# Test of the singly magic character of the $N=50$ isotone $^{83}$As populated in $^{83}$Ge decay

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(Received 29 December 1987)

The first information obtained on excited states of the $N=50$ isotone $^{83}$As populated in the $\beta$ decay of neutron-rich $^{83}$Ge is presented. The $^{83}$Ge half-life was measured to be $1.85\pm0.06$ s. Using $\gamma$ singles and $\gamma\gamma$ coincidence measurements, a total of 51 $\gamma$ rays were placed in a level scheme for $^{83}$As corresponding to 28 levels in a range of excitation energy up to 4.84 MeV. The density of levels up to 2.0 MeV excitation energy is reasonably well reproduced by shell-model calculations, indicating that $^{78}$Ni is probably a doubly magic nucleus. Approximately half of the $\beta$ intensity to excited states in $^{83}$As populates a group of levels above 3.5 MeV excitation energy which can be interpreted as primarily core polarization neutron particle-neutron hole states.

## I. INTRODUCTION

A central problem in nuclear physics is the determination of the extent to which the proton and neutron magic numbers known from studies of nuclei near stability remain valid for nuclei far away from the stable valley. Doubly magic regions centered about $^{78}$Ni and $^{132}$Sn will exist if the nucleon numbers $Z=28$ and 50 and $N=50$ and 82 are magic on the very neutron-rich side of stability. Unfortunately, at the present time it is only possible to study these regions by observing the decay of short-lived neutron-rich nuclei produced in fission.

The region around $^{132}$Sn has been extensively studied; in particular, the neutron-rich Sn nuclei and the $N=82$ isotones. It has been shown that the $^{132}$Sn region is doubly magic with an especially good shell closure.[1,2] This is confirmed by level structure information on $^{132}$Sn, $^{131}$Sn (core plus one neutron hole),[3] and $^{133}$Sb (core plus one proton).[4]

The doubly magic character of a region can most effectively be tested by studying the structure of nuclei in which either the proton or neutron number is magic. This is more difficult for nuclei in the region around $^{78}$Ni than for the $^{132}$Sn region, since $^{78}$Ni is further away from stability on the neutron-rich side. No structure information now exists for Ni ($Z=28$) nuclei heavier than $^{68}$Ni (see, for example, Ref. 5). Consequently, the most practical method of exploring the $^{78}$Ni region is to study the decay of fission products to levels of the $N=50$ isotones above $^{78}$Ni. The structure of the $N=50$ isotones has been well studied in the valley of stability down to $^{86}$Kr ($^{78}$Ni + 8 protons). Some information on $^{85}$Br ($^{78}$Ni + 7 protons) is available from the decay[6] of $^{85}$Se and the $(d,^{3}\text{He})$ reaction,[7] and information is also available on $^{84}$Se ($^{78}$Ni + 6 protons) from $^{84}$As decay[8] and the $(t,p)$ reaction.[9] No information is available on the structure of the lighter $N=50$ isotones with the exception of $^{82}$Ge ($^{78}$Ni + 4 protons), which is populated in the decay[10] of the fission product $^{82}$Ga.

As part of a program to explore the degree to which the region around $^{78}$Ni is doubly magic, the level structure of $^{83}$As ($^{78}$Ni + 5 protons) has been studied. Excited states in $^{83}$As were populated through the $\beta^-$ decay of $^{83}$Ge. The decays of $^{83}$Ge was first studied by del Marmol and Fettweis[11] who measured its half-life to be $1.9\pm0.4$ s by periodically milking the $^{83}$Se daughter from a $^{83}$Ge source and measuring the intensity of $^{83}$Se as a function of milking time. No other information was available on the decay of $^{83}$Ge.

This paper presents details of the decay of $^{83}$Ge to excited states in $^{83}$As. Section II details the experimental methods and results with the decay scheme discussed in Sec. III. In Sec. IV the concentration of $\beta$ strength above 3.5 MeV is examined while in Sec. V the level scheme is compared to shell-model calculations that utilize the complete proton model space ($f_{5/2}$-$p_{3/2}$-$p_{1/2}$-$g_{9/2}$) between $Z=28$ and 50. The conclusions are summarized in Sec. VI. A preliminary report of this work was given earlier.[12]

## II. EXPERIMENTAL METHODS AND RESULTS

### A. Source preparation

Sources of $^{83}$Ge were obtained at the TRISTAN isotope-separator facility operating on-line to the Brookhaven National Laboratory High-Flux Beam Reactor. For the present study, a high-temperature plasma ion source[13] containing a target of 5 g of enriched $^{235}$U was exposed to a neutron flux of $3\times10^{10}$ n/cm$^2$ s. Positive ion beams were extracted from the source, then ions with $A=83$ were mass separated and deposited on a movable aluminum-coated Mylar tape. The beam consisted primarily of Ge and As with small amounts of Ga. There was no evidence for cross contamination from adjacent masses.

### B. Measurements

$\gamma$-ray measurements were made with one Ge(Li) and one HpGe detector placed in 180° geometry at the point at which the beam was deposited onto the tape. A thin plastic scintillator with an acceptance solid angle of approximately $2\pi$ sr viewed the point of deposit. The resulting signals served as a beam monitor and a $\beta$ coincidence gate for some of the singles spectra. The $\beta$-gated spectra were free of all background lines except Pb x-rays and $\gamma$ rays at 667 and 772 keV from $^{132}$I (from long-lived $^{132}$Te) remaining in the beam line from a previous experiment. Enhancement of $^{83}$As $\gamma$ lines, which follow the decay of $^{83}$Ge, relative to those which follow the decay of $^{83}$As and $^{83}$Se daughters, was achieved by moving the tape after a short buildup and decay cycle. Sixteen $\gamma$ singles spectra were recorded at 0.5 s intervals during each tape cycle. They were used for isobar identification and half-life measurement. The first eight of these spectra ($\Delta t = 4$ s) were accumulated with the ion beam on (growth period). The last eight spectra ($\Delta t = 4$ s) were accumulated while the ion beam was deflected (decay period). The total running time was about 3.5 d. To check the effect of $\beta$ gating on the $\gamma$-ray intensity pattern, an ungated $\gamma$ singles spectrum was also collected.

The energy range covered by both coincidence and singles experiments was 0.04–5 MeV. $\gamma$ rays from $^{83}$Ge decay were observed up to 4.84 MeV. The energy calibration of the system was made by simultaneously measuring $\gamma$ rays from the $A = 83$ decay chain and a $\gamma$-ray standard source. Escape peaks were used to extend the energy calibration beyond that given directly by the standard source. From these data the nonlinearities of the system were determined and the $\gamma$-ray energies were calculated. For the higher energy $\gamma$ rays, energies were determined using both the full energy and escape peaks.

