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First observation of high-spin states in ^{83}Se

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The level structure of ^{83}Se was studied via prompt γ-ray spectroscopy of fragments following the fission of the compound nucleus ^{226}Th formed in the ^{18}O (91 MeV) + ^{208}Pb fusion-evaporation reaction. The first four high-spin states above the 9/2$^+$ ground state were established. The coupling of the neutron hole in the $g_{9/2}$ orbital to the yrast states in the ^{84}Se core can account for these states. The experimentally observed high-spin states are compared with predictions of shell-model calculations.

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I. INTRODUCTION

The high-spin level structure of the ^{83}Se isotope with only one neutron hole in the $N = 50$ shell is very interesting because of the relatively limited number of single-particle configurations available in the construction of these levels. Some information exists on low-spin states for this isotope obtained in β-decay measurements and in single-nucleon pickup reactions [1]. However, there is no spectroscopic information on high-spin states in this isotope. The 9/2$^+$ ground state of ^{83}Se originates from the neutron hole in the $g_{9/2}$ orbital. Hence, the lowest positive-parity high-spin states are expected to originate from the coupling of this hole to the first excited states in the $N = 50$ ^{84}Se core.

Yet, in the heavier odd-mass isotopes in this mass region, a wealth of spectroscopic information is available for states above the corresponding 9/2$^+$ states. In ^{85}Kr [2] the ground state originates from the same configuration, while in ^{87}Rb [3,4] and ^{89}Y [5] the occupation of the $g_{9/2}$ orbital by the odd proton can account for the observed 9/2$^+$ isomers. In all of these isotopes the first positive-parity high-spin states above the 9/2$^+$ states have been identified and shell-model calculations support the coupling of the odd nucleon to the first excited states of the corresponding cores for their interpretation. The ^{85}Kr and ^{87}Rb isotopes differ by one neutron hole and proton particle from ^{86}Kr, respectively, while ^{87}Rb and ^{89}Y differ by one proton hole and proton particle from ^{88}Sr, respectively. There is not enough spectroscopic information on 9/2$^+$ and higher-spin states in the other neighboring nuclei, ^{85}Br [3,4], ^{87}Kr and ^{87}Sr [6], and ^{89}Sr [7], to further compare with ^{83}Se.

The shortage of information on high-spin states for ^{83}Se is mainly because of the difficulty of studying this isotope as evaporation residue in heavy-ion fusion reactions. ^{83}Se is a neutron-rich nucleus and, hence, cannot be populated with stable beam-target combinations in such a reaction. An alternative way to study neutron-rich isotopes could be the prompt γ-ray spectroscopy of fission fragments in fusion-evaporation reactions. Such methods have been used several times recently to collect information on high-spin states of nuclei near the line of stability (see, for instance, Ref. [4] and references therein). Because of its proximity to the line of stability, ^{83}Se can be populated as a fission fragment in such reactions, as was done in the present work.

II. EXPERIMENT

The beam for the experiment described in this article was provided by the 88-Inch Cyclotron Facility at Lawrence Berkeley National Laboratory and the Gammasphere array was used to detect prompt-time coincidences between γ rays. Gammasphere comprised 100 Compton-suppressed large volume HPGe detectors. A ^{226}Th compound nucleus was populated in the ^{18}O + ^{208}Pb reaction at 91 MeV and the target was 45 mg/cm^2 in areal density. About 2.5×10^9 fourfold γ-ray coincidences were collected in the experiment. A symmetrized, three-dimensional cube was constructed to investigate the coincidence relationships between the γ rays.

