New excited states in ^{82}Ge: Possible weakening of the $N = 50$ closed shell

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Excited states in ^{82}Ge, populated in the spontaneous fission of ^{248}Cm, have been studied by means of prompt γ spectroscopy, using the EUROGAM2 multidetector array. The known level at 2287 keV is assigned spin and parity 4^+. Two new excited levels in ^{82}Ge, with spins and parities 5, 6^+, are proposed at 2930 and 3228 keV. At least one of the new levels is expected to be be due to neutron excitations across the $N = 50$ shell gap. Its low energy, as compared to heavier $N = 50$ isotones, supports the suggestion of other works that the $N = 50$ shell closure is weakening when approaching the expected double shell closure at ^{78}Ni.

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Neutron-rich nuclei from the region around $^{78}_{28}\mathrm{Ni}_{50}$ have attracted much attention recently [1–8]. An interesting question is whether the $N = 50$ neutron shell still exists at a proton number of $Z = 28$. It is clearly present at $Z = 36$ (Kr) and $Z = 34$ (Se) but there are indications [3] of its weakening when the proton number decreases from $Z = 38$ to $Z = 34$. One would like to know the magnitude of this weakening and whether this process continues further with downward Z number. A strong $N = 50$ shell gap below ^{78}Ni should significantly influence the path of the astrophysical r-process (see, e.g., Fig. 8 in Ref. [9]). The strong $N = 82$ shell closure is clearly manifested as a pronounced peak at mass $A \sim 128$ in the r-process composition [10]. Similarly, one expects a chain of waiting-point nuclei along the $N = 50$ line, producing another peak in the r-process composition at $A \sim 78$. However, evidence for this peak is not as clear as for the one at $A \sim 128$ (see Fig. 2 in Ref. [10]), which justifies questions concerning the $N = 50$ shell gap around ^{78}Ni.

In Ref. [3] the $N = 50$ shell closure was probed by observing neutron excitations across the $N = 50$ gap from the $\nu g_{9/2}$ orbital below $N = 50$ to the $\nu d_{5/2}$ orbital above the gap. The lower the excitation energy, the smaller the shell gap, as observed in Ref. [3] for ^{86}Kr and ^{84}Se. The observation of such neutron excitations may serve as a tool for testing the $N = 50$ shell gap also in lighter $N = 50$ isotones, for instance in ^{82}Ge.

Large arrays of anti-Compton spectrometers (ACS) developed over the past several years now allow studies of medium-spin excitations in exotic neutron-rich nuclei populated in fission, providing high amounts of triple-γ coincidence events. Their resolving power is sufficient to identify radiation from individual nuclei, despite high complexity of prompt γ radiation following the fission process [1–3,5–7,11].

In the present work we report on the study of excited states in ^{82}Ge performed using the EUROGAM2 ACS array [12] to measure prompt γ radiation following spontaneous fission of ^{248}Cm. In the measurement triple- and higher fold γ coincidence events were collected. The coincidence event was accepted by a trigger composed of six unsuppressed γ signals, observed in coincidence. The first of the six signals forming the trigger was used to define the so-called prompt time, when the fission act happened. The large amount of coincidence events (about 10^{10} Compton-suppressed triple coincidences) along with efficient analysis techniques [13,14] provided a resolving power of 10^8 [15] for this experiment, enabling the observation of prompt γ rays from ^{82}Ge, populated rather weakly in the fission of ^{248}Cm. We note that in fission one can observe levels with spins higher than those seen in β-decay measurements.

In the fission of $^{248}_{96}\mathrm{Cm}_{152}$ the Ge nuclei are produced together with Gd nuclei. Because 3.5 neutrons are emitted, on average, following the fission process, the most abundant, secondary (i.e., after neutron emission) fission-fragment partner to ^{82}Ge is ^{162}Gd. Consequently, one expects γ rays from ^{162}Gd to be in prompt coincidence with γ rays of ^{82}Ge.