A total of $4 \times 10^6$ $\gamma\gamma$ coincidence events were recorded on magnetic tape as address triplets representing $\gamma$-ray energies and their time separation. The fast coincidence system used standard time-to-amplitude conversion. The time resolution at FWHM was 20 ns.

### C. Half-life

The decay portion of the moving tape cycle described above was used to determine the $^{83}$Ge half-life. The decay curve for the strong $\gamma$ ray at 306 keV is shown in Fig. 1. A fit of this curve yielded a half-life of $1.85 \pm 0.06$ s. (The yield of the $^{83}$Ga present was very weak compared to $^{83}$Ge and the $^{83}$Ga decayed primarily by delayed neutron emission.) This is in good agreement with the previously reported value[11] of $1.9 \pm 0.4$ s.

### D. $\gamma$-ray energies, intensities, and coincidence relationships

A representative $\beta$-gated, $\gamma$ singles spectrum is shown in Fig. 2. The only background is from $^{132}$I and Pb x rays. In Fig. 3 the $\gamma$-ray spectrum in coincidence with the 306-keV $\gamma$ ray is shown. The $\gamma$ energies, relative intensities, placements, and coincidence relationships among the $\gamma$ transitions are summarized in Table I. The uncertainties associated with the energies are due to statistical uncertainties in determining peak centroids and system nonlinearities, while the uncertainties associated with the relative intensities reflect uncertainties in the determination of peak areas and detector efficiencies. Corrections for coincidence summing were made. No measurable distortion of intensities due to $\beta$ gating was observed.

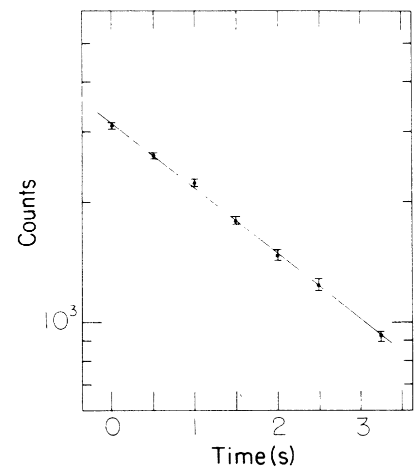


FIG. 1. Decay curve for the 306-keV $\gamma$ ray following the decay of $^{83}$Ge. The line represents a fit for the half-life of 1.85 s.

### E. Delayed-neutron emission in the $A = 83$ decay chain

Delayed-neutron emission has been observed for the $A = 83$ decay chain by Rudstam and Lund[14] who ascribed a neutron activity with half-life of $0.31 \pm 0.01$ s to $^{83}$Ga decay. The possibility of delayed-neutron emission from $^{83}$Ge is an unresolved question since mass formulas disagree on this matter. However, no definite evidence for $\gamma$ radiation from excited states in $^{82}$As was observed in our spectra. The two observed $\gamma$ rays at 950 and 1093 keV, which could possibly be attributed to delayed neutron emission in $^{83}$Ge, are firmly placed in the $^{83}$As level scheme on the basis of $\gamma\gamma$ coincidences. A $\gamma$ ray at 1348 keV was observed with a half-life very short compared to that for $^{83}$Ge. We attribute this $\gamma$ ray to delayed-neutron emission from $^{83}$Ga and assign it to the deexcitation[10] of the $2_1^+$ state in $^{82}$Ge. A weak long-lived component of the 1093-keV $\gamma$ ray is probably due to $\beta$ decay of $^{82}$Ge which is fed by $^{83}$Ga delayed $n$ emission.

## III. THE $^{83}$Ge DECAY SCHEME

The level scheme for the $N = 50$ isotone $^{83}$As populated in $^{83}$Ge decay is shown in Fig. 4. The scheme is based on our $\gamma$-ray singles and coincidence measurements. Placements for individual $\gamma$ rays are indicated in Table I. Due to the fact that ions other than $^{83}$Ge were present in our $A = 83$ beam, it was not possible to determine the ground-state $\beta$ feeding for $^{83}$Ge decay. It was thus not possible to calculate exact log*ft* values. The decay of $^{85}$Se to the $N=50$ isotones $^{85}$Br has been studied[6] in some detail. As will be discussed below, the $^{85}$Br level scheme is qualitatively similar to that proposed for $^{83}$As except that the ground state is $J^\pi=\frac{3}{2}^-$ and first excited state is $J^\pi=\frac{5}{2}^-$. The $p_{3/2}$-$f_{5/2}$ spacing is 345 keV in $^{85}$Br compared to 306 keV for the revised sequence in $^{83}$As. We have therefore calculated log*ft* values for $^{83}$Ge under two assumptions: (1) that the log*ft* for the $^{83}$As ground state is the same as for the 345-keV level in $^{85}$Br and (2) that the log*ft* for the 306-keV level in $^{83}$As is the same as that for the $^{85}$Br ground state. A $Q_\beta$ of 8.96 MeV from the tables of Möller and Nix[15] along with our measured half-life for $^{83}$Ge were used in the calculation. In all cases except for the ground state, the two sets of log*ft* values differ by only 0.26. Therefore, an average for each set (log*ft* and log$f_1t$) is reasonable. The results are shown in Table II along with the level energies and their uncertainties. Uncertainties for the log*ft* values are estimated to be less than 0.2 within the constraints discussed above. The levels observed in this work are discussed below and then compared with the results of large-space shell-model calculations in Sec. V.

### A. $^{83}$Ge ground state

The $J^\pi$ for the $^{83}$Ge ground state would be determined by the shell-model orbital of the 51st neutron. For the

