

LEVEL STRUCTURE OF ^{72}As STUDIED WITH THE (α, xnp) REACTION

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Received 4 December 1975

Abstract: States of ^{72}As , excited through the $^{70}\text{Ge}(\alpha, np)$ and $^{72}\text{Ge}(\alpha, 3np)$ reactions at $E_\alpha = 30$ to 55 MeV, were studied. Excitation functions, γ -ray angular distributions, $\gamma\text{-}\gamma$ coincidences and γ -time distributions with respect to the beam bursts, were determined. Five excited states are identified with levels previously observed with the (p, n) reaction. In addition seven new levels and their decay pattern are incorporated into a level scheme. A half-life of 17 ± 3 nsec was determined for the 309.8 keV state, and evidence for the existence of a long-lived state (> 100 nsec) was obtained. A simple scheme based on simple particle shell-model configurations accounts for the gross properties of the low lying levels. While definite spin and parity assignment for the upper excited states require further measurements, tentative spin values up to 7 are obtained.

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NUCLEAR REACTION $^{70}\text{Ge}(\alpha, np\gamma)$, $^{72}\text{Ge}(\alpha, 3np\gamma)$, $E = 30$ to 55 MeV; measured E_γ , I_γ , $\sigma(E, E_\gamma, \theta, t)$, $\gamma\gamma$ -coin. ^{72}As deduced levels, $J, \pi, T_{1/2}$. Enriched Ge targets. Ge(Li) detector.

1. Introduction

Doubly odd nuclei have in general a complicated structure even at low excitations. In certain cases however one finds states which can be described in relatively simple shell-model terms. These are negative parity states arising mainly from the coupling of the odd proton and neutron with either one lying in the orbit whose parity is opposite to that of the other orbits in the shell. For certain angular momenta very few configurations (perhaps only one) contribute, to first order, to the wave function of these states. This for example appears to be the case for the 2^- ground states of ^{72}As and ^{74}As whose most likely configuration is $[\pi f_{7/2}, \nu g_{7/2}]_2^-$. Other possible configurations involve higher seniority and their contribution at low excitation energy should not be important. For other spins the coupling of $p_{3/2}$ and $p_{1/2}$ protons with a $g_{3/2}$ neutron will also mix in and the wave function may not be as simple as that for the ground state. Thus, starting from the study of the simpler states, one may hope to gain information about the more complicated ones. In particular the negative parity multiplets arising from this coupling provides valuable data for the study of p-n inter-

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actions. In this regard it is of interest to investigate these nuclei through the bombardment of high energy projectiles so that high spin members of those multiplets can also be observed. Reactions like the (α, xn) or (HI, xn) have not been very much used in the past to study doubly odd nuclei, although some investigations have been recently reported ¹⁾ involving nuclei in other regions of the periodic table.

The present work deals with the study of ^{72}As excited through the $^{70}\text{Ge}(\alpha, np)$ reaction. Prior to this work our information on levels of this nucleus stemmed from radioactive decay ²⁾ and $^{72}\text{Ge}(p, n)$ reaction ^{3, 4)} studies.

The decay of $^{72}\text{Se}(8, 4d)$ populates ²⁾ almost exclusively ($100 \pm 8\%$) the first excited state of ^{72}As at 46 keV.

Further information on levels of ^{72}As comes from reaction data obtained by Bertschat *et al.* ³⁾ and Mordechai *et al.* ⁴⁾ through the (p, n) reaction and will be discussed with more detail in sects. 3 and 4. Some discrepancies are noted between these results. In particular, the nature of the second excited state at about 214 keV remains unclear as the spin-parity assignments proposed in both investigations differ from each other.

In the following we report results obtained from the study of the $^{70}\text{Ge}(\alpha, np)$ reaction at energies between 30 and 55 MeV. As a complement the reaction $^{72}\text{Ge}(\alpha, 3np)$ has also been studied although the smaller cross section makes this reaction less favourable than the former. The results contribute new data to the level structure of ^{72}As . The first five excited states are identified with levels previously observed ^{3, 4)}. In addition other seven new levels and their decay pattern are incorporated into a level scheme. A new lifetime has been measured and evidence for the existence of a long-lived isomer has been obtained. It is shown that a simple scheme based on single-particle shell-model configurations accounts very well for the gross properties of the low lying levels.

2. Experimental procedures and results

Targets of ^{72}Ge and ^{70}Ge enriched to 82 % and 88 % respectively were bombarded with the α -particle beam obtained from the Buenos Aires Synchrocyclotron at energies between 30 and 55 MeV. Different runs were carried out with the purpose of determining (a) excitation functions, (b) γ - γ coincidence, (c) angular distributions and (d) timing. Several γ -ray Ge(Li) detectors with efficiencies between 3 % and 6 % and about 3 keV resolution for the ^{60}Co lines were used. In addition a small Ge(Li) X-ray detector with 300 eV resolution at 6 keV was used in some of the coincidence runs and timing measurements.

The data were accumulated in a two-parameter 4096-channel Intertechnique analyzer and analyzed with a program developed in this laboratory ⁵⁾ which enables the user to subtract background under the peaks by means of a light pen and then perform a computer fit of multiplets containing up to seven peaks.

2.1. SINGLES γ -RAY SPECTRA

The detector efficiencies were obtained using sources of ^{152}Eu and ^{133}Ba . These two sources were also used as energy calibration standards ^{6, 7}). The singles γ -ray spectrum taken at 35 MeV α -particles on ^{70}Ge is shown in fig. 1.

