Levels of S^{36} from $S^{34}(t,p)S^{36}$†

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Levels of S^{36} have been investigated via the $S^{34}(t,p)S^{36}$ reaction, using targets of Sb_2S_3 with the sulfur content enriched to 86% in the isotope S^{34}. The excitation energies (given in MeV) of the levels observed, together with the restrictions on spins and parities resulting from this investigation and also previous work, are as follows: 3.29, 2^+; 3.34, 0^+; 4.19, 3^-; 4.52, 1^+; 4.57, 2^+; 5.26, 1, 2, 3; 5.38, 1, 2, or (3); 5.50, 2, (3), 4; 5.57, 1, (2), 3; 6.20, 2, 3; 6.51, 4^+; and 7.12, 1^+ or 2^+. Information on the γ-ray branching of these levels and on the angular-correlation patterns of major branches was obtained from two-parameter p-γ coincidence studies utilizing collinear detection of the reaction protons. The 3.29-MeV level decays by $E2$ radiation directly to the S^{36} $J^\pi=0^+$ ground state. An intermediate-image pair spectrometer was used to determine that the 3.34-MeV level has $J^\pi=0^+$, since it decays by an $E0$ transition to the ground state. With the exception of the 4.52-, 5.38-, and 7.12-MeV levels, which decay mainly to the ground state, the higher-lying levels were observed to deexcite primarily by cascade transitions through the 3.29-MeV level. Ge(Li) studies of γ-ray Doppler shifts determine the following mean-lifetime restrictions for the indicated levels (excitations in MeV): 3.29, $\tau=0.20\pm0.03$ psec; 4.19, $\tau>2$ psec; and 4.57, $\tau<0.1$ psec. Additional but less restrictive limitations are given for several of the remaining levels. The lifetime of the 0^+ 3.34-MeV state was measured by electronic techniques which determine a mean life $\tau=12.7\pm0.3$ nsec. The spin-parity limitations deduced herein are from a combination of the results of the angular-correlation analysis and these lifetime limitations. No evidence was obtained for the existence of states at 2.00 and 2.85 MeV previously reported from the $S^{34}(t,p)S^{36}$ reaction. Finally, the observed level structure as deduced from this and previous experiments is compared with relevant shell-model calculations on the even- and odd-parity states of this $T_z=2$ nucleus.

I. INTRODUCTION

Of the even-even nuclei in this upper region of the s-d shell, S^{36} is particularly interesting, since the neutron number ($N=20$) corresponds to the closure of a major shell. The proton number ($N=16$) corresponds to four holes in the same shell, and one can therefore predict[1] a relatively simple spectrum of low-lying even-parity levels based on the coupling of these four proton holes. An interesting feature of the calculation of these even-parity states by Glaudemans, Wiechers, and Brussaard[1] is that the lowest of these should be a 2^+ state at the relatively high excitation energy of 2.83 MeV. Conversely, one can also expect[2] a fairly simple spectrum of odd-parity states, corresponding to the promotion of a single nucleon into the $f_{7/2}$ shell. Theoretical calculations by Erne[2] result in the prediction that the lowest lying of these should be a $J^\pi=3^-$ level at only 3.38 MeV. Under the assumption that these theoretical calculations are approximately correct, an experimental description of the S^{36} level structure should be especially interesting, insofar as it may demonstrate the interplay of these two distinctly different configurations in generating the level spectrum of this $T_z=2$ nucleus.

As recently as 1968, the only precise spectroscopic information on the nucleus S^{36} was that quoted[3] from unpublished studies of the $S^{34}(t,p)S^{36}$ reaction at $E_t=11.9$ MeV. Levels were reported from this reaction at excitation energies (in MeV) of 2.000, 2.885, 3.304, 3.360, and 4.204, with an uncertainty in these determinations of ±15 keV. Angular-distribution studies of the reaction protons led to assignments $J^\pi=2^+$ for the 2.885-MeV state and $J^\pi=0^+$ for the states reported at 2.00 and 3.36 MeV. An assignment $J^\pi=2^+$ or 3^- was additionally suggested for the state at 3.304 MeV. Levels in S^{36} had also been reported[4] at $E_{ex}\sim3.5$ and ~4.7 MeV from studies of the $Ar^{40}(\gamma,\alpha)S^{36}$ reaction at $E_\gamma=17.71$ MeV.

More-recent studies[5-7] of the proton-pickup reaction $Cl^{37}(d,He^3)S^{36}$ have confirmed some of the (t,p) results, as well as providing additional information on higher-lying levels. From measurements at $E_d = 28.9$ MeV Gray *et al.*[5,6] report levels at 3.295 ± 0.010, 4.523 ± 0.010, 4.577 ± 0.010, 6.511 ± 0.015, 7.12 ± 0.02, and 7.71 ± 0.025 MeV. Distorted-wave Born-approximation (DWBA) analysis of the angular distributions determines that for the 3.30-, 4.52-, and 4.57-MeV levels the pickup (presumably of an $s_{1/2}$ particle) is $l = 0$, and thus the levels are individually restricted to have $J^\pi = 1^+$ or 2^+. For the levels at 6.51 and 7.12 MeV, their results determine that the reaction proceeds by $l = 2$ pickup of a $d_{5/2}$ proton, and thus these levels are also of even parity with $J \leq 4$. The measured spectroscopic factors indicate that these four levels account for a major portion of the $s_{1/2}$ and $d_{5/2}$ strengths.

Similar studies at $E_d = 23.4$ MeV by Puttaswamy and Yntema[7] are in essential agreement. They report levels at 3.31 ± 0.015 and 4.58 ± 0.02 MeV formed by $l = 0$ pickup, and thus $J^\pi = 1^+$, 2^+. The level reported by them[7] at 6.60 ± 0.04 MeV is presumably that reported by Gray *et al.*[5,6] at 6.51 MeV, although the spectroscopic factors are not in very good agreement in this case. Both studies[6,7] confirm an $l = 2$ pickup and thus even parity for the 0^+ S^{36} ground state.

In summary, the experimental spectrum of S^{36} states determined from the individual (t, p) and (d, He^3) studies appears in reasonably good agreement. We note, however, that the 2.000-, 2.885-, 3.360-, and 4.204-MeV levels were observed only in the (t, p) reaction,[3] while those at 6.51, 7.12, and 7.69 have been seen[5-7] only in (d, He^3). This is not in itself surprising, since as pointed out previously[6,7] the two reactions can be expected to populate markedly different configurations.

It is from the vantage point gained by the information summarized above that the present investigation of the S^{36} level structure via the $S^{34}(t, p\gamma)S^{36}$ reaction was begun. We note that whereas the (d, He^3) reaction is expected to populate primarily the even-parity four-hole configurations of S^{36}, the (t, p) reaction can in principle populate a broader range of configurations. This is especially true at the triton energies used in the present experiment ($E_t < 3.5$ MeV) since one may expect the reaction to proceed, to a considerable extent, through compound-nucleus processes.

A primary aim of these studies was the determination of the previously unreported electromagnetic decay modes of these levels. In Sec. II we report two-parameter studies of p-γ coincidence measurements which determine the principal decay modes of those states of excitation energies ≤ 7.2 MeV. These measurements utilized detection of the particles in an annular surface-barrier detector, placed at 180° to the beam direction (Method II Geometry of Litherland and Ferguson),[8] with γ rays detected in an NaI(Tl) detector. Additional measurements of the particle spectra, together with Ge(Li) studies of the Doppler shift of some of the deexcitation γ rays, are included. In Sec. III, we describe measurements on the internal-pair deexcitation of the $J^\pi = 0^+$ 3.34-MeV state, and a measurement of its lifetime. An analysis of the angular-correlation data of Sec. II, together with a summary of our conclusions on the spin-parity assignments of the states and the multipole character of the deexcitation γ rays, are given in Sec. IV. Finally, in Sec. V, the results of the present experiment are compared with previous conclusions[3,5-7] on the S^{36} level scheme and with the theoretical predictions[1,2,6] for this nucleus.

II. MEASUREMENTS OF PROTON AND γ-RAY SPECTRA

The triton beam for all these experiments was provided by the Brookhaven National Laboratory (BNL) 3.5-MV Van de Graaff accelerator. The target material was obtained from the Oak Ridge National Laboratory (ORNL) Isotopes Division in the form of antimony sulfide (Sb_2S_3) with the sulfur content enriched to 85.61% in the isotope S^{34}. The relative abundances of the remaining isotopes were: S^{32}, 13.91%; S^{33}, 0.18%; and S^{36}, 0.30%. Targets were prepared by vacuum evaporation of the Sb_2S_3 in thicknesses of 200–600 $\mu g/cm^2$ onto 0.003-in. backings of molybdenum. The choice of Sb_2S_3 as the target material was based on the fact that it is readily evaporated to form uniform, thin layers, and also that it holds up very well under bombardments corresponding to energy dissipation (in the target and backing) of ~20 W.

In order to ascertain the character of the S^{36} level scheme, a sequence of high-resolution measurements was undertaken to study separately the proton and γ-ray spectra, utilizing, respectively, Si and Ge(Li) detectors and also coincidence studies of the $S^{34}(t, p\gamma)S^{36}$ reaction. The results are reported in separate subsections; it must be remembered, however, that the conclusions are interrelated. A detailed description of the experimental apparatus and methods of analysis used in this work has been given previously.[9-11] Reference to specific examples are also given in the following presentation.

A. Proton-γ Coincidence Measurements

A two-parameter analysis of p-γ coincidences in the $S^{34}(t, p\gamma)S^{36}$ reaction was carried out at $E_t = 3.12$ MeV using a 400-$\mu g/cm^2$ target of Sb_2S_3 which was placed at the center of an 8-in.-diam scattering chamber. Protons were detected in an annular surface-barrier detector placed at 180° to the triton beam direction, set to detect protons within the range $165° \leq \theta_p \leq 170°$. γ rays were detected by a 5×6-in. NaI(Tl) detector placed 20 cm from the target, which could be rotated about the target center in the range $0° \leq \theta_\gamma \leq 90°$. The brass walls of the scattering chamber (within this angular quadrant) were of 0.010-in. brass, so that γ-ray absorption was negligible. The gain of the NaI(Tl) detector was stabilized using a spectrastat which was set on the 662-keV line of a weak Cs^{137} source placed near the front face of the detector. With this system, no γ-ray gain changes were apparent. The particle detector was a 900-μ-thick silicon surface-barrier detector operated at 175-V bias, with a measured intrinsic resolution of 20 keV for 5.48-MeV α particles. A 10-mg/cm^2 Al foil placed in front of the detector was used to stop tritons elastically scattered from the target.

Time-coincident pulses from the two detectors were analyzed by a TMC 16 384-channel analyzer set to operate in a 128×128-channel mode. The analyzer was gated on by an external coincidence circuit of resolving time $2\tau = 80$ nsec. At the triton beam current used for these coincidence measurements (~40 nA) the ratio of real/random counts was better than 20: 1.

Coincidence data were recorded for five positions of the NaI(Tl) detector corresponding to $\theta_\gamma = 0$, 30, 45, 60, 90° (in arbitrary order) and then repeated as a check on reproducibility. The individual runs required bombardment times of about 20 h, corresponding to a charge deposited on the beam collector cup of 2.5×10^{-3} C. A standard current integrator was used to record the charge deposited during each run, which then served as a normalization for the correlation data. The individual data were stored on magnetic tape, and at the conclusion of the correlation measurements the sum of all data was obtained for investigation of the γ branching of the S^{36} states.

Figure 1 shows a portion of the data obtained in these experiments. The upper plot (solid dots) shows the proton spectrum measured by the annular detector at $E_t = 3.12$ MeV using the Sb_2S_3 target enriched in S^{34}. The solid curve illustrates the spectrum due primarily to the S^{32} contamination, as determined with a separate target of ordinary Sb_2S_3. The expected positions of proton groups 2–17 from the $S^{32}(t,p)S^{34}$ reaction are indicated according to the S^{34} level scheme given by Endt and Van der Leun.[3] The S^{34} ground-state and first-excited-state groups were observed, though not shown in Fig. 1. In addition to the ground-state group from the $S^{34}(t,p)S^{36}$ reaction, proton groups are clearly evident corresponding to excited states in S^{36} at 3.29, 3.34, 4.19, 4.57, 5.26, 5.38, 5.50, 5.57, 6.20, 6.51, and 7.12 MeV. These groups are labeled as due to population of states in the final nucleus S^{36}, where the quoted excitation energies represent the best values as obtained in the present experiment. In addition to these strong groups listed above, we see a proton group due to $C^{12}(t,p_0)C^{14}$ resulting from carbon buildup on the target. The resolution obtained for these spectra (~90 keV) was limited due to the energy straggling introduced by the absorber foil required to stop the triton beam backscattered from the thick target. The insert shows the results of a separate measurement at $\theta_p = 135°$ using a 200-μg/cm^2 Sb_2S_3 target on a 2-mg/cm^2 gold backing. With this target the elastic scattering was low enough so that the proton groups from the (t,p) reaction could be detected in the presence of the tritons. With the improved resolution thus obtained (~30 keV), the separation of the 3.3-MeV doublet states in S^{36} is clearly seen.

The lower plot in Fig. 1 shows a portion of the two-parameter data, illustrating the proton spectra measured in coincidence with γ rays of 3.29 and 0.51 MeV, which (as we shall show) characterize the deexcitation of the doublet states at 3.3 MeV in S^{36}. The data shown for channels 1–128 were obtained as part of the correlation measurements described above, while that for the channel region greater than 128 were obtained from a second run covering the region 110–230, which was undertaken to search for the possible existence of S^{36} states of $E_{ex} < 3$ MeV. Normalization for the two sets of data was based on the overlap region covering the 3.3-MeV doublet states. Before proceeding to a detailed discussion of the conclusions allowed from the data of Fig. 1, we consider the γ-ray spectra coincident with the various strong proton groups illustrated.

Figure 2 shows the γ-ray spectra measured by the 5×6-in. NaI(Tl) detector in coincidence with protons leading to the states observed below 5-MeV excitation in S^{36}. In each spectrum, the "background" level due primarily to $S^{32}(t,p\gamma)S^{34}$ contributions underlying the S^{36} spectrum is indicated. In coincidence with the 3.3-MeV doublet states, we see strong γ rays of energies 3.29 and 0.51 MeV. That these γ rays originate from two different states in S^{36} has been demonstrated in Fig. 1(b), which shows the proton peaks measured in coincidence with 3.29- and 0.51-MeV γ rays. The 3.29-MeV γ ray characterizes the ground-state deexcitation of the lower lying of these states, at 3.29 MeV. The 0.51-MeV γ rays result from annihilation of the positrons resulting from the deexcitation of the 3.34 ± 0.02-MeV state which (as shown in Sec. IV) takes place by internal-pair conversion. In summary, these two lower-lying states are found to decay by the transitions 3.29

→ 0 and 3.34 → 0. No evidence is found for transitions to states at 2.00 or 2.85 MeV, and an upper limit of 7% can be set on such possible cascades.