In the β-decay study of ^{82}Ga [16] eight γ transitions in ^{82}Ge were reported, among them two with energies of 1348.1 and 939.3 keV. The γ coincidence spectrum shown in Fig. 1(a) is double gated on the 1348-keV line of ^{82}Ge and the known 253-keV line of ^{162}Gd. The spectrum was obtained from a three-dimensional histogram, a ppp cube, sorted by triple-γ events consisting of prompt γ rays, registered within a 50-ns time interval, counted from the "prompt" time. In the spectrum one clearly observes a line at 939 keV. Therefore it must be due to prompt γ radiation following the fission process. We thus conclude that the 2287-keV level, observed previously in the β decay of ^{82}Ga, is also populated in the spontaneous fission of ^{248}Cm. This remark is important, because in our measurement we also collected γ rays following β decays of the secondary fission fragments. However, the number of these in the ppp cube, which has a narrow time windows, should be negligible. In the spectrum one can see the 165-, 336-, 411-, and 480-keV lines from the yrast cascade of ^{162}Gd, supporting these conclusions.

We do not see in the spectrum any line corresponding to the 867-keV transition reported in the β-decay measurement [16]. This indicates that the 2215-keV level in ^{82}Ge, populated in the β decay of ^{82}Ga and de-excited by the 867-keV transition, is not populated in the spontaneous fission of ^{248}Cm and that in the ppp cube we do not have many events produced in the β decay of ^{82}Ga. The 2215.4-keV level was tentatively assigned spin 2^+, based on the observation that it has a strong decay branch to the 0^+ ground state. It is then surprising that the 866-keV line is observed in the deep-inelastic reaction [1], as this kind of process populates predominantly yrast states (compare Figs. 6 and 7 in Ref. [1]). We cannot explain this but, as pointed in Ref. [5], the 867-keV line is a complex line belonging also to ^{83}Ga. In Ref. [5] it is also reported that in the β-n decay of ^{83}Ga the 2287-keV level is populated but the 2215-keV level is not. This may indicate different spins for the two levels. Considering the 2^+ spin and parity assignment for the 2215-keV level and the fact that there is no 2287-keV branching to the ground state we conclude that the spin of the 2287-keV level is higher than $2\hbar$.

We do not observe the 1468-keV transition and the corresponding level at 3682 keV in ^{82}Ge, as was tentatively proposed in Ref. [1]. We also do not see the 681- and 1577-keV transitions, depopulating the 2029- and 3607-keV levels, respectively, which were tentatively proposed in ^{82}Ge in Ref. [2]. As remarked in Ref. [1], both lines are also present in ^{87}Kr.

One would expect that both processes, the spontaneous fission studied here and the deep-inelastic reaction reported in Refs. [1,2], should similarly populate yrast and near-yrast states. In previous paragraphs we have shown that the 939-keV transition is clearly in coincidence with the 1348-keV line and is of prompt character (populated in fission, rather than in β decay). Although we are convinced of the validity of our arguments, we cannot explain why the 939-keV line is not seen in Refs. [1,2].

In Fig. 1(b) we show a part of the spectrum doubly gated on the 253- and 336-keV lines in ^{162}Gd, where one observes the 939- and the 1348-keV lines. The contaminating lines are due to impurities in the gates as almost all low-energy lines in fission spectra are multiplets. We have checked, though, that none of the contaminating lines is in coincidence with the 1348-keV line. From Fig. 1(b) one obtains the relative population of both lines, yielding $I_\gamma(1348) = 100(10)$ and $I_\gamma(939) = 80(8)$.

The 939-keV line observed in Fig. 1(a) is a doublet. In the spectrum doubly gated on the 1348- and 939-keV lines, shown in Fig. 1(c), there is a clear line at 939 keV. In Fig. 1(d) we show a spectrum doubly gated on the 939-keV line. In the spectrum one observes the 1348-keV line.