In order to determine the γ -ray excitation functions the different spectra were normalized to the intensity of the γ -ray corresponding to the $2^+ \rightarrow 0^+$ transition in the target nucleus. The excitation functions of some γ -rays assigned to ^{72}As from the $^{70}\text{Ge}(\alpha, np)$ and $^{72}\text{Ge}(\alpha, 3np)$ reactions are shown in fig. 2. These curves have been used for preliminary identification of γ -rays of ^{72}As . This identification procedure was used in turn, to choose the gating γ -rays in our coincidence runs. Table 1 contains the information obtained from the analysis of the single spectra.

2.2. ANGULAR DISTRIBUTIONS

For the angular distribution measurements the target size was reduced to a width of about 3 mm in order to improve the angular resolution. The moving detector was

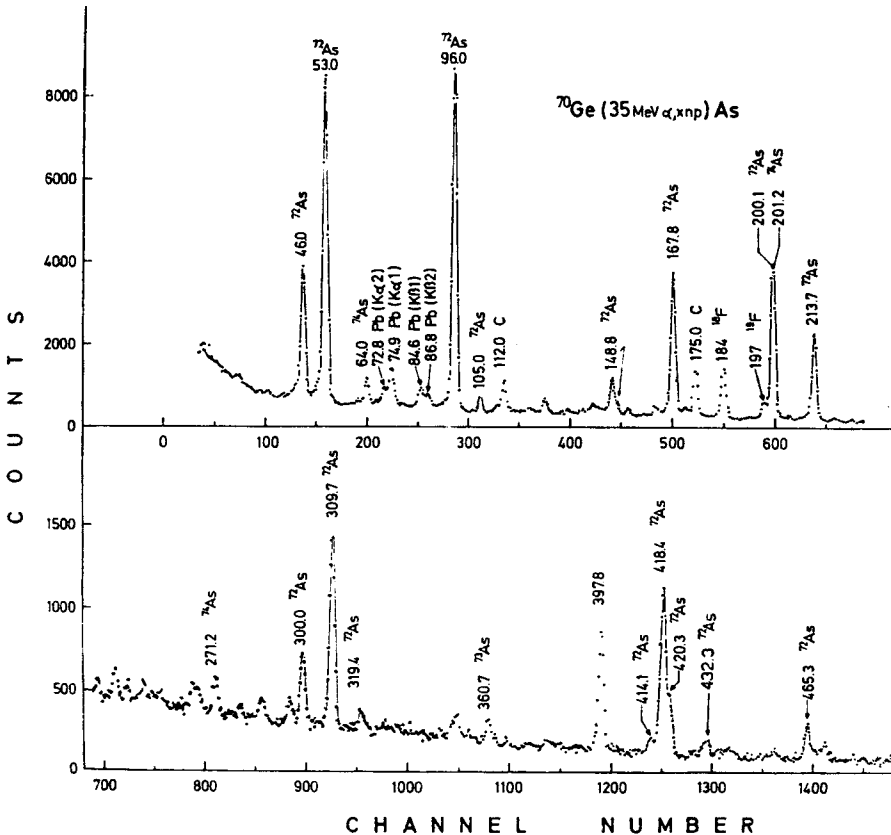


Fig. 1. Single γ -ray spectrum from the $^{70}\text{Ge} + \alpha$ reaction at $E_\alpha = 35$ MeV. Most of the strongest lines are labelled. The letter C denotes a line from the target backing.

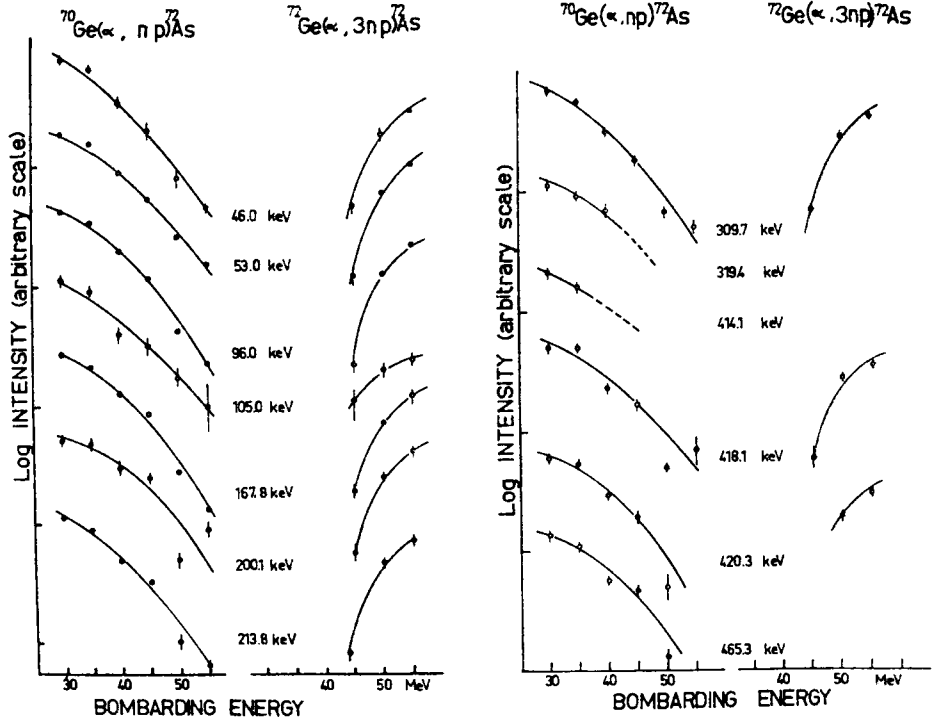


Fig. 2. Excitation functions of γ -rays assigned to ^{72}As , corresponding to the $^{70}\text{Ge}(\alpha, np)$ and $^{72}\text{Ge}(\alpha, 3np)$ reactions. The γ -intensities were normalized to the intensity of the $2^+ \rightarrow 0^+$ transition in the target nucleus arising from inelastic scattering.

