Reaction $S^{36}(p,\gamma)Cl^{37}$ and Properties of Cl^{37}

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(Received 15 November 1967; revised manuscript received 6 February 1968)

The $S^{36}(p,\gamma)Cl^{37}$ reaction has been studied in the range $E_p=800$–1940 keV in order to determine properties of excited states of Cl^{37}. Over 80 narrow resonances due to this reaction were identified and located in proton energy with an accuracy of ±3 keV. The observed resonance strengths $(2J_r+1)\Gamma_\gamma\Gamma_p/\Gamma$ vary between 0.1 and 6.3 eV, with the exception of the outstanding resonance at 1887 ± 2 keV, which has a strength of 130 ± 20 eV. The general behavior of the average resonance strength as a function of proton energy is in agreement with predictions based upon well-known approximate relationships between the level density and the radiative and proton widths Γ_γ and Γ_p. Detailed studies of the γ-ray decay schemes of resonances at $E_p=940$, 969 (doublet), 983, 1079, and 1120 keV with large NaI(Tl) and Ge(Li) detectors provide evidence for previously unreported levels in Cl^{37} at $E_x=3.62$, 3.74, and (4.4) MeV. All of the new bound levels decay to the ground state. No evidence was found for a possible level in Cl^{37} near 0.8 MeV. Spin assignments for each of the resonances listed above were derived from γ-ray angular-correlation measurements. The 1887-keV resonance ($E_x=10.22$ MeV) decays predominantly to the 3.105-MeV level. The resonance and 3.105-MeV levels are each shown to have $J^\pi=\frac{7}{2}^-$ and to exhibit other expected properties of the $T=\frac{5}{2}$ and $T=\frac{3}{2}$ members of the $1f_{7/2}$ single-nucleon configuration. The resonance is identified as the analog of the S^{37} ground state. The $3.105(\frac{7}{2}^-)\rightarrow(\frac{3}{2}^+)$ transition is mixed $E3$-$M2$ with $\delta=-0.18\pm0.01$. The resonance$\rightarrow$ 3.105 transition is pure $M1$ with an observed strength of 1.7 ± 0.3 Weisskopf units, in excellent agreement with a calculated value of 1.6 Weisskopf units for a $(1f_{7/2},\ T=\frac{5}{2})\rightarrow(1f_{7/2},\ T=\frac{3}{2})$ transition. A $S^{36}(p,\gamma)Cl^{37}$ reaction Q value of 8.382 ± 0.008 MeV was determined from Ge(Li) spectra.

I. INTRODUCTION

RECENT interest in the properties of $2s_{1/2}$-$1d_{3/2}$ subshell nuclei prompted this study of the nucleus Cl^{37} by means of the radiative proton-capture reaction $S^{36}(p,\gamma)Cl^{37}$. Previous investigations of Cl^{37} include a study of the $Cl^{37}(p,p')Cl^{37}$ reaction by Endt *et al.*,[1] who observed levels at (0.838), 1.728, 3.087, and 3.105 MeV. Using the same reaction, Schiffer *et al.*[2] had reported the level at 1.7 MeV. Wirjoamidjojo and Kern[3] recently reinvestigated the β decay of S^{37} to Cl^{37}. Prior work with the $S^{37}(\beta^-)Cl^{37}$ decay scheme had been done by Bleuler and Zünti[4] and later by Morinaga and Bleuler,[5] who observed β^- transitions to $Cl^{37}(0)$ and $Cl^{37}(3.1)$. Wirjoamidjojo and Kern observed, in addition, a weak transition to a level at 3.73 MeV in Cl^{37}. The existence of a level at 3.71 ± 0.02 MeV was later confirmed by Nichols, Kern, and McEllistrem[6] by means of the $Cl^{37}(n,n'\gamma)Cl^{37}$ reaction. The $S^{36}(p,\gamma)Cl^{37}$ reaction has received little attention prior to the present work, primarily because of the very low (0.014%) natural isotopic abundance of S^{36}. Koval' *et al.*[7] have studied this reaction with small NaI(Tl) detectors and proton energies in the 1.4–2.1 MeV region. Koval' *et al.*[8] later extended the study to $E_p=3.2$ MeV. The $S^{36}(p,\gamma)Cl^{37}$ reaction also has been observed by van der Leun.[9]

In Sec. II, the $S^{36}(p,\gamma)Cl^{37}$ reaction in the energy region $E_p=800$–1800 keV is discussed. γ-ray singles and coincidence spectra and angular-correlation data were obtained, with large NaI(Tl) detectors and a Ge(Li) detector, at several resonances in this energy region. Resonance spins and decay schemes are derived. In Sec. III are presented the results of coincidence excitation-curve measurements in the region $E_p=1640$–1940 keV made in an attempt to locate the $T=\frac{5}{2}$ and $\frac{3}{2}$ members of the $1f_{7/2}$ single-nucleon configuration in Cl^{37}. A strong resonance found at $E_p=1887$ keV is

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[1] P. M. Endt, C. H. Paris, A. Sperduto, and W. W. Buechner, Phys. Rev. **103**, 961 (1956).
[2] J. P. Schiffer, C. R. Gossett, G. C. Philips, and T. E. Young, Phys. Rev. **103**, 134 (1956).
[3] S. Wirjoamidjojo and B. D. Kern, Bull. Am. Phys. Soc. **10**, 245 (1965); and (private communication).
[4] E. Bleuler and W. Zünti, Helv. Phys. Acta **19**, 137 (1946).
[5] G. Morinaga and E. Bleuler, Bull. Am. Phys. Soc. **1**, 30 (1956).
[6] D. B. Nichols, B. D. Kern, and M. T. McEllistrem, Phys. Rev. **151**, 897 (1966).
[7] A. A. Koval', E. G. Kopanets, Yu. S. Korda, L. N. Sukhotin, and S. P. Tsytko, Zh. Eksperim. i Teor. Fiz. Pis'ma v Redaktsiyu **2**, 402 (1965) [English transl.: Soviet Phys.—JETP Letters **2**, 252 (1965)].
[8] A. A. Koval', E. G. Kopanets, Yu. S. Korda, L. N. Sukhotin, and S. P. Tsytko, Izv. Akad. Nauk SSSR, Ser. Fiz. **30**, 1213 (1966); Ukrayin Fiz. Zh. (USSR) **12**, 747 (1967).
[9] C. van der Leun (private communication).

identified as the $(J^\pi,T)=(\frac{7}{2}^-,\frac{5}{2})$ analog of the ground state of S^{37}. The results of γ-ray spectra, angular-correlation, and linear-polarization measurements made at this resonance are presented. The resonance is shown to decay preferentially by γ emission to the $(J^\pi,T)=(\frac{7}{2}^-,\frac{3}{2})$ member of the $1f_{7/2}$ single-nucleon configuration at $E_x=3.105$ MeV. The results are summarized and discussed in Sec. IV.

II. $E_p=800$–1800-keV REGION

A. Excitation Curve

The reaction was initiated by a proton beam from the ARL 2-MeV Van de Graaff accelerator. The hydrogen-ion beam from the accelerator was separated into its two mass components by an analyzing magnet. The proton beam was deflected through beam-defining apertures, a liquid-nitrogen-cooled trap, and into the target chamber. The diatomic beam was deflected into a 25°, 24-in.-radius electrostatic analyzer, the exit slits of which were arranged to provide a signal for the control of the accelerator voltage.

Targets used during the excitation-curve measurements were prepared from a CdS sample (isotopic abundance[10] of S^{36} enriched to 2.4%) by evaporation *in vacuo* onto 0.010-in.-thick tantalum backings. Although a liquid-nitrogen cold finger was placed 15 in. from the target to minimize contaminant buildup, resonances due to proton-induced reactions on C^{12}, C^{13}, N^{15}, F^{19}, and Na^{23} were identified in the yield curve. Target deterioration was monitored by periodic checks of the yield of the $E_p=1214$-keV resonance in the same target due to the $S^{34}(p,\gamma)Cl^{35}$ reaction. Four targets, each approximately 4-keV thick at $E_p=1$ MeV, were used to complete the yield curve. The total time required was 136 h. The electrostatic analyzer on the diatomic-beam drift tube was used to measure the beam energy. The analyzer was calibrated using the reactions $Al^{27}(p,\gamma)Si^{28}$, $E_p=991.9$ keV; $C^{13}(p,\gamma)N^{14}$, $E_p=1746.5$ keV; and $Si^{30}(p,\gamma)P^{31}$, $E_p=619.6$ and 1481 keV.

