Identification of ^{88}Se and new levels in ^{84,86}Se

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From the analysis of γ-γ-γ coincidence data taken with Gammasphere of the prompt γ rays in the spontaneous fission of ^{252}Cf, the $2^+ \rightarrow 0^+$ transition in ^{88}Se was identified for the first time. Also, the $4^+ \rightarrow 2^+$ and $6^+ \rightarrow 4^+$ transitions in ^{86}Se were identified along with four new states above 4^+ in ^{84}Se. Surprisingly, the 2^+ energy rises in ^{88}Se compared to ^{86}Se. This increase in energy could arise from the interaction of a low-lying excited 0^+ state with different deformation and the 0^+ ground state to depress the ground-state energy.

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The levels of $N = 50$, 52, and 54 selenium nuclei provide interesting tests of the spherical shell model around the $N = 50$ closed shell. The 0^+, 2^+, 4^+, and one higher level were previously known below 3371.8 keV in ^{84}Se from the β decay of ^{84}As [1], as were the 0^+ and 2^+ levels in ^{86}Se [2]. The ground state of ^{88}Se decays to ^{88}Br with a half-life of 1.52 s [2]. The systematics of the previously known 2^+ and 4^+ states in the Se isotopes [2] are shown in Fig. 1. One can clearly see in Fig. 1 the effect of $N = 50$ shell closure, where the 2^+ and 4^+ energies rise dramatically. The energies of the $4^+ \rightarrow 2^+$ and $2^+ \rightarrow 0^+$ sequence decrease in ^{86}Se. Therefore, it is interesting to extend the systematics to more neutron-rich nuclei and to higher spin states in the known nuclei.

With our γ-γ-γ coincidence data in the spontaneous fission of ^{252}Cf obtained with Gammasphere, identification of the levels in ^{88}Se is possible along with extension of the levels in ^{84}Se and ^{86}Se above 4^+. Since this work was completed [3], the levels of ^{84}Se have been studied by deep-inelastic processes with quite similar overall results [4].

Our Gammasphere γ-γ-γ coincidence study of the spontaneous fission of ^{252}Cf with 102 detectors and a 62-μCi ^{252}Cf source yielded 5.7×10^{11} triples and higher fold coincidences. A coincidence resolving time of about 200 ns was used. Further experimental details are found in Luo *et al*. [5]. With the new 2000 data, we were able to see transitions that were not clearly discernible with our earlier Gammasphere data.

The previously established 1455.1-keV $2^+ \rightarrow 0^+$ and 667.1-keV $4^+ \rightarrow 2^+$ transitions in ^{84}Se [1] and the 704.1-keV $2^+ \rightarrow 0^+$ transition in ^{86}Se [2], along with the relative spontaneous fission yields of ^{84,86,88}Se [6], make possible the identification of new transitions in these selenium isotopes. The high 2^+ energy of 1455.1 keV in $N = 50$ ^{84}Se also provides a gating transition that is relatively clean.

When we gate on known transitions in ^{84}Se or in ^{86}Se, the yields are such that we should see transitions in their fission partners ^{160,162,164}Gd. Identification of the ^{162,164}Gd levels is reported elsewhere [7,8]. The relative yields of ^{162,164}Gd should change when gating on ^{84}Se and ^{86}Se transitions. The yields are typically maximum for the 4*n* channel [9]. This was found to be the case here also. From the measured intensities of the ^{84}Se and ^{86}Se $2^+ \rightarrow 0^+$ transitions when double gating on the 164.8-keV and 253.6-keV transitions in ^{162}Gd, we find that the ^{86}Se yield is six times that of ^{84}Se. That is, the 4*n* channel is six times larger than the 6*n* channel, in agreement with the expected trends.

Figure 2 shows a double gate on the previously established 1455.1-keV $2^+ \rightarrow 0^+$ and 667.1-keV $4^+ \rightarrow 2^+$ transitions in ^{84}Se. The 1249.6-keV transition in Fig. 1 is known from β decay to feed the 4^+ level [2]. The new strong 1415- and 1580-keV transitions and the weak 1360-keV one are assigned in this work to ^{84}Se. The 1249.6-, 1415-, and 1580-keV transitions are also seen in the deep inelastic work [3], but the 1360-keV transition is not.

