Intruder structures in ^{75}Se

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High-spin states in ^{75}Se were populated via the ^{48}Ti(^{30}Si,2pn)^{75}Se thin-target reaction at 90 MeV and studied using γ-γ techniques. The $\pi=+$ band was extended to the $(\frac{41}{2}^+)$ level, and a return was observed to the larger signature splitting characteristic of the lower-spin states. Two separate band structures were observed above the band crossing in the negative-parity bands, as in ^{77}Kr. [S0556-2813(99)05202-4]

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The role of quasiparticles (qp) in intruder and unique-parity orbitals in the $A\approx80$ region has recently been studied rather extensively. The unique-parity $g_{9/2}$ orbital plays a large role in the structure of yrast and near yrast high-spin states in this region, and band-crossings are invariably interpreted as due to alignments of a pair of $g_{9/2}$ particles. Quasiparticles in these low-K Nilsson orbitals arising out of the $g_{9/2}$ and the intruder $d_{5/2}$ and $h_{11/2}$ spherical shells often have very strong γ-driving effects, and can lead to large values of β_2. In the cases of ^{77}Kr [1] and ^{81}Sr [2] high deformation has been attributed to the strong polarizing effects of the $[431]\frac{1}{2}$ Nilsson state arising out of the $d_{5/2}$ intruder orbital.

Strong similarities as well as illuminating differences have been observed among the $N=41$ isotones [3]. A highly-deformed negative-parity band with properties somewhat intermediate between those of normal and superdeformed rotational structures was recently observed in $^{77}_{36}$Kr$_{41}$ [1]. A neutron in the $[431]\frac{1}{2}$ orbital arising from the $d_{5/2}$ sub-shell appears to help drive this $3qp$ structure to high deformation ($\beta_2\approx0.37$). A previous investigation of $^{75}_{34}$Se$_{41}$ [3] gave hints of a possible forking behavior in the high-spin region of the negative-parity sequences, leading to the possiblility of a highly-deformed 3qp structure in this nucleus.

An interesting signature-splitting pattern has been observed in the yrast positive-parity bands of ^{75}Se and ^{77}Kr. Changes in signature splitting with qp alignments have been interepreted as due to changes in the triaxiality shape parameter γ caused by competition between the opposing γ-driving effects of quasineutrons and quasiprotons. Before the present work, the yrast band of ^{75}Se was not known in the 5qp region, where inverted signature splitting was predicted.

The present investigation of the high-spin structure of ^{75}Se was undertaken to look for a possible high-lying, highly-deformed negative-parity band and to explore signature splitting in the 5qp region of the yrast positive-parity sequence. Earlier investigations [4,5] into low-spin states of ^{75}Se through β-decay studies of ^{75}Br provided the initial level scheme information for this nucleus. Further exploration [6] established high-spin states, populated up to $\frac{21}{2}^+$ and $\frac{15}{2}^-$, in the ^{72}Ge(α,n) reaction. The latest [3] investigation extended the positive-parity sequence to $(\frac{29}{2})$ and the negative-parity to $\frac{19}{2}$ in the ^{59}Co(^{19}F,2pn) thick-target reaction. Lifetime measurements for eleven states were performed.

In the present investigation of ^{75}Se high-spin states were populated in the ^{48}Ti(^{30}Si,2pn) reaction using a 90 MeV ^{30}Si beam from the Florida State University Tandem-LINAC facility. The 190 μg/cm^2 thick target was enriched to 99% in ^{48}Ti. Prompt γ-γ coincidences were detected using the Pitt-FSU combined detector array [7] with ten Compton-suppressed Ge detectors, and analyzed using the RADWARE [8] software. Results are summarized for selected levels and decays, with energies, intensities, multipolarities, DCO ratios, and spin assignments in Table I. I_γ is normalized to the intensity of the 801 keV $\frac{13}{2}^+\rightarrow\frac{9}{2}^+$ yrast decay, whose value was set to 100. Altogether 21 new transitions were identified, two tentatively, leading to 15 new excitation states, of which one is tentative. The present level scheme is shown in Fig. 1. Placement in the level scheme was determined from relative intensities and coincidence relationships.

