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Levels in ^{73}As through the ^{72}Ge (^{3}He, d) reaction

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The ^{72}Ge (^{3}He,d) ^{73}As reaction has been investigated at a ^{3}He bombarding energy of 20 MeV. Nearly 25 new bound levels in ^{73}As have been observed beyond 3 MeV excitation. The relative spectroscopic factors for the bound states have been extracted and are compared with the predictions of the simple pairing theory. Several isobaric analog states of ^{73}Ge have also been identified.

[NUCLEAR REACTIONS ^{72}Ge (^{3}He, d)^{73}As, $E = 20$ MeV; measured $\sigma(E;\theta)$, DWBA analysis; deduced ^{73}As levels, l_p, S. Enriched target.]

I. INTRODUCTION

Nuclei in the region of germanium and arsenic have been the subject of several recent theoretical and experimental investigations. The properties of the energy levels of these nuclei have been calculated in terms of the pairing-plus-quadrupole model[1] and models with single-particle core coupling.[2,3] It has been shown recently that the inclusion of Coriolis coupling and a residual interaction of the pairing type in the statically deformed collective model can equally well describe the positive and negative parity states of these nuclei.[4,5]

Early experimental investigations[6-10] were concerned with the study of the arsenic isotopes through gamma transitions following the beta-decay of selenium isotopes and the decay studies have yielded information about the energy levels up to about 2 MeV. The earlier (^{3}He, d) experiments on ^{72}Ge leading to ^{73}As have yielded the spectroscopic factors of states up to 3 MeV.[11,12] In this paper, we present the results of our investigation on bound states up to 5.3-MeV excitation and the isobaric analog states from 8.9 to 11.0-MeV excitation in ^{73}As.

II. EXPERIMENT

The ^{72}Ge target of ~20 μg/cm^2 thickness was prepared by evaporating isotopically enriched $^{72}GeO_2$ onto thin carbon films. A 20-MeV $^3He^{++}$ beam of ~200 nA current from the MP tandem Van de Graaff accelerator at the Max Planck Institut fur Kernphysik, Heidelberg was used to bombard the target. The total charge collected was 2.5 mC. The outgoing deuterons from the ^{72}Ge(^{3}He, d)^{73}As reaction were analyzed by a multigap magnetic spectrograph having an energy resolution of about 20 keV full width at half maximum (FWHM). The deuteron tracks were recorded in Ilford K2 nuclear emulsion plates of 50 μm thickness. The plates were scanned in steps of 0.5 mm under a binocular microscope. Angular distributions were measured experimentally from 5.5° to 58°.

III. RESULTS AND ANALYSIS

A. Bound states

A typical deuteron spectrum measured at the laboratory angle of 9.5° is shown in Fig. 1. The different deuteron groups from the ^{72}Ge(^{3}He, d) reaction are numbered as indicated in Table I; deuteron groups due to the contaminant isotopes ^{12}C, ^{13}C, and ^{16}O are labeled by the corresponding states in the residual nuclei. The Q value for the ^{72}Ge(^{3}He, d) reaction was taken to be 0.169 MeV.[13] The excitation energies corresponding to the different deuteron groups were determined at several angles and their average values are given in Table I; the uncertainty in the energies is estimated to be ±10 keV for levels below 2.5 MeV and ±15 keV for levels above 2.5-MeV excitation in ^{73}As. The results from the previous experiments[11,12] are also shown in the Table. The analysis of the spectrum in the high background region of 3.5 to 5.3 MeV was carried out with the peak-fitting program MALIK.[14] Angular distributions for states up to 5.3-MeV excitation energy are classified according to the different l_p values and