TABLE 1

Energies, level assignments, intensities, and angular correlation coefficients of γ -rays from the $^{70}\text{Ge}(\alpha, np)^{72}\text{As}$ reaction at $E_\alpha = 35$ MeV

$E_\gamma \pm 0.15$ (keV)	Level assign- ment (keV)	I_γ	A_2	A_4
46.0	46.0	100	0.04 ± 0.09	0.01 ± 0.10
53.0	362.8	181	-0.05 ± 0.09	0.05 ± 0.10
96.0	309.8	110	-0.04 ± 0.06	0.02 ± 0.06
105.2	319.4	4.5		
148.8	562.9	3.2		
167.8	213.8	56	0.15 ± 0.05	-0.06 ± 0.06
200.1	562.9	75		
213.7	213.8	49	-0.38 ± 0.07	*)
300.0	662.8	18		
309.7	309.8	50	0.26 ± 0.12	-0.02 ± 0.14
319.4	319.4	4.1		
414.1	414.1	5.0		
418.1	981.0	72	-0.30 ± 0.08	-0.03 ± 0.07
420.3	783.1	22		
432.3	795.1	19		
465.3	828.1	16		

*) The computation with both A_2 and A_4 as free parameters yielded very large errors, with A_4 consistent with zero. Hence we quote the results of fitting the data with A_4 fixed and equal to zero.

placed at about 14 cm from the target and the angle relative to the beam direction was varied between 75° and 140° .

A second fixed detector placed at 90° on the opposite side of the beam line was used

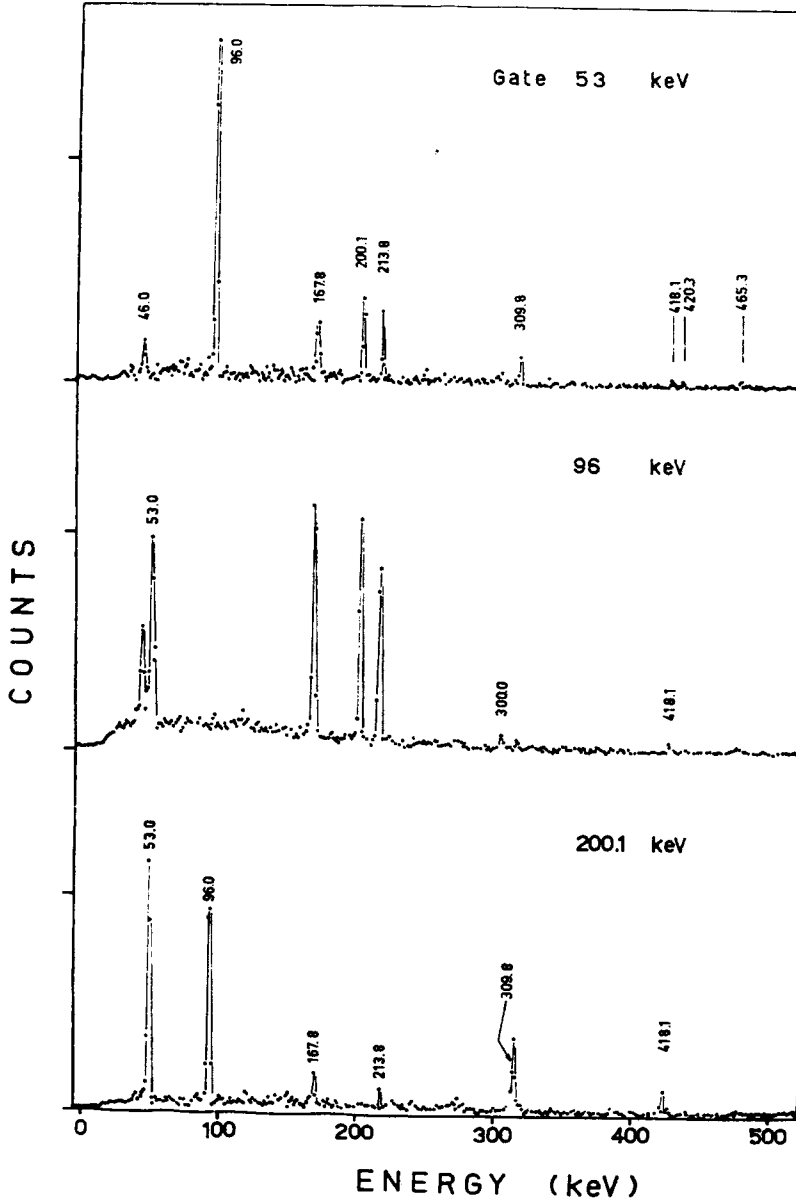


Fig. 3. The $\gamma\text{-}\gamma$ coincidence spectra obtained by gating on the 53.0, 96.0 and 200.1 keV lines. The anomalous intensity of the 309.8 keV γ -ray in the lowest spectrum is due to the contribution of back-scattering radiation from the 511 keV peak.