In the usual method, DCO ratios were obtained by gating, whenever possible, on known electric quadrupole transitions, and these ratios are found in column R^1_{DCO}. It was necessary to use the strong $\frac{3}{2}^-\rightarrow\frac{5}{2}^+$286 keV transition for determining many of the multipolarities in the negative-parity structures. The DCO of this unstretched electric-dipole transition when gated by an $E2$ is predicted to be ≈0.74 if there were intervening $\Delta I=1$ transitions, and ≈0.7 otherwise. This is consistent with the measured value of 0.71(6). When the 286 keV transition is itself used as the determining gate, $E2$ transitions should have a DCO ratio of ≈1.41, and an unmixed $M1$ should have a DCO ratio of ≈0.70. DCO ratios measured in this way appear in column R^2_{DCO}. Multipolarities of the transitions were assigned based on the DCO ratios where possible, and on systematics where not. In the latter cases, the spins are shown in parentheses where no previous assignments were found in the literature.

The present work confirms previous [3–6] results in the yrast positive-parity sequences (bands 1 and 2). Three additional transitions, of energies 1395, 1578, and 1795 keV were added to the $\alpha=+\frac{1}{2}$ signature, with DCO ratios obtained for the first two consistent with stretched $E2$ transi-

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TABLE I. Energies, intensities, and DCO ratios of selected states and γ decays in ^{75}Se.

E_x (keV)	I_i^π	I_f^π	E_γ (keV)	I_γ	R^1_{DCO}	R^2_{DCO}
5474.9	$\frac{29}{2}+$	$\frac{25}{2}+$	1276.9(4)	10	0.92(8)	
		$\frac{27}{2}+$	644.2(10)	4	0.56(6)	
6869.5	$\frac{33}{2}+$	$\frac{29}{2}+$	1394.6(16)	6	1.06(10)	
8447.0	$\frac{37}{2}+$	$\frac{33}{2}+$	1577.5(18)	3	0.95(13) [a]	
10242.0	$(\frac{41}{2}+)$	$\frac{37}{2}+$	1795.0(20)	2		
6171.5	$\frac{31}{2}+$	$\frac{27}{2}+$	1341.1(10)	10	1.03(14)	
		$\frac{29}{2}+$	696.5(10)	3	0.55(7)	
7754.9	$\frac{35}{2}+$	$\frac{31}{2}+$	1583.4(18)	5	0.95(13) [a]	
2870.5	$\frac{17}{2}-$	$\frac{13}{2}-$	966.6(2)	8	1.08(10)	1.67(19)
3883.5	$\frac{21}{2}-$	$\frac{17}{2}-$	1013.0(20)	3		1.47(22)
(5036.3)	$(\frac{25}{2}-)$	$\frac{21}{2}-$	[1152.8(10)]	1		
3430.1	$\frac{19}{2}-$	$\frac{15}{2}-$	1040.8(10)	5	0.96(24) [a]	
		$\frac{17}{2}-$	560.7(10)	2	0.36(11)	0.72(16)
4471.0	$\frac{23}{2}-$	$\frac{21}{2}-$	1040.1(10)	4	0.96(24) [a]	
5584.7	$(\frac{27}{2}-)$	$\frac{23}{2}-$	1113.7(10)	2		
3288.4	$\frac{19}{2}-$	$\frac{15}{2}-$	898.8(10)	14		1.68(24)
4268.7	$\frac{23}{2}-$	$\frac{19}{2}-$	978.5(10)	4		1.37(13)
2839.0	$\frac{17}{2}-$	$\frac{13}{2}-$	935.1(1)	12	1.02(15)	1.53(15)
		$\frac{15}{2}-$	449.6(1)	8	0.77(15)	0.77(6)
3304.5	$\frac{19}{2}-$	$\frac{17}{2}-$	465.4(1)	8	0.56(9)	0.70(8)
		$\frac{15}{2}-$	[915(1)]	1		1.71(49)
3644.9	$\frac{21}{2}-$	$\frac{17}{2}-$	806.1(1)	9	0.98(8)	1.37(12)
		$\frac{19}{2}-$	340.4(1)	9	0.52(9)	0.68(6)
		$\frac{17}{2}-$	774.6(10)	2	0.80(20)	
		$\frac{19}{2}-$	357.2(10)	4		0.81(11)
4705.2	$\frac{25}{2}-$	$\frac{21}{2}-$	1060.3(2)	5	1.10(31)	1.52(24)
		$\frac{23}{2}-$	439.0(20)	2		0.93(12)
6057.9	$\frac{29}{2}-$	$\frac{25}{2}-$	1352.7(10)	4		1.42(19)
7648.1	$\frac{33}{2}-$	$\frac{29}{2}-$	1590.2(10)	2		1.73(28)