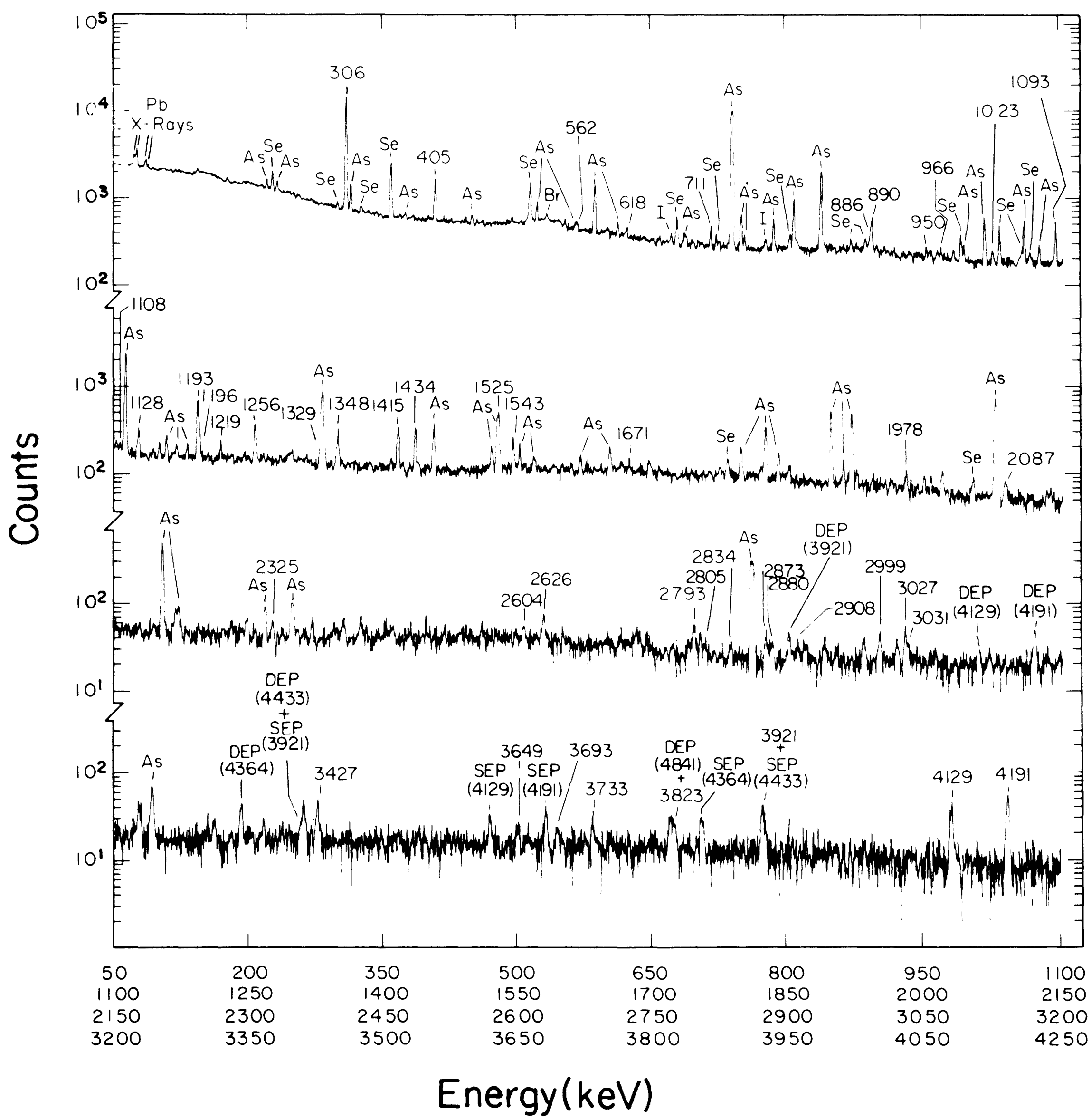


FIG. 2. $\gamma$-ray singles spectrum from the decay of a mass 83 source. Lines associated with the decay of $^{83}$Ge are labeled by their energies in keV. Known lines following other decays are labeled as follows: $^{83}$As (As), $^{83}$Se (Se), $^{83}$Br (Br), and $^{132}$I (I). SEP and DEP indicate single- and double-escape peaks, respectively. Escape peaks for $\gamma$ rays below 3.9 MeV are not indicated on the figure. The line at 1348 keV is from the delayed-neutron decay of $^{83}$Ga.

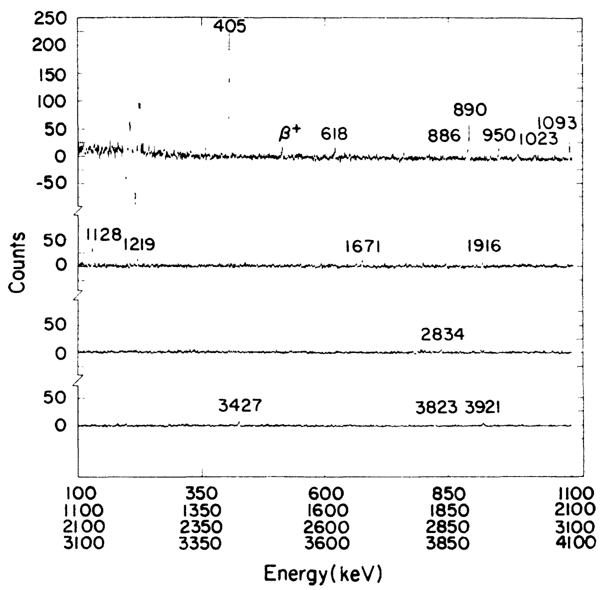


FIG. 3. $\gamma$-ray coincidence spectrum from the decay of $^{83}$Ge for the 306-keV line. The appropriate Compton gate has been subtracted. The peak-valley pairs at about 200 keV result from backscattering of the 510- ($^{83}$Se) and 529-keV ($^{83}$Br) $\gamma$ rays. Only definite coincidences are indicated.

$N=51$ isotones from $^{89}$Sr to $^{95}$Ru the ground-state $J^\pi$ values are well established to be $\frac{5}{2}^+$, indicating a $d_{5/2}$ orbital for the 51st neutron. The first excited states of all known $N=51$ isotones are $\frac{1}{2}^+$. The excitation energy of the $\frac{1}{2}^+$ states rises from 779 keV in $^{95}$Ru to 1205 keV in $^{91}$Zr and then falls to 529 keV in $^{87}$Kr. The corresponding information is not available for $^{85}$Se, but it can be assumed that the $\frac{1}{2}^+$ level does not cross below the $\frac{5}{2}^+$ level, and thus that $J^\pi=\frac{5}{2}^+$ for the $^{83}$Ge ground state.

### B. $^{83}$As ground state

It is well established that the first two orbitals in the proton shell between 28 and 50 are $f_{5/2}$ and $p_{3/2}$. Since $Z=33$ for $^{83}$As, $J^\pi$ for the ground state would be $\frac{5}{2}^-$ for either order of the above two orbitals. Furthermore, studies of the $^{86}$Kr($d$,$^3$He)$^{85}$Br reaction[7] have established that the ground state of the $N=50$ isotone $^{85}$Br is $\frac{3}{2}^-$, thus our assumption that the $f_{5/2}$ orbital is filled first is reasonable. This is in contrast to the value of $\frac{3}{2}^-$ suggested by As isotope systematics.

### C. 306-keV level

This level is well established by the coincidence data of Table I and the fact that the 306-keV $\gamma$ ray is over four times more intense than any other $\gamma$ ray. We postulate that $J^\pi=\frac{3}{2}^-$ for this level, based on systematics.

