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Use of the (γ, γ') Reaction for Studying the Energy Levels of ^{75}As

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Elastic and inelastic nuclear resonant scattering of monochromatic photons from ^{75}As have been studied using a 47-cc Ge(Li) detector. The γ source was provided by thermal-neutron capture in iron. The energy of the resonance level in ^{75}As was found to be 7.646 MeV. Assuming the high-energy lines to be primary transitions deexciting the resonance level, 25 energy levels were found from the ground state up to 2.6 MeV, seven of which may be identified with recently reported levels. By measuring the angular distribution of the scattered radiation, the spin of the scattering level was determined to be $\frac{1}{2}$ and the spins of 14 low-lying levels were thus found to be either $\frac{1}{2}$ or $\frac{3}{2}$. The total radiative width of the resonance level was determined and was found to be $\Gamma = 0.36 \pm 0.10$ eV and $\Gamma_0/\Gamma = 0.11$. The ^{75}As levels are compared with the predictions of the Coriolis coupling model.

I. INTRODUCTION

RECENTLY, several investigations[1-4] of high- and low-lying energy levels of nuclei were carried out using the (γ, γ') reaction, the γ source being produced by thermal neutron capture on several elements. In an earlier publication,[2] the potentialities of using the (γ, γ') reaction in nuclear studies was discussed in some detail and a comparison with the use of the (n, γ) technique was given.

In this paper, the deexcitation of the 7.646-MeV level of ^{75}As excited by Fe-capture γ rays has been studied in detail with a Ge(Li) detector. The spin and radiative width of the scattering level were determined. The decay scheme of the 7.646-MeV resonance level in ^{75}As was constructed. The positioning of some new levels were made by relying on the assumption that strong high-energy γ rays are emitted in primary transitions.

The energy levels of ^{75}As below 2 MeV are summarized in Ref. 5 and a more recent study of ^{75}As levels below 700 keV was reported by Spiedel *et al.*[6] using the decay of ^{75}Se. In the present work, 16 new energy levels were found in the excitation region below 2.8 MeV and suggested spin values for 15 levels are given.

II. EXPERIMENTAL PROCEDURE

The neutron source was provided by the Israel Research Reactor-2 (IRR-2). A schematic drawing of the experimental arrangement is shown in Fig. 1. The production of the capture γ rays and the scattering arrangement remained the same as that of a previous report.[2] The flux near the Fe source is about 2×10^{13} n/cm^2 sec yielding typical γ intensities of the order of 10^8 monoenergetic photons/cm^2 sec on the target. The temperature of the Fe source was about 360°C. The scattered γ rays were observed by using a 7-gm/cm^2-thick As powder target of 11.5 cm diam. enclosed in a thin acoulon container. The detectors used were either a 5×5-in. NaI crystal or a 47-cc Ge(Li) coaxial crystal. The spectrum was recorded with a 1024-channel TMC analyzer. The full width at half-maximum of a γ line obtained by the Ge(Li) detector during operating conditions was 12.5 keV at 7.6 MeV.

Time normalization in angular distribution measurements was achieved by a preset number of counts in a fixed 1.5×1.5-in. NaI detector which monitored the scattered intensity from the arsenic target. It may be noted that other normalization procedures such as the direct monitoring of the incident beam, or monitoring the Compton scattered γ rays, all suffer from inherent errors introduced by temperature changes of the Fe source which can cause variations of the resonant scattering cross section. The temperature changes of the source are dependent mainly on the power level of the reactor and to a much smaller extent on neutron flux variations in the vicinity of the iron source.

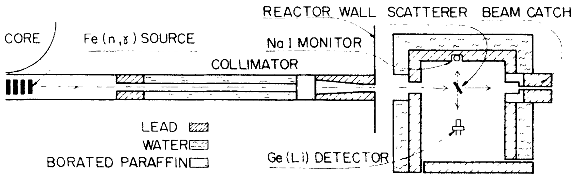

FIG. 1. Horizontal section of the experimental arrangement.

The variable energy response of the 47-cc Ge(Li) detector was calibrated with reference to the well-known line intensities of the (n, γ) spectrum of Cl[7] by em-

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[1] N. Shikazono and Y. Kawarasaki, Nucl. Phys. **A118**, 114 (1968).