As illustrated in Fig. 2, both of the states at 4.19 and 4.57 MeV deexcite by transitions to the 3.29-MeV state. From these data we conclude that a possible 4.19 → 0 transition is less than 2% of the observed 4.19 → 3.29 intensity. For the 4.57-MeV level, we note that the peak in channel 110 (Fig. 2) is too low in energy, by ~40 keV, to fit as a 4.57 → 0 transition. Further, it appears in coincidence with a proton peak displaced also ~40 keV from the 4.57-MeV proton peak measured in coincidence with the 3.29 → 0 γ-ray transition [see Fig. 1(b)]. These data therefore point to a doublet of levels at ~4.5-MeV excitation in S^{36}: one at 4.57 MeV which decays by 4.57 → 3.29 → 0, and one at 4.52 MeV which decays by 4.52 → 0. The intensity of the 4.52-MeV γ-ray peak is only 8% that of the 3.29-MeV γ-ray peak, which is of the order expected for $S^{32}(t,p\gamma)S^{34}$ contributions to the net two-parameter spectrum due to the 14% S^{32} content in the target. These data alone are therefore not conclusive evidence for such a doublet nature. However, a similar doublet separation was observed in a separate p-γ coincidence measurement made at a higher bombarding energy $E_t = 3.4$ MeV, indicating the kinematics are consis-

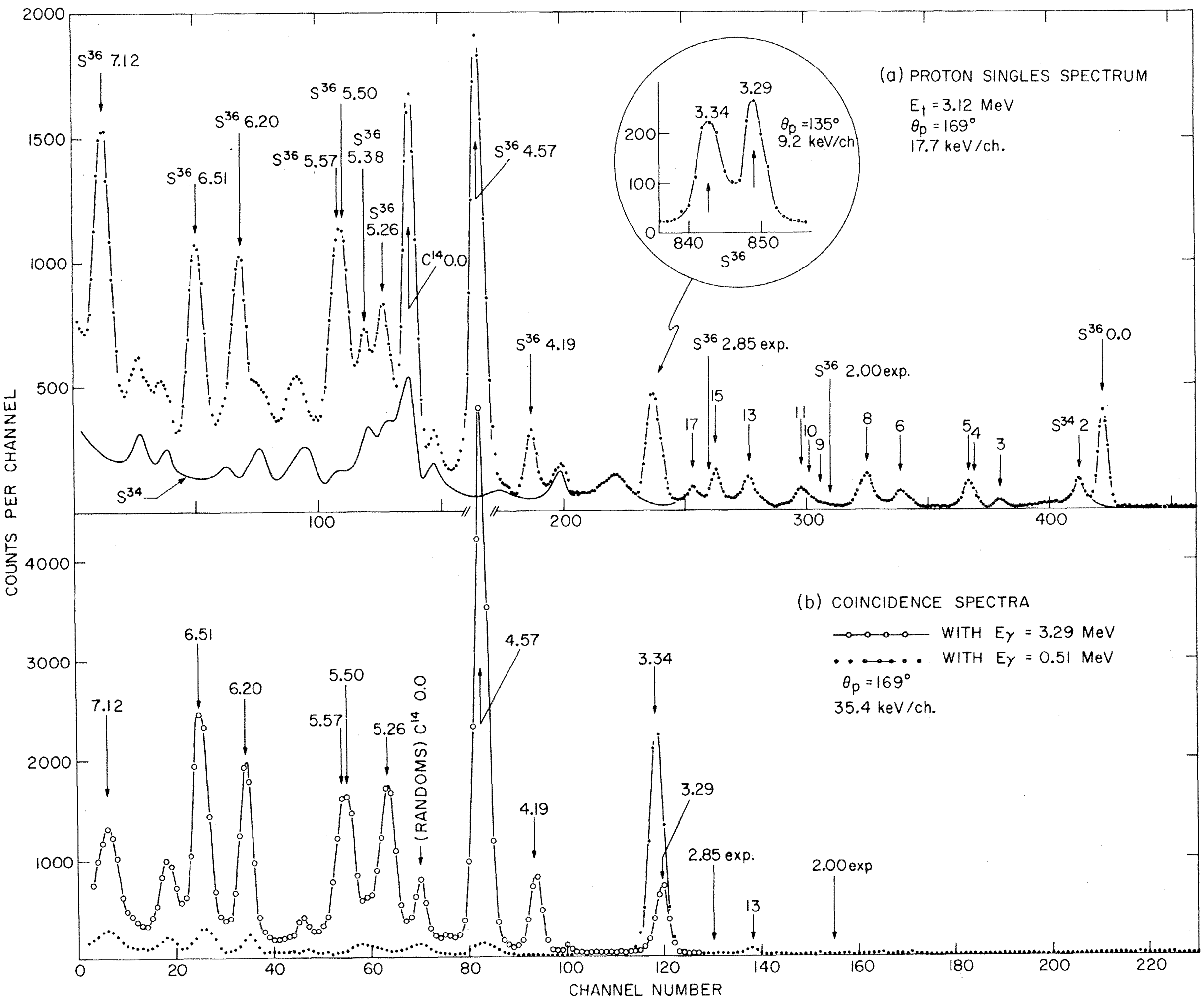

FIG. 1. (a), (b) Spectra of protons resulting from 3.12-MeV triton bombardment of an Sb_2S_3 target enriched to 86% in the isotope S^{34}, as measured with an annular silicon detector placed at $\theta_p = 180°$. The upper plot shows the direct singles spectrum, while the lower plots show the spectra measured in coincidence with 3.29- and 0.51-MeV γ rays. Proton groups identified as originating from the $S^{34}(t,p)S^{36}$ reaction are labeled by giving the S^{36} excitation energies in MeV. The solid curve in the upper plot illustrates the contribution to the net spectrum due to the 14% S^{32} in the target material: The expected positions of groups 2–17 from $S^{32}(d,p)S^{34}$ are indicated. Also identified is the ground-state group from $C^{12}(t,p_0)C^{14}$, arising from carbon buildup on the target. The insert shows a higher-resolution measurement made at $\theta_p = 135°$, illustrating the doublet nature of the "peak" at 3.3-MeV excitation in S^{36}.

tent with *both* levels being in S^{36}. Finally, we take the excellent agreement between the excitation energies deduced in the present experiment to those given previously by Gray *et al.*[6] as confirming evidence for the existence of the weaker member of this doublet at 4.52-MeV excitation in S^{36}. In conclusion, the 4.52-MeV level decays primarily (>60%) via a 4.52 → 0 transition, an upper limit of 40% being set on a possible 4.52 → 3.29 transition. Conversely, the 4.57-MeV level decays via a 4.57 → 3.29 → 0 cascade, with an upper limit of 5% being set on possible ground-state transitions from this level.

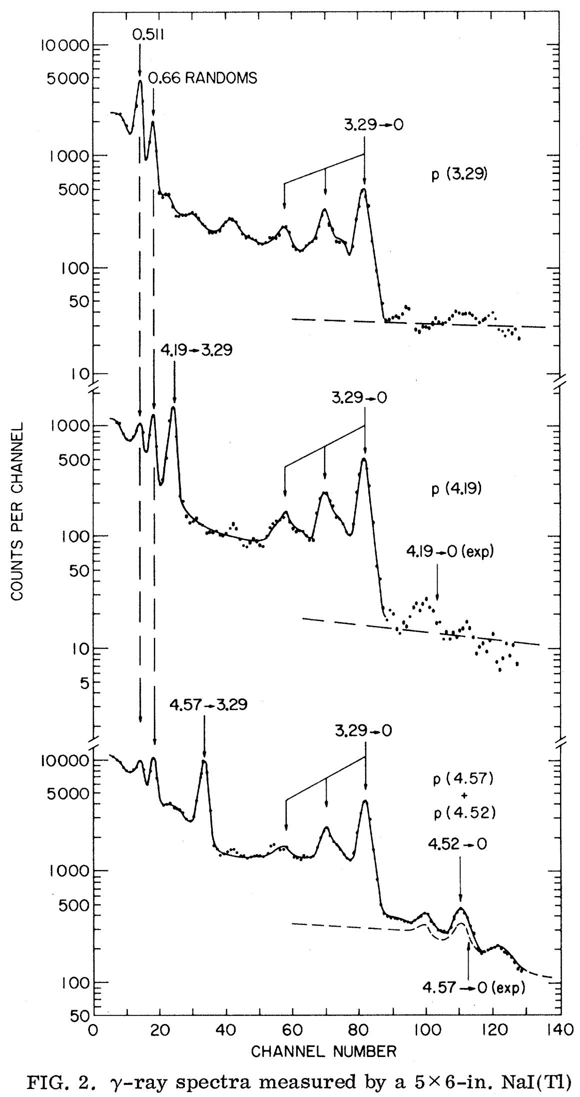

FIG. 2. γ-ray spectra measured by a 5×6-in. NaI(Tl) detector in coincidence with specific proton groups from the $S^{34}(t,p)S^{36}$ reaction at $E_t = 3.12$ MeV, illustrating the decay of the S^{36} levels at 3.29, 4.19, 4.52, and 4.57 MeV. γ-ray peaks are identified according to the levels between which the transitions occur. The expected peak positions of some other possible transitions are indicated. The dashed lines indicate for each spectrum the approximate background level, due primarily to the $S^{32}(t,p\gamma)S^{34}$ reaction, as determined from the γ-ray spectra coincident with proton channels adjacent to the S^{36} peak channels.

That none of these three states decays to the 3.34-MeV state is evident from the results of Fig. 1. In coincidence with 0.51-MeV annihilation radiation, which characterizes the $E0$ decay of the 3.34-MeV state, we see a strong particle peak only at 3.34-MeV excitation in S^{36}. For the remaining states, the weak peaks seen in coincidence with 0.51-MeV γ radiation would seem to be due mainly to the external-pair conversion of those γ rays of energy greater than 1.02 MeV. (In particular, the decay of each state in S^{36} is character-

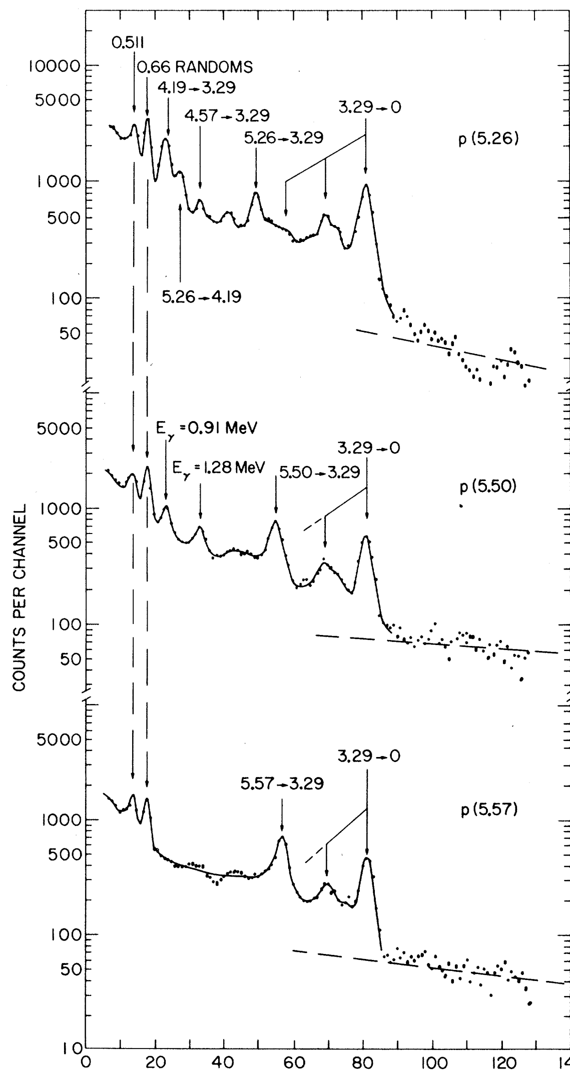

FIG. 3. Partial results of a two-parameter study of p-γ coincidences in the $S^{34}(t,p\gamma)S^{36}$ reaction at $E_t = 3.12$ MeV, illustrating the γ deexcitation of S^{36} states at 5.26, 5.50, and 5.57 MeV. These spectra were measured with a 5×6-in. NaI(Tl) detector in coincidence with the indicated proton groups. The γ-ray peaks are identified according to the levels between which the transitions occur.

ized by γ rays of energy greater than 3.29 MeV.) We conclude that for each of the states observed in Fig. 1, decays to the 3.34-MeV state represent less than 5% of the total decay intensity. The presence in all these data of a γ-ray peak at 662 keV results from chance coincidences with the Cs^{137} γ ray used for stabilization of the γ detector. The fact that the 662-keV line was ~10 times stronger in the "singles" spectra determines that the random-coincidence rates do not significantly affect the coincidence spectra illustrated.

Figure 3 illustrates the decay modes of the three states observed between 5- and 6-MeV excitation in S^{36} which, as indicated in Fig. 1(b). deexcite at least partially by cascade transitions leading through the 3.29-MeV state. From a comparison of the spectra shown in both (a) and (b) of Fig. 1, it is evident that the 5.38-MeV state must decay by an alternate mode. As illustrated in Fig. 3, the 5.26-MeV state is observed to decay primarily to the 3.29-MeV state, with somewhat weaker branches to the states at 4.19 and 4.57 MeV. The states at 5.50 and 5.57 MeV are separated by only 70 keV, and with the experimental

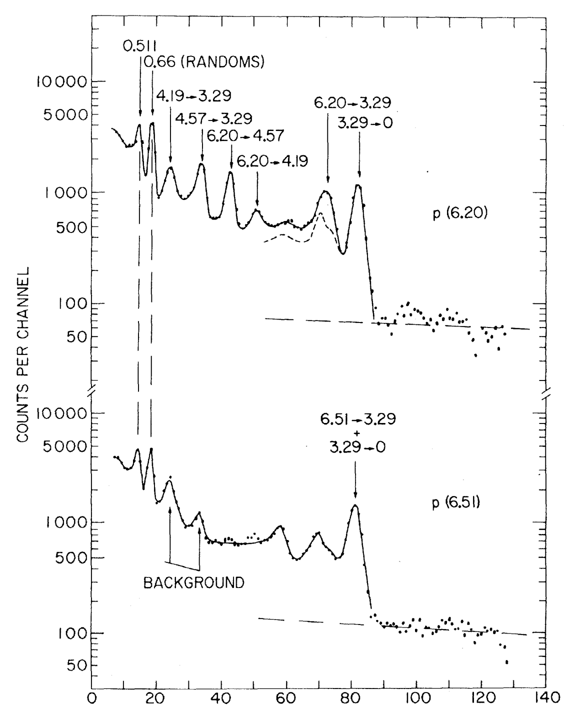

FIG. 4. Partial results of a two-parameter study of p-γ coincidences in the $S^{34}(t,p\gamma)S^{36}$ reaction at $E_t = 3.12$ MeV, illustrating the γ deexcitation of S^{36} states at 6.20 and 6.51 MeV. In these spectra, measured with a 5×6-in. NaI(Tl) detector, the various γ-ray peaks are identified according to the levels between which the transitions occur.

particle-detector resolution of ~90 keV are observed as a single broadened peak in Fig. 1. However, the decay modes are markedly different, and hence the γ spectra illustrating the decay of each were easily retrieved from the two-parameter data, as shown. The 5.57-MeV state deexcites ~100% to the 3.29-MeV state, while the 5.50-MeV state deexcites predominantly to the 3.29-MeV state, with a weaker branch (or branches) to the 4.19- and 4.57-MeV state (or states).