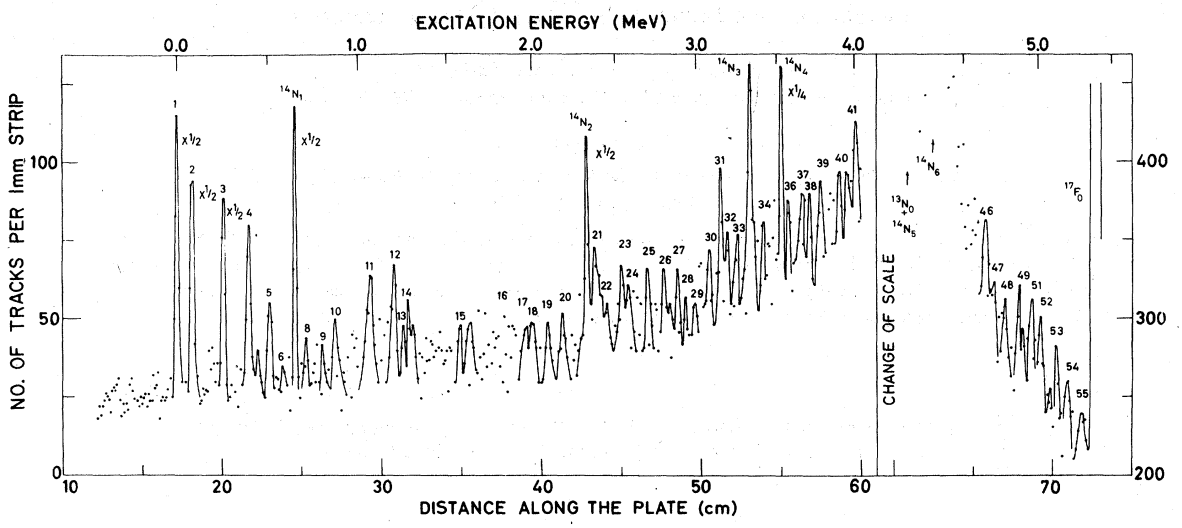

FIG. 1. Spectrum of deuterons from the ^{72}Ge(^{3}He, d)^{73}As reaction measured at the laboratory angle 9.5°. The levels are labeled according to the level numbers given in Table I. $^{14}N_0$, $^{14}N_1$, $^{14}N_2$, etc., represent the ground and the excited states of ^{14}N due to the contaminant ^{13}C.

are shown in Figs. 2–5. The error bars in these figures indicate the errors due to statistics and background subtraction.

Theoretical angular distributions were computed using the code DWUCK.[15] The optical potential used was of the form

$$V(r) = -V_0 f(x) - i[W - 4W_D(d/dx')]f(x') + V_c(r, r_c),$$

where $f(x)$ was taken to be of the Woods-Saxon form, i.e., $f(x) = (1+e^x)^{-1}$ where $x = (r - r_0 A^{1/3})/a$. The set of optical-model parameters[16] used in the present analysis is shown in Table II. In the calculation of the form factor, a value of 25 MeV was used for the coefficient of the spin-orbit potential and the real well depth was searched in order to reproduce the experimental separation energy of each level.

The characteristic features of the experimental angular distributions are well reproduced by the calculated angular distributions for each l_p value (see Figs. 2–5). The doublet levels at excitation energies of 0.079, 0.410, 1.320, and 5.07 MeV were not resolved in the present experiment; the angular distributions in these cases, shown in Fig. 6, were computed assuming two possible l_p values and χ^2 was minimized. The states near 4.3-MeV excitation were obscured by the contaminant peaks at several angles and hence the experimental angular distribution for these states could not be obtained. The l_p values shown within parentheses in Table I are doubtful assignments.

The single-particle states $2p_{3/2}$, $2p_{1/2}$, $1f_{5/2}$, $1g_{9/2}$, $3s_{1/2}$, $2d_{5/2}$, and $2d_{3/2}$ are the most probable ones for the excitation of the low-lying states in the germanium region. Thus the spin and parity assignment for the states populated by $l_p = 0$, 3, and 4 transfers are taken as $\frac{1}{2}^+$, $\frac{5}{2}^-$, and $\frac{9}{2}^+$ respectively. For $l_p = 1$ transfer, the $2p_{3/2}$ and $2p_{1/2}$ states cannot be distinguished in the present experiment. Hence the spectroscopic strength G (referred to below and quoted in Table I) for the low-lying levels is extracted on the basis of the assignments made in Ref. 17; the G values quoted within parentheses in column 4 of Table I refer to the spin assignments given within the parentheses in column 5. However, $l_p = 1$ levels beyond 1-MeV excitation energy have been assumed to be $2p_{1/2}$ states; the $2p_{3/2}$ spectroscopic strength is then normalized with the value predicted by the pairing theory (see Sec. IV). For $l_p = 2$ transfers, $2d_{5/2}$ states have been generally assumed.

The spectroscopic strength $G = [(2J_f+1)/(2J_i+1)]C^2S$ for each level has been extracted using the following relation:

$$\sigma_{\text{expt}}(\theta) = NG[(2s+1)/2(2j+1)]\sigma_{\text{DWUCK}}(\theta).$$

Here J_i and J_f are the spins of the target nucleus and the residual nuclear state, respectively; s and j are the spin and total angular momentum of the transferred proton. S is the spectroscopic factor

TABLE I. Summary of the results for the ^{72}Ge (^{3}He, d) ^{73}As reaction.

