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High-spin states and band structure in ^{76}Se

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High-spin states of ^{76}Se have been investigated through observations of γ rays produced in the ^{71}Ga(^{7}Li,2n) reaction by bombarding an enriched ^{71}Ga target with 15- to 22-MeV ^{7}Li ions. Measurements were made of γ-ray singles and γ-γ coincidence spectra, excitation functions, γ-ray angular distributions, γ-γ angular correlations, and Doppler broadening of photopeaks. Level energies, decay modes, spins and parities, γ-ray branching ratios, γ-ray radiative admixtures, and lifetimes were deduced. There is evidence for a strongly excited quasirotational band with the highest member observed being a 12^+ state at 5432 keV, for an odd-parity band built on a 5^- state, and for a $\Delta J = 1$ band which has the characteristics of a γ-vibrational band in a deformed nucleus. Interacting boson approximation model calculations are compared with the experimental results.

[NUCLEAR REACTIONS ^{71}Ga(^{7}Li, 2n) E=15–22 MeV; measured E_γ, I_γ, $\gamma(\theta)$, $\gamma\gamma(\theta)$, $\Delta E_\gamma(\tau)$; ^{76}Se deduced levels, J, π, δ, τ, γ branching.]

I. INTRODUCTION

In recent years, studies of in-beam γ rays from heavy-ion nuclear reactions have been used to investigate the higher-spin states in many nuclei. Investigations of even-mass nuclei in the region around $A=70$ have revealed a variety of bands,[1,2] which include the following types: (1) ground-state bands, (2) deformed bands built on the low-lying excited 0^+ levels, (3) even-parity bands built on states resulting from two rotational-aligned $g_{9/2}$ quasiparticles, (4) odd-parity bands built on states resulting from the coupling of a $g_{9/2}$ quasiparticle with one in the $p_{1/2}$, $p_{3/2}$, or $f_{5/2}$ orbital, and (5) $\Delta J=1$, even-parity, γ-vibrational bands. Not all of these types have been observed in all of the nuclei in this mass region, and there appear to be significant differences between bands in neighboring even-mass nuclei.

As part of a systematic study of high-spin states and band structure of even-mass nuclei around $A=70$, we have investigated the high-spin states of ^{76}Se. Results on ^{76}Se through 1976 are given in the compilation by Bertrand and Auble.[3] The ground-state band up to 10^+ has been observed by Lieder and Draper[4] using the ^{74}Ge(α, 2n) reaction. They also report the second 2^+ and 4^+ states. Our results agree with theirs with the exception of the energy of the 10^+ state. The 3^- octupole state has been reported at 2.45 MeV by Lin.[5] A 3^+ state at 1689 keV has been identified by Barclay *et al.*[6] from the decay of oriented ^{76}As nuclei, and also by Nagahara.[7] Lifetimes of several low-lying states were obtained by Barrette *et al.*[8] using Coulomb excitation.

We have produced ^{76}Se in the ^{71}Ga(^{7}Li, 2n) reaction, and have made measurements of γ-ray singles and γ-γ coincidence spectra, excitation functions, γ-ray angular distributions, γ-γ angular correlations, and Doppler broadening of photopeaks. We have constructed an energy level scheme with levels through 12^+, and have deduced spins and parities, γ-ray branching ratios, radiative admixtures, and lifetimes for some of the levels.

II. EXPERIMENTAL PROCEDURE

A target of 25 μm-thick enriched ^{71}Ga on a 25 μm-thick Cu backing was bombarded with ^{7}Li ions from the ORNL EN tandem accelerator. Because the melting point of Ga is low, the target was cooled with a dry-ice-alcohol mixture to prevent it from melting during bombardment. Singles γ-ray spectra were measured for ^{7}Li projectile energies of 15.0, 17.0, 18.5, and 22.0 MeV. From yield curves obtained from these spectra, the projectile energy which optimized the ^{71}Ga(^{7}Li, 2n)^{76}Se

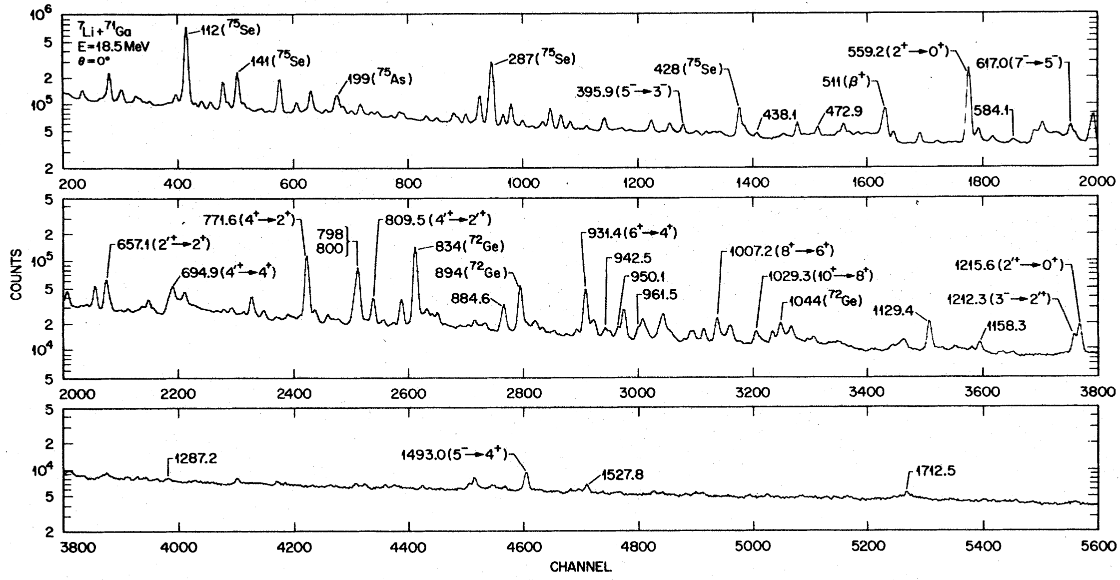

FIG. 1. In-beam singles γ-ray spectrum resulting from the bombardment of a ^{71}Ga target with 18.5-MeV ^{7}Li ions. Energies are in keV. Unless otherwise indicated, those photopeaks which are labeled are assigned to ^{76}Se.

reaction, 18.5 MeV, was selected and was used for subsequent measurements.