### D. 711-keV level

The second excited state of $^{83}$As, which lies lower in energy than the corresponding states[6,16] in $^{85}$Br (955 keV) and $^{87}$Rb (845 keV), is well established by coincidence data. The estimated value of the $\log f_1 t$ of 9.2 is not low enough to rule out first-forbidden unique $\beta$ transitions,[17] thus its $J^\pi$ value could be $\frac{1}{2}^-$, $\frac{3}{2}^\pm$, $\frac{5}{2}^\pm$, $\frac{7}{2}^\pm$, or $\frac{9}{2}^-$. If it is assumed that no observed $\gamma$ transition has multipolarity higher than $E2$, then its $J^\pi$ value is limited to $\frac{1}{2}^-,\frac{3}{2}^\pm,\frac{5}{2}^\pm,\frac{7}{2}^-$, since the level decays both to the $\frac{5}{2}^-$ ground state and $\frac{3}{2}^-$ level at 306 keV. Shell-model arguments would favor a negative parity for this state.

### E. 1193- to 1543-keV levels

A major feature of the $^{83}$As level scheme is a group of eight levels between 1.1 and 1.6 MeV that, with the exception of the 1543-keV level, are well established by coincidence information and the fact that they feed both the ground and 306-keV states. Similar groupings of levels have been observed[6,16] in the $N=50$ isotones $^{85}$Br and $^{87}$Rb, but the level density is somewhat higher for $^{83}$As. All of the above levels have significant $\beta$ feeding, but in all cases the estimated $\log ft$ values are greater than 6.4 and $\log f_1 t$ values are greater than 8.5. Thus first-forbidden unique transitions cannot be ruled out and the $J^\pi$ limitations are the same as for the 711-keV level. The $\log ft$ values and energies of these levels are consistent with their interpretation as being mostly negative-parity three-quasiparticle states outside of the $^{78}$Ni core. The 1543-keV level is dashed since it is only established by a single $\gamma$ ray to the ground state. This placement is based on the absence of the 1543-keV $\gamma$ ray in various coincidence spectra.

### F. Levels between 1.6 and 3.5 MeV

It is striking that between 1.6 and 3.5 MeV only four levels were observed. The level at 3100 keV is dashed since it is based only on the placement of the 2793-keV $\gamma$ ray and its coincidence with the 306-keV transition. A similar "gap" is observed in the level structure of $^{85}$Br where only four levels are observed between 2.0 and 3.5 MeV in decay[6] studies.

### G. Levels between 3.5 and 4.9 MeV

Almost half (42%) of the $\beta$ intensity to excited states in $^{83}$As feeds a set of 13 levels between 3.5 and 4.9 MeV. Levels at 4191, 4364, and 4841 keV decay only to the $^{83}$As ground state but are considered to be well established since the corresponding $\gamma$ rays are fairly intense, yet no coincidences with the 306-keV transition or other appropriate $\gamma$ rays are observed. The level at 4030 keV is dashed since only one deexciting $\gamma$ ray at 2834 keV is observed. This concentration of $\beta$ strength around 4 MeV is also observed in the decay of $^{85}$Se to the $N=50$ isotone $^{85}$Br, where 12 excited states are observed between 3.5 and 4.6 MeV. The $N=50$ isotone $^{87}$Rb has a much more uniform level density between 2.0 and 6.0 MeV, however.

## IV. BETA STRENGTH FOR $^{83}$Ge DECAY

In the decay of $^{83}$Ge there is a strong concentration of $\beta$ intensity to a group of states above 3.5 MeV. Approxi-

TABLE I. $\gamma$ transitions observed in $^{83}$Ge decay.

| $E_\gamma$ (keV) | $I_\gamma$ | Placement (keV) | Coincident[c] $\gamma$ rays (keV) |
|---|---|---|---|
| 306.51±0.05 | 100 ±0.5 | 306-0 | 405,618,886,890,950 1023,1093,(1108), 1128,1219,1671,1916 (2793),2834,3427 (3649),(3693),3823, 3921 |
| 405.18±0.05 | 11.4±0.7 | 711-306 | 306,618,1093 |
| 562.6 ±0.3 | 1.1±0.3 | 1977-1414 | |
| 618.37±0.12 | 2.5±0.3 | 1329-711 | 306,405,(711) |
| 711.66±0.08 | 3.1±0.3 | 711-0 | |
| 886.96±0.20[a] | 2.2±0.5[a] | 1193-306 | 306 |
| 890.01±0.15 | 9.9±0.8 | 1196-306 | 306,3031 |
| 950.14±0.18 | 2.4±0.3 | 1256-306 | 306 |
| 966.24±0.22 | 1.6±0.3 | 2222-1256 | |
| 1023.1 ±0.3[a] | 2.6±0.7[a] | 1329-306 | 306 |
| 1093.10±0.10[a,b] | 5.5±1.3[a,b] | 1804-711 | 306,405,(711) |
| 1108.4 ±0.3 | 1.4±0.3 | 1415-306 | |
| 1128.52±0.16 | 6.3±0.8 | 1434-306 | 306 |
| 1193.77±0.11 | 20.5±1.2 | 1193-0 | 3027 |
| 1196.2 ±0.5 | 0.7±0.5 | 1196-0 | |
| 1219.15±0.24[a] | 2.1±0.4[a] | 1525-306 | 306 |
| 1256.81±0.11 | 8.8±0.7 | 1256-0 | 966,2873 |
| 1329.61±0.18 | 7.0±1.1 | 1329-0 | |
| 1415.09±0.11 | 11.1±0.8 | 1415-0 | 562,(2805) |
| 1434.87±0.11 | 11.8±0.8 | 1434-0 | (2999) |
| 1525.50±0.14 | 13.6±1.2 | 1525-0 | (2604),(2908) |
| 1543.39±0.15 | 7.9±0.6 | 1543-0 | |
| 1671.2 ±0.3 | 2.2±0.4 | 1977-306 | 306 |
| 1916.0 ±0.4[a] | 2.4±1.0[a] | 2222-306 | |
| 1978.1 ±0.3 | 2.6±0.5 | 1977-0 | |
| 2087.7 ±0.3 | 3.2±0.4 | 3522-1434 | (306) |
| 2194.7 ±0.6 | 1.3±0.5 | 3999-1804 | |
| 2325.9 ±0.4 | 2.4±0.5 | 3522-1196 | |
| 2604.8 ±0.4 | 2.1±0.5 | 4130-1525 | |
| 2626.8 ±0.4 | 4.8±0.8 | 3956-1329 | 1329 |
| 2793.6 ±0.3 | 5.3±0.6 | 3100-306 | 306 |
| 2805.7 ±0.6 | 1.4±0.4 | 4221-1415 | |
| 2834.0 ±0.5 | 1.7±0.5 | 4030-1196 | 306,890 |
| 2873.3 ±0.4 | 3.6±0.5 | 4130-1256 | |
| 2880.1 ±0.4 | 2.1±0.4 | 4405-1525 | |
| 2908.8 ±0.5 | 1.8±0.4 | 4434-1525 | |
| 2999.3 ±0.5 | 3.2±0.4 | 4434-1434 | (1434) |
| 3027.7 ±0.5 | 5.0±0.6 | 4221-1193 | 1193 |
| 3031.2 ±0.9 | 1.2±0.6 | 4228-1196 | |
| 3427.1 ±0.5 | 5.8±0.7 | 3733-306 | 306 |
| 3649.4 ±0.6 | 2.1±0.4 | 3956-306 | 306 |
| 3693.2 ±0.6 | 2.2±0.5 | 3999-306 | 306 |
| 3733.1 ±0.6 | 2.6±0.5 | 3733-0 | |
| 3823.2 ±0.6 | 4.1±1.2 | 4130-306 | 306 |
| 3921.9 ±0.5 | 5.8±1.3 | 4228-306 | 306 |
| 4129.9 ±0.5 | 7.6±0.7 | 4130-0 | |
| 4191.4 ±0.4 | 9.9±0.9 | 4191-0 | |
| 4364.3 ±0.5 | 8.8±0.9 | 4364-0 | |
| 4405.6 ±0.6 | 3.9±0.7 | 4405-0 | |
| 4433.6 ±0.5 | 7.7±0.8 | 4434-0 | |
| 4841.6 ±0.7 | 7.9±1.0 | 4841-0 | |