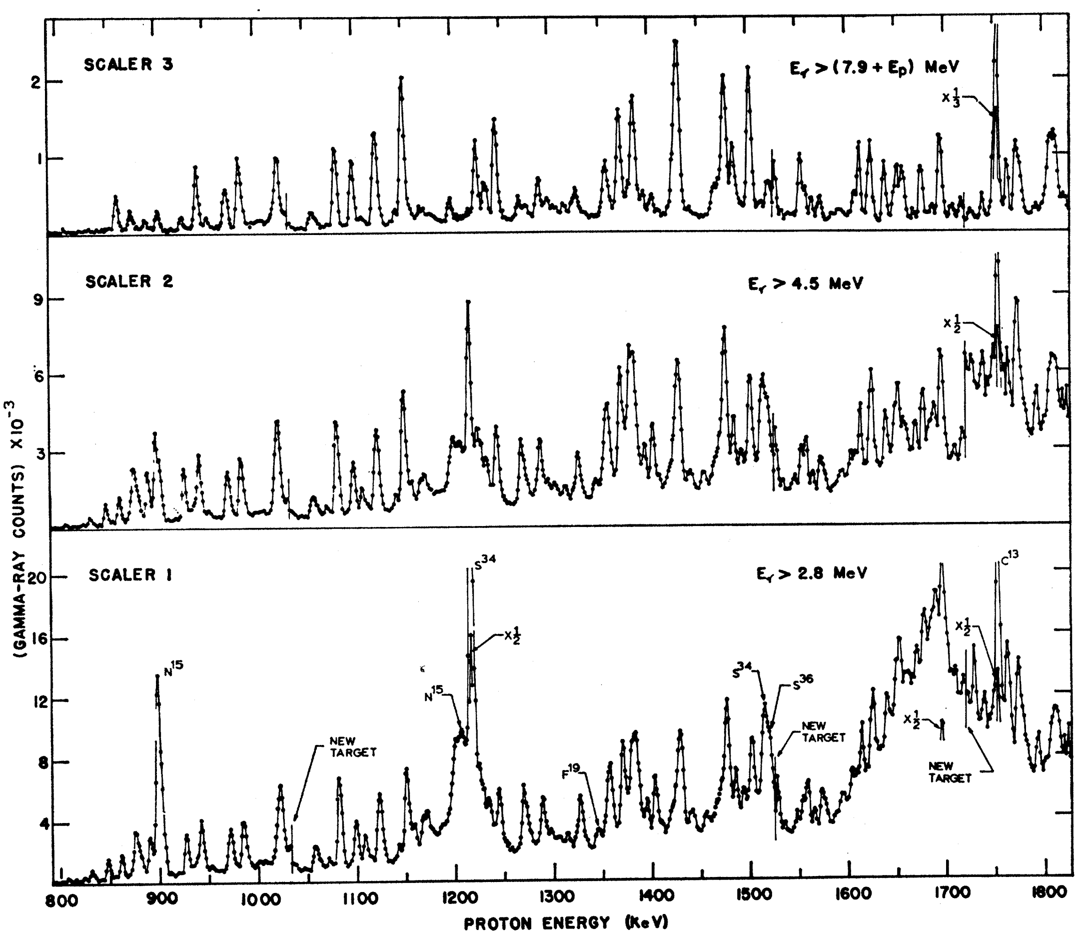

FIG. 1. Resonance excitation curve for the $S^{36}(p,\gamma)Cl^{37}$ reaction in the energy region $E_p=800$–1800 keV. The three scalers registered counts arising from γ rays with energies: (1) $E\geq2.8$ MeV; (2) $E\geq4.5$ MeV; (3) $E\geq(7.9+E_p)$ MeV.

[10] The enriched S^{63} was obtained from ORNL in the form of CdS. Isotopic composition: S^{32}, 91.1%; S^{33}, 1.5%; S^{34}, 5%; S^{36} 2.4%.

The yield of γ rays as a function of proton energy was detected by a lead-shielded 5-in.-diam×5-in.-long NaI(Tl) scintillation crystal located 0.5 in. from the target at an angle of 55° relative to the proton beam. The detector pulses were amplified, shaped, and recorded by three discriminators and scalers. The discriminator channels were set so as to accept pulses corresponding to (1) $E_\gamma \geq 2.8$ MeV, (2) $E_\gamma \geq 4.5$ MeV, and (3) $E_\gamma \geq (7.9+E_p)$ MeV.

The Q values for (p,γ) reactions involving sulfur isotopes are such that only the $S^{36}(p,\gamma)Cl^{37}$ reaction can produce counts in scaler 3. Summing effects in scaler 3 were small because of the low counting rates involved. The yield of γ rays observed with these discriminator settings is shown in Fig. 1 for the region $E_p = 800$–1800 keV. The strong resonances due to N^{15}, S^{34}, F^{19}, and C^{13} are indicated in the figure. The broad "hump" starting at about $E_p = 1600$ keV is probably due to overlapping resonances in F^{19} and C^{12}. Most of the 80 resonances appearing in the plot of counts in scaler 3 are due to the $S^{36}(p,\gamma)Cl^{37}$ reaction. The resonance energies, excitation energies in Cl^{37}, and resonance strengths are given in Table I. The resonance energies were determined with an accuracy of ± 3 keV with the calibration procedures used.

The Cl^{37} excitation energy E_x is based on a reaction Q value of 8.382 ± 0.008 MeV which was determined from the analysis of Ge(Li) spectra (Sec. II B). The error in E_x (± 9 keV) is due mostly to the uncertainty in the Q value.

The resonance strengths $S = (2J_r+1)\Gamma_p\Gamma_\gamma/(\Gamma_p+\Gamma_\gamma)$ were obtained by normalizing the yield of each of the resonances relative to the yield of the $E_p = 1214$ keV resonance in the $S^{34}(p,\gamma)Cl^{35}$ reaction. The strength of this resonance is 21 ± 3 eV.[11] The 5% relative abundance of S^{34} present provided the convenient reference in the same target. The strengths listed for the resonances in the $S^{36}(p,\gamma)Cl^{37}$ reaction are estimated to be individually valid only to within a factor of about 2 because of the high level density and the fact that the decay schemes were not, in general, known. Correction of the yield for target deterioration was found not to be necessary.

The resonance strengths range from 0.1 to 6.3 eV. Because of the low enrichment of S^{36} in the targets, many weak resonances were undoubtedly not observed. At lower proton energies, the threshold for observation was about $S = 0.06$ eV. At higher energies, because of the increased level density, resonances with strengths $S \leq 0.5$ eV may not have been observed.

An excitation curve for the $S^{36}(p,\gamma)Cl^{37}$ reaction in the energy region $E_p = 1400$–2100 keV has been measured by Koval' *et al.*[7] In the interval of overlap, $E_p = 1400$–1800 keV, there appears to be good agreement on resonance energies.

There are several resonances that appear in the excitation curve at the same energies as known resonances in the reactions $S^{33}(p,\gamma)Cl^{34}$ and $S^{34}(p,\gamma)Cl^{35}$.[12–15] In these cases, a resonance was attributed to the $S^{36}(p,\gamma)Cl^{37}$ reaction on the basis of ground-state transitions that gave rise to counts in scaler 3 [$E_\gamma \geq (7.9+E_p)$ MeV].

[11] G. A. P. Engelbertink and P. M. Endt, Nucl. Phys. 88, 12 (1966).

TABLE I. Resonances in the $S^{36}(p,\gamma)Cl^{37}$ reaction. The proton energies, resonance strengths, and excitation energies are given. $S = (2J_r+1)\Gamma_\gamma\Gamma_p/\Gamma$. Uncertain values are enclosed in parentheses.

E_p (keV)	S (eV)	E_x (MeV)	E_p (keV)	S (eV)	E_x (MeV)
805±3	0.11	9.165	1424	5.4	9.768
830	0.22	9.190	1435	(0.88)	9.778
860	0.66	9.219	1449	0.82	9.792
875	(1.7)	9.233	1461	(1.1)	9.804
899	(1.6)	9.257	1471	(6.3)	9.813
940	1.6	9.297	1480	2.1	9.822
950	0.22	9.306	1488	0.82	9.830
969[a]	1.2	9.325	1497	3.8	9.839
983	1.6	9.338	1514	(3.4)	9.855
(1020)	(2.8)	9.374	1522	2.5	9.863
1055	0.7	9.408	1529	0.5	9.870
1079	2.8	9.432	1542	0.93	9.882
1096	1.6	9.448	1548	2.2	9.887
1105	1.3	9.457	1553	(2.5)	9.893
1120	2.7	9.472	1559	0.99	9.899
1140	(0.6)	9.491	1569	(1.6)	9.909
1147	3.7	9.498	1581	0.44	9.920
1154	(0.9)	9.505	1588	0.77	9.927
(1164)	0.88	9.515	1603	(1.2)	9.942
(1167)	0.99	9.517	1608	3.1	9.947
(1172)	0.55	9.522	1619	4.3	9.957
(1186)	0.50	9.536	1633	2.4	9.971
1195	(2.3)	9.545	1643	(2.8)	9.981
1221	(2.8)	9.570	1646	(3.6)	9.984
(1225)	2.2	9.574	1651	(1.9)	9.988
(1230)	1.7	9.579	1653	(1.5)	9.990
1241	2.9	9.589	1662	(1.9)	9.999
(1247)	0.44	9.595	1670	3.2	10.007
1265	2.4	9.613	1691	5.0	10.027
1272	(0.93)	9.620	1711	(1.8)	10.047
1284	(2.2)	9.631	1721	(2.7)	10.056
1293	(0.88)	9.640	1732	2.6	10.067
(1303)	0.70	9.650	1756	(3.5)	10.091
1310	0.60	9.657	1757	(6.0)	10.101
1322	1.7	9.668	1770	(2.8)	10.104
1352	(3.7)	9.697	1803	(4.0)	10.136
1366	5.0	9.711	1806	(3.6)	10.139
1380	(3.6)	9.725	1814	1.9	10.147
1390	2.0	9.734	1817	2.2	10.150
1398	2.9	9.742	1887±2	130±.20	10.218
1404	(0.88)	9.748			

[a] Doublet. S includes both members which are of approximately equal strengths.