Figure 4 shows the decay of the states at 6.20 and 6.51 MeV. The 6.20-MeV state deexcites mainly via comparable branches to the states at 3.29 and 4.57 MeV, with a weak branch to the state at 4.19 MeV. The only observed decay mode for the 6.51-MeV state is via a 6.51 → 3.29 transition, which is not resolved from the resultant 3.29 → 0 cascade. As evident in Figs. 2–4, the range of γ-ray analysis for these two-parameter measurements was only sufficient to observe ground-state transitions for levels of $E_{ex} < 5$ MeV. Accordingly, a second measurement was made with the same range of proton analysis, but with the range of γ analysis set to cover possible ground-state transitions from levels of $E_{ex} < 7.5$ MeV. In this measurement the NaI(Tl) detector was set at 12-cm distance and $\theta_\gamma = 55°$, in order to minimize possible correlation effects on the measured intensities. From these measurements we conclude that for the levels at 5.26, 5.50, 5.57, 6.20, and 6.51 MeV, possible ground-state branches are individually less than 5% of the total decay modes. Both of the levels at 5.38 and 7.12 MeV exhibit relatively strong ground-state transitions, as shown in Fig. 5. The 7.12-MeV level decays predominantly to the S^{36} ground state, with weaker branches to the 3.29- and 4.57-MeV levels. We remark that some evidence for a 7.12 → 4.52 transition was seen from a γ-ray peak at 4.52 MeV, corresponding to the known 4.52 → 0 transition. The intensity, however, was ≲4%, and so this result cannot be taken as conclusive evidence for such a transition. For the 5.38-MeV level, the only decay mode observed is 5.38 → 0, and an upper limit of 10% can be placed on possible alternate decay modes. The peaks observed in this spectrum at $E_\gamma = 1.17$, 2.13, and 3.30 MeV result from the deexcitation of the 3.304-MeV level of S^{34} formed via the $S^{32}(t,p)S^{34}$ reaction. The fact that this second excited state of S^{34} decays to both the ground state (55%) and 2.13-MeV first excited state (45%) provided in these analyses a convenient means for distinguishing γ rays corresponding to the S^{36} 3.29 → 0 transition and to S^{34} 3.30 → 0.

The information presented in Figs. 1–5 is summarized schematically in Fig. 6, which illustrates the observed decay modes for the levels below 7.2

MeV in S^{36}. (For completeness, the information on spin-parity assignments obtained in the present work is also included.) The two-parameter data obtained at the five angles of the correlation measurement were next analyzed to obtain the angular correlation of the prominent γ rays, measured relative to the beam direction and the collinear particle detection. The γ-ray intensities for each angle were normalized according to the integrated beam current. The resultant data points were then fitted with the even-order Legendre-polynomial expansion $W(\theta)=\sum_\nu a_\nu P_\nu(\cos\theta)$. The results are summarized in Table I, which gives the a_ν and the normalized goodness-of-fit parameter, χ^2, for the two cases, where $\nu_{max}=2$ and $\nu_{max}=4$. These results will be discussed more fully with respect to the correlation analyses given in Sec. IV.

The branching ratios summarized in Fig. 6 were obtained from the measured peak areas of the various transitions, after incorporating the energy dependence of the peak efficiency curve for a 5 × 6-in. NaI(Tl) detector; and also small (<10%) corrections due to the effect of the angular correlations (Table I) on the intensities evident in Figs. 2–4.

As a final consideration, we note that some information on the lifetime of these S^{36} states is evident from the two-parameter data partially displayed in Figs. 1–5. The relative population of the individual states deduced from the coincidence measurements is within ~10% error identical to that evident in the singles measurement of Fig. 1. This observation, in conjunction with the resolving time used in the coincidence measurements, determines that these states have mean lives $\tau<40$ nsec. In the above, as below, the 3.34-MeV state is excepted from consideration.

For some of these states, an additional restriction can be placed from the observation – or nonobservation – of Doppler effects in the γ-ray spectra measured at angles $0°\leq\theta_\gamma\leq 90°$. At a bombarding energy $E_t=3.12$ MeV, the detection of protons within a "backward" cone of $\theta_p<10°$ ensures that the recoil S^{36} ions are moving forward within a narrow cone of half angle $\theta_R<3°$, with a well-defined recoil velocity $v_R/c=0.0070\pm0.0002$. This is large enough so that for states with short lifetimes there should be a measurable shift in the energy of the γ rays measured at $\theta_\gamma=0$ and 90°.

Accordingly, for each of the states illustrated in Figs. 2–4, the peak position of the $3.29\to 0$ transition was determined for both $\theta_\gamma=0$ and 90°. Measurable Doppler shifts were observed in this transition resulting from the decay of the states at 3.29, 4.57, 5.50, 6.20, 6.51, and 7.12 MeV, while the data for the levels at 4.19, 5.26, and 5.57 MeV were consistent with no shift. These results imply that the initial levels in the first group have lifetimes shorter than the slowing-down time of S^{36} ions in the target material, while those in the second group have lifetimes longer than this slowing-down time. A quantitative interpretation of these results is given in Sec. II C, as based on the somewhat more precise results of a Ge(Li) study of Doppler shifts for the lower lying of these levels.

B. Additional Measurements of Proton Spectra

In order to improve upon the particle resolution (~90 keV) obtained in the data illustrated in Fig. 1, a second sequence of measurements was undertaken employing a 200-μg/cm^2 target of Sb_2S_3 (enriched in S^{36}) on a 2-mg/cm^2 gold backing. With this target the particle spectra could be viewed directly in the presence of the tritons elastically scattered from the gold backing. Measurements were thus made at detection angles of $\theta_p=135$ and 167°. In the energy region above the elastic scattering background, peaks were clearly evident

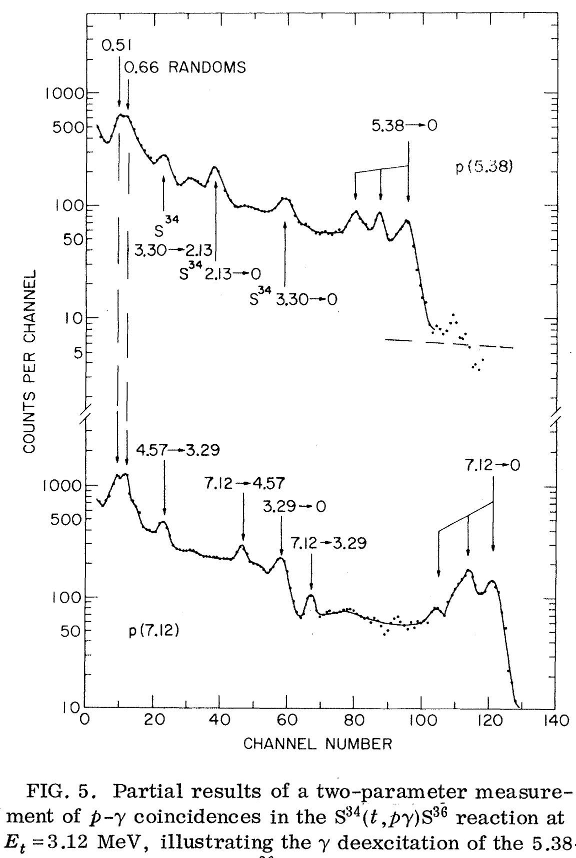

FIG. 5. Partial results of a two-parameter measurement of p-γ coincidences in the $S^{34}(t,p\gamma)S^{36}$ reaction at $E_t=3.12$ MeV, illustrating the γ deexcitation of the 5.38- and 7.12-MeV states of S^{36}. The γ-ray peaks are identified according to the levels between which the transitions occur. Evidence for a $S^{32}(t,p\gamma)S^{34}$ contamination of the 5.38-MeV spectrum is discussed in the text.

corresponding to the S^{36} ground state and to states at excitation energies in S^{36} of 3.29, 3.34, 4.19, 4.52, and 4.57 MeV. The identification of these peaks as due to $S^{34}(t,p)S^{36}$ was based on comparison measurements using targets of ordinary Sb_2S_3. The identification of α groups from $S^{34}(t,\alpha)P^{33}$ was based on the energy losses of the various peaks due to the insertion of a 250-μg/cm^2 aluminum absorber foil.

A portion of the data for $\theta_p = 135°$ illustrating the doublet levels at 3.29 and 3.34 MeV in S^{36} has been shown in Fig. 1. Table II summarizes the excitation energies thus determined for these states, relative to a value 3.287 ± 0.0015 MeV for the excitation energy of the 3.29-MeV state. The latter result is taken from the Ge(Li) measurements on the $3.29 \to 0$ transition as summarized in Sec. II C. No evidence was seen in these data for population of states at 2.00- and 2.85-MeV excitation in S^{36}, as previously reported[3] from the S^{34}-$(t,p)S^{36}$ reaction. From comparisons of the spectra measured with targets of ordinary sulfur content and targets enriched in S^{34}, it appears that all of the observed peaks in the proton energy region corresponding to S^{36} excitation energies of $0 < E_{ex} < 3$ MeV can be attributed to known states of S^{34} formed via $S^{32}(t,p)S^{34}$ resulting from the 14% S^{32} content of the enriched target.

In order to further check this point, additional measurements were undertaken at $\theta_p = 135$, 45, and 0°, using an aluminum absorber foil to stop elastically scattered tritons. By stopping the elastically scattered particles, higher beam currents could be utilized to improve statistics – although the poorer resolution necessitated a comparison of natural and enriched targets for each angle and triton bombarding energy.

To summarize the results: For all measurements, the maximum possible population of a 2.00-MeV (0^+) state is less than 5% that observed for population of the known 0^+ ground state and that at 3.34-MeV excitation. Similarly, the population of a possible 2.85-MeV (2^+) state is less than 10% that observed for population of the known 2^+ state at 3.29 MeV. In measurements at $\theta = 45$ and 135° for $E_t = 3.4$ MeV, which were specifically designed to search for these states, the corresponding limits on their population are individually <2%.

We now turn briefly to a reconsideration of the data illustrated partially in Fig. 1(b). The two-parameter data were specifically examined for the presence of 2.85- and 0.85-MeV γ rays, which would correspond, respectively, to the transitions $2.85 \to 0$ and $2.85 \to 2.00$. The results were negative indicating the population of a 2.85-MeV state, if present, was less than 5% that for population of the known 2^+ state at 3.29 MeV.

The only available decay mode for a 2.00-MeV

TABLE I. Results of an even-order Legendre-polynomial fit, of the form $W(\theta) = \sum_\nu a_\nu P_\nu(\cos\theta)$, for p-γ correlation data measured in the $S^{34}(t,p\gamma)S^{36}$ reaction at $E_t = 3.12$ MeV. Solutions for the a_ν and the corresponding χ^2 are given for $\nu_{max} = 2$ and 4, with $a_0 = 1$. These results are not corrected for detector size: The corresponding Q_ν are $Q_2 = 0.93$ and $Q_4 = 0.79$.

E_i (MeV)	Transition $E_i \to E_f$	$\nu_{max}=2$ a_2 (%)	χ^2	$\nu_{max}=4$ a_2 (%)	a_4 (%)	χ^2
3.29	$3.29 \to 0$	+24 ± 5	157	+51 ± 4	−105 ± 6	1.2
4.19	$4.19 \to 3.29$	−30 ± 4	1.8	−34 ± 4	+8 ± 4	0.9
	$3.29 \to 0$	+47 ± 5	17.9	+55 ± 5	−43 ± 6	0.8
4.52	$4.52 \to 0$	−7 ± 5	1.8	−7 ± 6	−7 ± 7	2.7
4.57	$4.57 \to 3.29$	+53 ± 5	0.7	+54 ± 5	−28 ± 6	1.0
	$3.29 \to 0$	+69 ± 6	35.0	+50 ± 6	+66 ± 7	0.3
5.26	$5.26 \to 3.29$	−46 ± 9	1.0	−43 ± 10	−8 ± 10	1.3
5.50	$5.50 \to 3.29$	+31 ± 9	4.3	+43 ± 10	−31 ± 10	1.8
	$3.29 \to 0$ [a]	+45 ± 6	3.4	+49 ± 6	−14 ± 6	3.0
5.57	$5.57 \to 3.29$	0 ± 6	1.4	−5 ± 7	+12 ± 8	1.0
	$3.29 \to 0$	+47 ± 8	1.3	+49 ± 8	−10 ± 8	1.2
6.20	$6.20 \to 4.57$	+17 ± 8	0.7	+12 ± 9	+13 ± 9	0.1
	$4.57 \to 3.29$	+30 ± 7	1.3	+32 ± 8	−5 ± 8	1.8
	$6.20 \to 3.29$	+57 ± 12	1.9	+53 ± 12	+12 ± 12	2.4
	$3.29 \to 0$ [a]	+36 ± 3	0.8	+32 ± 3	+16 ± 3	1.2
6.51	$6.51 \to 3.29$	+24 ± 8	5.9	+29 ± 8	−28 ± 8	1.5
	$3.29 \to 0$	+46 ± 8	0.5	+46 ± 8	−22 ± 8	0.7
	$6.51 \to 3.29 \to 0$ [b]	+38 ± 2	16.4	+41 ± 2	−18 ± 3	1.7

[a] In these cases the 3.29-MeV state is fed by cascade transitions other than those indicated.

[b] Correlation pattern given is for the net intensity of the incompletely resolved members of the $6.51 \to 3.29 \to 0$ cascade transitions.

$J^{\pi}=0^+$ state would be by $E0$ decay to the 0^+ ground state. In the particle spectrum measured in coincidence with 511-keV γ rays, there is no evidence for a peak corresponding to a state at 2.00 MeV in S^{36}, while the known 0^+ state at 3.34 MeV is seen quite clearly. From this we conclude that the 2.00-MeV state is either not populated under these experimental conditions, or the state must have a lifetime appreciably longer than the resolving time ($\tau = 40$ nsec) used in the coincidence experiment. Thus the net evidence appears to rule rather strongly against the existence of states in S^{36} at 2.00- and 2.85-MeV excitation.

