Properties of P^{30} Levels from the $Si^{29}(p,\gamma)P^{30}$ Reaction. I

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γ-ray decay schemes of seven resonances in the $Si^{29}(p,\gamma)P^{30}$ reaction in the range E_p=700–1750 keV have been studied in order to gain additional information on properties of resonant and bound levels of P^{30}. The results also provide necessary information for the analysis of γ-ray angular-correlation and polarization measurements, which are in progress. Singles and coincidence spectra were obtained at each of the resonances at E_p=730, 917, 1302, 1470, 1505, 1686, and 1748 keV (all ±2 keV) using large-volume NaI(Tl) detectors and a Ge(Li) detector. The resonance strengths were measured relative to the strength of the resonance at E_p=416 keV in the same reaction, which is known from previous work. Consistent resonance decay schemes were derived, along with decay schemes of lower-lying bound states which, in many cases, differ considerably from previously available information. New results, or results significantly different from earlier reports, were obtained for the decay properties of the 3.02-, 3.74-, 3.93-, 4.14-, 4.18-, 4.23-, 4.43-, 4.50-, 4.62-, and 4.92-MeV levels of P^{30}. The existence of a weak transition from the 4^-, 4.23-MeV level to the 1^+ ground state is shown. Another unusual transition found is one from the 3^-, 4.92-MeV level to the 1^+, 0.709-MeV level. The energies of 17 bound levels of P^{30} were determined from the Ge(Li) data to a greater accuracy than heretofore available. Evidence is found for a previously unreported level at 4.468±0.003 MeV, which is proposed to be the $J=0$, $T=1$ analog of the 3.79-MeV level of Si^{30}. The decay schemes of the E_p=730-, 917-, and 1302-keV resonances indicate they are quite pure $T=0$ levels. The new value Q=5.597±0.003 MeV for the $Si^{29}(p,\gamma)P^{30}$ reaction was derived from the Ge(Li) spectra.

I. INTRODUCTION

PROPERTIES of levels of the odd-odd nucleus P^{30} were reviewed in 1962 by Endt and Van der Leun.[1] The energies of 30 bound states below E_x=5.8 MeV were known from the magnetic analysis of α particles from the $S^{32}(d,\alpha)P^{30}$ reaction by Endt and Paris.[2] Isobaric spins for these levels were also assigned on the basis of relative cross sections in this reaction and by comparison with the level scheme of Si^{30}. Most of the information on decay properties, spins, and parities of P^{30} levels were obtained from studies of decay schemes and angular correlations at resonances below E_p=1 MeV in the $Si^{29}(p,\gamma)P^{30}$ reaction.[3–5] The more recent work has dealt with proton-capture resonances above E_p=1 MeV. The most comprehensive is the study of Moore[6] of decay schemes and some angular distributions at 10 resonances in the range E_p=1100–1800 keV. Similar work has been done by Val'ter *et al.*[7] on the E_p=1308-keV resonance; by Ejiri *et al.*[8] on this same resonance and on a "resonance" at 1333 keV which was shown by Moore to be a doublet with components at E_p=1324 and 1327 keV; and by Phelps *et al.*[9] on five resonances in the range E_p=1470–2120 keV. In addition, nine resonances in the elastic scattering of protons from Si^{29} have been observed by Storizhko and Popov between E_p=1200 and 2200 keV.[10]

Very little new information on properties of lower-lying levels, except in the study by Moore, has been obtained in the recent work quoted above. The present study was undertaken primarily in order to obtain additional and less ambiguous data on the spins and parities of bound states of P^{30}. However, it was discovered in the analysis of preliminary angular-correlation data that in several instances the coincidence spectra were in significant disagreement with previously reported γ-ray decay schemes. It thus became necessary to preface the planned angular-correlation and polarization study with a detailed reinvestigation of decay schemes at several resonances. The work was greatly aided by the availability of large-volume NaI(Tl) detectors and a lithium-drifted germanium [Ge(Li)] detector. Furthermore, the accuracy of branching ratios for the decay of several levels was significantly improved by the analysis of coincidence spectra obtained in the course of triple-correlation measurements. In this way, good statistics resulted by adding the spectra obtained at several angles, and also the effects of angular correlations on the relative γ-ray intensities could thereby be taken into account. Although the angular correlations are not discussed in the present paper, the branching-ratio results quoted here are corrected for these effects where applicable.

