Structure of the $N=Z+1$ nucleus ^{69}Se

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Charged-particle-γ and charged-particle-neutron-γ coincidences have been used to identify in-beam γ-ray transitions in ^{69}Se produced in the reaction ^{40}Ca(^{32}S,$2pn$)^{69}Se. Charged-particle-γ-γ coincidences, neutron-γ-γ coincidences, and neutron-gated γ-ray angular distributions were used to deduce the level scheme. A long-lived isomer attributed to the $g_{9/2}$ state was found; its half-life was measured with charged-particle-γ timing as 1023±110 ns. The presence of strong $\Delta J=1$ and $\Delta J=2$ transitions in the band built on the $\nu g_{9/2}$ neutron single-particle state and the measured sign of the $E2/M1$ mixing ratio for the $\frac{11}{2}^+ \rightarrow \frac{9}{2}^+$ transition are consistent with a theoretically predicted oblate shape for this nucleus.

I. INTRODUCTION

Proton-rich nuclei in the $A=60$–80 region have been the subject of much recent theoretical and experimental work, following the discovery[1,2] of a new region of strong prolate deformation in the light Kr and Sr isotopes ($Z=36$ and 38, respectively) close to $N=Z$. Strutinsky-model calculations[3–5] suggest that many isotopes in this region are soft with respect to both prolate and oblate deformation, with the prolate shape usually associated with the deepest minimum in the total potential energy surface. However, the calculations of Bengtsson *et al.*[3] predict a region centered around the odd-odd nucleus ^{70}Br ($N=Z=35$), in which oblate shapes should be energetically favored. One of the principal aims of the present work was to test this prediction by investigating the structure of the neighboring isotone ^{69}Se ($Z=34$), and in particular the pattern of collective rotation built on the $g_{9/2}$ single-particle state. An additional motivation was the desire to extend in-beam measurements to heavier nuclei in the vicinity of the $N=Z$ line, where relatively little information is available about excited states due to the difficulty of identifying and studying such systems, which are produced with only a small fraction of the total reaction cross section.

Particle-γ coincidence techniques, used in conjunction with heavy-ion fusion-evaporation reactions, can provide the information required for identification of a previously unknown nucleus, along with the improvement in peak-to-background necessary for a quantitative investigation of its structure. For example, if the initial compound system is well determined, identification of all of the evaporated charged particles on an event-by-event basis provides an unambiguous measurement of the charge Z of the residual nucleus associated with each set of emitted γ rays. If the total number of evaporated particles in a given channel can be independently established, e.g., by measuring the yield as a function of bombarding energy, the mass of the residual nucleus can be determined, completing the identification. Furthermore, the coincidence requirement improves the signal-to-noise ratio by rejecting peaks and Compton tails of γ rays produced in evaporation channels other than the one of interest. The effectiveness of such techniques depends strongly on the efficiency and solid angle of the particle detectors, which determine the extent to which one can approach the ideal of an *exclusive* measurement in which all particles from each event are detected. Particles missed by the detector apparatus lead to feedthrough of unwanted channels into the γ-ray spectrum of interest, which limits the sensitivity and can make the channel identification ambiguous (particularly if the detection probability decreases sharply as the number of detected particles increases). We have developed a 4π array of up to 24 phoswich telescopes (optimized for detection of evaporation protons and alpha particles) for use in such measurements. The system can also be used in conjunction with neutron detectors to increase further the sensitivity of the measurements. A complete description of the device is given in Ref. 6. The system has been used to identify and study a number of nuclei near $N=Z$ with $A=60$–80, including our recently reported results[7] on ^{65}Ge and ^{64}Ge.

In the following section we begin by summarizing the experimental techniques used for this investigation. The measurements and analysis leading to the identification of γ rays in ^{69}Se are then described in detail, followed by a discussion of the level scheme deduced from the particle-γ and particle-γ-γ measurements. The results are interpreted in light of predictions of oblate deformation in this mass region. A preliminary account of this work has been given previously.[8] Subsequently, two additional studies of ^{69}Se have been reported by other groups.[9,10] In both cases, the identification of ^{69}Se was inferred from measurements of n-γ coincidences and comparisons with calculated cross sections. Our results resolve a discrepancy between these two studies with respect to the lifetime of the isomeric $\frac{9}{2}^+$ level. In addition, the present work is not consistent with some of the results of Refs. 9 and 10, in particular with respect to the properties of the first excited state of ^{69}Se.

II. EXPERIMENTAL APPARATUS AND PROCEDURE

Most of the work in this investigation has involved the ^{40}Ca(^{32}S,2pn)^{69}Se reaction. The ^{32}S beams used in the experiments were generated by the tandem Van de Graaff accelerator at the University of Pennsylvania. The targets were 300–500 $\mu g/cm^2$ ^{40}Ca evaporated onto 30 mg/cm^2 Au backings. A layer of Au (100–200 $\mu g/cm^2$) was also evaporated on top of the Ca in order to minimize oxidation during target transfer. The experiments performed included (1) charged-particle-γ coincidence measurements as a function of bombarding energy ($E_{beam}=76$–105 MeV); (2) charged-particle-neutron-γ, charged-particle-γ-γ, and neutron-γ-γ coincidences at 101 MeV; (3) γ-ray angular distributions in coincidence with neutrons at 96 MeV; and (4) out-of-beam measurements of delayed γ rays using a 96 MeV chopped beam. In-beam β-γ coincidences were also obtained as part of the charged-particle-γ coincidence data mentioned previously.

The charged-particle-γ excitation function measurements were made with phase I of the 4π phoswich array (see Ref. 6). Phase I consisted of six phoswich telescopes which covered approximately $\frac{1}{3}$ of 4π; most of the remaining solid angle was covered with charged-particle-sensitive veto detectors. An unsuppressed Ge detector ($\epsilon_\gamma=25\%$ relative to a 7.6 cm$\times$7.6 cm NaI(Tl) detector at 1.33 MeV) was placed 9 cm from the target at 135° with respect to the incident beam. From the charged-particle-γ timing information, an isomeric transition was identified among a group of transitions believed to originate from ^{69}Se. Since the half-life was comparable to the 1 μs range of the initial measurements, a second charged-particle-γ experiment was performed to provide a more accurate determination of the half-life. The electronics for the phoswich array in this run were adjusted to enable observation of γ rays delayed up to 3 μs with respect to the charged particles. These data were taken at a bombarding energy of 98 MeV with phase II of the phoswich array, in which $\frac{2}{3}$ of 4π was covered with telescopes and the remaining solid angle was subtended by a veto detector. The Ge detector was in the same position as in phase I.

The charged-particle-γ-γ, charged-particle-neutron-γ, and neutron-γ-γ coincidence data at 101 MeV were obtained simultaneously, using phase I of the 4π array in conjunction with a large volume neutron detector. Five phoswich telescopes in the array were used, allowing two Ge detectors ($\epsilon_\gamma=25\%$) to be placed 9 cm from the target at 90° and 135° with respect to the incident beam. The neutron detector consisted of a 40 cm$\times$76 cm$\times$30 cm thick tank filled with liquid scintillator, with the front face located 41 cm downstream from the target at 0°. A single 20 cm diam hemispherical photomultiplier (Hamamatsu R1408) was immersed in the scintillator. Neutron-γ separation was obtained by time of flight, using the detection of a charged particle in the array as the start signal. For the neutron-γ-γ events, the veto detectors were used as well as the phoswich telescopes to provide start signals for the time-of-flight measurements. Figure 1 is a typical time-of-flight spectrum which shows the separation of neutrons and γ rays which was obtained.

The γ-ray angular distribution measurements were made in coincidence with a cylindrical liquid scintillator neutron detector (12.7 cm diam$\times$15.2 cm deep) located at 0°, with its front face 13.6 cm downstream from the target, and a 2.5 cm lead shield used as a γ ray absorber. Pulse shape discrimination was used to differentiate between neutrons and γ rays. Two unsuppressed Ge detectors ($\epsilon_\gamma=25\%$) at a distance of 16.3 cm from the target were used to detect γ rays at angles of 90°, 120°, 135°, and 150° with respect to the incident beam. A fixed Ge(Li) detector was used as a monitor to normalize different runs. The relative efficiencies of the two Ge detectors were determined from n-γ coincidence yields with both

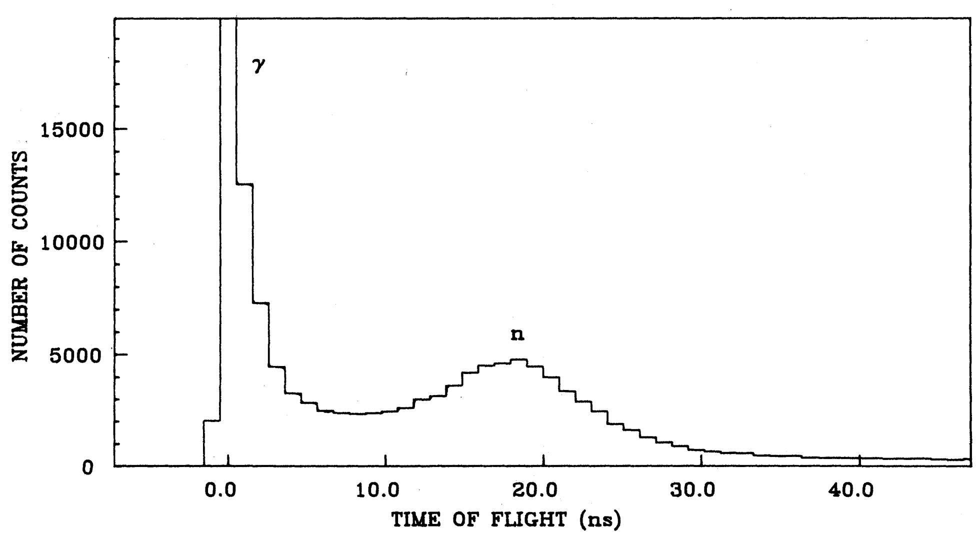

FIG. 1. Time-of-flight spectrum showing the separation between neutrons and γ rays in the large neutron detector, for 101 MeV ^{32}S on a ^{40}Ca target.

detectors at 90°, from singles measurements of lines from target activity, and from ^{133}Ba and ^{152}Eu sources. Partial channel selection was accomplished by the n-γ coincidence requirement.