C. Ge(Li) Measurements of γ-Ray Spectra

For these measurements a 400-μg/cm^2 target of Sb_2S_3 placed at the center of a 1.3-in.-diam glass-walled chamber was used. γ rays were detected by a 40-cc Ge(Li) detector mounted on a goniometer which could be rotated to study the region $0° \leq \theta_\gamma \leq 140°$. Pulses from the detector, after amplification using standard pole-zero and dc restoration equipment were analyzed by a 4096-channel analog-to-digital converter and stored in $\frac{1}{4}$ section of a 16 384-channel memory. Spectra were measured at $\theta_\gamma = 90°$ in order to determine accurately the transition energies for those lines which could be identified as arising from transitions in S^{36}. Additional measurements at $\theta_\gamma = 0$ and 135° were made to search for possible Doppler shifts of these transitions, in order to gain some information on the lifetimes of these states.

Figure 7 shows a portion of the data measured at 0 and 90°, illustrating the line shapes observed for transitions from the levels at 3.29, 4.19, and 4.57 MeV. The dispersion is 1.162 keV/channel and the resolution, as measured for the 1.33-MeV line of Co^{60}, was 1.9-keV (full width at half maximum). The measured S^{36} transition energies are: $3.29 \to 0$, 3287 ± 1.5 keV; $4.19 \to 3.29$, 902 ± 1.5 keV; and $4.57 \to 3.29$, 1284 ± 1.5 keV. Energy calibration was based on the presence in these data of annihilation radiation and of transitions from known states[3] of Cl^{36} formed via the (t,n) reaction. Additional energy calibrations were based on sources of Co^{60} (1.173 and 1.332 MeV) and RaTh (2.614 MeV). Table II summarizes the values for the excitation energies of these S^{36} states as derived from this work. The identification of the 902- and 1284-keV lines as due to transitions in S^{36} is based in part upon the close correspondence of the excitation energies as determined in the Ge(Li) measurements and in the proton measurements as summarized in Table II.

The identification of transitions from higher-lying states in S^{36} was complicated by the fact that the $S^{34}(t,p)S^{36}$ reaction cross section was only equal to that of the competing $S^{34}(t,\alpha)P^{33}$ reaction and approximately three times weaker than the $S^{34}(t,n)Cl^{36}$ reaction. Also present in these data were lines from the (t,p) and (t,n) reactions on the 14% S^{32} present in the target. Accordingly, we present

TABLE II. Excitation energies for S^{36} states of $E_{ex} > 3$ MeV as determined in this and previous experiments. Energies are in MeV; the corresponding uncertainties (in keV) are given in parentheses. The combined results of the p-γ coincidence measurements are summarized in column 1, while columns 2 and 3 list the results from the high-resolution proton and γ-ray singles measurements. The previous results are taken from, or are averages of, the values quoted in the references cited. The last column summarizes the best values, obtained as a weighted average of all the entries.

Present results: method indicated				
p-γ	Protons	γ rays	Previous results	Average
3.287[a]	3.287[a]	3.287 (1.5)	3.297 (10)[b,c]	3.287 (1.5)
3.335 (10)	3.342 (4)	3.338 (16)[d]	3.360 (15)[b]	3.342 (4)
4.183 (8)	4.187 (5)	4.189 (3)	4.204 (15)[b]	4.188 (3)
4.510 (12)	4.515 (6)	···	4.523 (10)[c]	4.518 (6)
4.568 (8)	4.567 (5)	4.571 (3)	4.57 (10)[c]	4.570 (3)
5.260 (10)				5.260 (10)
5.375 (10)				5.375 (10)
5.495 (10)				5.495 (10)
5.567 (10)				5.567 (10)
6.202 (10)				6.202 (10)
6.508 (10)			6.511 (15)[c]	6.508 (10)
7.12 (20)			7.12 (20)[c]	7.12 (20)

[a]Taken as a calibration energy based on the result given in column 3.

[b]See Ref. 3.

[c]See Ref. 6.

[d]Taken from measurement of the internal-pair spectrum. The remainder of the values in this column are based on Ge(Li) measurements.

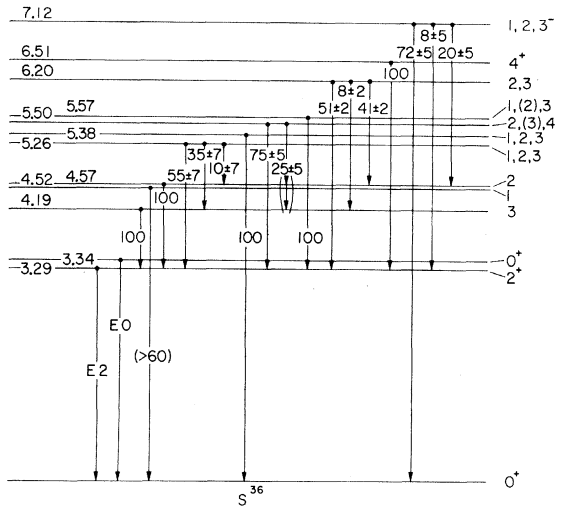

FIG. 6. Level diagram for S^{36} summarizing the results of the present investigation. The γ-ray branching data are discussed in Sec. II A, and the spin-parity assignments in Sec. III and IV.

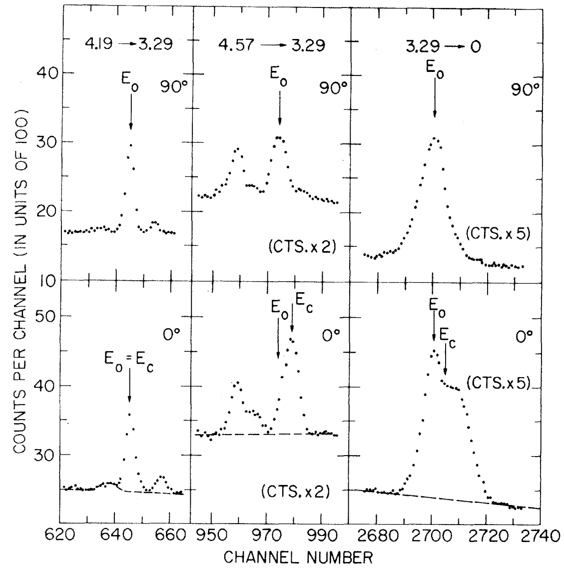

FIG. 7. Ge(Li) spectra of γ rays illustrating the line shapes observed at $\theta_\gamma = 0$ and $90°$ for the primary transitions from S^{36} levels at 3.29, 4.19, and 4.57 MeV, formed via the $S^{34}(t, p\gamma)S^{36}$ reaction at $E_t = 3.40$ MeV. The lines are labeled according to the levels between which the transitions occur. For the 0° data the centroid energy E_c of each distribution is indicated, as is also the rest energy E_0, as determined from the peak positions observed at 90°. The dashed lines show the backgrounds assumed in the centroid calculations for $\theta_\gamma = 0°$. The dispersion is 1.162 keV/channel.

here only those results for which the identification is quite certain. To check this point, the 4.19 → 3.29 and 4.57 → 3.29 transitions were also observed in coincidence with the 3.29 → 0 transition as detected by a 5×6-in. NaI(Tl) detector, thus establishing positive identification of their origin.

As is evident in Fig. 7, significant Doppler effects are seen for both the 3.29 → 0 and 4.57 → 3.29 transitions. We take (see for examples Refs. 9 and 10) the mean velocity of the recoiling S^{36} ions as $\nu_R/c = \beta_{c.m.}(1 + \beta_R\langle \cos\theta_{c.m.}\rangle)$, where $\beta_{c.m.}$ is the velocity of the center of mass, β_R is the velocity of the recoil ion in the center-of-mass system, and $\langle\cos\theta_{c.m.}\rangle$ is the mean angle of the recoil ion, also in the center-of-mass system. Under the assumption that the angular distribution is essentially isotropic, we use[9] as an estimate $\langle \cos\theta_{c.m.}\rangle = 0 \pm 0.3$, and thus calculate that for a bombarding energy $E_t = 3.1$ MeV, $\nu_R/c = 0.0038 \pm 0.0012$. Thus the kinematic 0-90° shift ΔE_k is expected to be $(0.38 \pm 0.12)\%$ of the transition energy.

The transition energies for $\theta_\gamma = 90°$ were determined from Gaussian fits to the peak shapes, and also by computing the centroid of the net peak spectrum, after subtraction of a smooth background. The assumed backgrounds used in the determination of the centroids for $\theta_\gamma = 0°$ are indicated in Fig. 7, as are also the centroid positions. From these data the Doppler-shift-attenuation factors were calculated as $F(\tau) = \Delta E_{\rm exp}/\Delta E_k$, where $\Delta E_{\rm exp}$ is the experimentally measured 0-90° centroid shift. (Specific examples of this approach, together with a discussion of the method, have been given previously.[10,12])

The results indicate no shift for the 4.19 → 3.29 transition, $F(\tau) < 0.06$; while a full shift $F(\tau) > 0.70$ is observed for the 4.57 → 3.29 transition. Curves of $F(\tau)$ versus τ were calculated for S^{36} ions for the kinematics specified above, using a computer program which accounts for the slowing down in both the Sb_2S_3 target and the Mo backing. The electronic and nuclear stopping powers for S^{36} ions in Sb_2S_3 and Mo were calculated from the Lindhard-Scharff-Schiøtt representations[13] of the stopping process – and the effects of nuclear stopping were taken explicitly into account.[14] The results determine that the restrictions on $F(\tau)$ given above correspond to the following restrictions on the mean life τ: 4.19-MeV level, $\tau > 2$ psec; 4.57-MeV level, $\tau < 0.1$ psec. For the 3.29 → 0 transition, the value of $F(\tau)$ calculated directly from the data of Fig. 7 is certainly too low, to the extent that the 3.29-MeV level is populated in part by transitions from higher-lying levels, some of which (as for example the 4.19-MeV level) are longer lived. The contribution to the net 3.29 → 0 intensity due to the 4.19 → 3.29 feeding is 15%, as calculated from the relative intensities of Fig. 7. This contribution, which must appear as a symmetric Gaussian contribution at E_0, was directly subtracted. As based on the $4.57 \rightarrow 3.29$ intensity, and on the intensity of the 4.57 and 3.29-MeV peaks seen in the particle spectra at several angles θ_p, we calculate that ~50% of the measured intensity results from feeding of the 3.29-MeV state via the short-lived 4.57-MeV level and from direct population in the (t,p) reaction. The remainder (~35%) must therefore arise from cascade transitions from higher-lying states which, as shown in Sec. II A, are predominantly short lived. We thus take $F(\tau) = 0.48 \pm 0.06$ as a central value which incorporates the above uncertainties. The corresponding value for the mean life is $\tau = 0.20 \pm 0.035$ psec.

We now turn to a quantitative interpretation of the lifetime information obtained in the p-γ coincidence measurements of Sec. II A. All of these latter measurements were made on the Doppler-shift attenuations evident in the $3.29 \rightarrow 0$ transition, as resulting from the deexcitation of the various initial levels, and hence the lifetime of the 3.29-MeV level is an essential parameter of the analysis.

For the 4.19-MeV level, the result $F(\tau) < 0.24$ is in agreement with the lifetime restriction obtained in the Ge(Li) measurement. The results obtained for the 3.29- and 4.57-MeV levels were $F(\tau) = 0.4 \pm 0.2$ and $F(\tau) = 0.6 \pm 0.1$, respectively. From the Ge(Li) results on the $4.57 \rightarrow 3.29$ transition, it is evident that the NaI(Tl) result obtained for the 4.57-MeV level is dominated by the lifetime of the 3.29-MeV level, and we thus take for the $3.29 \rightarrow 0$ transition the average value $F(\tau) = 0.55 \pm 0.10$. From curves of $F(\tau)$ versus τ calculated for the S^{36} recoil velocity $v_R/c = 0.0070$, the corresponding value of the mean life of the 3.29-MeV level is $\tau = 0.19 \pm 0.05$ psec. This is in satisfactory agreement with the Ge(Li) results given above, and we adopt the average value $\tau = 0.20 \pm 0.03$ psec for the 3.29-MeV level.

For both the 5.26- and 5.57-MeV levels, the experimental restriction on the $3.29 \rightarrow 0$ transition is $F(\tau) < 0.40$, corresponding to a restriction on the primary transition $F(\tau) < 0.6$, and thus on the mean lives of these levels of $\tau > 0.2$ psec. Conversely, the implied restriction on the primary transitions from the 5.50-, 6.20-, and 7.12-MeV levels is $F(\tau) > 0.5$, corresponding to mean lifetimes $\tau < 0.3$ psec. A similar restriction $\tau < 0.3$ psec is obtained for the 6.51-MeV level, after accounting for possible correlation effects on the measured shift of the unresolved $6.51 \rightarrow 3.29 \rightarrow 0$ cascade transitions.

III. DEEXCITATION OF THE S^{36} 3.34-MeV STATE

In the p-γ coincidence measurements described above, the only radiation observed in coincidence with the 3.34-MeV proton group was 0.51-MeV radiation. These results determine that there is no measurable decay to the 3.29-MeV state, which is only 55 ± 5 keV lower in excitation energy. In view of the 0^+ assignment previously set forth for this level via the (t,p) reaction[3], it is suggested that the major decay is by internal-pair emission to a lower-lying state, presumably to the 0^+ ground state. Since lower-lying states were also reported[3] at 2.85 and 2.00 MeV, the latter of which is also suggested as a $J^\pi = 0^+$ level, a direct measurement of the 3.34 decay mode was deemed necessary. In the following, therefore, we report a measurement of the internal-pair-conversion deexcitation of the 3.34-MeV level, and also a measurement of the lifetime of the state.

A. Measurement of the Internal-Pair-Conversion Spectrum

The 3.34-MeV level was formed via the $S^{34}(t,p)$-S^{36} reaction at $E_t = 3.4$ MeV, using a 1-mg/cm^2 enriched target of Sb_2S_3 on a 1.7-mg/cm^2 Ni backing. The target was located at the object position of an intermediate-image spectrometer used for the measurements. The operation and calibration of the device as an internal-pair spectrometer has been described in detail previously,[15,16] and we therefore merely outline the general procedure. Very briefly, positron-electron pairs emitted at an angle $\alpha = 46 \pm 1°$ relative to the beam axis are

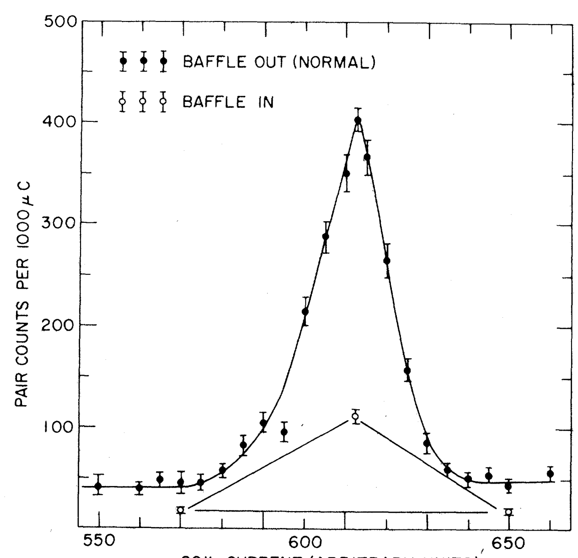

FIG. 8. Spectrum of internal pairs from the $S^{34}(t,p)S^{36}$ reaction, illustrating the $E0$ transition $3.34 \rightarrow 0$ in S^{36}. These data were measured with an intermediate-image spectrometer at $E_t = 3.45$ MeV, with an instrumental resolution of ~2.8%. The open circles show the points measured with the correlation baffle in place, which uniquely determines the character of the transition as $E0$.

focused by an axial magnetic field to form an intermediate image at an annulus (whose radial dimensions determine the spectrometer resolution) before being brought to a final focus approximately on axis. The positron-electron pairs thus follow helical paths, of opposite sense, and are detected in coincidence at the focal region by a pair of crystal-photomultiplier detectors.

