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Level structure of ^{70}Se

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The level structure of ^{70}Se was studied via the ^{58}Ni(^{14}N,pn)^{70}Se reaction at a beam energy of 38 MeV. Measurements were made of γ-ray singles and γ-γ coincidence spectra, γ-ray angular distributions, and γ-γ directional correlations. Level energies, decay modes, spins and parities, γ-ray mixing ratios, and γ-ray branching ratios were deduced. The levels in the yrast band through 8^+, a tentative second (0^+) state at 2011.2 keV, and a 3^- state at 2519.2 keV are some of the new results obtained from the present investigation. The moment-of-inertia plot shows a break around 6^+ for the yrast levels, which is attributed to band crossing. Interacting boson approximation calculations were performed and are compared with the experimental values for the energy levels.

[NUCLEAR REACTIONS ^{58}Ni(^{14}N,pn)^{70}Se, $E=38$ MeV; measured E_γ, I_γ, $\gamma(\theta)$, $\gamma\gamma(\theta)$; ^{70}Se deduced levels, J, π, δ, γ branching.]

I. INTRODUCTION

In recent years, in-beam γ-ray spectroscopy studies via heavy-ion induced reactions have played an important role in developing a deeper understanding of the structure of the nucleus. For several years the Vanderbilt-ORNL group has been involved in a systematic investigation of the even-even nuclei in the $A=60-80$ mass region including Ge,[1,2] Se,[3-7] and Kr (Refs. 8 and 9) isotopes. A wide variety of collective band structures are observed. The coexistence of different shapes in the same nucleus, both forward-bending and back-bending of the moment of inertia for the yrast cascades in different nuclei, and negative-parity and γ-type-vibrational bands are some of the important results we have obtained in this region.[10-12] However, not all of these types have been observed in all of the nuclei belonging to this mass region, and there appear to be significant differences as N and Z vary. Indeed, this mass region is now seen as an important testing ground for nuclear models because of the richness of the motions observed and the rapidity of their changes for small changes in N and Z.

Even-parity and odd-parity bands have been observed in ^{72,74,76}Se.[3-7] The results in ^{72}Se provided important evidence for shape coexistence[3] with bands built on a near spherical ground state and a deformed excited 0^+ state. The anomalous behaviors of the first excited 0^+ states which fall at 937 and 854 keV (75 and 219 keV above the first excited 2^+ states) in ^{72}Se and ^{74}Se, respectively, gave important clues for suggesting a coexistence picture.[3,6] The first excited 0^+ states in these nuclei have been interpreted as heads of bands built on more strongly deformed shapes. The yrast levels in ^{72}Se are characterized as vibrational at low spins and rotational at high spins with the same trends observed in ^{74}Se. The levels of ^{76}Se (Ref. 7) were found to lie somewhat between vibrational and rotational character.

To help unravel our understanding of the structure of even-even Se nuclei with increasing neutron deficiency, we have investigated the levels in ^{70}Se by in-beam γ-ray spectroscopy via the ^{58}Ni(^{14}N,*pn*)^{70}Se reaction at a beam energy of 38.0 MeV. In a previous study[13] of this nucleus, only the first 2^+ (945.4-keV), the second 2^+ (1601.3-keV), and 4^+ (2039.6-keV) levels were identified. Subsequent to our preliminary report of our results,[10,15] Wadsworth *et al.*[14] published their results on ^{70}Se. Our more complete work agrees well with their results except for the 3525.2 keV level which they assign as (5^-), whereas our assignment is (4) for this level. Details of our results concerning ^{70}Se, based on the measurements of γ-ray singles and γ-γ coincidence spectra, γ-ray angular distributions $\gamma(\theta)$, and γ-γ directional correlations, are reported in this paper. Interacting-boson-approximation[16] (IBA) calculations were also performed for both even-parity and odd-parity energy states.