This picture and Fig. 1(c) indicate that the 939-keV line is self-gating and that both components are in cascade with the 1348-keV transition, defining a new excited level in ^{82}Ge at 3228 keV. Seen in Figs. 1(b) and 1(c) are also lines belonging to the complementary ^{162}Gd fission fragment. This indicates that both the 2287- and the 3228-keV levels are

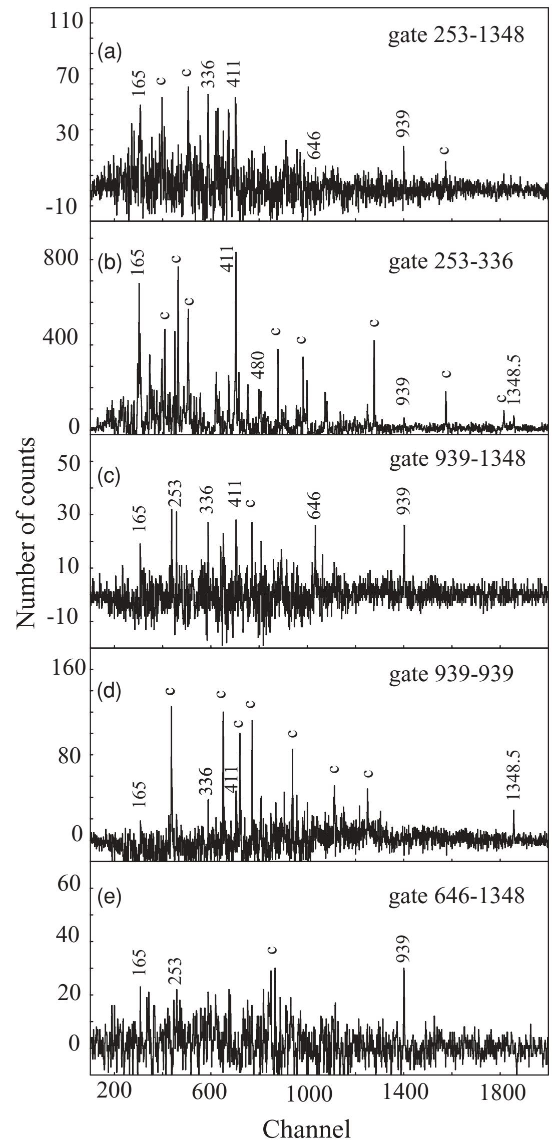

FIG. 1. Coincidence spectra gated on lines in ^{82}Ge and ^{162}Gd isotopes. Energies of lines belonging to ^{82}Ge and ^{162}Gd are given in keV. The label "c" denotes a contamination line.

populated in the fission of ^{248}Cm and de-excite by prompt γ transitions.

In Fig. 1(c) there is also a new line at 646 keV. A spectrum double gated on the 646- and the 1348-keV lines is shown in Fig. 1(e). The spectrum shows the 939- and the 165-keV lines of ^{162}Gd. We note that the intensity of the 939-keV line is higher than the intensity of the 165-keV line (after correcting for detector efficiency), which shows that the 646-keV line corresponds to a γ transition in ^{82}Ge rather than in ^{162}Gd. Since the 646-keV line is not seen in Fig. 1(d) we conclude that this line feeds the 2287-keV level, defining a new level in ^{82}Ge at 2930 keV.

These results are summarized in Fig. 2, where a partial decay scheme of ^{82}Ge is shown, as observed in the fission of ^{248}Cm. In the scheme we show more precise transitions energies, obtained from fitting Gaussian shapes to lines seen

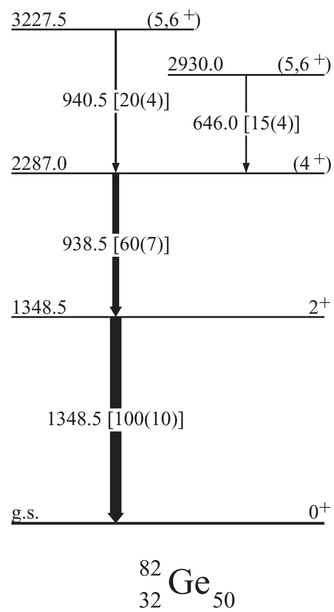

FIG. 2. Partial level scheme of ^{82}Ge as obtained in this work. Energies of levels and transitions are in keV. Relative γ intensities, as observed in the fission of ^{248}Cm, are given in square brackets.

in the coincidence spectra of Fig. 1, as well as their relative γ intensities. In particular we resolved the 939-keV line by fitting two Gaussian shapes. The 940.5-keV component was placed in a cascade above the more intense 938.5-keV component.