In the present paper, measurements of decay schemes of resonances at E_p=730, 917, 1302, 1470, 1505, 1686, and 1748 keV in the $Si^{29}(p,\gamma)P^{30}$ reaction are discussed. As a result, new or improved data on properties of 18

* Part of the Office of Aerospace Research, U. S. Air Force.
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bound levels of P^{30} are presented. The results of angular correlation and polarization measurements will be presented in a subsequent publication (II).

II. EXPERIMENTAL PROCEDURE

Targets of enriched elemental silicon[11] (71% Si^{29}) evaporated onto 10-mil thick Ta backings were bombarded by protons from the ARL, 2-MeV Van de Graaff accelerator. Details of the experimental arrangement have been described previously.[12,13] The proton beam was focused into a target spot size of about 3-mm diam with an energy resolution of approximately 1 keV for most of the present work. γ-ray singles spectra were first obtained with an 8-in.-diam×8-in.-long NaI(Tl) detector located at $\theta=55°$, where θ is the angle between the axis of the detector and the direction of the proton beam. As an aid in the analysis and interpretation of the NaI(Tl) spectra, the spectra were later also recorded using a 2-cc, Ge(Li) detector located at the same angle. Coincidence spectra were obtained using the 8-in.×8-in. detector and a 5-in.-diam×5-in.-long NaI(Tl) detector which provided the gate pulses. In a few cases coincidence spectra were also obtained using the Ge(Li) and 8-in.×8-in. NaI(Tl) detectors. The data were stored in a 512-channel, pulse-height analyzer and then read out on punched paper tape. Tape-to-card conversion was used to prepare the data for subsequent computer analysis.

Room background and nonresonant target background was automatically accounted for in the NaI(Tl) singles spectra by a special switching circuit.[13,14] This circuit was constructed to switch the multichannel analyzer from its add-mode to substract-mode after a predetermined number of analyzer live-time clock pulses, and at the same time to shift the proton beam energy to a value off resonance by changing the current in the beam-analyzing magnet. The system was adjusted to cycle in this manner several hundred times during the measurement. The NaI(Tl) spectrum analysis was done using a stripping program (SPKFIT) developed for use with an IBM-7094 computer by Graber and Watson.[15] The resonance strengths $S=(2J+1)\Gamma_\gamma\Gamma_p/\Gamma$ (where J is the resonance spin and Γ_γ, Γ_p, and Γ are the radiative, proton, and total widths, respectively), were determined from the derived decay schemes and comparison of the areas under the thin-target yield curves. The relative strengths thus obtained were converted to absolute strengths by comparison with the strength $S=0.70\pm0.10$ eV of the $Si^{29}(p,\gamma)P^{30}$ resonance at $E_p=416$ keV determined by Engelbertink and Endt in a recent careful survey of strengths of selected resonances in 16 *s-d* shell nuclei.[16] The resonance energies quoted in the present paper are from Moore.[6] The excitation energies of P^{30} corresponding to the resonance levels were determined from the γ-ray energy measurements. The resulting values are consistent with those computed from the proton energies of Moore and the reaction Q value derived from the present study. The calibration for the γ-ray energy measurements was obtained from Cs^{137}, Na^{22}, Co^{60}, and ThC″ sources and from the $F^{19}(p,\alpha\gamma)O^{16}$ reaction which occurred from the slight fluorine contamination present in all targets. The γ-ray energies were all corrected for Doppler shifts due both to the γ-ray emission and to the nuclear recoil from the captured proton. The latter correction amounted to about 1.2 keV/MeV γ-ray energy.