II. EXPERIMENTAL PROCEDURES AND RESULTS

An enriched target of 15-mg/cm^2-thick ^{58}Ni on a natural nickel backing was bombarded with 38-MeV ^{14}N ions extracted from the ORNL EN tandem accelerator. In-beam γ-ray experiments involving singles γ-ray spectra, γ-γ coincidences, angular distribution of γ-rays $\gamma(\theta)$, and gamma-gamma directional correlation, were performed. The γ-ray detection was accomplished by two large volume Ge(Li) detectors with a resolution of 2.5 keV at 1.33 MeV and an efficiency of 18% of a 7.6 cm $\times$ 7.6 cm NaI detector.

The singles γ-ray spectrum following the reaction ^{58}Ni(^{14}N,*pn*)^{70}Se measured at 55° with respect to the beam direction is shown in Fig. 1. Energies of the γ rays assigned to ^{70}Se are given. In addition, strong peaks that belong to other isotopes are marked in the figure. Gamma-gamma coincidence measurements were made with two Ge(Li) detectors placed at 0° and 90° with respect to the beam direction, at 5 cm from the target. The coincidence events were stored on a magnetic tape as a 1024×1024 matrix for subsequent analysis. Selected coincidence spectra, corrected for background, are shown in Fig. 2. The angular distribution yields of the γ rays were measured at 0°, 55°, and 90° with respect to the beam direction with a Ge(Li) detector. A second Ge(Li) detector placed at 225° served as a monitor. A ^{226}Ra source was placed at the target position after the conclusion of the experiment to determine the magnitude of the

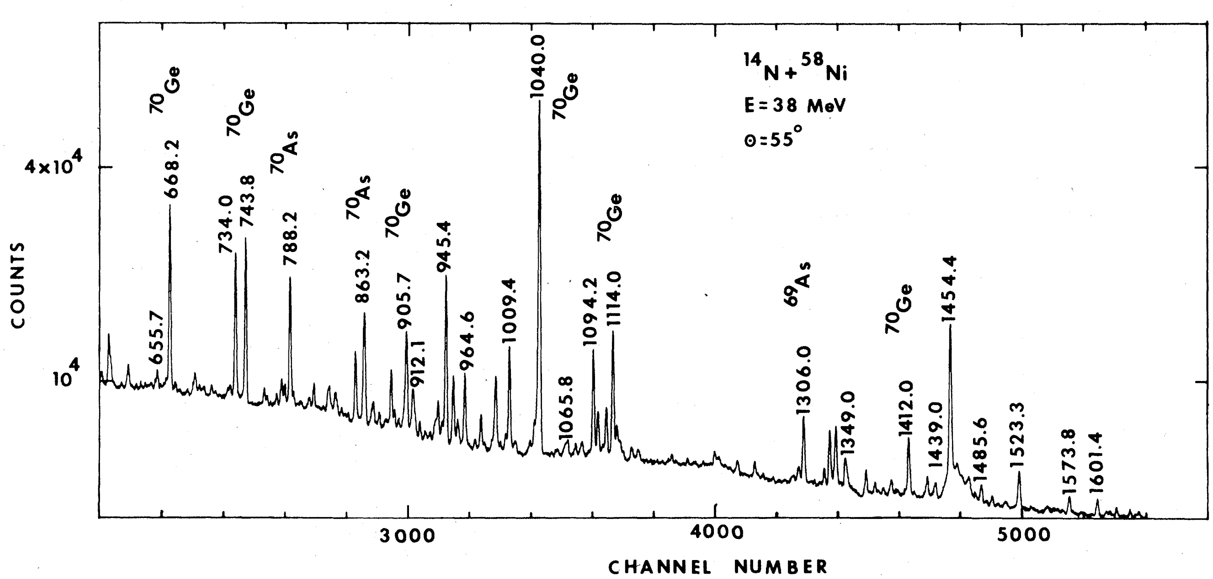

FIG. 1. In-beam singles gamma-ray spectrum from the ^{58}Ni(^{14}N,*pn*)^{70}Se reaction at a beam energy of 38 MeV. Energies are in keV and those photopeaks which are labeled only with energies are assigned to ^{70}Se.