Measurements of γ rays from the radioactive decay of the various fusion-evaporation products were used to supplement the in-beam particle-γ coincidence studies. These activity measurements provide an independent determination of the total production cross section for the ground state (or any β-decaying excited state). Comparison of the cross section inferred from β decay with that deduced from the directly observed yrast γ rays can be useful in estimating the feeding of any low-lying levels which may be unobserved as a result, for example, of fragmentation of the decay scheme into multiple parallel branches. The radioactivity measurements utilized a chopped beam apparatus. A ^{40}Ca target was exposed to a ^{32}S beam for 3.2 min (activation), after which the beam was steered away from the target while γ-singles data were taken for 32 successive intervals of 0.1 min (measurement). This activation-measurement cycle was repeated 15 times. The data were sorted on-line into a 4096×32 channel E_γ vs time matrix for subsequent off-line analysis. The Ge detector was placed 16.3 cm from the target. This technique has the advantage that the β-decay lifetimes are measured, thereby lending confidence to the deduced production cross sections.

In-beam e^+-γ coincidences were also obtained as part of the charged-particle-γ measurements described earlier. One advantage of this technique is that it allows the same data set to be used for both the radioactive and evaporative decay measurements. Relative feeding of the ground state and excited states can then be compared directly, thus avoiding any complications caused by comparing in-beam and out-of-beam measurements. As an example, knowledge of the target thickness is not required. The ability to identify events from radioactive decay from the in-beam data is also useful in that these γ rays often have well-known energies and are not subject to Doppler shifts. They can thus be useful in obtaining in-beam γ-ray energy calibrations which include any effects such as small baseline shifts resulting from high count rates in the Ge detector. In our data, γ rays from the β decay of various evaporation products were used to determine a preliminary energy calibration. This preliminary calibration was used to identify γ rays from known evaporation channels, and a combination of activity and evaporation lines was used to determine the final energy calibration. Singles spectra from ^{133}Ba and ^{152}Eu sources placed in the target position were used to determine the relative efficiencies of the Ge detectors as a function of the γ-ray energy for each of the measurements described above.

III. RESULTS AND DISCUSSION

A. Identification of ^{69}Se

At the time this work was begun, no excited states were known in ^{69}Se. Using a ^{32}S beam on a ^{40}Ca target, ^{69}Se was formed by $2pn$ evaporation. The following criteria were used to evaluate candidate γ rays. First, the candidates must be in coincidence with two protons, not in coincidence with three protons, and not in coincidence with alpha particles. This latter point is particularly important, since statistical model calculations predict similar excitation curves for $2pn$ and αpn evaporation, although the cross section for αpn evaporation is predicted to be substantially smaller. Second, the γ transitions must be in coincidence with neutrons. Third, the γ-ray excitation function must be consistent with three-particle evaporation, as established by comparison with channels measured simultaneously in which the number of evaporated particles is known, e.g., $3p$ evaporation.

The identification of the charged-particle component of the evaporation channel is illustrated in Figs. 2(a)–(c), which show γ spectra gated by the detection of two protons, three protons, and an α-particle plus two protons, respectively. Lines in several previously known channels are labeled. Transitions in the strong $3p$ and $\alpha2p$ channels are clearly seen in the $3p$-γ and $\alpha2p$-γ spectra, respectively. There is also considerable "feedthrough" of such lines into lower multiplicity channels. For example, γ rays from the strong $3p$ and $\alpha2p$ channels are seen in coincidence with two protons due to events in which the additional proton or alpha particle escapes detection (due to the small gaps between the detector modules or the dead areas near the beam entrance tube, the target support, and the Ge detector). This feedthrough does not hinder the identification, since such lines are at least equally clearly observed in the spectrum gated on *all* of the emitted charged particles ($3p$-γ or $\alpha2p$-γ in this case). In contrast, other lines in coincidence with two protons, such as the 676 keV transition, are clearly absent in both the $3p$-γ and $\alpha2p$-γ spectra. Such transitions can be produced only by $2pxn$ evaporation. Candidates for $2pxn$ transitions can also be readily identified by subtracting the "feedthrough" contributions to the $2p$-γ spectrum. In this procedure, multiples of the $3p$-γ and $\alpha2p$-γ spectra are subtracted from the $2p$-γ spectrum to eliminate the $3p$ and $\alpha2p$ feedthrough. The result of this procedure is shown in Fig. 2(d). Lines marked with an "o" are from the known $2p$ channel leading to ^{70}Se, and lines marked with an "x" are from $2pxn$ reactions from the likely target contaminants ^{16}O and ^{12}C. The surviving lines at 676, 715, 773, 808, and 1079 keV are in ^{69}Se, as can be verified from the raw data. Note that the line at 1016 keV, which comes from the $4p$ channel, is oversubtracted by this procedure.

The usefulness of charged-particle-neutron-γ coincidences is illustrated by the spectra in Fig. 3, which show γ rays observed in coincidence with two or three protons (detected in the array) and one or more neutron(s) (detected in the large volume neutron detector described above). The $2pxn$ signature (with $x\geq1$) of the 676 and 1079 keV transitions is clear. Comparison of the relative number of $2pn$-γ and $2p$-γ coincidences for the candidate lines with the corresponding ratio ($3pn$-γ to $3p$-γ) for transitions associated with the known $3pn$ channel leading to ^{68}As suggests a neutron multiplicity of one. The only other possibility would be $2p2n$ evaporation leading to ^{68}Se ($N=Z$). This channel is expected to be produced with a very much smaller cross section and its excitation function should peak at a significantly higher bombarding energy.

Other evidence in support of a neutron multiplicity of one has been obtained by analyzing the $2p$-γ coincidence data obtained with phase II of the charged-particle array using the technique of complete kinematic reconstruction.[11] In the analysis, the measured vector momenta of the detected protons is used to deduce the excitation energy, E_x of the rest of the system, which consists of the residual nucleus plus any evaporated neutrons. Since approximately 12 MeV of binding energy is associated with each neutron in this system, events with higher calculated values of E_x are more likely to be associated with the evaporation of additional neutrons. The expected difference can be made quantitative by examining the $3p$-γ coincidence events which were obtained at the same time. In the analysis a two-dimensional matrix of E_γ vs E_x was formed for all events in which three protons were detected by the 4π array. The E_x distribution associated with a given γ ray was obtained by projecting the spectrum onto the E_x axis; the underlying Compton background was subtracted using an adjacent flat region of the γ spectrum in the standard manner. The average value of E_x obtained in this way for three representative transitions in the $3p$ and $3pn$ evaporation products were 21 ± 1 and 31 ± 1 MeV, respectively. The difference is comparable to the neutron separation energy, as expected. Application of the same analysis procedure to the $2p$-γ coincidence events gave average values of E_x of 21 ± 2 and 31 ± 1 MeV for the $2p$ channel and the $2pn$ candidates, respectively. In all cases the error quoted on the value of E_x is taken as the standard deviation of the measured E_x values for

