States of ^{35}Cl via the ^{32}S(α,p)^{35}Cl Reaction*

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Protons from the ^{32}S(α,p)^{35}Cl reaction were analyzed with broad-range magnetic spectrographs. Data were taken at nominal bombarding energies of 20.0 and 20.28 MeV and at observation angles ranging from 15 to 120°. 102 levels have been identified in ^{35}Cl in the region of excitation from the ground state to 10.8 MeV. Uncertainties in excitation energies above 3.2 MeV have been reduced by as much as a factor of 5 from previous work and 57 previously unreported levels were observed.

I. INTRODUCTION

Recent theoretical calculations[1-3] of the nuclear structure of ^{35}Cl have stimulated renewed interest in its energy spectrum. The energy level structure of ^{35}Cl has been studied by a variety of reactions, each generally over narrow regions of excitation. Early investigations of the ground state to 4-MeV excitation regions were made with the ^{35}Cl(p, p') and ^{32}S(α, p) reactions[4] with excitation energies being measured to about 5 keV. Recent measurements of the low-lying states of ^{35}Cl by the ^{35}Cl(p, $p'\gamma$) reaction[5] have reduced uncertainties in the excitation energies to the 0.1-keV range; however, measurements extend only to 3.163 MeV. The ^{34}S(^{3}He, d) and the ^{32}S(α, $p\gamma$) reactions[6,7] have been used to investigate excitations up to 6 MeV. But between 4 and 6 MeV many states seen in one reaction are not seen in the other and the uncertainties in the excitation energies are of the order of 10 to 25 keV. The region between 7 and 9 MeV has been investigated via ^{34}S(p, γ) resonance studies[4] with uncertainties in the proton energy of ~1 keV, while the region above 9 MeV has been investigated via resonances in the ^{31}P(α, p_0)^{34}S reaction, where the uncertainty in the α-particle energy ranges from 3 to 10 keV. No previous investigation has been undertaken to study the entire excitation region from the ground state to the highest measured state ~10 MeV with a single reaction. It is the purpose of the present work to investigate levels in ^{35}Cl via the ^{32}S(α, p)-^{35}Cl reaction over this entire region of excitation. New levels in the previously uninvestigated region between 6 and 7 MeV are presented and a comparison of the remaining known levels with our study is given in Table I.

II. EXPERIMENTAL PROCEDURE

Natural sulfur targets were prepared by vacuum evaporation of CdS onto 20-μg/cm^2 carbon foil backings. The natural abundance of ^{32}S is about 95% with there being traces of ^{33}S, ^{36}S, and 4.22% of ^{34}S. Because of possible contaminant groups from ^{34}S and from the Cd isotopes as well as from carbon and oxygen, several runs were made at different bombarding energies and observation angles to allow identification of the ^{35}Cl proton groups. α particle beams were produced with the University of Notre Dame FN tandem Van de Graaff accelerator with the nominal energy of the incident α-particle beam being determined by magnetic analysis. During the course of the experiment, data were taken with two magnetic spectrographs. Nuclear track plates mounted at the focal surface of each spectrograph were employed as particle detectors.

Five runs were made using the University of Notre Dame 50-cm broad-range magnetic spectrograph. These data were taken at 15, 30, and 70° at a bombarding energy of 20.284 MeV and at 15 and 30° at 20.025 MeV. Mylar foils placed over the plates made proton track identification certain. Figure 1 shows a spectrum at 15° and 20.284 MeV. One of the most prominent features of the spectrum is the hydrogen recoil group; however, by 70° this group is no longer in the region of interest. Two additional runs at 90 and 120° at a bombarding energy of 19.991 MeV were made using a new magnetic spectrograph constructed at the University of Notre Dame.[8] For a particle deflection of 90° (ρ_0) the radius of the exit pole face is 100 cm. The spectrograph has a large energy range of E_{max} / E_{min} of 3.7 and the distance scale along the ten nuclear track plates extends from 0 to 265 cm. A spectrum at 120° and bombarding energy of 19.991 MeV is shown in Fig. 2. The ground-state group at 237.70 cm and the first few states are not shown. The high dispersion of the new spectrograph greatly aids in analysis of the data as a comparison of Fig. 1 and Fig. 2 would suggest.