Coincidence measurements were made with two large-volume Ge(Li) detectors placed at 0° and 90° with respect to the beam direction, and 5 cm from the target. The angular distributions of the γ rays were measured at 0°, 55°, and 90° with respect to the beam direction using a large-volume Ge(Li) detector placed 15 cm from the target. A second Ge(Li) detector at 270° served as a monitor. A ^{226}Ra source was placed at the target position at the conclusion of the angular distribution experiments to determine the magnitude of the correction for the target's not being at the exact center of rotation of the table. This source was also used to determine the energy and efficiency calibrations of the detectors.

III. RESULTS

A. Level scheme

A representative singles γ-ray spectrum is shown in Fig. 1, and selected coincidence-gated spectra are shown in Fig. 2. The results of γ-γ coincidence measurements were used to identify those γ rays belonging to ^{76}Se and to construct a level scheme, which is shown in Fig. 3. The γ-ray energies are given in Table I. Relative γ-ray intensities obtained from the singles spectra were used to establish the order of the cascades. These intensities are given in Table I, and are indicated graphically by the widths of the transition arrows in the level scheme (Fig. 3). The level energies were obtained by a least-squares fit to all of the γ-ray energies.

With the following exceptions, each of the γ rays placed in the level scheme showed a coincidence with all the other γ rays in its cascade, and was not in coincidence with other γ rays. The 739-keV γ ray was very weak and was masked in the singles spectra by a strong impurity peak from ^{75}Se. It was in coincidence with the 395.9-, 472.9-, 559.2-, and 1129.4-keV γ rays, and was placed in the level scheme because it fits energetically and has been reported by Barclay *et al.*[6] Placement of the 1133-keV γ ray was difficult due to the presence of the much stronger 1129.4-keV γ ray, but a gate around 1133 keV, excluding 1129 keV, did show coincidences with the 771.6-, 931.4-, 1007.2-, and 1029.3-keV γ rays, and gates around 1007 and 1029 keV each showed a photopeak at 1133 keV.

B. Excitation functions

Yield curves for the γ rays were obtained from singles spectra measured at $E_{^7\mathrm{Li}} = 15.0$, 17.0, 18.5, and 22.0 MeV. The mean slope S of the excitation function for each γ ray is given in Table I. It was calculated by a least-squares fit to the function

$$\ln(I_\gamma/I_{\mathrm{total}}) = S(E_{^7\mathrm{Li}} - E_0)\,, \quad (1)$$

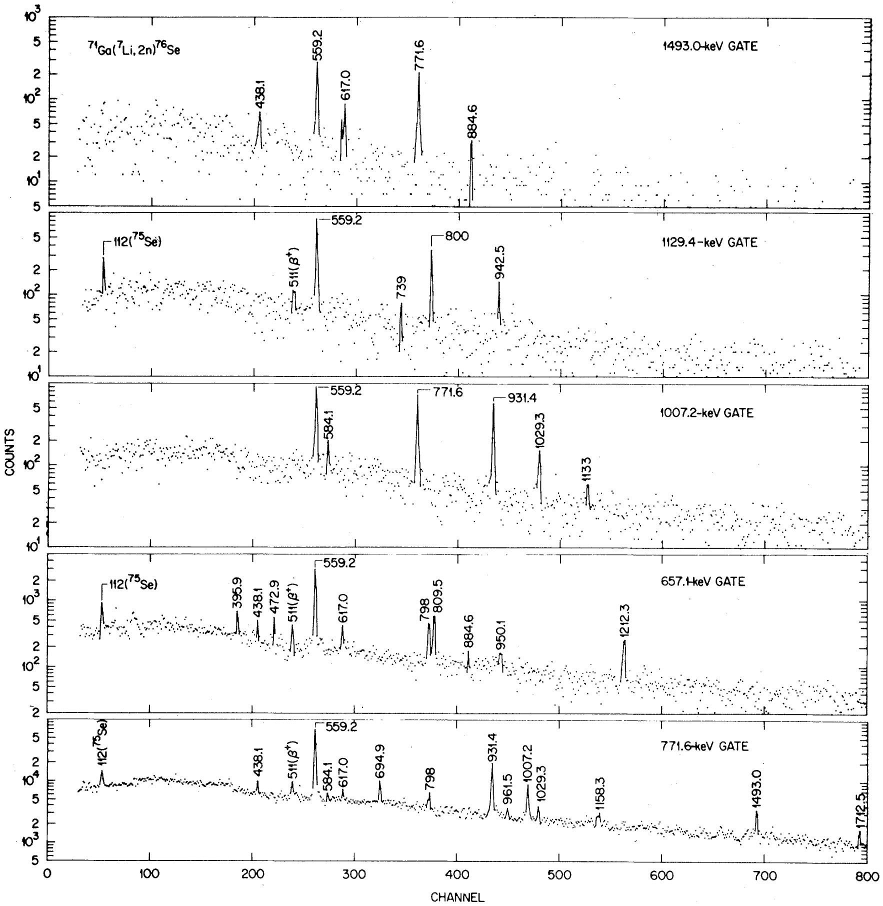

FIG. 2. Selected $\gamma-\gamma$ coincidence-gated spectra of transitions in ^{76}Se. Each spectrum shown is the result of the difference between two spectra, one with a gate set on the γ-ray photopeak, and the other with a gate set on the continuum above and below the photopeak.

where S and E_0 are adjustable parameters, $E_{^7\mathrm{Li}}$ is the bombarding energy, I_γ is the γ-ray intensity at that energy, and I_{total} is the total γ-ray intensity to the ground state at that bombarding energy. A graph of the mean slope S of each transition *versus* the assigned spin of the initial level is shown in Fig. 4. It is seen that, in general, S increases with increasing spin. (See the discussion of spin assignments in Sec. III F.)