Level No.[a]	Present experiment			Ref. 17	Ref. 11			Ref. 12		
(1)	(2) E[b] (MeV)	(3) l_p	(4) G[c]	(5) J^π	(6) E (MeV)	(7) l_p	(8) G[c]	(9) E (MeV)	(10) l_p	(11) G[c]
1	g.s.	1	1.03	$\frac{3}{2}^-$	g.s.	1	1.03	g.s.	1	0.92
2	0.079	3	4.9	$\frac{5}{2}^-$	0.072[h]	3	4.92	0.067	3	5.53
		1	0.65 (0.92)	$\frac{3}{2}^-(\frac{1}{2}^-)$		1	0.85[g]	0.084	1	0.67
3	0.250	1	0.46 (0.46)	$\frac{1}{2}^-(\frac{3}{2}^-)$	0.253	1	0.49	0.253	1	0.47
4	0.410[f]	1	0.22 (0.28)	$\frac{3}{2}^-(\frac{1}{2}^-)$	0.418[h]	1	0.16	0.393	1	0.17
		4	2.12	$\frac{9}{2}^+$		4	2.46	0.427	4	2.42
5	0.510	2	0.37	$\frac{5}{2}^+$	0.513	2	0.44	0.509	2	0.33
6	0.570			$\frac{5}{2}^-(\frac{5}{2}^+)$	0.586	3	0.13	0.578		
7	0.650			$\frac{3}{2}^-$[h]				0.654		
8	0.715									
9	0.785			$\frac{5}{2}$	0.776	3	0.22	0.766		
				$\frac{5}{2}$				0.846	0	0.05
								0.856	+	+
10	0.886	0	0.05	$\frac{7}{2}^-(\frac{7}{2}^+)$	0.886	0	0.08	0.880	(2)	(0.04)
11	1.079	(1)	(0.14, 0.12)[d]	$\frac{7}{2}(\frac{1}{2}, \frac{3}{2})$	1.080[c]			1.073	1 + 3	0.05 + 0.18
12	1.213	1	(0.16, 0.10)[d]	$\frac{7}{2}$	1.218	1	0.21			
13	1.265			$\frac{7}{2}$						
14	1.326[f]	1	(0.05, 0.04)[d]	$\frac{1}{2}, \frac{3}{2}$	1.323	2	0.08	1.307	1 + 2 or	0.02 + 0.04 or
		2	0.04	$\frac{5}{2}^+$					1 + 3	0.03 + 0.17
15	1.596	(0)	0.02		1.599	1	0.04	1.590	1 + 3	0.03 + 0.12
16	1.851	4	1.71		1.861	4	3.05	1.852	4	2.48
17	1.968	3	0.77		1.982	3	0.91	1.976	4	0.84
18	2.026	0	0.02		2.040	0	0.04	2.032	0	0.02
19	2.096				2.137					
20	2.218	3	0.65		2.253			2.220		
					2.324			2.311		
21	2.386	2	0.13		2.392	2	0.22	2.394	1 + 2	0.16 + 0.16
22	2.436	2	0.21		2.443	(2)	0.19	2.436		
								2.480	(1)	(0.03)
23	2.552				2.562			2.552	2	0.08
24	2.609				2.609	0	0.02	2.605	0	0.02
25	2.703	1	0.05		2.738			2.716	0 + 1	0.02 + 0.01
26	2.802	(0)	0.02		2.831			2.823	2 + 4	0.03 + 0.18
27	2.892	2	0.08		2.902	2	0.07	2.903	2	0.06
28	2.931									
29	3.003									
30	3.087									

TABLE I. (*Continued*)

Level No.[a]	Present experiment			Ref. 17	Ref. 11			Ref. 12		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
	E[b] (MeV)	l_p	G[c]	J^π	E (MeV)	l_p	G[c]	E (MeV)	l_p	G[c]
31	3.157	0	0.03							
32	3.203									
33	3.257	3	0.43							
34	3.392				3.393	(0)	0.09			
35	3.532	(1) + (3)	0.03 + 0.44		3.561	(1)	0.09			
36	3.610									
37	3.666									
38	3.724									
39	3.791									
40	3.880									
41	3.994									
42	4.267									
43	4.470									
44	4.518									
45	4.600									
46	4.650	0	0.03							
47	4.712	2	0.07							
48	4.780									
49	4.860									
50	4.900	4	3.80							
51	4.952	2	0.18							
52	5.010									
53	5.070[f]	0 + 2	0.03 + 0.14							
54	5.190	2	0.13							
55	5.278	2	0.13							

[a] The level numbers correspond to the numbers of the deuteron groups shown in Fig. 1.
[b] Estimated uncertainty is ± 10 keV for $E_x < 2.5$ MeV and ± 15 keV for $E_x > 2.5$ MeV.
[c] $G = [(2J_f + 1)/(2J_i + 1)]\, C^2S$, $J_i = 0$.
[d] The G values correspond to the J values of $\frac{1}{2}$ and $\frac{3}{2}$ respectively.
[e] Normalized to the value of Ref. 11.
[f] Doublet.
[g] This value assumes $p_{1/2}$ transfer; a $p_{3/2}$ transfer would reduce the spectroscopic strength.
[h] Reference 24.