B. γ-Ray Spectra

Singles and coincidence spectra were obtained at several resonances, using targets made by evaporation of elemental sulfur (enriched[16] to 3.5% in S^{36}) onto

[12] P. M. Endt and C. van der Leun, Nucl. Phys. 34, 1 (1962).

[13] P. M. Glaudemans, L. Eriksson, and J. A. R. Werkhoven, Nucl. Phys. 55, 559 (1964).

[14] N. Hazewindus, W. Lourens, A. Scheepmaker, and A. H. Wapstra, Physica 29, 681 (1963).

[15] A. K. Hyder, M. S. thesis, U. S. Air Force Institute of Technology, 1964 (unpublished).

[16] This sample of enriched S^{36} was obtained from ORNL in elemental form. Isotopic composition: S^{32}, 90%; S^{33}, 1%; S^{34}, 5.5%; S^{36}, 3.5%.

0.010-in. silver backings.[17] For each of the resonances at $E_p=940$, 969, 983, 1079, and 1120 keV, singles spectra were accumulated using an 8-in.-diam.×8-in.-long NaI(Tl) detector and also with a 2-cc Ge(Li) detector. Coincidence spectra were measured using the 8×8-in. NaI(Tl) detector at +90° and a 5×5-in. NaI(Tl) detector at −90° with respect to the proton-beam direction. Both detectors were placed 1.6 in. from the target. Some measurements were repeated with 15- and 40-cc Ge(Li) detectors which became available after the initial measurements. No substantial changes in earlier conclusions were necessary as a result of these measurements.

Each of the five resonances was examined in order to identify possible doublets. This was done by comparison of NaI(Tl) spectra taken on the high and low sides of each resonance. In this manner, the "resonance" at $E_p=969$ keV was clearly shown to be a doublet. The two spectra were markedly different. The remaining resonances are either single or (more unlikely) are doublets with nearly identical decay properties.

A Ge(Li) spectrum at $E_p=969$ keV obtained with a 3-keV-thick target and approximately 2-keV proton-energy resolution is shown in Fig. 2. Transitions from both the upper and lower members of the doublet are present. Decay schemes derived from the NaI(Tl) and Ge(Li) spectra of the upper (969A) and lower (969B) resonances are given in the insert. The higher-energy resonance decays primarily to the 3.105-MeV level and to the ground state, while the lower resonance decays mostly to the 1.725-MeV level.

The excitation curve of Koval' *et al.*[7] and that of the present work each show a high level density in the region $E_x\approx 9.5$ MeV. The observed γ-ray spectra show evidence for weak transitions to many bound levels in the region above approximately $E_x=4.5$ MeV. The high level density above 4.5 MeV, together with the low isotopic abundance of S^{36}, makes an unambiguous identification of all observed γ-ray lines difficult. In the following, however, those levels are discussed which can be identified by reasonably unambiguous interpretations of the γ-ray spectra.

0.838-MeV Level

A level in Cl^{37} at $E_x=0.838$ MeV had been proposed from the results of $Cl^{37}(p,p')Cl^{37}$ work.[12] The existence of this level has since been questioned by many investigators, including Endt,[18] who originally proposed it. None of the resonances studied in this work showed evidence for transitions to a level near this energy.

1.725-MeV Level

This level was known from the reactions $Cl^{37}(p,p')Cl^{37}$ and $Cl^{37}(n,n'\gamma)Cl^{37}$.[6,12] At most of the resonances studied, transitions to this state from the resonance level were observed. The energy of this level was found to be in good agreement with the recent measurement of 1.725±0.005 MeV by Nichols *et al.*[6]

3.087-3.105-MeV Doublet

This doublet was known from the reaction $Cl^{37}(p,p')Cl^{37}$.[12] Wirjoamidjojo and Kern observed the β decay of S^{37} to the doublet.[19] The level involved was

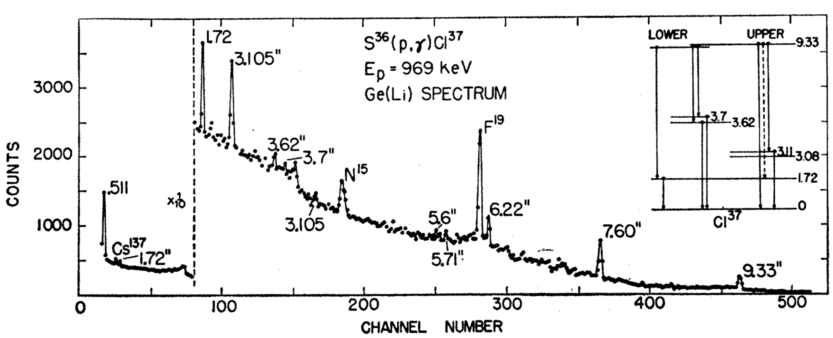

FIG. 2. γ-ray spectrum obtained at the $E_p=969$-keV doublet with a 2-cc Ge(Li) detector. The decay scheme for the two resonances was deduced by comparing spectra taken on the high and low sides of the "resonance" with an 8-in.-diam×8-in.-long NaI(Tl) detector. A measurement of the Q value for the $S^{36}(p,\gamma)Cl^{37}$ reaction was made using a 15-cc Ge(Li) spectrum. Double primes identify double-escape peaks.

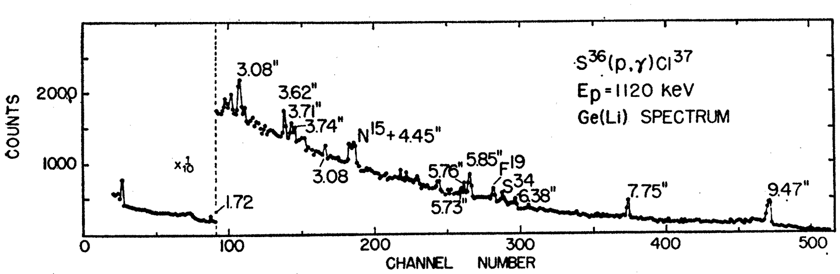

FIG. 3. γ-ray spectrum of the $E_p=1120$ keV resonance in the $S^{36}(p,\gamma)Cl^{37}$ reaction obtained with a 2-cc Ge(Li) detector. The doublet at 3.7 MeV appears in these data.

[17] D. D. Watson, Rev. Sci. Instr. **37**, 1605 (1966).
[18] P. M. Endt (private communication).
[19] S. Wirjoamidjojo and B. D. Kern, Phys. Rev. **163**, 1094 (1967).

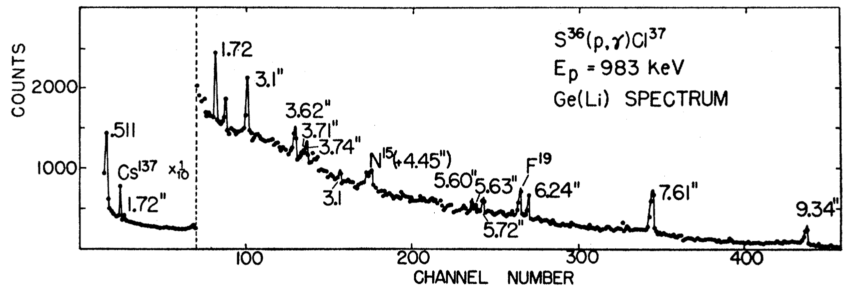

FIG. 4. Spectrum of γ rays observed at the $E_p=983$ keV resonance with a 2-cc Ge(Li) detector. The two peaks at $3.62-2mc^2$ and $5.72-2mc^2$ correspond to the two members of a cascade through the previously unreported level at 3.62 MeV.

determined to be the upper member of the doublet. In the present work both members of the doublet were observed. Figure 2 shows a Ge(Li) spectrum taken at $E_p=969$ keV. The transition ($E_\gamma=6.22$ MeV) from the resonance to the 3.105-MeV member of the doublet can be seen. A $(r\rightarrow 3.087\rightarrow 0)$ cascade is seen in Fig. 3 in a Ge(Li) spectrum taken at the $E_p=1120$ keV resonance. Both members of the doublet were observed to decay only to the ground state.

3.62-MeV Level

At the 1120-keV resonance, and at the $E_p=983$ keV resonance (Fig. 4), the second-escape peak of a 3.62-MeV γ ray is seen. In each case a γ ray with energy corresponding to a $(r\rightarrow 3.62)$ transition is present. The upper half of Fig. 5 shows a spectrum of the 1120-keV resonance taken in coincidence with γ rays in an energy window corresponding to a $(r\rightarrow 3.62)$ transition (5.86 MeV). The 3.62-MeV γ ray is seen to be partially resolved from the 3.7-MeV γ ray. The 3.62-MeV level appears to decay only to the ground state.

3.71-3.74-MeV Doublet

A level in Cl^{37} at 3.73 MeV had been observed[3] in the β decay of S^{37}. Later work using the $Cl^{37}(n,n'\gamma)Cl^{37}$ reaction showed the existence of a level at 3.71 ± 0.02 MeV.[6] Ge(Li) spectra taken at the $E_p=1120$ keV resonance (Fig. 3) and at other resonances show evidence for a possible doublet with members at 3.71 and 3.74 MeV. γ rays with energies corresponding to $(r\rightarrow 3.71)$ and $(r\rightarrow 3.74)$ transitions were observed at several resonances. For example, primary γ rays to both levels are seen at the 983-keV resonance (Fig. 4). There is no evidence that either level decays to levels other than the ground state.