Figure 8 shows the pair spectrum measured for the decay of the 3.34-MeV level. Illustrated here are the pair events measured as a function of the coil current providing the spectrometer field, using a spectrometer resolution of 2.8%. The energy calibration of the spectrometer was determined independently by measuring the internal-pair spectrum of the O^{16} 6.06 → 0 MeV $E0$ decay, and also by using the device as a simple spectrometer in order to observe the K conversion line of the Bi^{207} 1.064-MeV γ-ray transition.

The energy of the transition evident in Fig. 8 is determined as 3.338 ± 0.016 MeV. The transition is clearly 3.34 → 0, and the excitation energy thus deduced for the initial state in S^{36} is in excellent agreement with that obtained from the particle spectra as summarized in Table II. No evidence was seen for a possible 2.0-MeV pair transition, corresponding to a possible 2.000 (0^+) → 0.0 (0^+) transition in S^{36}. However, since the internal-pair-conversion coefficient decreases rapidly with transition energy,[15] conclusions on the nonexistence of a 0^+ state of 2.00 MeV are weaker than

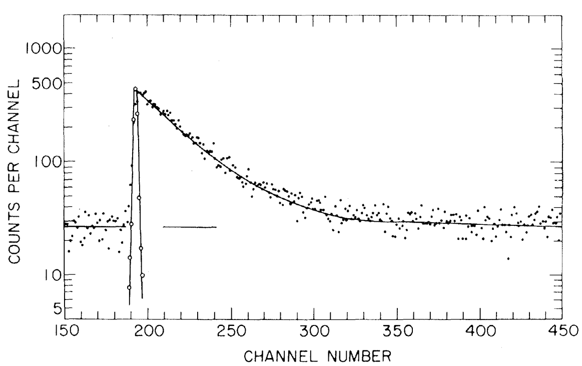

FIG. 9. Spectrum of coincidence pulses from a time-amplitude converter (TAC) illustrating the delayed spectrum of pulses from the $E0$ decay of the S^{36} 3.34-MeV level. The TAC was started by a fast signal provided by a voltage gate set on the 3.29- and 3.34-MeV proton groups, and stopped by fast pulses from a gate set on the γ spectrum. The open circles show the prompt peak measured in coincidence with γ rays of energy >0.6 MeV due to the 3.29 → 0 transition. The solid points were measured simultaneously with the voltage gate set to observe the 0.51-MeV radiation resulting from annihilation of the positron. The dispersion is 0.215 nsec/channel. The solid curve shows a two-component fit to these data, which determines $\tau_m(3.34) = 12.7 \pm 0.3$ nsec.

that obtained from the proton studies of Sec. II B. The multipole character of the transition was determined uniquely, following procedures given previously,[15,16] by the insertion of a special baffle at the spectrometer annulus. The function of the baffle is to restrict the pair flux to correspond to β^- and β^+ pairs emitted within a definite range of azimuthal angles ω^+ and ω^-. (This is possible, since the helical paths of β^+ and β^- are of opposite sense.) The results of this measurement, which provide information on the β^+-β^- correlation, are shown by the open circles in Fig. 8. Defining as previously the ratio $R_\omega = Y(\text{in})/Y(\text{out})$, where Y(in) and Y(out) are the net peak intensities measured with the baffle "in" and "out," respectively, we find for the S^{36} 3.34 → 0 MeV transition $R_\omega = 0.26 \pm 0.02$. From the previously established calibration[16] for the spectrometer, the expected ratios are $R_\omega = 0.25$ if the transition is $E0$, $R_\omega = 0.17$ if $E1$, while the values of R_ω for the higher-order multipoles are increasingly smaller. The calibration was again checked by measuring R_ω for the O^{16} 6.06 → 0 pair line, with the result for this transition $R_\omega = 0.240 \pm 0.005$. Since R_ω is not a function of energy for $E0$ transitions, this establishes a satisfactory check on the calibration and we conclude that the S^{36} 3.34 → 0 transition is indeed $E0$.

B. Measurement of the Mean Lifetime

The mean life of the 3.34-MeV level was measured by the associated-particle technique.[12] Protons from the $S^{34}(t,p)S^{36}$ reaction, initiated by 3.26-MeV triton bombardment of a 400-μg/cm^2 Sb_2S_3 target, were detected by an annular detector centered at $\theta_p = 180°$. 511-keV γ rays resulting from annihilation of the positron member of the internal-pair deexcitation transition were detected by a 3-in.-diameter × 2-in.-thick plastic scintillator coupled to a fast (RCA 8575) photomultiplier. The spectrum of time-delay pulses was generated by a time-to-amplitude converter (TAC) set to operate in the range 0–200 nsec. A $t = 0$ signal was supplied by a voltage gate set on the (unresolved) proton groups corresponding to the 3.29- and 3.34-MeV levels. The conversion was stopped by a second pulse signaling detection of the associated 511-keV γ ray in the plastic scintillator. The pertinent data are summarized in Fig. 9. The solid points show the spectrum measured with a voltage gate set on the pulse region in the γ detector corresponding to the energy region 200 keV $\leq E_\gamma \leq$ 500 keV. The resultant spectrum shows a flat background (due to random counts) on which is superimposed the time-delay spectrum characterizing the lifetime of the 3.34-MeV state. For comparison, the time resolution of the system

(~0.5 nsec) is shown in Fig. 9 by the spectrum measured with a voltage gate set for $E_\gamma > 600$ keV, illustrating the "prompt" decay of the 3.29-MeV level. At this bombarding energy, the relative population of these two states were in the ratio (3.34/3.29)/(4/1). The time dispersion for these data was established by observing the shift of the prompt peak as a function of known delays inserted in one or the other of the two timing channels. The calibration gives 0.215 nsec/channel.

The delayed spectrum of Fig. 9 was next fitted by a least-squares program, in which the data were represented as the sum of two exponentials, with the decay time for one set as $\tau = \infty$ to approximate the background due to random coincidences. From fits to various regions of the decay spectrum we obtain the value $\tau = 12.7 \pm 0.3$ nsec for the mean lifetime of the S^{36} 3.34-MeV level, where the quoted uncertainty was chosen large enough to cover the divergence of solutions for the various regions of the fit.

IV. ANGULAR-CORRELATION ANALYSIS

A. General Procedure

The angular-correlation information obtained in the proton-γ-ray coincidence measurements (Sec. II) has been partially summarized in Table I, which shows the results of an even-order Legendre-polynomial fit to the experimental data. Results are shown for those γ rays originating from the indicated initial levels whose intensities could be reliably extracted, as a function of angle θ_γ, from the experimental data. Certain restrictions on the spins of the initial levels are immediately apparent from the results summarized in Table I: The observation of a statistically significant (nonzero) term in $P_4(\cos\theta)$ for one or more of the deexcitation transitions determines that the initial level has $J \geq 2$. Thus for the levels at 3.29, 4.19, 4.57, 5.50, 6.20, and 6.51 MeV, possible spin assignments 0 or 1 are immediately ruled out. For the remaining levels, the observation of significant terms in $P_2(\cos\theta)$ determines $J \geq 1$.

In the following, we discuss the quantitative interpretation of these results for each of the levels of S^{36} thus studied. The method is that designated as Method II by Litherland and Ferguson,[8] and uses explicitly the formalism of Polletti and Warburton,[17] which is in accord with the phase definition of Rose and Brink.[18] The general procedure has been illustrated in considerable detail previously,[9,10,17] and we therefore outline those specific considerations which apply to correlation measurements in the $S^{34}(t,p\gamma)S^{36}$ reaction. We note first that the collinear detection of protons insures that the initial levels of S^{36} formed by the (t,p) reaction are restricted to magnetic substates for which the magnetic quantum number m has $|m| \leq 1$. That is, for a given level $J \geq 1$, only the $m = 0$ and $m = \pm 1$ substates are involved in the emission of the subsequent primary γ radiations.

The procedure of analysis, very briefly, was therefore as follows: For a given initial level as formed directly in the (t,p) reaction, the experimental correlation data were fitted by a least-squares computer program for various sets of assumed spins for the initial level and those levels linked by the deexcitation transitions. The parameters of the fit were the magnetic-substate population parameters, $P(\alpha)$, where the $\alpha = |m|$ and the normalization is such that $P(0) + 2P(1) = 1$. Fits were thus attempted for discrete values of the $(L+1)/L$ mixing in the cascade radiations. For each such theoretical fit the normalized χ^2 was calculated as an indication of the acceptability of the computed fit. The expectation value of χ^2 is unity for the physically correct set of spins and mixing ratios: Probability tables were subsequently used to rule against cases for which the values of χ^2 were inordinately large. Examples of this procedure are illustrated in the following discussion of the various levels.

A minor complication of these analyses arises from the fact that the proton detector subtends a finite solid angle, and thus permits a weak population of the $m = +2$ substate.[17] This was accounted for in this analysis by allowing for a population $P(2)$ of the $m = +2$ substate up to 10% of the total population. Unless otherwise stated, the effect was generally small, and has been incorporated in the illustrated results.

In the following, we discuss the conclusions obtained from the correlation analysis for each level studied. The information provided by the lifetime restrictions (Sec. II) has been used in some cases to ascertain the multipole character of the primary transitions from these levels, and also from the levels at 3.34-, 5.38-, and 7.12-MeV, which were not studied in the correlation measurements.

B. Results

3.29-MeV Level

The observation of a large term in $P_4(\cos\theta)$ in the measured distribution (see Table I) coupled with the measured lifetimes immediately suggests $J^\pi = 2^+$ for this level. Since the transition to the ground state must be a pure multipole of order $L = J$, the only parameter of the fit is the substate population ratio $P(0)/P(1)$. The data were fitted for assumed spins $J \leq 4$ for the initial level, with the resultant goodness of fit parametrized as follows: For $J=0$, 1, 3, or 4, $\chi^2>150$, which considerably exceeds the 0.01% probability limit at $\chi^2=5.5$. For $J=2$, an excellent fit is obtained as indicated by a value $\chi^2=0.84$, which compares well with the simple Legendre-polynomial fit given in

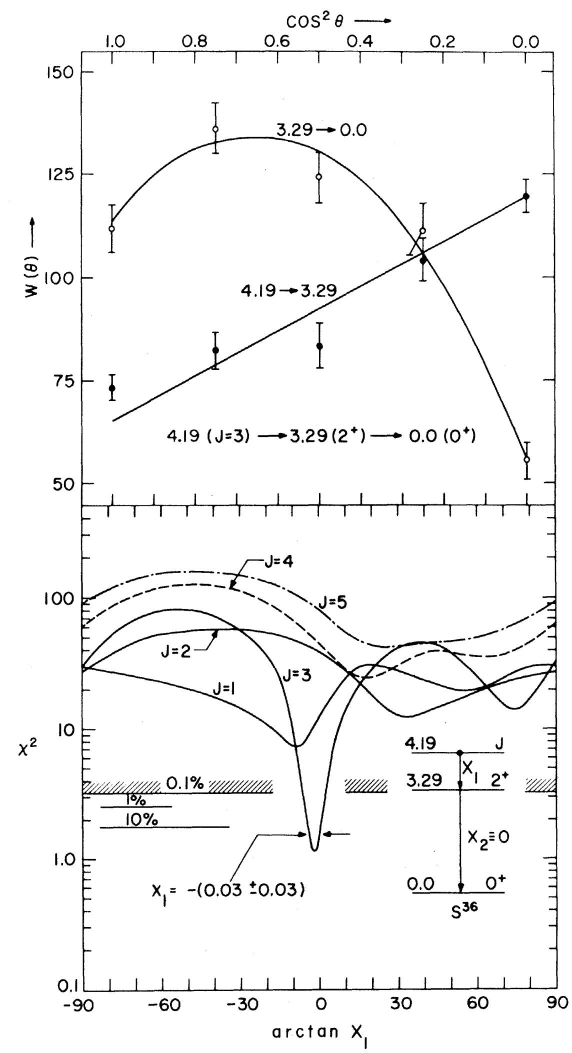

FIG. 10. Results of a least-squares fit to correlation patterns measured for the $4.19 \rightarrow 3.29 \rightarrow 0$ cascade transitions. The upper plot shows the measured correlations. The lower plot shows the results of an attempt to fit these data simultaneously for assumed spins for the 4.19-MeV level of $1 \geq J \geq 5$. Here we have plotted the goodness-of-fit parameter χ^2 as a function of x_1, the mixing ratio in the $4.19 \rightarrow 3.29$ transition. As indicated in the inset level diagram, the spin of the 3.29-MeV level is taken as $J=2$ (as determined previously) and the mixing in the 3.29 $\rightarrow 0$ transition is given as $x_2=0$ (pure quadrupole in character). The various confidence limits are indicated. For example, the statistical probability (for a correct set of J and x_1) that χ^2 exceeds the 0.1% limit is simply 0.1%. As seen, only $J=3$ is an acceptable fit to the data obtained. The solid curve in the upper plots shows the theoretical distributions calculated for $J=3$, $x_1=-0.03$.

Table I for $\nu_{max}=4$. From the measured mean lifetime for this level, $\tau=0.20\pm0.03$ psec, the corresponding transition strengths, in Weisskopf units (W.u.), were computed[19] for the alternate possibilities of $E2$ or $M2$ character for the transition. If the transition were $M2$, the corresponding transition strength would be $|M(M2)|^2=52\pm8$ W.u., which we reject on the basis of local systematics[20] as inordinately large. Thus, the 3.29-MeV level has even parity, $J^\pi=2^+$, since it decays by an $E2$ transition to the S^{36} 0^+ ground state. The computed $E2$ strength is $|M(E2)|^2=1.47\pm0.22$ W.u.

