MEDIUM SPIN STATES IN THE ^{87}Se ISOTOPE PRODUCED IN NEUTRON INDUCED FISSION OF ^{233}U AND ^{235}U TARGETS*

K. Gajewska[a], Ł.W. Iskra[a], B. Fornal[a], S. Leoni[b,c]
C. Michelangoli[d], S. Bottoni[b,c], N. Cieplicka-Oryńczak[a]
G. Colombi[b,d], C. Costache[e], F.C.L. Crespi[b,c], J. Dudouet[f]
M. Jentschel[d], F. Kandzia[d], Y.H. Kim[d], U. Köster[d], R. Lica[e]
N. Mărginean[e], R. Mărginean[e], C. Mihai[e], R.E. Mihai[e]
C.R. Nita[e], S. Pascu[e], E. Ruiz-Martinez[d], A. Turturica[e]

[a]Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland
[b]INFN sezione di Milano, via Celoria 16, 20133, Milano, Italy
[c]Dipartimento di Fisica, Università degli Studi di Milano, 20133 Milano, Italy
[d]ILL, 71 Avenue des Martyrs, 38042 Grenoble CEDEX 9, France
[e]Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH) Bucharest, Romania
[f]Université Lyon 1, CNRS/IN2P3, IPN-Lyon, 69622 Villeurbanne, France

Received 13 January 2025, accepted 24 January 2025, published online 10 April 2025

The level scheme of the neutron-rich ^{87}Se isotope has been extended up to 2397 keV excitation energy. The isotope of interest was produced in a neutron-induced fission reaction of a ^{235}U target at the Institut Laue-Langevin in Grenoble. During the analysis, six new gamma transitions were identified by employing multifold gamma-ray coincidence relationships, measured with the FIPPS array. Based on the gamma angular correlations technique, tentative spin-parity assignments have been proposed for the low-lying levels.

DOI:10.5506/APhysPolBSupp.18.2-A41

1. Introduction

The exploration of the nuclear chart portion located northeast of the doubly magic ^{78}Ni isotope serves as a testing ground for various theoretical approaches based on the shell model. The study of those nuclei has been a central activity of experimental and theoretical groups around the

* Presented at the 57$^{\text{th}}$ Zakopane Conference on Nuclear Physics, *Extremes of the Nuclear Landscape*, Zakopane, Poland, 25 August–1 September, 2024.

world [1–3], however, only recently, Taniuchi *et al.* [4] confirmed the double-magic character of ^{78}Ni. The authors also indicated the breakdown of the $N = 50$ and $Z = 28$ magic numbers beyond ^{78}Ni, caused by competition with deformed structures, which aligns with recent large-scale shell model calculations [5]. These results further strengthen the interest in studying the region in proximity to the ^{78}Ni isotope. In this context, the Se isotopic chain, located six protons away from the $Z = 28$ closed shell, shows a clear competition between configurations associated with different shapes [6–8]. Our goal is to extend the spectroscopic information on ^{87}Se, so far poorly known. Prior to our work, only two papers referred to the structure of the ^{87}Se isotope [9, 10]. The first three transitions in ^{87}Se, with energies of 92, 744, and 886 keV, were identified based on a spontaneous fission experiment of a ^{248}Cm source using the cross-coincidence method, and the spin-parity assignments were based on a comparison with shell model calculations [9]. The 92 and 744 keV lines were confirmed in the β-decay measurement of the ^{87}As isotope [10], moreover, three new low-spin states were reported.

2. The experiment

Data for the analysis were collected during the experiment at the Institute Laue-Langevin (ILL) in Grenoble, France. The isotope of interest was produced during the fission process of ^{235}U target, induced by thermal neutrons from the ILL reactor. Target material was diluted in a liquid scintillator, providing a clean fission tag and enabling the subtraction of β-decay events from the fission data [11]. The emitted gamma rays were recorded with the FIPPS array [12], which consists of 16 HPGe clover detectors. High-statistic data were sorted into three-dimensional gamma coincidence cubes. This dataset was recently used to establish new level schemes in the ^{89}Br [13] and ^{96}Y [14] isotopes.

3. Analysis and results

During the fission process of ^{235}U, the ^{87}Se isotope is produced together with ^{148}Ce, ^{147}Ce, and ^{146}Ce nuclei, with ^{146}Ce as the dominant fission partner. As a first step, the gamma cross-coincidence technique has been used by placing gates on the ground-state transition in ^{87}Se (92 keV) and the strongest line in ^{146}Ce (258 keV). As a result, the spectrum presented in Fig. 1 was obtained, where the 744 and 886 keV transitions in ^{87}Se can be recognized, as reported in [9]. Additionally, a new 1380 keV line is visible.