TABLE II. Optical-model parameters used in DWBA analysis of the ^{72}Ge (^{3}He, d) ^{73}As reaction at $E(^{3}\mathrm{He})$ = 20 MeV.

Channel	V_o	r_o	a	W	W_D	r_o'	a'	r_{oc}
^{72}Ge + ^{3}He	177.8	1.14	0.72	15	...	1.54	0.80	1.40
^{73}As + d	92.7	1.15	0.81	...	19.6	1.34	0.68	1.15
Bound state	53.0[a]	1.20	0.65					1.25

[a] Adjusted to give the transferred proton a binding energy $B_p = Q(p,\gamma) - E_x$.

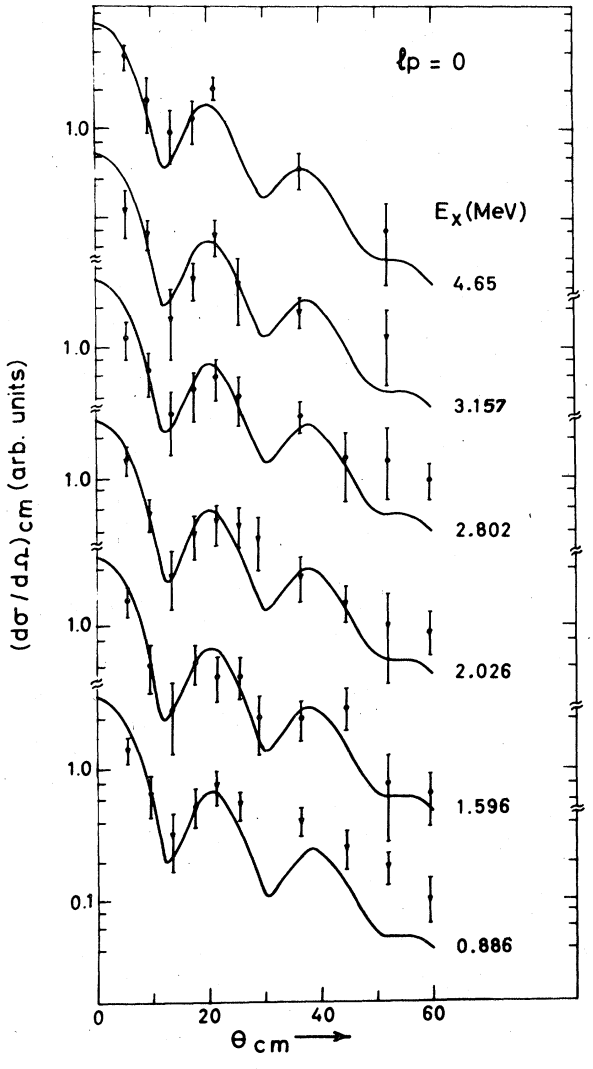

FIG. 2. Angular distributions of deuterons from the ^{72}Ge(^{3}He, d)^{73}As reaction at $E(^{3}\mathrm{He})$ = 20 MeV. The curves are DWBA predictions for l_p = 0 transfer and are based on the parameters given in Table II.