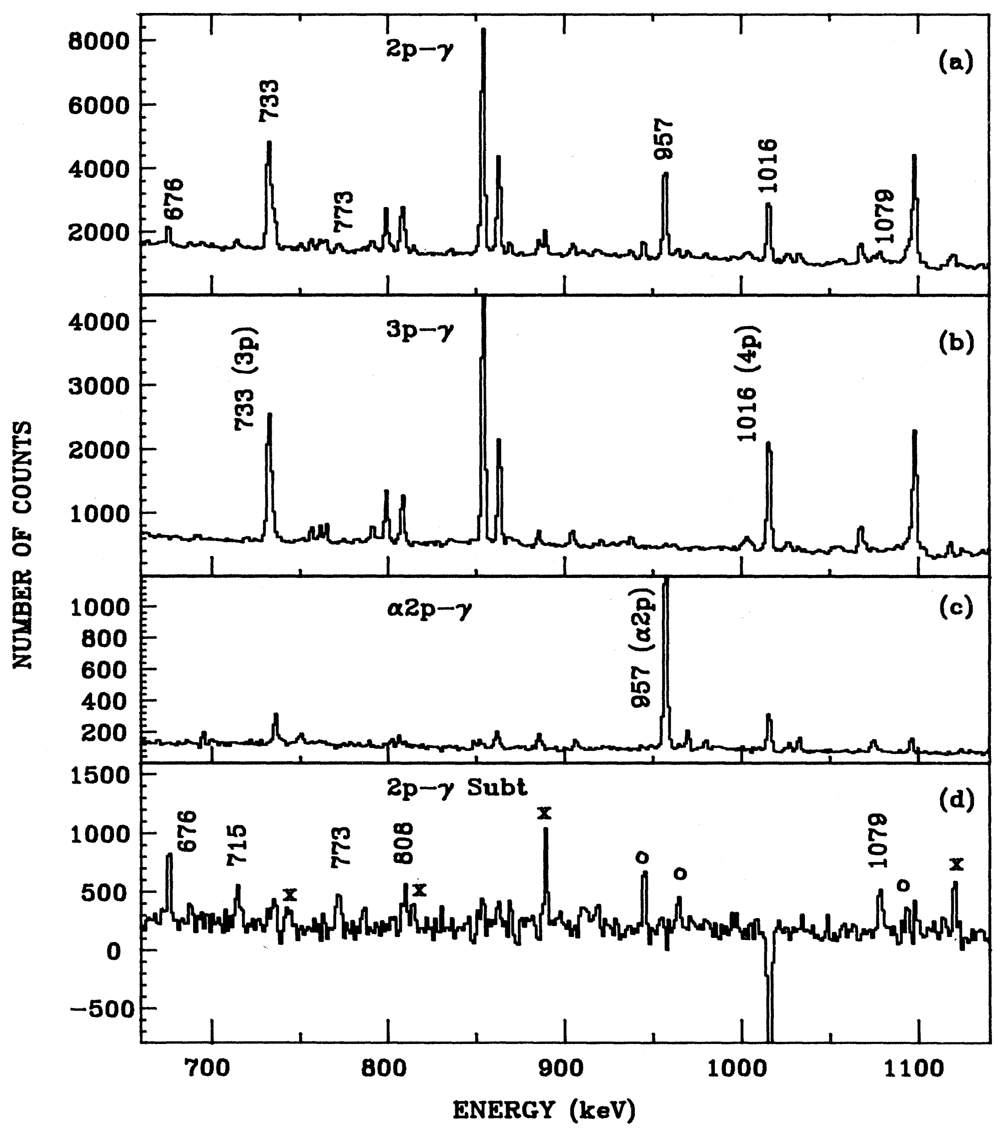

FIG. 2. Spectra of γ rays observed in coincidence with the indicated evaporation particles. The top three spectra were obtained simultaneously at 98 MeV. (d) is the $2p$-γ subtracted spectrum obtained from the other spectra. See text for discussion.

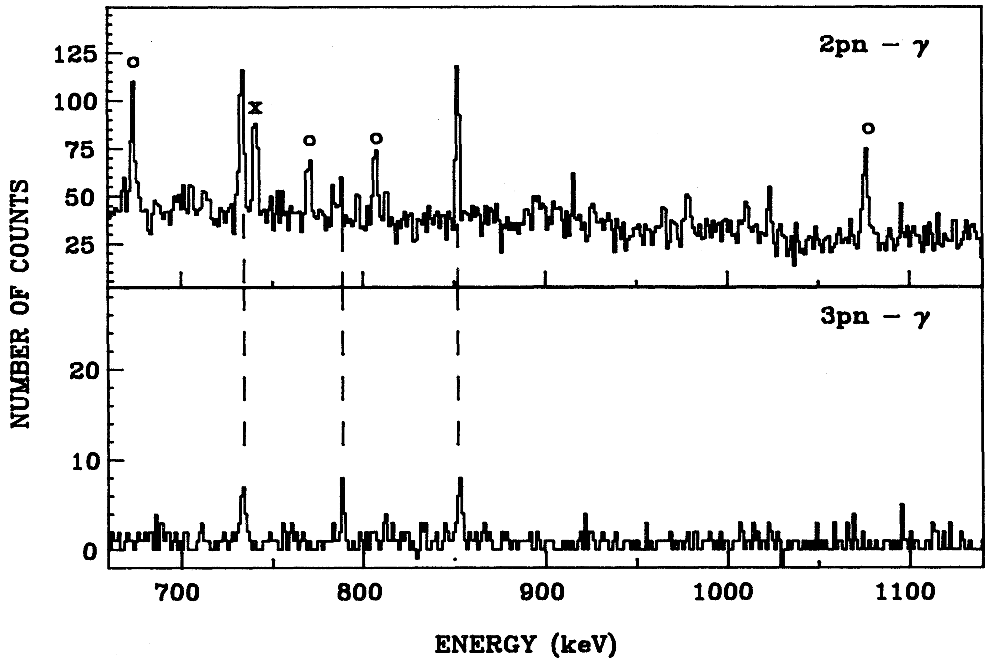

FIG. 3. Spectra of γ rays in coincidence with two protons and a neutron (top) or with three protons and a neutron (bottom). γ rays from ^{69}Se are marked with a circle, γ rays from known contaminants are marked with an x, and γ rays joined by dashed lines are from the $3pn$ evaporation channel leading to ^{68}As.

three different γ transitions. The similarity of the shift in $\langle E_x \rangle$ observed in the two cases lends strong support to the assumed neutron multiplicity of one. We note that similar comparisons in other systems where $2p$, $2pn$, and $2p2n$ evaporation are all observed have shown that the difference in E_x between $2p$ and $2pn$ is comparable to the difference between $2pn$ and $2p2n$, as would be expected from the relevant neutron separation energies.

Excitation functions for the ^{69}Se candidates are shown in Fig. 4, along with data for known transitions[12–15] in ^{70}Se (produced by $2p$ evaporation), ^{69}As ($3p$), ^{68}Ge ($4p$), and ^{66}Ge ($\alpha 2p$). These data were taken at 76, 86, 96, and 105 MeV with phase I of the charged-particle array. In an attempt to smooth differences among transitions and to improve statistics, several transitions have been averaged for each channel. The lines used were $2p$: 945, 965; $2pn$: 129, 403, 535, 676, 773, 1079; $3p$: 98, 442, 864, 1205; $\alpha 2p$: 521, 957; $3pn$: 158, 214, 339, 344; $4p$: 1016; all energies are in keV. As expected, the excitation functions are primarily sensitive to the number of evaporated particles. (Channels involving α emission tend to peak somewhat higher in energy, as reflected in a comparison of the curves for the $\alpha 2p$ and $3p$ channels, for example. Two-particle emission channels, which are strongly suppressed by the Coulomb barrier, also tend to not be easily distinguishable from three-particle evaporation.) The excitation curves measured for the individual ^{69}Se candidates are generally consistent with the behavior expected for three-particle evaporation. Taken together with the evidence from reconstruction of the total excitation energy, we regard the association of the ^{69}Se candidates with $2pn$ evaporation as conclusive. Finally, addi-

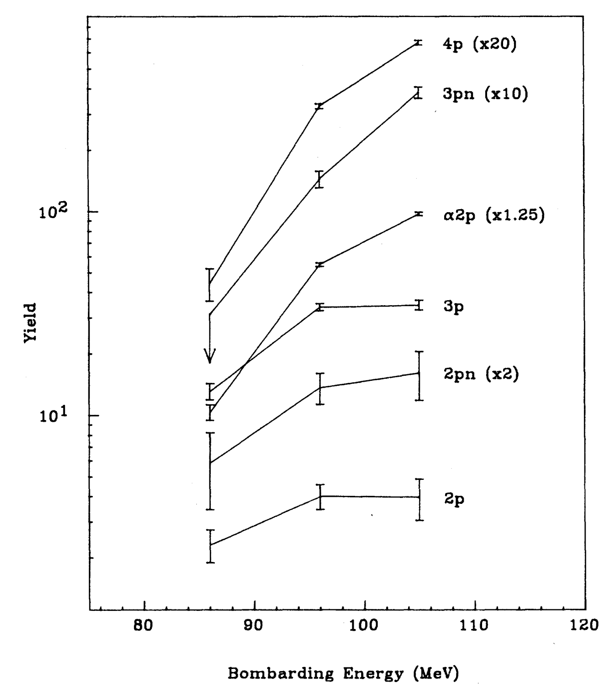

FIG. 4. Excitation functions for the channels indicated from measurements of charged-particle-γ coincidences. In each case the average of several transitions is shown, as described in the text. The yields are given in arbitrary units, and have not been corrected to reflect channel-to-channel differences in particle detection efficiencies. None of the γ rays used in the averaging were observable at $E_{^{32}\mathrm{S}}=76$ MeV as a result of attenuation of the fusion cross section by the Coulomb barrier.

tional measurements using targets of ^{12}C and WO_3 rule out the possibility that any of the ^{69}Se candidates arise from $2pn$ reactions on the likely target contaminants ^{12}C and ^{16}O.

As mentioned earlier, two recently published reports on in-beam γ-ray transitions in ^{69}Se using n-γ coincidence measurements[9,10] have included transitions consistent with our identification. Lacking charged-particle-γ coincidence measurements, both experiments were forced to depend upon neutron-multiplicity arguments (which can be strongly affected by kinematic focusing, given small channel-to-channel differences in neutron energies) and on fusion-evaporation calculations of predicted cross sections for identification of transitions in ^{69}Se. The present work conclusively establishes the identification of ^{69}Se. In particular, it cleanly eliminates the αpn channel (^{66}As) as a potential source of these transitions. We have examined the spectrum of γ rays in coincidence with an α particle and a proton to search for in-beam γ rays in ^{66}As. When corrected for feedthrough from events where one proton is missed from $\alpha 2p$ evaporation and for events where two protons striking the same detector are misidentified as an α particle, the principal lines remaining are attributable to αpxn evaporation from known target contaminants. We are thus able to confirm in a qualitative way the prediction from statistical evaporation calculations that αpn evaporation is significantly weaker than $2pn$. We note further that the β-γ coincidence measurements can probably not add any information here since the spin and parity of the ^{66}As ground state is expected to be 0^+; the resulting superallowed decay would presumably feed the ^{66}Ge ground state.