In two spectra from double gates on the ^{84}Se transition at 1415 keV with the 164.8-keV peak, which could be the $4^+ \rightarrow 2^+$ transition in ^{162}Gd in Fig. 3(a), and with the much stronger yield 4*n* partner ^{164}Gd 168.6-keV $4^+ \rightarrow 2^+$ transition [7] in Fig. 3(b), one sees that the 164.8-keV peak is essentially a real transition in ^{84}Se with little if any contribution from ^{162}Gd because the 1455.1-keV transition is much stronger in Fig. 3(a) than in Fig. 3(b), whereas it should be significantly smaller if it were only from the 6*n* channel. A 165-keV transition with the same placement is seen in the deep inelastic work [2].

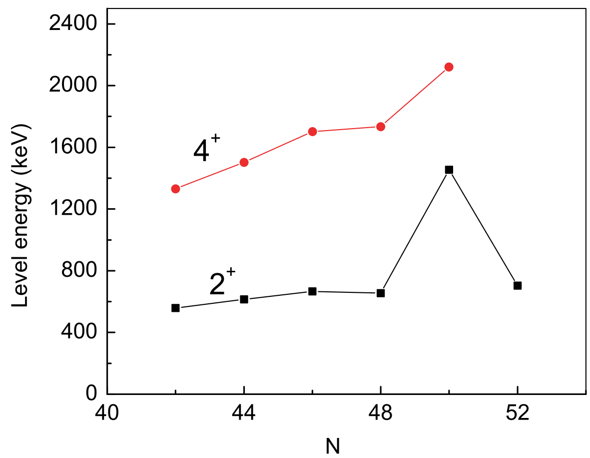

FIG. 1. (Color online) Systematics of the 2^+ and 4^+ states in the Se isotopes.

As further evidence for the 164.8-keV transition in ^{84}Se, a double gate on the 164.8-keV transition (with gate width of ≈2 keV) and the 1455.1-keV $2^+ \rightarrow 0^+$ transition in ^{84}Se clearly shows the newly identified 1415-keV transition and very little if any of the new 1580-keV $6^+ \rightarrow 4^+$ transition in ^{84}Se. In a double gate on the 4*n* channel 168.6-keV ^{164}Gd $4^+ \rightarrow 2^+$ transition (again with gate width of a single channel) and the 1455.1-keV $2^+ \rightarrow 0^+$ transition in ^{84}Se, one sees both the 1415- and 1580-keV ^{84}Se transitions with essentially equal intensities to those in Fig. 1, but with about one-sixth the intensity of the 1415-keV transition in the (164.8–1455.1)-keV double gate, not six times more as expected from the 4*n*, 6*n* channel yields [6]. Thus, the newly assigned 165-keV transition clearly feeds the 1415-keV transition in ^{84}Se.

A γ transition at 703.5 keV is seen weakly in our spectra and is assigned to ^{84}Se. In a double gate on the new 703.5-keV and known 667.1-keV transitions, one sees the newly assigned 1415- and 1580-keV transitions, along with the known 1455.1-keV one. Thus the 703.5-keV transition is placed above the 1580-keV one. Double gates on the (667.1–1415)-keV transitions and the (703.5–1415)-keV transitions confirm the 703.5- and 1415-keV transitions and their placements.

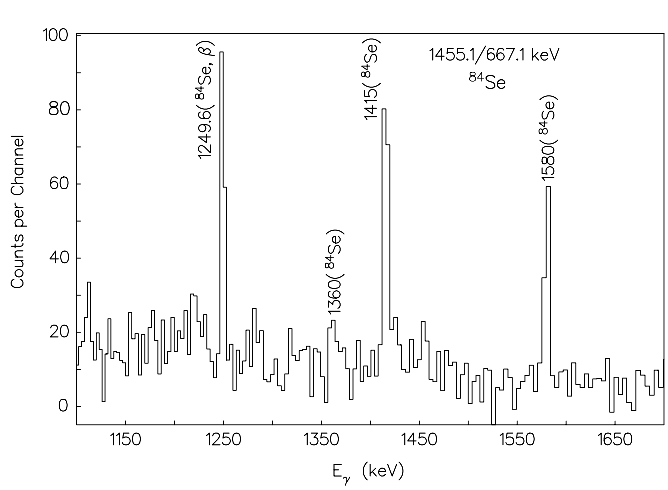

FIG. 2. Double gate on 1455.1- and 667.1-keV transitions in ^{84}Se.