[2] R. Moreh and A. Nof, Phys. Rev. **178**, 1961 (1969).

[3] Y. Schlesinger, M. Hass, B. Arad, and G. Ben-David, Phys. Rev. **178**, 2013 (1969).

[4] R. Moreh and A. Wolf, Phys. Rev. **182**, 1234 (1969).

[5] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Science—National Research Council, Washington. D. C. 20025, 1959–1967).

[6] K. H. Speidel *et al.*, Nucl. Phys. **A115**, 421 (1968).

[7] N. C. Rasmussen, Y. Hukai, T. Inouye, and V. J. Orphan, MITNE Report No. 85 (unpublished).

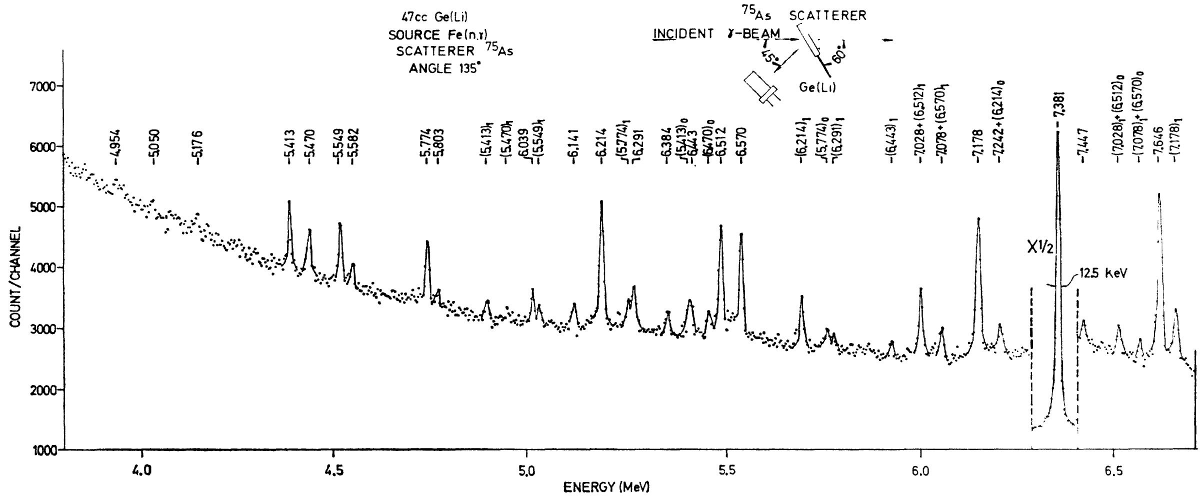

FIG. 2. Scattered γ spectrum from an As target at an angle of 135° measured by a 47-cc Ge(Li) detector. The lines with subscripts 0 and 1 refer to the photopeak and first escape peak, respectively; other lines refer to double escape peaks.

ploying the external thermal-neutron beam facility at IRR-2.

III. RESULTS

A. Energy Spectrum

High- and low-energy scattered spectra were measured with the 47-cm Ge(Li) detector. Figure 2 shows the high-energy part of the scattered spectrum from a 7-g/cm^2-thick natural As target. Bismuth, about 8 mm thick, was placed in front of the detector for filtering out the large number of low-energy pulses obtained from atomic interactions of the direct γ beam with the scatterer. For comparison purposes, the same spectrum as measured by a 5×5-in. NaI detector is given in Fig. 3, which also shows the spectrum of a nonresonant scatterer of Br in the form of NH_4Br.

The scattered spectrum from ^{75}As (Fig. 2) shows the elastic component at 7.646 MeV. The other lines of the spectrum may be shown to be inelastic components corresponding to transitions to excited levels in ^{75}As. In order to avoid ambiguities in the identification of the photopeaks, and the first and second escape peaks, the scattered spectrum was also measured using a 10-cm^3 Ge(Li) detector and was compared with that obtained using a 47-cc detector; several difficulties were thus resolved. In particular, it was concluded that the transition intensity from the resonance state to known levels at 0.401 and 0.572 MeV are negligible. The ambiguity in this case arose because the second escape peaks of lines corresponding to these levels happened to coincide to about 4 keV with the photopeak and single escape peak of the 6.214- and 6.570-MeV lines, respectively.