[a]Energy and intensity from spectrum in coincidence with the 306-keV $\gamma$ ray.
[b]Energy and intensity from spectrum in coincidence with the 405-keV $\gamma$ ray.
[c]Possible coincidences are indicated in parentheses.

mately 28% of the $\beta$ intensity to excited states goes to seven states in $^{83}$As lying between 4.13 to 4.43 MeV. A similar pattern was observed[18] in the decay of $^{136}$I to levels in the $N=82$ isotone $^{136}$Xe. Studies with the $^{136}$Xe$(p,p')$ reaction[19] established that a number of neutron particle-neutron hole states in that nucleus were being excited at around 4.5 MeV excitation energy. A similar explanation for the strong $\beta$ feeding to levels just above 4 MeV in $^{83}$As is reasonable. The 51st neutron in $^{83}$Ge is $d_{5/2}$, thus it cannot decay by an allowed transition to the available proton orbitals $(f_{5/2}, p_{3/2}, p_{1/2}, g_{9/2})$. Neutron particle-neutron hole states can be formed when a neutron in one of the filled subshells between $N=28$ and 50 in $^{83}$Ge decays to an available proton orbit in $^{83}$As by an allowed $\beta$ transition. This is consistent with the fact that the log$ft$ values estimated for the above seven states range from 5.5 to 6.0. The resulting states would consist of a neutron particle-neutron hole configuration consisting of a $d_{5/2}$ particle and a hole in any one of the orbits $(p_{1/2}, p_{3/2}, f_{5/2})$ in the shell between $N=28$ and 50. These states could then couple with the five valence protons to give a variety of positive-parity states. The above arguments are consistent with such particle-hole excitation at around 4 MeV relative to the $N=50$ neutron core.

In cases far from stability, where $Q_\beta$ is large, $\beta$ decay occurs to regions of high level density. It is convenient to express the effects of nuclear structure on $\beta$ decay in terms of a $\beta$ strength function[20] $S_\beta(E)$. The structures likely to be observed in $S_\beta(E)$ have been classified in review articles by Klapdor and Wene[21] and Klapdor *et al.*[22]

The $\beta$ strength function measured in this work for $^{83}$Ge decay is shown in Fig. 5. A prominent feature is the concentration of strength about 4.2 MeV. Using formulas from Ref. 22, the approximate energies for various features of $S_\beta(E)$ using[15] $Q_\beta=8.96$ MeV have been estimated. Features calculated to occur between 2.5 and 6 MeV in excitation are summarized in Table III. The anti-isobaric analogue states (AIAS) only exhaust significant strength[21] of the Gamow-Teller resonance if

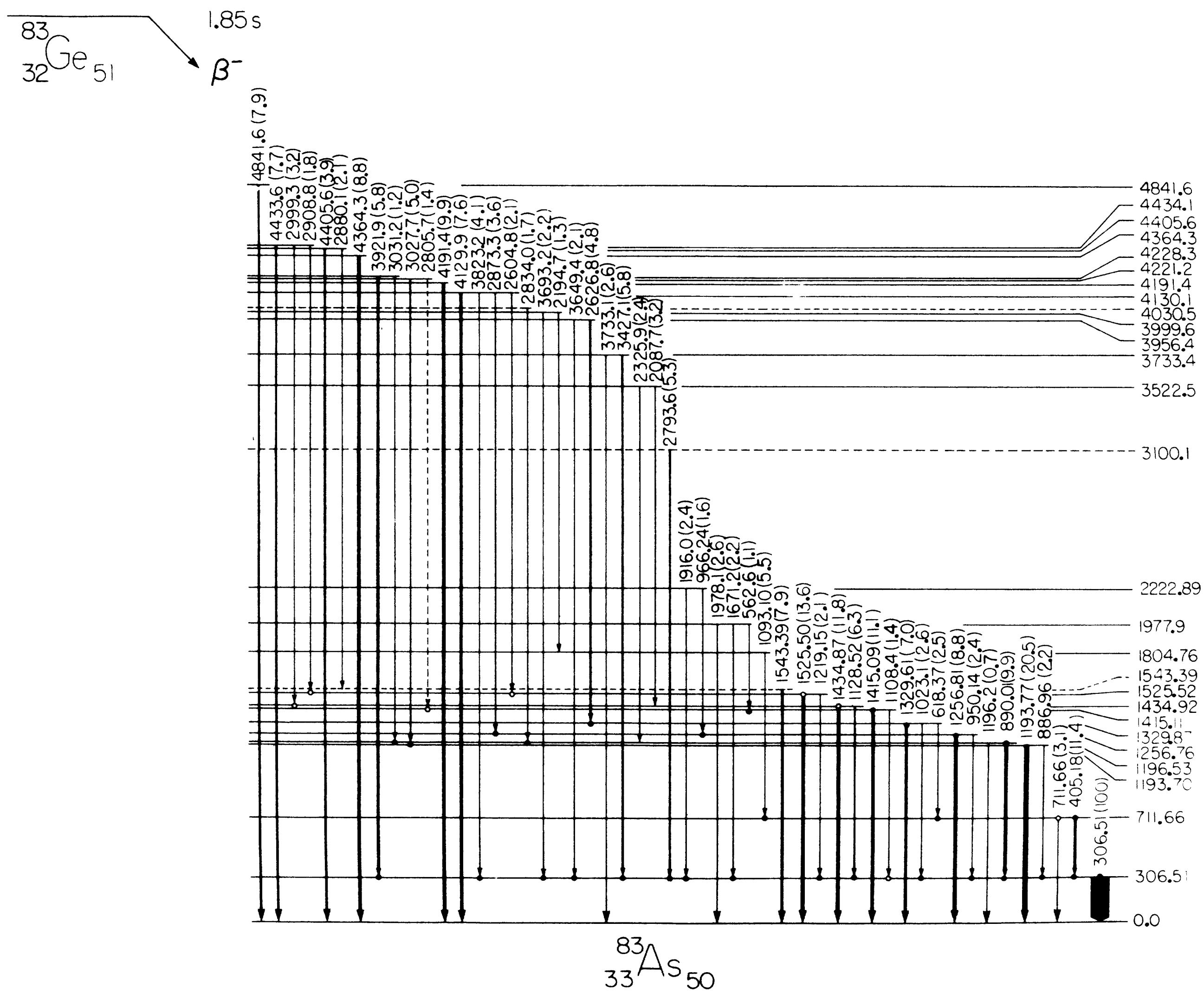


FIG. 4. Decay scheme for $^{83}$Ge. All energies are in keV.