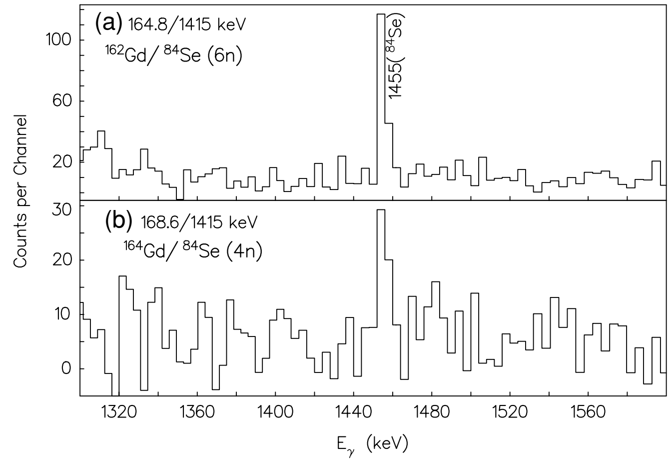

FIG. 3. High-energy region of double gates (a) on ^{84}Se + (^{162}Gd) 164.8- and ^{84}Se 1415-keV transitions and (b) on ^{164}Gd 168.6- and ^{84}Se 1415-keV transitions.

In a double gate on the 164.8-keV $4^+ \rightarrow 2^+$ and the 253.6-keV $6^+ \rightarrow 4^+$ transitions in ^{162}Gd, as seen in Fig. 4(a), one can see the known 704.1-keV and presently assigned 863.8- and 505.5-keV transitions in the 4*n* channel ^{86}Se, and also the 667.1-keV transition in the 6*n* channel ^{84}Se. The 703.5-keV transition in ^{84}Se has one-eighth the intensity of the 667.1-keV one and so contributes very little to the 704.1-keV transition in ^{86}Se. In a double gate on background at 160 keV and the 253.6-keV $6^+ \rightarrow 4^+$ transition in ^{162}Gd, the transitions in ^{162}Gd and ^{84,86}Se disappear. The placements of the new 863.8- and 505.5-keV transitions in ^{86}Se are confirmed by their intensities in various different double gates and are assigned as the $4^+ \rightarrow 2^+$ and $6^+ \rightarrow 4^+$ transitions. For example, in a double gate on the 164.8-keV $4^+ \rightarrow 2^+$ transition in ^{162}Gd and the newly assigned 863.8-keV $4^+ \rightarrow 2^+$ transition in ^{86}Se, shown in Fig. 4(b), we see the expected transitions in ^{162}Gd and the new 505.5-keV and known 704.1-keV transitions in ^{86}Se. In a (505.5–863.8)-keV double gate, we see the 704.1-keV ^{86}Se line and the ^{162}Gd ones, both of which disappear in a background double gate.

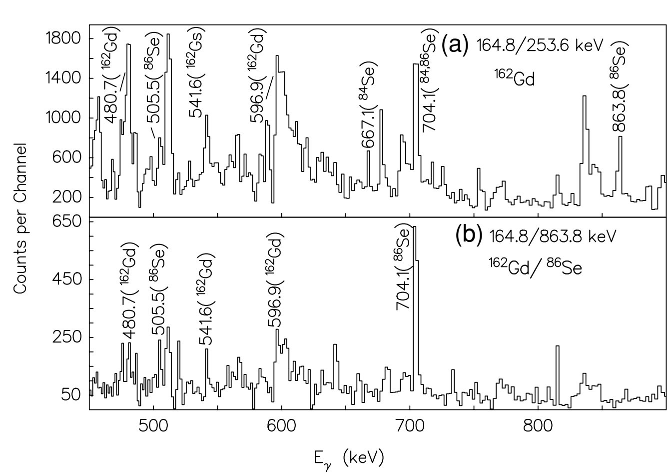

FIG. 4. Double gates (a) on 164.8- and 253.6-keV transitions in ^{162}Gd and (b) on ^{162}Gd 164.8- and ^{86}Se 863.8-keV transitions.