B. Resonance Scattering Cross Section

Nuclear resonance scattering of iron capture γ rays by As was not reported hitherto. The effective cross section σ_{eff} for elastic scattering[8] is weak and may be seen to be smaller than the inelastic cross section to the 0.265-MeV level in ^{75}As (see Fig. 3). The value of σ_{eff} was determined by measuring the normalized ratio of the scattered intensities from an As target and a Tl target[4,9] which is known to be one of the strongest scatterers of the 7.646-MeV line. The σ_{eff} for As was thus evaluated and found to be 4.4 mb.

C. Decay Scheme

In order to construct the decay scheme and hence the energy levels of ^{75}As, it must be noted that only the

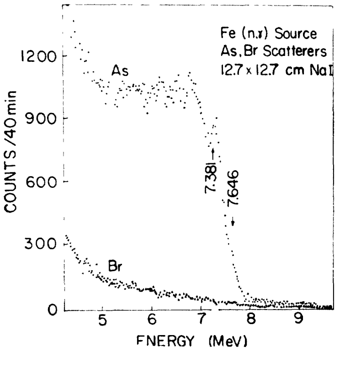

FIG. 3. Scattered γ spectrum from an As target at an angle of 135° measured by a 5×5-in. NaI detector. The background spectrum is obtained using a Br scatterer in the form of NH_4Br.

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[8] F. R. Metzger, Progr. Nucl. Phys. **7**, 53 (1959).

[9] G. Ben-David, B. Arad, J. Balderman, and Y. Schlesinger, Phys. Rev. **146**, 852 (1966).

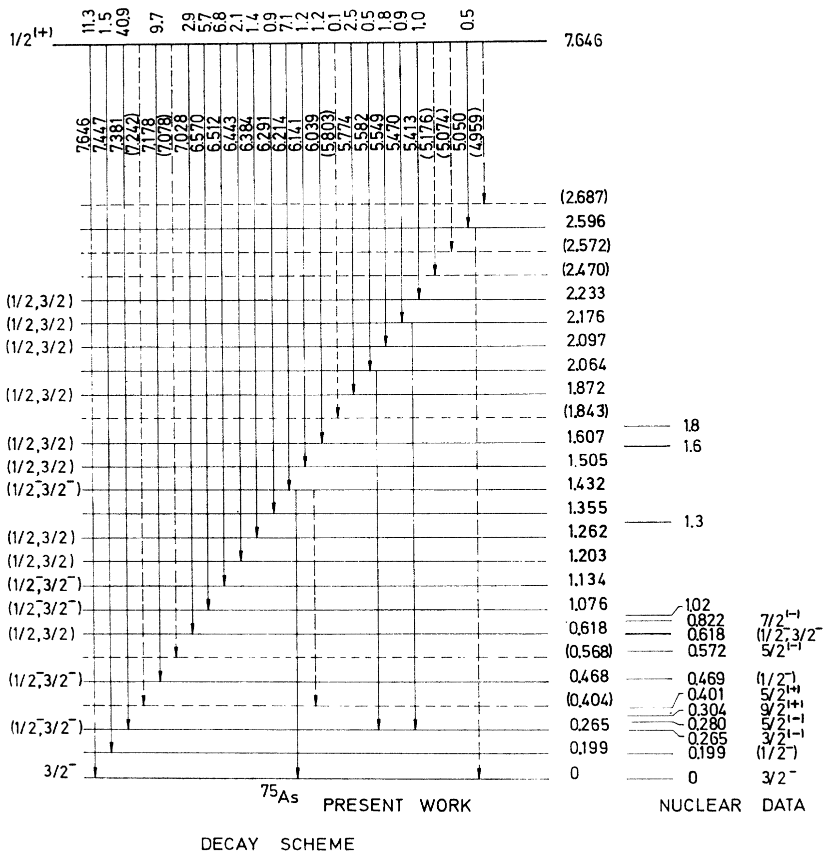

FIG. 4. Decay scheme of 7.646-MeV level of ^{75}As showing level energies and corresponding branching ratios as constructed by assuming that all high-energy γ lines in the scattered spectrum are emitted in primary transitions; broken lines indicate uncertain transitions and hence uncertain levels. Most probable spin and parities for some levels, assigned in the present work, are given where assignements in parentheses are uncertain. For comparison, the energy-level diagram as reported in Ref. 5 is also shown.