3.34-MeV Level

Obviously, no correlation information was obtained for this level. However, in view of the $J^\pi=2^+$ assignment established for the 3.29-MeV level, it is of interest to compute the probable intensity of a 3.34 $(0^+)\rightarrow 3.29$ (2^+) branch. The partial lifetime for $E0$ deexcitation of this level is essentially the measured meanlife, $\tau(E0)=12.7\pm0.3$ nsec. The partial lifetime calculated for a 55 ± 5-keV $E2$ transition $3.34\rightarrow3.29$, assuming an $E2$ strength of 1 W.u., is $\tau(E2)=22\times10^4$ nsec. The corresponding branching ratio for a possible $E2$ transition, 5.5×10^{-3}%, implies that a possible branch $3.34\rightarrow3.29$ would be extremely difficult to see experimentally, even assuming a significant enhancement of the $E2$ strength.

4.19-MeV Level

The experimental correlation patterns for the two members of the $4.19\rightarrow3.29\rightarrow0$ cascade transition are shown in the upper portion of Fig. 10. The lower plot summarizes the results of an attempt to fit these data simultaneously for assumed spins for the 4.19-MeV level of $1\leq J\leq5$. For each assumed spin J we have plotted the goodness-of-fit parameter χ^2 as a function of x_1, the $(L+1)/L$ mixing in the $4.19\rightarrow3.29$ transition. The mixing x_2 in the $2^+\rightarrow0^+$, $3.29\rightarrow0.0$ transition is identically zero, as indicated in the insert. An acceptable fit is obtained only for the $J=3$ possibility. For all others (including $J=0$ which is not shown) the minimal values of χ^2 exceed the 0.1% confidence limit, and are thus rejected. From the solution for x_1 indicated for $J=3$, $x_1=-(0.03\pm0.03)$, it is clear that the transition is predominantly dipole. If the parity of the 4.19-MeV level is even, then the $4.19\rightarrow3.29$ transition is $M1$ in character, and from the lifetime restriction $\tau>2$ psec, we calculate an upper limit on the corresponding $M1$ strength $|M(M1)|^2<0.021$ W.u. Assuming odd parity for the 4.19-MeV level, the corresponding restrictions on the $E1$ strength would be $|M(E1)|^2<0.0006$ W.u.

4.52-MeV Level

Although the correlation pattern measured for the $4.52 \to 0$ transition is not significantly different from isotropy, the level may not have $J=0$, since it connects by a γ-ray transition to the $J^{\pi}=0^{+}$ ground state. An acceptable fit to the data was obtained for an assignment $J=1$ for this level, as indicated in Table III. The minimal value of χ^2 for fits for $J=2$, 3, 4 was 27, which greatly exceeds the 0.1% confidence limit for three degrees of freedom. Thus for the 4.52-MeV level we have uniquely $J=1$. No information other than the crude limit $\tau < 40$ nsec is available for this level.

4.57-MeV Level

The experimental data on the $4.57 \to 3.29 \to 0$ correlation patterns are shown in the upper portion of Fig. 11. The results of a theoretical fit to these data for assumed spins for the 4.57-MeV level of $1 \leq J \leq 5$ are shown in the lower plot. Possible assignments $J=1$, 3, 4, 5 are excluded (as well as $J=0$), since the minimal values of χ^2 considerably exceed the 0.1% confidence limit. For $J=2$ we find an acceptable fit for a quadrupole-dipole mixing in the $4.57 \to 3.29$ transition of $x=-(0.06 \pm 0.06)$. The result is thus not inconsistent with the transition being pure dipole. From the lifetime limit established for this level, $\tau < 0.1$ psec, we obtain the following restrictions on the dipole transition strengths: if $M1$, then $|M(M1)|^2 > 0.15$ W.u., while if $E1$, then $|M(E1)|^2 > 0.0042$ W.u. Either possibility seems reasonable, and thus the parity of the 4.57-MeV level is not determined by this experiment.

5.26-MeV Level

Analysis of the correlation data on the $5.26 \to 3.29$ transition restricts the spin of the 5.26-MeV level to the possibilities $J=1$, 2, 3 with the corresponding restrictions on the mixing ratio as summarized in Table III. Unfortunately, the experimental lower limit on the lifetime of the 5.26-MeV level does not provide any interesting clues as to the character of the transition for these various possibilities. The angular distribution of the resultant $3.29 \to 0$ transition could not be reliably extracted from the data, due to a weak unresolved contribution from the S^{34} $3.30 \to 0$ transition.

5.50-MeV-Level

Analyses of the correlation data on the $5.50 \to 3.29$ transition restricts the spin of the initial level to the possibilities $J=2$, 3, or 4, with the corresponding restrictions on the mixing ratio summarized in Table III. As indicated in Table III, the minimal value of χ^2 obtained for the $J=3$ possibility has a statistical probability of only 0.8%, and hence we consider $J=3$ considerably less probable than $J=2$ or 4. We note that for J

TABLE III. Summary of restrictions on the $(L+1)/L$ mixing ratio x for the indicated transitions in S^{36}, as determined from p-γ correlation measurements. In some cases the correlation analysis allows more than one possibility J_i for the spin of the initial level E_i, and the corresponding solutions for x are indicated for each allowed possibility. Less-likely possibilities J_i are indicated in parentheses, as distinguished also by the larger values of χ^2 obtained in the fits to the data. For convenience, the restrictions on the mean lives of the initial levels are also given.

E_i (MeV)	τ (psec)	Transition $E_i \to E_f$	J_i (Assumed)	J_f	Restrictions on the $(L+1)/L$ mixing ratio $=x$	χ^2
3.29	0.20 ± 0.03	$3.29 \to 0$	2	0	$x=0$	0.8
4.19	>2	$4.19 \to 3.29$	3	2	$x=-(0.03 \pm 0.03)$	1.1
4.52	⋯	$4.52 \to 0$	1	0	$x=0$	1.8
4.57	<0.1	$4.57 \to 3.29$	2	2	$x=-(0.06 \pm 0.06)$	1.4
5.26	>0.2	$5.26 \to 3.29$	1	2	$x \leq -0.1$ or $x \geq 5$	1.0
5.26		$5.26 \to 3.29$	2	2	$x \geq 0.47$	0.9
5.26		$5.26 \to 3.29$	3	2	$x=0.09 \pm 0.09$ or $x=2.4 \pm 0.5$	1.0 or 1.5
5.50	<0.3	$5.50 \to 3.29$	2	2	$x=-(2.4 \pm 0.5)$	1.2
5.50		$5.50 \to 3.29$	(3)	2	$x < -0.25$	4.6 [a]
5.50		$5.50 \to 3.29$	4	2	$x=+(0.02 \pm 0.03)$	1.0
5.57	>0.2	$5.56 \to 3.29$	1	2	$x=+(0.07 \pm 0.07)$ or $x=+(4^{+7}_{-3})$	1.0 or 2.8 [a]
5.57		$5.56 \to 3.29$	(2)	2	$x=+(0.27^{+0.15}_{-0.09})$	2.6 [a]
5.57		$5.56 \to 3.29$	3	2	$x=-(0.17 \pm 0.05)$	1.0
6.20	<0.3	$6.20 \to 4.57$	2	2	$x=+(0.20 \pm 0.08)$	1.1
6.20		$6.20 \to 3.29$	2	2	$x=-(0.05 \pm 0.13)$	1.8
6.20		$6.20 \to 4.57$	3	2	$x=-(0.28 \pm 0.09)$ or $x > 5.6$	0.9
6.20		$6.20 \to 3.29$	3	2	$x=-(0.6 \pm 0.1)$	1.4
6.51	<0.3	$6.51 \to 3.29$	4	2	$x=+(0.03 \pm 0.03)$	1.2

[a] These values of χ^2 correspond to statistical probabilities of less than 1%.

= 4, the solution for x is consistent with the transition being pure quadrupole in character. Thus all possibilities are consistent with the experimental upper limit on the lifetime of the 5.50-MeV level. The remaining possibilities for J are quite firmly rejected. No attempt was made to fit the $3.29 \to 0$ correlation pattern, since the 3.29-MeV level is populated also by cascades other than $5.50 \to 3.29$. However, the value of χ^2 obtained from a simple Legendre-polynomial fit to the net $5.50 \to 3.29 \to 0$ correlation pattern is $\chi^2 = 5.1$ for $\nu_{max} = 2$, and $\chi^2 = 1.0$ for $\nu_{max} = 4$. Thus these results also rule very strongly against possible assignments $J = 0$ or 1.

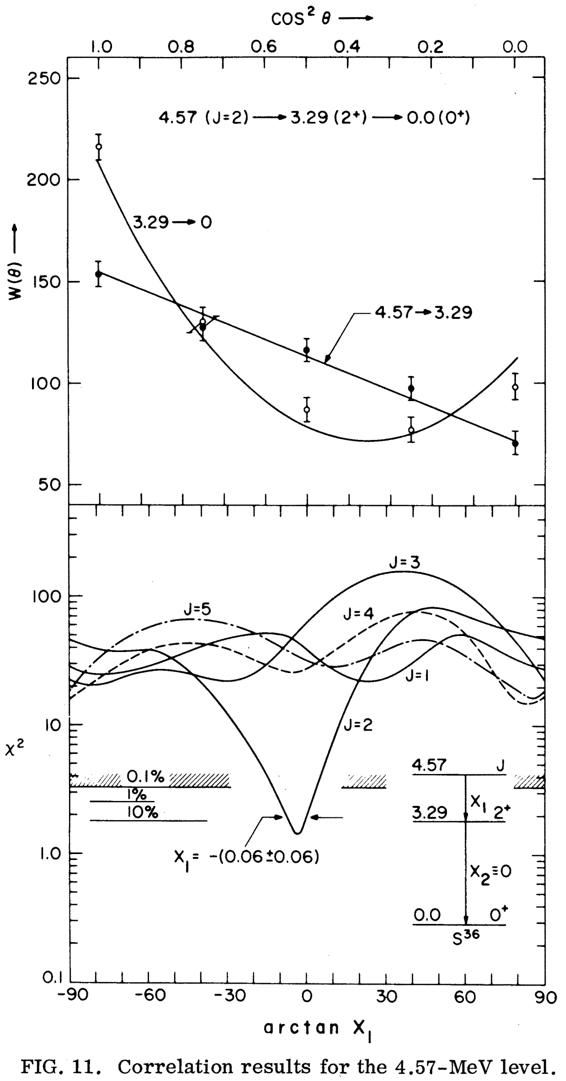

FIG. 11. Correlation results for the 4.57-MeV level. The upper plot shows the measured correlations. The lower plot shows the results of an attempt to fit these data simultaneously for assumed spins for the 4.57-MeV level of $1 \le J \le 5$. The inset level diagram shows the decay scheme. Only for $J = 2$ is an acceptable fit to the data obtained – the corresponding solution for x_1 is indicated. The solid curves in the upper plot show the theoretical correlations calculated for $J = 2$, $x_1 = -0.06$.

5.57-MeV Level

The 5.57-MeV level deexcites 100% to the 3.29-MeV level, and thus the correlation information summarized in Table I for both members of the cascade may be used in the correlation analysis. The results of a simultaneous fit to both members of the $5.57 \to 3.29 \to 0$ cascade transitions determine that the 5.57-MeV state has $J = 1$, 2, or 3. The allowed mixing ratios corresponding to these possibilities summarized in Table III. We note, as indicated in Table III, that the minimal value of χ^2 obtained for the possibility of $J = 2$ corresponds to a statistical probability of only 1%: Hence this possibility has been ruled against quite strongly.

6.20-MeV Level

The decay of this level is complex (see Fig. 6) as was also the subsequent analysis of the correlation data. The observation of a significant term in $P_4(\cos\theta)$ for the $3.29 \to 0$ transition ($a_4 = 0.16 \pm 0.03$: see Table I) restricts the spin of the initial state at 6.20 MeV to $J \geq 2$. The possibility $J^\pi = 4^-$ is excluded on the basis of the lifetime restriction $\tau < 0.3$ psec: For the most favorable case of $M2$ character for the $6.20 \to 4.57$ transition, the transition strength would be $|M(M2)|^2 > 460$ W.u. For the alternative possibility $J^\pi = 4^+$, assuming no $M3$ admixtures, the lower limits on the $E2$ strengths for the $6.20 \to 4.57$ and $6.20 \to 3.29$ transitions would be, respectively, 13 and 1 W.u. Thus the most likely possibilities are $J = 2$ or 3, of either parity, or $J^\pi = 4^+$.

The results of a quantitative analysis of these data are illustrated in part in Fig. 12. The insert shows the placement within the S^{36} level scheme of those transitions whose correlation patterns were measured. The upper plot shows the results of an attempt to determine the mixing x_1 in the $6.20 \to 4.57$ transition; i.e., the variable mixing ratio of the fit is defined to be $x = x_1$. The plot of χ^2 vs $x = x_1$ is for a simultaneous fit to the correlation patterns for the $6.20 \to 4.57 \to 3.29$ cascade and for the $6.20 \to 3.29$ transition. The mixing in the latter transition was allowed to vary, $-\infty \le x_3 \le +\infty$, while the mixing in the $4.57 \to 3.29$ was fixed at $x_2 = 0 \pm 0.1$, consistent with the previous conclusions on this transition. Acceptable fits are obtained for the possibilities $J = 1$, 2, or 3 for the indicated ranges of the mixing ratio $x = x_1$. The possibility $J = 0$ is excluded, as the minimal value of χ^2 for this case considerably exceeds the 0.1% confidence limit. The possibility $J = 4$ has been excluded from a simple fit to the $6.20 \to 4.57$ correlation pattern. The results indicate for this latter case a significant mixing of $L=3$ with $L=2$ radiation: from the considerations outlined above for the $E2$ or $M2$ strengths if $J=4$, this is clearly not possible.

The lower plot shows the results of a similar fit to the $6.20\to3.29$ and $3.29\to0$ correlation patterns, in order to determine the mixing in the former transition, i.e., the variable of the fit in this case is $x=x_3$. The influence on the $3.29\to0$ correlation due to feeding of the 3.29-MeV state via the $6.20\to4.57\to3.29$ cascade has been specifically included, following the restrictions on x_1 summarized in the upper plot. The dashed curves show the variations obtained by allowing for a variation of 2 standard deviations in the mixing ratio x_1 and in the indicated branching ratios. These results exclude the possibility $J=1$, and provide the restrictions on x_3, and also x_1, as summarized in Table III.

In summary, the 6.20-MeV level is found to have either $J=2$ or 3. If $J=2$, the results are not inconsistent with dipole character for both of the primary radiations from the 6.20-MeV state. From the lifetime restriction, the parity may be either even or odd, since reasonable dipole strengths are computed for either case. If $J=3$, then both major primary transitions have significant quadrupole components. If the parity were odd, then the mixing in the $6.20\to4.57$ transition would be $M2/E1$. Taking as a lower limit $x_1>0.10$, we compute a lower limit on the corresponding $M2$ strength of $|M(M2)|^2>5$ W.u., which seems rather improbable. Conversely, the lower limits on the $E2$ strengths, assuming a $J^\pi=3^+$ assignment for the 6.20-MeV level, are quite reasonable. Thus we conclude the 6.20-MeV level has $J=2$ or 3, with the possibility $J^\pi=3^-$ rather unlikely.