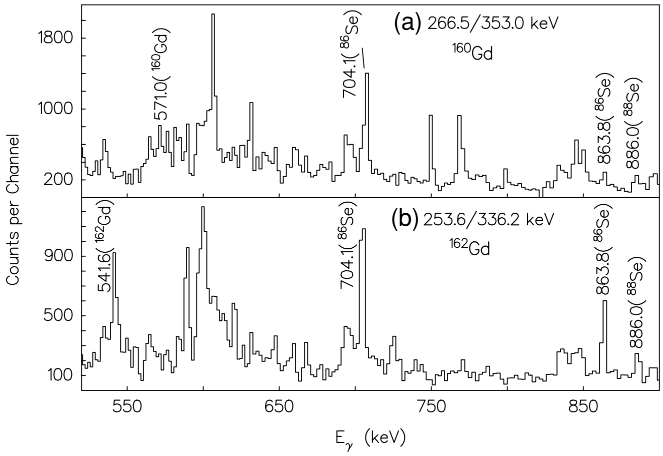

FIG. 5. Double gates (a) on 266.5- and 353.0-keV transitions in ^{160}Gd and (b) on 253.6- and 336.2-keV transitions in ^{162}Gd.

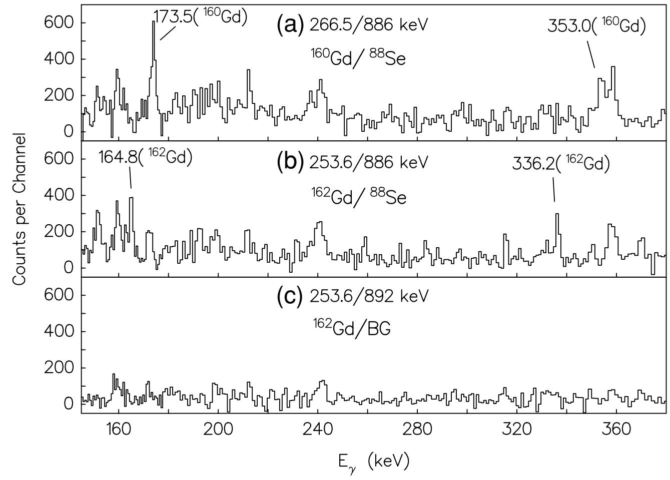

FIG. 6. Double gates (a) on 266.5-keV (^{160}Gd) and 886-keV (^{88}Se) transitions, (b) on 253.6-keV (^{162}Gd) and 886-keV (^{88}Se) transitions, and (c) on 253.6-keV (^{162}Gd) transition and background. Narrow gates were set on the low-energy transition.

In a double gate on the previously known 266.5-, 253.6-keV $6^+ \rightarrow 4^+$ transitions and 353.0-, 336.2-keV $8^+ \rightarrow 6^+$ transitions in ^{160,162}Gd, respectively, one sees peaks at 704.1 and 863.8 keV as shown in Figs. 5(a) and 5(b). These are the transitions in the partner isotope ^{86}Se (see Fig. 7). We also observed a new 886-keV transition in the partner isotope ^{88}Se. Double gates on the 886-keV transition in ^{88}Se and the 266.5-keV transition in the $4n$ partner ^{160}Gd, and on 886- and 253.6-keV transitions in the $2n$ partner ^{162}Gd as seen in Figs. 6(a) and 6(b) show their other respective ^{160,162}Gd transitions, all of which disappear in the background gate of Fig. 6(c). These and similar other double gates clearly establish the 886.0-keV transition in ^{88}Se.

These data lead to the level schemes of ^{84,86,88}Se shown in Fig. 7. The new 1360-, 1415-, and 1580-keV transitions feed the 4^+ level and the new 703.5- and 165-keV transitions feed and depopulate the (6^+) level in ^{84}Se. The new $4^+ \rightarrow 2^+$ 863.8-keV and $6^+ \rightarrow 4^+$ 505.5-keV transitions in ^{86}Se were identified. The 2^+ level of ^{88}Se was also identified. The $N = 50$ ^{86}Kr level scheme, from the work of Winter *et al.* [10], is compared to the new level scheme for ^{84}Se in Fig. 7. There is a strong similarity of these two nuclei. Based on this comparison, 6^+ is assigned to the level depopulated by the 1580-keV transition in ^{84}Se.

