Stability of oblate shapes in the vicinity of $N=Z=34$ ^{68}Se: Bands in ^{69}Se and ^{67}As

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The γ-ray decay schemes of ^{69}Se and ^{67}As have been considerably extended using the ^{40}Ca(^{32}S,$2pn$)^{69}Se and ^{40}Ca(^{32}S,αp)^{67}As reactions at 100 MeV and ^{40}Ca(^{36}Ar,$\alpha 2pn$)^{69}Se and ^{40}Ca(^{36}Ar,$2\alpha p$)^{67}As reactions at 145 MeV, with the aim of studying oblate bands arising from the strong coupling of a valence $g_{9/2}$ particle (or hole) to the oblate deformed ground state band of ^{68}Se. A new $T_{1/2}=12\pm2$ ns $J^\pi=9/2^+$ isomeric bandhead was identified in ^{67}As. A transitional quadrupole moment of $Q_0=-2.7(6)$ eb was deduced for the band built on the $9/2^+$ isomer in ^{69}Se, corresponding to a rigid oblate deformation of $\beta_2=-0.4(1)$, consistent with theoretical predictions. However, it appears that the relevant oblate configurations in ^{69}Se and ^{67}As are not nearly so favored as they are in ^{68}Se, and are rapidly crossed by prolate configurations that form the high spin yrast lines.

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I. INTRODUCTION

The observation of configurations associated with oblate shapes in nuclei is relatively rare despite naive expectations that would suggest roughly equal probabilities for the occurrence of oblate and prolate shapes based on the frequency of deformation-stabilizing down-sloping high-j orbitals for both shapes [1]. The reason for the suppression of oblate deformation is subtle and lies in the higher order effects both in liquid drop terms and residual interactions that all favor prolate shapes. Consequently, very strong oblate-driving shell effects are needed to overcome this tendency. The special configurations leading to oblate shapes are worthy of detailed investigation. Even in the few cases where an oblate shape does occur, rotational bands associated with the oblate shape are quickly supplanted by competing prolate configurations with larger moments of inertia, since an oblate spheroid rotating about an axis perpendicular to the symmetry axis has the lowest moment of inertia of all possible shapes.

Long standing predictions of a stable oblate minimum for $N=Z=34$ were recently confirmed by the observation of an oblate ground state band in ^{68}Se [2]. This configuration competes successfully with a prolate rotational band as it is more tightly bound by around 1 MeV so the crossing to energetically favored prolate shapes does not happen till $J\sim8\hbar$. The ground state band exhibits no back bending in the range that it is observed; an observation fully consistent with an oblate assignment. This successful study of ^{68}Se was partly prompted by earlier studies of ^{69}Se where indications of oblate shapes were found [3,4]. In the present work, we come full circle, and revisit ^{69}Se as well as ^{67}As, in a study of oblate bands and their competition with higher moment-of-inertia prolate configurations at high spin.

II. PREVIOUS WORK

The low-lying states in ^{69}Se are well known. Indeed, states in ^{69}Se were initially reported independently by three groups a decade ago. In the earliest of these papers in the literature, Wiosna *et al.* reported excited states in ^{69}Se [3]. Their identification employed an array of 11 compton-suppressed germanium detectors operated in conjunction with an eightfold neutron multiplicity filter. The principal features of their proposed level scheme included an isomeric $9/2^+$ state on which was built a band consisting of two $E2$ transitions and four competing mixed $M1/E2$ transitions. They were unable to extend the $g_{9/2}$ band beyond the $17/2^+$ state with the available statistics and were, hence, unable to examine the high spin behavior of the band. In a contemporary measurement, Ramdane *et al.* used a pair of Ge(Li) detectors and six neutron detectors to study ^{69}Se [5]. They assigned transitions to ^{69}Se on the basis of excitation functions and n-γ, n-γ-γ coincidences. Their work reported only five transitions that they could place with confidence in the level scheme of ^{69}Se. Arrison *et al.* independently confirmed the observations of both Wiosna *et al.* and Ramdane *et al.*, although their level scheme was less extensive than that of the former work [4]. They used charged particle as well as neutron coincidences to establish which γ rays were in ^{69}Se, thereby making their assignment firmer than the other two works that relied only on neutron-multiplicity arguments and expectations of the magnitude of the cross section. They also lacked sufficient statistics to extend the $g_{9/2}$ band beyond the $17/2^+$ level.

^{67}As has been less extensively investigated. Lang *et al.* studied ^{67}As "in-beam" and found a rotational band built on a postulated $9/2^+$ state as well as some irregular states parallel to this band [6]. A β-decay study of ^{67}Se found decays to the ground state and an excited state [7]. However, the

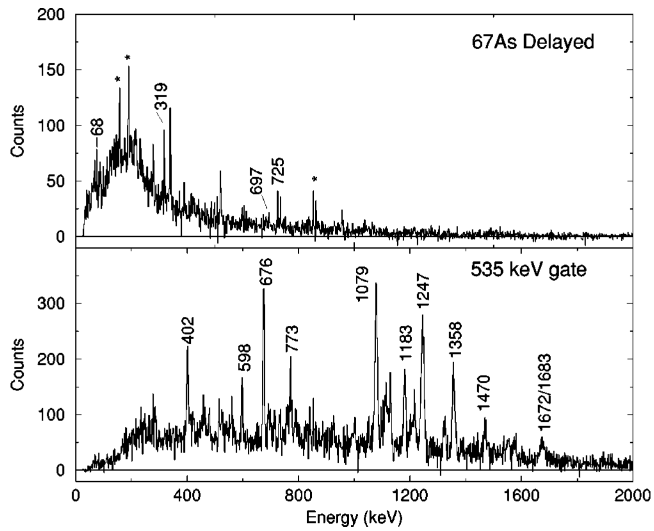

FIG. 1. Top: Delayed γ-ray spectrum for events where two α particles and one proton were detected. Delayed γ rays in ^{67}As are labeled. Those marked with an asterisk are contaminants from ^{68}As. Bottom: γ-ray spectrum of prompt transitions in ^{69}Se in coincidence with the delayed 535-keV γ ray.

excited state populated in the β decay did not coincide with any of the states known from the in-beam study and it was not possible to establish spins and parities for these states.