Experimental determination of spins and parities in ^{82}Ge was limited in the present work owing to a low population of ^{82}Ge and, consequently, low count rates. The only result is the angular correlation for the 1348–939 keV cascade. The correlation, obtained by using the techniques described in Refs. [13,14], is shown in Fig. 3. In the figure we have drawn the theoretically expected angular correlations between two pure, stretched quadrupole transitions in the $4^+ \rightarrow 2^+ \rightarrow 0^+$ cascade (QQ) and a pure, stretched quadrupole-dipole, $3^+ \rightarrow 2^+ \rightarrow 0^+$ cascade (QD), calculated for the present experimental setup [14]. It is seen that the experimental points for the 1348–939 keV cascade, although with large error bars, fit the QQ case better than the QD case. The quality of the data is too poor to draw definite conclusions. One may only say that the angular correlations suggest 4^+ spin and parity for the 2287-keV level. We note that because of the doublet character of the 939-keV line the data are consistent with the quadrupole character for both components of the 939-keV line. These suggestions are further supported by the well-established fact that spontaneous fission (here of ^{248}Cm) populates, predominantly, yrast states [17], as observed in dozens of yrast cascades in even-even nuclei studied in prompt γ experiments. On balance, we assign spin and parity 4^+ to the 2287.0-keV level. Such assignment was also proposed in Ref. [8], based on shell-model calculations.

The "yrast population" argument suggests that spins of the newly proposed levels in ^{82}Ge are higher than the spin of the 2287-keV level. This is supported by their decay pattern. The two levels do not decay to the 2^+ level at 1348 keV despite the high energy of the eventual crossover transitions. We tentatively assign spin 5 or 6 to both levels. Positive parity is associated with the $I = 6$ solution on the grounds that the 646.0- and 940.5-keV transitions, which are of prompt character, could not have an $M2$ multipolarity, considering their energies.

The decay scheme of ^{82}Ge is similar to decay schemes of the heavier $N = 50$ isotones. Therefore, it is of interest to look at the systematic behavior of excitation energies in the $N = 50$ isotones. In Fig. 4 the yrast excitations in ^{82}Ge, ^{84}Se, ^{86}Kr, ^{88}Kr, and ^{90}Zr are shown. The data for the $N = 50$ nuclei are from this work and Refs. [1,16,18,19]. Lines drawn in Fig. 4 are to guide the eye. In Fig. 4 we also show (as triangles) the 2^+ and 4^+ excitation energies in the $N = 82$

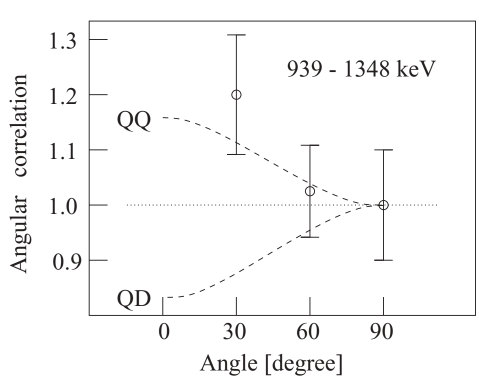

FIG. 3. γ-γ angular correlations for the 939–1348 keV cascade in ^{82}Ge, as measured in this work. Dashed lines represent theoretical angular correlations for the quadrupole-quadrupole (QQ) and quadrupole-dipole (QD) cascades, calculated for the present experiment [12].