C. Angular distributions

The angular distribution coefficients $A_2=a_2/a_0$ and $A_4=a_4/a_0$ were extracted from the expression

$$W(\theta)=a_0+a_2g_2P_2(\cos\theta)+a_4g_4P_4(\cos\theta)\,, \qquad (2)$$

where $W(\theta)$ is the normalized γ-ray intensity at angle θ with respect to the beam direction, and the corrections for the finite solid angle subtended by the Ge(Li) detector were $g_2=0.99$ and $g_4=0.97$. These angular distribution results are summarized in Table I.

D. DCO ratios

The directional correlation from oriented nuclei (DCO) ratio $R(\theta,\theta')$ is defined[9] to be

$$R(\theta,\theta')=W[\gamma_1(\theta),\gamma_2(\theta')]/W[\gamma_1(\theta'),\gamma_2(\theta)]\,, \qquad (3)$$

where $W[\gamma_1(\theta),\gamma_2(\theta')]$ is the coincidence intensity for detecting γ_1 at θ and γ_2 at θ', and $W[\gamma_1(\theta'),\gamma_2(\theta)]$ is the complementary intensity. As demonstrated by Grau *et al.*,[9] DCO ratios are often useful in determining spins and multipolarities of γ-ray cascades following heavy-ion reactions. DCO ratios for a number of γ-ray cascades were extracted from the coincidence spectra with

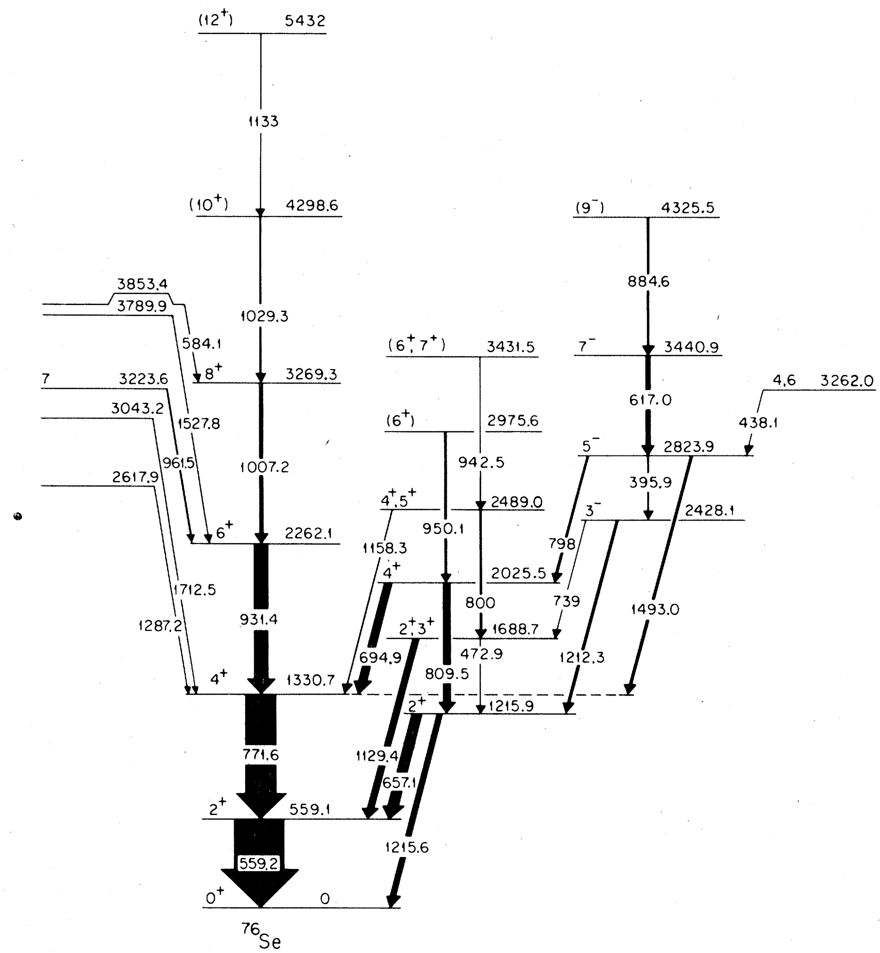

FIG. 3. Levels and transitions in ^{76}Se observed with the ^{71}Ga(^{7}Li, $2n$) reaction. Energies are in keV. Level energies are least-squares adjusted to all γ-ray energies.

$\theta = 90°$ and $\theta' = 0°$, and these results are given in Table II.

E. Lifetime measurements

Doppler shift broadening of some of the γ-ray photopeaks was observed in both singles and coincidence γ-ray spectra taken at an angle of 0° to the beam direction. The mean lifetimes of a number of states of ^{76}Se were determined by the Doppler-shift attenuation method, which is described in the review article by Schwarzchild and Warburton.[10] The computer code DOPCO[11] was used to calculate photopeak shapes for a series of mean lifetimes and to select the one which best matched the observed shape. The recoiling ^{76}Se nuclei were completely stopped in the Ga target, and the stopping powers used in the calculation were taken from the work of Brown and Moak.[12]

The lifetime results are given in Table III. Most of the lifetime results were obtained from coincidence spectra, which reduced the problem of contaminant γ rays. In one case (931.4 keV) the coincidence gate was set on a γ ray preceding the one of interest. In this case, corrections for the lifetimes of precursors could be readily made, since the only feeding would be through the gating γ ray. In all of the other cases, corrections were made for feeding by all known percursor γ rays.

F. Spin-parity assignments

The spin-parity assignments are given in Table III and are shown on the level scheme in Fig. 3. These have been assigned by using angular distributions and DCO ratios of γ rays as direct evidence. Supporting evidence was provided by the fact, as discussed by Taras and Haas,[13] that

TABLE I. Energies, relative intensities, excitation function slopes, and angular distributions of γ rays from ^{76}Se. Numbers in parentheses indicate probable errors in the last significant figures.