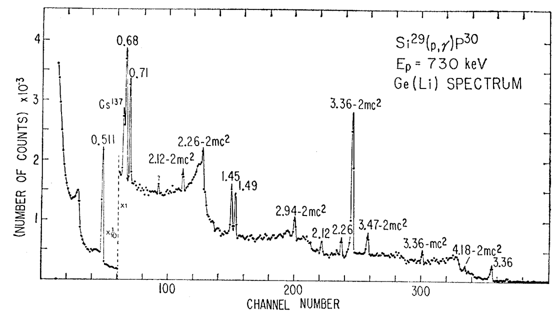

FIG. 1. γ-ray spectrum of the $E_p=730$-keV resonance in $Si^{29}(p,\gamma)P^{30}$ obtained with a 2-cc Ge(Li) detector and a dispersion of 9.32 keV/channel. The photopeaks and/or escape peaks of the γ-ray lines are identified by their energy in MeV. The line at 0.661 MeV is due to Cs^{137} contamination in the target room.

III. RESULTS

A preliminary decay scheme for each resonance was derived from the NaI(Tl) singles spectra and from results of previous investigations. These preliminary decay schemes were then checked and altered where necessary by means of the coincidence measurements and the high-resolution Ge(Li) spectra. Several previously unreported transitions were found in the high-resolution spectra which required, in some cases, considerable revision of the preliminary decay schemes. The data for each resonance are presented and the more significant details discussed. Following the discussion of the individual resonances is a summary of all the information obtained on the resonances and bound states of P^{30}. The level energies to be quoted are those determined in the present work (see Table II). As an aid in reading the text, the energies of transition between bound states are listed in Table III.

[11] We are indebted to L. W. Seagondollar of the University of Kansas (now at North Carolina State University) for the loan of targets used in this work.

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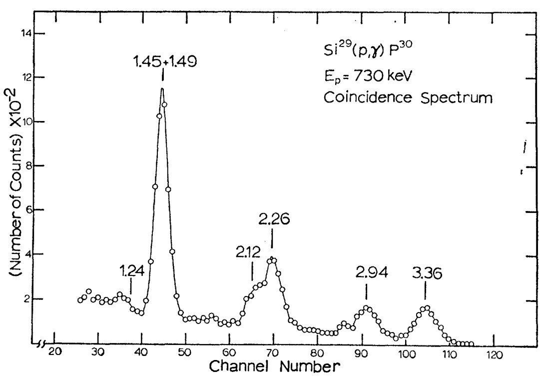

FIG. 2. Spectrum of γ rays observed with an 8-in.×8-in. NaI(Tl) detector in coincidence with photopeak pulses from the 2.94-MeV γ ray at the $E_p=730$-keV resonance. This spectrum results from the addition of spectra at five angles observed in a triple-correlation measurement. Note the absence of a 1.24-MeV γ ray which would arise from a previously reported 4.18 → 2.94 transition.

A. Resonance Decay Schemes

730-keV Resonance

The Ge(Li) spectrum obtained at the $E_p=830$-keV resonance is shown in Fig. 1. The values for γ-ray energies obtained from this spectrum, and the relative intensities obtained from NaI(Tl) singles and coincidence spectra (not shown), lead to the decay scheme shown in Fig. 11, which summarizes the results at all resonances. The resonance decay scheme is in good agreement with earlier work.[3,5] However, a weak, previously unreported transition to the 2.54-MeV level has been identified. The decay properties of the 2.94-MeV level are also in reasonable agreement with previous results. The branching ratio 19:37:44 for decay of this level to the ground state, 0.680- and 1.45-MeV levels, respectively, is determined from the coincidence spectra and is appropriately corrected for angular-correlation effects. It is interesting to note that the two members of the 2.94 → 1.45 → 0 cascade have been resolved for the first time in the Ge(Li) spectrum (see Fig. 1). Similarly, the transitions from the doublet near 0.7 MeV are resolved. The Ge(Li) spectra of the 730-, 917-, and 1748-keV resonances were each searched for evidence of a 2.94 → 0.709 transition with negative results. There is disagreement between this work and earlier work on the 4.18-MeV level. Both Baart *et al.*[5] and Van der Leun and Endt[3] report a transition from the 4.18-MeV level to the 2.94-MeV level. No evidence for the transition was found in any of the spectra obtained at the 730-keV resonance. Figure 2, for example, shows an 8-in.×8-in. NaI(Tl) spectrum in coincidence with pulses from the photopeak of the 2.94-MeV γ ray. There is no indication of a 1.24-MeV γ ray which would arise from a 4.18 → 2.94 transition. (The small hump in the spectrum at this energy is part of the Compton edges of the unresolved 1.45- and 1.49-MeV γ rays.) The present results confirm that the 4.18-MeV level decays to the 0.709-MeV level as reported by Baart *et al.*[5] The two-quantum escape peak of the corresponding 3.47-MeV γ ray can be seen in Fig. 1. There is no evidence for a 3.50-MeV γ ray from a 4.18 → 0.680 transition reported by Van der Leun and Endt.[3]