III. EXPERIMENTAL DETAILS

The present data on ^{69}Se and ^{67}As is extracted from two complementary measurements. The first experiment was primarily intended to locate new nanosecond isomers in the $A\sim70$ region. An ^{36}Ar beam accelerated to 145 MeV by the ATLAS accelerator at Argonne National Laboratory was incident on a thick ^{40}Ca target. ^{69}Se and ^{67}As were produced via the ^{40}Ca(^{36}Ar,$\alpha 2pn$) and ^{40}Ca(^{36}Ar,$2\alpha p$) reactions, respectively. The target consisted of 400 μg/cm^2 of ^{40}Ca covered on the front and back with 100 μg/cm^2 of gold to prevent oxidation. Recoiling nuclei were stopped 1 mm downstream of this target in a 15 mg/cm^2 thick gold foil. The second source of information on ^{69}Se and ^{67}As made use of a 100-MeV beam of ^{32}S incident on the same ^{40}Ca target as before, with the reactions of interest in this case being ^{40}Ca(^{32}S,$2pn$)^{69}Se ^{40}Ca(^{32}S,αp)^{67}As. However, the gold stopper foil was removed and, hence, the recoiling nuclei were not stopped. The resulting γ decay was detected by the Gammasphere array in this case consisting of 80 HPGe detectors. The forward five rings of germanium detectors were removed so that an array of 30 neutron detectors could be included. The Microball array of 95 CsI detectors was used to provide charged particle detection [8].

The ^{36}Ar data set was searched for the presence of new isomers. Transitions of 319, 725, 697, and 69 keV, previously associated with the decay of ^{67}As were observed in a delayed γ-ray spectrum with the additional particle condition that two alphas and one proton were detected (top of Fig. 1). This observation implies that the previously known 1422-keV level in ^{67}As is isomeric. By correlating the delayed γ rays

TABLE I. Energies, intensities relative to the 1358-keV γ ray and angular correlation ratios R of prompt γ rays in ^{69}Se. Assignments are made on the basis of angular correlation ratios, or where unobtainable, intensity and systematics (see text).

E_γ (keV)	I_γ	R	$J_i^\pi \to J_f^\pi$
57.2(2)	185(21)		$19/2^{(-)} \to 17/2^{(-)}$
117.3(4)	33(4)		$23/2^{(-)} \to 21/2^{(-)}$
128.4(1)	313(18)	0.49(12)	$3/2^- \to 1/2^-$
402.8(3)	342(25)	0.54(5)	$13/2^+ \to 11/2^+$
408.3(3)	10(2)		$17/2^+ \to (15/2^+)$
411.4(2)	358(23)	0.38(7)	$17/2^{(-)} \to 15/2^{(-)}$
448.1(2)	114(9)		$19/2^{(-)} \to (15/2^-)$
468.4(1)	155(21)	0.94(8)	$19/2^{(-)} \to 15/2^{(-)}$
597.8(2)	452(18)	0.46(5)	$21/2^{(-)} \to 19/2^{(-)}$
676.1(1)	770(52)	0.87(8)	$11/2^+ \to 9/2^+$
714.9(3)	190(20)	1.06(8)	$23/2^{(-)} \to 19/2^{(-)}$
762.7(3)	42(5)		$(27/2^-) \to (25/2^-)$
772.0(2)	95(6)		$15/2^{(-)} \to 11/2^-$
772.9(1)	458(34)	1.11(11)	$(15/2^+) \to 11/2^+$
786.4(1)	120(14)	0.88(14)	$7/2^- \to 3/2^-$
807.7(2)	311(18)	0.80(13)	$15/2^{(-)} \to 11/2^-$
840.2(4)	112(16)		$(15/2^+) \to 13/2^+$
876.3(1)	40(5)		$7/2^- \to 5/2^-$
877.3(3)	47(6)		$17/2^+ \to (15/2^+)$
994.7(3)	126(15)	0.81(13)	$7/2^- \to 3/2^-$
997.2(3)	91(8)		$25/2^{(-)} \to 23/2^{(-)}$
1001.6(4)	221(20)		$(29/2^+) \to (25/2^+)$
1079.6(1)	1426(84)	1.03(8)	$13/2^+ \to 9/2^+$
1081.3(3)	125(7)		$(29/2^-) \to (25/2^-)$
1084.6(3)	106(15)		$7/2^- \to 5/2^-$
1115.1(3)	319(21)	1.08(7)	$(25/2^-) \to 21/2^{(-)}$
1130.3(1)	446(14)		$29/2^+ \to 25/2^+$
1155.1(3)	68(5)		$(33/2^-) \to (29/2^-)$
1155.5(2)	28(5)		$(9/2)^- \to 5/2^-$
1182.5(1)	692(20)	0.94(12)	$25/2^+ \to 21/2^+$
1182.8(4)	130(10)		$15/2^{(-)} \to (15/2^+)$
1204.2(2)	143(9)		$(15/2^-) \to (15/2^+)$
1218.5(4)	96(6)		$(33/2^-) \to (29/2^-)$
1241.3(3)	36(7)		$11/2^- \to (9/2)^-$
1242.3(4)	227(16)		$(15/2^+) \to 11/2^+$
1247.3(3)	1415(17)	1.05(9)	$17/2^+ \to 13/2^+$
1275.2(2)	259(15)		$(11/2^-) \to (7/2^-)$
1324.2(4)	39(4)		$(37/2^-) \to (33/2^-)$
1358.0(1)	$\equiv 1000$	1.04(3)	$21/2^+ \to 17/2^+$
1409.3(3)	18(3)		$(41/2^-) \to (37/2^-)$
1470.0(2)	286(15)	1.11(5)	$33/2^+ \to 29/2^+$
1484.6(4)	48(7)		$11/2^- \to 7/2^-$
1501.2(2)	79(5)		$(29/2^-) \to (25/2^-)$
1521.8(4)	48(6)		$11/2^- \to 7/2^-$
1553.6(5)	279(10)	0.50(6)	$15/2^{(-)} \to 13/2^+$
1578.0(3)	228(11)		$(25/2^+) \to 21/2^+$
1672.2(6)	45(5)		$(41/2^+) \to (37/2^+)$
1682.6(4)	146(8)		$(37/2^+) \to 33/2^+$
1761.7(4)	81(8)		$(27/2^-) \to 23/2^{(-)}$
1988.0(7)	13(4)		$(41/2^+) \to (37/2^+)$