The final level scheme, presented in Fig. 2, was constructed by analyzing the gamma-coincidence spectra shown in Fig. 3. The gates were set on the 92–744 keV (panel (a)), 92–886 keV (panel (b)), and 92–1380 keV

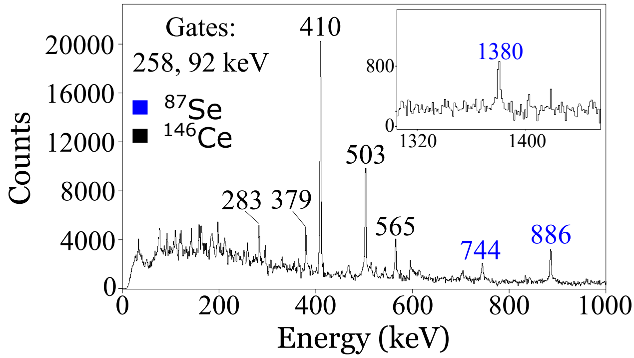

Fig. 1. Gamma spectrum from the triple coincidence cube. Double gates are placed on 92 and 258 keV gamma rays from ^{87}Se and ^{146}Ce, respectively.

(panel (c)) transitions in ^{87}Se. In all panels, the prominent lines from the ^{146}Ce, ^{147}Ce, and ^{148}Ce fission partners are present and marked in green/light gray, blue/dark gray, and red/gray, respectively. Additionally, a new 635 keV line is visible in Fig. 3 (a), and a trace of a 525 keV transition, later confirmed in Fig. 3 (c). Furthermore, three weak transitions of 494, 984, and 1419 keV have been identified above the 978 keV state based on the spectrum shown in panel (b) of Fig. 3.

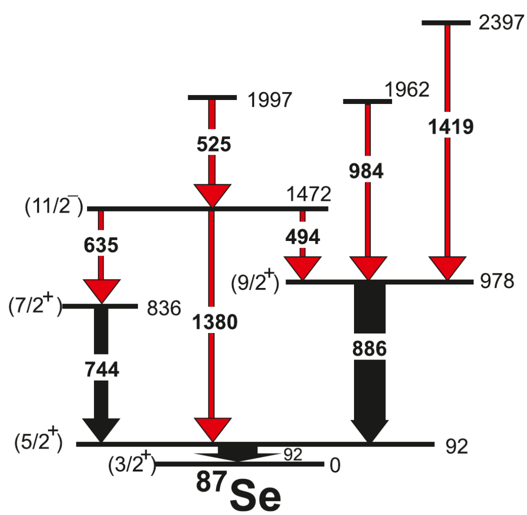

Fig. 2. (Color online) Level scheme of the ^{87}Se isotope with new lines marked in red/gray. The width of the arrows reflects the intensities normalized to the strongest 92 keV transition.

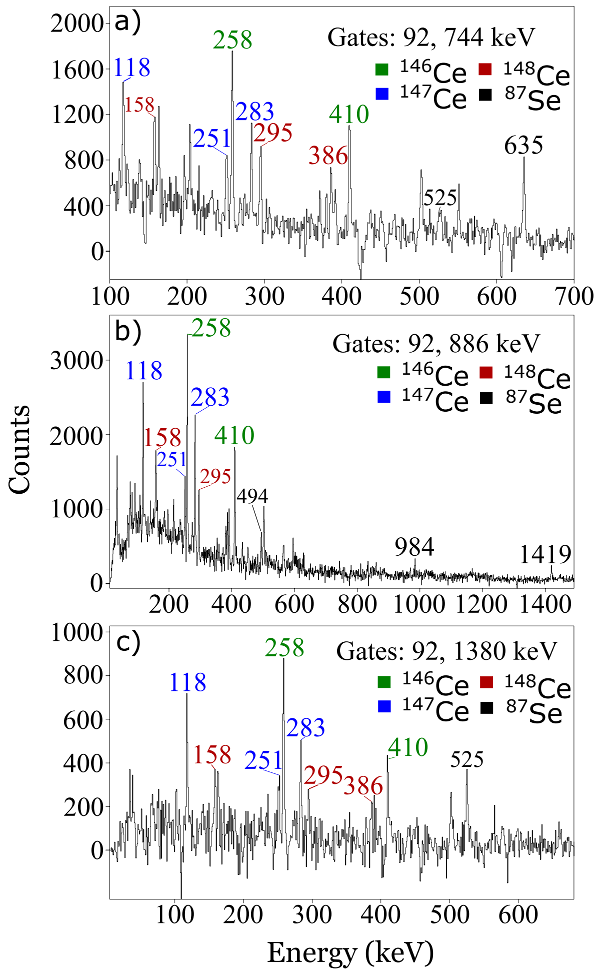

Fig. 3. (Color online) Gamma spectra, constructed based on the triple coincidence cube with gates on: (a) 92–744 keV, (b) 92–886 keV, (c) 92–1380 keV transitions in the ^{87}Se isotope.