4.45-MeV Level

Ge(Li) singles spectra accumulated at the 1120- and 983-keV resonances (Figs. 3 and 4) and other resonances, show evidence for the existence of a level at 4.45 MeV. The lower half of Fig. 5 shows a spectrum of the 1120-keV resonance taken in coincidence with γ rays in an energy window 4.0–4.5 MeV. A γ ray with energy $E_\gamma=5.0$ MeV is seen in the coincidence spectrum. Measurements at other resonances indicate that the 4.45-MeV γ ray is the secondary in the cascade. There is evidence that this level is a member of a possible doublet at $E_x=4.4$ MeV. The 4.45-MeV level appears to decay entirely to the ground state.

Decay schemes for those resonances which have been studied are presented in Fig. 14. From the analysis of the Ge(Li) spectra taken at the $E_p=969$ keV resonances, a Q value of 8.382 ± 0.008 MeV has been determined for the $S^{36}(p,\gamma)Cl^{37}$ reaction. This value is slightly lower than the previously reported value $Q=8.399\pm0.008$ MeV.[20]

C. Angular Correlations

Angular-correlation measurements were performed at the resonances which occur at $E_p=940$, 969 (A and B), 983, 1079, 1120, and 1887 keV. The resulting resonance spin assignments and multipolarity mixing ratios δ for primary transitions to the levels at $E_x=0$, 1.725, and 3.105 MeV are shown in Table II. The measurements at the 1887-keV resonance are discussed in Sec. III C. The other resonances are discussed in this section. The measurements discussed in this section fall into two subgroups. The first consists of angular-distribution measurements of the $(r\rightarrow 0)$ and $(r\rightarrow 1.725)$ transitions at the $E_p=940$-, 983-, 1079-, and

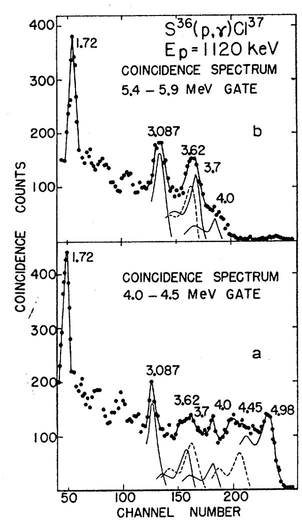

FIG. 5. (a) Spectrum of γ rays observed at the 1120-keV resonance with a 5-in.-diam×5-in.-long NaI(Tl) detector in coincidence with γ rays in an energy window 4.0–4.5 MeV from an 8-in.×8-in. NaI(Tl) detector. (b) Spectrum similar to (a), but in coincidence with γ rays corresponding to the primary transition to the 3.62-MeV level from the 1120-keV resonance.

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

Table II. Results of angular-correlation measurements at resonances in the $S^{36}(p,\gamma)Cl^{37}$ reaction.

E_p (keV)	J_r	$\delta(r\rightarrow 0)$	$\delta(r\rightarrow 1.725)$	$\delta(r\rightarrow 3.105)$
940	$\frac{3}{2}$	$+0.04\pm0.03$ or -5.6 ± 1.1	-0.11 ± 0.06 or $+2.2\pm0.5$	
969 A	$\frac{5}{2}$			-0.09 ± 0.03
969 B	$\frac{3}{2}$	-0.08 ± 0.03 or $+2.1\pm0.2$		
983	$\frac{3}{2}$	$\lvert\delta\rvert\geq10$ or $+0.26\pm0.06$	-0.28 ± 0.06 or $+3.7\pm0.5$	
	$\frac{1}{2}$	$\cdots$	$\cdots$	
1079	$\frac{3}{2}$	0.00 ± 0.06 or -3.8 ± 0.5	-0.37 ± 0.06 or $+6.3_{-1.8}^{+2.7}$	
1120	$\frac{3}{2}$	$+0.05\pm0.06$ or $-5.1_{-1.0}^{+1.2}$	-0.04 ± 0.04 or $+1.9\pm0.3$	
1887	$\frac{7}{2}-$			0.00 ± 0.02

1120-keV resonances. The second subgroup consists of a combined set of angular-distribution and triple-correlation measurements at the $E_p=969$ keV doublet.

The angular distributions were measured with two matched 5-in.-diam.×5-in.-long NaI(Tl) detectors placed 3 in. from the target and at an angle of 90° with respect to each other. Singles spectra were thereby recorded at the four angles 0°, 35.4°, 90°, and 125.2° with respect to the proton-beam direction with only one change in the position of the two detectors. (The 125.2° point is equivalent to a measurement at 54.8° because of the reaction symmetry about a plane perpendicular to the proton beam.) The angular distributions were normalized by means of a fixed monitor detector. Anisotropy corrections, and the relative normalization of the two movable detectors, were determined as a function of detector angle using the known isotropic transition from the resonance at $E_p=620$ keV in the $Si^{30}(p,\gamma)P^{31}$ reaction. A representative set of results, all of which correspond to $(r\rightarrow 1.725)$ transitions, is shown in Fig. 6.

The methods of data analysis used for the angular-correlation measurements have been described elsewhere.[21,22] A computer program based upon the method of Rose[23] was used to calculate the finite-geometry correction factors. The angular distribution of the $(r\rightarrow 1.725)$ transition is most sensitive to the value of the resonance spin, since the 1.725-MeV level is known to have $J=\frac{1}{2}$.[6] For resonance spin $J_r=\frac{1}{2}$, this transition would be isotropic, for $J_r=\frac{3}{2}$ terms higher than $P_2(\cos\theta)$ could not occur, and for $J_r=\frac{5}{2}$ it is very unlikely that a strong $P_4(\cos\theta)$ term would not appear. Resonances with $J_r\geq\frac{7}{2}$ would not be expected to decay to the 1.725-MeV level, although $J_r=\frac{7}{2}$ was considered in the analysis for the sake of completeness. Thus, contrary to the usual situation with an angular-distribution measurement alone, the $(r\rightarrow 1.725)$ transition can be expected in most cases to yield a unique resonance-spin assignment. The results of the χ^2 analysis on this transition at the resonances indicated above are shown in Fig. 7. A unique assignment results for each resonance except the one at $E_p=983$ keV. Here the isotropic angular distribution could result either from a $J_r=\frac{1}{2}$ resonance, or from a $J_r=\frac{3}{2}$ resonance with a special choice for the multipolarity mixing ratio. The solid lines in Fig. 6 are the theoretical angular distributions for the assigned spins and the values of the multipolarity mixing ratios which correspond to the minimum values of χ^2.

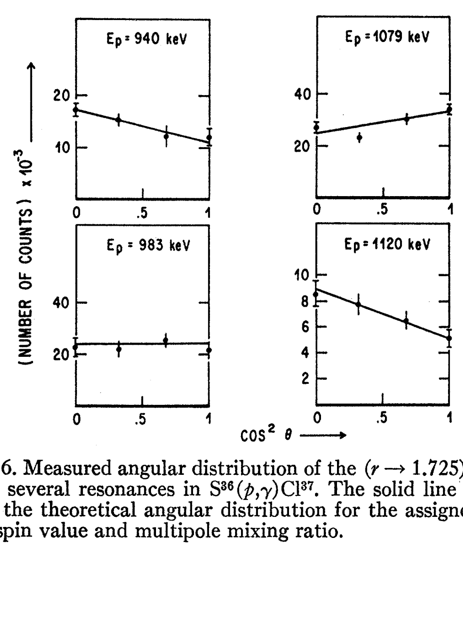

Fig. 6. Measured angular distribution of the $(r\rightarrow 1.725)$ transition at several resonances in $S^{36}(p,\gamma)Cl^{37}$. The solid line in each case is the theoretical angular distribution for the assigned resonance spin value and multipole mixing ratio.

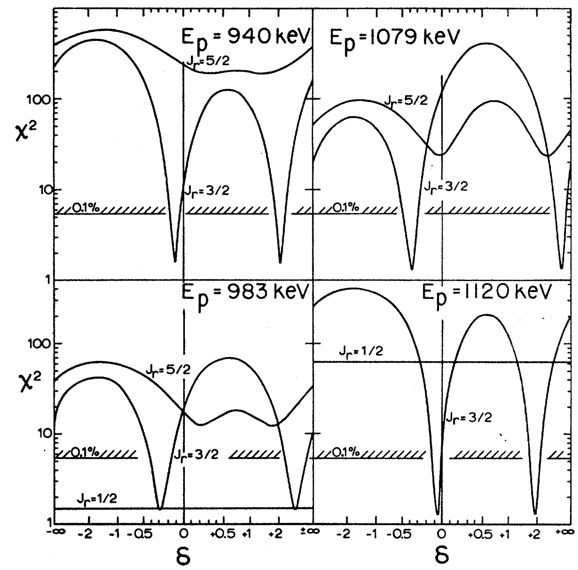

Fig. 7. Results of the χ^2 analysis for $(r\rightarrow 1.725)$ transitions for which the angular-distribution data are shown in Fig. 6. Only the curves for resonance spin values which resulted in the lowest minimum values of χ^2 are shown. The 0.1% "confidence limit" is shown.

Both angular-distribution and triple-correlation mea-

[21] G. I. Harris and D. V. Breitenbecher, Phys. Rev. **145**, 866 (1966).

[22] G. I. Harris, H. J. Hennecke, and D. D. Watson, Phys. Rev. **139**, B1113 (1965).