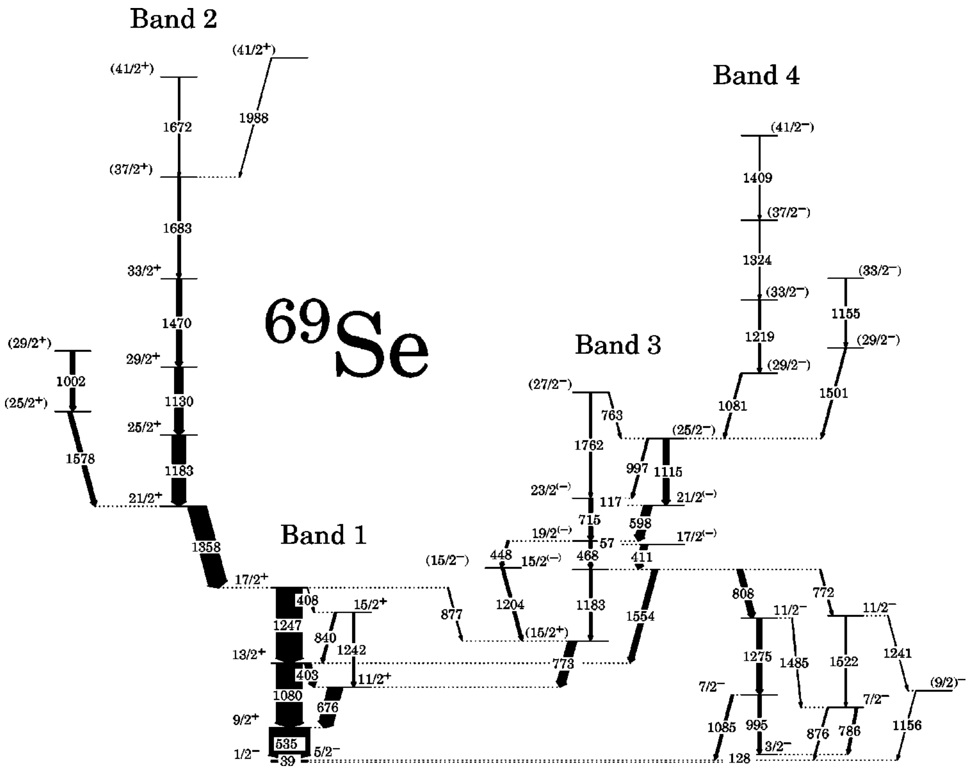

FIG. 2. Partial level scheme for ^{69}Se. The width of the arrows is proportional to the intensity of the transitions.

with the prompt 942-keV transition above the isomer, a half-life of 12(2) ns was obtained for the isomeric state.

The known 1 μs $9/2^+$ isomer in ^{69}Se was used to provide a sensitive tag of the band built on the isomer, by producing matrices of prompt-prompt γ rays in coincidence with the delayed 535-keV $9/2^+ \rightarrow 5/2^-$ transition from the ^{36}Ar data set. No further particle gating conditions were necessary, since the spectra proved relatively free of contaminants (bottom of Fig. 1). Indeed, of all the delayed transitions observed, the 535-keV transition was by far the longest lived. However, a gate on this delayed transition excludes the possibility of seeing transitions that bypass the isomer since by its very nature it demands those transitions that feed the isomeric level, thereby supplying a biased picture of the γ-ray flux. Accordingly, the larger ^{32}S data set was used to obtain information on states that do not feed the $9/2^+$ isomer. A matrix appropriate to ^{69}Se was generated from the ^{32}S data, with the additional constraint of the detection of either one proton and one neutron or two protons and one neutron. This matrix contained around 60×10^6 γ-γ events. In a similar fashion, a matrix appropriate to ^{67}As was sorted with a particle requirement of one α particle and one proton. This matrix contained approximately 40×10^6 γ-γ events. In order to obtain the best resolution for γ-ray spectra obtained from the ^{32}S data set, information on the energies of charged particles and the angle at which they were detected was used to refine the Doppler correction.