TABLE 2
The γ - γ coincidence intensities from the $^{70}\text{Ge}(\alpha, \text{np})^{72}\text{As}$ at $E_\alpha = 35 \text{ MeV}$

E_γ (keV) Gate energy (keV)	46.0	53.0	96.0	105.2	167.8	200.1	213.7	300.0	309.7	418.1	420.3	432.3	465.3	No. of experiments
46.0		55	50	57	15				10	8				2
53.0	25		109	30	44	30	31	40	6	10				3
96.0	110	737		192	204	178	26	30						3
167.8	140	195	180	8	48									1
200.1	6	280	128	27	7	157	96							1
309.7		40		19										1

Errors range from about 20% for the strongest lines up to 60% for the weakest.

for normalization in the usual way: signals from this detector were used to trigger a reference pulser whose pulses were in turn fed into the preamplifier of the moving detector.

The results of fitting the peak areas obtained at the different angles to the usual angular distribution function $W(\theta) = 1 + A_2P_2(\cos \theta) + A_4P_4(\cos \theta)$ are shown in table 1. In general the anisotropies are not large. The angular distribution of the weak peaks could not be determined. In addition, the peaks at 200 and 300 keV were broadened by the presence of the 197 keV peak from $^{16}\text{O}(\alpha, np)$ reaction and 201 keV line of ^{74}As in the first case and a 298 keV background peak in the second case, and the measurement of their angular distributions carried a large error. In all cases, except one, the A_4 coefficients are consistent with zero, so that another fit in which

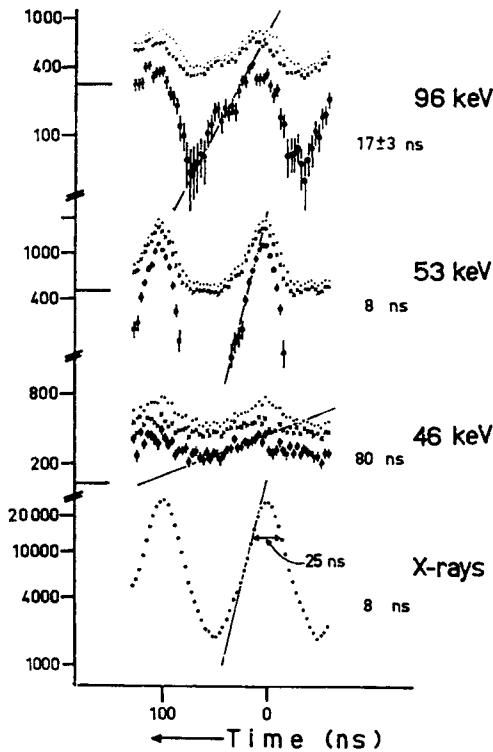


Fig. 4. The γ -ray time distributions with respect to the beam bursts. Solid dots, crosses and solid circles (with error bars) correspond, respectively, to the time spectrum obtained with (a) window set on γ -ray peak; (b) "peak minus background" spectrum and (c) net "short" time distribution obtained by subtracting the long-lived (flat) distribution. The contribution from the latter is indicated for the first three plots, by a short horizontal line on the left side of the figure. The system resolution involving an X-ray Ge(Li) detector was such as to give a minimum slope of 8 nsec. A later experiment; carried out with a scintillator and better timing performance allowed us to reduce the upper limit for the half-life of the 53.0 keV γ -ray to 3.7 nsec. The 80 nsec half-life indicated in the case of the 46 keV line corresponds to that reported in ref. ³⁾ for the 213.8 keV state which feeds the 46 keV state.

A_4 was fixed and equal to zero was carried out. The obtained A_2 coefficients were similar in both calculations. The results for the 167.8 and 309.7 keV γ -rays indicate $\Delta I = 2$ character for these transitions, while the other values given in table 1, for the 46.0, 53.0, 96.0, 213.7 and 418.1 keV lines, are all typical of $\Delta I = 1$ transitions.

2.3. THE γ - γ COINCIDENCE

The rate of acquisition of γ - γ coincidence data was considerably low due to the poor duty cycle of the Synchrocyclotron (about 6%). In addition the available system limited the measurements to four gates at a time. In spite of these difficulties, a number of definite coincidence relationships could be obtained which are summarized in table 2. Some of the corresponding spectra are shown in fig. 3.

Most of the γ - γ coincidence runs were carried out with a large (6% efficiency) Ge(Li) detector and low energy Ge(Li) X-ray spectrometer in order to improve the detection of low energy γ -rays as the most important transitions in ^{72}As observed in this work are found below 200 keV. The results shown in table 2 were obtained by assuming the detector efficiency as determined in a single experiment. Therefore the deviation from 100% efficiency performance of the coincidence circuitry, expected at low energies is not reflected in the numbers shown in the table. For some states more than one measurement was carried out. This is shown in the last column.

