RAPID COMMUNICATIONS

PHYSICAL REVIEW C VOLUME 42, NUMBER 4 OCTOBER 1990

# Identification of the $\pi g_{9/2}$ band in $^{67}$As

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(Received 25 July 1990)

Charged-particle-$\gamma\gamma$ and neutron-$\gamma\gamma$ coincidences are employed to identify $\gamma$-ray transitions in the $T_z = \frac{1}{2}$ nucleus $^{67}$As, produced in the $^{40}$Ca($^{32}$S,$\alpha p$)$^{67}$As and $^{40}$Ca($^{33}$S,$\alpha pn$)$^{67}$As reactions at bombarding energies between 95 and 110 MeV. $\gamma$-ray angular distributions, $\gamma\gamma$ coincidences, and $\gamma\gamma$ angular correlations are used to deduce a level scheme for $^{67}$As up to 5.7 MeV.

The region of nuclei with $N \sim Z$ and $70 < A < 80$ has been the focus of extensive theoretical and experimental study. These nuclei exhibit a range of interesting features, including oblate and strong prolate deformations as well as rapid variations in shape as a function of both spin and particle number. Such properties appear to reflect the existence of, and competition between, gaps in the oblate and prolate sequences of Nilsson levels which occur near nucleon numbers 35 and 38, respectively. These effects appear most dramatically in $N \sim Z$ nuclei because the shell gaps occur simultaneously for protons and neutrons. In-beam $\gamma$-ray measurements in this mass-region, employing both particle-$\gamma\gamma$ and recoil-$\gamma\gamma$ techniques to overcome low production yields, have been instrumental in identifying and studying the structure of new $N \sim Z$ nuclei. Examples of such work include the discovery of extreme prolate deformation ($\epsilon \sim 0.4$) in the light Sr isotopes,[1] the evidence found for shape coexistence in $^{72}$Kr (Ref. 2), and the confirmation of the oblate deformation predicted for $^{69}$Se.[3]

In this paper we present results from the first in-beam measurement of $\gamma$ rays from excited states in the $T_z = \frac{1}{2}$ nucleus $^{67}$As. A principal result of this study is the identification of the $^{67}$As $\pi g_{9/2}$ positive-parity band. The inferred structure of this band should reveal whether $^{67}$As reflects the properties of the nearby odd-$A$ Ge and As isotopes or whether it shows a change in structure which may indicate the onset of the quadrupole deformation observed in heavier $N \sim Z$ nuclei.

This work was conducted at the Lawrence Berkeley Laboratory's Electron-Cyclotron-Resonance (ECR) injected 88-Inch Cyclotron facility, where $^{67}$As was produced in the $^{40}$Ca($^{32}$S,$\alpha p$)$^{67}$As and $^{40}$Ca($^{33}$S,$\alpha pn$)$^{67}$As reactions at bombarding energies near the Coulomb barrier. The targets were 1-mg/cm$^2$ natural Ca evaporated onto 50-mg/cm$^2$ Pb backings. In-beam $\gamma$ rays were detected by the Compton-suppressed Ge detectors of the High Energy-Resolution Array (HERA) spectrometer.[4] Evaporated charged particles were detected by a 260-$\mu$m, 300-mm$^2$ Si counter placed 5 mm behind the target. Due to the different ranges of $\alpha$'s and protons in Si, the charged-particle spectrum [Fig. 1(a)] shows partially resolved $\alpha$ and proton components. A liquid scintillation counter which subtended 0.4 sr was employed to detect coincident neutrons. Pulse-shape discrimination provided the clear neutron-$\gamma$ separation displayed in Fig. 1(b). By employing $\gamma$-ray spectra gated on the $\alpha$ and neutron peaks, it was possible to identify $\gamma$ rays from $\alpha$- and neutron-coincident evaporation channels by their enhancement over transitions from the dominant $xp$ evaporation channels. Enhancement results obtained from

