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Low-spin structure of ^{85}Se and the βn branching of ^{85}As

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Fission fragments from neutron-induced fission of ^{235}U produced at the high-flux reactor of ILL Grenoble were separated with the LOHENGRIN separator to provide a beam of neutron-rich ^{85}As nuclei. The β^- decay of ^{85}As to ^{85}Se was studied using γ-γ and β-γ coincidence techniques. The ^{85}Se has also been studied using the prompt-γ coincidence data from spontaneous fission of ^{248}Cm and ^{252}Cf measured with the Eurogam2 and Gammasphere Ge arrays, respectively. The combination of β-decay and prompt-γ data enabled determination of spins and parities of low-energy excited states in ^{85}Se. There are new arguments supporting the $5/2^-$ assignment for the ground state of ^{85}As.

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The ^{85}As neutron-rich nucleus, with five protons outside the $Z = 28$ closed shell and two neutrons outside the $N = 50$ closed shell, is located in a region of intensive experimental and theoretical studies, which try to explain the structure of nuclei around ^{78}Ni, expected to be a doubly-magic nucleus, a hypothesis still to be verified. The properties of these nuclei and, ultimately, structure of ^{78}Ni, should provide a stringent test of nuclear forces. Another interesting topic in this region is the location of the path of the astrophysical nucleosynthesis via the rapid neutron capture, the *r*-process. The radioactive decay of ^{85}As, which populates excited states in ^{85}Se via β^- decay and excited states in ^{84}Se via β-delayed neutron emission, provides valuable data for such studies at an extreme N/Z ratio.

A significant decrease of the $1/2^+$ excitation energy in $N = 51$ isotones, from ^{91}Zr towards ^{78}Ni is reported (see e.g. Fig. 3 in Ref. [1] and Fig. 1 in [2]). As discussed in Ref. [2] this may lead to the near degeneracy of the $3s_{1/2}$ and the $2d_{5/2}$ neutron orbitals in the vicinity of ^{78}Ni, causing, for instance, a pronounced isomerism in odd-N nuclei there. Therefore, the experimental evidence for this $1/2^+$ excitation in ^{85}Se should be verified.

The spin of the ground state in ^{85}As is still not certain. Its determination could help answer a question about the relative position of the $2p_{3/2}$ and $1f_{5/2}$ proton orbitals [3]. It was first believed that the $\pi p_{3/2}$ subshell is located below the $\pi f_{5/2}$ subshell. Later works located it above [4] though very close to the $\pi f_{5/2}$ subshell [5]. Some recent observations [6] suggest that this may be still an open question. There is also a disagreement on this issue between Ref. [1], which proposes spin $5/2^-$ for the ground state of ^{85}As and the Nuclear Data Sheets compilation [7], which reports spin $(3/2^-)$ for this state.

Different values of β delayed neutron emission probability (P_n) for the β-decay of ^{85}As are reported for this important delayed-neutron emitter. Kratz *et al.* [8] found indirectly a value of $P_n = 23(3)\%$ using measured delayed-neutron yield and measured fission yield. In a 'direct' measurement, where the measured neutron intensity was compared to the number of ^{85}As β^- decays, Omtvedt *et al.* [1, 9] report a value of $P_n = 39(5)\%$. This should resolve the problem, but the strongest γ transition to the ground state in ^{85}Se has been reported with quite different energy in the works by Kratz *et al.* [10] and Omtvedt *et al.*, raising questions about the identification of ^{85}As (see comments in [1]).

To answer these questions we have measured β^- decay of ^{85}As produced in neutron-induced fission of ^{235}U produced at the high-flux reactor of the Institut Laue-Langevin in Grenoble. Fission fragments were analyzed using the Lohengrin separator, which selects ions with a given mass over ionic charge ratio, A/q. In our measurement the spectrometer setting was optimized for mass $A = 85$. Because some amount of ions of another mass, with similar A/q may appear in the focal plane, the measurement was made at three different q values, to identify γ lines from contaminating masses.

The beam of fission fragments separated by Lohengrin was implanted into a movable, metallized tape surrounded by three thin β scintillators and three Ge detectors. Two Ge detectors were of clover type (4 crystals of 30%) and the third was a 60% coaxial detector. The detectors were placed in a close geometry around the implantation point. An ionization chamber was used to identify the energy of the fission products.