2.4. TIMING

Finally the time correlation between beam bursts and γ -radiation was investigated. In these measurements an X-ray Ge(Li) diode was used in order to improve the system time resolution with the disadvantage that the practical energy range was limited to about 100 keV. This was not an important shortcoming as the main interest was centered on the 53.0 and 96.0 keV lines, and for checking purposes, the 46.0 keV line whose half-life was known. Pulses from this detector and the radio-frequency system were used as start and stop signals in a time-to-amplitude converter, in the usual fashion. A divider device was incorporated into the system so that only one every two r.f. pulses were active. The data were accumulated in the analyzer memory in a two-dimensional 64×64 format. The results are summarized in fig. 4. The lowermost plot represents the time distribution of "prompt" X-rays. The time resolution (FWHM) is about 25 nsec while the prompt slope of 8 nsec sets the lowest limit of the system for half-life determinations. The second plot corresponds to the 53 keV γ -ray. In this, as well as the other plots, solid dots, crosses and solid circles (with error bars) correspond, respectively, to the time spectrum obtained with (a) a window set on the γ -ray peak; (b) a "peak minus background" spectrum and (c) net "short" time distribution (i.e. total minus flat time distribution). The existence of a long-lived component is apparent from the 53 keV γ -ray data. After subtracting this contribution a "prompt" peak is obtained so that the level de-excited by the 53 keV transition has $T_{\frac{1}{2}} < 8$ nsec. Actually a second experiment of improved time resolution carried out with a scintillator, in which the 46 and 53 keV peaks could not be resolved,

enabled us to limit further the half-life of the 53 keV γ -ray to less than 3.7 nsec. The long lifetime is also discernible in the case of the 96.0 keV γ -ray. However a fairly accurate estimate of the long-lived contribution to the total γ -intensity, can only be obtained in the former case, whereas for the 96 keV γ -ray transition it can be deduced from the value obtained for the 53 keV line in conjunction with the available information on the level scheme, which is discussed in the following section. In the same manner one can proceed to evaluate the fraction of long-lived intensity present in the case of the 46 keV γ -ray (third plot). Such contributions are indicated on the figure for the three cases, by a short horizontal line on the left side of the plot.

In the case of the 96 keV γ -ray the net short time distribution (solid circles) clearly shows the existence of a 17 ± 3 nsec half-life. This half-life is assigned to the level depopulated by the 96 keV transition; it can be seen how the maximum of the distribution is shifted to the left once the background is subtracted, indicating absence of prompt γ -rays.

The line labelled 80 nsec in the plot of the 46 keV γ -ray data corresponds to the half-life previously determined³⁾ for the 213.8 keV level which partially decays into the 46 keV first excited state [whose own half-life⁸⁾ is 10 nsec]. The present measurements are seen to be fully consistent with that value.

3. Construction of the level scheme

On the basis of the data presented in the preceding section the level scheme shown in fig. 5c was constructed. For comparison, the level schemes from refs. ^{3, 4)}, are shown on the left of fig. 5. The main source of information, in this regard, is provided by the γ - γ coincidence measurement. The data shown in table 2 were analyzed so that consistency with the proposed scheme was achieved. A practical convenient method to check for this consistency was found to be the evaluation of an efficiency curve from each coincidence spectrum by assuming the level scheme of fig. 5c. For every gate a smooth curve, similar to that for the singles efficiency with slight differences on the low energy side, was obtained, and this was taken as a valid indication that the placement of the different γ -rays in the level scheme was correct.

Level at 46 keV. The first excited state at 46 keV is firmly established from radioactive decay studies²⁾. The conversion coefficient of this transition and the $\log ft$ value of the ^{72}Se decay to this state favours a $J^\pi = 1^+$ assignment. The half-life of this state has been measured to be 10.7 ± 0.3 nsec [ref. ⁸⁾]. The angular distribution coefficients obtained in the present work are consistent with a dipole assignment for this transition.

Level at 213.8 keV. This level decays to both the ground and first excited state with a branching close to unity and was previously observed in the (p, n) reaction studies^{3, 4)}. Mordechai *et al.*⁴⁾ have proposed spin 2 while Bertschat *et al.*³⁾ assign $J^\pi = 3^+$ to this level. Both the half-life ($T_{\frac{1}{2}} = 80$ nsec) and g -factor ($g = 0.525 \pm 0.005$) have been measured by the latter authors. Our angular distribution results are

