiplicity of each event.

3. Data analysis

In order to study the population of excited states in ^{85}Se in neutron-induced fission of ^{232}Th, known transitions in ^{85}Se [5–10] and its most abundant fission-fragment partners, ^{146}Ba and ^{147}Ba [14, 15], were investigated. The preliminary analysis of the γ–γ–γ coincidences of prompt γ rays emitted in the ^{232}Th(n,f) reaction indicates population of intermediate-spin states in ^{85}Se, which were not observed in spontaneous fission of ^{248}Cm and ^{252}Cf [10]. In Fig. 1 (a), we present a coincidence spectrum doubly gated on the 539 keV and 1436 keV γ rays corresponding to transitions belonging

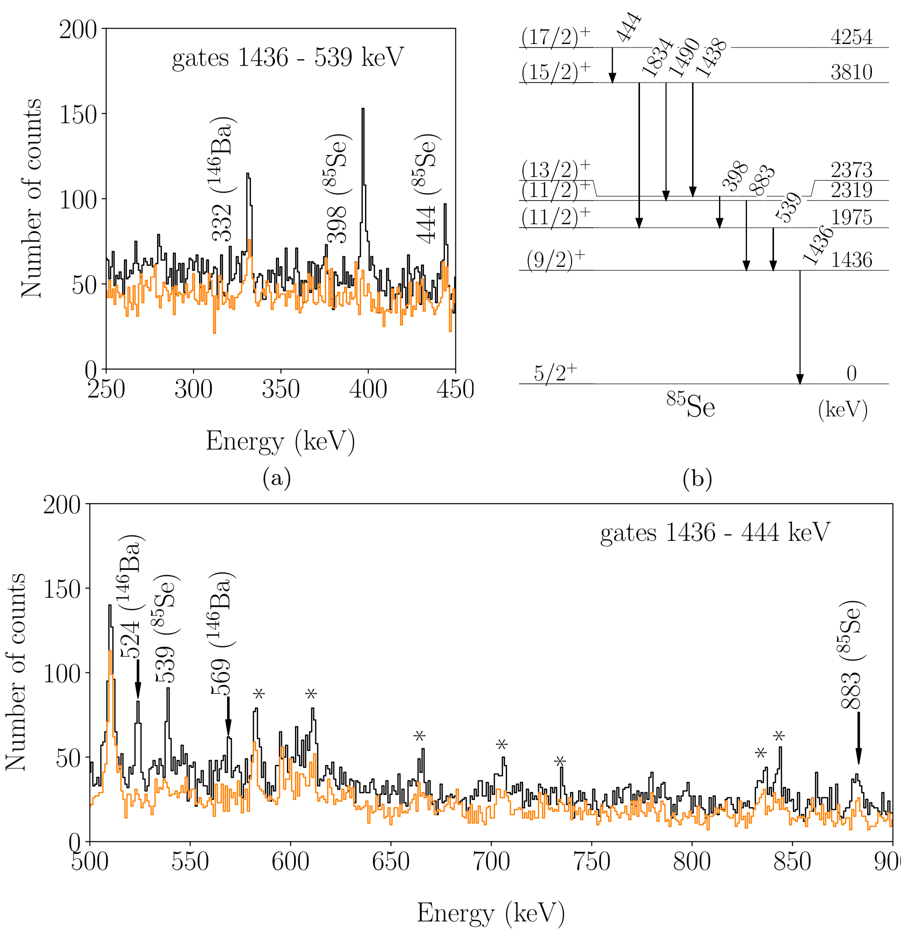

Fig. 1. (Colour on-line) (a) Part of γ-ray coincidence spectrum gated on 1436 keV and 539 keV transitions (black), and background gated on 1436 keV and on the area next to 539 keV (grey/orange). (b) Partial level scheme of ^{85}Se obtained in this work. The spin-parity assignments were adapted from Ref. [9]. (c) Part of γ-ray coincidence spectrum gated on 1436 keV and 444 keV transitions (black) and background analogously (grey/orange). Contamination lines are marked with an asterisk. The background gate has the same width as the original gate.

to the $(11/2^+) \rightarrow (9/2^+) \rightarrow 5/2^+$ cascade in ^{85}Se (see Fig. 1 (b)) [9]. The presence of the 444-keV γ ray in this spectrum is a clear evidence of the population of the $(17/2)^+$ state in ^{85}Se, being the highest-spin level in this nucleus, observed so far only in the fusion–fission reaction ^{18}O+^{208}Pb [9]. The coincidence between 444-keV and 539-keV lines is also shown in Fig. 1 (c). The partial level scheme of excited states in ^{85}Se, as obtained in the present work, is presented in Fig. 1 (b). All previously reported yrast levels in ^{85}Se were confirmed.

Due to the complexity of the background in our measurement (intrinsic activity of ^{232}Th, inelastic neutron scattering off target and other materials, inelastic scattering of the primary ^{7}Li beam, and β decays) at this stage of analysis, we do not report new transitions. Nevertheless, several candidates have been preliminarily identified as potentially new transitions in ^{85}Se and are currently under analysis. An important innovation of our experimental setup is the possibility to exploit information on the sum energy and multiplicity of each event in our analysis [12]. This, along with timing information relative to the beam pulse, will be used to reduce background and to unambiguously identify fission events.

4. Summary

Fast-neutron-induced fission of ^{232}Th has been investigated as a potential method for studying high-spin states in ^{85}Se. This reaction was employed for the first time to gain insight into the structure of neutron-rich Se isotopes. New information on yrast excitations in the $N = 51$ isotones above $Z = 28$ would be a valuable input for investigations of the evolution of the $\nu\, 1g_{7/2}$ and $\nu\, 1h_{11/2}$ effective single-particle energies above the ^{78}Ni core. The experiment was performed at the ALTO facility of the IPN Orsay by coupling the LICORNE directional neutron source with the high efficiency ν-ball spectrometer consisting of both high-energy resolution Ge detectors and $LaBr_3$(Ce) fast detectors. Although the analysis of collected data is currently in progress, prompt γ–γ–γ coincidences data revealed the population of $(17/2)^+$ state in ^{85}Se, which is significantly higher than previously observed in spontaneous fission of ^{248}Cm and ^{252}Cf.

This work was supported in part by the National Science Centre, Poland (NCN) under contract No. UMO-2015/18/E/ST2/00217, by the German Research Foundation (DFG) under grant No. BL 1513/1-1, by the NuSTAR DA BMBF 05P15RDFN1, and by the Spanish MINECO via projects FPA2015-65035-Pand RTI2018-098868-B-I00.

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