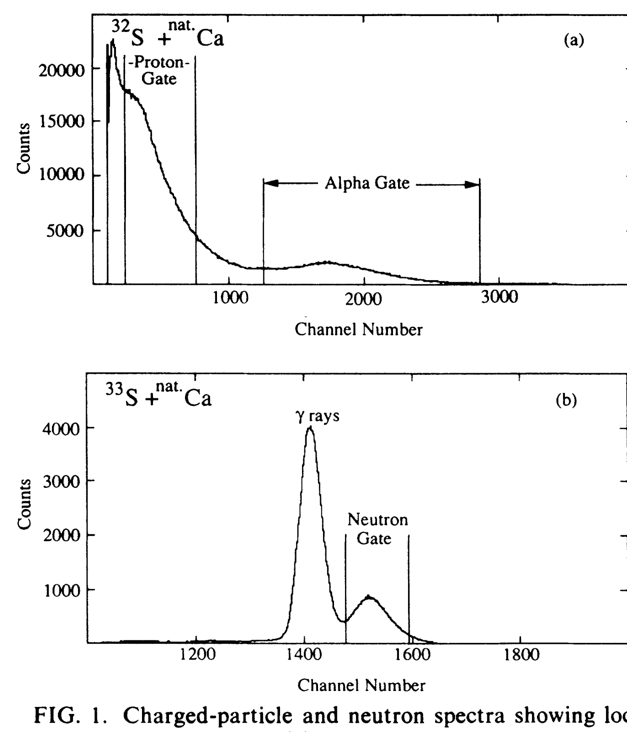


FIG. 1. Charged-particle and neutron spectra showing locations of coincidence gates. (a) Charged-particle spectrum showing partially resolved proton and $\alpha$ components. (b) Neutron counter pulse-shape discrimination spectrum. The $\gamma$ rejection level for the neutron counter was approximately 10:1.

 

TABLE I. Approximate enhancement factors for $\gamma$ rays from several $\alpha$- and neutron-coincident evaporation channels obtained from the $\alpha$-gated $\gamma$-ray spectrum in the $^{32}S+{}^{nat}Ca$ bombardment and the $\alpha$- and neutron-gated spectra in the $^{33}S+{}^{nat}Ca$ bombardment. The enhancements are taken relative to the 863- and 788-keV $\gamma$ rays from the $3p$ evaporation channels $^{69,70}As$. Listed in the table are several transitions from $^{67}As$ as well as $\gamma$ rays from $^{51}Mn$ and $^{66}Ge$, both known contaminant nuclei which are produced via $\alpha p$ and $\alpha 2p$ channels in the $^{32}S$ bombardment and $\alpha pn$ and $\alpha 2pn$ channels in the $^{33}S$ bombardment. Also listed for comparison are the 1306- and 485-keV transitions from $^{69}As$ and $^{70}As$.

| Reaction | $E\gamma$ (keV) | $R(\alpha-\gamma\gamma/\gamma\gamma)\,^{32}S$ [a] | $R(\alpha-\gamma\gamma/\gamma\gamma)\,^{33}S$ [b] | $R(n-\gamma\gamma/\gamma\gamma)\,^{33}S$ |
|---|---|---|---|---|
| $^{24}Mg(^{32(3)}S,\alpha p(n))^{51}Mn$ | 237 | 6 | 6 | 10 |
| $^{40}Ca(^{32(3)}S,\alpha 2p(n))^{66}Ge$ | 957 | 5 | 6 | weak |
| $^{40}Ca(^{32(3)}S,\alpha p(n))^{67}As$ | 638 | 2 | 4 | 4 |
| $^{40}Ca(^{32(3)}S,\alpha p(n))^{67}As$ | 697 | 4 | 3 | 5 |
| $^{40}Ca(^{32(3)}S,\alpha p(n))^{67}As$ | 898 | c | c | |
| $^{40}Ca(^{32(3)}S,\alpha p(n))^{67}As$ | 930 | c | 3 | 4 |
| $^{40}Ca(^{32(3)}S,\alpha p(n))^{67}As$ | 1357 | 4 | 7 | 7 |
| $^{40}Ca(^{32(3)}S,\alpha p(n))^{67}As$ | 1422 | c | c | |
| $^{40}Ca(^{32}S,3p)^{69}As$ | 1306 | 0.8 | | |
| $^{40}Ca(^{33}S,3p)^{70}As$ | 485 | | 1.3 | 1 |