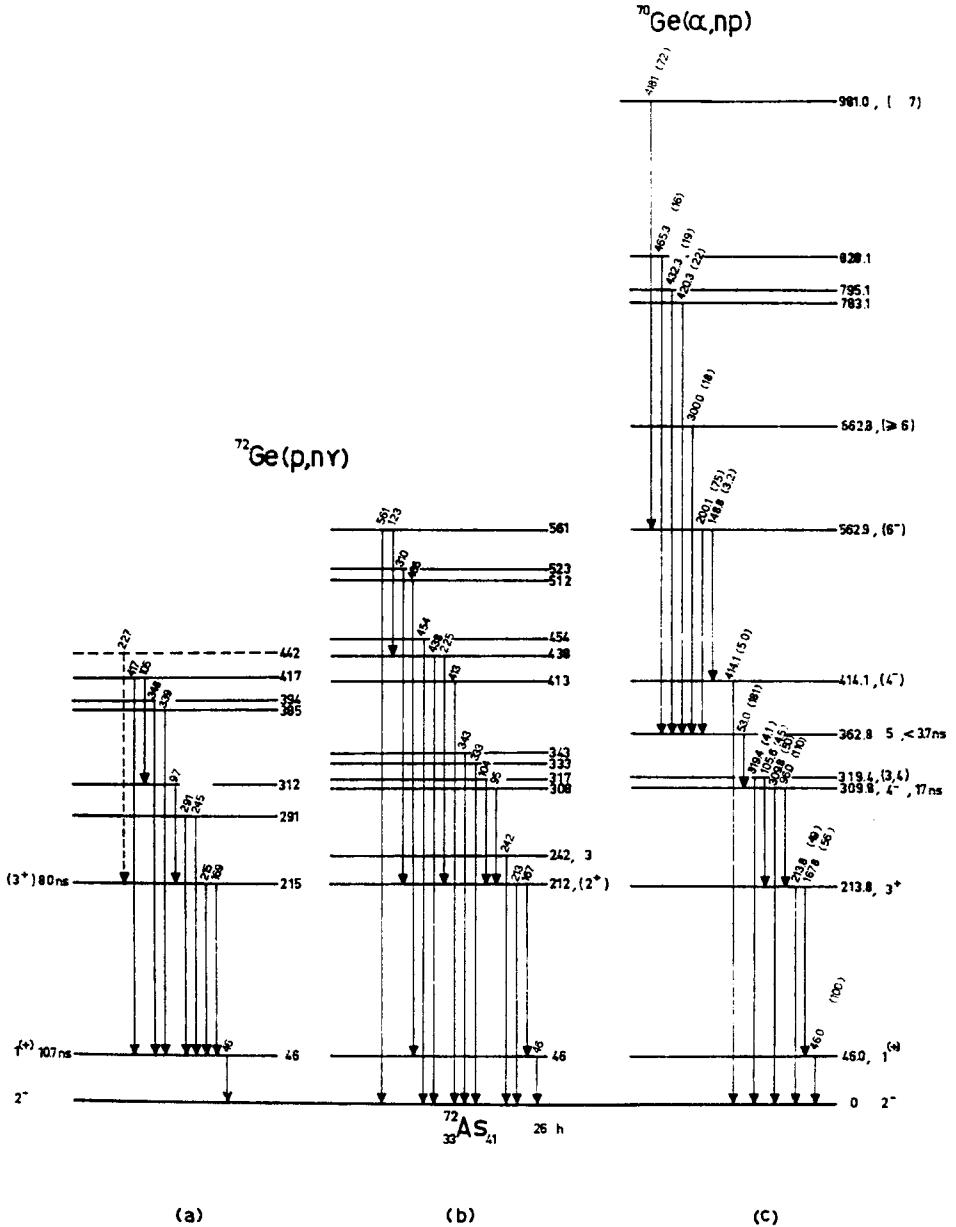


Fig. 5. Level scheme proposed in the present work (c) compared with those of previous (p, n) work, (a): ref. ³) and (b): ref. ⁴). The scheme (a) also includes results from refs. ^{2,8}).

in agreement with the assignment $J = 3$. In addition, a negative parity for this state would imply a pure M2 167.8 keV transition. Since M2 transitions are known not to be enhanced the half-life of the 213.7 keV state should be $\approx 10 \mu\text{sec}$. Therefore, positive parity is chosen for this state.

Level at 309.8 keV. This state can be identified with the 308 and 312 keV states excited with the (p, n) reaction $^3, ^4$), although the ground-state transition was not placed in the level schemes of these previous investigations. Mordechai *et al.* report a 310 keV γ -ray as de-exciting a level at 523 keV (not seen by Bertschat *et al.* or us). However it is noteworthy that this γ -ray is already seen in their spectra at bombarding energies high enough to populate the 309.8 keV state, as the 96 keV γ -ray is clearly seen in their spectra, but too low to excite levels above 400 keV. Thus, our proposed decay for this state seems to be consistent with the results of ref. 4), although not with their conclusion regarding the placement of the 309.7 keV transition. A half-life of 17 ± 3 nsec for this state is obtained from the present timing measurements. The angular distribution of the 96 keV γ -ray indicates dipole character of the $\Delta I = 1$ type, while the results for the 309.8 keV line indicate $\Delta I = 2$ for the ground-state transition. Thus the spin-parity 4^- is proposed. The rate for the 309.8 keV γ -ray agrees quite well with the E2 single-particle estimate, while even parity would imply M2 multipolarity which can not be reconciled with the measured lifetime. This assignment, in turn, lends further support for $J^\pi = 3^+$ proposed for the 213.8 keV level as the partial lifetime of the 96 keV line makes it only consistent with E1 character unless unusual departures from Weisskopf values are assumed.

Level at 319.4 keV. This state is weakly fed in the (α , np) reaction. Two transitions, one to the ground state and the other to the 213.8 keV level, were observed in the present experiment. This level is proposed on the basis of the observed 167.8-105.2 keV γ - γ coincidence and the energy fit achieved with the 319.4 keV line. It is probably the same state observed by Mordechai *et al.* at 317 keV, and it is noteworthy the similarity between its decay pattern and that of the 309.8 keV state. Owing to the low intensity, no further information on this level can be drawn from the angular distribution and timing measurements, but because it feeds states with $J = 2$ and 3 but apparently not with $J = 1$, its spin should be 3 or 4.

Level at 362.8 keV. This state has not been observed before. It seems to play a particular role in the decay of the residual nucleus as nearly 100 % of the reaction intensity feeds it. For this reason it was initially suspected that this state could be a high isomer. However the timing measurements allow us to set a maximum limit of 3.7 nsec for its half-life. This implies dipole character for the 53 keV γ -ray which depopulates it. At the same time the total intensity of this line would be too large if a higher multipolarity was assumed because of the internal conversion correction. The observed angular distribution corresponds to a $\Delta I = 1$ transition and it is consistent with this conclusion. This result, plus the non-observation of lines feeding into lower states indicates that the spin of this state is $J = 5$.

Levels above 400 keV. These levels are proposed on the basis of the γ -intensity balance and coincidence results. The 414 keV state can be identified with the 413 keV state reported by Mordechai *et al.* and the 417 keV state of Bertschat *et al.*, while the 562.9 keV state does not appear to be that reported by the former authors at 561 keV owing to their different decay patterns.