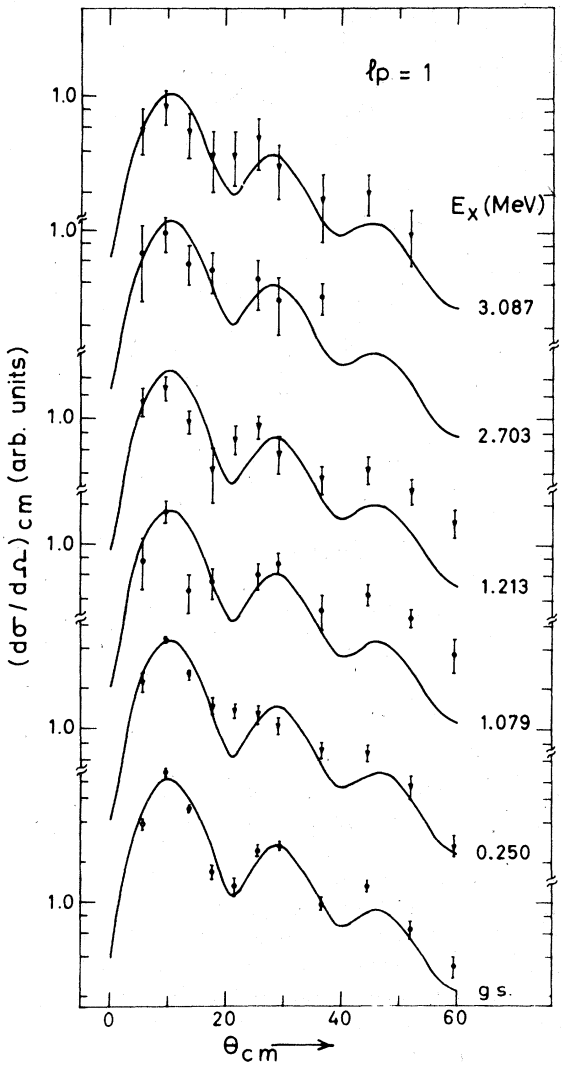

FIG. 3. Angular distributions of deuterons and the corresponding DWBA fits characteristic of the l_p=1 transfer.

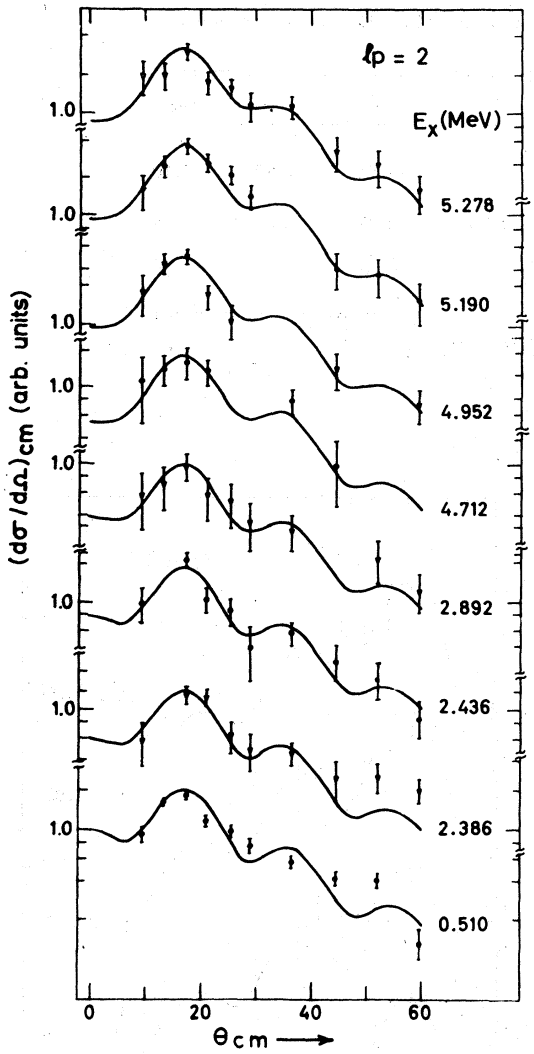

FIG. 4. Angular distributions of deuterons and the corresponding DWBA fits characteristic of $l_p = 2$ transfer.

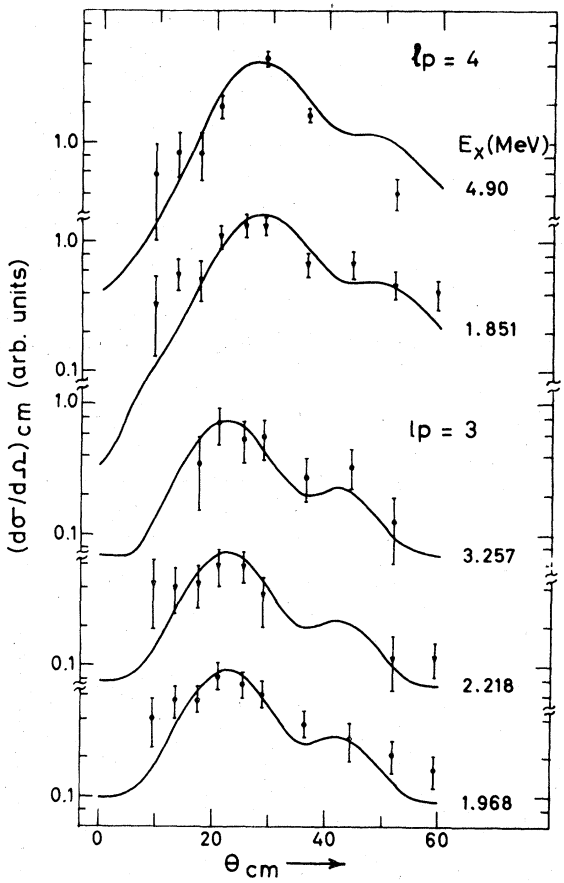

FIG. 5. Angular distributions of deuterons and the corresponding DWBA fits characteristic of $l_p = 3$ and 4 transfers.

and C is a Clebsch-Gordan coefficient connecting the isospins of the target and the residual nuclear states. The normalization factor N for the (^{3}He, d) reaction[18] has been taken to be 4.42.