III. ANALYSIS

Separation energies were measured with respect to the ground state in five of the seven runs. Because a reliable magnet cycling procedure had not

TABLE I. Levels in ^{35}Cl. A dagger indicates a possible doublet; a double dagger indicates a possible triplet.

Group number	Number of runs	Excitation energy (MeV ± keV)	σ_m (keV)	Endt and Van der Leun [a] (MeV ± keV)	^{35}Cl$(p, p'\gamma)$ [b] (MeV ± keV)	^{34}S$(^3$He$, d)$ [c] (MeV ± keV)	^{32}S$(\alpha, p\gamma)$ [d] (MeV ± keV)
0	5	0		0	0	0	
1	3(5)	1.2174 ± 2.6	0.5	1.220 ± 3	1.2194 ± 0.1	1.220 ± 10	
2	4(5)	1.7601 ± 2.4	0.8	1.762 ± 3	1.7632 ± 0.1	1.758 ± 10	
3	5	2.6449 ± 2.3	1.9	2.645 ± 5	2.6457 ± 0.2	2.645 ± 10	
4	1(4)	(2.693)		2.695 ± 5	2.6935 ± 0.1	2.686 ± 10	
5	3	3.0015 ± 3.1	2.0	3.006 ± 5	3.0025 ± 0.5	2.997 ± 10	
6	5	3.1582 ± 2.5	1.4	3.163 ± 5	3.1626 ± 0.1	3.156 ± 10	3.163 (cal)
						3.908 ± 10	
7	7	3.9437 ± 2.3	1.7			3.956 ± 10	3.945 ± 10
8	5	4.0569 ± 2.7	0.6	4.058 ± 5		4.048 ± 10	4.045 ± 10
9	7	4.1102 ± 2.9	1.1	4.113 ± 5			4.110 ± 10
10	7	4.1775 ± 2.4	1.3	4.175 ± 5		4.165 ± 10	4.175 ± 10
11	7	4.3466 ± 2.4	0.7				4.345 ± 15
12	4	4.6244 ± 3.1	1.2				4.620 ± 15
13	7	4.7708 ± 2.6	0.6				4.77 ± 15
14	5	4.8831 ± 2.9	0.8				4.885 ± 20
				5.030 ± 50		5.010 ± 15	5.015 ± 20
15	4	5.1617 ± 3.3	2.9			5.163 ± 15	5.175 ± 20
16	3	5.2066 ± 3.7	0.8	5.220 ± 40			5.230 ± 20
17	6	5.4020 ± 2.9	1.2			5.407 ± 15	5.415 ± 20
							5.535 ± 20
	2(3)	(5.576)					
18†	5	5.5918 ± 3.2	1.3				5.60 ± 20
19	5	5.6331 ± 3.2	1.2				5.65 ± 20
						5.660 ± 15 ($T = \frac{3}{2}$)	
20	4	5.6777 ± 3.4	3.0			5.684 ± 15	
						5.760 ± 15	
21†	4	5.8092 ± 3.4	2.9				5.85 ± 25
	(4)	(5.823)					5.93 ± 25
22	4	5.9274 ± 3.5	0.9				
23	7	6.0842 ± 2.9	1.6				
24	3(4)	6.1402 ± 4.0	0.8				
25	4	6.2249 ± 3.6	1.0				
26	5(6)	6.3790 ± 3.4	0.7				
27	3(4)	6.4024 ± 4.1	2.0				6.40 ± 25
	2(3)	(6.427)					
28	5	6.4919 ± 3.4	1.1				
29	7	6.6560 ± 3.1	1.1				
30	7	6.6808 ± 3.1	1.9				
31	7	6.7828 ± 3.2	1.3				
32	3(4)	6.8021 ± 4.2	3.6				
	2(3)	(6.867)					
33†	7	6.8935 ± 3.2	0.6				
34	6	6.9475 ± 3.4	1.4				
				^{34}S$(p, \gamma)^{35}$Cl			
35	6	6.9857 ± 3.4	1.4				
				7.065			
	2(3)	(7.105)		7.104			
36†	6	7.1208 ± 3.4	2.3				
37	3(4)	7.1790 ± 4.3	1.4	7.179			
				7.194			
38	4(5)	7.2101 ± 3.9	1.0				
				7.226			
39	6	7.2295 ± 3.4	1.7	7.234			
				7.271			
	2(4)	(7.301)					