917-keV Resonance

The only previous work on the 917-keV resonance appears to be that of Singh[4] and of Baart, Green, and Willmott.[5] The NaI(Tl) spectrum (for $E_\gamma \geq 1.2$ MeV) obtained at this resonance is shown in Fig. 3. The photopeak at 3.5 MeV in this spectrum is resolved into two peaks at 3.47 MeV$-2mc^2$ and 3.54 MeV$-2mc^2$ (both ±0.01 MeV) in a Ge(Li) spectrum (see inset in Fig. 3). Similarly, the peak at 2.3 MeV is resolved into two peaks at 2.26±0.01 and 2.30±0.01 MeV. These results are inconsistent with the decay scheme derived by Baart *et al.* from NaI(Tl) spectra alone, in which the resonance was believed to decay to the 3.02-MeV level by a 2.50-MeV γ ray. The high-resolution results of the present work show, instead, that the resonance decays to the 2.94- and 4.18-MeV levels as indicated in Fig. 11, in agreement with Singh.[4] The spectra of γ rays taken in coincidence with pulses from the peaks at 2.3 and 3.5 MeV confirmed these conclusions. There is no conclusive evidence in the present work for a Res. → 3.02 transition (where "Res." means the resonance being considered), although a very weak peak at 2.34 MeV which could be due to a 3.02 → 0.680 transition was observed in the Ge(Li) spectrum. A 3.02 → 0.680 transition could also appear because of feeding of the 3.02-MeV level from the 4.50-MeV level.

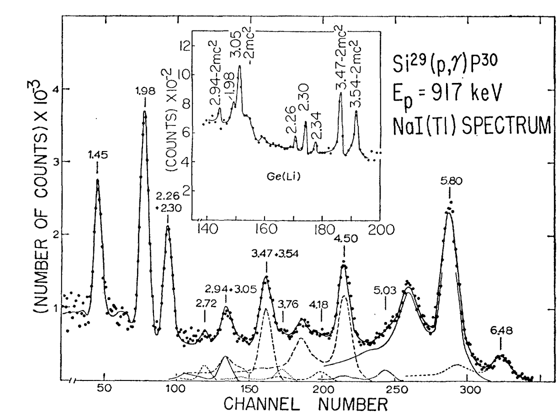

FIG. 3. γ-ray spectrum of the $E_p=917$-keV resonance in $Si^{29}(p,\gamma)P^{30}$ obtained with an 8-in.×8-in. NaI(Tl) detector. Nonresonant background has been automatically removed from the spectrum as described in the text. The solid line through the experimental points is the best fit to the data obtained by the program SPKFIT. Some of the component γ rays are shown by the broken lines. The inset shows a portion of a Ge(Li) spectrum of this resonance. The peak at 3.5 MeV in the NaI(Tl) spectrum is clearly shown by the Ge(Li) data to consist of two peaks at 3.47 and 3.54 MeV.

A 4.50 → 3.02 transition appears in the decay scheme of Baart *et al.* This transition, however, has been ruled out in the present work by means of coincidence measurements at the 917- and 1470-keV resonances. At both resonances, the spectrum of γ rays in coincidence with the photopeak at 1.5 MeV was obtained. (The coincidence spectrum obtained at the 1470-keV resonance is shown in Fig. 4.) These coincidence spectra should contain a 2.34-MeV γ ray if the supposed 4.50 → 3.02 transition exists. Instead of a 2.34-MeV γ ray, in each case a 3.05-MeV γ ray was found in addition to a γ ray having the correct energy for Res. → 4.50 transition. It must be concluded, therefore, that the 4.50-MeV level decays to the 1.45-MeV level and not observably to the 3.02-MeV level. The 4.50-MeV level was, of course, also found to decay to the ground state, in agreement with the previously reported results. There is no evidence in the Ge(Li) spectrum for a Res. → 0.709 transition reported by Singh.[4] The intensity of this transition is estimated from the present data to be less than 5% of that of the Res. → 0.680 transition.