The newly identified transitions are marked in red/gray in the level scheme of ^{87}Se (see Fig. 2), while the width of the arrows reflects their intensities normalized to the strongest 92 keV line. The intensity of the 92 keV transition was defined as 100 units, including the conversion coefficient factor taken from [15]. This is summarized in the last column of Table 1, along with the energies of the gamma rays (column 5) and their multipolarity (column 6). The first four columns provide the energies and spin parities of the initial and final states.

Table 1. Information on gamma rays, levels, and corresponding transitions in ^{87}Se (more in the text above). Newly identified states and transitions, together with their spin-parity assignments and multipolarities, are marked with asterisks.

E_i	J_i^π	E_f	J_f^π	E_γ	Multipolarity	γ Intensity
92.0	$(5/2^+)$	0	$(3/2^+)$	92.0(2)	(M1)	100
836.4	$(7/2^+)$	92.0	$(5/2^+)$	744.4(2)	(M1)	10.3(21)
977.9	$(9/2^+)$	92.0	$(5/2^+)$	885.9(2)	(E2)	31.1(32)
1472.0*	$(11/2^-)^*$	977.9	$(9/2^+)$	494.3(3)*	(E1)*	1.8(4)
		836.4	$(7/2^+)$	635.2(3)*	(M2)*	2.4(6)
		92.0	$(5/2^+)$	1380.3(3)*	(E3)*	5.5(10)
1962.4*		977.9	$(9/2^+)$	984.5(4)*		0.9(2)
1997.3*		1472.0*	$(11/2^-)^*$	525.4(3)*		6.0(12)
2397.1*		977.9	$(9/2^+)$	1419.2(4)*		1.4(4)

4. Angular correlations

The multipolarity of the strongest gamma rays in ^{87}Sr, and consequently the spin assignments of the lowest-lying levels, can be deduced using the gamma angular correlation technique. The symmetric arrangement of the FIPPS detectors allowed them to be grouped at specific angles of 0, 26, 46, 68, and 88 degrees. Figure 4 shows the results of the angular correlation analysis for the pair of transitions with energies 92 and 886 keV (panel (a)), and 92 and 1380 keV (panel (b)) as a function of the detector angle. The blue dashed and red solid curves represent the predictions based on the formalism described in [16], and the fit of the data with the function of the detector angles, respectively. In the case of the 92 and 886 keV pair, an $a2$ coefficient $a2 = -0.13(3)$ is found which agrees with a spin change of $\Delta I = 1$ and $\Delta I = 2$ for the 92 and 886 keV lines. This agrees with the tentative spin-parity assignment of $(9/2^+)$ for the 978 keV, and $(5/2^+)$ for the 92 keV levels. In panel (b) of Fig. 4, the correlation between the 92 and 1380 keV lines is shown. Due to the large experimental error bars, only a qualitative comparison with the theoretical curve can be made. The analysis leads to an $a2$ coefficient of $a2 = -0.17(10)$ which may suggest a $\Delta I = 3$ for the 1380 keV transition, leading to a tentative $(11/2^-)$ spin assignment for the 1472 keV level. The $(11/2^-)$ state has also been identified in the ^{89}Kr isotone at a similar energy (1172 keV) [17], however, no E3 transition to the ground state has been confirmed. In contrast, the corresponding E3 transition from the 2259 keV level has been observed in the ^{87}Kr isotope [18].

For the ^{87,89,91}Rb isotopes with $N \geq 50$, E3 transitions from $(9/2^+)$ to the $(3/2^-)$ ground states have been observed, accompanied by strong competing M2 branches. The B(E3) values of 2.3(5) W.u. [19], 2.4(8) W.u. [20], and 4.1(13) W.u. [21] for ^{87}Rb, ^{89}Rb, and ^{91}Rb, respectively, suggest the single-particle nature of the $(9/2^+)$ levels. Assuming a similar B(E3) transition rate for the $(11/2^-) \rightarrow (5/2^+)$ transition in ^{87}Se, we estimate a half-life of approximately 30 ns for the $(11/2^-)$ state. This half-life is below the detection limit in our experiment, given the low intensity of the E3 branch. We note that, in the current analysis, the tentative spin-parity assignment to the 836 keV level cannot be confirmed, due to strong background contamination.