TABLE II. Level energies and log$ft$'s for excited states in $^{83}$As.

| Level energy (keV) | log$ft$[a] | log$f_1t$[a] |
|---|---|---|
| 306.51±0.05 | 6.4 | 8.6 |
| 711.66±0.06 | 7.0 | 9.2 |
| 1193.70±0.13 | 6.5 | 8.6 |
| 1196.53±0.14 | 7.0 | 9.1 |
| 1256.76±0.09 | 6.9 | 9.1 |
| 1329.87±0.15 | 6.8 | 9.0 |
| 1415.11±0.10 | 6.6 | 9.0 |
| 1434.92±0.09 | 6.6 | 8.7 |
| 1525.52±0.11 | 6.6 | 8.8 |
| 1543.39±0.15 | 6.7 | 8.8 |
| 1804.76±0.11 | 7.0 | 9.1 |
| 1977.9 ±0.3 | 6.7 | 8.8 |
| 2222.89±0.21 | 6.9 | 8.9 |
| 3100.1 ±0.3 | 6.5 | 8.4 |
| 3522.5 ±0.3 | 6.3 | 8.2 |
| 3733.4 ±0.4 | 6.0 | 7.9 |
| 3956.4 ±0.3 | 6.1 | 7.9 |
| 3999.6 ±0.4 | 6.3 | 8.2 |
| 4030.5 ±0.5 | 6.7 | 8.4 |
| 4130.1 ±0.3 | 5.5 | 7.3 |
| 4191.4 ±0.4 | 5.7 | 7.5 |
| 4221.2 ±0.4 | 6.0 | 7.7 |
| 4228.3 ±0.4 | 5.9 | 7.7 |
| 4364.3 ±0.5 | 5.7 | 7.5 |
| 4405.6 ±0.3 | 5.9 | 7.6 |
| 4434.1 ±0.3 | 5.5 | 7.3 |
| 4841.6 ±0.7 | 5.6 | 7.2 |

[a]Log$ft$ and log$f_1t$ have assumed errors of 0.2. See text.

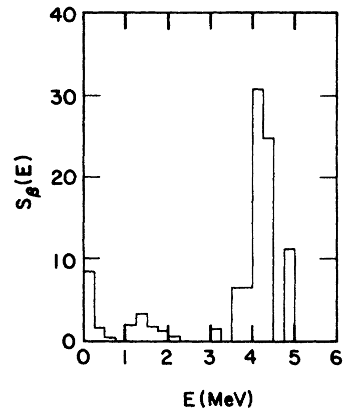


FIG. 5. $\beta$ strength function for $^{83}$Ge decay. $S_\beta(E)$ is in arbitrary units.

$N \approx Z$ so they are not treated here.

As can be seen from Table III, most of the strength of the $S_\beta(E)$ peak appears to reside in the core polarization states (CPS) fed by transitions of $p_{1/2}$ and $p_{3/2}$ neutrons between $N=28$ and 50. Small contributions could arise from other CPS and also back spin-flip states (BSFS) and spin-flip states (SFS) fed by transitions by the $p_{1/2}$ and $p_{3/2}$ neutrons, respectively. The estimated summed strength for $^{83}$Ge decay to levels between 3 and 5 MeV excitation in $^{83}$As gives a log$ft=4.8$. This is higher than one value of 3.0–3.5 estimated[23] for the pygmy resonances for neutron-rich $^{89-99}$Rb, and implies that in our case much of the strength has not been experimentally observed in our measurement.

## V. SHELL-MODEL CALCULATIONS

One of the most general predictions of the nuclear shell model is that systems with 28 protons or 50 neutrons are unusually tightly bound or "magic."[24] A major motivation of this work is to test the extent to which the above prediction holds for the region around neutron-rich $^{78}$Ni. A basic question about the structure of the proton-deficient $N=50$ nuclei, as exemplified by $^{83}$As, concerns the degree to which the assumption of an $N=50$ shell closure leads to an accounting of the low-lying ($\leq 2$ or 3 MeV excitation) energy levels.

Many model calculations have been made for the $N=50$ isotones above the $f_{5/2}$,$p_{3/2}$ subshell closure at $A=88$ by assuming a $^{88}$Sr closed core, with the extra-core protons filling the $p_{1/2}$ and $g_{9/2}$ orbits. Recently Blomquist and Rydström[25] have presented such calculations for nuclei up to $^{99}$In. Calculations using similar assumptions were carried out for $^{89}$Y through $^{94}$Ru by Ball, McGrory, and Larsen.[26] Gloeckner and Serduke[27] calculated both energy levels and $E2$ and $M4$ transition probabilities in the five $N=50$ isotones from $^{90}$Zr to $^{94}$Ru. They concluded that seniority breaking in the $p_{1/2}$-$g_{9/2}$ space is minimal. Only a small violation of seniority conservation is necessary to explain the rates for inhibited $E2$ transitions in $^{94}$Ru. The conclusion from these studies[25–27] is that the subshell closure at $^{88}$Sr is valid and that a good description of the $N=50$ isotones between $^{88}$Sr and $^{100}$Sn is obtained by consideration of only the $p_{1/2}-g_{9/2}$ proton space.

Only a few calculations have been attempted for the $N=50$ isotones with $A<88$. The low-lying states in $^{87}$Rb have been studied[28] in the framework in which a single quasi-proton was coupled to the collective motions of a $^{86}$Kr core. Properties of the lowest $2^+$, $4^+$, and $3^-$ states in $^{86}$Kr and $^{88}$Sr have been calculated[29] using two quasiparticle configurations for the open-shell and particle-hole configurations for the closed core. To our knowledge, no calculations have been done for $A<86$.