[a]Combined DCO ratio of doublet.

tions. This extends the favored band (1) to 10242 keV at $J^\pi=(\frac{41}{2}^+)$. The $\alpha=-\frac{1}{2}$ signature (band 2) has been extended by two transitions, of energies 1341 and 1583 keV, to an excitation energy of 7755 keV, with firm spin assignments based on DCO ratios of near unity establishing a spin and parity of $J^\pi=\frac{35}{2}^+$ for this state. Two additional $M1$ transitions, of energies 644 and 697 keV, connecting the signature partners were likewise added to the level scheme. Also found was a 1424 keV transition, in clear coincidence with yrast decays up to the $\frac{25}{2}^+$ level at 4198 keV. As this transition is also in strong coincidence with the yrast sequence in ^{75}Br and no continuation of a side-feeding band based on this transition was found, it was not shown in the level scheme.

As discussed in previous investigations, the positive-parity bands are built on the $\nu g_{9/2}$ unique-parity orbital $[422]\frac{5}{2}^+$ in both ^{75}Se [3] and ^{77}Kr [9,10]. In these nuclei the first band crossing has been interpreted as a $\pi g_{9/2}$ pair alignment due to neutron Pauli blocking. The proton alignment in ^{77}Kr had been observed [10] at a rotational frequency range of $\hbar\omega=0.5$ to 0.6 MeV for the $\alpha=+\frac{1}{2}$ signature, with a much sharper alignment at $\hbar\omega\approx 0.5$ MeV for the $\alpha=-\frac{1}{2}$

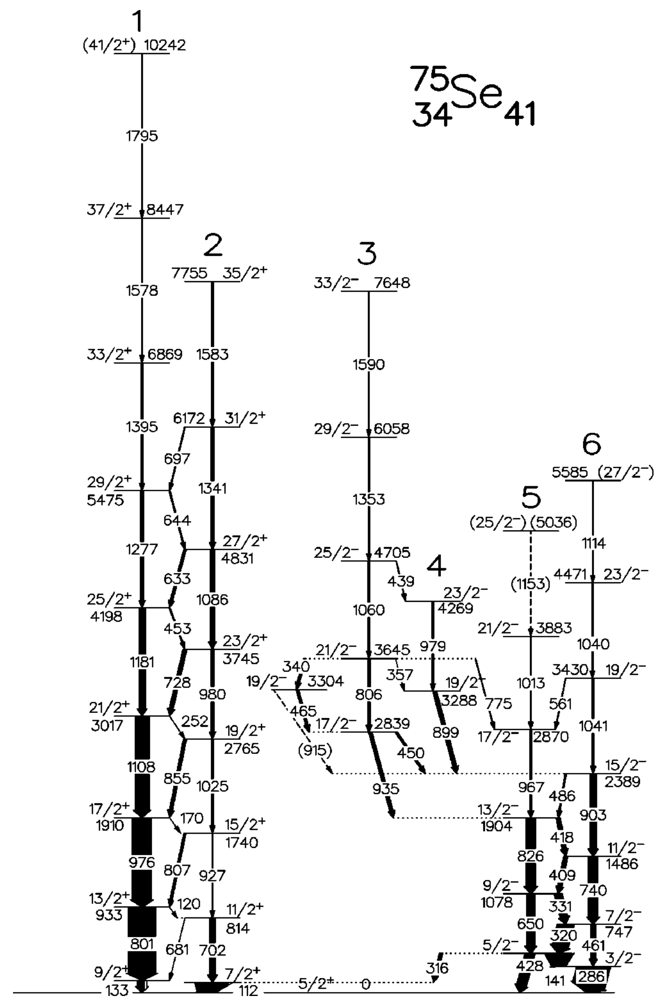

FIG. 1. The level scheme of ^{75}Se deduced from the present work.