In order to determine the multipolarity of the observed transitions, an angular correlation technique was applied. Two matrices were generated from the ^{32}S data for each of ^{69}Se and ^{67}As with particle gating appropriate to each case as described above. In the case of ^{69}Se, the first matrix contained γ rays detected at all angles against those at 90°. The second matrix contained all γ rays against those at angles around 35° and 145° (rings 2, 3, 15, and 16 of Gammasphere). Due to the much weaker population of ^{67}As, a slightly different technique was employed. The 90° axis of the second matrix was augmented with γ rays detected around 80° and 100° (rings 7, 8, 10, and 11 of Gammasphere). This averaging procedure attenuated the angular correlations somewhat but made it possible to obtain angular correlations for transitions in ^{67}As, which would not have been possible without augmenting the 90° axis.

By gating on γ rays lying below the transition of interest on the all detector axis and projecting spectra from each of the forward/backward angle and 90° matrices, the ratio of the intensity of transitions of interest, *R*, was obtained. This ratio was normalized and found to be in the range 1.0(1) for known stretched quadrupole transitions in strongly populated nuclei, such as, ^{68}As, whereas for a pure stretched dipole transition the ratio was determined to be 0.50(5). Under the variant procedure applied to ^{67}As, these ratios were closer to 0.9 and 0.6, respectively. Mixed $M1/E2$ dipole transitions could take on a wide range of values of *R* dependent on the sign and magnitude of the multipole mixing ratio. We note that an unstretched dipole transition ($J^\pi \rightarrow J^\pi$) will have the same angular correlation ratio the same as a stretched quadrupole transition. The assignment of such a multipolarity must accordingly be made in the context of other coincidence and decay scheme information. In keeping with the usual pattern of decay following heavy ion fusion evaporation reactions and excepting isomeric decays, we consider only the multipolarity possibilities: $M1$, $E1$, $E2$, and $M1/E2$ for prompt γ-ray transitions.

In the construction of the ^{69}Se level scheme we assume the assignment of low-lying levels and the $9/2^+$ isomer as made in previous work. In particular, we note the assignment of a spin and parity of $1/2^-$ to the ground state of ^{69}Se following the careful work of Pohl *et al.* in determining the multipolarity of the 40-keV transition that feeds the ground state [9]. The spectroscopic information on ^{69}Se obtained in the present work is tabulated in Table I. The energies and intensities presented in the table are exclusively derived from the ^{32}S data set. The level scheme obtained for ^{69}Se is presented in Fig. 2. Spectroscopic information on ^{67}As is tabulated in Table II and the level scheme is presented in Fig. 3.

IV. DISCUSSION

By combining the coincidence information afforded by the two separate data sets, it has been possible to enlarge the ^{69}Se level scheme considerably and to extend the $g_{9/2}$ band up to a tentative spin of $(41/2^+)$. In addition, the yrast band in ^{67}As has been extended to a tentative spin of $(33/2^+)$.

The ^{69}Se level scheme is rather complicated and the population is spread over several rotational bands as well as many irregular levels that are not readily categorized into rotational bands. The following discussion will be divided into a section concerning the high spin properties of bands 1 and 2 and a separate discussion of the remainder of the level scheme. The concluding section will discuss the new information on ^{67}As.

A. ^{69}Se bands 1

Our conclusions concerning the structure of band 1 below spin $J^\pi = 17/2^+$ are in broad agreement with those made earlier by Wiosna *et al.* [3]. However, we do not observe the second pair of dipole transitions (448 and 798 keV) that they indicated as crossing over the 1248-keV $17/2^+ \rightarrow 13/2^+$ transition in their level scheme [3]. Instead, we associate different transitions with the extension of the previously known (9/2)-(11/2)-(13/2) strongly coupled sequence, consisting of the 840- and 408-keV $\Delta I = 1$ transitions as well as a 1242-keV $(15/2^+) \rightarrow 11/2^+$ transition, which forms a near doublet with the 1247-keV transition in the signature partner band. This 1242-keV transition is very much weaker than its 1247-keV counterpart. This doublet is clearly evident in a gate on the 676-keV transition (top of Fig. 4). These transitions extending the strongly coupled sequence are too weak to obtain detailed angular correlation information. However, they do exhibit a similar degree of signature splitting to the previously known (9/2)-(11/2)-(13/2) sequence. We were unable to extend the supposed signature partner band beyond spin $(15/2^+)$, nor was there any evidence of this $(15/2^+)$ state being fed by any other structures.

Mixing ratios may be used to infer the sign of the nuclear deformation and in cases where the value of the effective g factor, $g_K - g_R$, is well established, the magnitude of the quadrupole moment may also be inferred. Two groups have previously extracted a positive mixing ratio for the lowest

TABLE II. Energies, intensities relative to the 943-keV γ ray and angular correlation ratios R of γ rays in ^{67}As. Assignments are made on the basis of angular correlation ratios, or where unobtainable, intensity and systematics (see text).