[23] M. E. Rose, Phys. Rev. **91**, 610 (1953).

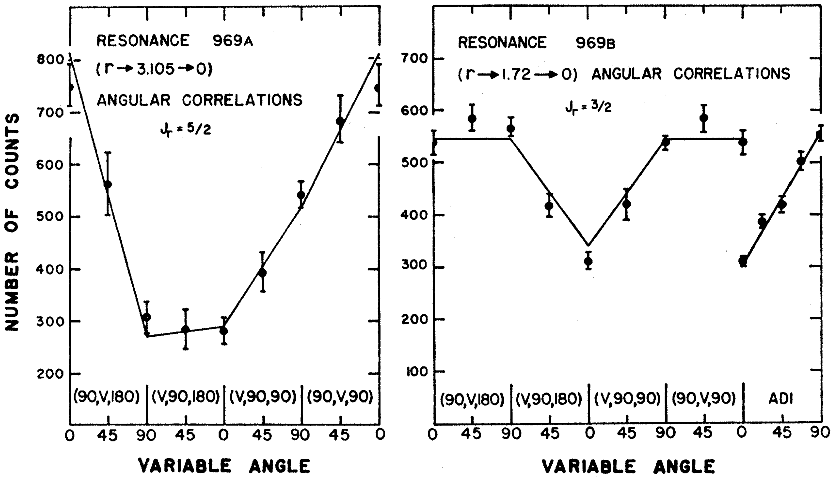

FIG. 8. Comparison of the measured and theoretical angular correlations of the ($r\rightarrow 3.105\rightarrow 0$) and ($r\rightarrow 1.725\rightarrow 0$) transitions at the E_p=969A- and 969B-keV resonances, respectively. The geometry labels are (θ_1,θ_2,ϕ).

surements were performed on the ($r\rightarrow 3.105\rightarrow 0$) and ($r\rightarrow 1.725\rightarrow 0$) cascades at the E_p=969 keV doublet. The basic experimental setup used for the triple-correlation measurements have been discussed elsewhere.[21,22] In the present experiment, however, the 8-in.-diam. ×8-in.-long and 5-in.-diam.×5-in.-long NaI(Tl) detectors used were placed 6.7 and 4.1 in., respectively, from the target. These unusually small target-to-detector distances were necessary because of the low S^{36} abundance of the targets and the consequent low γ-ray yields. Triple correlations were measured in the "geometries" (θ_1,θ_2,ϕ)=(V,90,90), (90,V,90), (V,90,180), and (90,V,180). The results of these measurements are presented in Fig. 8. The fixed and variable angles of the set (θ_1,θ_2,ϕ) are indicated in the figure for each of the triple-correlation geometries.

As discussed in Sec. II B., the ($r\rightarrow 1.725\rightarrow 0$) cascade at this doublet arises from the lower resonance (969B). As seen in Fig. 9, resonance spin $J_r=\frac{3}{2}$ yielded an acceptable fit to the data. No other value of J_r from $\frac{1}{2}$ to $\frac{7}{2}$ yielded a value for χ^2 less than 30. Values of $J_r>\frac{7}{2}$ would be clearly inconsistent with the decay scheme. The upper resonance (969A) was observed to decay both to the ground state ($J=\frac{3}{2}$) and to the $J=\frac{7}{2}$, 3.105-MeV level (see Sec. III). Correlation measurements performed on the ($r\rightarrow 3.105\rightarrow 0$) cascade agree with theoretical correlations for resonance spin $\frac{5}{2}$ or $\frac{9}{2}$. For $J_r=\frac{9}{2}$, the transition to the ground state would be at least octupole. From a measurement of the resonance strength (Table I) and the ($r\rightarrow 0$) branching ratio, the radiative width was determined. The resulting strengths $|M|^2(E3)\simeq 200$ Weisskopf units and $|M|^2(M3)\simeq 3000$ Weisskopf units are considered unreasonably large in comparison with the observed octupole transition rates of other nuclei in this mass region.[24] The spin of the E_p=969B keV resonance is therefore $\frac{5}{2}$.

The resonance spins and the corresponding multipolarity mixing ratios for the ($r\rightarrow 0$), ($r\rightarrow 1.725$), and ($r\rightarrow 3.105$) transitions are presented in Table II for the six resonances studied. The ($3.105\rightarrow 0$) transition is discussed in Sec. III C.

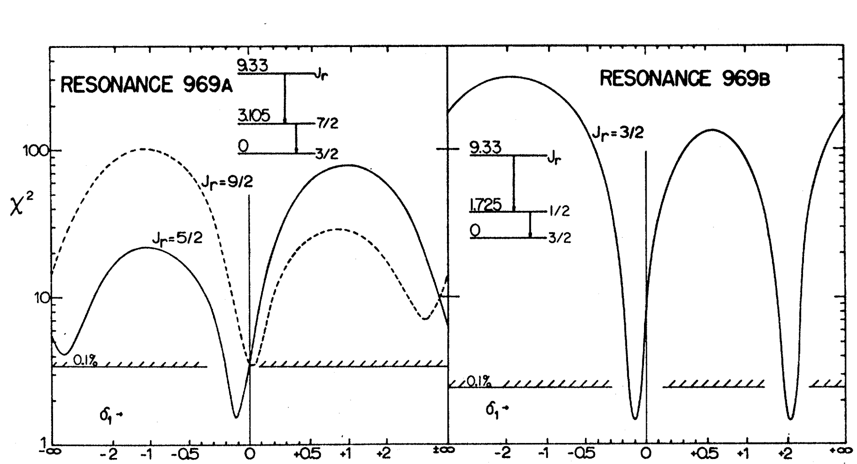

FIG. 9. χ^2 projection curves for the ($r\rightarrow 3.105\rightarrow 0$) (resonance 969A), and ($r\rightarrow 1.725\rightarrow 0$) (resonance 969B) cascades. $J_r=9/2$ is excluded for the 969A resonance because of the large octupole transition rate required for the observed ($r\rightarrow 0$) transition. $J_r=\frac{3}{2}$ is the only value that yielded an acceptable value of χ^2 for the 969B resonance (see text).

[24] S. J. Skorka, J. Hertel, and T. W. Retz-Schmidt, Nucl. Data 2, 347 (1966).

III. $E_p = 1887$ keV ANALOG RESONANCE

A. Introduction

The lowest-lying $T=\frac{5}{2}$ state in $Cl^{37}(T_z=\frac{3}{2})$ is the isobaric analog of the ground state of S^{37}. This state is expected to be a relatively pure $1f_{7/2}$ single-nucleon state, since S^{37} should be describable as a single $1f_{7/2}$ neutron around a S^{36} core in which the $2s_{1/2}$ proton and $1d_{3/2}$ neutron shells are closed. The log ft value for the $S^{37}(\beta^-)Cl^{37}$ ground-state transition, as observed by Wirjoamidjojo and Kern,[3] indicates a unique first-forbidden transition in agreement with the expected $J^\pi=\frac{7}{2}^-$ assignment for the ground state of S^{37}. The excitation energy of the analog state in Cl^{37} is estimated to be about 10.2 MeV on the basis of relative binding energies of S^{37} and Cl^{37}, the Coulomb-energy difference, and the neutron-proton mass difference.

The $1f_{7/2}$ state in Cl^{37} should be split into $T_>=\frac{5}{2}$ and $T_<=\frac{3}{2}$ components widely separated in energy due to isobaric-spin splitting. By methods analogous to those presented by French,[25] the excitation energy of the $T_>$ and $T_<$ states in Cl^{37} can be calculated from the expression

$$-[E(\mathrm{Cl}^{33})-E(\mathrm{S}^{32})]+E_x[\mathrm{Cl}^{33}(f_{7/2})]+E_{\mathrm{int}} = -[E(\mathrm{Cl}^{37})-E(\mathrm{S}^{36})]+E_x[\mathrm{Cl}^{37}(f_{7/2})],$$

where $E(Cl^{33})$, $E(S^{32})$, $E(Cl^{37})$, and $E(S^{36})$ are the binding energies of the respective nuclei; $E_x[Cl^{33}(f_{7/2})]$ and $E_x[Cl^{37}(f_{7/2})]$ are the excitation energies of the $1f_{7/2}$ states in Cl^{33} and Cl^{37}; and E_{int} is the interaction of the $f_{7/2}$ nucleon with the group of four $d_{3/2}$ nucleons. Thus we have

$$E_x[\mathrm{Cl}^{37}(f_{7/2})]=4.06\ \mathrm{MeV}+E_x[\mathrm{Cl}^{33}(f_{7/2})]+E_{\mathrm{int}}.$$

The interaction energy E_{int} follows from the monopole part of the interaction operator

$$H_{\mathrm{int}}=n\bar{E}+(V_1/A)(\mathbf{T}_0\cdot\mathbf{t}),$$

which, in the present case, gives

$$E_{\mathrm{int}}=4\bar{E}+\tfrac{1}{2}(V_1/A)[T(T+1)-T_0(T_0+1)-\tfrac{3}{4}],$$

where $\bar{E}$ is the center of gravity of the $T_>$ and $T_<$ states with a $(2J+1)$ $(2T+1)$ weight; V_1/A is proportional to the splitting between the $T_>$ and $T_<$ centers of gravity; and T_0, t, and T are the isobaric spins of the core, extra nucleon, and the resultant state, respectively. The excitation energy of the $1f_{7/2}$ level in Cl^{33} was not known. However, the $1f_{7/2}$ level in the mirror nucleus S^{33} has been shown to lie at $E_x=2.94$ MeV.[26] By comparison with the slight shift in excitation energies of the $1f_{7/2}$ levels in the mirror nuclei Si^{29} ($E_x=3.62$ MeV) and P^{29} ($E_x=3.47$ MeV), an excitation energy of $E_x=2.8$ MeV was estimated for the $1f_{7/2}$ level in Cl^{33}.