Since the target thickness could not be measured, only relative cross sections are quoted for the angular distributions; however, the spectroscopic strengths have been normalized to the ground-state value of 1.03 as given in Ref. 11.

B. Analog states

The spectrum of deuterons taken at the laboratory angle of 17°, corresponding to the analog states, is shown in Fig. 7. The states were identified on the basis of the relative spacings of the peaks in the spectra at various angles. The state at 8.9-MeV excitation was identified as the ground-state analog. This identification was made on the basis of values derived from (p,p) and (p,p') reactions[19,20] and from the proton separation energy[21] of 5.662 MeV. The excitation energies of the analog states and the corresponding parent states as obtained through the ^{72}Ge$(d,p)^{73}$Ge reaction[21,23] are tabulated in Table III.

The experimental angular distributions for these states could not be obtained because of the presence of the excited states of ^{13}N, ^{14}N, and ^{17}F produced by the contaminants ^{12}C, ^{13}C, and ^{16}O respectively.

IV. DISCUSSION

In the present work, the levels of ^{73}As have been investigated for an excitation energy of 0 to

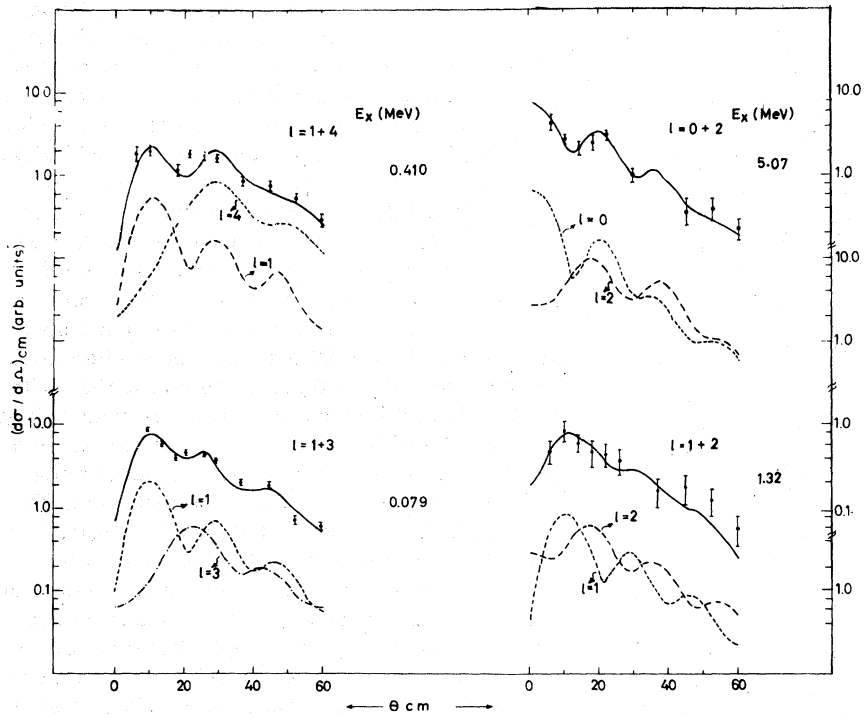

FIG. 6. Deuteron angular distributions for the doublets (solid lines). The dotted lines represent DWBA predictions for each of the unresolved levels.

TABLE III. Summary of the results on analog states seen in the ^{72}Ge (^{3}He, d) ^{73}As reaction.