III. EXPERIMENTAL RESULTS

The present work is the first spectroscopic study of high-spin states in ^{83}Se. Six new transitions have been observed above the ground state establishing the high-spin level scheme up to ∼2.5 MeV excitation energy. The level scheme of ^{83}Se

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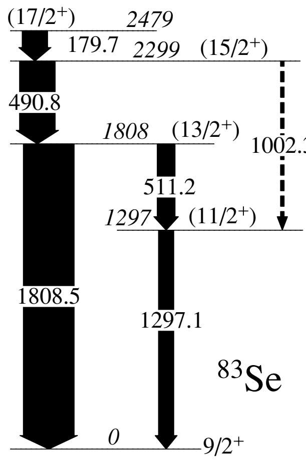

FIG. 1. Level scheme assigned to ^{83}Sr in the present work. Transition and excitation energies are given in keV. The width of the arrows is representative of the intensity of the transitions.

deduced in the present work is shown in Fig. 1. The transitions in Fig. 1 and their measured intensity are listed in Table I. The strong 1808.5-keV transition was assigned to ^{83}Se based on the coincidences established between this transition and previously known transitions of the complementary fission fragments ^{138,139,140}Ba [8] (from the 5, 4, and 3 neutron channels, respectively). The 1808.5-keV transition can be seen in Fig. 2, where spectra gated on ^{138,139,140}Ba are shown. The ratios of γ-ray intensities, observed in the ^{138,139}Ba-gated spectra in Fig. 2, for transitions in the known Se isotopes are summarized in Fig. 3, as well as the ratio for the 1808.5-keV transition. The ratio for the 1808.5-keV transition, intermediate between the values for ^{82}Se and ^{84}Se, supports the isotopic assignment to ^{83}Se. The other transitions assigned to ^{83}Se can be seen in the gated spectra in Fig. 4. A weak 1002.3-keV transition is seen in Fig. 4(b) and tentatively placed in Fig. 1. The similar intensities of the 511.2- and 490.8-keV transitions in this spectrum support the placements above the $(11/2^+)$ level and below the $(15/2^+)$ level in Fig. 1. Above the 2479-keV level no transitions were observed in the spectra gated on the transitions below it. The reasons for this could be one or more of the following: (i) the population of ^{83}Se in the present work as a fission fragment introduces a spin cutoff at higher spins; (ii) The $(17/2^+)$ level is an isomer (the corresponding $17/2^+$ state in ^{85}Kr [2] is also an isomer);

TABLE I. Energies, intensities, and spin-parity assignments of transitions assigned to ^{83}Se in the present work.

Energy[a] (keV)	Intensity (%)	$J_i^\pi \rightarrow J_f^\pi$
179.7	50(15)	$(\frac{17}{2}^+) \rightarrow (\frac{15}{2}^+)$
490.8	70(10)	$(\frac{15}{2}^+) \rightarrow (\frac{13}{2}^+)$
511.2	35(15)	$(\frac{13}{2}^+) \rightarrow (\frac{11}{2}^+)$
1002.3	7(2)	$(\frac{15}{2}^+) \rightarrow (\frac{11}{2}^+)$
1297.1	30(10)	$(\frac{11}{2}^+) \rightarrow \frac{9}{2}^+$
1808.5	≡100	$(\frac{13}{2}^+) \rightarrow \frac{9}{2}^+$

[a]The uncertainty on the γ-ray energies varies from 0.4 to 0.9 keV.