B. The isomeric $g_{9/2}$ state

The lowest single-particle orbitals in this mass region are the closely spaced $p_{1/2}$, $p_{3/2}$, and $f_{5/2}$ states, and the somewhat higher $g_{9/2}$ state. The proximity of the $g_{9/2}$ to the low-lying negative-parity orbitals from the fp shell produces an isomeric $\frac{9}{2}^+$ state in many of the odd-neutron nuclei in this mass region,[7,16–18] since the most favorable decay is a relatively low-energy $M2$ transition. Systematics suggest an energy of roughly 500 keV for the $g_{9/2}\rightarrow f_{5/2}$ transition in ^{69}Se, and a half-life of hundreds of nanoseconds. The good timing provided by the fast plastic scintillators used for the ΔE detectors in the phoswich array makes charged-particle-γ measurements an excellent tool for searching for such an isomer [even with a continuous (nonpulsed) beam]. The search was carried out by binning all events with a $2p$ signature into a two-dimensional matrix of γ-ray energy versus the output of a time-to-amplitude converter (TAC) started by the phoswich array and stopped by the timing pulse from the Ge detector. Examination of the projected spectrum of all delayed γ rays revealed a line at $E_\gamma=534.9$ keV with a long half-life. The time dependence of this γ ray was obtained from the two-dimensional matrix by subtracting from the time spectrum gated on the 535 keV line a time spectrum gated on the Compton-scattered background events in an adjacent portion of the spectrum. The data from the 98 MeV run with the phase II array are given in Fig. 5; a least-squares fit to an exponential plus a constant background leads to a half-life of $t_{1/2}=1023\pm110$ ns. The quoted error reflects the effect of counting statistics only. This is the only isomer ($t_{1/2}>3$ ns) which we have identified in ^{69}Se, and is the strongest transition we have found in the cascade. Since the transition energy fits well into the systematics, the lifetime is of the correct magnitude (see below), and the angular distribution is consistent with a quadrupole transition, we ascribe this transition to the expected $\frac{9}{2}^+$ to $\frac{5}{2}^-$ $M2$ decay. The transition strength corresponds to 0.041 ± 0.004 W.u.

A delayed 535 keV transition was also reported in Refs. 9 and 10. They are in disagreement, however, concerning the lifetime of the isomeric state. A half-life of

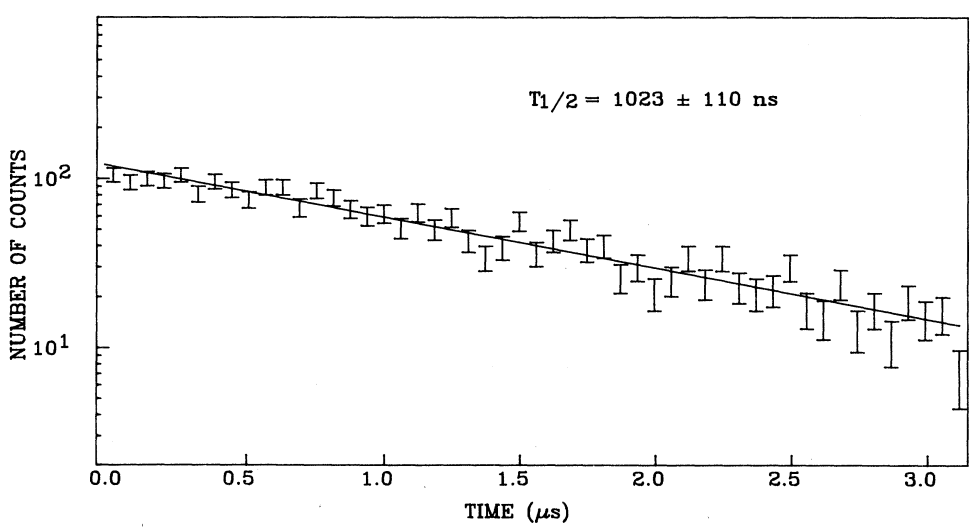

FIG. 5. Compton subtracted distribution of 535 keV γ rays in coincidence with two protons, as a function of time relative to the charged particles detected in the 4π array, for a 98 MeV ^{32}S beam on a ^{40}Ca target. The line represents a least-squares fit; see text for discussion.

$t_{1/2}=853\pm78$ ns was reported in Ref. 9, whereas the result in Ref. 10 corresponds to $t_{1/2}=280^{+350}_{-140}$ ns, a factor of 3 shorter (although with a substantial error). The present measurement is in reasonable agreement with the longer value found in Ref. 9. This is particularly interesting since it is the *shorter* half-life which would have been predicted from systematics. Figure 6 shows a plot of the known $M2$ transition probabilities for odd-neutron nuclides in this region (including our ^{69}Se measurement). The Zn and Ge isotopes show a pattern of increasing $B(M2)$ with decreasing neutron number. The ^{69}Se result, on the contrary, shows a sharp drop in $B(M2)$ as the neutron number decreases, a feature which has not been previously noted. The lifetime quoted in Ref. 10 would correspond to a $B(M2)$ sharply rising rather than sharply falling in Se as N decreases. The significance of the anomalous Se pattern in Fig. 6 is not clear, particularly since all of the transitions in Fig. 6 are rather strongly hindered to begin with. It is interesting to note, however, that such hindrances can be affected[19] by the magnitude and sign of the quadrupole deformation, and it would probably not be surprising to see a change if the nuclear shape switched from prolate to oblate, as has been predicted for this mass region.[3]

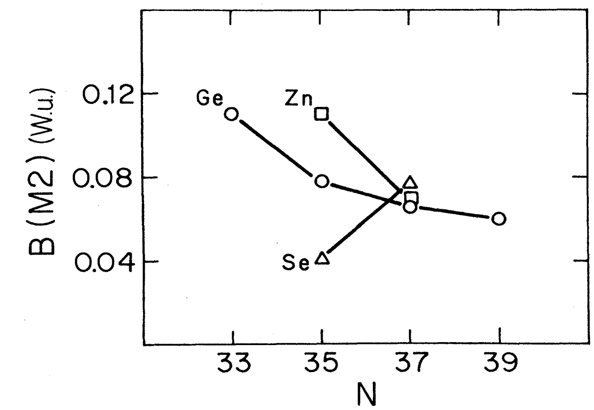

FIG. 6. Systematics of $\frac{9}{2}^+$ to $\frac{5}{2}^-$ $M2$ transition probabilities in Weisskopf units (W.u.). The ^{69}Se result is from the present work. The other $B(M2)$ values are calculated from lifetimes and energies reported in Ref. 16 (^{65,67}Zn, ^{69,71}Ge), Ref. 17 (^{67}Ge), Ref. 7 (^{65}Ge), and Ref. 18 (^{71}Se).

C. Level scheme of ^{69}Se

The charged-particle-γ-γ and neutron-γ-γ coincidence measurements were used along with the lifetime information, excitation functions, and neutron-γ angular distribution results, to establish the decay scheme. Figure 7 shows the spectrum of prompt γ rays in coincidence with two protons and with a delayed 535 keV transition, which establishes a number of transitions above the isomer. Figure 8 shows a partial level scheme deduced from the combination of all the data. The intensities of the γ rays were determined, for the most part, by analysis of the n-γ angular distribution data. The function

$$W(\theta)=I_\gamma(1+A_2P_2(\cos\theta)+A_4P_4(\cos\theta))$$

was fitted to these data to obtain the relative γ-ray intensity I_γ and the Legendre polynomial coefficients A_2 and A_4. The results of these fits are given in Table I. In cases where a transition could not be analyzed in the n-γ angular distribution data due to low yield, the relative intensity was taken from a spectrum obtained by adding together the spectra taken at the four angles of observation, thereby crudely integrating over the γ-ray angular distribution.

As noted previously, we expect low-lying states in ^{69}Se associated with the $p_{1/2}$, $p_{3/2}$, and $f_{5/2}$ orbitals. The spin of the ground state of ^{69}Se was suggested[20] to be $\frac{3}{2}^-$ in 1977 following the experimental study of the β^+-EC de-

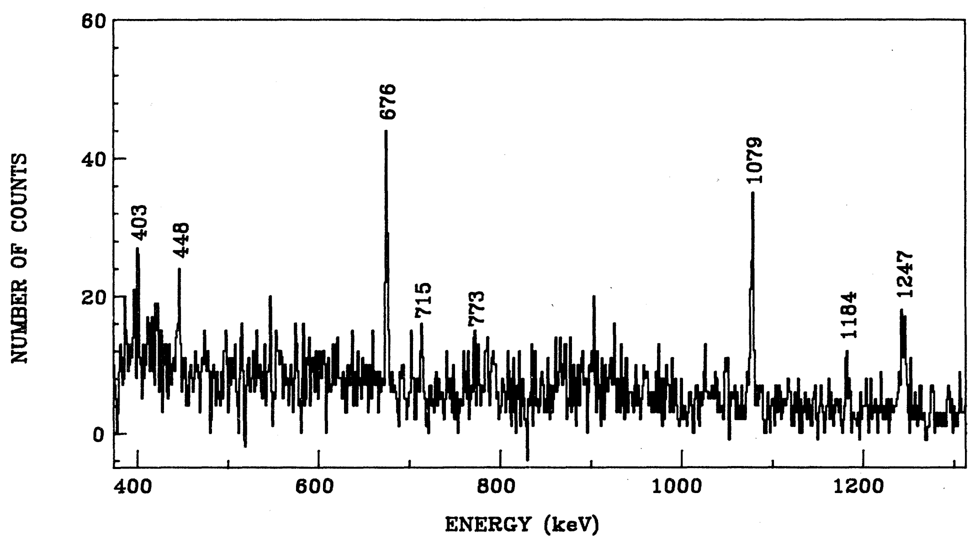

FIG. 7. Spectrum of γ rays in prompt coincidence with two protons in the 4π array and in coincidence with a delayed 535 keV γ ray. A Compton background has been subtracted.