signature. The observed crossing frequency in ^{75}Se [3] for the $\alpha=+\frac{1}{2}$ signature occurs over the same range as seen in in ^{77}Kr, whereas the $\alpha=-\frac{1}{2}$ crossing was observed [3] to occur sharply at a slightly lower value of $\hbar\omega$ just under 0.5 MeV. The previously predicted [3] second alignment of a $\nu g_{9/2}$ pair has been observed for the first time in ^{75}Se in the present work, at $\hbar\omega\approx 0.8$ MeV.

Figure 2 shows the normalized energy differences, calculated as $[E(I)-E(I-1)]/2I$ and plotted as a function of angular momentum, for the positive-parity bands in ^{77}Kr and ^{75}Se. A return to increased signature splitting at the $\frac{35}{2}^+$ state has been observed for the first time in ^{75}Se. The overall signature splitting pattern now appears qualitatively similar to that of ^{77}Kr, although there are some quantitative differences. The pattern is also similar to what has been seen in the $N=43$ isotones ^{77}Se [11] and ^{79}Kr [12].

These changes in signature splitting have been interpreted for ^{77}Kr [9,10] and ^{75}Se [3] as due to changes in the triaxiality shape parameter γ. Quasineutrons lying higher in the $g_{9/2}$ shell tend to drive the nuclear shape toward the negative-γ direction, while quasiprotons lower in the shell lean towards the positive-γ direction. This ''tug-of-war'' varies with the balance of quasiparticles, which changes with each subsequent pair alignment from an extra neutron to an extra proton and back to an extra neutron. A signature inversion

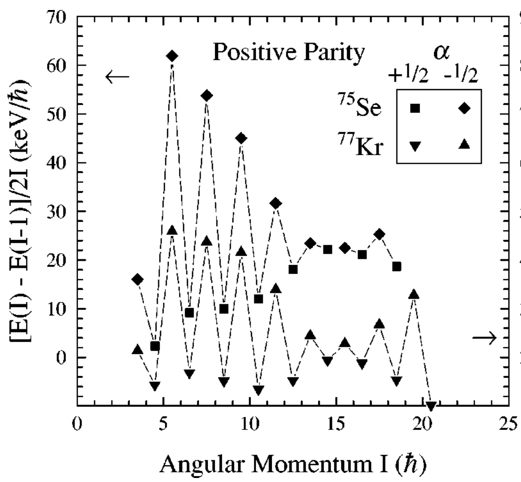

FIG. 2. Normalized energy differences $[E(I)-E(I-1)]/2I$ in the positive-parity bands in ^{75}Se and ^{77}Kr. The signature α is indicated in the legend.

with the $\alpha=-\frac{1}{2}$ signature favored was predicted [3] to occur at high ($\hbar\omega\geqslant 0.65$ MeV) frequency. Although a reduction is seen in the measured signature splitting, the inversion does not occur, and at the higher frequencies an increase in the normal signature splitting is observed. This would be consistent with a return of γ to negative values in the 5qp region, rather than the predicted change to $\gamma\approx 30°$.

The latest [3] investigation established the negative-parity sequence (bands 5 and 6) to $\frac{19}{2}^-$, and at the highest spins there was found to be a duplication of states, with two each