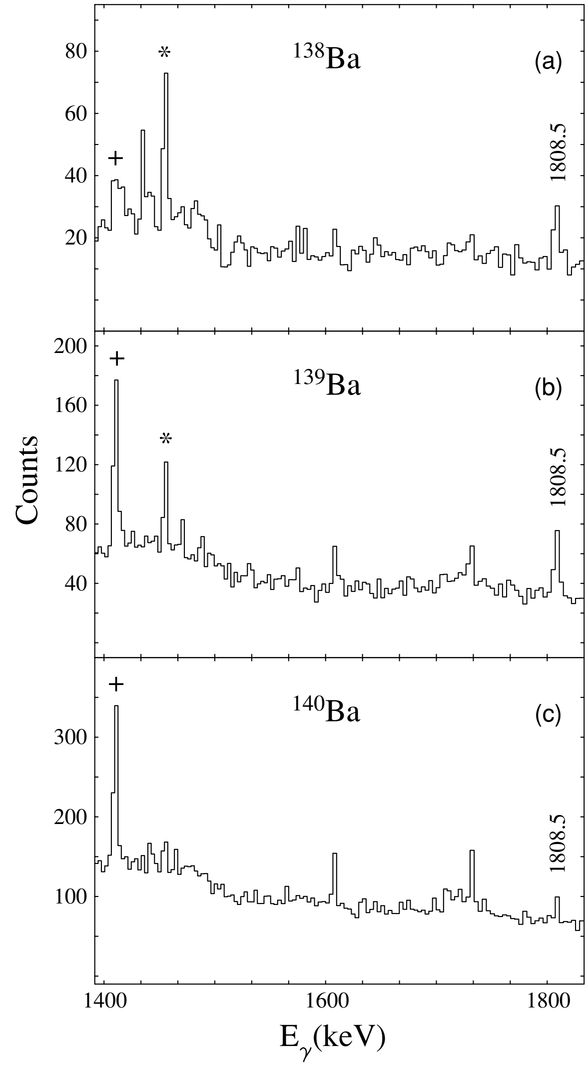

FIG. 2. Spectra gated on known transitions of ^{138,139,140}Ba [8]. Specifically, the spectra are double gates between the following transitions: (a) the ^{138}Ba spectrum, between the 1435.8- and 462.8-keV transitions; (b) the ^{139}Ba spectrum, between the 1308.1- and 520.6-keV transitions; and (c) the ^{140}Ba spectrum, between the 602.4- and 528.3-keV transitions. The 1808.5-keV transition assigned to ^{83}Se in the present work can be clearly seen. The peaks of the other complementary Se isotopes [8] are indicated by "+" (1409.9-keV transition of ^{82}Se) and "∗" (1454.6-keV transition of ^{84}Se).

(iii) the level scheme could be very fragmented above this level and the corresponding transitions very weak, an option that is deemed less likely here because such fragmentation is not observed in the heavier ^{85}Kr [2], ^{87}Rb [3,4], and ^{89}Y [5] isotopes.

Spin and parity assignments of all levels reported in this work are difficult to deduce experimentally because of the lack of directional correlation information for the fission products. However, based on comparison with probable assignments for the first high-spin excited states in ^{85}Kr [2], ^{87}Rb [3,4], and ^{89}Y [5] displayed in Fig. 5, spin and parity assignments for the four levels assigned to ^{83}Se in the present work are tentatively suggested, as discussed next.

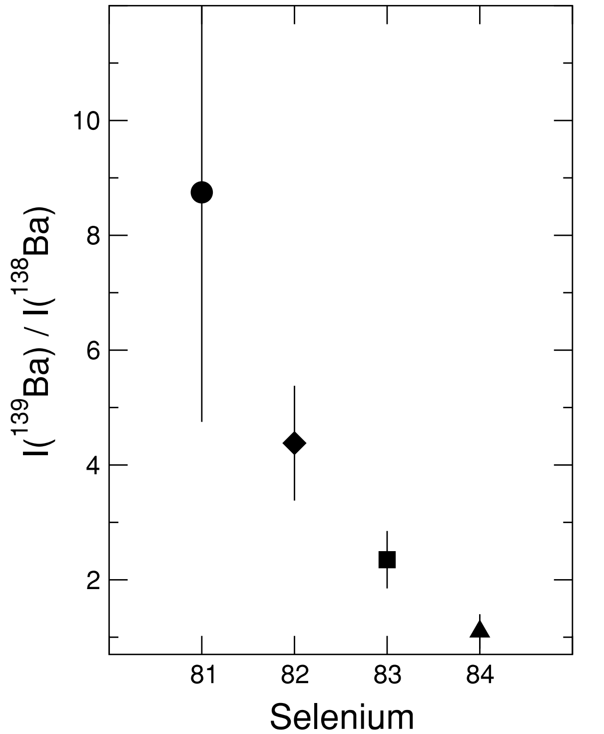

FIG. 3. Ratios of intensities of transitions in Se isotopes observed in spectra gated on ^{139}Ba [Fig. 2(b)] and on ^{138}Ba [Fig. 2(a)]. The known transitions in ^{81}Se (467.7-keV, circle), ^{82}Se (1409.9-keV, diamond), and ^{84}Se (1454.6-keV, triangle) were used, as well as the 1808.5-keV transition assigned to ^{83}Se (square). The ratio for the 1808.5-keV transition, intermediate between the values for ^{82}Se and ^{84}Se, supports this assignment.