E_γ (keV)	I_γ	R	$J_i^\pi \rightarrow J_f^\pi$
68.3(1)	261(15)		$3/2^- \rightarrow 5/2^-$
319.0(1)	368(25)	0.49(7)	$9/2^+ \rightarrow 7/2^-$
426.4(1)	132(10)		$21/2^+ \rightarrow (19/2^+)$
638.3(1)	256(19)	0.95(11)	$(19/2^+) \rightarrow (15/2^+)$
697.2(1)	678(21)	0.65(7)	$7/2^- \rightarrow 5/2^-$
704.0(2)	185(18)		$(15/2^+) \rightarrow (13/2^+)$
725.4(1)	725(25)	0.54(6)	$9/2^+ \rightarrow 7/2^-$
773.9(1)	719(31)	0.87(10)	$25/2^+ \rightarrow 21/2^+$
814.9(1)	78(6)		$(13/2^+) \rightarrow 13/2^+$
860.0(2)	225(14)		$(11/2^+) \rightarrow 9/2^+$
898.7(3)	260(14)		$(13/2^+) \rightarrow (11/2^+)$
930.4(2)	117(10)		$(19/2^+) \rightarrow 17/2^+$
942.5(1)	≡1000	0.96(11)	$13/2^+ \rightarrow 9/2^+$
984.3(2)	444(25)	0.86(10)	$29/2^+ \rightarrow 25/2^+$
1035.0(1)	273(25)	0.90(15)	$7/2^- \rightarrow 3/2^-$
1081.0(5)	118(15)		$(33/2^+) \rightarrow 29/2^+$
1102.7(3)	50(4)		$7/2^- \rightarrow 5/2^-$
1228.8(1)	707(33)	0.83(12)	$17/2^+ \rightarrow 13/2^+$
1357.9(1)	502(19)	0.87(11)	$21/2^+ \rightarrow 17/2^+$
1422.4(3)	132(15)		$9/2^+ \rightarrow 5/2^-$
1603.2(3)	174(12)		$(15/2^+) \rightarrow (11/2^+)$

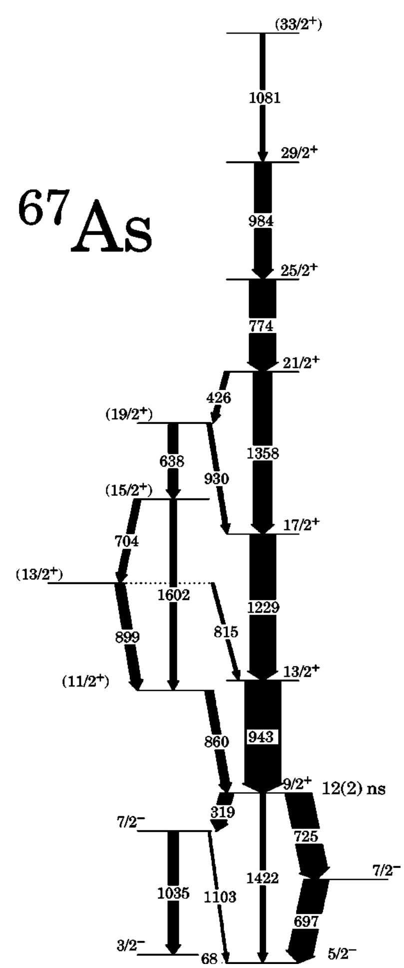

FIG. 3. Partial level scheme for ^{67}As. The width of the arrows is proportional to the intensity of the transitions.

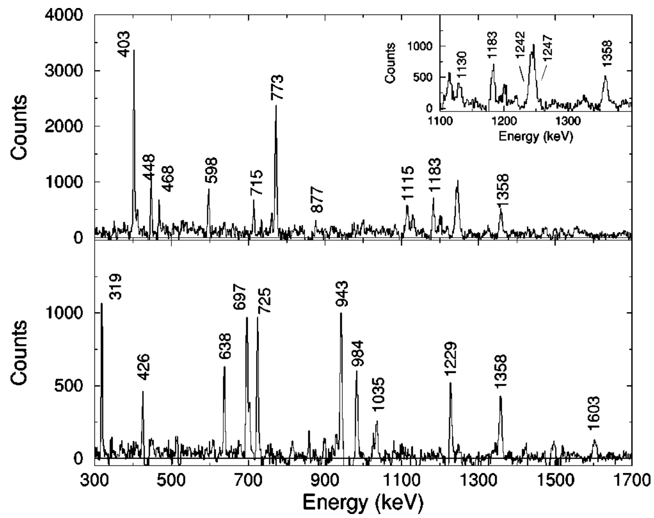

FIG. 4. Top: γ-ray spectrum gated on the 676-keV transition in the ^{32}S data set with a particle gating condition of 2 protons and 1 neutron. The inset shows an expanded region of the spectrum between 1100 and 1400 keV. The 1242- and 1247-keV transitions clearly appear as a doublet. Bottom: γ-ray spectrum gated on the 774-keV transition in the ^{32}S data set with the additional constraint of the detection of 1 α particle and 1 proton in microball.