(1) Level No.[a]	(2) E_x (^{3}He, d)[b] (MeV)	(3) (E_x - 8.89) (MeV)	(4) E_x (d, p)[c] (MeV)	(5) E_x (d, p)[d] (MeV)	(1) Level No.[a]	(2) E_x (^{3}He, d)[b] (MeV)	(3) (E_x - 8.89) (MeV)	(4) E_x (d, p)[c] (MeV)	(5) E_x (d, p)[d] (MeV)
$A1, A2$	8.890[e]	0.0	g.s.	g.s.	$A11$	9.860	0.970		0.925
			0.013	0.013	$A12$	9.950	1.060	1.051	1.036
			0.067	0.067	$A13$	9.990	1.100		1.123
				0.352	$A14$	10.040	1.150		
$A3$	9.260	0.370	0.368	0.361	$A15$	10.125	1.235	1.274	
$A4$	9.310	0.420		0.390					
$A5$	9.375	0.485	0.512	0.497	$A16$	10.190	1.300		1.308
									1.376
$A6$	9.435	0.545	0.562	0.551	$A17$	10.480	1.590		1.595
$A7$	9.510	0.620		0.593				1.617	1.623
$A8$	9.560	0.670	0.666	0.655				1.646	
$A9$	9.670	0.780		0.769					1.733
				0.820	$A18$	10.670	1.780	1.756	1.754
$A10$	9.755	0.865	0.864						
				0.888					
		0.904		0.904					

[a] The level numbers correspond to the numbers of the deuteron groups shown in Fig. 7.
[b] Present investigation.
[c] Reference 21.
[d] Reference 22.
[e] Doublet.

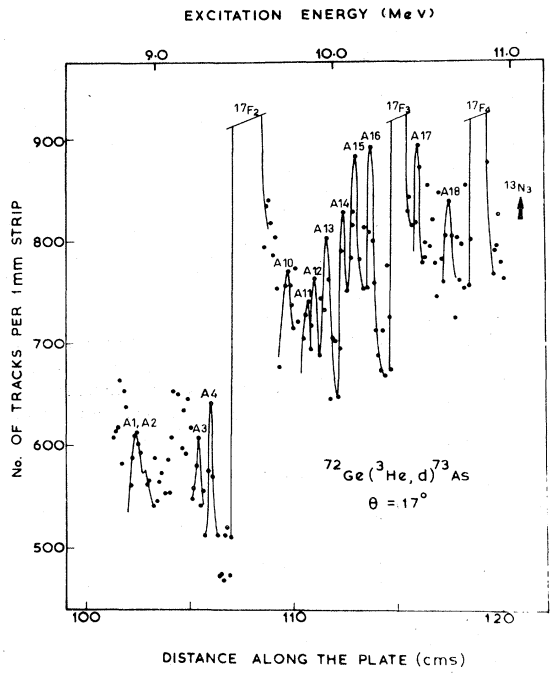

FIG. 7. Deuteron spectrum at $\theta_{lab}=17°$. A_i's are the isobaric analog states in ^{73}As.

5.3 MeV. Twenty-six levels above an excitation energy of 2.9 MeV, in particular, have been observed and, where possible, l_p values have been assigned. Unfortunately some of these levels are located in the neighborhood of contaminant peaks and thus the information from these is lost. Earlier measurements[11,12] on the same reaction at $E(^3\text{He})=17$ and 23 MeV report the parameters of the observed levels in ^{73}As up to 3 MeV. The results presented here agree in general with the earlier results as seen in Table I. However, there are a few discrepancies between our measurement at $E(^3\text{He})=20$ MeV and the earlier work. For example, the $l=0$ assignments for the 1.596 and 2.802-MeV levels differ from previous values; however, these levels are rather weakly excited and the assignments should be treated as tentative. The measured angular distribution for the 1.851-MeV level is not fitted well by distorted-wave Born-approximation (DWBA) calculations. In spite of the care taken to reanalyze the data in order not to overlook any errors, the fit is not very good and the spectroscopic factor is low as compared to the values reported by earlier workers, where the theoretical fit to the data is satisfactory. The reason for this behavior is not clear except for the possibility that some kind of underlying resonance structure may be affecting the cross section at 20 MeV.