E_γ (keV)	I_γ	S (MeV^{-1})	A_2	A_4
395.9 (4)	31 (3)	0.068 (25)	0.33 (4)	−0.08 (4)
438.1 (5)	38 (5)	0.039 (6)	−0.40 (4)	0.04 (5)
472.9 (4)	38 (4)	0.013 (12)	0.16 (4)	0.06 (4)
559.2 (3)	1000 (50)	0.000 (1)	0.10 (2)	−0.03 (2)
584.1 (6)	30 (10)	0.084 (43)	0.06 (12)	0.00 (12)
617.0 (5)	133 (33)	0.104 (11)	0.26 (3)	−0.05 (3)
657.1 (4)	243 (38)	−0.001 (7)	−0.02 (8)	0.02 (4)
694.9 (5)	189 (50)		0.17 (3)	−0.04 (3)
739 (2) [a]	2 (2)			
771.6 (4)	619 (31)	0.028 (8)	0.18 (2)	−0.02 (4)
798 (2) [a]	62 (12)	0.088 (9)		
800 (2) [a]	44 (15)	0.088 (9)		
809.5 (4)	142 (7)	0.039 (8)	0.18 (4)	−0.10 (4)
884.6 (5)	120 (10)		0.16 (4)	0.00 (4)
931.4 (4)	271 (14)	0.075 (20)	0.23 (2)	−0.05 (2)
942.5 (6)	31 (8)	0.027 (45)	0.15 (6)	−0.06 (6)
950.1 (6)	41 (8)	0.028 (37)	0.10 (5)	−0.06 (5)
961.5 (6)	50 (8)	0.120 (15)	−0.17 (4)	0.08 (4)
1007.2 (5)	110 (6)	0.127 (33)	0.38 (3)	−0.16 (4)
1029.3 (6)	52 (8)	0.124 (34)	0.52 (6)	−0.16 (6)
1129.4 (5)	115 (6)	0.027 (19)	0.39 (3)	−0.13 (3)
1133 (2) [a]				
1158.3 (6)	28 (5)	0.055 (39)	0.49 (12)	−0.27 (10)
1212.3 (6)	77 (4)	0.007 (9)	−0.14 (4)	0.03 (4)
1215.6 (6)	111 (6)	−0.005 (3)	0.14 (6)	−0.02 (6)
1287.2 (8)	8 (3)		0.05 (15)	−0.22 (17)
1493.0 (6)	62 (12)	0.069 (19)	−0.11 (4)	−0.04 (4)
1527.8 (6)	19 (7)	−0.014 (30)	0.24 (8)	−0.08 (8)
1712.5 (8)	30 (11)	0.061 (17)	0.22 (12)	−0.07 (10)

[a] E_γ obtained from coincidence spectra only.

the slopes of the excitation-function curves of γ rays increase with increasing spin. Further evidence was obtained from systematics of other even-mass nuclei in this mass region, and from the fact that in heavy-ion reactions, γ-ray cascades usually proceed from higher to lower spin. It was assumed that the observed transitions were of $E1$, $M1$, or $E2$ multipolarity, and consequently that if a spin change of $\Delta J=2$ were established between two levels, then they have the same parity.

The dependence of the theoretical angular distribution coefficients on the physical parameters is given (see Ref. 14, for example) by

$$A_k = \alpha_k(J_i)B_k(J_i)\,[\,F_k(11J_i\,J_f) + 2\delta F_k(12J_i\,J_f) + \delta^2 F_k(22J_i\,J_f)]/(1+\delta^2)\,, \qquad (4)$$

where $\delta = \langle J_f | L_2 | J_i\rangle / \langle J_f | L_1 | J_i\rangle$ is the multipole mixing ratio defined for emission radiation in the phase convention of Biedenharn and Rose,[15] $\alpha_k(J_i)$ is the attentuation coefficient of the alignment,

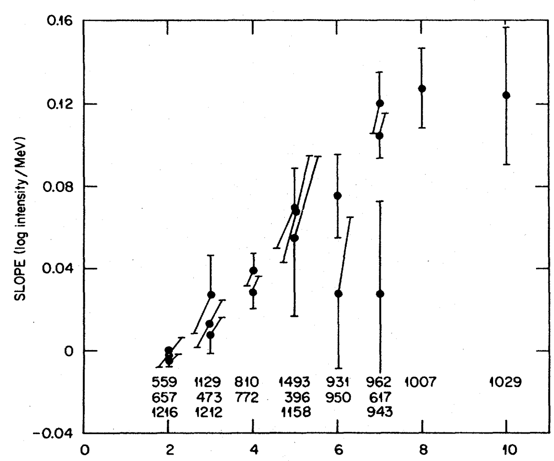

FIG. 4. Plot of the mean slope of the excitation function of a transition *versus* the spin of the initial level of the transition, shown for 18 transitions in ^{76}Se. The transition energies (in keV) are given in order below each group of points.

TABLE II. DCO ratios of γ rays from ^{76}Se. Numbers in parentheses indicate probable errors in the last significant figures.

E_{γ_1} (keV)	E_{γ_2} (keV)	$R(90°, 0°)$
395.9	1212.3	1.02 (24)
472.9	559.2	1.10 (17)
472.9	1215.6	1.4 (5)
617.0	395.9	1.0 (3)
771.6	559.2	0.79 (5)
931.4	771.6	1.07 (5)
1129.4	559.2	0.45 (8)
1158.3	771.6	1.01 (21)
1212.3	1215.6	2.0 (4)
1493.0	771.6	0.78 (21)

$B_k(J_i)$ is the statistical tensor for a system of nuclei completely aligned in a plane perpendicular to the beam direction, and the functions $F(L_1L_2J_iJ_f)$ are standard (see Ref. 14, for example). It is assumed that the population of magnetic substates can be described by a Gaussian function involving only one parameter, so that $\alpha_4(J_i)$ is uniquely related to $\alpha_2(J_i)$.

For possible values of the initial and final spins, the multipole mixing ratio δ and the attentuation parameter $\alpha_2(J_i)$ were varied in steps, and a goodness-of-fit index χ^2 was calculated at each step, where

$$\chi^2=[A_{2\,\mathrm{exp}}-A_{2\,\mathrm{cal}}(J_i,J_f,\delta,\alpha_2)]^2/\epsilon_{A_2}{}^2 + [A_{4\,\mathrm{exp}}-A_{4\,\mathrm{cal}}(J_i,J_f,\delta,\alpha_2)]^2/\epsilon_{A_4}{}^2\,, \quad (5)$$

and ϵ_{A_k} is the uncertainty in A_k. A value of χ^2 that corresponds to a probability of less than 1% in the event of a legitimate fit to the data was taken to exclude that combination of parameters.