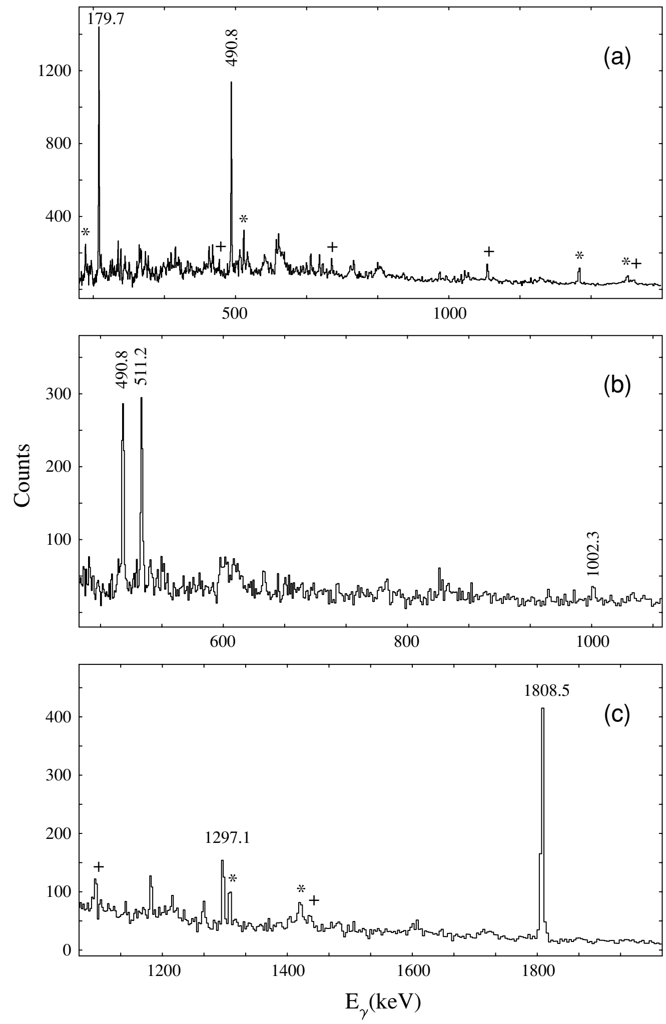

FIG. 4. Example of typical spectra of transitions assigned to ^{83}Se in the present work. (a) The sum of double gates on the 179.7- and 1808.5-keV transitions and on the 409.8- and 1808.5-keV transitions is displayed. (b) The double gate on the 179.7- and 1297.1-keV transitions is displayed. (c) The double gate on the 179.7- and 490.8-keV transitions is displayed. The energies of the transitions are in keV and the peaks of the complementary Ba isotopes [8] are indicated by "+" (^{138}Ba) and "$*$" (^{139}Ba).

IV. DISCUSSION

In ^{85}Kr [2] shell-model calculations suggest that the $11/2^+$ and $13/2^+$ or $15/2^+$ and $17/2^+$ states are formed by the coupling of a neutron $g_{9/2}$ hole to the lowest 2^+ or 4^+ states of the ^{86}Kr core, respectively. The $11/2^+$, $13/2^+$, and $17/2^+$ states are found at excitation energies between 1.5 and 2.0 MeV above the $9/2^+$ ground state, in excellent agreement with the experimental results [2] (the location of the $15/2^+$ state in ^{85}Kr still remains uncertain). A similar behavior is observed above the $9/2^+$, $\pi g_{9/2}$ isomers in ^{87}Rb [3,4] and ^{89}Y [5] (the $15/2^+$ state in both these isotopes has been located).