In this work the low-lying levels in $^{83}$As have been calculated. Elementary shell-model considerations suggest

TABLE III. Features of $^{83}$Ge $\beta$ strength function.

| State name | $J_i^\pi \rightarrow J_f^\pi$ | Excitation energy (MeV) |
|---|---|---|
| Core polarization state (CPS) | $\frac{1}{2}^- \rightarrow \frac{1}{2}^-$ | 4.0 |
| | $\frac{3}{2}^- \rightarrow \frac{3}{2}^-$ | 4.5 |
| | $\frac{5}{2}^- \rightarrow \frac{5}{2}^-$ | 5.0 |
| | $\frac{9}{2}^+ \rightarrow \frac{9}{2}^+$ | 6.0 |
| Back spin flip state (BSFS) | $\frac{1}{2}^- \rightarrow \frac{3}{2}^-$ | 2.5 (3.0)[a] |
| Spin flip state (SFS) | $\frac{3}{2}^- \rightarrow \frac{1}{2}^-$ | 6.1 (5.6)[a] |

[a]Estimates made using lower values for the $l \cdot s$ separation energy as given in Ref. 23.

that the proton orbits that dominate the low-lying states of the light ($Z=28-38$) $N=50$ isotones are $0f_{5/2}$ and $1p_{3/2}$, with the $1p_{1/2}$ and $0g_{9/2}$ orbits lying 1 to 2 MeV higher in excitation energy. The $0f_{7/2}$ orbit is presumed to be completely filled, and $^{78}$Ni is assumed to be an inert, doubly magic core. The above assumptions concerning the proton orbits are consistent with information from proton-transfer reactions[7,30,31] on $^{86}$Kr and $^{88}$Sr targets. Such experiments indicate that the fragments of the "giant" $0f_{7/2}$ hole state occur above 3 MeV in excitation energy and that the $0f_{5/2}$ and $1p_{3/2}$ orbits are effectively filled at $^{88}$Sr. The above theoretical ideas and empirical facts suggest that a model space restricted to four proton orbits ($0f_{5/2}$,$1p_{3/2}$,$1p_{1/2}$,$0g_{9/2}$) might explain the low-lying features of the $N=50$ isotones, with the $0f_{5/2}$ and $1p_{3/2}$ orbits dominating below $^{88}$Sr.

In the analysis of $^{83}$As, the experimental results were compared with basic shell-model calculations. From these comparisons, the issue of the competition of intruder configurations with states derived under the assumption of an inert $^{78}$Ni core could be examined. Such intruder configurations could arise from energetically advantageous $2p$-$2h$ states involving neutrons, protons, or both. Single-neutron transfer experiments on $^{86}$Kr and $^{88}$Sr indicate the energies of neutron single-hole and single-particle states to be higher in excitation than 3 MeV. However, two-neutron stripping reactions[9,32] leading to Se and Kr suggest that particle-pair hole-pair states may lie considerably lower. In the case of $^{83}$As, the well-founded assumption of $J^{\pi}=\frac{5}{2}^{+}$ for the $^{83}$Ge parent along with the log$ft$ values given in Table II limits the $J$ values for levels directly populated in $\beta$ decay to $\frac{9}{2}$ or less. As an example, in the decay of $^{85}$Se($\frac{5}{2}^{+}$) into $^{85}$Br, the closest analog to the $^{83}$Ge$\rightarrow$$^{83}$As decay, only states of $J=\frac{3}{2}$, $\frac{5}{2}$, and $\frac{7}{2}$ are directly populated.

Two separate calculations were performed utilizing different methods for establishing the two-body matrix elements (TBME) and the single-quasiparticle energies (SQPE). The first calculation utilized the surface delta interaction (SDI)[33] to parametrize the TBME of the Hamiltonian in terms of one scaling parameter. This parameter, along with the three energy differences of the four SQPE, was adjusted to best reproduce the well-established single-particle energy centroids and the well-determined low-lying $0^{+}$, $2^{+}$, and $4^{+}$ states in the $A=82-86$, $N=50$ region. The final values obtained for the above parameters were 0.332 for the SDI strength of 0.855, 2.670, and 3.618 MeV for the $f_{5/2}$-$p_{3/2}$, $f_{5/2}$-$p_{1/2}$, and $f_{5/2}$-$g_{9/2}$ SQPE separations, respectively.

The advantage of the SDI in such calculations is the uniqueness of the resulting parametrization of the model Hamiltonian; its limitation is that the resulting effective two-body Hamiltonian may be too rigid. The second calculation we present adopts the opposite extreme of characterizing the TBME. In this calculation all 65 TBME of the space, along with the 4 SQPE, were used as free parameters (FP) in an iterative least-squares search to find the optimum effective model interaction.[34] We used 175 ground-state binding energies and excitation-state energies in the $A=82-96$ range of the $N=50$ isotones as the data set. From these, 35 linear combinations of the 69 TBME and SQPE were determined. The $p_{1/2}$ and $g_{9/2}$ aspects of the FP Hamiltonian were very well determined in this procedure, since the data set was dominated by data for nuclei with $A\geq 88$. On the other hand, the $f_{5/2}$ and $p_{3/2}$ components, which are the dominating factors for the $A=82-87$ region, are not so well determined, because firm experimental information on energy levels in this region is much less abundant.

The results of these two quite different shell-model calculations are compared in Fig. 6 with each other and with our experimental results for the level structure of $^{83}$As. The calculations yield a ground state of $\frac{5}{2}^{-}$ and a first-excited state of $\frac{3}{2}^{-}$ in accord with our assumptions as previously described. The calculated energy separation between the above $\frac{5}{2}^{-}$ and $\frac{3}{2}^{-}$ states is in reasonable agreement with experiment, but the FP calculation significantly underestimates the separation. Both calculations indicate that the $\frac{5}{2}^{-}$ ground state contains most of the $f_{5/2}$ single-quasiparticle strength and that the first-excited $\frac{3}{2}^{-}$ state contains most of the $p_{3/2}$ single-quasiparticle strength. The predominant $p_{1/2}$ single-quasiparticle strength is predicted by the FP calculation to lie in the second and third $\frac{1}{2}^{-}$ states which have calculated excitation energies between 1.3 and 1.9 MeV. The SDI calculation concentrates most of the $p_{1/2}$ strength in a single state at 1.92 MeV. The first $\frac{1}{2}^{-}$ state is calculated to have a three-quasiparticle structure with very little $p_{1/2}$ strength. The $g_{9/2}$ single-particle strength is concentrated in a single state above 2.7 MeV excitation energy.