7.646-MeV level is excited by the incident Fe capture γ rays as may be seen by comparing the line energies of the scattered spectrum with the line energies of the incident spectrum. It was assumed that strong high-energy γ lines are all due to primary γ transitions de-exciting the resonance level. This assumption was justified by considering the energy dependence of the decay process[2,10] for the primary and secondary transitions. Using this assumption, it is very easy to construct the decay scheme of ^{75}As. However, one can not use this procedure before assuring that no other alternative process can possibly contribute to the γ spectrum. In the following, all processes which may apparently contribute to the appearance of γ lines are considered and are shown to have a negligible effect on the scattered spectrum: (a) the possibility that some of the lines may arise from thermal neutron capture in ^{75}As, the neutrons being background neutrons partly produced by the (γ, n) reaction on the Pb collimators and shielding. This possibility may be eliminated by considering the energies and intensities of the scattered spectrum. These lines were not found to fit those of the known γ lines obtained from thermal-neutron capture[7] in ^{75}As. (b) The possibility that the γ lines arise from the effect of epithermal or fast neutrons on ^{75}As may also be eliminated by considering the line intensities involved. An overestimate of the γ intensities for an assumed two-step process can be obtained by taking a cross section of 100 mb for both the (γ, n) reaction on the Pb collimators and the subsequent ^{75}As(n, γ) process. The total γ line intensity thus calculated is found to be about two order of magnitude lower than the weakest line observed in the present work. It may be remarked that no neutrons may be produced by the (γ, n) reaction on the target because the threshold for the ^{75}As(γ, n) reaction is 10.248 MeV,[11] which is higher than the maximum energy of the photons (10.04 MeV) in the incident Fe capture γ source.[7] As another confirmation of the unimportance of the above processes, it may be noted that no correlation whatever was observed between elements having strong resonance fluorescence effects and those having high cross sections for resonant or thermal-neutron capture. (c) The possibility that some of the γ line may arise from elastic scattering of a weak and probably unknown line in the incident spectrum may also be eliminated by considering the probability for such a process. The energy spectrum of the incident beam was measured with great accuracy[7];

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[10] G. A. Bartholomew, Ann. Rev. Nucl. Sci. **11**, 259 (1961).

[11] J. H. E. Mattauch, W. Thiele, and A. H. Wapstra, Nucl. Phys. **67**, 32 (1965).

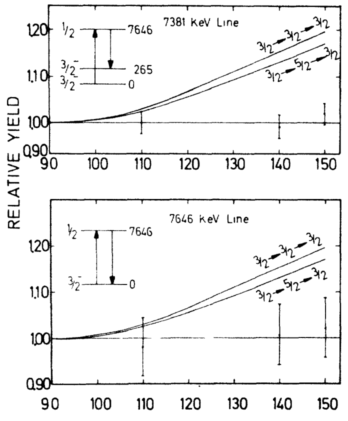

FIG. 5. Angular distribution of the elastic and the strongest inelastic line in ^{75}As as measured using a 47-cc Ge(Li) detector.

all weak lines down to 10^{-3} the intensity of the strongest line in the incident beam are known. If it is assumed that a line of weaker intensity in the incident spectrum occurs which gives rise to one of the scattered γ lines, this will mean that the effective resonance scattering cross section for the γ line in question is of the order of 10 b which is very unlikely to occur. (d) Another possibility that some of the γ lines may arise from strong inelastic components for which the elastic component is weak and therefore unobserved was discussed in detail in a previous paper[2] and was found to be negligible. It may thus be concluded that all γ lines of the scattered spectrum correspond to the deexcitation of the 7.646-MeV resonant level.

Table I lists the results of line energies, branching ratios, and level energies as obtained from the present work; the level energies as obtained by other investigators are also shown. By considering the energies of the high- and low-energy transitions, it was possible to obtain five cascades which lead to the ground and low-lying excited states. Figure 4 show the decay scheme which summarizes the above results.