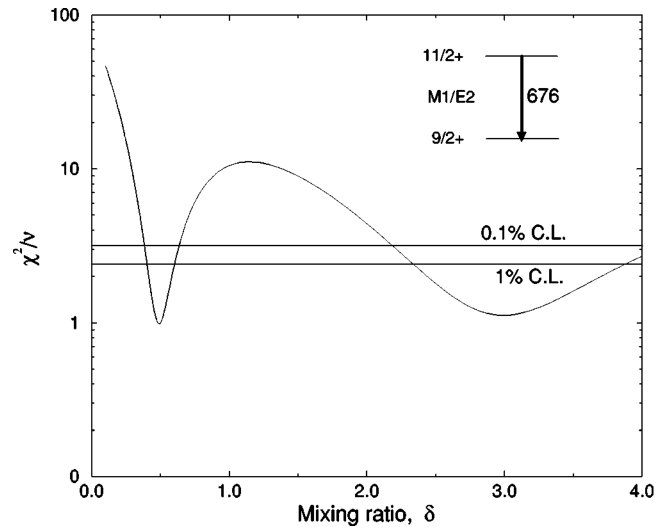

FIG. 5. χ^2 per degree of freedom for various values of mixing ratio delta for the 676-keV $M1/E2$ transition in ^{69}Se. The initial alignment parameter, σ/J for the fit was 0.54. The 1% and 0.1% confidence limits are indicated.

$\Delta I=1$ transition [3,4] in band 1. This was taken to indicate an oblate deformation for this band. Using the high statistics afforded by the present experiment, we have attempted to extract more precise mixing ratios for the $\Delta I=1$ transitions in band 1 and thus infer the magnitude of the deformation. The ^{32}S data was sorted into spectra for each of the rings of Gammasphere. The strong angular distributions of several $E2$ transitions in ^{69}Se were fitted in order to obtain a value for the Yamazaki alignment parameter, σ/J of 0.54. Starting from this alignment value, the multipole mixing ratio δ, and alignment were minimized and two solutions were found for the mixing ratio with very similar goodness of fit, χ^2 (see Fig. 5). The first solution for the 676-keV transition is a delta of $+0.5(1)$ while the second solution corresponds to a larger value of $+2.9(1)$, consistent with a value previously extracted by Wiosna *et al.* of $+3.3(4)$ [3]. An attempt was also made to fit the mixing ratio for this transition in the ^{36}Ar data set. However, in this case both the observed intensity of the transition was much lower and the nucleus was less strongly aligned due to the emission of an additional α particle compared to the reaction using the ^{32}S beam. These factors made it difficult to fit the observed angular distribution although the poor fit obtained again pointed to a positive mixing ratio.

Let us try to explore the implications of the two possible values of δ for the 676-keV transition. The calculations using a Woods-Saxon potential suggest a value of $g_K-g_R\approx-0.8$ for the odd neutron on the assumption that it occupies the high-K $[404]\frac{9}{2}$ orbital. This value is rather independent of deformation as there are no nearby high-K orbitals with which to mix. Given that the mixing ratio has a positive sign and g_K-g_R is negative, the sign of the quadrupole moment must also be negative, as expected for an oblate shape. While Wiosna *et al.* reached a similar conclusion, they did not proceed to interpret the large mixing ratio solution which they obtained ($\delta=3.3$) [3]. Such a large value is difficult to accommodate since the implied quadrupole moment is $Q_0\sim-20$ eb, in contrast to a value of $Q_0\approx-2$ eb for an oblate shape of $\beta_2=-0.3$ predicted by TRS calculations. Even using the quenched single particle Schmidt neutron magnetic moment of $g_n=-0.2$ for $g_{9/2}$ particles does not lead to a plausible quadrupole moment. Thus the large mixing ratio solution seems rather unlikely. In contrast, a mixing ratio of 0.5(1), our lower value, would imply a quadrupole moment, $Q_0=3.4(7)$ eb, more consistent with theoretical expectations. The 403-keV $\Delta I=113/2^+\rightarrow11/2^+$ transition has only a third the intensity of the 676 keV and its angular distribution was found to be approximately isotropic. A fit to the angular distribution implied a small positive value for δ of $+0.1(1)$, again suggesting oblate deformation and a quadrupole moment, $Q_0=-1.4(1.4)$ eb. Unfortunately, there were insufficient statistics to further extend our mixing ratio analysis to the 840- and 408-keV $\Delta I=1$ transitions. Taken together the weighted average of the quadrupole moments for the $13/2^+$ and $11/2^+$ levels is $Q_0=-2.7(6)$ eb, consistent with a rigid oblate shape with $\beta_2\sim-0.4(1)$.

A lifetime measurement would greatly assist in quantifying the magnitude of the deformation. In fact, Skoda *et al.* were able to obtain a lifetime for the 403-keV transition, but not the 676-keV transition, using the doppler shift attenuation (DSA) technique [10]. However, the necessity of gating below rather than above the transition of interest introduced a large feeding uncertainty into their result. The lifetime they obtained implied, in a rigid axial rotor model, a deformation, $|\beta_2|$ of between 0.24 and 0.85 [10].

B. Band 2

A clear change in structure in the yrast cascade occurs around spin $J^\pi=17/2^+$ where the strongly coupled band, band 1, is crossed by a decoupled band, band 2, for which no signature partner could be found despite a careful search.