6.51-MeV Level

The only observed decay mode for this level is via a $6.51\to3.29$ transition which was not experimentally resolved from the subsequent $3.29\to0$ transition to the ground state. Thus the correlation information that could be most simply extracted from the two-parameter data matrix was the variation in angle of the *net* intensity of the unresolved members of the $6.51\to3.29\to0$ cascade, as given in Table I.

Figure 13 summarizes the results of an attempt to fit these data for assumed spins for the 6.51-MeV level of $1\leq J\leq5$. The possibility $J=1$ is immediately excluded, as is also the possibility $J=0$. The solution for x for the possibility $J=5$ corresponds to a mixing of $L=4$ with $L=3$ radiation, which can be excluded from the lifetime restriction $\tau<0.3$ psec. We note that of the acceptable solutions, the minimal values of χ^2 obtained for $J=2$ or 3 are significantly larger than that for $J=4$.

Although not resolved by the NaI(Tl) detector, the energies of the transitions $6.51\to3.29$ (3221 $\pm$ 16 keV) and $3.29\to0$ (3287 ± 1.5 keV) differ by 66 ± 16 keV. The correlation patterns of the separate members of the cascade were extracted by two different methods: (1) from a fit to the data, in in which the peak at $E_\gamma\sim3.3$ MeV was represented as the sum of two Gaussian components, and (2) from a fit to the NaI(Tl) data, at various angles

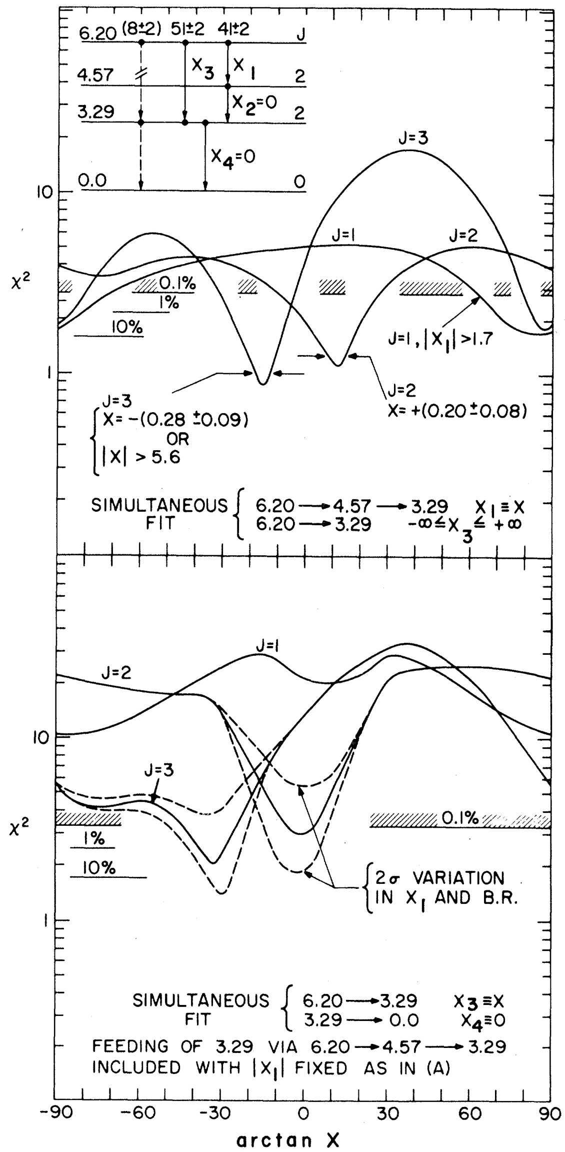

FIG. 12. Partial results of a least-squares fit to correlation data obtained for the 6.20-MeV level. These results lead to a restriction $J=2$ or 3 for the 6.20-MeV level, with the indicated restrictions on the quadrupole-dipole mixing ratio in the $6.20\to3.29$ transition.

θ_γ, to determine the coefficients a_2 and a_4 as a function of E_γ. Our conclusions on the correlation coefficients for the individual members of the $6.51 \rightarrow 3.29 \rightarrow 0$ cascade are also included in Table I. The correlation patterns are evidently quite similar, as must be the case if the cascade proceeds by quadrupole transitions linking states with the spin sequence $4 \rightarrow 2 \rightarrow 0$.

The "upper envelope" of the curves shown in Fig. 13 for $J=2$ and $J=3$ illustrates the results obtained from a simultaneous fit to the unresolved $6.51 \rightarrow 3.29 \rightarrow 0$ correlation intensity, when the restrictions placed on a_2 and a_4 for the individual members of the cascade transition are imposed. Precisely the same plot of χ^2 vs x is obtained for the $J=4$ possibility.

Thus we conclude that the 6.51-MeV level has $J=4$, and decays by a predominantly quadrupole transition to the 3.29-MeV level. If the parity were were odd, the transition would be $M2$, of strength >330 W.u. This possibility we reject. Therefore we conclude the level has $J^\pi = 4^+$, and the strength of the $E2$ $6.51 \rightarrow 3.29$ transition is >1 W.u.

5.38- and 7.12-MeV Levels

No correlation data was obtained for these levels. However, the measured branching ratios and lifetime restrictions permit some conclusions on possible spin assignments for these levels, which we outline here. First, since both levels connect to the $J^\pi = 0^+$ ground state by γ-ray transitions, neither level may have $J=0$. For the 5.38-MeV level, the only restriction on the lifetime is that obtained from the p-γ coincidence measurements, $\tau < 40$ nsec, which nevertheless insures that the transitions $5.38 \rightarrow 0$ has $L<4$. Thus the spin of the level is restricted to $J=1$, 2, or 3. For the 7.12-MeV level, $\tau < 0.3$ psec, which restricts the $7.12 \rightarrow 0$ transition to $L<3$, and thus for the 7.12-MeV level $J=1$ or 2, or possibly $J^\pi = 3^-$.

V. SUMMARY OF RESULTS AND DISCUSSION

A. Comparison with Previous Results

The description of the S^{36} level structure obtained from the present studies of the $S^{34}(t,p)S^{36}$ reaction has been presented schematically in Fig. 6, which summarizes the spin-parity restrictions obtained in this work together with the branching ratios for the electromagnetic deexcitation of the levels studied. Restrictions on possible multipole mixings in the primary transitions have been summarized in Table III, which also lists the information obtained on the mean lifetimes of the S^{36} excited states.

Before proceeding to a comparison with previous results, we reiterate that the restrictions on J^π summarized in Fig. 6 (and also Table III) have been derived wholly from the present investigation of the (t,p) reaction. While the previous results summarized in Sec. I obviously provided an invaluable guide to the design of the present experiment, the conclusions are nevertheless almost completely independent. It is therefore worthwhile to note that there is in general excellent agreement between the present results and the conclusions of Gray, *et al.*[6] on the even-parity levels of S^{36} as formed in the $Cl^{37}(d,He^3)S^{36}$ reaction. This has been noted partially in the comparison of S^{36} excitation energies given in Table II, where the agreement is really quite good.

It is also evident that the (d,He^3) reaction is considerably more selective than the (t,p) reaction, since we observe via the latter reaction all of the states reported from the (d,He^3) studies plus several others. This is not surprising, since some of the latter grouping presumably have odd parity, and arise from configurations which one would not expect to form strongly via the (d,He^3) pickup reaction. In the following, we discuss this feature in detail, and include also a comparison with the conclusions reported previously on the (t,p) reaction. Some recent results[21] on the linear polarization of

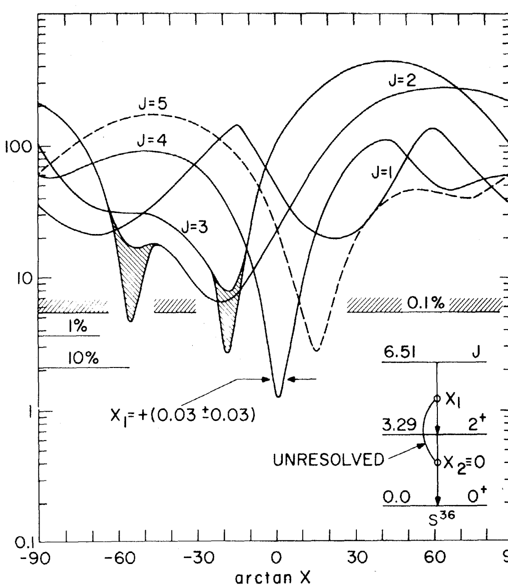

FIG. 13. Results of a least-squares fit to the correlation patterns of the $6.51 \rightarrow 3.29 \rightarrow 0$ cascade transitions. For the possibilities $J=2$ and $J=3$, the "lower envelope" shows the results of a fit to the angular intensity variation of the unresolved members of the cascade. The "upper envelope" illustrates the results obtained when the somewhat more poorly defined patterns of the individual members of the cascade are included as part of fit (i.e., the shaded region is excluded). These results lead to a $J=4$ assignment for the 6.51-MeV level.

γ rays from the $S^{34}(t,p\gamma)S^{36}$ reaction, which determine the parity of the 4.19- and 4.57-MeV levels, is also included.

3.29-MeV Level

The present experiment has provided an unambiguous assignment $J^\pi = 2^+$ for the 3.29-MeV level. This is in agreement with previous results reported from the (d, He^3) reaction, which determine[5-7] the transfer as $l=0$ and thus $J^\pi = 1^+$ or 2^+. Previous results from studies of the (t,p) reaction,[3] which suggested $J^\pi = 2^+$ or 3^- are also consistent with this conclusion. We note that the restrictions imposed individually by the two previously reported sets of experiments,[3, 5-7] when combined, also point to a $J^\pi = 2^+$ assignment for this level.

3.34-MeV Level

The determination $J^\pi = 0^+$ for the 3.34-MeV level provides rigorous confirmation of the 0^+ assignment quoted previously[3] from the (t,p) reaction. A somewhat surprising result of the present experiment was the determination that this level decays by $E0$ transition to the ground state rather than to a lower-lying 2^+ state suggested previously to be at $E_{ex} = 2.85$ MeV.

We now discuss the lifetime of this level against $E0$ pair emission (the competing internal-conversion process has a relative calculated strength of only some few parts in 10^3 and so may be neglected). The strength of the $E0$ transition, as computed from the measured lifetime for this state, is 0.039 in single-particle units.[22] Information on $E0$ strengths in light nuclei is sufficiently scanty to make worthwhile our bringing it together, which we do in Table IV. Here we have tabulated the experimentally measured $E0$ transition strengths for nuclei up to Ca^{48}. The strengths are given in single-particle units[22] with the Coulomb correction applied, where the data are taken from the indicated sources.[3, 23, 24] It can be seen from Table IV that our present transition is the weakest so far found in nuclei up to calcium, although not by a large margin. It is interesting that the strongest transitions are from "interloper" states, that is, states whose dominant configuration is believed to come from *outside* the dominant configuration of the ground states (to which all transitions of Table IV take place), whereas our present example need not involve any other than the ground state configuration for the excited state. We return to this in the discussion.

TABLE IV. $E0$ transition strengths in light nuclei (all are $J^\pi = 0^+ \to 0^+$). The strengths are in single-particle units with the Coulomb correction applied.

Nucleus	Transition energy (MeV)	Strength
Be^{10}	6.18	0.23 [a]
C^{12}	7.65	2.7 [a]
O^{16}	6.05	0.87 [a]
O^{18}	3.63	0.70 [a]
S^{36}	3.34	0.039
Ca^{40}	3.35	0.13 [b]
Ca^{42}	1.84	1.1 [b]
Ca^{48}	4.28	0.056 [c]

[a] From Ref. 23.
[b] From the summary of Ref. 3.
[c] From Ref. 24.

4.19-MeV Level

This level was not seen in the (d, He^3) reaction,[5-7] but has been previously reported[3] from the (t,p) reaction. The present results determine that the level has $J=3$, and deexcites by a dipole transition to the $J^\pi = 2^+$ 3.29-MeV level. Recent linear-polarization measurements determine[21] that the 4.19 $\to$ 3.29 transition is $E1$, and thus determine odd parity for the 4.19-MeV level. A model-based preference for a $J^\pi = 3^-$ assignment has been discussed previously.[6, 7]

4.52- and 4.57-MeV Levels

The observation of these "doublet" levels at ~4.5-MeV excitation in S^{36} was first reported from the (d, He^3) reaction[6] which determined that for each the transfer angular momentum is $l=0$, and thus $J^\pi = 1^+$ or 2^+. From the measured spectroscopic factors, Gray *et al.*[6] suggest a preference for a $J^\pi = 1^+$ assignment for the 4.52-MeV level. The present experiment provides unique assignments of spin for each level, in agreement with the above restrictions, and thus the experiments jointly determine $J^\pi = 1^+$ for the 4.52-MeV level and $J^\pi = 2^+$ for the 4.57-MeV level. The 4.52-MeV level deexcites to the S^{36} ground state by a pure $M1$ transition. The present experiment has determined that the $E2/M1$ mixing ratio for the 4.57 $\to$ 3.29 transition is $x = -(0.06 \pm 0.06)$. The linear-polarization measurements[21] determine independently that the transition is predominantly $M1$, and thus provide an independent determination of even parity for the 4.57-MeV level. These experiments jointly suggest that the 4.57 $\to$ 3.29 transition may have a small but measurable quadrupole component.

Levels of $5.0 < E_{ex}$(MeV) < 6.3

No levels have been previously reported within this range of excitation energies in S^{36}. The evidence obtained for the existence of states at 5.26, 5.38, 5.50, 5.57, and 6.20 MeV in the present (t, p) studies is nevertheless quite unambiguous. Evidence that the (t, p) reaction populates specifically these states is shown in Fig. 1; that the deexcitation γ rays fit the S^{36} level scheme is shown quite clearly in Figs. 3–6.

6.51- and 7.12-MeV Levels

Both these levels were seen in the (d, He^3) reaction by Gray *et al.*,[6] who determined for each level that the transfer momentum is $l = 2$, and thus the levels are of even parity with $J \leq 4$. In the present experiment we have determined for the 6.51-MeV level $J^\pi = 4^+$. For the 7.12-MeV level we find the restriction $J = 1$, 2, or 3^-. Combining the two results, we obtain the restriction for the 7.12-MeV level of $J^\pi = 1^+$ or 2^+. Gray *et al.*[6] suggest that these levels are formed by proton pickup from the $d_{5/2}$ rather than the $d_{3/2}$ shell; our results confirm this for the $J^\pi = 4^+$ 6.51-MeV level.