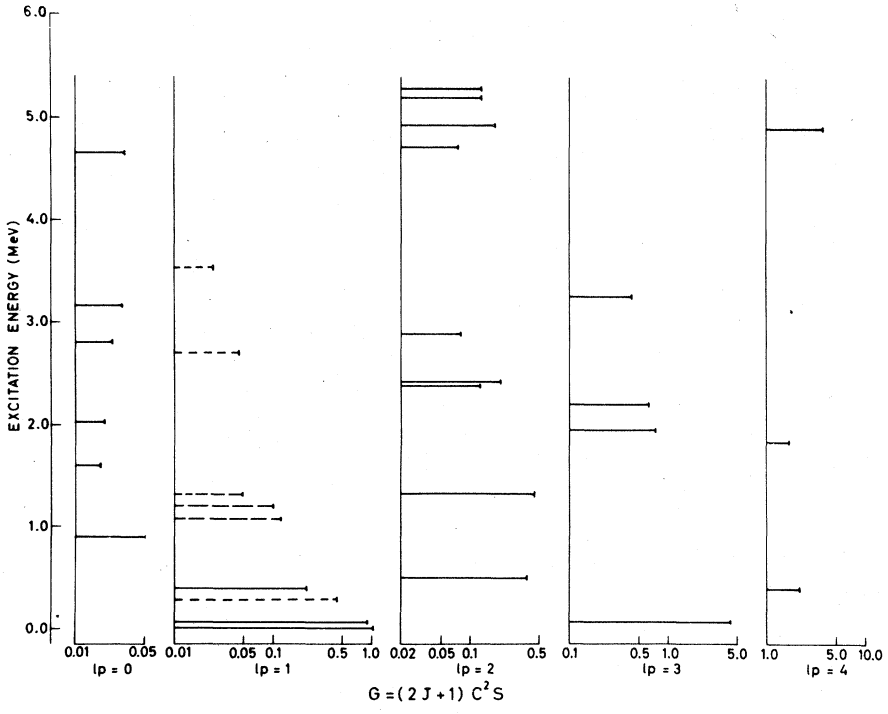

FIG. 8. Distribution of spectroscopic strengths (indicated by horizontal lines) arranged according to the different l_p values. For $l_p=1,2$ $P_{1/2}$ levels are denoted by dashed lines.

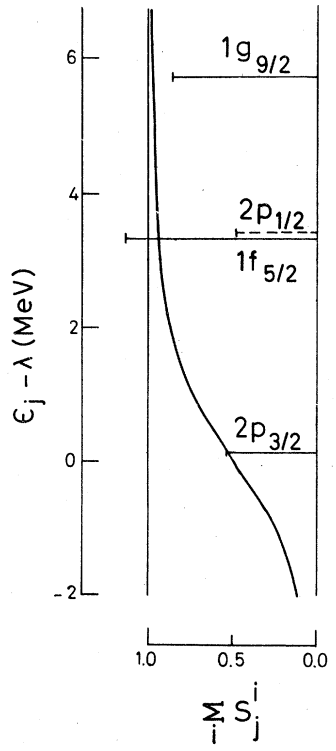

FIG. 9. Comparison of the experimental values of summed spectroscopic factors (horizontal lines) with the predictions of the pairing theory (solid curve), calculated with $\Delta = 1.74$.

The distribution of the spectroscopic strengths for each l_p value is shown in Fig. 8. For $l_p = 0$ the observed components have all small strengths. In the case of $l_p = 1$ it is possible that the contaminant peaks have obscured some of these levels leading to a small spectroscopic factor for the $2p_{1/2}$ single-particle level (see Fig. 9). A number of $l_p = 2$ levels beyond 4.6 MeV have appreciable spectroscopic strengths, and it is interesting to note that the 4.9-MeV state contains a high concentration of the $1g_{9/2}$ strength.

Table IV lists the energy centroids and the summed spectroscopic strengths for the single-particle states. The centroids $\bar{E}_j$ are computed using the experimental spectroscopic factors S_j as weighting factors, i.e.,

$$\bar{E}_j = \sum_i E_j^i S_j^i \Big/ \sum_i S_j^i .$$

TABLE IV. Centroids and summed spectroscopic strengths for the corresponding single-particle states.

l_j	$\bar{E}_j$ (MeV)	$G = (2J+1)\,C^2S$	S
$s_{1/2}$	...	0.17	0.10
$p_{1/2}$	0.740	0.86	0.48
$p_{3/2}$	0.074	1.90	0.53
$d_{5/2}$	...	1.48	0.28
$f_{5/2}$	0.767	6.11	1.14
$g_{9/2}$	2.969	7.63	0.86

The experimental spectroscopic factors are summed over all levels belonging to the same shell-model state j, to get the summed spectroscopic factor. The centroids for the $3s_{1/2}$ and $3d_{5/2}$ states are not computed since only a small fraction of their total spectroscopic strengths is seen in the present experiment; the low values of their summed strengths in Table IV suggest that considerable strengths for these states lie at excitation energies above 5.3 MeV. The experimental summed spectroscopic strengths for the $1f_{5/2}$ states suggest complete emptiness of this orbit.

Figure 9 shows a comparison of the summed spectroscopic factors (horizontal lines) with the predictions of the pairing theory (curved line). The $2p_{3/2}$ centroid energy has been normalized to the theoretical value. The large $1g_{9/2}$ spectroscopic strength observed for the 4.9-MeV level has improved the quality of agreement with the calculated value. The $2p_{1/2}$ state is indicated by a dashed line; since an appreciable portion of its strength is not seen in the present investigation, the summed spectroscopic factor for this state is expected to be smaller than that predicted by the pairing theory.

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