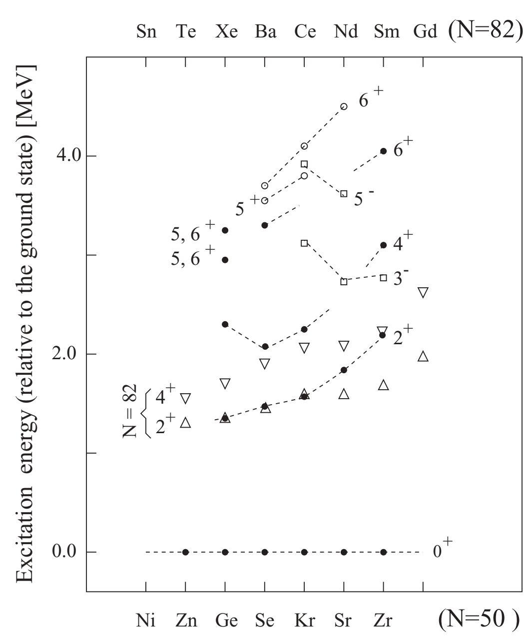

FIG. 4. Excitation energies in $N = 50$, neutron-rich isotones (circles and squares) and in $N = 82$ isotones (triangles). See text for further explanation.

isotones indicated on the upper scale. These data are taken from Ref. [19].

Excitation energies of the 2^+ levels in the $N = 50$ isotones vary smoothly with proton number, showing a remarkable similarity with 2^+ excitations observed in the $N = 82$ isotones. Analogous similarities are observed also for the 4^+ excitations in both isotonic chains, though the newly proposed 4^+ level in ^{82}Ge deviates slightly from the smooth trend. Some irregularities are expected when a subshell is filled. This is probably the cause of a deviation observed in the $N = 82$, 2^+ and 4^+ energies between Ce and Nd, where the $\pi g_{7/2}$ subshell is filled. An even stronger deviation is observed for 4^+ energies in the $N = 50$ isotones at ^{88}Sr, where both close-lying $\pi f_{5/2}$ and $\pi p_{3/2}$ orbitals are filled. Here the 4^+ level is expected around 4 MeV (although this is not shown in Fig. 4 because it is not yet clear which of the candidate levels corresponds to the first 4^+ excitation in this nucleus). By analogy, the kink at ^{82}Ge might correspond to the $\pi p_{3/2}$ subshell closure, implying that the $\pi p_{3/2}$ subshell is located below the $\pi f_{5/2}$ subshell. The order of these two subshells is an interesting problem [4]. In the past it was assumed that the $\pi p_{3/2}$ subshell is located below the $\pi f_{5/2}$ subshell, but further works located it above [20] though very close [1] to the $\pi f_{5/2}$ subshell. The present observation suggests that this may still be an open question.

We note that the 3^- levels, which result from the proton excitation from the $p_{3/2}$ orbital to the $g_{9/2}$ [21], are expected to increase in energy toward ^{78}Ni. The same applies to the 5^- levels, expected in ^{82}Ge at about 5 MeV [3]. This is consistent with the proposition that the 2287-keV level in ^{82}Ge has spin and parity 4^+.

The two new levels in ^{82}Ge at 2930 and 3228 keV fit well the trend of 5^+ and 6^+ excitations in the $N = 50$ isotones. The first 6^+ level in ^{84}Se is due to proton excitation whereas the 5^+ and the second 6^+ levels in ^{84}Se and ^{86}Kr, shown as open circles in Fig. 4, are due to neutron excitations across the $N = 50$ shell gap, as suggested in Ref. [3]. Therefore, at least one of the two new levels in ^{82}Ge is expected to be due to the neutron excitation. As seen in Fig. 4 this possible neutron excitation in ^{82}Ge has lower energy than in ^{84}Se. This observation further supports the proposition of Ref. [3] that the $N = 50$ spherical shell gap weakens as the proton number decreases toward $Z = 28$.

In summary, two new excited levels in ^{82}Ge have been observed in a measurement of prompt γ rays following the spontaneous fission of ^{248}Cm. Their probable spin and parity assignments are 5^+ or 6^+. The systematics of 5^+ and 6^+ excitations in the $N = 50$ isotones suggests that at least one of these levels is due to neutron excitation across the $N = 50$ shell gap. As the excitation energies of both new levels in ^{82}Ge are lower than 5^+ and 6^+ neutron excitation energies in ^{84}Se, we conclude that the present data provide further evidence for weakening of the $N = 50$ closed shell, when approaching the ^{78}Ni nucleus.

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