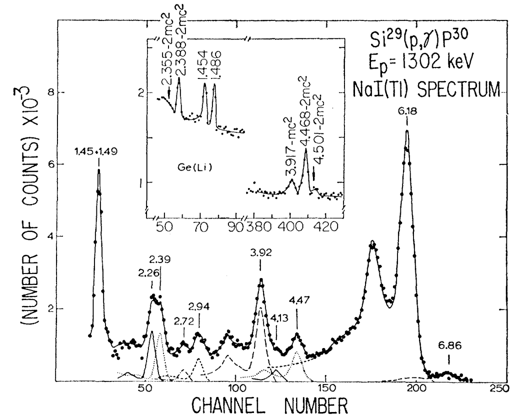

FIG. 5. γ-ray spectrum of the E_p=1302-keV resonance in Si^{29}(p,γ)P^{30} obtained with an 8-in.×8-in. NaI(Tl) detector. (See caption for Fig. 3.) The inset shows two portions of a high-resolution Ge(Li) spectrum of this resonance. The peaks at 2.388 MeV$-2mc^2$ and 4.468 MeV$-2mc^2$ correspond to the two members of a cascade through a previously unreported level at 4.468±0.003 MeV (see text). The positions at which the two members of a cascade through the 4.501-MeV level would appear are indicated at 2.355 MeV$-2mc^2$ and 4.501 MeV$-2mc^2$.

1302-keV Resonance

This resonance has been studied previously by Val'ter *et al.*,[7] Ejiri *et al.*,[8] and Moore.[6] A Res. → 2.54 transition with 12% relative intensity was reported by Val'ter which would require 4.320- and 2.536-MeV γ rays in the spectrum. On the other hand, Moore from his NaI(Tl) data proposed a Res. → 4.50 → 0 cascade which would yield γ rays with energies of 4.501±0.003 and 2.355±0.004 MeV. We find instead γ rays in coincidence with energies 4.468±0.004 and 2.388±0.003 MeV (see Fig. 5). Furthermore, it was shown at the 917-keV resonance and at the 1470-keV resonance (discussed below) that the 4.501-MeV level also decays to the 1.453-MeV level. There is no evidence in singles or coincidence spectra for the corresponding 3.048-MeV γ ray at the 1302-keV resonance. Thus it must be concluded that the 4.501-MeV level is not excited at the 1302-keV resonance, and that there must exist a previously unobserved level at 2.388 or at 4.468 MeV in P^{30}.

Although there is no way to determine directly from the data whether the 4.468- or the 2.388-MeV γ ray is emitted from the resonance level, and therefore whether the new level lies at 2.388 or at 4.468 MeV, there are strong reasons based upon the S^{32}(d,α)P^{30} data[2] and comparisons with the level scheme of Si^{30} to assign the new level at 4.468 MeV. Arguments for this assignment are presented below in Sec. IV. The final decay scheme given in Fig. 11 includes the 4.468-MeV level. There is no evidence for transitions from the 4.468-MeV level to levels other than the ground state.

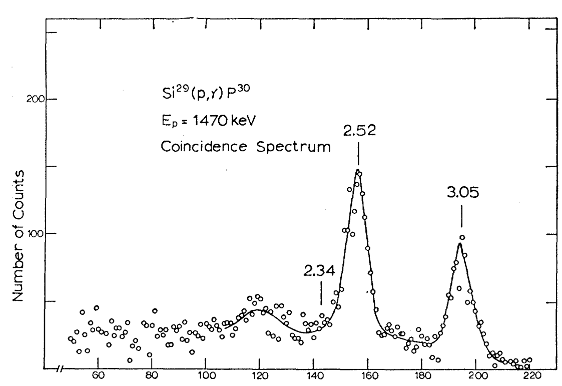

FIG. 4. Spectrum of γ rays observed with a 5-in.×5-in. NaI(Tl) detector in coincidence with the 1.45-MeV photopeak at the E_p=1470-keV resonance. This spectrum results from the subtraction of a spectrum in coincidence with pulses from a window set at an energy slightly above the 1.45-MeV photopeak from another spectrum in coincidence with a window of the same width set over the 1.45-MeV photopeak. Note the absence of a 2.34-MeV γ ray which would appear if a 4.50 → 3.02 transition exists.