[a] $R(\alpha-\gamma\gamma/\gamma)\,^{32}S=(\text{counts }X_{\alpha\gamma\gamma}/\text{counts }X_{\gamma\gamma})(\text{counts }863_{\gamma\gamma}/\text{counts }863_{\alpha\gamma\gamma})$.
[b] $R(\alpha,n-\gamma\gamma/\gamma\gamma)\,^{33}S=(\text{counts }X_{\alpha,n\gamma\gamma}/\text{counts }X_{\gamma\gamma})(\text{counts }788_{\gamma\gamma}/\text{counts }788_{\alpha,n\gamma\gamma})$.
[c] Peaks not visible in the ungated $\gamma\gamma$ sum spectra which appeared in the $\gamma\gamma$ sum spectra gated by $\alpha$'s and neutrons.

both the $^{32}S$ and $^{33}S$ bombardments are summarized and described in Table I.

The $\gamma$ rays assigned to $^{67}As$ are listed in Table II. These assignments are based on observed enhancements in the $\alpha$- and neutron-gated $\gamma$-ray spectra, particle-$\gamma\gamma$ coincidences, and excitation function measurements. First, the 697-, 638-, and 774-keV $\gamma$ rays are enhanced in the $\alpha$-gated spectrum in the $^{32}S$ bombardment and in both the $\alpha$-gated and neutron-gated spectra in the $^{33}S$ bombardment. Second, the other transitions in Table II appear in coincidence with one or more of these $\gamma$ rays and with an $\alpha$ particle in both the $^{32}S$ and $^{33}S$ bombardments. Excitation function measurements performed for both bombardments, moreover, show that several of these $\gamma$ rays are consistent with two- or three-particle evaporation channels. These assignments also agree with $^{32}S+{}^{40}Ca$ $\gamma$-ray data taken in conjunction with an array of phoswich particle telescopes.[5] Four of the strongest transitions in this group, those at 697, 725, 942, and 1357 keV, are observed to be in coincidence with one $\alpha$ particle and one proton. Finally, the $(\alpha p)$ evaporation products from fusion of $^{32}S$ with the known target contaminants ($^{24}Mg$, $^{44}Ca$, $^{12,13}C$, and $^{16,18}O$ yielding $^{51}Mn$, $^{71}As$, $^{39,40}K$, and $^{43,45}Sc$, respectively) are known and the new transitions identified in this work are not in coincidence with the $\gamma$ rays in their level schemes.

TABLE II. Energies, relative intensities [relative to 942-keV transition ($I^{\rm abs}_{942}=120$)], and anisotropy values for $\gamma$ rays assigned to $^{67}As$. The anisotropy values are discussed in the text.

| $E_\gamma$ (keV) | $I_\gamma$ | $R(37°/79°)$ |
|---|---|---|
| 319.5(2) | 70(3) | $0.8\pm0.1$ [a] |
| 427.5(3) | 7(1) | |
| 638.7(3) | 29(2) | $0.5\pm0.1$ [b] |
| 697.1(3) | 128(3) | $0.7\pm0.1$ [a] |
| 704.3(3) | 20(1) | |
| 725.4(3) | 85(4) | $0.3\pm0.1$ [a,c] |
| 774.6(3) | 73(3) | $1.2\pm0.2$ [a] |
| 814.1(3) | 11(1) | |
| 860.3(3) | 35(2) | |
| 898.0(3) | 25(2) | |
| 930.1(4) | 17(2) | |
| 942.5(4) | 120(2) | $1.7\pm0.1$ [b] |
| 1035.1(4) | 75(6) | $1.4\pm0.2$ [d] |
| 1228.0(4) | 72(4) | $1.8\pm0.1$ [b] |
| 1357.1(5) | 42(3) | $1.3\pm0.2$ [b] |
| 1422.2(5) | 31(6) | |
| 1520.1(5) | 17(2) | |

[a] Gated on 942-keV transition in 152° detectors.
[b] Gated on 774-keV transition in 152° detectors.
[c] Gated on 774-keV, $R(37°/79°)=0.35\pm0.05$.
[d] Gated on 319-keV transition in 152° detectors.