For those cases in which a DCO ratio was obtained, an additional term

$$[R_{\mathrm{exp}}-R_{\mathrm{cal}}(J_i,J_f,\delta,\alpha_2)]^2/\epsilon_R{}^2$$

was included in the expression for χ^2. R_{cal} was calculated by the method discussed by Robinson *et al.*,[16] and is identically equal to 1.0 for a stretched spin cascade, such as $J+2\to J\to J-2$, independent of the value of α_2.

The 559.1-keV level. The spin-parity assignment of $J^\pi=2^+$ was well established from Coulomb excitation studies[17] and is in good agreement with our angular distribution results for the 559.2-keV γ ray.

The 1215.9-keV level. The spin-parity assignment of $J^\pi=2^+$ was well established from Coulomb excitation studies[18] and is in good agreement with our angular distribution results for 1215.6- and the 657.1-keV γ rays.

The 1330.7-keV level. The spin-parity assignment of $J^\pi=4^+$ was well established from Coulomb excitation studies[19] and is compatible with our angular distribution results for the 771.6-keV γ ray.

The 1688.7-keV level. The angular distribution of the 1129.4-keV γ ray is compatible with spins of $J=2$ and 4, but the DCO ratio for the 1129.4-559.2-keV cascade rules out $J=4$. (For $J=4$, R must equal 1.0.) The angular distribution of the 472.9-keV γ ray is compatible with $J=1$, 2, 3, and 4, as is the DCO ratio for the 472.9-1215.6-keV cascade. Thus, a spin of $J=2$ is indicated. However, Barclay *et al.*[6] assign this level a spin-parity of $J^\pi=3^+$ on the basis of the angular distribution of the 740-keV γ ray following the decay of oriented ^{76}As nuclei, and Nagahara[7] also makes the assignment of $J^\pi=3^+$ on the basis of the angular correlation of the 1130-559-keV cascade, and the log*ft* value of the level, from the decay of ^{76}As. From studies of other nuclei in this mass region, we expect a 3^+ state,[2] and the slopes of the excitation-function curves (Fig. 4) for both the 472.9- and the 1129.4-keV γ rays are consistent with a $J=3$ assignment. The cause of this inconsistency is not clear, although it could be due to an impurity peak in the 1129.4-keV γ ray, so we include both spins.

The 2025.5-keV level. The angular distribution of the 809.5-keV γ ray is compatible with $J=1$, 2, 3, and 4, and for the 694.9-keV γ ray, $J=2$, 3, 4, 5, and 6. The slope of the excitation-function curve (Fig. 4) for the 809.5-keV γ ray favors $J=4$. Lieder and Draper[4] have assigned this level $J^\pi=4^+$ on the basis of angular distributions of the 810- and 695-keV γ rays of ^{76}Se from the ^{74}Ge$(\alpha,2n)$ reaction.

The 2262.1-keV level. The angular distribution of the 931.4-keV γ ray is compatible with $J=4$ and 6, and the excitation-function curve (Fig. 4) favors $J=6$. Lieder and Draper[4] have deduced $J^\pi=6^+$ for this level on the basis of the angular distribution of the 932-keV γ ray of ^{76}Se from the ^{74}Ge$(\alpha,2n)$ reaction.

The 2428.1-keV level. The angular distribution of the 1212.3-keV γ ray is compatible with $J=1$, 2, and 3, as is the DCO ratio for the 1212.3-1215.6-keV cascade. The excitation-function slope (Fig. 4) favors $J=3$, although it is also compatible with $J=2$. Lin[5] observed a $J^\pi=3^-$ state at 2.45 MeV by (d,d') scattering on ^{76}Se, and Barrette *et al.*[8] identify this level as a $J^\pi=3^-$ state through Coulomb excitation studies.

The 2489.0-keV level. The angular distribution of the 1158.3-keV γ ray is compatible with $J=3$, 4, 5, and 6, but the χ^2 fits are not as good for $J=3$ and 5 as for $J=4$ and 6. The DCO ratio for

TABLE III. Properties of the energy levels of ^{76}Se. Numbers in parentheses indicate probable errors in the last significant figures.

Level (keV)	J^π	E_γ (keV)	Branching ratio	δ	τ (ps)	$\frac{\lambda}{\lambda_{sp}}$
559.1 (3)	2^+	559.2		∞	17.7 (4) [a]	44 (1) [a]
1215.9 (3)	2^+	657.1	69 (4)	$-0.48<\delta<-0.32$	4.9 (2) [a]	43 (1) [a]
		1215.6	31 (4)	∞		1.26 (5) [a]
1330.7 (4)	4^+	771.6		∞	2.19 (6) [a]	71 (2) [a]
1688.7 (4)	$2^+, 3^+$	472.9	25 (2)			
		1129.4	75 (2)			
2025.5 (5)	4^+	694.9	57 (7)	$-0.35<\delta<1.5$		
		809.5	43 (7)	∞	61^{+95}_{-10} [a]	$2.0^{+0.4}_{-1.2}$ [a]
2262.1 (6)	6^+	931.4		∞	1.0 (8)	61^{+250}_{-25}
2428.1 (6)	3^-	739	3 (3)			
		1212.3	97 (3)	$-5.7<\delta<0.12$		
2489.0 (7)	$4^+, 5^+$	800	61 (9)	(∞)		
		1158.3	39 (9)			
2617.9 (9)		1287.2				
2823.9 (6)	5^-	395.9	20 (4)	∞		
		798	40 (6)			
		1493.0	40 (6)	$-9<\delta<0.11$		
2975.6 (8)	(6^+)	950.1		(∞)	1.2 (4)	46^{+23}_{-12}
3043.2 (9)		1712.5				
3223.6 (8)	7	961.5		$-11<\delta<0.07$		
3262.0 (8)	4, 6	438.1				
3269.3 (8)	8^+	1007.2		∞	0.4 (2)	104^{+104}_{-35}
3431.5 (9)	$(6^+, 7^+)$	942.5		(∞)		
3440.9 (8)	7^-	617.0		∞		
3789.9 (8)		1527.8				
3853.4 (10)		584.1				
4298.6 (10)	(10^+)	1029.3		(∞)	0.8 (4)	46^{+46}_{-15}
4325.5 (9)	(9^-)	884.6		(∞)		
5432 (2)	(12^+)	1133		(∞)		

[a] From Ref. 8.

the 1158.3-771.6-keV cascade is compatible with all four of these possible spins. The excitation-function slope (Fig. 4) for the 1158.3-keV γ ray is consistent with an assignment of $J=4$ and 5. The 800-keV γ ray was not resolved from the 798-keV γ ray, and so its angular distribution was not obtained. Since this level branches to the 1688.7-keV, $2^+, 3^+$ level, we ruled out $J=6$.