Two back bendings are observed in band 2; the first at a rotational frequency of around 0.60 MeV/$\hbar$, and a second irregularity at a higher frequency of around 0.85 MeV/$\hbar$. These rotational irregularities immediately point to a change in the nuclear shape between band 1 to band 2, since cranking calculations assuming an oblate deformation of $\epsilon_2 = -0.3$ indicate that no alignment processes take place for either protons or neutrons until very high rotational frequencies (>1 MeV/$\hbar$) are reached. In order to account for the decoupled nature of band 2 and the observed back bending, it is necessary to invoke a prolate deformation. Accordingly, cranking calculations were carried out for ^{69}Se using principal axis cranking codes [11] in order to explore the expected alignment properties of a band in the prolate minimum. An axial prolate deformation of $\epsilon_2 = 0.3$ was assumed and a pairing gap, Δ of 1.3 MeV was employed for both protons and neutrons. The alignment of the first pair of $g_{9/2}$ protons is predicted to occur at a rotational frequency around 0.55 MeV/$\hbar$. In the case of the neutrons, the first crossing is blocked by the occupation of the lowest neutron orbit by the odd neutron in ^{69}Se. However, the second crossing is not blocked and occurs around 0.90 MeV/$\hbar$. The predicted crossings are in good agreement with those observed experimentally. However, one should emphasize that in the absence of lifetime measurements, the deformation employed in the cranking calculations have been estimated. Moreover, the effects of reduced pairing have not been explored and these may prove more important for higher rotational frequencies.

The initial alignment of band 2 is found to be around 4 $\hbar$ that is consistent with a $g_{9/2}$ neutron occupying a low-K orbit in accordance with the expectation of prolate deformation. The gain in alignment as a result of this first backbending is around 7 $\hbar$, which is consistent with the alignment of a pair of $g_{9/2}$ protons. Due to the limited statistics, the band was not observed right through the second back bend, preventing the extraction of an incremental alignment for this latter crossing process.

C. Other structures

As well as extending the $g_{9/2}$ band, information has also been obtained on additional levels in ^{69}Se. One feature of interest in ^{69}Se is the suggested occurrence of octupole softness. Nazarewicz *et al.* predict that ^{69}Se is soft with respect to octupole deformation [12]. In the neighboring odd-A nucleus, ^{65}Ge, for which octupole softness is also predicted, it was originally claimed that there was a very strongly populated $15/2^-$ state that was assigned the configuration of the $g_{9/2}$ neutron coupled to an octupole phonon [13]. However, later work, making use of both angular distribution and linear polarization measurements showed both that the $15/2^-$ assignment was incorrect and that the relevant $15/2^-$ states lay at much higher excitation energies more consistent with their systematic appearance in heavier odd-A germanium isotopes [14]. There was, therefore, no evidence for enhanced octupole correlations in ^{65}Ge. In the present work, a possible candidate for an octupole state in ^{69}Se has been observed at 3.208 MeV. The 1554-keV γ ray that decays from this level has an angular correlation ratio consistent with that for a pure dipole suggesting that it is an $E1$ transition and that the 3.208-MeV state from which it decays, most likely has a spin/parity of $15/2^-$. Moreover, this state decays strongly toward the low-lying negative parity states giving further confidence to this parity assignment. Clearly, linear polarization measurements would be useful in confirming this assignment. Built on top of this $15/2^-$ state we see a strongly coupled sequence (band 3). Assuming an oblate deformation and that the $g_{9/2}$ neutron lies in a high-K orbital and is coupled to an underlying $K=3^-$ band in ^{68}Se, we extract an alignment for this band of around 3 $\hbar$ relative to band 1, which is entirely consistent with octupole character. At a tentative spin of $(25/2^-)$ band 3 is crossed by a decoupled band, band 4. The change in character between bands 3 and 4 is very similar to that between bands 1 and 2. Indeed, the structure of bands 3 and 4 could be interpreted as an octupole phonon coupled to the underlying configurations responsible for bands 1 and 2.

A further level of interest is the 3.229-MeV state lying close to the $15/2^-$ 3.208-MeV level. It has not been possible to confirm the spin and parity of this state but given its decay path it seems likely that this would also have a spin/parity of $(15/2^-)$. One could speculate that this arises from the coupling of an octupole phonon to the (unobserved) $9/2^+$ state in the prolate band leading to a closely spaced doublet of $(15/2^-)$ states.

D. ^{67}As

By searching for delayed γ rays in the ^{36}Ar data set, we have found a new isomer in ^{67}As with a half-life, $T_{1/2} = 12(2)$ ns at an excitation energy of 1422 keV. This state was previously assigned a tentative spin/parity of $(9/2^+)$ by Lang *et al.* [6]. Given the systematic appearance of isomeric $9/2^+$ states in neighboring odd-A nuclei, we also assign the state spin/parity of $9/2^+$. Using the ^{32}S data, we were able to observe a 68-keV transition that feeds the ground state. The intensity of the 68-keV γ ray is very close to that of the 1035-keV transition that feeds it. Given that the conversion coefficient for such a transition would be ~ 3 for an $E2$ and ~ 0.1 for an $M1$ transition, we prefer an $M1$ assignment for this transition. $E1$ multipolarity may be ruled out on the grounds that $9/2^+$ is the lowest positive parity level that we expect to see. Fixing the multipolarity of the 68-keV transition in this way and making use of angular distribution information for other transitions, allows us to assign the spins and parities of the states below the isomer. In addition to clarifying the low spin levels, we have extended the $g_{9/2}$ band in ^{67}As by two transitions (bottom of Fig. 4). In contrast to the lower part of the $g_{9/2}$ band in ^{69}Se there does not appear to be a signature partner band that might be expected if the associated deformation were oblate. Indeed, the structure running parallel to the band proper is highly irregular. A back bending occurs in the $g_{9/2}$ band at a rotational frequency of around 0.5 MeV/$\hbar$ with an associated gain in alignment of 5–6$\hbar$ that is consistent with the alignment of a pair of $g_{9/2}$ neutrons. As in the case of ^{69}Se, the presence of a rotational alignment points strongly to a prolate shape. Despite the tempting interpretation of the structure of ^{67}As in