TABLE I *(Continued)*

Group number	Number of runs	Excitation energy (MeV ± keV)	σ_m (keV)	Endt and Van der Leun [a] (MeV ± keV)	^{35}Cl$(p, p'\gamma)$ [b] (MeV ± keV)	^{34}S$(^3$He$, d)$ [c] (MeV ± keV)	^{32}S$(\alpha, p\gamma)$ [d] (MeV ± keV)
40	3	7.3483 ± 4.4	0.6				
				7.360			
				7.397			
41	3	7.4175 ± 4.4	0.8				
				7.451			
42	5	7.5030 ± 3.7	2.2	7.504			
				7.518			
				7.538			
				7.549 ($T = \frac{3}{2}$)			
43	6	7.5676 ± 3.5	1.4	7.561			
44	4(6)	7.5872 ± 4.0	0.7				
				7.601			
				7.619			
45†	4	7.6501 ± 4.0	1.1	7.657			
	2(4)	(7.671)		7.673			
				7.685			
				7.707			
	2	(7.730)					
46†	5	7.7427 ± 3.8	1.2	7.747			
47	3	7.7763 ± 4.5	0.7	7.779			
				7.783			
48	7	7.8008 ± 3.5	0.8	7.799			
				7.837 ($T = \frac{3}{2}$)			
49	7	7.8685 ± 3.5	1.0	7.873			
				7.884			
50	5	7.9006 ± 3.8	1.5	7.903			
				7.929			
51	7	7.9786 ± 3.5	0.8				
52	4	8.0007 ± 4.1	1.6				
53	7	8.0192 ± 3.5	1.7				
				8.049			
54	3	8.0751 ± 4.6	1.4	8.073			
				8.087			
55†	4(5)	8.1038 ± 4.2	1.7	8.103			
	2	(8.121)		8.106			
				8.142			
56	4	8.1717 ± 4.2	3.2	8.171			
				8.180			
				8.197			
57	3	8.2102 ± 4.6	2.5	8.210			
58	4	8.2460 ± 4.2	1.6	8.250			
				8.259			
59†	4	8.2706 ± 4.2	0.6				
	2(3)	(8.292)					
				8.312			
60	6	8.3210 ± 3.8	1.6	8.320			
61	6	8.3988 ± 3.8	1.2				
				8.416			
62	5	8.4292 ± 4.0	1.4				
63	6	8.4823 ± 3.8	1.3				
64	3	8.5051 ± 4.7	1.3	8.491			
65	4	8.5324 ± 4.3	1.1				
66	7	8.5679 ± 3.7	0.8				
67	7	8.6169 ± 3.7	1.5				
				8.630			
68	5	8.6541 ± 4.1	1.3				
	2(3)	(8.698)					
69†	7	8.7209 ± 3.7	1.4				