The proposed $^{67}As$ level scheme displayed in Fig. 2 is based on $\gamma\gamma$ coincidences, intensity balance, and energy-summing relationships. An example of the $\gamma\gamma$ coincidence data is given in Fig. 3, which shows a partial spectrum of the $\gamma$ rays in coincidence with the 725-keV transition.

$\gamma$-ray angular distributions and $\gamma\gamma$ angular correlations were employed in conjunction with the systematics of the odd-$A$ nuclei in the region to estimate spins and parities for some of the $^{67}As$ states. The measured angular distributions could be reproduced with the expression:

$$W(\theta)=\sum_\lambda B_\lambda A_\lambda P_\lambda(\cos\theta),\ \lambda=0,2,4\,,$$

where the orientation parameter $B_\lambda$ depends on the width $\sigma$ of the distribution of $m$ states populated in heavy-ion reactions and where the $A_\lambda$ depend on the spins of the initial and final states and the multipolarity and mixing ratio of

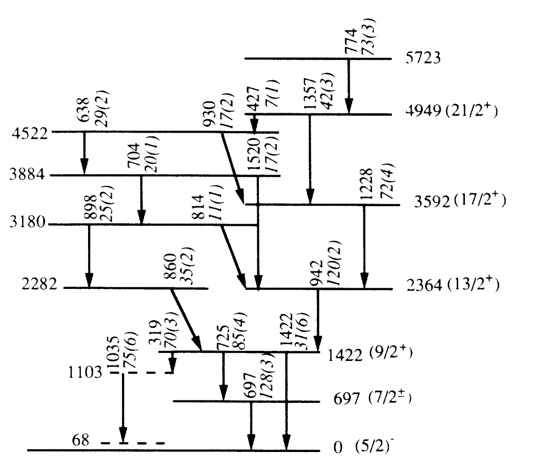


FIG. 2. Proposed level scheme for $^{67}$As. The relative placement of the 319- and 1035-keV transitions is not rigorously established from the $\gamma\gamma$ coincidence data. No evidence for a 68-keV transition was found in these data but a low-lying state at this energy would be consistent with the structures of the nearby odd-$A$ nuclei. Relative intensities are in italic type.

the transition. The angular correlation procedure employed the detectors located at 152°, 37°, and 79° relative to the beam direction. In this procedure, gates were placed on transitions detected in the 152° counters and coincident lines were projected out in the 37° and 79° detectors. For $^{67}$As, it was possible to gate on the strongest transitions (697, 942, 774, and 319 keV) and extract $R(37°/79°)$ anisotropy values for the strongest coincident lines. These experimental values could then be compared to calculated ratios which were functions of the $\gamma$-ray multipolarities and mixing ratios. The choice of the 152° detectors as gating counters was made to simplify the angular correlation calculations. The angular correlation between two $\gamma$ rays emitted from an oriented source is a function of three angles $W(\theta_1,\theta_2,\Phi)$. $\theta_1$ and $\theta_2$ are the emission angles relative to the beam direction and $\Phi$ is the angle between the two planes which contain the beam axis and the individual photon directions. Due to the particular geometrical arrangement of the HERA detectors, the angle $\Phi$ between the 152° counters and all the other detectors employed in this procedure was uniquely 62°. Any other choice of gating detectors would have required a complicated averaging of several $\Phi$. A general expression for $W(\theta_1,\theta_2,\Phi)$ is given in Ref. 6.

The relevant single-particle orbitals in the odd $A\sim70$, $N\sim Z$ nuclei are the nearly degenerate $2p_{1/2}$, $2p_{3/2}$, and $1f_{5/2}$ orbitals, which form the first negative-parity states, and the nearby $1g_{9/2}$ orbital, which produces low-lying positive-parity states. These $g_{9/2}$ states, which are observed throughout the region to decay via isomeric $M2$ transitions to lower-lying $f_{5/2}$ states, form bandheads for sequences of positive-parity levels connected by stretched $E2$ transitions. These sequences are normally yrast, and are usually interpreted as the coupling of a $g_{9/2}$ nucleon to excitations of an adjacent even-even core. Higher-lying negative-parity states are generated by coupling of $2p_{1/2}$, $2p_{3/2}$, and $1f_{5/2}$ nucleons to the same core excitations.