Except for the 414.1 keV state, all others are not seen to deexcite into levels below 362.8 keV and hence they should be high spin states which were not observed in the (p, n) reaction at low bombarding energies^{3, 4}). From the decay of the 562.9 keV level it could be tentatively assumed that the spin-parity of this state is $J^\pi = 6^-$, in view of the 148.8–414.1 keV cascade from this state to the ground state which, in addition, appears to limit the spin-parity of the 414.1 keV level to $J^\pi = 4^-$.

From the non-observation of crossover transitions it appears that the spins of levels above 600 keV are equal or larger than 6. In the particular case of the 981.0 keV state the most probable spin is 7 since this state only decays into the 562.9 keV state and the 418.1 keV line shows a $\Delta I = 1$ angular distribution.

4. Discussion of the results

Although it is usually difficult to discuss the structure of a doubly odd nucleus because considerable configuration mixing is expected, an interpretation of the low lying states in ^{72}As can be attempted. It will be seen, in fact, that a fairly simple description can account very well for the known properties of the lowest states.

From the level schemes of the odd- A As isotopes, an estimate of the single-particle energies for the last unpaired proton in ^{72}As can be obtained. Likewise the neutron single-particle energies can be obtained from the spectra of ^{69}Zn , ^{71}Ge and ^{73}Se . The adopted energies for the lowest configurations in ^{72}As are shown in table 3 together with the expected zero order configuration at lowest energies. Assuming small mixing with higher energy excitations the ground state of ^{72}As should be closely described by the pure $[(f_{7/2})_\pi, (g_{7/2})_\nu]_2$ - configuration.

TABLE 3
Lowest energy single-particle configurations for ^{72}As

States (energy in keV)	Configuration	Spin J
$\pi f_{7/2}^{-1}$ (0)	$\pi f_{7/2}, \nu p_{3/2}$	$2^+, 3^+$
$\nu p_{3/2}^{-1}$ (0)	$\pi p_{3/2}, \nu p_{3/2}$	$1^+, 2^+$
$\pi p_{3/2}^{-1}$ (40)	$\pi f_{7/2}, \nu g_{7/2}$	$2^-, \dots 7^-$
$\nu g_{7/2}^{-1}$ (100)	$\pi p_{3/2}, \nu g_{7/2}$	$3^-, \dots 6^-$
$\nu f_{7/2}^{-1}$ (140)	$\pi f_{7/2}, \nu f_{7/2}$	$0^+, \dots 5^+$
	$\pi p_{3/2}, \nu f_{7/2}$	$1^+, \dots 4^+$

A good check for the validity of this simple wave function can be made by comparing the magnetic moment corresponding to this configuration with that of the ground state which is known⁹) to be $|\mu_{\text{exp}}| = 2.2$. Within the present scheme the magnetic moment should be determined by the contributions of the last unpaired proton and neutron.

$$\mu = \langle gJ \rangle = \langle g_p J_p + g_n J_n \rangle,$$

where

$$g = \frac{1}{2} (g_p + g_n) + (g_p - g_n) \frac{J_p(J_p + 1) - J_n(J_n + 1)}{2J(J + 1)},$$

and g_p and g_n are the Schmidt values for a single proton and neutron. For $f_{\frac{3}{2}}$ protons and $g_{\frac{3}{2}}$ neutrons we find $g_p = 0.345$ and $g_n = -0.425$. Replacing above with $J_p = \frac{5}{2}$, $J_n = \frac{9}{2}$ and $J = 2$ we obtain $\mu_{th} = -2.09$ in excellent agreement with the experimental value, so that the plausibility of the assumption above regarding the ground-state configuration is confirmed.

The 1^+ first excited state wave function will have the terms $[(p_{\frac{3}{2}})_{\pi}, (p_{\frac{1}{2}})_{\nu}]_{1^+}$, $[(f_{\frac{3}{2}})_{\pi}, (f_{\frac{3}{2}})_{\nu}]_{1^+}$ and $[(p_{\frac{3}{2}})_{\pi}, (f_{\frac{3}{2}})_{\nu}]_{1^+}$. All these terms give zero contributions to the $B(E1)$ reduced probability connecting with the ground state, yielding the usual result that E1 transitions within one major shell are forbidden. This result is borne out by the measured half-life of the 46 keV state which implies a hindrance factor of about 10^4 .

The second excited state at 213.8 keV has a half-life of 80 nsec. It was mentioned in the preceding section that proposed spins for this state are 2 or 3. In the framework of the present discussion only one 2^- state can be obtained from the low energy configurations shown in table 3. Since the ground state is 2^- , this assignment should be ruled out for the 213.8 keV level. Based on the long lifetime of this state we can also dismiss (always within the framework of the model) the possibility $J^{\pi}(213.8) = 2^+$ because otherwise the wave function would contain the same terms as those contributing to the 46.0 keV state configuration and an M1 transition with single-particle strength should then be observed (i.e. $T_{\frac{1}{2}} \approx 10^{-11}$ sec). Furthermore, $J^{\pi} = 3^-$ implies an extremely enhanced 167.8 keV M2 transition so that this assignment is not possible either. Thus, we are left with the possibility $J^{\pi} = 3^+$ proposed by Bertschat *et al.* and obtained from our data.