TABLE I *(Continued)*

Group number	Number of runs	Excitation energy (MeV ± keV)	σ_m (keV)	Endt and Van der Leun[a] (MeV ± keV)	^{35}Cl$(p,p'\gamma)$[b] (MeV ± keV)	^{34}S$(^3$He$, d)$[c] (MeV ± keV)	^{32}S$(\alpha,p\gamma)$[d] (MeV ± keV)
70	7	8.7863 ± 3.8	1.2				
71	7	8.8403 ± 3.8	0.9				
72	5	8.8875 ± 4.1	2.5				
73	4	8.9575 ± 4.4	1.5	8.962			
74	6	8.9969 ± 4.0	1.7				
75	7	9.0274 ± 3.8	0.8				
				^{31}P$(\alpha,p_0)^{34}$S			
76	7	9.0857 ± 3.8	0.6				
77	3(5)	9.1093 ± 4.9	1.4				
				9.131			
78	5	9.1600 ± 4.2	1.2	9.165			
79	7	9.1940 ± 3.9	1.0				
80	7	9.2649 ± 3.9	1.7	9.261			
81	7	9.3162 ± 3.9	1.9				
82	4	9.3340 ± 4.6	3.0				
83	6	9.3760 ± 4.1	1.9				
				9.404			
				9.461			
84[e]	5	9.4755 ± 4.3	0.6	9.485			
85†	6	9.5081 ± 4.1	2.5				
		(9.525)					
				9.555			
				9.678			
86	5	9.7118 ± 4.4	0.8	9.717			
87	7	9.7404 ± 4.0	1.0				
				9.755			
88	4	9.7992 ± 4.7	1.9				
				9.818			
89	5	9.8361 ± 4.4	1.3				
	1(4)	(9.870)		9.875			
				9.905			
				9.926			
90††	3	9.9686 ± 5.2	1.9				
	2	(9.992)					
	2	(10.009)					
91††	4	10.0752 ± 4.8	0.5				
	1(3)	(10.098)					
	1(2)	(10.117)					
92	3	10.1627 ± 5.3	1.4				
93	3	10.1791 ± 5.3	2.7				
94	5	10.2180 ± 4.6	1.6				
95	3	10.3952 ± 5.4	3.1				
	2	(10.443)					
96†	4	10.4632 ± 4.9	3.0				
97	3	10.5171 ± 5.4	2.1				
98	3(4)	10.5483 ± 5.4	1.1				
99	3	10.5795 ± 5.4	0.6				
100	4	10.6430 ± 5.0	2.4				
	2(3)	(10.717)					
101†	4	10.7321 ± 5.0	1.9				
102	3	10.7591 ± 5.5	0.8				

[a] Reference 4.
[b] Reference 5.
[c] Reference 6.
[d] Reference 7.
[e] Calibration state for new spectrograph runs (see text).

been developed for the new spectrograph at the time the two runs at 90 and 120° were taken, it was necessary to analyze these data somewhat differently than the 50-cm spectrograph data. Analysis of the 50-cm spectrograph data is discussed in Sec. A. and the new spectrograph data is discussed in Sec. B.

A. 50-cm Spectrograph

Since the range of the 50-cm spectrograph did not allow the simultaneous measurement of the ground state and states up to 11 MeV, for two of the five runs, separation energies were measured with respect to the 4.0574 ± 0.0033-MeV state. The excitation energy is our value obtained from an average of the other three (α, p) runs which included the ground state. The bombarding energies for the (α, p) runs were calculated from the position of the ground state using the Q value calculated from the 1971 Mass Tables,[9] or from the position of the 4.0574-MeV state. The separation energies measured from the ground state or the 4.0574-MeV state are quite insensitive to the input energy, and the resulting excitation energies depend mainly on the measured energy differences of the proton