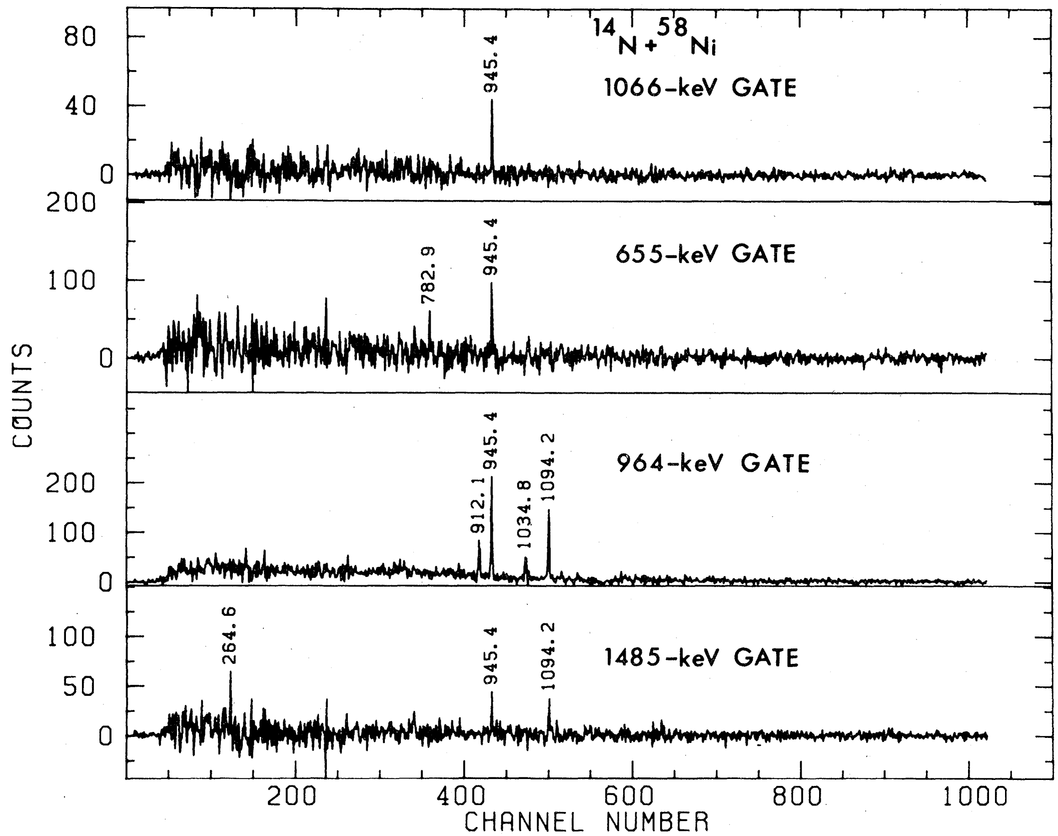

FIG. 2. Illustration of typical γ-γ coincidence gated spectra of transitions in ^{70}Se. Each spectrum is corrected for background.