1470-keV Resonance

The Ge(Li) spectrum obtained at the 1470-keV resonance is shown in Fig. 6. As found for the resonances discussed above, the analysis of the Ge(Li), NaI(Tl), and coincidence spectra leads to a decay scheme (Fig. 11) significantly different from earlier work done with NaI(Tl) detectors alone. The earlier work of Moore[6] and Phelps *et al.*[9] gave results in good mutual agreement. The changes made necessary by the present work, however, include the decay scheme of the 4.50-MeV level (discussed above), a decay mode of the 4.14-MeV level to the 0.709-MeV level instead of to the 1.45-MeV level, and the discovery of a Res. → 2.54 → 0 cascade which has members nearly equal in

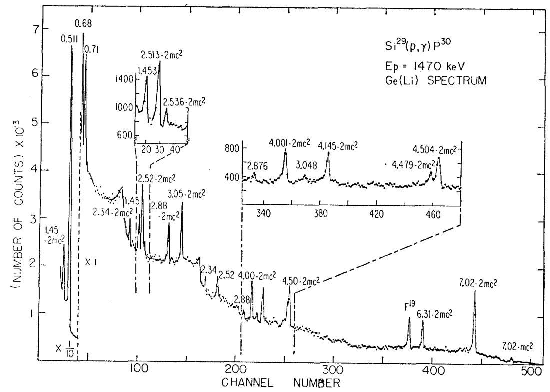

FIG. 6. γ-ray spectrum of the $E_p = 1470$-keV resonance in $Si^{29}(p,\gamma)P^{30}$ obtained with the Ge(Li) detector and a dispersion of 13.3 keV/channel. The insets show two portions of the spectrum obtained using a biased amplifier with the same detector and a dispersion of 4.57 keV/channel. The line at 4.50 MeV observed in earlier studies of this resonance using NaI(Tl) detectors is clearly shown in the inset on the right to consist of two lines at 4.479 MeV$-2mc^2$ and 4.504 MeV$-2mc^2$. Similarly, the 2.50-MeV line in earlier work is shown in the inset on the left to consist of two lines at 2.513 MeV$-2mc^2$ and 2.536 MeV$-2mc^2$. These γ rays arise from two-step cascades from the resonance through the 2.536- and 4.501-MeV levels (see text).

energy with those of the Res.$\to$4.50$\to$0 cascade. (The decay of the 4.14-MeV level is discussed below in connection with the 1686-keV resonance.) The existence of a Res.$\to$2.54 transition is significant because of its possible influence on the results of previous attempts[9,17] to measure the spin of the 4.50-MeV level by means of (p,γ,γ) angular-correlation measurements at this resonance. Angular correlations of what were assumed to be the 2.52- and 4.50-MeV members of the Res.$\to$4.50$\to$0 cascade were measured with NaI(Tl) detectors. However, as shown in the insets of Fig. 6, the "2.50"- and "4.50"-MeV lines are resolved in a high-dispersion Ge(Li) spectrum into lines at 2.513, 2.536, 4.479, and 4.504 MeV (all ± 0.004 MeV). Thus previous conclusions based upon angular correlations regarding the spin of the 4.50-MeV level of P^{30} are invalid. From the Ge(Li) spectrum, it can be estimated that the intensity of a possible Res.$\to$0.680 transition is less than about 5% that of the Res.$\to$0.709 transition.