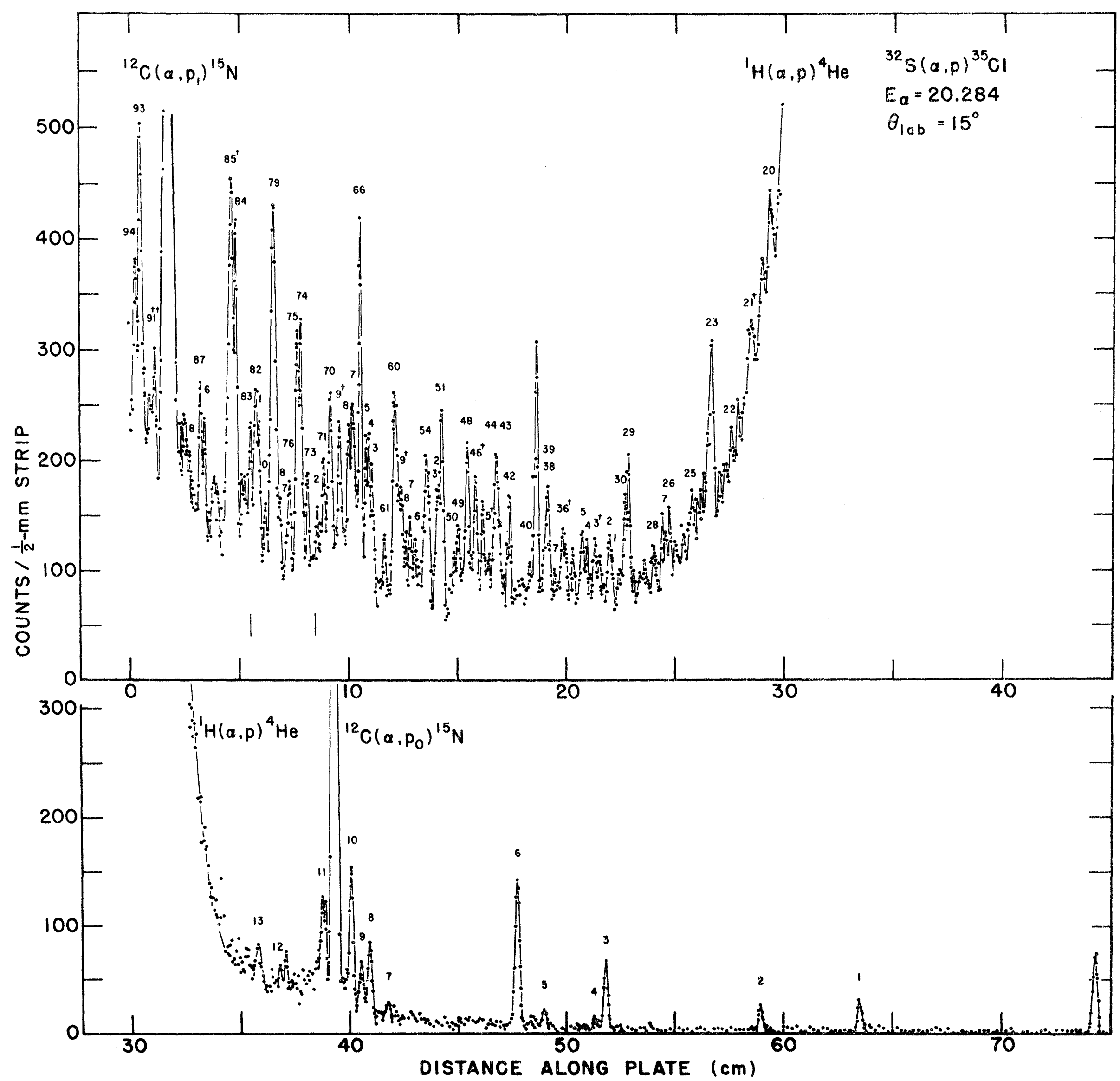

FIG. 1. Proton spectrum from the ^{32}S(α, p)^{35}Cl reaction obtained with the 50-cm broad-range magnetic spectrograph. The numbers above the groups refer to levels in ^{35}Cl. (See Table I.)

groups and the excitation energy assumed for the reference state.

B. New Spectrograph

The magnetic field of the new spectrograph is measured with a single NMR probe. Unless the magnet is cycled, the field measured by the NMR probe has subsequently been shown to be slightly different from the effective field of the magnet because of differential hysteresis. The maximum difference is of the order of 0.1%. Since the magnet was not cycled, a two-point calibration was used to determine both the magnetic field and the input energy. The two states used for this purpose were the ground state and 9.4755-MeV state. The 9.4755-MeV level was chosen since it is strongly populated in all seven runs and is widely separated from the ground state. The excitation energy of 9.4755 ± 0.0043 MeV is our value obtained from an average of the five 50-cm spectrograph runs. Having determined the field and the input energy, separation energies were measured with respect to the ground state. The validity of the two-point calibration can be judged by the small standard deviation of the mean of the excitation energies obtained from an average of both the 50-cm and new spectrograph runs. The standard deviations of the