The 2823.9-keV level. The angular distribution of the 395.9-keV γ ray is compatible with $J=2$, 3, 4, and 5, but the χ^2 fits are not as good for $J=2$ and 4 as for $J=3$ and 5. The angular distribution of the 1493.0-keV γ ray is compatible with $J=3$, 4, and 5. The excitation-function slopes (Fig. 4) for both of these γ rays favors $J=5$. From systematic studies of other nuclei in this mass region,[1,2] we expect a 5^- level to feed the 3^- level.

The 2975.6-keV level. The angular distribution of the 950.1-keV γ ray gave no definitive information about the spin of this level. It is tentatively assigned $J^\pi = 6^+$ from systematics, and it is noted that its excitation-function slope (Fig. 4) is low for this assignment.

The 3223.6-keV level. The angular distribution of the 961.5-keV γ ray is compatible with $J = 5$ and 7, and the excitation function slope (Fig. 4) strongly supports an assignment of $J = 7$.

The 3262.0-keV level. The angular distribution of the 438.1-keV γ ray is compatible with $J = 4$ and 6. The spin of $J = 6$ is preferred, since a transition is observed to the 5^- state, but not to the lower 3^- state. However, the excitation function slope suggests $J = 4$. Thus, the spin is either 4 or 6.

The 3269.3-keV level. The angular distribution of the 1007.2-keV γ ray is compatible with $J = 6$ and 8, and the excitation function slope (Fig. 4) favors $J = 8$. Lieder and Draper[4] identify this level as $J^\pi = 8^+$ on the basis of the angular distribution of the 1008-keV γ ray of ^{76}Se from the ^{74}Ge$(\alpha, 2n)$ reaction.

The 3431.5-keV level. The angular distribution of the 942.5-keV γ ray gave no definitive information about the spin of this level. It is tentatively assigned $J^\pi = 6^+, 7^+$, assuming that the 942.5-keV γ ray is a stretched-$E2$ transition. It is noted that the excitation function slope (Fig. 4) is low for this assignment.

The 3440.9-keV level. The angular distribution of the 617.0-keV γ ray is compatible with $J = 3$, 4, 5, 6, and 7, but the χ^2 fits are much better for $J = 5$ and 7 than for $J = 3$, 4, and 6. The excitation-function slope (Fig. 4) favors $J = 7$. From studies of other nuclei in this mass region, we expect a 7^- level to feed the 5^- level.

The 4298.6-keV level. The angular distribution of the 1029.3-keV γ ray is compatible with $J = 8$ and 10. This level is assigned $J^\pi = 10^+$ on the basis of systematics of ground-state bands in this mass region.

The 4325.5-keV level. The angular distribution of the 884.6-keV γ ray gave no definitive information about the spin of this level. It is tentatively assigned $J^\pi = 9^-$ from systematics.

The 5432-keV level. This level is tentatively assigned $J^\pi = 12^+$ from systematics.

IV. DISCUSSION

In Table III we have summarized the level properties of ^{76}Se. This table gives, for each level, the level energy, the spin and parity, the γ rays depopulating the level and their branching ratios, the multipole mixing ratio δ, the mean lifetime τ, and the ratio of the measured transition rate to the single-particle transition rate. The single-particle transition rates are the Weisskopf estimates[20] calculated with $r_0 = 1.2 \times 10^{-13}$ cm.

The levels and transitions of ^{76}Se are shown in Fig. 3. Many of the levels can be grouped into bands, based on their energy spacing and assigned spins. The most prominent band is the ground-state band, which is seen through the 12^+ member. The moment-of-inertia plot[21] of this band, shown in Fig. 5, does not exhibit the backbending observed in some of the nuclei in this mass region (see Refs. 1 and 2), but does have an upward bend between 8^+ and 10^+ before bending forward again at 12^+. The level spacing falls between that of a pure vibrational model, which would give a vertical line in the moment-of-inertia plot, and a rotational model with a constant moment of inertia, which would give a horizontal line.

In addition to the ground-state band, we also see an odd-parity band built on the 5^- 2823.9-keV state. Similar bands have been observed in ^{68,72}Ge, ^{74}Se, and ^{76,78,80}Kr (Refs. 22–27, respectively). Although the 3^- octupole state is included, it is more likely that the bandhead is the 5^- state, since then, both here and in the other nuclei mentioned, the relative spacing of the band members is closely correlated with that of the ground-state band, although the energy differences are consistently larger in the 5^- bands. This is apparent in the comparison given in Fig. 6. (See also the discussion in Refs. 1 and 2.)

A possible explanation of the 5^- bandhead is that it is formed by two rotational-aligned quasiparticles: one in the $g_{9/2}$ orbital and the other in either the $p_{1/2}$, $p_{3/2}$, or $f_{5/2}$ orbital. It is expected that the two quasi-particles are either both protons or both neutrons, since otherwise the

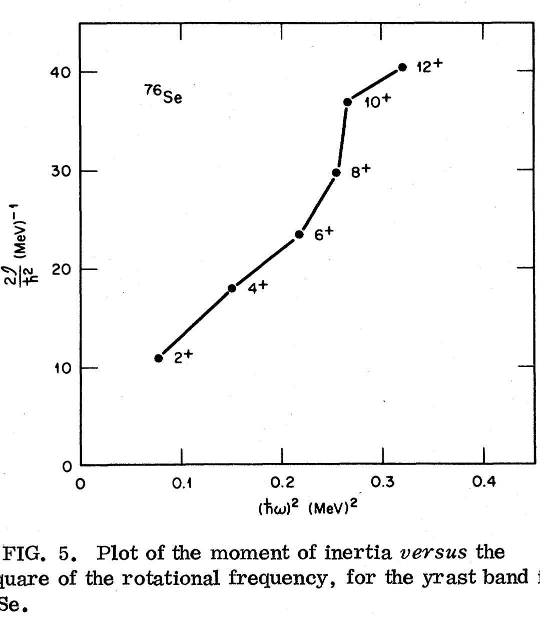

FIG. 5. Plot of the moment of inertia *versus* the square of the rotational frequency, for the yrast band in ^{76}Se.