The $^{67}$As ground state is restricted to $J^\pi=(\frac{3}{2}^-,\frac{5}{2}^-)$.[7] As can be seen from Fig. 4, the systematics of the odd As isotopes favor a $\frac{5}{2}^-$ assignment. The ground state is fed by the decay of a state at 697 keV. In the $^{33}$S+$^{40}$Ca data, this transition appeared cleanly in the raw $\gamma$-ray spectrum, permitting extraction of its angular distribution. Assuming an $m$-state distribution width of $\sigma=2.5$, which reproduced known stretched-quadrupole transitions for a range of spins in $^{67}$Ge (the $\alpha 2p$ evaporation product in $^{33}$S+$^{40}$Ca), the best agreement with the angular distribution data for the 697-keV $\gamma$ ray was obtained with an assignment of $\Delta J=1$, $0.0<\delta<0.1$. The 697-keV state is thus expected to be $J=\frac{7}{2}$. A strongly populated $\frac{7}{2}^-$ state is expected at this energy, based on the systematics of the region.

The state at 1422 keV may be considered as a candidate for the $\frac{9}{2}^+$ level. Its excitation energy is consistent with the trend of smoothly increasing $\frac{9}{2}^+\rightarrow\frac{5}{2}^-$ transition energies as a function of decreasing neutron number in the odd-$A$ As isotopes (see Fig. 4). The 1422-keV level, moreover, decays both to the proposed $\frac{7}{2}^-$ state at 697 keV and to the $\frac{5}{2}^-$ ground state with a branching ratio similar to those observed for the $\frac{9}{2}^+$ states in $^{69}$As and $^{65}$Ge. This state is fed by two parallel cascades, one of

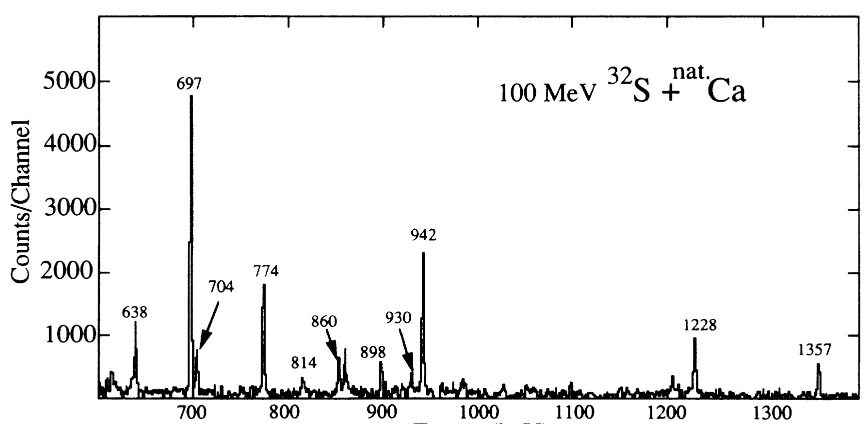


FIG. 3. $\gamma$ rays in coincidence with the 725-keV transition. Unlabeled peaks are $^{69}$As and $^{66}$Ge contaminants.

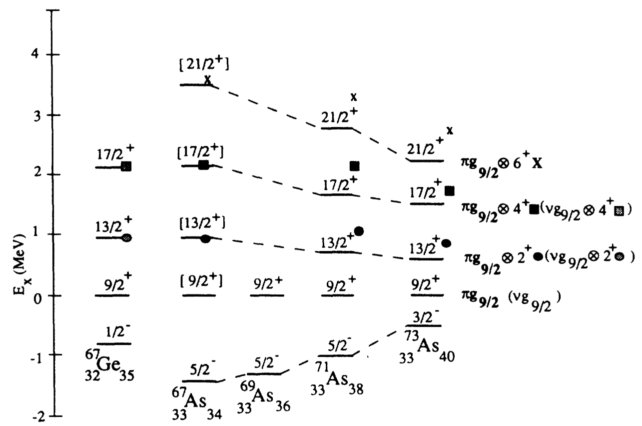


FIG. 4. Systematics of ground states and $\pi g_{9/2}$ states in the odd-$A$ As isotopes. All energies are relative to $\frac{9}{2}^+$ states, which are set equal to zero. Squares, circles, and $X$'s represent excitations in the $^{66,70,72}$Ge cores, respectively. The $\nu g_{9/2}$ band in $^{67}$Ge is displayed for comparison.