1505-keV Resonance

The unusual decay scheme of the 1505-keV resonance has been presented in an earlier brief paper[18] in which γ-ray angular-correlation and polarization measurements were discussed. That decay scheme was based upon the analysis of NaI(Tl) singles and coincidence spectra. Some minor revisions have been found necessary as a result of the subsequent Ge(Li) data. The high-resolution Ge(Li) spectra confirm that the most prominent decay of the 1505-keV resonance is to the 4.23-MeV level, in agreement with Moore,[6] instead of to the 4.18-MeV level as reported by Antuf'ev *et al.*[19] However, the weak Res.$\to$4.18 transition reported by Moore was not observed. The peak near 4.2 MeV in the NaI(Tl) spectra which was assigned to a 4.92$\to$0.709 transition[18] was resolved into two lines at 4.209 MeV$-2mc^2$ and 4.227 MeV$-2mc^2$ in the Ge(Li) spectrum shown in Fig. 7. At first sight, these lines appear to be transitions from the 4.92-MeV level to both members of the 0.7-MeV doublet. However, in a Ge(Li) spectrum obtained in coincidence with pulses from the 8-in.$\times$8-in. NaI(Tl) detector corresponding to the photopeak of the 2.13-MeV feeder of the 4.92-MeV level, only the 4.209 MeV$-2mc^2$ line appeared. A similar spectrum in coincidence with photopeak pulses from the 2.82-MeV feeder to the 4.231-MeV level showed both lines. The higher-energy line at 4.227 ± 0.003 MeV$-2mc^2$ must therefore be due to a 4.231$\to$0 transition. Since the 4.231-MeV level was shown[18] to have spin and parity 4^-, this transition must be electric octupole. The intensity of this ground-state transition relative to the other transitions from the 4.231-MeV level is approximately 3%. Estimates based upon the efficiency and solid angle subtended by the Ge(Li) detector show that the contribution from summing effects is negligible. The lower-energy line at 4.209 MeV$-2mc^2$ must be primarily due to a 4.92$\to$0.709 transition. However, from the coincidence data it appears that a weak 4.21-MeV transition from the resonance to the 2.84-MeV level may also be present;

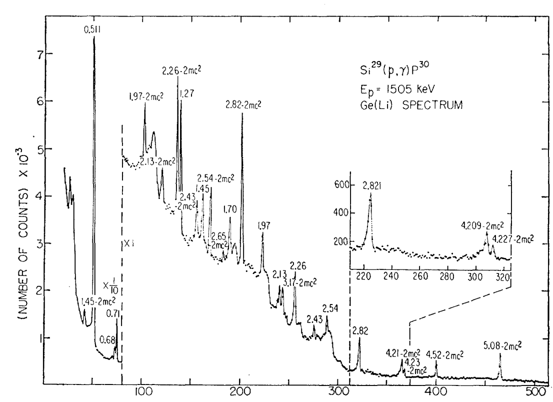

FIG. 7. γ-ray spectrum of the $E_p = 1505$-keV resonance in $Si^{29}(p,\gamma)P^{30}$ obtained with the Ge(Li) detector and a dispersion of 8.65 keV/channel. The inset shows a portion of the spectrum obtained as in Fig. 6 but with a dispersion of 4.59 keV/channel. The structure near 4.2 MeV is clearly shown in these data to contain two γ rays with energy 4.209 and 4.227 MeV. The higher-energy γ ray is due to an octupole transition from the 4.231-MeV level to the ground state.

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but it is not included in Fig. 11 because of its uncertainty. Another difference from the decay scheme presented earlier is the observation of a $4.62 \rightarrow 2.94$ transition, and possibly a weak $4.62 \rightarrow 1.97$ transition, in addition to the $4.62 \rightarrow 1.45$ transition.[20] The relative intensities for decay of the 1.97-MeV level shown in Fig. 11 were also determined at this resonance from coincidence spectra (corrected for angular-correlation effects) with estimated errors of $\pm 2\%$. The 2.54-MeV level was observed to decay predominantly to the ground state. No evidence is seen for a $2.54 \rightarrow 0.680$ transition reported by Baart *et al.*[5] The upper limit of intensity of cascade transitions from the 2.54-MeV level is estimated from the Ge(Li) spectrum to be 15%.