To obtain the half-life information on the investigated nuclei an electrostatic chopper was used to pulse the ion beam delivered to the implantation point. At the beginning of each cycle the data acquisition was started and the ion beam was implanted on the tape for 6 seconds. For the next 10 seconds the beam was closed and decay data were collected. Finally, the data collection was stopped for 2 seconds and the tape was moved to remove the remaining activity.

In Fig. 1 we show a singles gamma spectrum gated on time, with time gate from 2.5 s to 8.0 s after the start of the chopper-tape cycle. The contribution from longer-

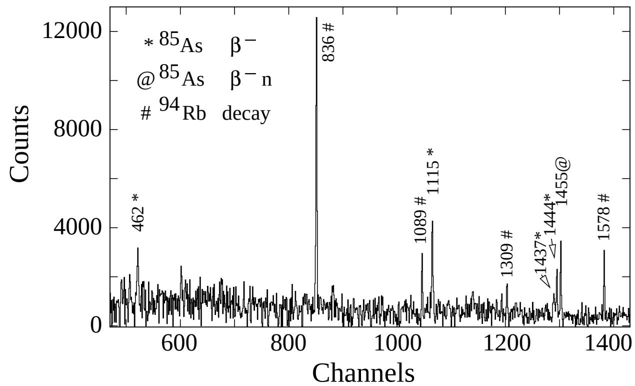

FIG. 1: Background subtracted (see text) γ spectrum gated on times from 2.5 s to 8.0 s after the start of the chopper-tape cycle. Line labels are in keV.

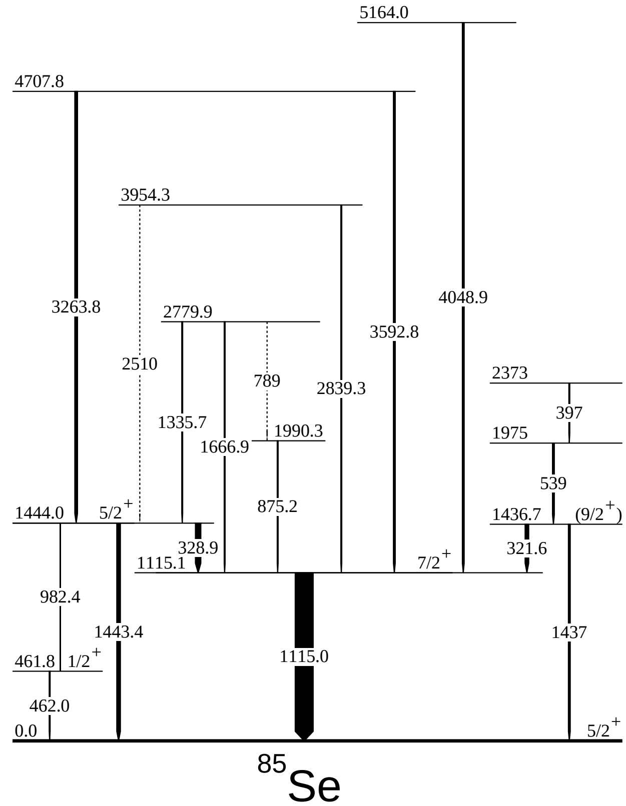

FIG. 2: Partial scheme of excited levels in ^{85}Se, populated in β-decay of ^{85}As, as observed in this work. The levels at 1975- and 2373-keV, and their decays were observed in prompt-gamma fission of ^{248}Cm and ^{252}Cf in this work.

lived decays has been removed by subtracting a 'background' spectrum gated on times from 10.5 s to 16.0 s. The resulting spectrum reveals known lines at 462-, 1115-, 1437- and 1444-keV [1] corresponding to the decay of ^{85}As. There are also lines corresponding to the decay of ^{94}Rb. Both nuclei have similar half-lives, of 2.03 s and 2.69 s, respectively. In the present measurement the Lohengrin separator was optimized for mass $A = 85$ and charge $q = 19$. The A/q ratio for mass $A = 94$ and charge $q = 21$ is nearly the same, causing strong $A = 94$ contaminantion. In the spectrum there is also the 1455-keV line of ^{84}Se but the coincident 667 keV line is not visible so supporting its low intensity (compared to 1455 keV) as reported in [1].

We sorted γ-γ coincidence histograms, with the time window of 600 ns between the consecutive γ signals, to look at time coincidences. These data have allowed to build a scheme of excited levels in the ^{85}Se nucleus, populated in β^- decay of ^{85}As. In Fig. 2 we show a partial scheme of excited levels in ^{85}Se, as observed in the present work. The levels at 1975 and 2373 keV, and their decays were observed in prompt-gamma fission of ^{248}Cm and ^{252}Cf, as described further in the text.

