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

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From the analysis of $\gamma$- $\gamma$ $\gamma$ coincidence data taken with Gammasphere of the prompt $\gamma$ 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 $\beta$ 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 $\gamma$-$\gamma$-$\gamma$ 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 $\gamma$-$\gamma$-$\gamma$ coincidence study of the spontaneous fission of $^{252}$Cf with 102 detectors and a 62-$\mu$Ci $^{252}$Cf source yielded $5.7 \times 10^{11}$ 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 $^{88}$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 $4n$ 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 $4n$ channel is six times larger than the $6n$ 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 $\beta$ 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 $4n$ 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 $6n$ channel. A $165$-keV transition with the same placement is seen in the deep inelastic work [2].
As further evidence for the 164.8-keV transition in $^{84}\text{Se}$, a double gate on the 164.8-keV transition (with gate width of $\approx 2$ keV) and the 1455.1-keV $2^+ \rightarrow 0^+$ transition in $^{82}\text{Se}$ clearly shows the newly identified 1415-keV transition and very little if any of the new 1580-keV $6^+ \rightarrow 4^+$ transition in $^{84}\text{Se}$. In a double gate on the $4\pi$ channel 168.6-keV $^{164}\text{Gd}$ $4^+ \rightarrow 2^+$ transition (again with gate width of a single channel) and the 1455.1-keV $2^+ \rightarrow 0^+$ transition in $^{84}\text{Se}$, one sees both the 1415- and 1580-keV $^{84}\text{Se}$ 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 $4\pi$, $6\pi$ channel yields [6]. Thus, the newly assigned 165-keV transition clearly feeds the 1415-keV transition in $^{84}\text{Se}$.

A $\gamma$ transition at 703.5 keV is seen weakly in our spectra and is assigned to $^{84}\text{Se}$. 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.

In a double gate on the 164.8-keV $4^+ \rightarrow 2^+$ and the 253.6-keV $6^+ \rightarrow 4^+$ transitions in $^{162}\text{Gd}$, 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 $4\pi$ channel $^{86}\text{Se}$, and also the 667.1-keV transition in the $6\pi$ channel $^{84}\text{Se}$. The 703.5-keV transition in $^{84}\text{Se}$ has one-eighth the intensity of the 667.1-keV one and so contributes very little to the 704.1-keV transition in $^{86}\text{Se}$. In a double gate on background at 160 keV and the 253.6-keV $6^+ \rightarrow 4^+$ transition in $^{162}\text{Gd}$, the transitions in $^{162}\text{Gd}$ and $^{84,86}\text{Se}$ disappear. The placements of the new 863.8- and 505.5-keV transitions in $^{86}\text{Se}$ 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 $^{162}\text{Gd}$ and the newly assigned 863.8-keV $4^+ \rightarrow 2^+$ transition in $^{86}\text{Se}$, shown in Fig. 4(b), we see the expected transitions in $^{162}\text{Gd}$ and the new 505.5-keV and known 704.1-keV transitions in $^{86}\text{Se}$. In a $(505.5–863.8)$-keV double gate, we see the 704.1-keV $^{86}\text{Se}$ line and the $^{162}\text{Gd}$ ones, both of which disappear in a background double gate.

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

FIG. 4. Double gates (a) on 164.8- and 253.6-keV transitions in $^{162}\text{Gd}$ and (b) on $^{162}\text{Gd}$ 164.8- and $^{86}\text{Se}$ 863.8-keV transitions.
In a double gate on the previously known 266.5-, 253.6-keV \(6^+ \rightarrow 4^+\) transitions and 353.0-keV \(8^+ \rightarrow 6^+\) transitions in \(^{160}\text{Gd}\) and \(^{162}\text{Gd}\), 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 \(^{86}\text{Se}\) (see Fig. 7). We also observed a new 886-keV transition in the partner isotope \(^{88}\text{Se}\). Double gates on the 886-keV transition in \(^{88}\text{Se}\) and the 266.5-keV transition in the \(4n\) partner \(^{160}\text{Gd}\), and on 886- and 253.6-keV transitions in the \(2n\) partner \(^{162}\text{Gd}\) as seen in Figs. 6(a) and 6(b) show their other respective \(^{160}\text{Gd}\) 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 \(^{88}\text{Se}\).

These data lead to the level schemes of \(^{84,86,88}\text{Se}\) 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 \(^{84}\text{Se}\). The new \(4^+ \rightarrow 2^+\) 863.8-keV and \(6^+ \rightarrow 4^+\) 505.5-keV transitions in \(^{86}\text{Se}\) were identified. The \(2^+\) level of \(^{88}\text{Se}\) was also identified. The \(N = 50\) \(^{86}\text{Kr}\) level scheme, from the work of Winter \textit{et al.} [10], is compared to the new level scheme for \(^{84}\text{Se}\) 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 \(^{84}\text{Se}\).

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

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

![FIG. 7. (Color online) Level schemes of \(^{84,86,88}\text{Se}\) and \(^{86}\text{Kr}\) [10]. The 3482.2-, 3537.2-, 3702.2-, and 4405.7-keV states in \(^{86}\text{Se}\), the 1567.9- and 2073.4-keV states in \(^{88}\text{Se}\), and the 886-keV state in \(^{88}\text{Se}\) are identified in the present work.](image)
There are marked differences in the level structures of $^{84}\text{Se}$ with a spherical closed neutron shell at $N = 50$ and $^{86}\text{Se}$ with $N = 52$. The $^{84,86}\text{Se}$ level schemes are very similar to those of $N = 50, 52$ $^{86}\text{Kr}$. The levels of $^{88}\text{Kr}$ and $^{86}\text{Se}$ both have lower $2^+$ energy and a smaller energy for the $4^+ \rightarrow 2^+$ transition. It is surprising that the $2^+ \rightarrow 0^+$ transition in $^{88}\text{Se}$ increases in energy compared to $^{86}\text{Se}$. The 707.5-keV $2^+ \rightarrow 0^+$ and 799.2-keV $4^+ \rightarrow 2^+$ transitions in $N = 54$ $^{90}\text{Kr}$ are lower than those in $^{88}\text{Kr}$ (774.7 and 868.8 keV, respectively).

In $^{74,76}\text{Kr}$, the $2^+ \rightarrow 0^+$ 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 $2^+ \rightarrow 0^+$ energies are characteristic of near-spherical ground states. However, lifetime measurements indicate large deformation for the yrast levels in $^{74,76}\text{Kr}$. 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 $2^+ \rightarrow 0^+$ energy characteristic of a spherical shape [11]. The unexpected increase in the $2^+ \rightarrow 0^+$ energy in $^{88}\text{Se}$ compared to $N = ^{86}\text{Se}$ 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 $^{88}\text{Se}$ since it is only four neutrons away from the $N = 50$ closed shell.

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