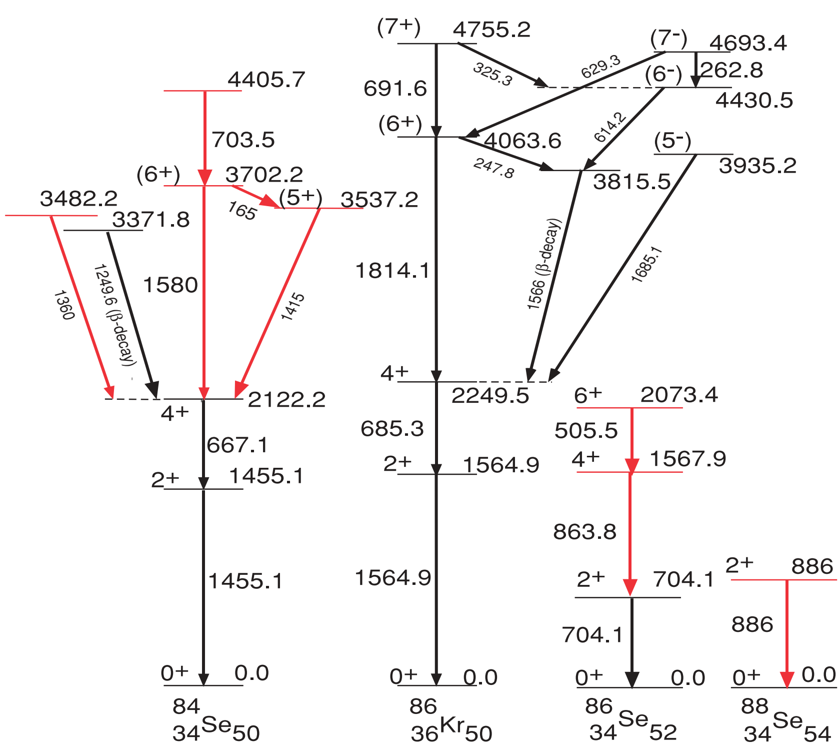

FIG. 7. (Color online) Level schemes of ^{84,86,88}Se and ^{86}Kr [10]. The 3482.2-, 3537.2-, 3702.2-, and 4405.7-keV states in ^{86}Se, the 1567.9- and 2073.4-keV states in ^{86}Se, and the 886-keV state in ^{88}Se are identified in the present work.

There are marked differences in the level structures of ^{84}Se with a spherical closed neutron shell at $N = 50$ and ^{86}Se with $N = 52$. The ^{84,86}Se level schemes are very similar to those of $N = 50, 52$ ^{86,88}Kr. The levels of ^{88}Kr and ^{86}Se both have lower 2^+ energy and a smaller energy for the $4^+ \to 2^+$ transition. It is surprising that the $2^+ \to 0^+$ transition in ^{88}Se increases in energy compared to ^{86}Se. The 707.5-keV $2^+ \to 0^+$ and 799.2-keV $4^+ \to 2^+$ transitions in $N = 54$ ^{90}Kr are lower than those in ^{88}Kr (774.7 and 868.8 keV, respectively).

In ^{74,76}Kr, the $2^+ \to 0^+$ transitions were found to be much larger than would have been expected from an extrapolation of the moments of inertia of higher energy yrast levels, which have superdeformation [11]. The $2^+ \to 0^+$ energies are characteristic of near-spherical ground states. However, lifetime measurements indicate large deformation for the yrast levels in ^{74,76}Kr. The 0^+ energies were found to be pushed down by 256 and 187 keV from their unperturbed energies by the interaction of a low-lying near-spherical 0^+ state with the deformed ground state to make the $2^+ \to 0^+$ energy characteristic of a spherical shape [11]. The unexpected increase in the $2^+ \to 0^+$ energy in ^{88}Se compared to $N =$ ^{86}Se could likewise arise from the interaction of a low-lying 0^+ state with different deformation and the ground band to push down the ground-state energy. Unfortunately, not enough is known about the higher yrast levels to determine the relative deformations here. Probably, the ground state is near spherical in ^{88}Se since it is only four neutrons away from the $N = 50$ closed shell.

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