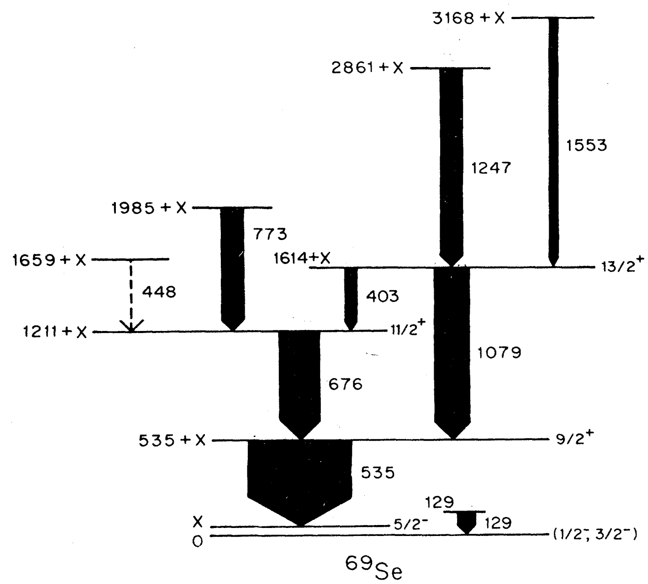

FIG. 8. Partial level scheme for ^{69}Se. Energies are given in keV. The γ-ray intensities are proportional to the widths of the arrows in the figure.

cay of ^{69}Se to levels in ^{69}As. (Decays to proton-unbound levels were also observed; the motivation for the work of Ref. 20 was to study the β-delayed protons in the ^{69}Se decay.) The authors of Ref. 20 reported allowed β^+ decays of ^{69}Se to the three lowest bound levels of ^{69}As. The ground state of ^{69}As was known to have $J^\pi=\frac{5}{2}^-$;[21] the first excited state ($E_x=98$ keV) has recently been assigned $\frac{3}{2}^-$ (Ref. 22); the spin of the second excited state ($E_x=164$ keV) is unknown, but might reasonably be expected to be $\frac{1}{2}^-$ on the basis of comparison with nearby nuclei and because no crossover transition is observed connecting the 164 keV level to the ground state. (At

TABLE I. Properties of transitions in ^{69}Se from the ^{40}Ca(^{32}S,$2pn$)^{69}Se reaction.

E_γ (keV)[a]	I_γ (%)[b]	A_2	A_4
129.2	13.4±3.0	−0.27±0.12[c]	(0)
403.2	8.5±1.0	−0.52±0.23	0.06±0.31
448.0	5.2±1.3[d]		
534.9	(100)	0.08±0.17	−0.10±0.23
676.4	30.9±1.3	0.37±0.09	−0.15±0.13
715.1	10.4±1.2	0.22±0.26	−0.25±0.35
773.3(±1.2)	16.3±1.3	0.29±0.19	−0.07±0.25
808.7	11.5±2.4[d]		
1078.9	27.9±1.7	0.15±0.14	−0.06±0.18
1246.8	17.2±5.5	−0.08±0.43	0.10±0.76
1553.5(±0.8)	4.6±1.8[d]		

[a]Energies obtained from phase II charged-particle-γ measurements; accurate to ±0.5 keV except where noted.
[b]γ-ray intensities normalized to the 535 keV transition.
[c]Average of fits with A_4 set equal to zero in the ^{32}S+^{40}Ca and ^{35}Cl+^{40}Ca systems (see text).
[d]Intensity from γ spectrum summed over angles. No angular distribution was measured.

such a low energy an $E2$ transition connecting two single-particle states might not be expected to compete favorably with an $M1$ decay to the $\frac{3}{2}^-$ state.) The assumption that the three lowest states of ^{69}As have spins of $\frac{5}{2}^-$, $\frac{3}{2}^-$, $\frac{1}{2}^-$, taken with the observation of allowed β decays to all three states, would require the spin and parity of the ^{69}Se ground state to be $\frac{3}{2}^-$.

Before accepting this conclusion, however, it should be noted that a measurement of the intensity of the β branch to the ^{69}As ground state requires subtracting the sum of the branches to excited states (deduced from the observed γ rays) from the intensity of the annihilation radiation; as a result of this process the quoted branching ratio has a large error, (19.2±12.0)%. Based on Ref. 20 alone, the existence of a β branch to the ^{69}As ground state has thus only been established at the 1.5σ level. The situation is further complicated by the recent work of Dessagne *et al.*, who recently remeasured[23] the β^+-EC decay of ^{69}Se, and identified several new β^+-EC branches to higher-lying excited states of ^{69}As. As a result, it was concluded in Ref. 23 that only upper limits could be established for the β-decay branches leading to the ground state and 98 keV excited state of ^{69}As. Acceptance of this conclusion would imply that no allowed β^+ decays of the ^{69}Se ground state to any states of known spin have been firmly established. However, the data reported in Ref. 23 do not support the conclusions in that paper. Specifically, only one of the 14 new states to which β decays are identified was observed to γ decay directly (and only weakly) to the ground state of ^{69}As. The newly observed β branches can therefore only rearrange the strength among excited states, and cannot lead to significant changes in the conclusions about the β branch to the ground state. A more complete discussion of the β decay of ^{69}Se will be given elsewhere.[24] Two points are noteworthy and should be mentioned here. First, the more recent work (Ref. 23) did not measure the total β decay strength using annihilation radiation. Consequently, the value of the ground state β branch must rely on the original measurement of the total strength in Ref. 20. Second, all of the new branches found in Ref. 23 produce γ rays which are in coincidence with the strong low-energy lines at 66 and 98 keV. This calls into question whether additional branches feeding the ground state would have been seen in the work reported in Ref. 23. (For example, it is not stated in Ref. 23 whether γ singles were recorded as a function of time. If not, it might be difficult to associate weak γ rays which feed only the ground state and are therefore not in coincidence with known transitions in ^{69}As.) Our conclusion is that all of these facts, taken together, suggest that the presence of a β decay branch from the ^{69}Se ground state to the $J^\pi=\frac{5}{2}^-$ ground state of ^{69}As cannot be regarded as definitively established. We will therefore take the view that the β decay experiments establish that there is an allowed decay to the $E_x=164$ keV level, whose spin is likely $\frac{1}{2}^-$. This would restrict the possible spins of the ^{69}Se ground state to $\frac{1}{2}^-$ or $\frac{3}{2}^-$. In either case, the 535 keV transition we have identified with the $\frac{9}{2}^+\rightarrow\frac{5}{2}^-$ isomer must feed an excited state. To allow for this possibility, the $\frac{5}{2}^-$ state is labeled X in Fig. 8. In contrast to other recently published reports,[9,10] we have not observed a low-energy γ ray depopulating the $\frac{5}{2}^-$ level.

Above the $\frac{9}{2}^+$ isomer, the cascade is quite fragmented in comparison to other odd-neutron nuclei in this mass region, which typically show a single strong yrast cascade of $E2$ transitions. This fragmentation of the yield, combined with the modest production cross section, makes it difficult to build an extensive decay scheme; nevertheless, some of the more important features can be elucidated. The main feeding of the $\frac{9}{2}^+$ isomer is through a cascade of two transitions (676 and 403 keV) in parallel with a crossover transition (1079 keV) of comparable strength. The 1079 keV crossover has an angular distribution consistent with a stretched quadrupole, and fits very smoothly into the systematics of $\frac{13}{2}^+ \rightarrow \frac{9}{2}^+ E2$ transitions in the odd selenium isotopes. The energies of these transitions are systematically slightly higher than those of the $2^+ \rightarrow 0^+$ transitions in the neighboring even-even selenium isotopes. (The $2^+ \rightarrow 0^+$ energies in ^{70}Se and ^{72}Se are 945 keV and 862 keV, respectively, while the $\frac{13}{2}^+ \rightarrow \frac{9}{2}^+$ transition energy in ^{71}Se is 1038 keV). The angular distributions of the 676 and 403 keV lines are consistent with mixed dipole transitions (see below), implying an $E2/M1$ cascade in parallel with the 1079 keV $E2$ transition. It is natural to interpret the 1079 keV transition as arising from a coupling of the $g_{9/2}$ single particle to the core 2^+ excitation, as has been done in the heavier isotopes, as well as in odd nuclei throughout this region. The crucial new feature in ^{69}Se is that for the first time in this mass region, a strong $M1$ cascade competes with the $E2$ decay (which is the overwhelmingly dominant cascade above the isomer in all other cases). We will return to this point later.

Above the $\frac{13}{2}^+$ state, the 1247 keV transition is a good candidate for the $\frac{17}{2}^+ \rightarrow \frac{13}{2}^+$ transition, although our data are insufficient to determine the multipolarity due to limited statistics and the presence of interfering neighboring peaks. We have similarly not been able to extend the $M1$ cascade above the $\frac{13}{2}^+$ state. No other major cascades could be found, despite the presence of occasional individual transitions which were strongly excited (in particular, the 773 keV line). This again appears to reflect a substantial fragmentation of the yrast decay in ^{69}Se.