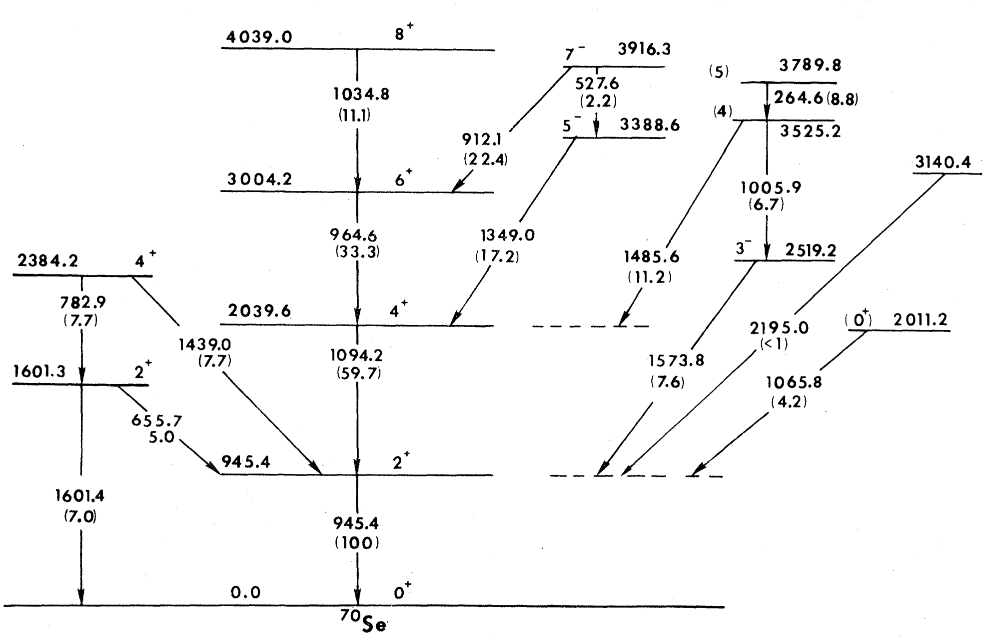

FIG. 3. The decay scheme of ^{70}Se as deduced from the present investigation. Energies are in keV. The relative intensities of γ transitions are given in parenthesis.

TABLE I. Angular distribution coefficients of γ rays from the reaction ^{58}Ni(^{14}N,pn)^{70}Se at 38 MeV. The spins, parities, multipolarities, and mixing ratios are also given.

E_{level}	E_γ	A_2	A_4	$J_i \rightarrow J_f$		Multipolarity	$\delta(Q/D)$
3790	264.6	−0.281 (58)	0.087 (69)	(5)	(4)	$E2$	
3916	527.6	0.236 (105)	−0.121 (134)	7^-	5^-	$E2$	
1601	655.7	−0.229 (49)	0.019 (71)	2^+	2^+	$M1, E2$	$-1.0^{+0.1}_{-0.2}$
2384	782.9	0.30 (10)	−0.20 (9)	4^+	2^+	$E2$	
3916	912.1	−0.226 (31)	+0.071 (34)	7^-	6^+	$E1, M2$	-0.15 ± 0.05
945	945.4	0.172 (16)	−0.077 (20)	2^+	0^+	$E2$	
3004	964.6	0.181 (18)	−0.040 (22)	6^+	4^+	$E2$	
3525	1005.9	−0.164 (25)	0.069 (31)	(4)	3^-		$-0.06^{+0.09}_{-0.02}$
2011	1065.8	−0.038 (101)	0.210 (113)	(0^+)	2^+	$E2$	
2040	1094.2	0.218 (19)	−0.083 (22)	4^+	2^+	$E2$	
3389	1349.0	−0.052 (28)	−0.092 (34)	5^-	4^+	$E1, M2$	+0.12 (large uncertainty)
2384	1439.0	0.194 (64)	−0.172 (76)	4^+	2^+	$E2$	
2519	1573.8	−0.360 (46)	−0.054 (54)	3^-	2^+	$E1, M2$	-0.26 ± 0.15
1601	1601.4	0.177 (57)	−0.113 (70)	2^+	0^+	$E2$	

correction for the target's not being at the exact center of rotation of the table. This source also was used to determine the efficiency and energy calibrations of the two Ge(Li) detectors.

The levels of ^{70}Se, their energies and decay modes as deduced from the present measurements, are summarized in Fig. 3. The energies and relative intensities of the γ rays are also given in Fig. 3. The errors in the determination of relative intensities range from 5% to 20%, depending on the strength of the transition.

The angular distribution data were fitted to the polynomial

$$W(\theta)=1+\sum_{k=2,4} Q_k A_k P_k(\cos\theta)$$

in order to determine the angular distribution coefficients A_k. $W(\theta)$ is the normalized γ-ray intensity at the angle θ with respect to the beam direction and the Q_k's are the solid angle corrections. The experimental A_k in their final form are given in Table I, together with the assigned spin sequences. The mixing ratio of a γ-ray transition is defined as

TABLE II. Experimental and theoretical DCO ratios of γ rays from ^{70}Se.