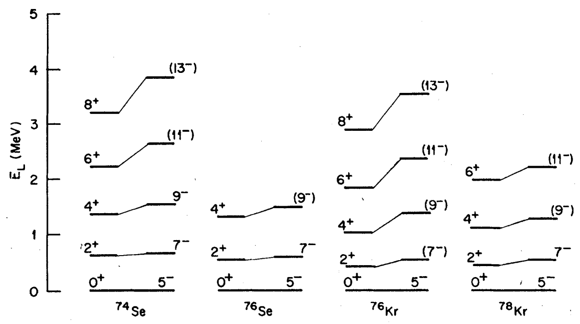

FIG. 6. Comparison of the yrast band with the 5^- band in ^{74,76}Se and ^{76,78}Kr.

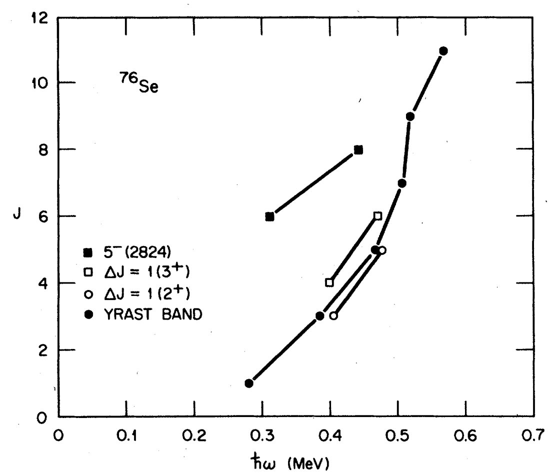

FIG. 7. Plot of average angular momentum *versus* rotational frequency for the yrast band, the $\Delta J=1$ band, and the odd-parity band built on the 5^- 2823.9-keV state in ^{76}Se. The $\Delta J=1$ (2^+) and $\Delta J=1$ (3^+) plots are, respectively, for even-spin and odd-spin members of the proposed $\Delta J=1$ band.

alignment would require the breaking of two pairs.

There is evidence for an even-parity band with $\Delta J=1$ character built on the second 2^+ state at 1215.9 keV. There is some uncertainty in the spins of the 1688.7-, 2489.0-, and 3431.5-keV levels, but if they do have spins of 3^+, 5^+, and 7^+ respectively, as is expected from systematics, then these levels, together with those at 1215.9, 2025.5, and 2975.6 keV, appear to be members of such a band. This type of band has been identified in ^{68}Ge, ^{74}Se, and ^{76,78,80}Kr (Refs. 22 and 24–27), and has several characteristic properties of a γ-vibrational band: (1) the bandhead is the second 2^+ state, (2) the band is a $\Delta J=1$ type, (3) the states decay primarily by skipped $E2$ transitions, (4) the level spacing at higher spins follows the $J(J+1)$ rule for even-spin levels and odd-spin levels separately, and (5) transitions to the ground-state band from higher members of this band are weak.

Bohr and Mottelson[28] have pointed out the usefulness of plotting the total angular momentum J *versus* the frequency $\hbar\omega(J)$ for a band, where

$$\begin{aligned}\hbar\omega(J)&=[E(J+1)-E(J-1)]/[(J+1)-(J-1)]\\&=[E(J+1)-E(J-1)]/2\,.\end{aligned}\qquad(6)$$

They propose that the vertical difference between the curve for a given band and the one for the ground-state band, $i_\alpha(\omega)$, gives a measure of the band's intrinsic spin. Peker, Rasmussen, and Hamilton[29] have shown that $i_\alpha(\omega)$ is not strictly related to the intrinsic band spin, but is strongly influenced by the properties of the ground-state band. While $i_\alpha(\omega)$ does not give definite information on the value of the alignment of the angular momentum on the rotation axis, the Bohr-Mottelson plots are, nevertheless, very useful in differentiating between different types of bands, such as rotational-aligned bands and bands strongly coupled to the deformation.

In Fig. 7 we show such a plot for the yrast band, the odd-parity band, and the $\Delta J=1$ band in ^{76}Se. The odd-parity band has an intrinsic spin $i_\alpha(\omega)$ of approximately 4, which supports a rotational-aligned picture. Both the even-spin and odd-spin members of the $\Delta J=1$ band have $i_\alpha(\omega)$ values very close to zero. This is consistent with the band's being a true γ-vibrational band, as is found in deformed rare-earth nuclei. The yrast band has an interesting shift between spins 6^+ and 10^+. Such a shift at these spins is clearly seen in ^{68}Ge where the neutron and proton $(g_{9/2})^2$ bands cross the ground-state band.[1,2] Thus, the shift in ^{76}Se may indicate that the higher-spin members of the yrast band are part of a rotational-aligned band. It may seem strange that the value of $i_\alpha(\omega)$, 4, is the same for both this band crossing the ground-state band and for the odd-parity band, because the latter band should have one particle in a lower j orbital. However, Peker *et al.*[29] have described how an odd-parity band may have an even larger value of $i_\alpha(\omega)$ than the even-parity band that crosses the ground-state band, when the two even-parity bands strongly mix.

Arima and Iachello[30] have proposed an interacting boson approximation (IBA) model, which provides a unified description of collective nuclear states in terms of a system of interacting bosons. These bosons are identified with fermion pairs coupled to $L=0$ (s) and to $L=2$ (d). Negative-parity states are formed, in this model, by the inclusion of one

TABLE IV. Energy levels of ^{76}Se calculated using the IBA model.