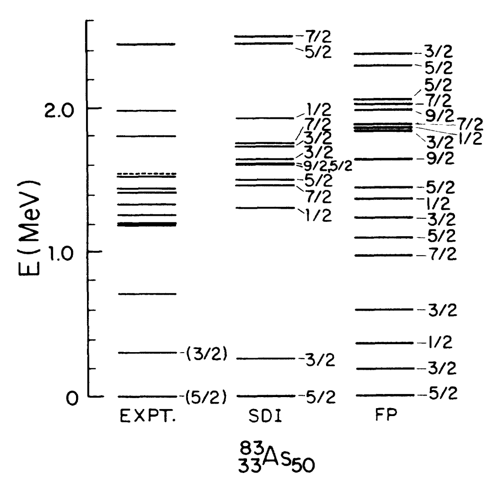


FIG. 6. Comparison of experimentally determined excited states in $^{83}$As with the results of two shell-model calculations. SDI indicates a calculation using the surface-delta interaction and FP indicates the free-parameter calculation described in the text.

A dominant feature of the experimental level scheme is the cluster of eight states between 1.1 and 1.6 MeV. The experimental density of states between 1 and 2 MeV is fairly well matched by both calculations (excluding the second and third $\frac{1}{2}^{-}$ states). They each characterize these states as having a three-quasiparticle structure with the $f_{5/2}$ and $p_{3/2}$ orbits dominating the orbit occupation. The two calculations differ in that the SDI calculation places the three-quasiparticle states somewhat higher in energy than does the FP calculation.

A striking feature of the experimental spectrum is a well-established low-lying state at 711 keV. This state could not be reproduced in the SDI calculation, even though several different choices for the input parameters were tried. This discrepancy was the stimulation for the second calculation with the FP Hamiltonian. The FP calculation yields *two* states below 0.8 MeV, with $J^\pi$ values of $\frac{1}{2}^-$ and $\frac{3}{2}^-$. Both of these states are three-quasiparticle in character. The existence of low-lying three-quasiparticle states in the spectra of nuclei below $^{88}$Sr results from a combination of the small values of $j$ for the dominant orbitals and few-valence-particle effects. We favor the interpretation, in analogy with the case of the $N=50$ isotone $^{85}$Br, that the experimentally observed state has $J^\pi=\frac{3}{2}^-$ rather than $\frac{1}{2}^-$, since $J^\pi=\frac{1}{2}^-$ must be fed by a first-forbidden unique $\beta$ transition. However, such a transition is not absolutely excluded by our log$ft$ results.

If an extrapolation[35] of $J^\pi$ is made using lower-mass As isotopes it would be concluded that $J^\pi=\frac{3}{2}^-$ for the $^{83}$As ground state. Unfortunately, the presently available experimental information does not distinguish between $J^\pi=\frac{3}{2}^-$ and $\frac{5}{2}^-$. Using isotopic extrapolation to predict $J^\pi$ for a neutron magic nucleus is risky due to strong effects from the $n$-$p$ force. Because of this we took the approach of extrapolating from the higher mass *$N=50$ isotones*. This extrapolation took the form of the shell-model calculations which reproduce the securely known features of $^{85}$Br and $^{87}$Rb with constant single-quasiparticle energies and two-body interaction matrix elements. In this sort of shell-model analysis the *effective* single-quasiparticle energies change as a function of mass because of the $N$ dependence of the two-body interaction energy contributions. This extrapolation, as noted, yields a $\frac{5}{2}^-$ ground state for $^{83}$As along with a $\frac{3}{2}^-$ ground state for $^{85}$Br and $^{87}$Rb. Nevertheless, an assignment of $\frac{3}{2}^-$ for the $^{83}$As ground state cannot be absolutely excluded.

In order to test the supposition that the $^{83}$As ground state is $\frac{3}{2}^-$, a SDI calculation was performed in which the $p_{3/2}$ single-quasiparticle energy was below that of the $f_{5/2}$ orbit. The SDI strength was chosen to give correct $2_1^+\rightarrow 0_1^+$ energy spacings for the even-even $N=50$ isotones. Employing a wide range of $p_{3/2}$-$f_{5/2}$ spacings, it was not possible to bring the $\frac{3}{2}^-$ level in $^{83}$As below the $\frac{5}{2}^-$ level and still preserve the well-established[7] $J^\pi$ of $\frac{3}{2}^-$ for the $^{85}$Br ground state. At best the $\frac{5}{2}^-$ and $\frac{3}{2}^-$ levels in $^{83}$As become degenerate.

It is evident from Fig. 6 that neither calculation is completely satisfactory in describing the $^{83}$As level structure. The SDI calculation is too simplistic to give reasonable TBME, and the FP calculation gives a separation between the lowest $\frac{5}{2}^-$ and $\frac{3}{2}^-$ states that is too small. Consequently it is necessary to improve the FP calculation data set by determining experimentally more information on states in the lighter mass $N=50$ isotones. This will allow a better determination of the $f_{5/2}$ and $p_{3/2}$ components of the calculated wave functions.

## VI. CONCLUSIONS

We have presented here the first experimental information on excited states in the $N=50$ nucleus $^{83}$As. It appears that the observed levels can be understood in terms of a doubly magic $^{78}$Ni core plus five extra-core protons. Reasonable agreement is found between the experimentally observed levels up to 2 MeV and shell-model calculations based on a $^{78}$Ni core plus five protons restricted to the $f_{5/2}, p_{3/2}, p_{1/2}$, and $g_{9/2}$ orbits.

The calculations indicate the $f_{5/2}$, $p_{3/2}$, and $g_{9/2}$ single-quasiparticle strengths to be highly concentrated in single levels while the $p_{1/2}$ strength is slightly more fragmented. The level density of states between 1 and 2 MeV is adequately mirrored by the calculations, which indicate that these states are predominately three-quasiparticle in character. A low-lying state observed at 711 keV could not be reproduced by the SDI calculation, but the FP calculation suggests that it is a three-quasiparticle state with $J^\pi=\frac{3}{2}^-$. We thus conclude that there is no need to introduce intruder configurations to account for this low-lying state or to describe the low-lying level structure observed in $^{83}$As.

Between 1.16 and 3.5 MeV excitation energy only four states are observed. This results from the fact that the higher states are three and five quasiparticle. Thus, compared to lower-lying states, there is a greater mismatch with the $\beta$ decaying state in $^{83}$Ge and the smaller $Q_\beta$ further reduces the transition probability, so few of these states are observed. Approximately half of the $\beta$ intensity to excited states is observed to populate a number of levels between 3.5 and 4.9 MeV. We interpret most of these states as being positive-parity, neutron particle-neutron hole states coupled to the odd protons. These states are probably populated by allowed $\beta$ transitions between $p_{3/2}$ and $p_{1/2}$ states and thus are favored even though their energies are quite high.

## ACKNOWLEDGMENTS

One of us (J.C.H.) acknowledges interesting conversations with J. Zylicz concerning the $^{83}$Ge $\beta$ strength function. This work was supported in part by the U.S. Department of Energy under Contracts W-7405-ENG-82 and DE-AC02-76CH00016 and in part by the National Science Foundation Grants No. 85-09736 and No. 83-12245.

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