Values for the monopole parameters $\bar{E}$ and V_1/A for the $d_{3/2}$-$f_{7/2}$ interaction were obtained from the ($1f_{7/2}$, $T=\frac{3}{2}$) and ($1f_{7/2}$, $T=\frac{1}{2}$) states in Cl^{35} at $E_x=7.54$ and 3.16 MeV, respectively. The isobaric-spin splitting is given by

$$E_{T>}-E_{T<}=\tfrac{1}{2}(2T_0+1)/(V_1/A).$$

The results for the Cl^{37} analog states were $E_x(T_>)=10.1$ MeV and $E_x(T_<)=3.2$ MeV.

It is expected then that we should find two $\frac{7}{2}^-$ states in Cl^{37} with properties similar to those observed in Cl^{35}, Al^{27}, and P^{31}.[27–29] As has been noted by Endt,[28] the $T_>$ state of the type discussed here has three characteristics by which it can be recognized in a (p,γ) reaction: (1) a large reduced proton width, (2) a large radiative width, and (3) a simple γ decay to, in the best cases, the $T_<$ state of the same configuration. This type of behavior is seen in the three cases mentioned above. Similar properties have been observed for analog states of the ($2s_{1/2}$,$1f_{7/2}$) configuration in P^{30} and the ($1d_{3/2}$,$1f_{7/2}$) configuration in Ar^{38}.[30,31]

B. Excitation Curve, Resonance Strengths, and γ-Ray Spectra

The excitation energy of 10.2 MeV predicted for the ($1f_{7/2}$, $T=\frac{5}{2}$) state in Cl^{37} corresponds to $E_p\approx1.8$ MeV in the S^{36} $(p,\gamma)Cl^{37}$ reaction. It is expected then that there should be a strong resonance around $E_p=1.8$ MeV that decays primarily via a 7-MeV transition to a level ($1f_{7/2}$, $T=\frac{3}{2}$) at about $E_x=3.2$ MeV. This $T_<$ level is expected to be one member of the previously reported doublet in Cl^{37} at $E_x=3.1$ MeV. Both the excitation curve reported in Sec. II of this paper ($E_p=800$–1800 keV), and in the work of Koval' *et al.*[7,8] ($E_p=1400$–2100 keV), fail to show evidence for the analog state. A resonance with the decay properties assumed for this state would not, however, have been observed in the latter work because of the γ-ray energy bias settings used. Consequently, a new search was conducted for the analog state in the region $E_p=1640$–1940 keV. Targets used in this work were prepared in the manner described in Sec. II B. The yield of γ rays was detected by 8-in.×8-in. and 5-in.×5-in. NaI(Tl) detectors, each placed 1.0 in. from the target at 90° with respect to the proton-beam direction and at 180° with respect to each other. The yield was recorded in three scalers subject to the following conditions:

[25] J. B. French, in *Proceedings of the Conference on Nuclear Spectroscopy with Direct Interactions*, edited by F. E. Throw (Argonne National Laboratory, Argonne, Ill., 1964), Report No. ANL 6878.

[26] R. W. Krone, J. M. O'Dell, and F. W. Prosser, in *Proceedings of the Conference on Bases for Nuclear Spin-Parity Assignments, Gatlinburg, 1965* (Academic Press Inc., New York, 1966).

[27] D. D. Watson, Phys. Letters **22**, 183 (1966).

[28] P. M. Endt, Aerospace Research Laboratories Report No. ARL 66-0221, 1966 (unpublished).

[29] G. I. Harris, H. J. Hennecke, and F. W. Prosser, Jr., Phys. Letters **9**, 324 (1964).

[30] G. I. Harris and A. K. Hyder, Jr., Phys. Letters **22**, 159 (1966).

[31] F. C. Erné, W. A. M. Veltman, and J. Wintermans, Nucl. Phys. **88**, 1 (1966).

Scaler A. Pulses from the two crystals in sum-coincidence with the sum channel set between 9.8 and 10.2 MeV.

Scaler B. Coincidence between pulses in 2.8–3.2-MeV and 6.8–7.2-MeV channels.

Scaler C. Pulses from either or both crystals in a 9.8–10.2-MeV channel.

The channels used with scaler B were selected under the assumption that the analog state might decay through a member of the 3.1-MeV doublet. The "sum" channel corresponds to a $r \rightarrow 0$ transition.

The counts recorded in each of these scalers as the proton energy is varied in small steps over the region of interest is given in Fig. 10. The curve is seen to exhibit several weaker resonances in addition to a very strong resonance at $E_p = 1887 \pm 2$ keV which is shown, as discussed below, to possess the expected properties of the analog state. No evidence is seen for the relatively strong resonance previously reported[7,8] at 1744 keV. The resonance appearing at $E_p = 1905$ keV is due to the $S^{34}(p,\gamma)Cl^{35}$ reaction.[32]

The resonance strength was measured by comparison of the yield from a thin target with that of the $E_p = 1214$ keV resonance in the reaction $S^{34}(p,\gamma)Cl^{35}$ as discussed in Sec. II. The measurement gave the value $(2J+1)\Gamma_\gamma\Gamma_p/\Gamma = 130 \pm 20$ eV for the strength of the $E_p = 1887$ keV resonance. The observed total width, $\Gamma_{ob} \approx 4$ keV, can be attributed to target thickness and beam-energy spread.

Singles γ-ray spectra were accumulated using the 8-in.×8-in. NaI(Tl) crystal and a 2-cc Ge(Li) detector. In one measurement, the Ge(Li) detector was used in a three-crystal pair spectrometer mode with two 5-in.

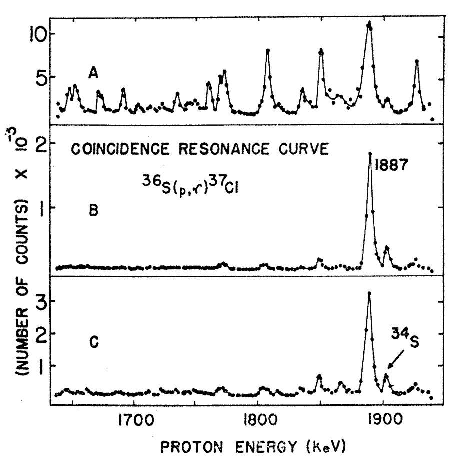

FIG. 10. Resonance excitation curve for the $S^{36}(p,\gamma)Cl^{37}$ reaction in the region of proton energies $E_p = 1640$–1940 keV. The three curves correspond to (a) pulses from γ rays with energies in a 9.8–10.2 MeV channel; (b) coincidences between pulses in a 2.8–3.2 MeV and a 6.8–7.2 MeV channel; and (c) coincidences between pulses corresponding to γ rays whose sum is in a 9.8–10.2 MeV channel (see text).

[32] D. D. Watson, Ph.D. thesis, University of Kansas, 1965 (unpublished).

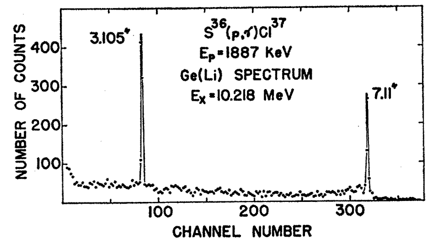

FIG. 11. Spectrum observed at the $E_p = 1887$ keV resonances in $S^{36}(p,\gamma)Cl^{37}$ with a three-crystal pair spectrometer which consists of a 2-cc Ge(Li) detector and two 5-in.×5-in. NaI(Tl) detectors. Members of the $(r \rightarrow 3.105 \rightarrow 0)$ cascade are evident. A much weaker $(r \rightarrow 3.71 \rightarrow 0)$ cascade does not appear in these data.

×5-in. NaI(Tl) detectors. The latter spectrum is shown in Fig. 11. It is clear that the resonance level decays primarily through the 3.105-MeV member of the doublet at 3.1 MeV. There is evidence in other NaI(Tl) and Ge(Li) spectra for a weak transition to the 3.71-MeV $(J^\pi = \frac{5}{2}^-)$ level.[6,22]

C. Angular Correlations and Linear Polarizations

A brief report of the results obtained at the 1887-keV resonance has been given earlier.[33] Angular-distribution (AD), (p,γ,γ) triple-correlation (TC), and linear-polarization measurements were performed on members of the $r \rightarrow 3.105 \rightarrow 0$ cascade at the 1887-keV resonance. The high strength of this resonance made it possible to move the detectors to the more standard distances from the target, which were used in most previous work.[24] A departure from earlier techniques was to conduct the TC measurements in a way such that the various "geometries" were mutually normalized. The importance of this procedure in a similar case has been emphasized by Watson.[27] The AD and TC data are shown in Fig. 12. The fixed and variable angles of the set (θ_1,θ_2,ϕ) for each of the TC geometries are indicated in the figure. The designations AD1 and AD2 refer to angular distributions of the primary and secondary members of the $(r \rightarrow 3.105 \rightarrow 0)$ cascade, respectively. The solid lines indicate the theoretical angular correlations for the assigned spin values and multipolarity mixings. The χ^2 analysis of these data was performed for spin combinations for the resonance and 3.105-MeV levels from $J = \frac{1}{2}$ through $J = \frac{9}{2}$ with the restrictions of $\Delta J \leq 2$ for the primary transition and $\Delta J \leq 3$ for the secondary transition. Only the combination $\frac{7}{2} \rightarrow \frac{7}{2}$ for these two levels resulted in χ^2 value below the 0.1% "confidence limit." The projections of the χ^2 surface onto the $\chi^2-\delta_1$ and $\chi^2-\delta_2$ planes for the assigned spin values are shown in Fig. 12. Also shown for comparison are the projections for the next-most-likely spin combination $\frac{5}{2} \rightarrow \frac{5}{2}$. The resonance and 3.105-MeV levels are, therefore, both $J = \frac{7}{2}$ as expected. The multipolarity mixings are found to be $\delta_1 = 0.00 \pm 0.02$ and $\delta_2 = -0.18$

[33] A. K. Hyder, Jr., and G. I. Harris, Phys. Letters **24B**, 273 (1967).