D. Angular Distributions

Angular distribution measurements of the scattered spectrum were carried out at three angles using the Ge(Li) detector set at 45 cm away from the scattering target. Corrections for the atomic absorption of the incident and scattered beams in the target were introduced. Figure 5 shows the distribution of the 7.646-MeV elastic line which may be seen to be isotropic thus the spin of the 7.646-MeV level is $\frac{1}{2}$. It follows that the distribution of all inelastic lines is also isotropic. A typical distribution of the inelastic lines is also given in Fig. 5. As a further confirmation of the isotropy of the inelastic lines, the angular distribution of the scattered radiation in the energy range 5.2–7.8 MeV was measured using a 5×5-in. NaI detector. Again, the distribution was found to be isotropic to less than 1%. It is therefore impossible to determine the spins of the low-lying excited states by angular distribution measurements. It also follows that the resonantly scattered photons are not polarized and hence it is impossible to measure the parity of the 7.646-MeV level by polarization measurements.[12]

E. Branching Ratios and Radiation Width

Since the spin of the resonance level is $\frac{1}{2}$, it follows that the branching ratios for the decay of this level can

TABLE I. γ energies and level energies in ^{75}As from (γ,γ') reaction. The level energies are obtained by assuming that the γ lines are emitted in primary transitions. The branching ratios of the decay of the 7.646-MeV level are given. Line energies are accurate to ±4 keV. Branching ratios of the strong intensity lines are accurate to ±8%. The existence of γ lines and levels in parentheses is uncertain.

γ energy (MeV)	Branching ratio (%)	Level energies (MeV) Present work	Ref. 5
7.646	11.3	0	0
7.447	1.5	0.199	0.199
7.381	40.9	0.265	0.265
...	...	...	0.280
...	...	...	0.304
(7.242)	...	(0.404)	0.401
7.178	9.7	0.468	0.469
(7.078)	...	(0.568)	0.572
7.028	2.9	0.618	0.618
...	...	...	0.822
...	...	...	1.021
6.570	5.7	1.076	...
6.512	6.8	1.134	...
6.443	2.1	1.203	...
6.384	1.4	1.262	...
...	...	...	1.3
6.291	0.9	1.355	...
6.214	7.1	1.432	...
6.141	1.2	1.505	...
6.039	1.2	1.607	1.6
...	...	...	1.8
(5.803)	0.1	(1.843)	...
5.774	2.5	1.872	...
5.582	0.5	2.064	...
5.549	1.8	2.097	...
5.470	0.9	2.176	...
5.413	1.0	2.233	...
(5.176)	...	(2.470)	...
(5.074)	...	(2.572)	...
5.050	0.5	2.596	...
(4.959)	...	(2.687)	...
2.596	...	...	...
1.911	...	...	...
1.799	...	...	...
1.432	...	...	...
1.028	...	...	...

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[12] R. Moreh and M. Friedman, Phys. Letters **26B**, 579 (1968).

TABLE II. Partial radiation widths Γ_i, and $E1$ and $M1$ radiation strengths of intense transitions from the 7.646-MeV resonance state; the most probable spins and parities are also given where values in parentheses indicate uncertain determinations. The level spacing D was taken to be 750 eV.

Transition energy (MeV)	Level energy (MeV)	Spin and parity	$\Gamma_i \times 10^3$ (eV)	$k_{E1} \times 10^9$ (MeV)$^{-3}$	$k_{M1} \times 10^9$ (MeV)$^{-3}$
7.646	0	$\frac{3}{2}^-$	41	6.8	121
7.381	0.265	$(\frac{1}{2}^-, \frac{3}{2}^-)$	147	27.5	488
7.178	0.468	$(\frac{1}{2}^-, \frac{3}{2}^-)$	35	7.1	126
7.028	0.618	$(\frac{1}{2}, \frac{3}{2})$	10	2.3	40
6.570	1.076	$(\frac{1}{2}^-, \frac{3}{2}^-)$	21	5.4	97
6.512	1.134	$(\frac{1}{2}^-, \frac{3}{2}^-)$	25	6.6	118
6.443	1.203	$(\frac{1}{2}, \frac{3}{2})$	8	2.1	38
6.384	1.262	$(\frac{1}{2}, \frac{3}{2})$	5	1.5	26
6.214	1.432	$(\frac{1}{2}^-, \frac{3}{2}^-)$	26	8.0	142
6.141	1.505	$(\frac{1}{2}, \frac{3}{2})$	4	1.4	25
6.039	1.607	$(\frac{1}{2}, \frac{3}{2})$	4	1.5	26
5.774	1.872	$(\frac{1}{2}, \frac{3}{2})$	9	3.5	62
5.549	2.097	$(\frac{1}{2}, \frac{3}{2})$	7	2.8	51
5.470	2.176	$(\frac{1}{2}, \frac{3}{2})$	3	1.5	26
5.413	2.233	$(\frac{1}{2}, \frac{3}{2})$	4	1.7	30
	7.646	$\frac{1}{2}^{(+)}$			