E_{γ_1}	E_{γ_2}	R_{exp}	Spin sequence	R_{theor}[a]	δ
1094	945	0.9 (1)	$4\rightarrow2\rightarrow0$	1.0	
964	1094	1.16 (15)	$6\rightarrow4\rightarrow2$	1.0	
912	964	1.75 (38)	$7\rightarrow6\rightarrow4$	1.7 (1)	−0.15 (5)
1035	964	0.89 (23)	$8\rightarrow6\rightarrow4$	1.0	
1573	945	1.00 (25)	$3\rightarrow2\rightarrow0$	1.0 (1)	−0.26 (15)
1439	945	0.68 (24)	$4\rightarrow2\rightarrow0$	1.0	
1485	1094	0.82 (23)	$4\rightarrow4\rightarrow2$	0.93 (7)	1.35 (35)[b]
1349	1094	2.44 (1.18)	$5\rightarrow4\rightarrow2$	1.38 (23)	0.12
1066	945	0.82 (20)	$0\rightarrow2\rightarrow0$	1.0	
783	655	0.52 (18)	$4\rightarrow2\rightarrow2$	0.50 (2)	
655	945	1.72 (34)	$2\rightarrow2\rightarrow0$	1.8 (2)	$-1.0^{+0.1}_{-0.2}$

[a]Calculated using α_2 and δ values deduced from the angular distribution measurements of Table I.
[b]This δ value is deduced from the experimental DCO ratio.

$\delta = \langle f || T(Q) || i \rangle \,/\, \langle f || T(D) || i \rangle$ and is in the phase notation of Biedenharn and Rose.[17] Experimental values of δ were determined by a least squares fitting procedure for a given spin sequence by using the values of $A_k^{\max}$ and $\alpha_k (= A_k / A_k^{\max})$ with the help of the tables of Yamazaki.[18] The δ values and the multipolarities of the γ transitions are also summarized in Table I.

Directional-correlation-from-oriented-nuclei (DCO) ratios were extracted from the data on γ-γ coincidences. The experimental DCO ratio is defined as

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

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. In the present study, the choice of the angles was $\theta = 0°$ and $\theta = 90°$. DCO ratios for a number of cascade γ rays from ^{70}Se are given in Table II. The theoretical DCO ratio for a spin sequence $J+2 \to J \to J-2$ is unity, independent of the values of α_2.

III. LEVEL AND γ-RAY PROPERTIES

Prior to our work, little was known[19] about the levels of ^{70}Se. We have placed 13 levels in the decay scheme of ^{70}Se as shown in Fig. 3, of which ten are proposed for the first time. Spin-parity assignments for each level and the multipole character of gamma transitions were deduced on the basis of $\gamma(\theta)$ and DCO measurements and systematics. The values of α_2 and α_4 which may be deduced from Table I are smaller than the values normally found in this mass region. It is interesting to note that this is a common feature for both ^{70}Se and ^{80}Kr, which are four neutrons to either side of the $N=40$ subshell. In the following, the spin-parity assignments of each level are explained.

The 945.4-keV level. Both the angular distribution and DCO results give a 2^+ assignment, which is in agreement with the previous one.[13]

The 1601.3-keV level. The angular distributions of the 655.7- and 1601.4-keV transitions depopulating this level, as well as the DCO ratio of the 655.7 – 945.4-keV cascade, support the previous 2^+ assignment.[13]

The 2011.2-keV level. The angular distribution of the 1065.8-keV transition depopulating this level is consistent with a $4 \to 2$ transition, but has large errors. Since it would be unusual to find three 4^+ states so close in energy, we prefer another assignment. Since the angular distribution is isotropic we suggest a tentative assignment of (0^+) for this level.