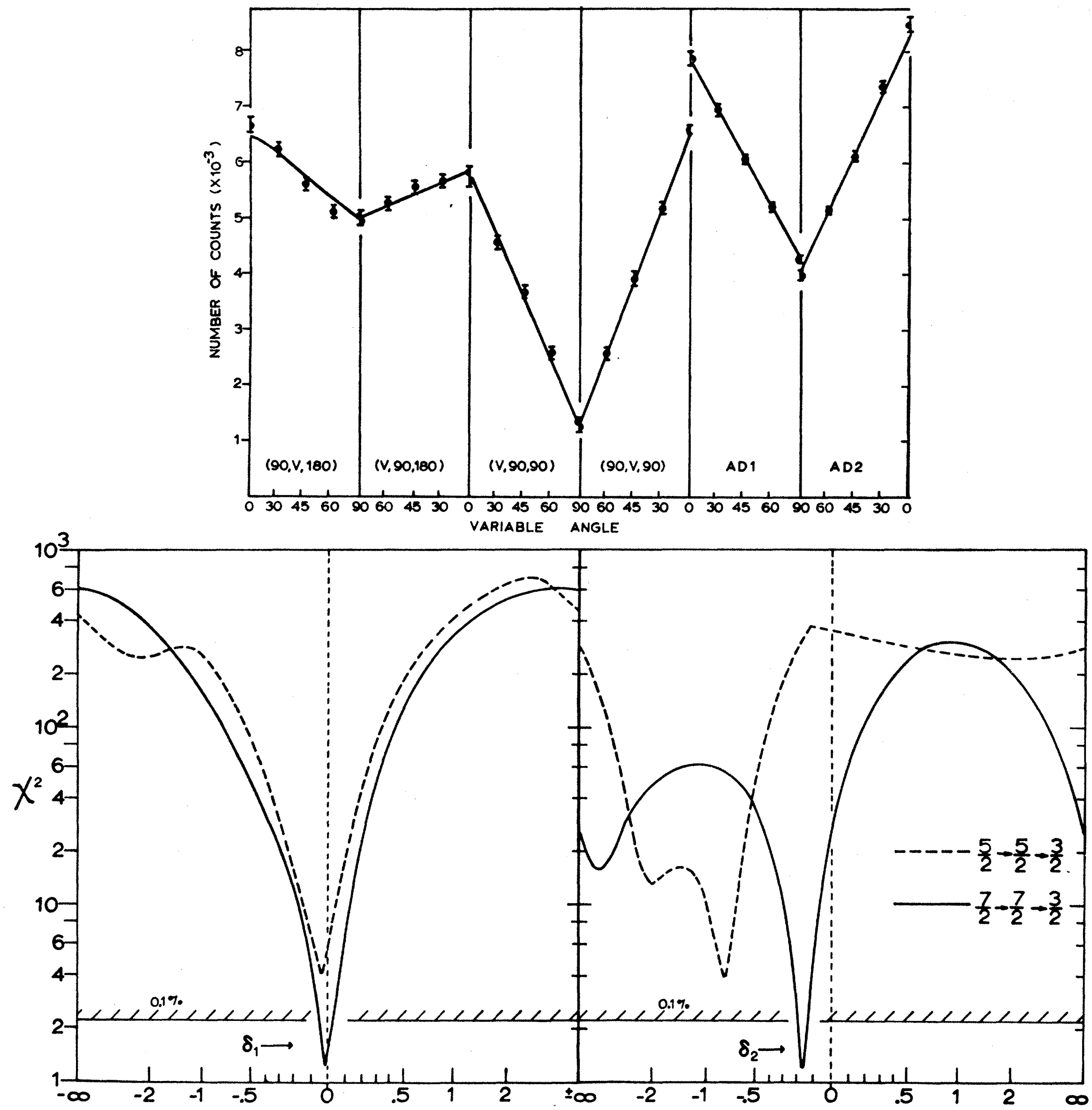

FIG. 12. Comparison of the measured and theoretical angular correlations for the $(r \rightarrow 3.105 \rightarrow 0)$ cascade at the $E_p = 1887$ keV resonance. The theoretical curves shown are those for the assigned spins and multipole mixing ratios. Also shown are the χ^2-projection curves for the $(r \rightarrow 3.105 \rightarrow 0)$ cascade.

± 0.01, where the nonzero value of δ_2 implies a quadrupole-octupole mixing in the $3.105(\frac{7}{2}) \rightarrow$ G.S$(\frac{3}{2}+)$ transition.

The linear polarizations were measured using a Compton polarimeter arrangement.[34] A 2-in.-diam$\times$2-in.-long NaI(Tl) crystal placed 3.9 in. above the target $(\theta = 90°)$ was used as the scattering crystal. Two 5-in. $\times$5-in. NaI(Tl) detectors, each shielded from the target, were used to detect the scattered γ rays. One detecting crystal was placed in the reaction plane $(\phi = 0°)$ while the other was placed perpendicular to the reaction plane $(\phi = 90°)$. The two larger crystals were periodically interchanged by rotating the entire polarimeter by $\phi = 90°$ to reduce the effects of polarimeter asymmetries. Sum-coincidence spectra from the two scattering-crystal–detecting-crystal combinations were recorded in separate subgroups of a multichannel analyzer. The polarimeter was tested and calibrated by a separate measurement of the polarizations of the members of the $7.54(\frac{7}{2}^-) \rightarrow 3.16(\frac{7}{2}^-) \rightarrow$ G.S.$(\frac{3}{2}^+)$ cascade at the $E_p = 1214$ keV resonance[27] in the reaction $S^{34}(p,\gamma)Cl^{35}$. For the 1887-keV resonance, the expected polarization

[34] H. Willmes and G. I. Harris, Phys. Rev. **162**, 1027 (1967). See also D. D. Watson and G. I. Harris, Nucl. Data **3**, 25 (1967).

P as defined in Ref. 34 for the primary transition is -0.94 with parity change or $+0.94$ with no parity change. For the secondary transition, $P=-0.84$ or $+0.84$ with or without parity change, respectively. The experimental results were $P=+0.95\pm0.43$ for the primary transition, and $P=-0.90\pm0.27$ for the secondary transition. The resonance level ($E_x=10.22$ MeV) and the 3.105-MeV level therefore must both have odd parity. The primary transition is pure $M1$ and the secondary transition is mixed $E3$-$M2$.

IV. SUMMARY AND DISCUSSION

A large number of resonances in the $S^{36}(p,\gamma)Cl^{37}$ reaction, corresponding to Cl^{37} excitation energies between $E_x=9.1$ and 10.2 MeV, were found in the bombarding energy region studied (Figs. 1, 10, and Table I). These results are in reasonable agreement, in the region of overlap, with excitation-curve studies by Koval' *et al.*[7] for $E_p=1.4$–2.1 MeV. A histogram of the resonance strength S versus proton energy E_p, where S is averaged over 200-keV intervals in E_p, is shown in Fig. 13. The initial increase of resonance strength with E_p is probably due to the increasing proton width Γ_p. At higher proton energies Γ_p tends to become much larger than Γ_γ. In this region $\Gamma_p\Gamma_\gamma/\Gamma\cong\Gamma_\gamma$, which varies much more slowly with proton energy. This "leveling off" of the resonance strength is revealed clearly by the histogram. The general behavior of the excitation curve is in general agreement with that which would be expected on the basis of estimates of Γ_p and Γ_γ as functions of spacings between levels, D[35]:

$$\Gamma_\gamma=\Gamma_\gamma(\text{pure})D/D_s$$

and

$$\Gamma_p\sim(4k/K)\nu_l D/2\pi\,,$$

where Γ_γ(pure) is on the order of the γ-ray width expected from a pure single-particle model, D_s is a level spacing characteristic of spacings between major shells, and $(4k/K)\nu_l$ is the transmission coefficient of order l. Under the assumption that most of the resonances decay primarily to the ground state by dipole transitions, a reasonable estimate for Γ_γ(pure) is 200 eV. Then for $D_s\approx5$ MeV and the observed value $D=0.013$ MeV, the general behavior of the excitation curve can be reproduced for various mixtures of s-, p-, d-, and f-wave capture. A typical prediction is shown by the solid curve in Fig. 13 which was computed for the above parameter values and a mixture of 30% p-wave and 70% d-wave capture. It is emphasized that although this mixture represents a best and most reasonable fit, the over-all behavior is relatively insensitive to the contributions of the various physically reasonable partial waves.