be evaluated directly from the relative intensities of the lines at any angle after correcting for the atomic attenuation of the various γ energies in the target and in the absorber surrounding the Ge(Li) detector. The results thus obtained are given in Table I. The branching ratio to the ground state may be seen to be 0.11, which is equal to Γ_0/Γ, where Γ_0 is the ground-state partial radiation width and Γ is the total radiation width. In order to determine the parameters of the resonance level, three independent experiments were carried out. In the first, the ratio between the resonant scattering cross section at liquid-nitrogen temperature and at room temperature was measured. In the second, the self-absorption ratio was obtained and in the third the effective cross section for elastic resonance scattering relative to that of a Tl scatterer was determined (see Sec. III B). The result of each measurement is a function of Γ, Γ_0/Γ, and the separation energy δ between the peaks of the incident energy and the resonance level of ^{75}As. The values obtained were $\Gamma_0 = 0.041 \pm 0.011$ eV, $\Gamma = 0.36 \pm 0.10$ eV, and $\delta = 7.4 \pm 0.3$ eV. It is very interesting to note that the value of Γ_0/Γ as determined here is consistent with that obtained from branching ratio measurements.

IV. DISCUSSION

A. γ-Ray Transition Strengths

Since the partial radiation widths of the 7.646-MeV level is known, it is possible to calculate the γ-ray transition strengths and to compare them with the systematics of the radiation widths of high-energy primary neutron capture γ rays of known multipolarity in neighboring nuclei. Since the spin of the resonance level is $\frac{1}{2}$, a dipole transition will imply that the spin value of the final state is either $\frac{1}{2}$ or $\frac{3}{2}$.

The $E1$ radiation strength k_{E1} and the $M1$ radiation strength k_{M1} as defined by Bartholomew[10] are

$$k_{E1} = \Gamma_i (E_i^3 A^{2/3} D)^{-1}, \qquad k_{M1} = \Gamma_i (E_i^3 D)^{-1},$$

where Γ_i is the radiative width, D is the average spacing for levels of the same spin and parity near the resonance energy, E_i is the γ line energy, and A is the mass number of the scattering nucleus. The k_{E1} and k_{M1} values of the elastic and strong inelastic transitions were calculated by assuming $D = 750$ eV for levels of the same spin in ^{75}As. This value is about three times higher than that of the level spacing of neutron resonances in neighboring nuclei[13,14] such as ^{76}As, ^{75}Se, ^{78}Se, and ^{72}Ga whose average spacing is about 220 eV. This choice of D was made after considering the level spacing of γ resonances as obtained by Axel[15] from the results of Riebel and Mann.[16] It turned out that the level spacing of γ resonances is generally higher than that of neutron resonances. In the case of Cu, it is higher by a factor of about 3, and the same factor was taken for the present case. As pointed out by Riebel and Mann, this discrepancy between the spacing of γ resonances and neutron resonances arises because the resonance scattering experiments select only

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[13] *Neutron Cross Sections*, compiled by D. J. Hughes and R. B. Schwartz, Brookhaven National Laboratory Report No. BLN-325 (U.S. Government Printing Office, Washington. D.C., 1958), 2nd ed.

[14] V. D. Huynh *et al.*, in *Conference on Nuclear Data* (International Atomic Energy Agency, Paris, 1966).