The 2039.6-keV level. The angular distribution of the 1094.2-keV transition from this level and the DCO ratio of the 964.6 – 1094.2-keV cascade suggest a $\Delta J = 2$ character. These data support the previous 4^+ assignment.[13]

The 2384.2-keV level. The A_2 and A_4 values of the 782.9-keV transition, although large, along with those of the 1439.0-keV transition depopulating this level, allow a spin-parity assignment of 4^+. The experimental DCO ratio value for the 1439.0 – 945.4-keV cascade is unity within the experimental errors (Table II), in agreement with the theoretical value for a $4 \to 2 \to 0$ spin sequence. Thus, a 4^+ assignment is made to this level.

The 2519.2-keV level. The $\gamma(\theta)$ of the 1573.8-keV transition from this level to the final 2^+ (945.4-keV) level indicates a $\Delta J = 1$ character. The DCO results do not give any definitive information about the spin. A spin of 3 is assigned based on the $\gamma(\theta)$ value and systematics. In even-even Ge, Se, and Kr nuclei 3^- levels are seen at an energy around 2500 keV. Thus, we suggest a 3^- assignment for this level. The energy of this level in ^{70}Se is compatible with the systematics of 3^- level energies of even-even Se isotopes, as shown in Fig. 4. The data for the other Se isotopes were taken from Refs. 3, 6, and 7.

The 3004.2-keV level. Both the $\gamma(\theta)$ of the 964.6-keV transition from the decay of this level and the DCO ratio of the 964.6 – 1094.2-keV cascade yield an assignment of 6^+ to this level.

The 3140.4-keV level. Coincidence data show that this level feeds the first 2^+ state at 945.4-keV through a 2195-keV γ ray. This transition is too weak for $\gamma(\theta)$ and DCO measurements to make a spin assignment for this level.

The 3388.6-keV level. The angular distribution of the 1349.0-keV transition depopulating this level, as well as the DCO ratio of the 1349.0 – 1094.2-keV cascade, permit a spin assignment of 5. The energies of 5^- levels of even-even nuclei for A around 70 lie in the vicinity of 3300 keV. A spin-parity assignment of 5^- to the 3388.6-keV level is compatible with the 5^- energy levels for even-even Se nuclei, as shown in Fig. 4.

The 3525.2-keV level. The DCO ratio of the 1485.6 – 1094.2-keV cascade allows spin assignments of 3 to 6, while the A_2 and A_4 values of the

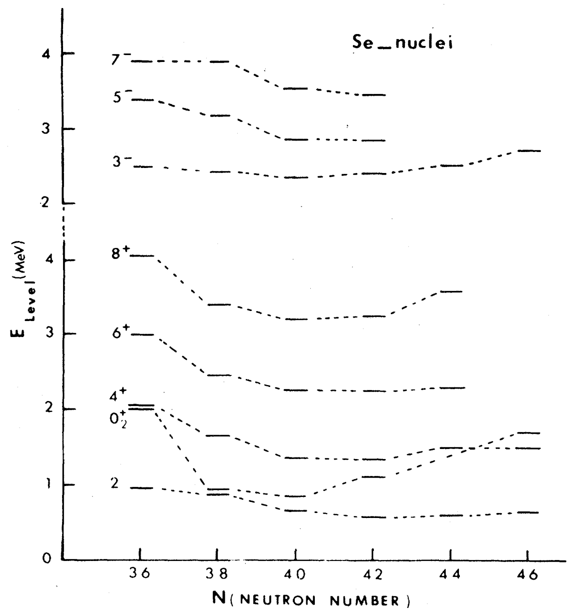

FIG. 4. Energy-level systematics for even-parity and odd-parity states in even-even Se isotopes.

1005.9-keV transition from this level indicate a $\Delta J=1$ character. These data yield a spin assignment of 4 but do not fix the parity.

The 3789.8-keV level. The angular distribution of the 264.6-keV transition from this level to a final level with spin 4 favors a spin assignment of 5.

The 3916.3-keV level. The DCO ratio of the 912.1–964.6-keV cascade favors spin values of 5 and 7. The angular distribution of the 912.1-keV transition from this level is also consistent with the assignments 5 and 7. However, the A_2 and A_4 values of the 527.6-keV transition from this level to the final 5^- level allow a $\Delta J=2$ character. Together these results give a spin assignment of 7. A negative parity is preferred since no $M2$ transitions around this energy are seen in the neighboring even-even nuclei. An assignment of 7^- is also compatible with the systematics shown in Fig. 4.