A similar pattern is expected for the first-excited states above the $9/2^+$ ground state in ^{83}Se from the coupling of the neutron $g_{9/2}$ hole to the first-excited states of the ^{84}Se core [3]. Indeed, the 1297-, 1808-, 2299-, and 3644-keV states and their linking transitions in Fig. 1 fit this behavior perfectly, suggesting $11/2^+$, $13/2^+$, $15/2^+$, and $17/2^+$ assignments, respectively. In Fig. 5 the partial level schemes of ^{83}Se, ^{85}Kr, ^{87}Rb, and ^{89}Y above the $9/2^+$ states are shown.

V. SHELL-MODEL CALCULATIONS

Shell-model calculations for ^{83}Se have been performed in the present work using a new effective interaction designed to understand the neutron-rich nuclei in the vicinity of ^{78}Ni. The new effective interaction has been derived from the realistic G-matrix interaction based on the Bonn-C NN potential. The interaction is constructed for the configurational space that includes $p_{3/2}$, $f_{5/2}$, $p_{1/2}$, and $g_{9/2}$ orbitals. The interaction is uniquely defined by 133 two-body matrix elements and 4 single-particle energies. The $T = 1$ part of this interaction is described in Ref. [9]. The full interaction, which includes both $T = 1$ and $T = 0$ parts adjusted to reproduce the spectra of Ni, Cu, Zn, Ga, and Ge isotopes, is described elsewhere [10].

The results of the calculation are compared to the experimentally observed excitation energies of the high-spin states in Fig. 6. In the same figure the excitation energies of the lowest 2^+ and 4^+ states of the $N = 50$ ^{84}Se core [3] are shown together with the shell-model predictions for these states. There is excellent agreement between theory and experiment

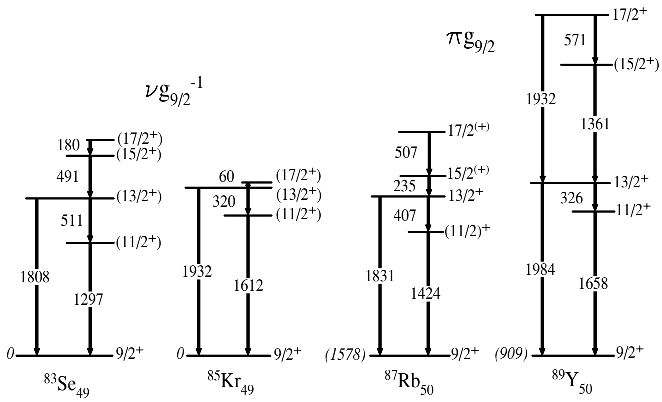

FIG. 5. Comparison of the high-spin states assigned to ^{83}Se in the present work with known high-spin states in ^{85}Kr [2], ^{87}Rb [3,4], and ^{89}Y [5]. The excitation energy of the $9/2^+$ isomers in ^{87}Rb (1578 keV) and ^{89}Y (909 keV) has been normalized to zero.

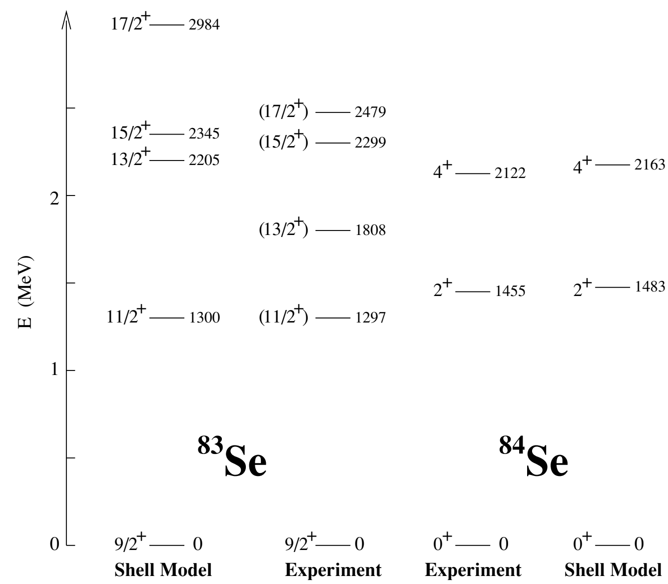

FIG. 6. Comparison of the high-spin states assigned to ^{83}Se in the present work with the predictions of the shell-model calculations described in the text. The first two excited states in the $N = 50$ core of ^{84}Se [3] are shown together with the shell-model prediction for these states.