The basis states which contribute to a 3^+ wave function are indicated in table 3, so that

$$\psi_{3^+}(213.8) = \alpha[(f_{\frac{3}{2}})_{\pi}(p_{\frac{1}{2}})_{\nu}]_{3^+} + \beta[(f_{\frac{3}{2}})_{\pi}(f_{\frac{3}{2}})_{\nu}]_{3^+} + \gamma[(p_{\frac{3}{2}})_{\pi}(f_{\frac{3}{2}})_{\nu}]_{3^+}.$$

Recalling the 1^+ state configuration, it is readily seen that ψ_{3^+} will yield a single-particle E2 transition rate to the 1^+ state, which, in this case corresponds to a half-life $T_{\frac{1}{2}} \approx 100$ nsec. This result is in excellent agreement with the experimental value ($T_{\frac{1}{2}}(\text{partial}) = 160$ nsec) for the partial half-life of the 167.8 keV γ -ray. The 213.8 keV γ -ray, on the other hand, would then be a hindered E1 which is again the case since none of the terms in $\psi_{3^+}(213.8)$ will connect with the ground-state configuration $[(f_{\frac{3}{2}})_{\pi}(g_{\frac{3}{2}})_{\nu}]_{2^-}$ through the electric dipole operator.

Finally one can also use ψ_{3^+} to compute the magnetic moment of the 213.8 keV state. The experimental value, measured by Bertschat *et al.*, is $g_{exp} = 0.525 \pm 0.005$. The terms in ψ_{3^+} only contribute to the diagonal matrix elements of the magnetic

dipole operator so that the result is a function of the squares of the α -, β - and γ -coefficients. Using the same formalism as above, we obtain

$$g_{th}(3^+) = 0.500 \alpha^2 + 0.45 \beta^2 + 1.13 \gamma^2.$$

Taking $\alpha^2 + \beta^2 + \gamma^2 = 1$, it can be seen that agreement with experiment is obtained for $\alpha^2 \lesssim 0.96$, $\beta^2 \lesssim 0.90$ and $\gamma^2 \lesssim 0.10$. While it is not possible to determine the relative weight of the first two terms, the calculation shows that the contribution of the third term corresponding to the $(p_{\frac{3}{2}})_{\pi}(f_{\frac{3}{2}})_{\nu}$ configuration is quite small.

We now turn to discuss the possibility $J^{\pi} = 4^-$ for the 309.8 keV state as suggested by our experimental data, discussed in the preceding section. This assignment and the measured lifetime implies a hindered ($\approx 10^4$) E1, 96 keV transition and a single-particle strength for the E2, 309.8 keV γ -ray. Table 3 shows the two terms contributing to ψ_{4-} . Both of them yield the right E2 rate for the transition to the ground state. On the other hand all possible E1 terms connecting with ψ_{3+} are forbidden. Thus, the description of this state is also qualitatively correct.

The *jj* coupling model for doubly odd nuclei has been studied by several authors¹⁰⁻¹²). Brennan and Bernstein¹¹) have revised the Nordheim rules dealing with ground-state spins on doubly odd nuclei and have shown that the new rules can be understood on the basis of previous calculations¹²) of Schwartz and de-Shalit. In these calculations the energies of the levels arising from a particular proton-neutron configuration are obtained assuming an interaction of the form

$$V = V_0[(1 - \alpha) + \alpha \sigma_1 \cdot \sigma_2] \delta(r_1 - r_2),$$

where V_0 is a constant, σ_1 and σ_2 are the spin operators for the proton and neutron, and r_1 and r_2 are their radial coordinates. The strength of the spin dependent part of the interaction is determined by the parameter α .

Brennan and Bernstein¹¹) propose three rules. The first one is Nordheim's strong rule and applies when the two particles (holes) are in *j*-states such that $j_1 = l_1 \pm \frac{1}{2}$ and $j_2 = l_2 \mp \frac{1}{2}$. In this case the lowest state corresponds to $J = |j_1 - j_2|$. For seniority one states, the calculations show that this is so for any value of α . Furthermore for α less than about 0.3, for which most data are fitted, the second lowest state is that with $J = j_1 + j_2$, while those with intermediate values of J lie above and their order depends more appreciably on the specific configuration and the value of α .

In our case the ground-state configuration $[(f_{\frac{3}{2}})_{\pi}^1, (g_{\frac{3}{2}})_{\nu}^1]_J$ corresponds to this coupling rule and therefore we expect the 2^- state to lie lowest. On the other hand the next excited state of this multiplet should be a 7^- state. We do not have unfortunately an estimate of its excitation energy. This state should be populated in the reaction with α -particles. If its excitation energy is less than about 600 keV it should have been observed as an isomeric state. A long-lived ($\gg 100$ nsec) isomeric state has been detected in this work but could not be identified although we know it must lie above ≈ 362.8 keV. Further work would be of interest in order to clarify the nature of this isomer and establish whether it corresponds to the $J = j_1 + j_2$ member of the above configuration.

5. Conclusions

In this work new states of ^{72}As excited through (α, np) reaction have been found and new or more precise information has been obtained on the hitherto known low lying states. Two new half-lives have been observed. The first one was measured to be 17 ± 3 nsec and it is assigned to the 309.8 keV state. The second is long compared to the 100 nsec cyclotron period and corresponds to an unobserved state above 362.8 keV. It is shown that the assumption of simple, rather pure, shell-model configurations yields a fairly accurate description of the properties of the low lying states. While definite spin and parity assignment for the upper states require further measurements, the data yield preliminary evidence for levels of spin values up to 7.

Some points of interest could not be elucidated in this study of ^{72}As and stimulate further work, like the identification of both the observed long-lived isomer and the 7^- state corresponding to the ground-state configuration.

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