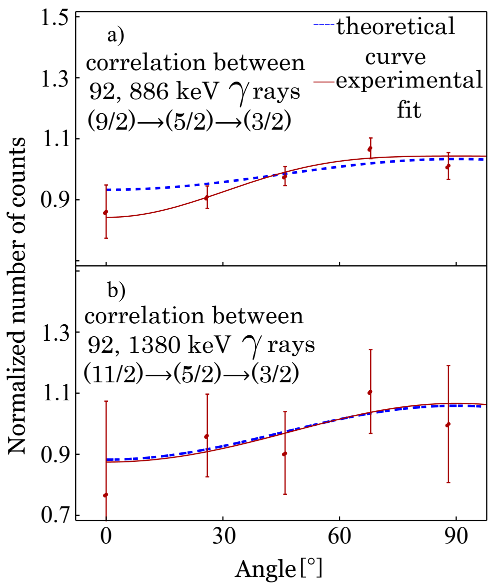

Fig. 4. (Color online) Angular correlations between the 92 keV and 886 keV transitions (panel (a)) and 92–1380 keV (panel (b)). The experimental fits (the blue dashed curves) are compared with the theoretical ones (the red solid ones). The experimental angular correlation $a2$ coefficients of $-0.13(3)$ for the 92–886 keV pair and $-0.17(10)$ for the 92–1380 keV pair were obtained.

5. Conclusions

Prior to our work, only three transitions were known in ^{87}Se isotope (92, 744, and 886 keV). Based on the data from the ^{235}U fission experiment at ILL, it was possible to identify six new transitions in ^{87}Se and extend the level scheme up to 2397 keV excitation energy. Moreover, tentative spin-parity assignments have been confirmed for the 92, 978, and proposed for the 1472 keV levels by employing the gamma angular correlation method. The analysis suggests that the 1472 keV state has spin-parity $(11/2^-)$, thus implying its decay via (E3), (M2), and (E1) competing branches. The presented analysis will be continued for more neutron-rich selenium isotopes strongly produced in neutron-induced ^{235}U fission data.

This work was supported in part by the National Science Centre (NCN), Poland, under research project No. 2020/39/D/ST2/03510, the Italian Istituto Nazionale di Fisica Nucleare, and the Romanian Ministry of Research, Innovation and Digitization Nucleu Project No. PN 23 21 01 02. The authors acknowledge Gilbert Belier for providing the active target material.

REFERENCES

[1] C. Delafosse *et al.*, *Phys. Rev. Lett.* **121**, 192502 (2018).
[2] M. Lettmann *et al.*, *Phys. Rev. C* **96**, 011301(R) (2017).
[3] K. Rezynkina *et al.*, *Phys. Rev. C* **106**, 014320 (2022).
[4] R. Taniuchi *et al.*, *Nature* **569**, 53 (2019).
[5] F. Nowacki *et al.*, *Phys. Rev. Lett.* **117**, 272501 (2016).
[6] K. Heyde, J.L. Wood, *Rev. Mod. Phys.* **83**, 1467 (2011).
[7] T. Materna *et al.*, *Phys. Rev. C* **92**, 034305 (2015).
[8] C. Lizarazo *et al.*, *Phys. Rev. Lett.* **124**, 222501 (2020).
[9] T. Rząca-Urban *et al.*, *Phys. Rev. C* **88**, 034302 (2013).
[10] A. Korgul *et al.*, *Phys. Rev. C* **92**, 054318 (2015).
[11] F. Kandzia *et al.*, *Eur. Phys. J. A* **56**, 207 (2020).
[12] C. Michelagnoli *et al.*, *EPJ Web. Conf.* **193**, 04009 (2018).
[13] J. Dudouet *et al.*, *Phys. Rev. C* **110**, 034304 (2024).
[14] Ł.W. Iskra *et al.*, *Phys. Rev. C* **102**, 054324 (2020).
[15] T. Kibédi *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **589**, 202 (2008).
[16] A.J. Ferguson, «Angular Correlation Methods in Gamma-ray Spectroscopy», *North-Holland Publishing Company*, Amsterdam 1965.
[17] J.K. Hwang *et al.*, *Phys. Rev. C* **78**, 017303 (2008).
[18] S. Raman *et al.*, *Phys. Rev. C* **28**, 602 (1983).
[19] T.D. Johnson, W.D. Kulp, *Nucl. Data Sheets* **129**, 1 (2015).
[20] B. Singh, *Nucl. Data Sheets* **114**, 1 (2013).
[21] C.M. Baglin, *Nucl. Data Sheets* **114**, 1293 (2013).