Evidence for an Octupole Rotational Band in ^{74}Se

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(Received 7 July 1976)

From in-beam γ-ray spectroscopy in ^{74}Se, a negative-parity band to (11^-) with rotational properties built on a 3^- collective octupole state is established along with the positive-parity (Barrette *et al.*) yrast band to (14^+). The negative-parity band has essentially a constant moment of inertia in sharp contrast to the positive-parity band. This is the first negative-parity band outside those in deformed nuclei with such pure rotational behavior.

In further tests of the coexistence of spherical and deformed shapes in selenium nuclei, we have discovered in ^{74}Se a negative-parity band to spin (11^-) built on a 3^- level assigned to be an octupole state from its Coulomb excitation.[1] As we shall see, there are marked differences in the behavior of the negative-parity band and the positive-parity yrast band in ^{74}Se. In particular the moments of inertia as a function of $(\hbar\omega)^2$ are quite different for the positive- and negative-parity bands in ^{74}Se. Indeed the negative-parity band has all the properties of a very well-behaved rotational band and is the first such negative-parity band built on a known 3^- collective octupole state outside the region of well-deformed nuclei.

A 99.8%-enriched ^{60}Ni target was bombarded with 45-MeV ^{16}O ions from the Oak Ridge National Laboratory tandem Van de Graaff accelerator. Angular distribution measurements were made at 0°, 55°, and 90° with a large volume Ge(Li) detector. Coincidence data, from two large Ge(Li) detectors at 0° and 90° relative to the beam direction, were stored in a 1000-by-1000 matrix and 25 0° coincidence spectra were taken with 4000 resolution. Angular distribution studies were also made with the reaction ^{64}Ni(^{12}C, $2n\gamma$)^{74}Se where the radioactive ^{74}Br decay to low-spin states in ^{74}Se is eliminated.

Mean lives were obtained by analyzing the shapes of Doppler-shifted lines at 0° in both the coincidence and singles spectra using the computer code DOPCO.[2] Again, as shown in our ^{72}Se work,[3] γ-γ coincidence spectra are important for obtaining accurate mean lives. However, these 6^+ and 4^+ states do not have strong long-lived sidefeeders as in ^{72}Se. Here, gates below the level of interest show greater Doppler shifts in the transition out of the level than gates above because of the fast sidefeeders. In this case, the use of gates above and below the level of interest can yield more accurate results. The density of γ-ray lines makes coincidence data essential for the establishment and lifetime measurements of states in the negative-parity band. In our analysis, one starts with the highest member of a band and works down, applying feeding corrections for each of the higher members. For the (14^+) state a feeding correction for an unobserved yrast feeder was assumed.

Two cascade bands as shown in Fig. 1 were ex-

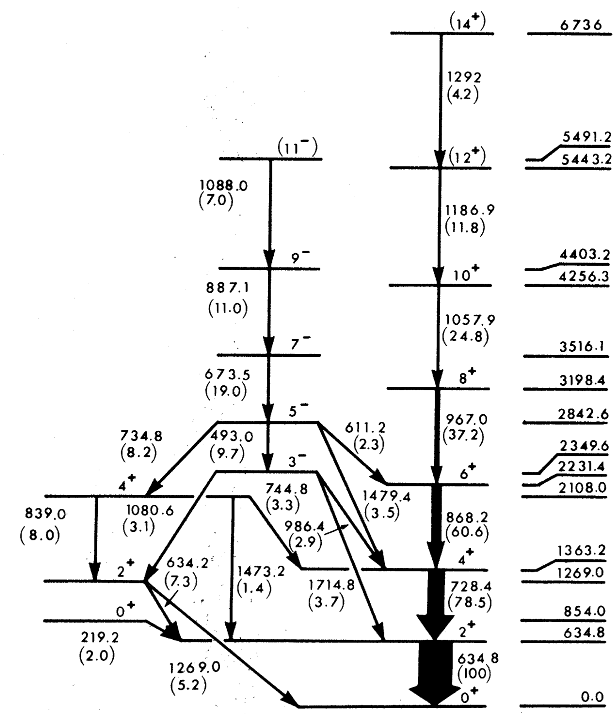

FIG. 1. Negative- and positive-parity bands in ^{74}Se as seen in our in-beam studies.