In the heavier odd selenium isotopes, additional (usually weaker) cascades are observed which bypass the $g_{9/2}$ isomer to feed the ground state directly. The strongest transition which we could clearly identify with the $2pn$ channel, and which was found not to be feeding the isomer, was a line at 129.2±0.3 keV. Unfortunately, we could determine no coincidence relationships involving this transition due to its low strength and to the large Compton background at this energy. The excitation function and E_x results for this transition are consistent with a placement near the bottom of the level scheme. It is tempting to speculate that the 129 keV transition originates from a level which, taken with the $\frac{5}{2}^-$ state and the ground state, would constitute the expected low-lying $\frac{3}{2}^-$, $\frac{1}{2}^-$, and $\frac{5}{2}^-$ triplet. (Note that in Fig. 8 we have arbitrarily shown the 129 keV transition as feeding the ground state. Our data are also consistent with it feeding the $\frac{5}{2}^-$ state.)

Particular attention was paid to the observed angular distribution of the 129 keV γ ray, since if this transition were to originate from a $\frac{1}{2}^-$ state it must be isotropic. In the case of the ^{32}S+^{40}Ca data, the angular distribution measurements for low-energy γ rays were hampered by γ-ray absorption in the target frame at some angles. A correction could be made, however, since the nearby 158 keV γ ray in ^{68}As (the $3pn$ reaction product) has an angular distribution which could be independently determined from a separate experiment in which γ-ray angular distributions in coincidence with neutrons were measured in the ^{35}Cl + ^{40}Ca system. (In this system, ^{68}As and ^{69}Se are produced via the $\alpha 2pn$ and αpn channels, respectively.) In the latter case particular care was taken to avoid the problem heretofore noted, including measurements in which γ-ray detection efficiency for low-energy γ rays was measured directly as a function of angle of observation of the γ ray using radioactive sources. By assuming that the absorption change is the same at 158 and 129 keV it is possible to correct the angular distribution for the 129 keV transition in the ^{32}S+^{40}Ca n-γ data; the 129 keV line can also be directly analyzed in the ^{35}Cl+^{40}Ca data, although with rather lower statistical accuracy. Because of the substantial experimental errors and the desire to focus on the simple question of whether or not the transition is isotropic, the data in both cases were fitted to the expression $W(\theta)=A_0(1+a_2P_2(\cos\theta))$, where $P_2(\cos\theta)$ is the Legendre polynomial of order 2. The results of the two fits are $a_2=-0.16\pm0.16$ (^{35}Cl+^{40}Ca) and $a_2=-0.38\pm0.17$ (^{32}S+^{40}Ca). These are consistent with each other, but unfortunately do not give a conclusive answer to the question of isotropy, although the data show a mild preference for some anisotropy. (Even in the second case, an isotropic transition is only ruled out at about the 90% confidence level.) The data thus do not distinguish between $\frac{1}{2}^-$ and $\frac{3}{2}^-$ for the spin of the level emitting the 129 keV γ ray. We note that a $\frac{1}{2}^-$ assignment would disagree with the spin assignments and decay scheme reported in Ref. 10. If, on the other hand, the level emitting the 129 keV γ ray were to be assigned a spin and parity of $\frac{3}{2}^-$, and assumed to be a member of a low-lying triplet with spins $\frac{1}{2}^-$, $\frac{3}{2}^-$, and $\frac{5}{2}^-$, then the ground would be required to have $J^\pi=\frac{1}{2}^-$. As noted above, this possibility is not excluded by existing knowledge of the β decay of ^{69}Se. We note that the neighboring isotone ^{67}Ge has a ground-state spin of $\frac{1}{2}^-$ with a very low-lying $\frac{5}{2}^-$ excited state.[15] All of these facts lead us to conclude that further experimental work is needed to clarify the spins and parities of the low-lying negative-parity states in ^{69}Se (see below for additional discussion).

To determine whether the 129 keV transition is the only decay path that does not feed the isomer, the production cross section for the ^{69}Se ground state was deduced from the observation of its β decay using a chopped beam. To avoid difficulties associated with measuring an absolute cross section, the ^{69}Se ground-state production was measured relative to that for the ground state of ^{69}As, produced by $3p$ evaporation. Comparing the $E_\gamma=98$ keV (Ref. 20) line from the ^{69}Se β decay ($t_{1/2}=27.4$ s) with the $E_\gamma=233$ keV γ ray (Ref. 25) from the ^{69}As β decay ($t_{1/2}=15.1$ min) yields a ratio of production cross sections $\sigma_{\rm As}/\sigma_{\rm Se}=8.9\pm0.6$. In obtaining this ratio, the observed yields were connected to production cross sections using the previously known γ-ray intensities and nuclear lifetimes to account numerically for the activation/measurement timing cycles used in the experiment. The cross section ratio was checked using e^+-γ coincidence measurements made in-beam; in that case a small correction had to be applied for the somewhat higher efficiency of the phoswich array to detect the higher-energy positrons from the ^{69}Se decay. This latter measurement gives $\sigma_{\rm As}/\sigma_{\rm Se}=8.5\pm0.2$. We adopt a weighted average of 8.6 ± 0.7, where the quoted error includes contributions from statistics and estimates of other sources of uncertainty. Once the ratio $\sigma_{\rm As}/\sigma_{\rm Se}$ is known, it can be combined with the ^{69}As yield measured in-beam with $3p$-γ coincidences to predict the in-beam yield for ^{69}Se. To do this, we need to know ϵ_{3p}, the efficiency of the phase I array to detect three protons from ^{69}As. For a channel with a large cross section such as $3p$ evaporation, ϵ_{3p} can be straightforwardly determined by comparing the γ singles spectrum with the simultaneously obtained $3p$-γ coincidence spectrum. The result, $\epsilon_{3p}=0.067\pm0.010$, was obtained using the $E_\gamma=442$ and 1306 keV lines in ^{69}As. These lines are not fed in the ^{69}Se β decay, so it is assumed that in the singles spectrum these lines come exclusively from $3p$ evaporation. The quoted error reflects counting statistics and an estimate of the reproducibility obtained from the spread of values from the different lines. Once ϵ_{3p} is known, we can predict the in-beam yield of ^{69}Se from the relation

$$Y_{^{69}\rm Se}=\frac{I_{3p}(^{69}\rm As)}{\epsilon_{3p}}\times\left[\frac{\sigma_{^{69}\rm As}}{\sigma_{^{69}\rm Se}}\right]^{-1}_{\beta\ \rm decay}, \quad (1)$$

where $I_{3p}(^{69}\rm As)$ is the sum of the intensities of the 442 and 1306 keV transitions in ^{69}As (representing the bulk of the ground-state feeding in that channel) obtained by correcting the yield at $\theta_\gamma=135°$ for the known γ-ray angular distribution. The value of $Y_{^{69}\rm Se}$ so obtained can be compared with the observed in-beam yield of the 535 and 129 keV γ rays as determined from $2p$-γ coincidences. It is unfortunately not possible to determine the required two-proton efficiency of the array directly, since the strongest $2pxn$ channel, $2pn$ leading to ^{69}Se, is still quite weak and no peak can be reliably integrated in the singles spectrum. We have therefore obtained ϵ_{2p} from the approximate relationship $\epsilon_{2p}=(\epsilon_{3p})^{2/3}$, which has been verified empirically in other systems where $2p$ lines can be easily measured. The result is $\epsilon_{2p}=0.165\pm0.016$. An estimate can now be made of any undetected weak or fragmented γ branches feeding the ground state but not going through either the isomer or the 129 keV transition. The result obtained is

$$\frac{Y_{535}+Y_{129}}{Y_{^{69}\rm Se}}=1.14\pm0.34\ , \quad (2)$$

suggesting that we have identified the only major cascades in ^{69}Se. From the relative intensities of the 129 and 535 keV transitions, we find that $(89\pm26)\%$ of the ground-state production comes through the isomer. This is in disagreement with the result of Ref. 9, which claims from a comparison of in-beam and out-of-beam yields that the isomer accounts for only 47% of the total ground-state production. (No individual transitions in parallel with the isomer were identified, however, in Ref. 9.) Using the intensities as indicated by the arrow widths in Fig. 2 of Ref. 10, we can deduce that Ref. 10 measures roughly 76% of the ground-state feeding coming through the isomer, in good agreement with the present work.

D. Comparison with other results for levels in ^{69}Se

Since our preliminary results were reported, two independent accounts of work on ^{69}Se have recently appeared, as mentioned above in our discussion of the identification of ^{69}Se and the measurement of the isomeric lifetime. Both experiments used the ^{40}Ca(^{32}S,$2pn$) reaction and neutron-γ and neutron-γ-γ coincidence measurements. Ramdane *et al.* utilized a "neutron wall" arrangement of six hexagonal liquid scintillator detectors, and a single pair of unsuppressed Ge(Li) detectors for their measurements.[9] No angular distribution or correlation information was reported for the determination of multipolarities. The level scheme represented in Ref. 9 includes the 535, 1079, 676, and 403 keV transitions in the same order as the present results (see Fig. 8). One additional transition is shown, a 40 keV $\frac{5}{2}^-\to\frac{3}{2}^-$ ground-state decay, to which we will return shortly. The second experiment,[10] of Wiosna *et al.*, used an eightfold neutron multiplicity filter in conjunction with the OSIRIS array of 11 Compton-suppressed Ge detectors. In this case, neutron-gated angular distribution data provided information for some multipolarity assignments. The higher γ-γ efficiency and the use of Compton suppression would be expected to be particularly useful in identifying weak cascades and branches, and the level scheme presented in Ref. 10 does contain many weak parallel cascades in addition to the strong yrast decays presented in Fig. 8. However, there are important discrepancies between the results of Ref. 10 and the present work, even for relatively strong transitions. We have already noted a factor of three discrepancy between Ref. 10 and our results on the lifetime of the $\frac{9}{2}^+$ isomer. Another major disagreement is on the report in Ref. 10 of observation of a very intense 39 keV $\frac{5}{2}^-\to\frac{3}{2}^-$ ground-state transition. Because of its importance, we will discuss this question in some detail.