The 4039.0-keV level. The 1034.8-keV γ ray coming from this level appears to be a doublet with a γ ray from ^{70}Ge. The $\gamma(\theta)$ measurements yielded no definitive spin information. The experimental DCO ratio of the 1034.8–964.6-keV cascade is unity (Table III) within the experimental errors, favoring a spin sequence $8\to6\to4$ for the cascade. The coincidence intensities of the cascade transitions in the 1034.8-keV gate also indicate that this level is a member of the yrast band. These data and the systematics of this region, as shown in Fig. 4, strongly favor an assignment of 8^+ for the 4039.0-keV level.

IV. IBA CALCULATIONS

Arima and Iachello[15] 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 $L=2$ (d). Negative-parity states are formed in this model by including one 3^- (f) boson. We have performed calculations of level energies of positive-parity and negative-parity states of ^{70}Se by using the computer code PHINT[20].

TABLE III. Energy levels of ^{70}Se calculated in an IBA model.

J^π	$E_{exp.}$ (keV)	$E_{cal.}$ (keV)	Difference (keV)
0^+	0	0	0
2^+	945	978	33
4^+	2039	1992	−48
6^+	3004	3041	37
8^+	4039	4034	−5
(0^+)	2011	1957	−54
2^+	1601	1632	32
4^+	2385	2474	89
3^-	2519	2461	−58
5^-	3388	3331	−57
7^-	3916	3927	+11

For ^{70}Se there are seven active bosons formed by three proton (particle) pairs and four neutron (particle) pairs outside of the $N=28$ closed shell. In the program PHINT, energy levels were found by diagonalizing the IBA 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. Only the three energies of the experimental levels 2^+, 2_2^+, and 4^+ (Fig. 3) were used in the fit, while the other positive-parity energy levels were predicted by the fitting parameters.

Values of the parameters in PHINT giving the best fit are the following (in MeV): HBAR $= 0.978$, $C(2)=-0.325$, and $C(4)=0.035$. The other parameters, F, G, CH1, and CH2 were set equal to zero in as much as they are not important in the SU(5) limit. While fitting the positive-parity states, the level energies for the 2^+, 2_2^+, and 4^+ states were given weights proportional to $1/E_L$. Positive-parity level energies calculated by the IBA model are compared with the experimental values in Table III. Thus, we have obtained seven excited positive-parity levels by adjusting three 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 the weights proportional to $1/E_L$.

Values obtained for the parameters are the following in (MeV): HBAR3 $= 2.519$, EPSD $=-0.127$, $k=-0.188$, $k'=0.166$. Values of parameters which depend on k and k' are the following: $F3=0.224$, $D(1)=0.376$, $D(2)=0.364$, $D(3) = -0.013$, $D(4)=-0.344$, $D(5)=0.034$. Negative-parity level energies calculated by the IBA model are compared with experimental values in Table III.

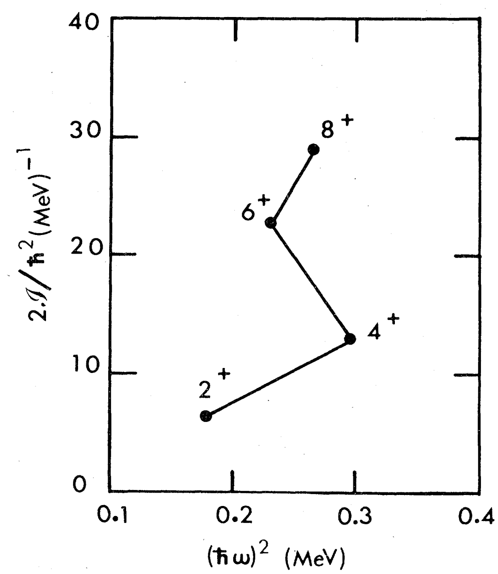

FIG. 5. Plot of the moment-of-inertia versus the rotational frequency squared for the even-spin yrast band.