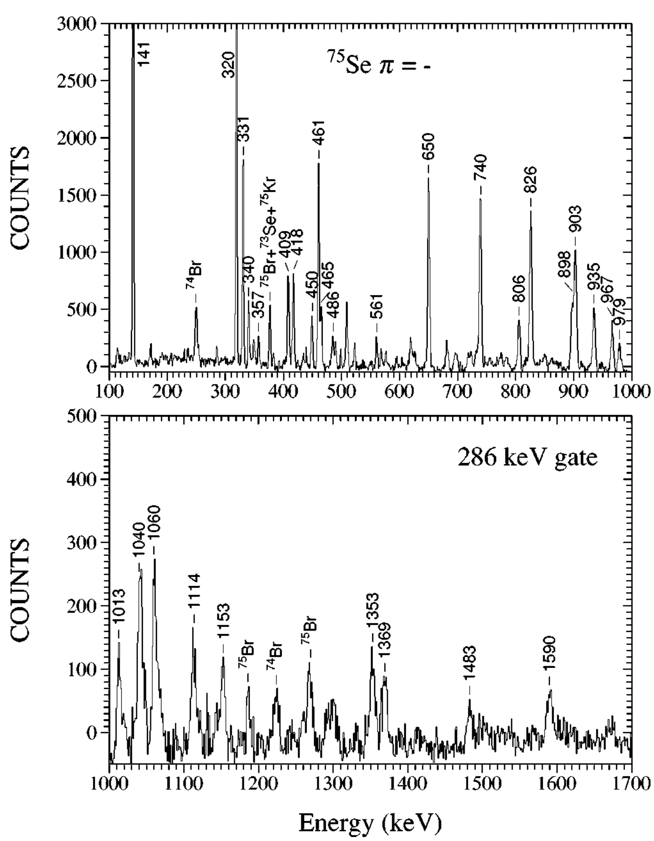

FIG. 3. The spectrum of γ rays in coincidence with the 286 keV $\frac{3}{2}^-\rightarrow\frac{5}{2}^+$ transition in ^{75}Se.

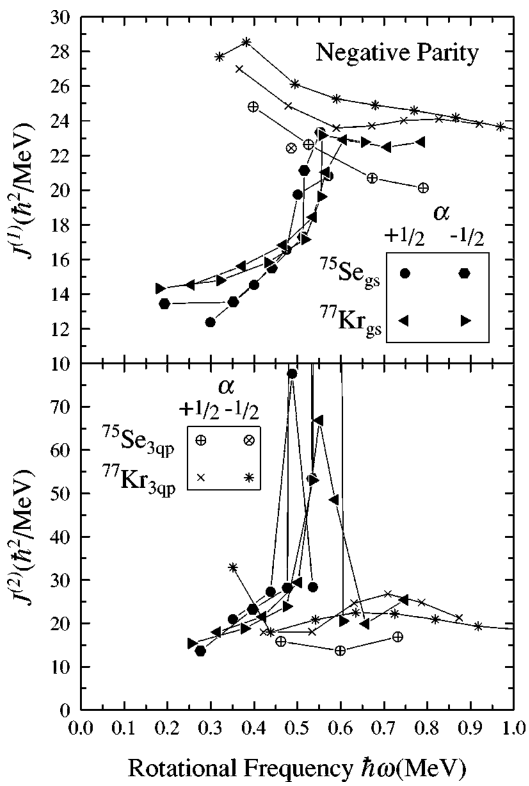

FIG. 4. Kinematic $J^{(1)}$ and dynamic $J^{(2)}$ moments of inertia for the negative-parity bands in $N=41$ isotones ^{75}Se and ^{77}Kr. The subscript ''gs'' refers to bands 5 and 6 in ^{75}Se, while ''3qp'' refers to bands 3 and 4.

of the $\frac{17}{2}^-$ and $\frac{19}{2}^-$ levels, though the spin and parity of the level decaying via a 1041 keV transition was only tentatively assigned.

The present work confirms these levels, including the duplication of spin states. Each of these branches was extended. The 1041 keV line was found to be a doublet of two stretched $E2$ transitions. An 1114 keV transition feeds into this doublet, extending band 6 to 5585 keV with a tentative assignment of $J^\pi=(\frac{27}{2}^-)$. A stretched $E2$ transition of energy 1013 keV feeds into the $\frac{17}{2}^-$ state at 2870 keV, extending band 5 to 3883 keV. A 1153 keV transition is tentatively placed as feeding into this new level, but could not be unequivocally placed due to relatively weak statistics and contamination from competing channels. These two bands, based on energy spacings, are believed to be the extension of the low spin structure after the band crossing. All of the negative-parity transitions, both old and new, may be observed in the spectrum of γ-rays coincident with the 286 keV transition, seen in Fig. 3.