Both Refs. 9 and 10 claim to have measured the excitation energy of the first excited state as 40 keV. In Ref. 9, for example, it is claimed that a 40.2 keV γ ray is observed with an intensity of 65% of that of the 535 keV γ ray from the decay of the isomer. Figure 2 of Ref. 10 shows a γ-ray intensity for a 39.4 keV transition which is larger than the 535 keV intensity. Figure 9 shows the relevant portions of the spectrum of γ rays in delayed coincidence ($t=218$–3146 ns) with two protons detected in the phoswich array. There are approximately 2500 counts in the 535 keV peak; if the results of Ref. 9 were

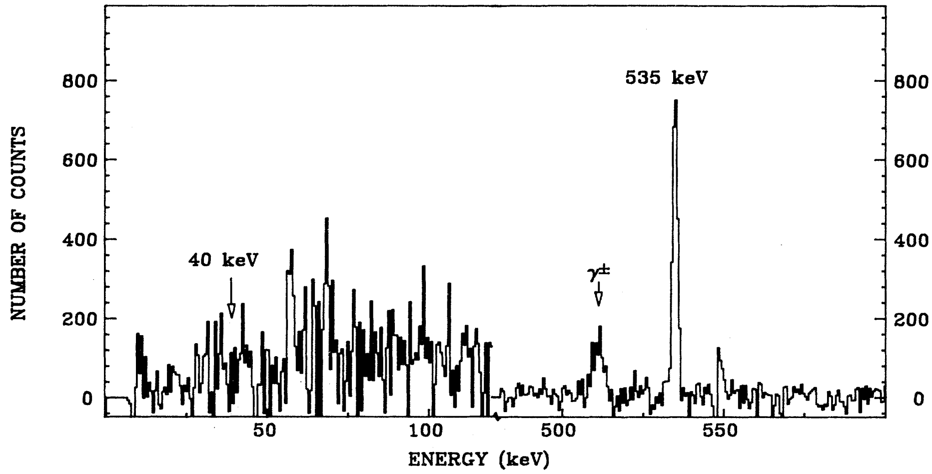

FIG. 9. γ rays observed in delayed coincidence with two protons in the $^{32}S+^{40}Ca$ system. The bombarding energy is 98 MeV. Note the discontinuity in the horizontal scale.

correct, we would expect about 4150 counts in a peak at 40 keV (and even more if Ref. 10 were correct). In fact, fewer than 200 counts are observed (see Fig. 9). The relative efficiency of our Ge detector required for this comparison was measured using the known intensity of Sm K_α and K_β x rays relative to high-energy γ rays from a ^{152}Eu source. For comparison, the peak at 57 keV contains approximately 1200 counts. The origin of this peak is uncertain; a 56.2 keV transition is known in ^{69}As and a 56.8 keV transition (presumably prompt) has been assigned to ^{69}Se.[9,10] Note that the peak in Fig. 9 cannot result from a 56.8 keV line attributed to the 3674.7 keV to 3617.9 keV transition in ^{69}Se in Ref. 10, since then many other delayed γ rays should also be present. (The time spectrum associated with the 57 keV peak does not show the characteristic lifetime of the 535 keV transition, but rather shows a prompt peak and a slight excess of counts on the delayed side.)

It is possibly worth noting that both Refs. 9 and 10 have failed to point out that there is a known 40 keV transition,[26] in ^{45}Ti, which is produced copiously by the $2pn$ reaction on ^{16}O, a contaminant which is difficult to avoid with calcium targets. Figure 10 shows the low-energy portion of a spectrum of γ rays observed in coincidence with two protons and a neutron when a WO_3 target was bombarded with a 96 MeV ^{32}S beam. The transition labeled has an energy of 40.0±0.3 keV, and is attributed to the decay of the second excited state of ^{45}Ti. This state has a lifetime of only 11.9 ns, so this γ ray should not be mistaken for the transition of interest in ^{69}Se.

We conclude that the claims in Refs. 9 and 10 of observation of a strong 40 keV transition in ^{69}Se cannot be supported. Therefore Ref. 9 provides no information on the excitation energy of the $\frac{5}{2}^-$ state in ^{69}Se. The level scheme of Ref. 10 supplies additional but considerably

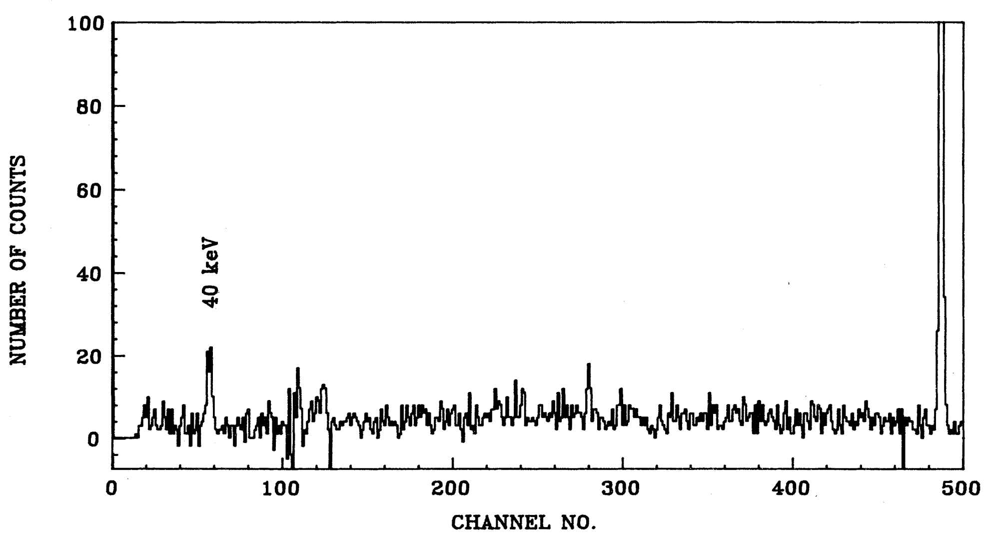

FIG. 10. $2pn$-γ coincidences for 96 MeV $^{32}S+^{16}O$. The very strong peak in channel 488 is the 293 keV transition in ^{45}Ti.

weaker evidence that the $\frac{5}{2}^-$ state is at 39.4 keV, based on the coincidence relationships of the very weak transitions feeding the $\frac{5}{2}^-$ and ground states in parallel with the isomeric transition. Only one transition (the 129 keV line) is placed as feeding the ground state (g.s.) directly, while two cascades involving the 129 keV transition, if correct, require a 39 keV $\frac{5}{2}^- \rightarrow$g.s. spacing. However, this conclusion is based on coincidence relationships between several of the weakest transitions reported in Ref. 10. If this scheme is correct, then rather severe limits are placed on the properties of the $\frac{5}{2}^-$ decay as a result of our nonobservation of this transition.

Interpretation of the low γ-ray intensity depends on the assumed multipolarity of the 40 keV transition. If it is an $M1$, then our failure to observe it must be attributed to an anomalously long lifetime, since internal conversion is a small effect. The upper limit on the intensity quoted previously would correspond to a transition strength of approximately 5×10^{-6} W.u. For an $E2$ transition, on the other hand, most of the inhibition could be attributed to internal conversion and the lifetime could well be short. (Both effects could also occur. In ^{67}Ge, the first excited state at $E_x=18.3$ keV has a lifetime of 20 μs and an internal conversion coefficient greater than 300.[15]) We note that the systematics of $\frac{5}{2}^- \rightarrow \frac{3}{2}^-$ transitions in this mass region would suggest a mixed $E2/M1$ transition with a small mixing ratio and a lifetime in the microsecond range. This would not have been missed by our experiment. Further work aimed at a test of the level scheme by direct observation of the ground-state transition and measurements of its properties would certainly be of interest.

We now summarize some of the remaining comparisons between our data and the experimental results reported in Ref. 10. Most of the strongest coincidences we observed among the transitions that feed the isomer are in qualitative agreement with the level scheme published in Ref. 10. There are some differences, however. We find the 1553 keV transition to have an intensity about 3 times smaller than that which would be inferred from the width of the arrow in Fig. 2 of Ref. 10. This perhaps provides a partial explanation for our inability to establish coincidence relationships involving the transitions placed in Ref. 10 above the $E_x=(3168+X)$ keV level. In Ref. 8 we placed the 715 keV γ ray as feeding the isomeric $\frac{9}{2}^+$ state directly because we did not observe the 715 keV line in coincidence with any γ rays except the 535 keV transition depopulating the isomer. In Ref. 10 this line is placed above the 1553 keV line (which it feeds through a 468.6 keV transition in parallel with a 56.8+411.8 keV cascade). However, comparison of the upper limits observed in our 403, 676, and 1079 keV gates with what would be expected if the 1553 keV transition is substantially weaker than found in Ref. 10, leads to the conclusion that the present study is probably not inconsistent with the placement of the 715 keV transition in Ref. 10. We also do observe a 57 keV γ ray in coincidence with the 715 keV line, as required by the level scheme of Ref. 10.