TABLE I. Mean life and angular distribution results for ^{74}Se, $B(E2)$ values in Weisskopf units, and rms deformations calculated from them with the rotational formula (Ref. 4).

Transition Energy (keV)	$J_i^\pi \rightarrow J_f^\pi$	A_2^{exp}	A_4^{exp}	τ (psec)	$\frac{B(E2)}{B(E2)_{sp}}$, W	$\lvert \beta_2 \rvert$
634.8	$2^+ \rightarrow 0^+$			10.7(4)[a)]	40^{+2}_{-1}	0.30 ± 0.01
728.4	$4^+ \rightarrow 2^+$	0.30(2)	−0.04(2)	2.7(1)[a)]	81 ± 3	0.35 ± 0.01
868.2	$6^+ \rightarrow 4^+$	0.31(2)	−0.09(2)	2.40(30)	38^{+6}_{-4}	0.23 ± 0.01
967.0	$8^+ \rightarrow 6^+$	0.43(5)	−0.08(5)	0.80(10)	66^{+9}_{-2}	0.30 ± 0.02
1057.9	$10^+ \rightarrow 8^+$	0.41(4)	−0.08(4)	0.53(10)	64^{+15}_{-11}	$0.29^{+.03}_{-.03}$
1186.9	$(12^+) \rightarrow 10^+$	0.29(8)	−0.11(8)	0.30(15)	63^{+63}_{-21}	$0.28^{+.12}_{-.05}$
1292	$(14^+) \rightarrow (12^+)$			0.35(15)[b)]	36^{+26}_{-11}	$0.21^{+.07}_{-.04}$
493.0	$5^- \rightarrow 3^-$	0.32(2)	−0.09(2)			
673.5	$7^- \rightarrow 5^-$	0.34(2)	−0.07(2)	5.0(20)	64^{+43}_{-18}	$0.30^{+.08}_{-.05}$
887.1	$9^- \rightarrow 7^-$	0.39(6)	−0.14(6)	0.70(20)	116^{+46}_{-26}	$0.39^{+.07}_{-.05}$
1088.0	$(11^-) \rightarrow 9^-$	0.34(14)	−0.21(21)	0.40(5)[b)]	78^{+11}_{-8}	$0.32^{+.02}_{-.02}$

[a]Barrette *et al*. (Ref. 1).
[b]Calculated using a feeding lifetime of 0.20 psec.

tracted from our γ-γ coincidence data. The spins of the levels are determined from our angular distribution data in Table I, and the parities from the known ones of the low-spin states,[1] the quadrupole character of the upper transitions, and our mean lives. Transitions between the two bands are extremely weak, if present at all, except at lower-spin states. The positive-parity yrast cascade also has been studied recently in α-γ coincidence work by Halbert *et al.*[5] to high spin. Our yrast levels are in agreement, but they did not decompose their lifetimes into feeder and state lifetimes as has been done here.

The most striking feature of ^{74}Se is the discovery of a negative-parity band to high spin. Coulomb excitation studies[1] have found a collective $I^\pi = 3^-$ octupole level at 2350.2 keV with $B(E3; 3 \rightarrow 0)$ of 9 single-particle units. We see that this state and our angular distribution data confirm the spin to be 3. Our coincidence, τ, and angular distribution data (see Table I) establish states with $I^\pi = 5^-$, 7^-, 9^-, and tentatively 11^- for a band of levels starting at the 3^-, 2349.6-keV level as shown in Fig. 1.