The rest of the new transitions seen in Fig. 3 were found to feed predominately into the states previously established above the 935 and 899 keV transitions. The $\alpha=-\frac{1}{2}$ signature (band 4) was extended by one transition of 979 keV feeding the $\frac{19}{2}^-$ state at 3288 keV, and the $\alpha=+\frac{1}{2}$ sequence (band 3) by four transitions, with energies of 806, 1060, 1353, and 1590 keV feeding the $\frac{17}{2}^-$ state at 2839 keV. A 1369 keV transition, though in coincidence with many of the negative-parity transitions, could not be placed in the level scheme.

These new sequences (bands 3 and 4) show some similarities with the high-lying highly deformed bands found in ^{77}Kr [1]. Though the more highly populated signature in the high-lying bands in ^{77}Kr is opposite to that of ^{75}Se, both sequences appear more deformed and are more strongly populated than the ground-state sequences in their respective nuclei above the band crossing. Like its ^{77}Kr counterpart, this sequence ‘‘bleeds out’’ to various available negative-parity states.

Figure 4 shows the kinematic (top panel) and dynamic (bottom panel) moments of inertia for the negative-parity bands of ^{75}Se and ^{77}Kr. The behaviors of both nuclei are rather similar. The first crossing in the $\alpha=+\frac{1}{2}$ signature for ^{75}Se occurs over a range of $\hbar\omega=0.45$ to 0.5 MeV, in a reasonably gradual fashion, which is consistent with previous results [3]. The alignment in ^{77}Kr [1] is likewise gradual, delayed relative to ^{75}Se by about 0.05 MeV. The alignments in the $\alpha=-\frac{1}{2}$ signatures for both nuclei are sharp, again occuring about 0.05 MeV earlier in ^{75}Se ($\hbar\omega\approx 0.50$ MeV), relative to ^{77}Kr ($\hbar\omega\approx 0.55$ MeV). This alignment has been interpreted [9] as a $g_{9/2}$ proton band crossing on top of the $\nu[301]\frac{3}{2}^-$ ground-state configuration [13].

The curves for the moments of inertia for the excited 3qp structures in both nuclei are almost identical. Specifically, the kinematic and dynamic moments are very regular, showing little evidence of alignments. The kinematic moments see a gradual reduction at higher frequencies, but remain above the moments for the ground-state sequences, whereas the dynamic moments are almost flat.

As was the case in ^{77}Kr, the new band in ^{75}Se is not observed below an energy region where known bands show their first alignments. This is an indicator that the new structures are inherently three quasiparticle in nature. These states decay weakly out of band. The $B(E2)$ strengths for the decays out of the new bands in ^{77}Kr [1] were found to be significantly weaker than those for the in-band transitions. In the single case where an $E2$ branching was observed in ^{75}Se, the $B(E2)$ strength for the out-of-band decay from the 3645 keV $\frac{21}{2}^-$ state was found to be 18% of that of the in-band decay.

An additional $\frac{19}{2}^-$ state at 3304 keV connected with the new band structure was seen in ^{75}Se. No counterpart is known in ^{77}Kr.

Thus, like ^{77}Kr, these new bands in ^{75}Se appear to have a 3qp structure not closely related to the lower lying bands, and capable of driving the shape to a higher degree of deformation than the other known bands — but not to a 2:1 axis ratio. In analogy to the intruder structure in the heavier isotope, a possible configuration for the excited 3qp band in ^{75}Se is $\nu[431]\frac{1}{2}^+\otimes\pi[312]\frac{3}{2}^-\otimes\pi[440]\frac{1}{2}^+$.

In summary, high-spin states in ^{75}Se were populated with the ^{48}Ti(^{30}Si,$2pn$) reaction at 90 MeV and observed using the Pitt-FSU γ-detector array. The yrast positive-parity band was extended into the 5qp region where the signature splitting was found to differ from earlier predictions. A new 3qp negative-parity band structure was observed. Various properties, such as a higher, more constant moment of inertia and weak decays out of band, are similar to those of a highly-deformed band recently observed in ^{77}Kr.

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