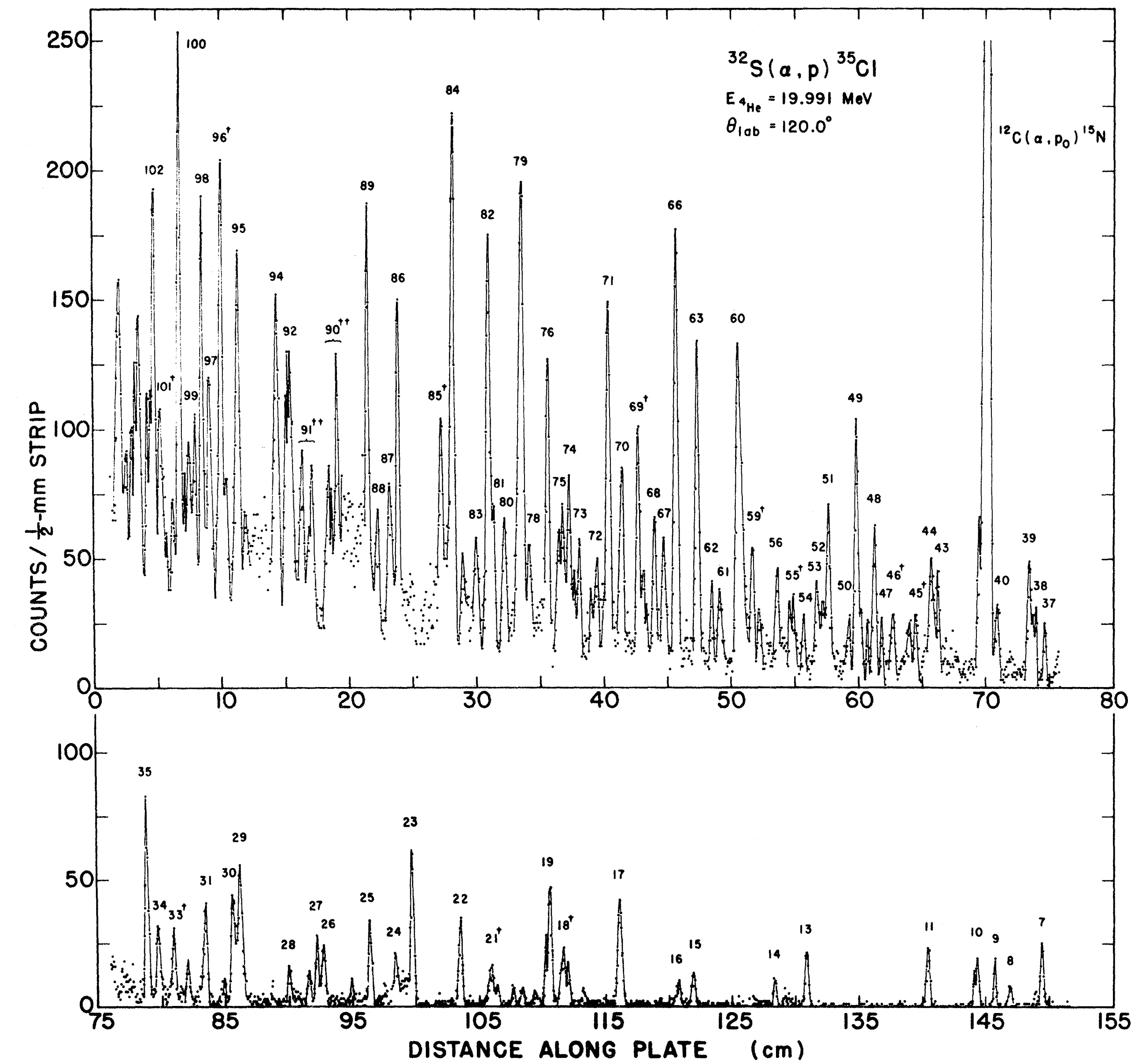

FIG. 2. Proton spectrum from the $^{32}S(\alpha,p)^{35}Cl$ reaction obtained with the new broad-range magnetic spectrograph. The ground state and first few states are not shown. The numbers above the groups refer to levels in ^{35}Cl. (See Table I.)

mean are given in Table I.