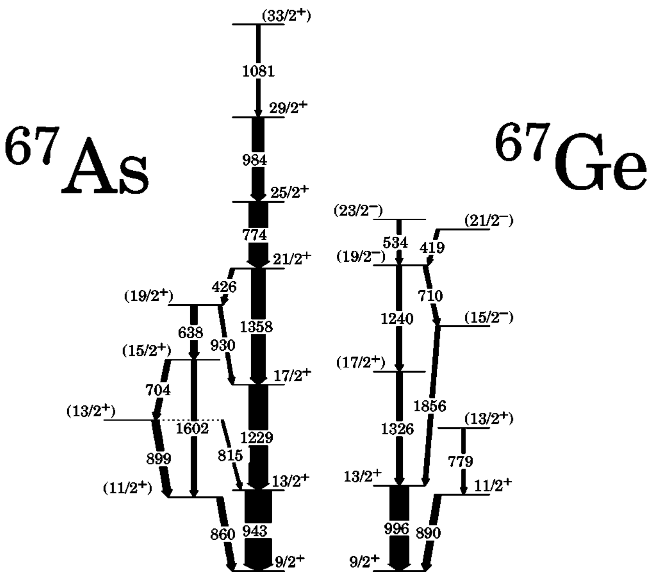

FIG. 6. Comparison of high-spin states built on the $9/2^+$ isomer in ^{67}As (left) and ^{67}Ge (right).

terms of the coupling of a proton $g_{9/2}$ hole to the known rotational bands in ^{68}Se, there is little evidence for oblate collective rotation in ^{67}As. Instead of comparing to ^{68}Se, it might be more relevant to interpret ^{67}As in terms of a $g_{9/2}$ proton weakly coupled to the weakly deformed ^{66}Ge core and to compare with ^{67}Ge whose high-spin spin structure has been interpreted in the past as a $g_{9/2}$ neutron coupled to the known states in ^{66}Ge [15]. The high-spin structure of ^{67}As and ^{67}Ge are compared in Fig. 6. Clearly as far as the $17/2^+$ state the states are very similar. However, at a higher spin, the comparison breaks down since the yrast high-spin states in ^{67}As are of positive parity while they are of negative parity in ^{67}Ge [15]. ^{67}As appears to be more deformed than ^{67}Ge that exhibits a more vibrational pattern of states [15]. A comparison of ^{69}As and ^{69}Ge reveals similar behavior. The prolate yrast $g_{9/2}$ band in ^{69}As extends to high spin, while irregular negative parity states form the high-spin yrast line in ^{69}Ge [16,17].

In recent years several isomers ranging from tens of nanoseconds to microseconds have been discovered in the $A = 65$–85 neutron deficient region, both from fragmentation and fusion reactions. The underlying structural cause of the isomerism is often the decay between structures based on the $g_{9/2}$ intruder orbital and fp-shell configurations. These isomers have modest spin change—1 or 2 units of angular momentum—but the electromagnetic decays are retarded. The neutron deficient nuclei in this region tend to be highly prolate deformed, which brings the low-K, low-J $g_{9/2}$ states down in excitation energy, so the isomerism is often enhanced as the transitions may also be low in energy. ^{76}Rb [18] and ^{80}Y [19] show particularly good cases of this isomerism, with isomers of $T_{1/2}=3.2\pm0.1$ and 6.0 ± 1.5 μs corresponding to $B(E1)$'s of 2.6×10^{-8} and 1.2×10^{-7} Weisskopf units (Wu), respectively. The unusually large suppressions in these cases are attributed to parent and daughter states being very different in structure, and the decays do not correspond to simple single-nucleon changes of orbit.

The $T_{1/2}=12\pm2$ ns isomer found in ^{67}As also has very inhibited $E1$ decays, of 3.1 ± 0.5 and $0.5\pm0.1\times10^{-7}$ Wu. In this case, the high-K $g_{9/2}$ state is the lowest positive parity state, indicating an oblate shape, but its excitation energy of 1.4 MeV indicates modest deformation. The presence of two low-lying $J^\pi=7/2^-$ states indicates more than one mode of excitation is present near the groundstate, possibly due to vibration coupling and coexisting shapes. However, they appear highly mixed and no clear collective band structures built on top of these states were found.

V. CONCLUSION

In conclusion, we have extended the previously known $K=9/2^+$ oblate band in ^{69}Se and find that it is rapidly crossed by a prolate configuration that continues to high spin. We could not observe any extension of the oblate band beyond the crossing point. This could indicate a lowering of the barrier between oblate and prolate states, which lies lowest at fixed deformation ($|\beta_2|\sim0.3$), involving mixing through triaxial shapes. The difficulty in studying the oblate structure also reflects a difference in total binding energy of the configurations. In ^{68}Se, the oblate configuration is *more* bound than its prolate counterpart by about 1 MeV and hence remains relatively pure at low spin [2]. In ^{69}Se, the oblate configuration is about 0.5 MeV *less* bound than the prolate states and is rapidly immersed in nearby states with which to mix. In contrast there seems little evidence for oblate collectivity in ^{67}As that has one proton hole with respect to the $N=Z=34$ core and this nucleus is more readily described in terms of the weak coupling of a $g_{9/2}$ proton to the ^{66}Ge core.

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