which, the $1357 \rightarrow 1228 \rightarrow 942$ sequence, has a level spacing consistent with the $\pi g_{9/2}$ structures seen in the neighboring odd-$A$ nuclides. If this sequence forms the $\pi g_{9/2}$ band, then the states at 1422, 2364, 3592, and 4949 keV should have spins of $\frac{9}{2}^+$, $\frac{13}{2}^+$, $\frac{17}{2}^+$, and $\frac{21}{2}^+$, respectively. This conjecture is consistent with angular correlation data for the 1228- and 942-keV transitions. These $\gamma$ rays, when gated by the 774-keV line, have nearly identical $R(37°/79°)$ anisotropies of $1.7 \pm 0.1$ and $1.8 \pm 0.1$, respectively, which are consistent with stretched quadrupole assignments for the $1357 \rightarrow 1228 \rightarrow 942$ sequence. The relative intensities observed for these $\gamma$ rays tend to support this hypothesis. Heavy-ion studies of the odd-$A$ As isotopes[8] have measured $\pi g_{9/2}$ sequences up to $\frac{21}{2}^+$ and have observed their intensities to be factors of 2–4 greater than the parallel sequences of $\Delta J = 1$ transitions also found in these nuclei. In $^{67}$As, the 1357-, 1228-, and 942-keV transitions have relative intensities of 42(3), 72(4), and 120(2), respectively, whereas the transitions in the parallel $638 \rightarrow 704 \rightarrow 898$ sequence have relative intensities that vary between 20 and 30. In summary, angular correlation and intensity data are consistent with $J^\pi$ assignments of $\frac{9}{2}^+$, $\frac{13}{2}^+$, $\frac{17}{2}^+$, and $\frac{21}{2}^+$ to the states at 1422, 2364, 3592, and 4949 keV, respectively. Due to low coincidence yield, it is difficult to propose spins and parities for the states in the weaker parallel sequence.

The structure of the proposed $\pi g_{9/2}$ band in $^{67}$As as displayed in Fig. 4 appears to be consistent with the systematics of the nearby odd-$A$ As and Ge isotopes. In the odd-$A$ As isotopes, the energies of the individual $\pi g_{9/2}$ states are observed to increase smoothly with decreasing neutron number, with no sharp changes occurring near $N \sim Z$. The $\pi g_{9/2}$ states in $^{67}$As, moreover, appear to line up well with the ground-state band of $^{66}$Ge, which would indicate that the $\pi g_{9/2}$ band in $^{67}$As is generated by coupling of an odd $g_{9/2}$ proton to excitations of a $^{66}$Ge core. As shown in Fig. 4, this behavior is consistent with the properties of the $\nu g_{9/2}$ states in $^{67}$Ge.[9]

In conclusion, we have employed the $^{40}$Ca($^{32}$S,$\alpha p$)$^{67}$As and $^{40}$Ca($^{33}$S,$\alpha pn$)$^{67}$As reactions in conjunction with charged-particle-$\gamma\gamma$ and neutron-$\gamma\gamma$ coincidences to observe the decays of excited states in the neutron-deficient nucleus $^{67}$As. Based on angular correlation data and systematic evidence, the states at 1422, 2364, 3592, and 4949 keV appear to form its $\pi g_{9/2}$ band. The structure of this band appears consistent with the $\pi g_{9/2}$ systematics of the other odd-$A$ As isotopes and with coupling of the odd $g_{9/2}$ proton to excitations of the even-even core $^{66}$Ge.

We would like to thank Dr. R. M. Diamond for his critical reading of this paper and his useful suggestions. We are also grateful to Dr. Diamond, Dr. F. S. Stephens, and Dr. M. A. Deleplanque for their assistance in taking this data. This work was supported by the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

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