J^{π}	$E_{\gamma\,exp}$ (keV)	$E_{\gamma\,cal}$ (keV)	Difference (keV)
0^+	0	0	0
2^+	559	597	−38
4^+	1331	1332	−1
6^+	2262	2211	51
8^+	3269	3237	32
10^+	4299	4410	−111
12^+	5432	5730	−298
$0'^+$	1122 [a]	1123	−1
$2'^+$	1216	1190	26
$4'^+$	2025	1969	56
$6'^+$	2976	2881	95
3^+	1689	1842	−153
5^+	2489	2682	−193
7^+	3432	3657	−225
3^-	2428	2383	45
5^-	2824	2872	−48
7^-	3441	3494	−53
9^-	4326	4264	62

[a] From Ref. 3.

TABLE V. Reduced transition probabilities of transitions in ^{76}Se calculated using the IBA model. Numbers in parentheses indicate probable errors in the last significant figures.

$J_i^{\pi} \to J_f^{\pi}$	E_{γ} (keV)	$B(E2)_{exp}$ (e^2 fm^4)	$B(E2)_{cal}$ (e^2 fm^4)
$2^+ \to 0^+$	559	840 (20) [a]	840
$2'^+ \to 0^+$	1216	24 (1) [a]	24
$2'^+ \to 2^+$	657	820 (20) [a]	1134
$4^+ \to 2^+$	772	1360 (40) [a]	1389
$4'^+ \to 2'^+$	810	39^{+6}_{-24} [a]	827
$6^+ \to 4^+$	931	1170^{+4700}_{-470}	1648
$6'^+ \to 4'^+$	950	880^{+450}_{-220}	1125
$8^+ \to 6^+$	1007	1980^{+1980}_{-660}	1667
$10^+ \to 8^+$	1029	890^{+890}_{-300}	1487

[a] From Ref. 8.

$3^-(f)$ boson.

We have made calculations of level energies of positive- and negative-parity bands of ^{76}Se, and of $E2$ transition probabilities, using the computer codes PHINT and FBEM written by Scholten.[31] For ^{76}Se, there are seven active bosons, formed by three proton (particle) pairs and four neutron (hole) pairs outside of closed shells. In the program PHINT, energy levels were found by diagonalizing the Hamiltonian, and the values of the two-body matrix elements coupling the s and d bosons were adjusted in a least-squares fit to the experimental positive-parity level energies.

Values of the parameters in PHINT giving the best fit that we obtained are as follows (in MeV): HBAR$=0.617$, $C(0)=-0.065$, $C(2)=-0.077$, $C(4)=0.133$, $F=0.062$, and $G=-0.035$. (CH1 and CH2 were fixed equal to zero.) Transition probabilities were calculated by the program FBEM, using the eigenfunctions of the Hamiltonian with the above best-fit parameters, and were normalized to the experimental values for $B(E2;2^+\to 0^+)$ and $B(E2;2'^+\to 0^+)$. Values of the two parameters in FBEM are $E2SD=9.597$ $(e^2\mathrm{fm}^4)^{1/2}$ and $E2DD=-4.732$ $(e^2\mathrm{fm}^4)^{1/2}$. While fitting the positive-parity states, the level energies for the $0'^+$, 2^+, $2'^+$, 4^+, and 6^+ states were given weights proportional to $1/E_L$, while the other positive-parity level energies were given weights proportional to $0.1/E_L$.

Level energies calculated by the IBA model are compared with experimental values in Table IV. The calculated energies of the 10^+ and 12^+ states of the yrast band are larger than the measured values, and would produce less of an upward rise at 8^+ in the moment-of-inertia plot (Fig. 5) than is actually observed. The fact that these experimental 10^+ and 12^+ levels have energies less than the calculations suggests that they may not be members of the ground-state band, but could instead be members of a rotational-aligned band, as seems likely from our earlier discussion. It is interesting to note that, in the $\Delta J=1$ band, the energies of the even-spin members are all calculated to be lower than observed, while the energies of the odd-spin members are calculated to be higher.

Calculations of reduced transition probabilities are compared with experimental values in Table V. With the definite exception of the $4'^+\to 2'^+$ transition, the calculated values are all in reasonably good agreement with experimental results, although the calculated $B(E2)$ value for the $2'^+\to 2^+$ transition is somewhat high. We have thus fitted 13 positive-parity levels by adjusting six parameters, and have calculated nine transition probabilities by using only two additional parameters.

To obtain negative-parity energy levels, the matrix elements coupling the single f boson to the s and d bosons were adjusted in a least-squares fit to the experimental negative-parity level energies, which were given weights proportional to $1/E_L$.

Values of the parameters which we obtained are (in MeV) HBAR3 = 2.433, EPSD = − 0.050, K = − 0.083, and K' = − 0.153. [Values of other parameters which depend on K and K' are $F3$ = 0.119, $D(1)=0.258$, $D(2)=0.245$, $D(3)=0.080$, $D(4)=-0.226$, and $D(5)=-0.059$.]

It is seen in Table IV that the IBA model fitted the four negative-parity states more or less equally well, perhaps in part because four parameters were being used to fit four experimental values. We have included the calculation here mainly for completeness. We should also point out the fact, which was discussed earlier, that it seems likely that the 5^- state is the bandhead of a rotational-aligned band. This version of the IBA model is not able to treat such a situation. It is possible that the 5^-, 7^-, and 9^- states are members of a rotational-aligned band which only accidentally falls near the 3^- octupole state.

V. CONCLUSION

We have found evidence in ^{76}Se for several bands: (1) the ground-state band, (2) an odd-parity band built on a 5^- state, and (3) a $\Delta J=1$ band which has the characteristics of a γ-vibrational band in a deformed nucleus. The 5^- bandhead of the odd-parity band may be formed by two rotational-aligned quasiparticles. The higher-spin members of the yrast band may be part of a rotational-aligned band that crosses the ground-state band.

Calculations of level energies and transition probabilities were made using the interacting boson approximation model. With a few exceptions, the agreement of the calculations with the experimental results is reasonably good.

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