Excited states in ^{85}Se were studied previously in β-decay works [1, 9, 10], in prompt-γ measurements [11, 12] and in transfer reactions [13]. In the latter, the ground state of ^{85}Se was assigned firmly spin and parity $5/2^+$.

The β-decay works reported the 1111.5(5) keV [10] or 1114.9(2) keV [1] γ transition to the ground state in ^{85}Se. A pronounced line at 1115.0(1) keV, observed in our data, clearly confirms the value of Omtvedt [1]. As was the case in Ref. [1] we also do not see other transitions reported in [10], except the 462-keV transition. The 462-keV transition was reported in Ref. [9] and, most importantly, in the transfer-reaction work [13], where the 462-keV level was assigned spin and parity $1/2^+$ (though, there is an unfortunate misprint of $L = 2$ instead of $L = 0$ in Table II of Ref. [13] - see comments in the compilation for mass $A = 85$ [14]). This is the crucial data point in the systematics of $1/2^+$ levels for the $N = 51$ isotones, displayed in Fig. 3 of Refs. [1, 2].

In this work we do observe the 462.0-keV line in time coincidence with the 982.4-keV line, which fits well the summed energy of the 1115.0- and 328.9-keV cascade and the energy of the 1443.4-keV, crossover transition. These results support the presence of the 461.8-keV level in ^{85}Se (unfortunately the rate for the 3263.8-982.4 keV coincidence was below the detection limit). We also confirm, with the coincidence data, the levels at 1115-, 1437-, 1444-, 3954-, 4708- and 5164-keV and introduce a new level at 2780 keV.

Many of the decays of high-energy levels to the ground state, reported in Ref. [1], among them the 1804.8-, 2774.8-, 4125.8-, 4291.2-, 4388.9-, 4653.8- and 4782.1-keV lines reported in [1], are not seen in our work. This may be due to a worse quality of our singles spectra, which are dominated by decays of ^{85}Se to ^{85}Br and contain a strong admixture of mass $A = 94$. On the other hand, our coincidence data are better than that of Ref. [1].

Most of the high-energy levels decay to the 1115.1 keV level. This may be due to both, the spin-selection rules or the similarity of the underlying single-particle structures. Therefore, it is interesting to learn about the structure of the 1115.1-keV level. In Ref. [1] this level has been assigned spin and parity $3/2^+$ or $7/2^+$. The 1115-

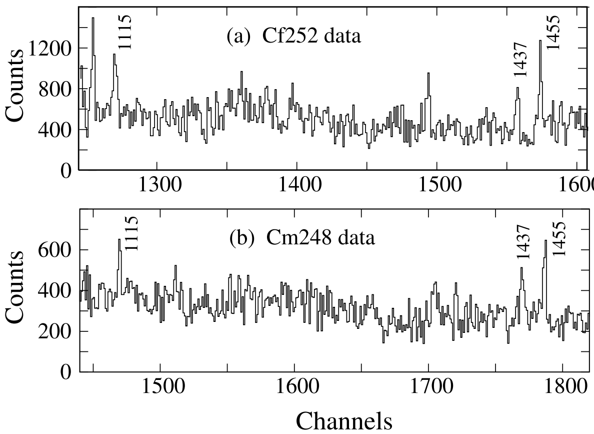

FIG. 3: Prompt-γ spectra gated on the 1437-keV line a) in ^{252}Cf fission data and b) in ^{248}Cm fission data. Lines are labelled in keV.

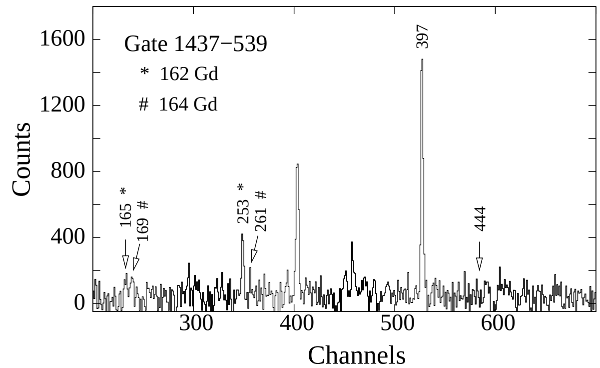

FIG. 4: A spectrum doubly gated on the 1437- and 539-keV lines of ^{85}Se. Lines and gates are labelled in keV.