B. Discussion of Results

Evidence Against the 2.00-MeV (0^+) and 2.85-MeV (2^+) Levels

As discussed in Sec. III, no evidence was obtained for the population of these levels, either directly in the (t, p) reaction or indirectly via cascade γ-ray transitions from higher-lying levels in S^{36}. As can be seen in Fig. 6, several of these higher-lying states are observed to deexcite directly to the 0^+ ground state.

Although the energetics rule somewhat against possible transitions to the 3.34-MeV 0^+ state, we would nevertheless expect to find at least some evidence for transitions to a 2.00-MeV 0^+ state, which would be energetically somewhat more favored. Also, the latter transitions would be experimentally more easily detected. Again, the higher-lying states are observed (see Fig. 6) to connect rather strongly to the known $J^\pi = 2^+$ states at 3.29 and 4.57 MeV. Although possible transitions to a 2.85-MeV 2^+ state would be energetically favored, and also easily detected experimentally, no such transitions were observed.

Another point of evidence arises from the observed decay of the 3.34-MeV 0^+ state, which is observed to deexcite only to the 0^+ ground state. An upper limit on a possible $3.34 \rightarrow 3.29$ transition is given in Sec. IV, which indicates such a transition would be experimentally very difficult to detect. However, a possible $3.34 \rightarrow 2.85$ transition would be energetically more favored, since the transition energy would be in this case ~0.49 MeV. From the absence of $2.85 \rightarrow 0$ or $2.85 \rightarrow 2.00$ transitions in the p-γ coincidence spectrum, we set an upper limit on the $E2$ strength of a possible $3.34 \rightarrow 2.85$ transition of $|M(E2)|^2 < 0.02$ W.u. Such an inhibition seems unreasonably large. In conclusion, the results of the present experiment cast considerable doubt on the previous identification of these levels within the S^{36} level scheme.

Hinds and Middleton have reexamined[25] the unpublished $S^{34}(t, p)S^{36}$ data that gave rise to the reported levels at 2.00 and 2.85 MeV. They report that although the proton groups are weak they appear to be definite and to behave in a kinematically correct way and that there is therefore no reason for them to reject their earlier conclusions. It would be of great interest to repeat the earlier work under the same experimental conditions and until this is done some doubt must remain concerning the identification of these states.

Comparison with Theory

As mentioned in the Introduction, two calculations are available at present against which the experimental results of this paper may be compared. The first[1] treats S^{36} as $(1d_{3/2}, 2s_{1/2})^{-4}$ below Ca^{40} and therefore generates only states of even parity. The second[2] treats S^{36} as $1d_{3/2}{}^3, 1f_{7/2}$ above S^{32} and therefore concerns itself only with states of odd parity with the single exception that the lowest-lying ($J^\pi = 0^+$) state of $1d_{3/2}{}^2 1f_{7/2}{}^2$ is also considered. In Fig. 14 we compare the experimental data with these calculations, making some tentative associations between experimental and theoretical levels.

Also shown in Fig. 14 is the theoretical spectrum of S^{36} levels set forth by Gray *et al.*[6] who have calculated the even-parity spectrum resulting from the coupling of four proton holes in the $1d$-$2s$ shell. The two results are based on two different interaction potentials: the first, a Yukawa interaction; the second, a realistic forces interaction as given implicitly in the matrix elements of Kuo[26] which were used in this second calculation.

As evidenced in Fig. 14, the results obtained for a Yukawa interaction appear to give the better agreement with the experimental spectrum, primarily because of the relative position of the lowest-lying 1^+ state, which we tentatively identify with that observed experimentally at 4.52 MeV. The observed ground-state γ-ray decay of this 1^+ level is forbidden in the picture given by Glaudemans, Wiechers, and Brussaard,[1] since a transition between the $1d_{3/2}$ and $2s_{1/2}$ shells via an $M1$ operator would be required. Such a transition can occur according to the description of Ref. 6, since these authors include excitations of the $d_{3/2}$ shell. Hence, it is not surprising that the model calculation of Ref. 6 is better able to predict the correct position of the 4.52-MeV level than is that of Ref. 1.

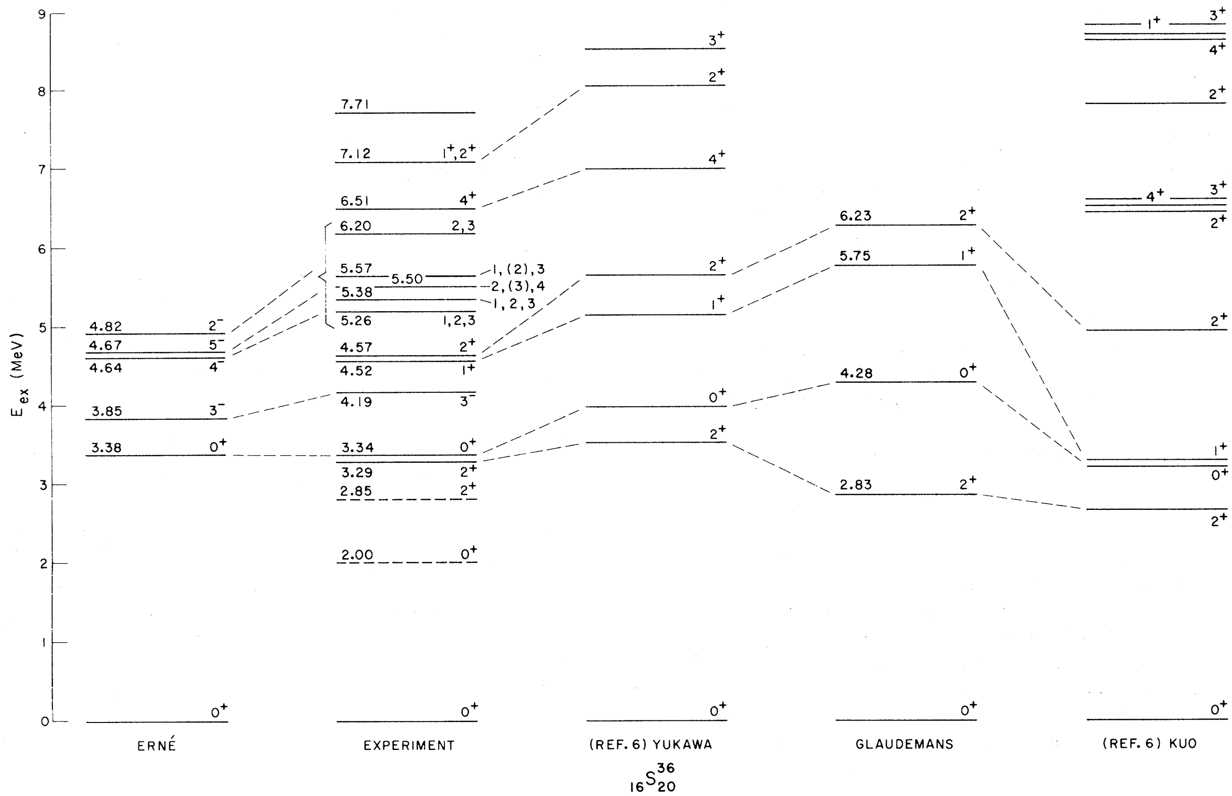

FIG. 14. A comparison with experiment of the various theoretical predictions for the spectra of even- and odd-parity states of S^{36}. Tentative correspondences are indicated by the dashed connecting lines, as explained in the text.

We shall not discuss the comparison between theory and experiment in any detail because the more powerful computational methods now available should soon permit comparison with a more realistic calculation. In particular we should expect, in this upper region of the s-d shell, significant mixings of these simple four-hole configurations with configurations involving $f_{7/2}{}^2$ excitations. However, if one makes the identification between theoretical and experimental even-parity states, indicated in Fig. 14 by the dashed lines, the correspondence seems quite reasonable, except that the theoretical states (for a Yukawa potential) appear at excitation energies that are increasingly too large. For the most part, the indicated identifications are supported by the fact that these even-parity levels are most strongly excited in the (d, He^3) pickup reaction, which is expected to populate preferentially these four-hole configurations.

With respect to the odd-parity levels, the identification of the lowest-lying $J^\pi = 3^-$ state is quite certain. The cluster of levels of $5.26 \le E_{ex} \le 6.20$ MeV were not observed in the (d, He^3) reaction; it is quite likely that at least two of these levels belong to the spectrum of odd-parity levels predicted by Erné.[2] From the indicated restrictions on J for these levels, it seems that we have not formed the 5^- level at the bombarding energy used ($E_t = 3.12$ MeV) in the present studies of the (t,p) reaction. This is perhaps not surprising, since the formation would in this case involve a transfer angular momentum of $l = 5$, which is energetically less probable than that involved in formation of the remaining states.

With respect to further understanding the S^{36} level spectrum, it is evident that the identification of possible odd-parity states at $E_{ex} \sim 6$ MeV would be particularly interesting. A major point of significance with respect to further studies concerns the $J^\pi = 0^+$ level at 3.34 MeV. Such $J^\pi = 0^+$ states are seen to be generated both by the $(1d_{3/2}, 2s_{1/2})^{-4}$ calculation and by the $(1d_{3/2})^{-6}\, 1f_{7/2}{}^2$ at about the same excitation, whereas experimentally only one $J^\pi = 0^+$ state has been located with certainty. This must provide reconsideration of the possible $J^\pi = 0^+$ level reported at 2.00 MeV. It must be supposed that the two theoretical levels will mix strongly; all that can be said is that the $J^\pi = 0^+$ level identified with certainty at 3.34 MeV cannot be a pure $(1d_{3/2})^{-6}\, 1f_{7/2}{}^2$ state (at least if the ground state itself contains no $1f_{7/2}{}^2$ component), because it connects to the ground state by the $E0$ transition.

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[1]P. W. M. Glaudemans, G. Wiechers, and P. J. Brussaard, Nucl. Phys. 56, 548 (1964).
[2]F. C. Erné, Nucl. Phys. 84, 91 (1966).
[3]P. M. Endt and C. Van der Leun, Nucl. Phys. A105, 1 (1967).
[4]M. A. Reimann, J. R. MacDonald, and J. B. Warren, Nucl. Phys. 66, 465 (1965).
[5]W. S. Gray, T. Wei, J. Jänecke, and R. M. Polichar, Phys. Letters 26B, 383 (1968).
[6]W. S. Gray, P. J. Ellis, T. Wei, R. M. Polichar, and J. Jänecke, Nucl. Phys. A140, 494 (1970).
[7]N. G. Puttaswamy and J. L. Yntema, Phys. Rev. 177, 1624 (1969).
[8]A. E. Litherland and A. J. Ferguson, Can. J. Phys. 39, 788 (1961).
[9]J. W. Olness and E. K. Warburton, Phys. Rev. 151, 792 (1966).
[10]E. K. Warburton, J. W. Olness, and A. R. Poletti, Phys. Rev. 160, 938 (1967).
[11]W. R. Harris, K. Nagatani, and J. W. Olness, Phys. Rev. C 2, 1412 (1970).
[12]See e.g., A. Z. Schwarzschild and E. K. Warburton, Ann. Rev. Nucl. Sci. 18, 265 (1968).
[13]J. Lindhard, M. Scharff, and H. E. Schiøtt, Kgl. Danske Videnskab. Selskab, Mat.– Fys. Medd. 33, No. 14 (1963).
[14]A. E. Blaugrund, Nucl. Phys. 88, 501 (1966).
[15]E. K. Warburton, D. E. Alburger, A. Gallmann, P. Wagner, and L. F. Chase, Jr., Phys. Rev. 133, B42 (1964).
[16]J. W. Olness, E. K. Warburton, D. E. Alburger, and J. A. Becker, Phys. Rev. 139, B512 (1965).
[17]A. R. Poletti and E. K. Warburton, Phys. Rev. 137, B595 (1965).
[18]J. J. Rose and D. M. Brink, Rev. Mod. Phys. 39, 306 (1967).
[19]D. H. Wilkinson, in *Nuclear Spectroscopy*, edited by F. Ajzenberg-Selove (Academic Press Inc., New York, 1960) Pt. B, p. 862ff.
[20]E. K. Warburton and J. Weneser, in *Isospin in Nuclear Physics*, edited by D. H. Wilkinson (North-Holland Publishing Company, Amsterdam, The Netherlands, 1970), p. 174ff.
[21]F. Jundt, E. Aslanides, A. Gallmann, and D. E. Alburger, to be published.
[22]D. H. Wilkinson, Nucl. Phys. A133, 1 (1969).
[23]D. E. Alburger, E. K. Warburton, A. Gallmann, and D. H. Wilkinson, Phys. Rev. 185, 1242 (1969).
[24]N. Benczer-Koller, G. G. Seaman, M. C. Bertin, J. W. Tape, and J. R. MacDonald, Phys. Rev. C 2, 1037 (1970).
[25]S. Hinds and R. Middleton, private communication.
[26]T. T. S. Kuo, Nucl. Phys. A103, 71 (1967).

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Lifetime of the $\frac{1}{2}^-$ 2791-keV ^{21}Ne Level*

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The mean lifetime of the $J^\pi = \frac{1}{2}^-$ ^{21}Ne level at an excitation energy of 2791 keV was measured by the gas-target variant of the recoil-distance technique. The result of 84 ± 10 psec is discussed in terms of the structure of mass-21 states.

I. INTRODUCTION

In 1966, the discovery[1,2] that the 2.8-MeV level of ^{21}Ne was actually a doublet comprised of levels with excitation energies of 2791 ± 2 and 2797 ± 2 keV resolved several apparent experimental discrepancies. It was soon clear that the upper member of this doublet was $J^\pi = \frac{1}{2}^+$. To date the properties of this state seem compatible with theoretical expectations and with those of its mirror at 2432 keV in ^{21}Na. The properties of the 2791-keV level, however, have proven to be remarkedly elusive. Only recently has the spin-parity of $\frac{1}{2}^-$ been determined.[3,4] Both the ^{21}Ne 2791-keV level and its probable mirror[5] at 2804 keV in ^{21}Na appear to have quite small reduced widths for the ^{20}Ne ground state[3,6] but quantitative numbers have not yet been obtained. The smallness of these reduced widths is consistent with the speculation[3] that the 2791-keV level is largely a $p_{1/2}$-hole state, i.e., $p_{1/2}^{-1}(2s, 1d)^6$. Such a $p_{1/2}$-hole state is expected to have parents of $(J^\pi, T) = (0^+, 1)$ and $(1^+, 0)$ in mass 22, and from local systematics we expect the lowest $(0^+, 1)$ state of ^{22}Ne and ^{22}Na to dominate this parentage. The ^{22}Ne$(p, d)^{21}$Ne results of Howard, Pronko, and Whitten[3] are consistent with this expectation. The electromagnetic transitions connecting the 2791-keV level with lower states of ^{21}Ne should provide stringent and valuable tests of any proposed wave functions. Accordingly, a