A detailed investigation of six resonances between 900 and 1120 keV revealed the presence of three previously unreported bound levels at $E_x=3.62$, 3.74, and (4.4) MeV. In addition, the γ-ray spectra show evidence for weak transitions to many other levels in the region $E_x=4$–6 MeV. The data were not considered to be good enough in these cases to make unambiguous assignments of new levels. Those levels that were assigned were confirmed by γ-γ coincidence measurements and the variation of the primary γ-ray energy from resonance to resonance. A total of 16 odd-parity $T=\frac{3}{2}$ levels with $\frac{1}{2}\leq J\leq13/2$ are predicted by Erné[36] between $E_x=2.9$ and 5.8 MeV as a result of a shell-model calculation with a S^{32} core plus residual interactions between $(1d_{3/2})^4$ nucleons and one nucleon in the $1f_{7/2}$ orbit. Two $\frac{3}{2}^+$ levels are predicted at 4.94 and 6.37 MeV in a similar calculation based upon a Si^{28} core and residual interactions between $2s_{1/2}^{-}$ $1d_{3/2}$ nucleons by Glaudemans *et al.*[37] Bansal,[38] on the basis of calculations conducted in an attempt to understand the effects of core polarization when an inequivalent particle is added to a core having a closed neutron shell, predicts four $\frac{7}{2}^-$ levels between 2.6 and 5.9 MeV in Cl^{37}. Thus many levels are expected in a region in which the complexity of the γ-ray spectra also suggests their presence.

The derived decay schemes and spin assignments resulting from the angular-correlation measurements are summarized in Fig. 14. Unique resonance-spin assignments were obtained for all but the $E_p=983$ keV resonance. The dipole-quadrupole mixing ratios δ for primary transitions to the levels at $E_x=0$, 1.725, and 3.105 MeV are listed in Table II. From studies of capture-resonance decay schemes of many nuclei in this mass region, it is known that primary transitions involving a spin change $\Delta J=2$ or greater are rare. Thus the following most likely spin assignments can be given for bound levels for which no angular-correlation data are available: 3.087 $(\frac{1}{2},\frac{3}{2},\frac{5}{2})$, 3.62 $(\frac{3}{2},\frac{5}{2})$, 3.74 $(\frac{3}{2},\frac{5}{2})$, 4.4 $(\frac{3}{2},\frac{5}{2})$. The 3.087-MeV level is probably the $(J^\pi,T)=(\frac{5}{2}^+,\frac{3}{2})$ level predicted[37] at 2.53 MeV. The same conclusion has been reached by Wirjoamidjojo and Kern.[19]

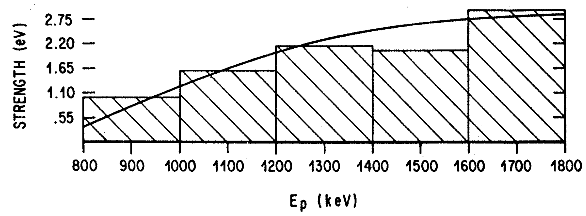

FIG. 13. Histogram of the resonance strength $S=(2J_r+1)\Gamma_p\Gamma_\gamma/(\Gamma_p+\Gamma_\gamma)$ versus proton energy. S is averaged over 200-keV intervals in E_p. The solid line is a theoretical fit to the histogram based on estimates of Γ_p and Γ_γ as functions of the spacings between levels. The calculated resonance-strength curve was drawn for a mixture of 30% p-wave and 70% d-wave protons (see text).

[35] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley & Sons, Inc., New York, 1952).

[36] F. C. Erné, Nucl. Phys. **84**, 91 (1966).

[37] P. W. M. Glaudemans, G. Wiechers, and P. J. Brussaard, Nucl. Phys. **56**, 548 (1964).

[38] R. K. Bansal, Phys. Rev. **153**, 1084 (1967).

TABLE III. Comparison of the isobaric-analog states with the $1f_{7/2}$ configuration in Cl^{35} and Cl^{37}. The Cl^{35} data is from Watson.[a]

	E_x(MeV) (J^π,T) $T_>$	$T_<$	θ_p^2 (Res.)	$\Gamma_\gamma(T_> \to T_<)$ (Weisskopf units) Expt.	Theor.	δ_1	δ_2	V_1(MeV)
Cl^{35}	$7.54(\frac{7}{2}^-,\frac{3}{2})$	$3.163(\frac{7}{2}^-,\frac{1}{2})$	≥ 0.2	1.6 ± 0.3	2.2	0.07 ± 0.02	-0.16 ± 0.01	102
Cl^{37}	$10.22(\frac{7}{2}^-,\frac{5}{2})$	$3.105(\frac{7}{2}^-,\frac{3}{2})$	≥ 0.03	1.7 ± 0.3	1.6	0.00 ± 0.02	-0.18 ± 0.01	105

[a] Reference 27.

The outstanding resonance at $E_p=1887$ keV was located as a result of a deliberate search based upon expected properties as discussed in Sec. III. It was shown to have the properties expected of the $(J^\pi,T)=(\frac{7}{2}^-,\frac{5}{2})$ member of the $1f_{7/2}$ single-nucleon configuration. It decays mainly to the 3.105-MeV level which was shown to have $J^\pi=\frac{7}{2}^-$ as expected for the $(J^\pi,T)=(\frac{7}{2}^-,\frac{3}{2})$ member of the same configuration. The resonance excitation energy in Cl^{37} is very close to that expected for the analog of the ground state of S^{37}. The S^{37} ground state is thus almost certainly $\frac{7}{2}^-$ as expected on the basis of shell-model considerations.

The similarity of the properties of the 1887-keV resonance and 3.105-MeV levels with the 1214-keV resonance and 3.16-MeV levels observed in $S^{34}(p,\gamma)Cl^{35}$ is quite striking. The comparison is presented in Table III. The lower limits on the reduced proton widths θ_p^2 result from the resonance-strength measurements. The difference in the two cases reflects the difference in $l=3$ barrier penetrabilities. Unfortunately, the natural widths of the two resonances are too small to be observed directly with presently available resolution. When the isobaric-spin Clebsch-Gordan coefficient is taken into account, a pure single-particle $(f_{7/2},T=\frac{5}{2})$ resonance would have $\theta_p^2=0.20$, while for an $(f_{7/2},T=\frac{3}{2})$ resonance, $\theta_p^2=0.33$. The $M1$ speed in Weisskopf units for the $(T_> \to T_<)$ transition in each case is quite close to the pure single-nucleon value calculated in a manner discussed by Watson *et al.*[39] Perhaps most remarkable is the close agreement of the $E3$-M2 mixings in the two secondary transitions. In each case the value for the mixing *intensity* is about 16 times greater than the ratio of Weisskopf estimates for $E3$-$M2$ mixing. Finally, the parameter V_1 in the isospin monopole-interaction term $(V_1/A)\mathbf{T}\cdot\mathbf{t}$ is nearly identical in the two cases.

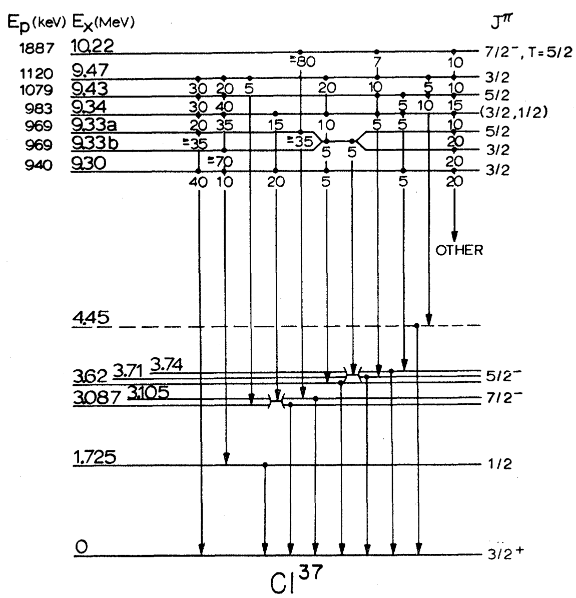

FIG. 14. Decay schemes of resonances and bound levels in Cl^{37}. The J^π assignments for the levels at $E_x=0$, 1.725, and 3.71 MeV are from earlier work.

In a recent calculation, Bansal[38] has shown that the $(J^\pi,T)=(\frac{7}{2}^-,\frac{3}{2})$ state in Cl^{37} may be fragmented into four levels at $E_x=2.60$, 4.85, 5.30, and 5.90 MeV due to core-polarization effects. If this is the case, then the level at 3.105 MeV should probably be identified with the fragment predicted at 2.60 MeV which retains most of the strength (48%) of the configuration. The $(J^\pi,T)=(\frac{7}{2}^-,\frac{5}{2})$ member is predicted by Bansal at 9.79 MeV in reasonable agreement with the observed value of 10.22 MeV.

ACKNOWLEDGMENTS

We wish to express our thanks for the assistance given by members of the Nuclear Structure Group, in particular, the invaluable support given by D. V. Breitenbecher and W. A. Anderson in the maintenance and operation of the accelerator and associated equipment. We also thank Yu. S. Korda and B. D. Kern for correspondence and reports relating to the reaction under study.

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