The behavior of the moments of inertia with increase in spin is shown in Fig. 2. Note the marked difference between the negative- and positive-parity bands. The negative-parity band has a remarkably constant moment of inertia and an excellent fit of its energies by $E_0 + AI(I+1) + BI^2(I+1)^2$ with very small B as characteristic of a

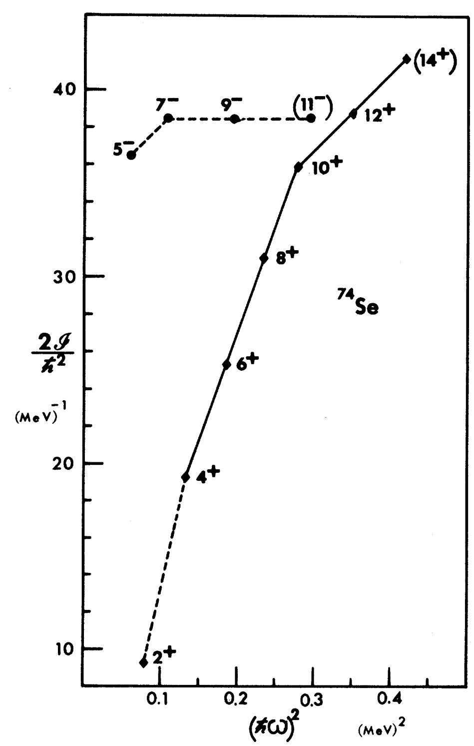

FIG. 2. Plots of $2\mathcal{J}/\hbar^2$ versus $(\hbar\omega)^2$ for the yrast positive-parity and negative-parity bands in ^{74}Se.

good rotor. The theoretical energies, with the experimental ones in parentheses, for $A = 2.67 \times 10^{-2}$ and $B = -3.99 \times 10^{-6}$, 2355 (2350), 2833 (2842), 3518 (3516), 4406 (4403), and 5490 (5492) keV, have a standard deviation of only 3 keV from the experimental values. This is the first band with such pure rotational characteristics built on a collective octupole state seen in Coulomb excitation outside the known regions of the deformed nuclei.

The rms β_2 deformation of the negative-parity band as extracted from the mean lives is larger on the average than for the positive-parity band. Figure 2 shows that $\hbar^2/2\mathscr{I}$ is constant and equal to about 26.0 keV for the negative-parity band. This value is much closer to the irrotational value of 34.4 keV than the rigid-body value of 2.5 keV calculated with $\beta = 0.3$. The $B(E2)$ values of 80–100 single-particle units show that the transitions are highly collective for the negative-parity band.

Recently a negative-parity band has been discovered[6] in ^{152}Gd and interpreted in terms of the coupling of the octupole vibration to a transitional or deformed core.[6,7] Arima and Iachello[8] introduced an interacting octupole-quadrupole boson model for nuclei in regions of transition from near-spherical to deformed shapes and applied it to ^{152}Gd. In this model, the negative-parity energy levels are related to the ground-band levels. More recently, this model[8] was also successfully applied[9] to ^{100}Ru and ^{150}Sm.

As an alternative approach, we have tried to fit the negative-parity band with the interacting quadrupole-octupole boson model of Arima and Iachello,[8] where the negative-parity and yrast bands are related. We can fit the levels of the yrast band, but the levels in the odd-spin band built on this yrast band in their model do not agree with our experimental levels. This could have been expected since the two bands have completely different moments of inertia and energy patterns, as clearly shown in Figs. 1 and 2.

The positive-parity yrast band structure has been discussed in two other recent studies.[5,10] We can summarize by saying that the positive-parity states for $I \leq 10^+$ may be more complex than those in ^{72}Se where near-spherical and deformed states are well separated except at $I = 2$ (Ref. 3). As suggested by Halbert *et al.*,[5] a band with stronger rotational behavior may be emerging at $I = 10^+$ as indicated by the forward bend in the moment of inertia there.

In summary, fascinating new evidence for rotational behavior is found in this region where for the first time outside the region of well-deformed nuclei, we find in ^{74}Se a negative-parity rotational band built on a collective 3^- octupole state.

*Work supported in part by grants from the National Science Foundation and the U. S. Energy Research and Development Administration.

†Research supported by the U. S. Energy Research and Development Administration under contract to Union Carbide Corporation.

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