An additional comment should be made concerning the 4.0574-MeV state. When the values of the excitation energy for this state measured with the new spectrograph are included with the three 50-cm spectrograph runs, the average is changed by 0.5 keV. (See Table I.) Because separation energies were measured from this state in two of the 50-cm spectrograph runs, the excitation energy of the 9.4755-MeV state would be decreased by 0.16 keV if this new excitation energy were used. The value of 9.4755 MeV was used however since the position of this group cannot be measured to closer than 0.6 keV with the new spectrograph.

IV. RESULTS AND DISCUSSION

The results of the present work are given in Table I. Each level has been assigned a number, and these numbers appear above the respective proton groups in Fig. 1 and Fig. 2. The number of values used in the average to obtain the excitation energy is given in the second column of the table. The accompanying number in parentheses indicates the number of times a group was observed but for which it was not possible to obtain accurate excitation energies. Unless three values have been used in the average, the group is considered as only a possible level in ^{35}Cl and no group number has been assigned. The only exception is group number 4 which is a well-known level in ^{35}Cl. The excitation energies of these groups are given in parentheses and no uncertainty is quoted. The group numbers with a dagger indicate possible doublets, and group numbers with double daggers indicate possible triplets. The standard deviation of the mean in keV for each level is given in column 5 and the uncertainties given in column 4 for our excitation energies are the internal errors calculated according to standard procedures described in Ref. 10. These include estimates of uncertainties in the following quantities: the position of a group on the plate, beam spot position, reaction angle, input energy, spectrograph field, and spectrograph calibration curve.

A comparison with other work is given in the remaining columns of the table. Agreement within the quoted uncertainties is in general, quite good in the region of excitation from the ground state to 6 MeV. We observed most of the levels previously reported in this region with one noticeable exception being the 5.01-MeV state which was observed both in the ^{34}S(^{3}He, d) reaction by Graue *et al.*[6] and the ^{32}S(α, $p\gamma$) reaction by Hooton *et al.*[7] The ^{32}S(α, p) reaction should not populate $T=\frac{3}{2}$ states and the states which have been identified as $T=\frac{3}{2}$ in other work are indicated in the table. The two $T=\frac{3}{2}$ assignments of 7.549 and 7.837 MeV, included with the compilation values of Endt and Van der Leun,[4] are discussed by Wiesehahn.[11] In the 6- to 7-MeV region of excitation no comparison is possible as these states have not previously been reported.

A comparison with the ^{34}S(p, γ) and ^{31}P(α, p_0) resonance data is made difficult because of the large number of levels involved. For purposes of comparison, if the excitation energies are within 10 keV they have been placed on the same line in the table. Though many more levels were observed in the ^{34}S(p, γ) resonance studies in the 7- to 8.3-MeV region of excitation than we observed with the ^{32}S(α, p) reaction, agreement in excitation energies is quite good. Above 8.3 MeV, however, we observe many more levels than previously reported in either the ^{34}S(p, γ) or ^{31}P(α, p_0) resonance studies. Because only a few states seen in the ^{31}P(α, p_0) resonance studies match with states in our work, a meaningful comparison is difficult.

V. SUMMARY

By using the ^{32}S(α, p) reaction, we have identified 102 states in ^{35}Cl in the region of excitation from the ground state to 10.8 MeV. Our work overlaps many other types of reactions and agreement where comparisons can be made is quite good. 57 previously unreported levels have been presented which includes the uninvestigated region of excitation between 6 and 7 MeV as well as new states above 8.3 MeV.

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