[15] P. Axel, Phys. Rev. **126**, 671 (1962).

[16] K. Riebal and A. K. Mann, Phys. Rev. **118**, 701 (1960).

those levels which have large dipole matrix elements. Such levels occur with a correspondingly larger spacing.

Table II lists only those transitions whose radiation strength exceeds the criterion value adopted here for dipole radiation. These values are $K_{E1}=3.9\times10^{-9}$ MeV^{-3} and $K_{M1}=20\times10^{-9}$ MeV^{-3}. The fact that the criterion value for $M1$ radiation is numerically larger than that for $E1$ is probably misleading, it is related to the way these radiation strengths are defined. The criterion value of K_{E1} was obtained by Carpenter[17] after averaging over 26 $E1$ transitions from neutron resonance on nuclei in the range $144\geq A\geq 202$. The value of K_{M1} was obtained by Bollinger[18] who averaged the results of 17 $M1$ transitions from neutron resonances.

In order to determine whether a certain transition is $E1$, the K_{E1} values for this transition was calculated. When the K_{E1} value was found larger than the criterion value, then the transition was taken to be $E1$. For cases where the calculated K_{M1} value exceeded the criterion value, the transition was taken to be dipole, namely, $E1$ or $M1$; otherwise the transition may be either dipole or quadrupole.

From Table II it follows that since the ground state of ^{75}As is $\frac{3}{2}^-$ then the 7.646-MeV resonant level is very probably $\frac{1}{2}^+$ and that all low-lying levels whose transition strengths exceed the $E1$ criterion value, are probably $\frac{1}{2}^-$ or $\frac{3}{2}^-$. This does not mean that all $E1$ transitions should be strong. An example is the weak transition, presumably $E1$, to the 0.199-MeV state known[5] to be $\frac{1}{2}^-$. The above expectations are borne out experimentally as may be seen by comparison with the results of other investigators[5] (Fig. 4). It should be remarked that these conclusions should be treated with some reserve because of the uncertainties involved in deriving them. First, there is a large uncertainty in the choice of the level spacing. Second, there is some evidence for the existence of abnormally strong $M1$ transitions[19,20] whose radiation strength exceed the criterion value of K_{M1} by a factor of about 6.

B. Energy Levels of ^{75}As

Figure 1 summarizes the present information regarding the ^{75}As levels. Apart from the results obtained in the present work, the figure shows levels obtained by various authors.[5] As expected, no direct transition was found to occur between the 7.646-MeV resonant level, $\frac{1}{2}^{(+)}$, and any level whose spin is larger than $\frac{3}{2}$. In particular, no transition was observed to levels at 0.280, 0.304, 0.401, 0.572, and 0.822 which are believed to be $\frac{5}{2}^-$, $\frac{9}{2}^+$, $\frac{5}{2}^+$, $\frac{5}{2}^-$, and $\frac{7}{2}^-$, respectively.

In the ^{75}As nucleus, the $2p_{3/2}$ and $1f_{5/2}$ proton subshells and the $2p_{1/2}$ and $1g_{9/2}$ neutron subshells are being filled. In each case, the energy difference between the subshells is very small, therefore conditions are favorable for the existence of deformations in this nucleus.

The energy levels of ^{75}As were recently calculated by Scholz and Malik[21] using the Coriolis coupling model with a residual interaction of the pairing type. An interesting point regarding this calculation is the relatively large number of $\frac{1}{2}^-$ and $\frac{3}{2}^-$ levels predicted. The results of the present work combined with those reported in Ref. 5 indicate that there are at least seven levels below 1.5-MeV excitation whose spins are $\frac{1}{2}^-$ and $\frac{3}{2}^-$. Theoretically, however, only seven such levels are predicted. Regarding other levels of spins larger than $\frac{3}{2}$, nothing may be said with certainty, since the present experiment is best suited for populating levels whose spins are either $\frac{1}{2}$ or $\frac{3}{2}$. It should be mentioned that similar calculations of the ^{75}As energy levels were performed by Imanishi *et al.*[22] However, these authors report only levels below 0.85-MeV excitation.

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[22] N. Imanishi, M. Sakisaka, and F. Fukusawa, Nucl. Phys. **A125**, 626 (1969).