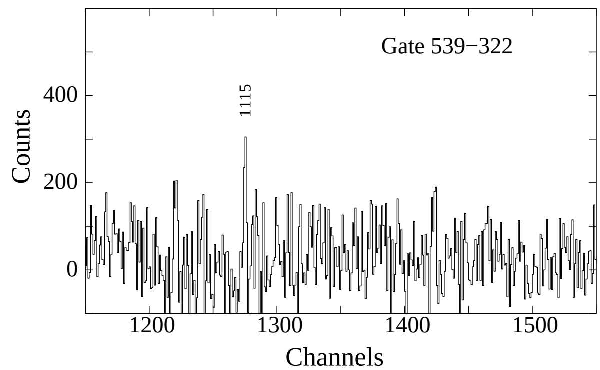

FIG. 5: A spectrum doubly gated on the 539- and 322-keV lines of ^{85}Se. Lines and gates are labelled in keV.

keV level has been also seen in the prompt-γ measurement [11] and a tentative, 1113-keV decay is shown in Ref. [12]. Both prompt-γ measurements [11, 12] report a $9/2^+$ level, which in Ref. [11] has energy 1437 keV and in Ref.[12] 1436 keV. In our work we report a level at 1436.66(16) keV. Its excitation energy is the sum of the energy of the 1115.06(6)-keV level and the 321.60(14)-keV transition. In the work of Omtvedt et al. [1] an energy of 1437.6 keV is quoted (their 1114.9-keV level and 322.0-keV transition sum up to 1436.9 keV). Therefore, the $9/2^+$ level reported in prompt-γ works could correspond to the level 1437 keV, seen in β-decay measurements, though no link between the 1115- and 1437-keV levels has been seen in previous prompt-γ measurements.

In this work we have analyzed prompt-γ decays observed in fission of ^{248}Cm [15] and ^{252}Cf measured with the Eurogam2 and Gammasphere Ge arrays, respectively (for details of these measurements Refs. [15, 16]). We confirm the assignment of the 1115-keV line to a Se isotope. The 1115-keV line is in prompt coincidence with the ground-state cascades of ^{162}Gd and ^{164}Gd, which are the most abundant fission partners for ^{85}Se in the ^{252}Cf fission. Figure 3(a) shows the sum of gates on the cascades in ^{162}Gd and ^{164}Gd. The 1115-keV line is also in prompt coincidence with the ground-state cascades of ^{158}Sm and ^{160}Sm seen in ^{248}Cm fission data, as shown in Fig. 3(b). We note that in both spectra there is also the 1437-keV line of ^{85}Se and the 1455-keV line of ^{84}Se.

In Fig. 4 we show coincidence spectra doubly gated on the 1437-and 539-keV lines, reported in Refs. [11, 12], obtained from the ^{252}Cf fission data. In the spectrum the 397-keV line is seen, together with lines from ^{162}Gd and ^{164}Gd. There is no evidence for the 444-keV line, reported in [12]. It is possible, that in Ref. [12], using heavy-ion-induced fission, high-spin levels were populated stronger. On the other hand, the 1438-keV line seen in the upper panel of Fig. 7 in [12] may be due to coincidences with ^{138}Ba.

Finally, in Fig. 5 we show a coincidence spectrum doubly gated on the 539- and 322-keV lines in ^{252}Cf fission data, where the 1115-keV line is seen, linking the fission and β-decay excitations.

The above observations and the results of Refs. [11, 12] provide a reliable evidence for the 1437-, 1975- and 2373-keV levels in ^{85}Se. Spins and parities were not measured, but as commonly observed, the fission process populates predominantly yrast levels. Therefore, a spin $(9/2^+)$ proposed in Refs. [11, 12] for the 1437-keV level is rather probable. The link between the 1115- and 1437-keV keV levels established in the present work allows to propose spin 7/2 for the 1115-keV level. Positive parity for the 1115-keV level has been assigned in Ref. [1].

One may now conclude that the high-energy levels of ^{85}Se populated in β-decay of ^{85}As, which predominantly decay to the 1115-keV level, have spins not lower than 5/2. This is another argument in favor of the $5/2^-$ spin and parity assignment to the ground state of ^{85}As [1], rather than $(3/2^-)$ [7]. Consequently, we support the proposition of Winger et al. [17] that the $f_{5/2}$ proton orbital is filled before the $p_{3/2}$ proton orbital. We also note that due to the observed branchings, the only acceptable spin and parity assignment for the 1444-keV level is $5/2^+$.