for the ^{84}Se core. However, the theoretical predictions only reproduce some of the excitation energies observed in ^{83}Se. The energies of the stretched states $13/2^+$, which should be dominated by the $\nu^{-1}\ g_{9/2}$ coupled to 2^+, and $17/2^+$, which should be dominated by $\nu^{-1}\ g_{9/2}$ coupled to 4^+, are predicted to be significantly higher than those of the observed candidates, as well as the empirical core excitations. This could be due to the theoretical prediction that there are extra correlations in the ground state, summarized in Table II. This would effectively lower the energy of the ground state relative to the "pure" $\nu^{-1}\ g_{9/2} \otimes 4^+\ 17/2^+$ configuration. That the candidate for the $17/2^+$ state in ^{83}Se is only 357 keV above the 4^+ in ^{84}Se suggests that the calculated extra correlations in the ^{83}Se ground state may be overestimated. The calculations do reproduce well the energies of the nonstretched $(11/2^+)$ and $(15/2^+)$ states.

Finally, we note here that the results of the shell-model calculation in Fig. 6 come from a global fit in this mass region [10], and the parameters were not "tweaked" to improve the agreement for Se isotopes. Attempts to adjust the parameters to fit ^{83}Se resulted in disagreement between the calculation and the experimental results in ^{82}Ge. The next higher-spin states predicted by the calculation ($19/2^+$ and $17/2^-$) are above 4 MeV excitation energy and were not observed in the present work.

TABLE II. Dominant configurations of high-spin states in ^{83}Se in terms of a $\nu g_{9/2}$ hole coupled to the J_k^+ states of ^{84}Se. Components accounting for more than 10% are shown.

E_x (keV)	I^π	Shell model configurations $(\%)[\nu g_{9/2}^{-1} \otimes J_k^\pi]_{I^\pi}$		
		$J_k^\pi = 0_1^+$	$J_k^\pi = 0_2^+$	$J_k^\pi = 2_1^+$
0	$\frac{9}{2}^+$	72	11	15
		$J_k^\pi = 2_1^+$	$J_k^\pi = 4_2^+$	
1297	$(\frac{11}{2}^+)$	76	13	
		$J_k^\pi = 2_1^+$	$J_k^\pi = 4_2^+$	
1808	$(\frac{13}{2}^+)$	53	23	
		$J_k^\pi = 4_1^+$	$J_k^\pi = 3_2^+$	
2299	$(\frac{15}{2}^+)$	31	47	
		$J_k^\pi = 4_1^+$		
2479	$(\frac{17}{2}^+)$	95		

VI. SUMMARY

In summary, the first four high-spin states above the $9/2^+$ ground state in ^{83}Se were established in the fission of a compound nucleus formed in a fusion-evaporation reaction. The assignment of the transitions to ^{83}Se is based on coincidences with transitions in the complementary fission fragment Ba isotopes. Based on comparison to similar states in the neighboring ^{85}Kr, ^{87}Rb, and ^{89}Y isotopes, the first high-spin states above the $9/2^+$ ground state in ^{83}Se can be understood as originating from neutron configurations involving the coupling of the $g_{9/2}$ hole to the first-excited states in the ^{84}Se core. Generally, good agreement is obtained between measured level energies and those predicted by shell-model calculations except for the stretched ($\nu^{-1}\ g_{9/2} \otimes$ core) states, $J^\pi = 13/2^+$ and $17/2^+$.

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