The cascades in parallel with the 535 keV isomeric decay were too weak to be unraveled given the statistics of our data. However, we do find that the γ rays at 808, 771, 786, 1084, and 1154 keV are in coincidence with two protons and a neutron, consistent with the assignment of these lines to ^{69}Se in Ref. 10. As we mentioned earlier, our observation of a low-lying 129 keV transition is consistent with its placement in Ref. 10 as feeding the ground state. The strongest transition reported in Ref. 10 which does not feed the isomer is the 808 keV transition. Attempts to identify coincidences involving this line from the charged-particle-γ-γ data were hampered by the existence of a previously unreported 808 keV transition in ^{69}As. (This line could be clearly identified as being in coincidence with three protons and with known transitions in ^{69}As.) In addition, a nearby 810 keV transition in ^{42}Ca, strongly fed by $\alpha 2p$ evaporation involving the ^{16}O contaminant in the target complicated the analysis further. Our n-γ-γ data did not have adequate statistics to overcome these problems.

E. Interpretation of the level scheme

Above the isomeric $\frac{9}{2}^+$ level, the yrast states in this mass region are usually interpreted as being generated by coupling the odd $g_{9/2}$ particle to collective excitations of the even-even core. In the simplest rotational picture, the details of the coupling depend on the location of the Fermi level and on the sign and magnitude of the core deformation. Here, the Fermi level would be near the bottom of the $g_{9/2}$ shell. For a modest prolate deformation, one would expect to see a decoupled $\Delta J=2$ band, with the single-particle angular momentum aligned with the core, and the level spacings similar to those of the core. The dominant yrast cascades in odd-A nuclei throughout the region generally do consist of stretched quadrupole transitions which have been widely interpreted in this way. On the other hand, for an oblate deformation, as has been predicted for ^{69}Se, the $g_{9/2}$ particle would be filling a high-Ω level, strongly coupled to the core, producing a band of $M1$ transitions with $E2$ crossovers. In Fig. 8, we see evidence of the beginnings of such a structure involving the 676 and 403 keV $M1/E2$ transitions with a 1079 keV $E2$ crossover. It is also likely that the 1247 keV transition is the next $E2$, although we have been able to determine no candidates for the pair of $M1$ transitions that would go with this $E2$.

This is the first case in this mass region in which a strong $\Delta J=1$ cascade competes with the $E2$'s built on the $\frac{9}{2}^+$ state. Information on the sign of the deformation for the intrinsic state of this band can be obtained from the sign of the $E2/M1$ mixing ratios for the $\Delta J=1$ transitions. In the simplest rotational model, the sign of δ is determined by the sign of $(g_K-g_R)/Q_0$, where g_K and g_R are the intrinsic and rotational g factors, and Q_0 is the intrinsic electric quadrupole moment.[27] Since the numerator should be negative for the $g_{9/2}$ neutron,[27] the sign of the mixing ratio determines the sign of Q_0. Note that this argument requires all mixed transitions in the band to have $E2/M1$ mixing ratios of the same sign.

The two transitions which can be used to determine this sign in the present work are the 676 and 403 keV transitions. Determination of the $E2/M1$ mixing ratio from the angular distribution requires a knowledge of the alignment of the state emitting the γ ray of interest. A standard technique is to use quadrupole transitions to determine the alignment as a function of excitation energy, and then to fix the alignment and vary the mixing ratio of the $\Delta J=1$ transitions to fit their angular distributions. In the present case this procedure is not easy to apply, primarily because of poor statistics. Estimates from studies in neighboring nuclei suggest a Gaussian width parameter σ of approximately 2.5. Fitting the 1079 keV angular distribution assuming this yields a reduced χ^2 of 1.67. Fitting the angular distribution of the 676 keV transition assuming a Gaussian width parameter of 2.5 unambiguously demonstrates that the mixing ratio is positive; the phase convention is that of Ref. 28. The goodness of fit parameter χ^2 is shown as a function of the mixing ratio as a heavy line in Fig. 11. The qualitative result, i.e., the sign of the mixing ratio, is relatively insensitive to the value of σ.

The 403 keV transition is somewhat more difficult to analyze, both because it is weaker and because the background appears to be more complicated. Taking no account of possible systematic errors resulting from the uncertainty in background subtraction, which are substantial, the measured angular distribution suggests a negative mixing ratio, although with a large error. In an attempt to shed further light on this question, we have examined some more recent data[29] in which γ-ray angular distributions were measured in coincidence with neutrons in the ^{35}Cl$+^{40}$Ca system. ^{69}Se in that case is produced by

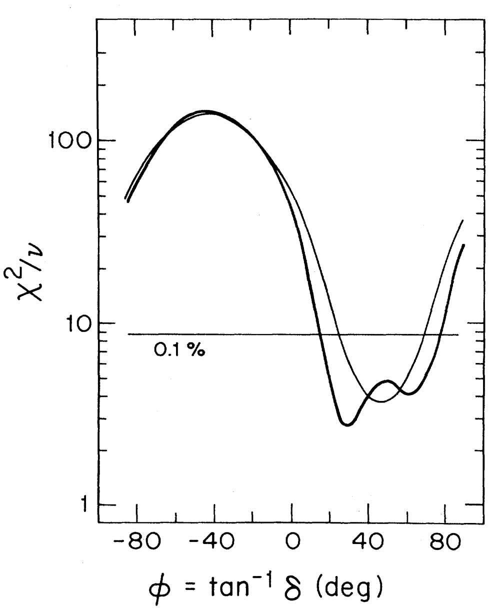

FIG. 11. Plot of χ^2 vs $\tan^{-1}\delta$ for the 676 keV transition in ^{69}Se. The heavy line is from n-γ coincidence measurements in the ^{32}S$+^{40}$Ca system; the light line is a fit to the sum of the above data and an angular distribution obtained for the same transition populated by αpn evaporation in a separate experiment involving the ^{35}Cl$+^{40}$Ca system (Ref. 29).

αpn evaporation. The angular distribution observed for the 676 keV transition was found to be consistent with that described above. The χ^2 vs δ plot is shown for an analysis including both sets of data as the light line in Fig. 11 for comparison. In the case of the 403 keV transition, the data were consistent with an isotropic angular distribution, which would suggest a positive $E2/M1$ mixing ratio. The errors in this case are even larger than in the ^{32}S$+^{40}$Ca data described above, mainly because the presence of many strong nearby lines made estimation of the background difficult. We conclude that the mixing ratio of the 676 keV transition is clearly positive, as would be expected for an oblate shape. The results for the 403 keV transition are inconclusive. Clearly more precise information on angular distributions for the $\Delta J=1$ transitions would be desirable to place conclusions concerning the shape on firmer ground. It would also clearly be useful to have information on the magnitude of the deformation as well as its sign. Unfortunately, as the lifetimes of the relevant states are unknown, information can only be deduced about $E2$ strengths if model-dependent assumptions are made about the competing $M1$ transitions. In Ref. 10 the experimental level scheme in ^{69}Se was compared to a calculation using the asymmetric rotor+vibration model; the comparison suggested a value of β_2 between -0.2 and -0.3. (The sign of the deformation was also inferred from the mixing ratio of the 676 keV transition, as has been done in the present work.) This result is consistent with the value of $|\beta_2|=0.30(3)$ deduced from the lifetime of the 2^+ state in ^{70}Se.[30] Note, however, that in ^{70}Se a band-crossing at relatively low spin is known to reduce $E2$ strengths as the spin increases. The possible influence of such effects in ^{69}Se is unknown.

IV. CONCLUSIONS

In conclusion, we have studied in-beam transitions in the $N=Z+1$ nucleus ^{69}Se, with particular emphasis on providing an unambiguous identification of these previously unknown transitions, constructing a level scheme, and establishing the lifetime of the $\frac{9}{2}^+$ isomeric state in this nucleus. Our investigation has used charged-particle-γ, charged-particle-neutron-γ, and neutron-γ coincidences to assign γ-rays to ^{69}Se. The expected $\frac{9}{2}^+$ isomeric state was found, and its half-life was deduced to be 1023 ± 110 ns. A 535 keV γ ray depopulates this state, and delayed-prompt and prompt-prompt γ-γ coincidences gated on charged-particle or neutron detection were used to construct a level scheme. In addition, a 129 keV transition with a clear $2pn$ signature was found that does not feed the isomer. Comparison of the in-beam γ rays with those from the β decay of ^{69}Se suggests that we have found the bulk of the strength feeding the ^{69}Se ground state.

The present work provides a conclusive identification of ^{69}Se, and provides evidence for a major change in the yrast structure compared to other odd-neutron isotopes in this mass region. The observation of both strong $M1$ and strong $E2$ transitions built on the $\nu g_{9/2}$ state, and the sign of the $E2/M1$ mixing ratio for the $\frac{11}{2}^+ \rightarrow \frac{9}{2}^+$ transition, are consistent with predictions of oblate shapes in the region near ^{70}Br. Our measurement of the $B(M2)$ for the $\frac{9}{2}^+ \rightarrow \frac{5}{2}^-$ isomer resolves a discrepancy between two independent investigations of ^{69}Se which have been recently reported. Our data do not support the reported observations of a strong 40 keV ground-state transition, and further suggest that the spin of the ^{69}Se ground state may not be regarded as firmly established. Further experimental work will clearly be required to elucidate further the properties of the ground and low-lying states and the higher members of the $g_{9/2}$ band.

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