We note that the $I \geq 5/2$ spin assignment to the high-energy levels observed in our work does not, on its own, explain why these levels decay predominantly to the 1115-keV level and not to the ground state. It is then likely that this is due to their structure. The $7/2^+$ assignment to the 1115-keV level suggests the $\nu g_{7/2}$ single-particle nature for this level. Consequently, the high-energy levels decaying to the 1115-keV level should also contain $g_{7/2}$ neutron in their wave functions and a simple picture may explain this. The wave function of β-decaying, $5/2^-$ ground state of ^{85}As contains the $f_{5/2}$ proton and a pair of neutrons, predominantly in the $d_{5/2}$ orbital with a small admixture of the $g_{7/2}$ pair of neutrons. Therefore the dominating channel in the β-decay of ^{85}As, estimated to be about 50% [1], is the direct population of the ground state in ^{85}Se via the $\nu d_{5/2} \rightarrow \pi f_{5/2}$ proton. The decay to high-energy levels may correspond to a decay of the $g_{7/2}$ neutron of the ground state of ^{85}As. This has been considered in Ref. [1] to explain the observation of γ decays of levels in ^{85}Se, which are located well above neutron-binding energy. The preference for γ decays to the $\nu g_{7/2}$ level at 1115-keV supports the $\nu g_{7/2}\pi(f_{5/2})^2$ structure of these levels.

The admixture of the $g_{7/2}$ neutron pair is probably small, coinciding with the small population of the proposed $\nu g_{7/2}\pi(f_{5/2})^2$ three-quasiparticle states (about 5% in total [1]). It is likely that the remaining β-decay strength of ^{85}As corresponds to the population of levels, which decay to ^{84}Se by neutron emission. The $\nu d_{5/2}\pi(f_{5/2})^2$ three-quasiparticle configurations would be favored here, due to a lower centrifugal barrier for neutron emission. However, such levels should have spins 3/2 or higher, preferably 5/2. Therefore their direct decay to the 0^+ ground state of ^{84}Se should be hindered. This is at odds with Ref. [1], which claims that 90% of β-delayed neutrons feeds the ground state of ^{84}Se, but would agree with the earlier work [18] claiming that β-delayed neutrons should predominantly populate excited states in ^{84}Se. In our β-decay data we see a clear coincidence of the 1455-keV line with the 667-keV line, depopulating the 4^+, level at 2122-keV in ^{84}Se (such a coincidence was not reported in Ref. [1]). As the ^{84}Se nucleus was in our work populated by delayed neutrons only, the observation of the 667-keV line indicates spin $I \geq 2$ for excited levels in ^{84}Se populated by delayed neutrons.

Finally, we note that the ratio of γ intensities for the 1115- and 1455-keV lines seen in the singles spectrum of Fig. 1 in our data is $I_\gamma(1115)/I_\gamma(1455) = 1.76(25)$ while it is clearly lower in Ref. [1]. Using the data from Table 1 of Ref. [1] one gets $I_\gamma(1115)/I_\gamma(1455) = 1.07(15)$. This discrepancy may indicate that the βn branching for β-decay of ^{85}As is different from that reported in Ref. [9]. The scale of this difference is difficult to assess. We note that the yield of delayed-neutrons following β-decay of ^{85}As has not been measured directly (in Ref. [9] there is a reference to a 'Private communication', Ref. [13], only). Furthermore, the 50% feeding to the ground state of ^{85}Se, has also been deduced indirectly in Ref.[1], based on the βn branching reported in [9]. Consequently, both values may be inaccurate.

In summary, combining β-decay and prompt-γ measurements we have determined spins and parities of low-lying levels in ^{85}Se. Our results support the $5/2^-$ spin for the ground state of ^{85}As. We also propose that spins of those excited levels in ^{85}Se, which decay by delayed neutrons, should be $I \geq 3/2$. This raises questions about the rate of delayed neutrons populating directly the ground state in ^{84}Se. A dedicated measurement of βn branching, where all three decays, β, γ and neutron are measured in time coincidence, should be performed to resolve questions about the decay of ^{85}As, which is one of the major delayed-neutron emitters in the ^{235}U(n_{th}, f) fission.

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