V. DISCUSSION

The level scheme of ^{70}Se shown in Fig. 3 contains a number of new features. The yrast band is seen up to 8^+ and the energy level spacings of the yrast band are quite unusual. The moment-of-inertia plot, which is $2\mathscr{I}/\hbar^2$ versus the rotational frequency squared, is given in Fig. 5 for the yrast levels. Here $\mathscr{I}$ does not exhibit the smooth trends seen in ^{72,74}Se or other nearby nuclei. There is a big break at 6^+. It could be associated with the crossing of the ground state band (GSB) by a rotation-aligned band built on a $(f_{5/2})^2$ or on a $(g_{9/2})^2$ configuration as seen in ^{68}Ge.[2] It is possible that there are other levels perturbing the first 2^+ level, as discussed below. The very low energy of the first excited 0^+ levels in ^{72}Se and ^{74}Se led to the interpretation of the coexistence of states[3,6] built on a near spherical ground state and a deformed shape with a band built on the 0_2^+ state associated with it. The tentative (0^+) state observed at 2011.2 keV is strikingly higher in energy than the 0_2^+ in ^{72}Se. Earlier[14] we reported tentative evidence for an excited 0_2^+ level at 711 keV based on coincidence data. The in-beam electron spectrum of ^{70}Se was studied at the University of Köln and no evidence was found for an $E0$ transition at 711 keV.[21] Presumably, the alternative interpretation[14] that these transitions (which were thought to be associated with a 0_2^+ state in ^{70}Se) are in another isotope is correct. There could still be another 0^+ state which has not been seen. The dip in the 0_2^+ level positions in ^{72}Se and ^{74}Se may be a sharp function of a shape transition around the $N=40$ shell closure.[22]

The 3^- state at 2519.2 keV is in accordance with the energies of similar states in this mass region and with those of Se nuclei shown in Fig. 4, and accordingly, it may be regarded as an octupole vibrational state. It is seen from Fig. 4 that a strong correlation exists between the energies of the

5^- and 7^- levels in ^{70}Se and other isotopes of selenium with little correlation with the 3^- levels. The negative-parity states 5^- and 7^- are similar to those seen[3,6–8] as members of excited bands in ^{68}Ge, ^{74,76}Se (see Fig. 4), and ^{76,80}Kr. Two quasiparticle plus rotor calculations for ^{68}Ge (Ref. 2) and ^{80}Kr (Ref. 8) indicate that these bands are formed by one particle in the $g_{9/2}$ orbital and the other in either the $p_{1/2}$, $p_{3/2}$, or $f_{5/2}$ orbitals with a 5^- bandhead. The 3^- level in ^{70}Se cannot be a member of this excited band, as it is much too far away from the 5^- and 7^- levels. This is consistent with the interpretations of 5^- levels as bandheads of the negative parity bands in nearby nuclei.

We see only two possible candidates, the 2_2^+ and 4_2^+ levels for a gamma-type band. Typically such gamma-type bands with $\Delta J = 1$ character are seen to spin up to 11^+ in other nuclei in this mass region. One of the further problems in this work is the lack of Doppler shifts of the γ rays and the low values of the alignment parameters. These features are common to our work in ^{80}Kr which have four neutrons more than the $N = 40$ subshell closure. This could suggest some type of isomeric feeding, but such a hypothesis needs further testing.

The even-parity level energies calculated by the IBA model show reasonable agreement with the experimental energies, as seen in Table III, to support the collective nature of these states. However, as the fluctuations in the fit show, the calculation does not reproduce the oscillation in the moment of inertia seen in Fig. 5. It is seen in Table III that the IBA model fitted the three observed negative-parity states more or less equally well, but this is not meaningful because four parameters were used to fit three experimental values. This calculation is mainly included for completeness. As already discussed earlier, the 5^- state is more likely to be the bandhead of a two quasiparticle plus rotor band, in which case the IBA model cannot be applied to those negative-parity states.

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