1686-keV Resonance

The spectra obtained at this resonance exhibit a prominent cascade to the ground state through the 4.14-MeV level, in agreement with the results of Moore.[6] However, the present data contradict his conclusion that the 4.14-MeV level also decays to the 1.45-MeV level by the emission of 2.69-MeV γ rays. Instead, lines at 2.60 MeV$-2mc^2$ and 3.17 MeV$-2mc^2$ are found in the Ge(Li) spectrum which were shown to be in coincidence with the 1.45-MeV γ ray using NaI(Tl) detectors. [The Ge(Li) spectrum obtained at this resonance is shown in Fig. 8.] Hence, the resonance must also decay by a cascade through the 4.62-MeV level discussed above. The unexplained 1.69-MeV γ ray observed by Moore is thus due to a $4.62 \rightarrow 2.94$ transition. This conclusion is confirmed by coincidence measurements and is in agreement with the preliminary results of Bergstrom.[20] A weak line at 3.43 MeV$-2mc^2$ in the Ge(Li) spectrum probably arises from a $4.14 \rightarrow 0.709$ transition. Weak cascades through the 2.84-, 3.74-, and 3.84-MeV levels reported by Moore are not confirmed by the present data. For example, a line at 4.39 MeV$-2mc^2$ in the Ge(Li) spectrum, which may be supposed to correspond to a Res.$\rightarrow 2.84$ transition, is believed to be due to the broad resonance at 1652 keV in the $Si^{28}(p,\gamma)P^{29}$ reaction. A 2.84-MeV γ ray is not observed.

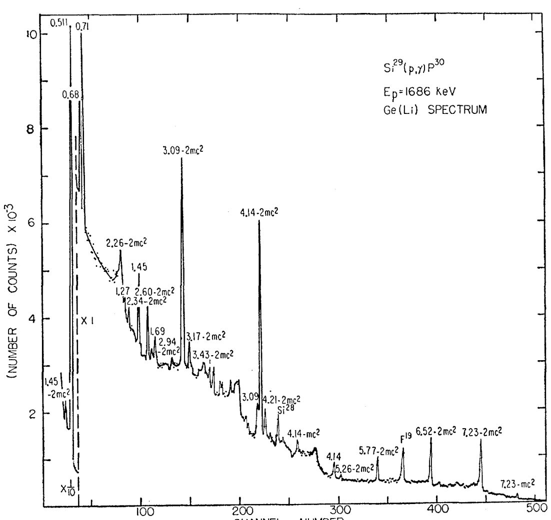

FIG. 8. γ-ray spectrum of the E_p=1686-keV resonance in $Si^{29}(p,\gamma)P^{30}$ obtained with the Ge(Li) detector and a dispersion of 13.6 keV/channel. The peak labeled Si^{28} is believed to arise from the broad resonance at 1652 keV in the $Si^{28}(p,\gamma)P^{29}$ reaction. Similarly, the peak labeled F^{19} is due to the $F^{19}(p,\alpha\gamma)O^{16}$ reaction.

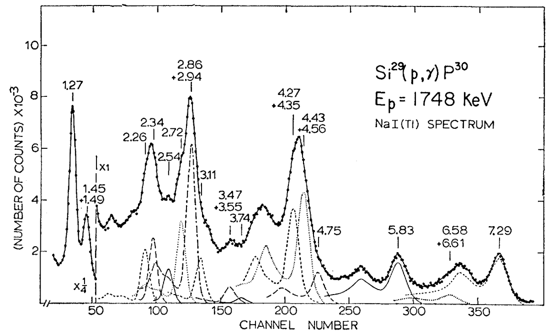

FIG. 9. γ-ray spectrum of the E_p=1748-keV resonance in $Si^{29}(p,\gamma)P^{30}$ obtained with the 8-in.$\times$8-in. NaI(Tl) detector. (See caption for Fig. 3.) Most of the component γ-ray lines given by the program SPKFIT are shown. Several lines can be seen to be unresolved by comparison with Fig. 10. The 1.27-MeV γ ray is from the $Si^{29}(p,p',\gamma)Si^{29}$ reaction which competes with radiative capture at this resonance.

1748-keV Resonance

It was found to be difficult to derive a consistent preliminary decay scheme for this resonance from the relatively simple appearing NaI(Tl) spectrum (Fig. 9). The reason for the difficulty is apparent in Fig. 10, which shows a Ge(Li) spectrum. The peak near 4.4 MeV in the NaI(Tl) spectrum is found in the Ge(Li) spectrum to be composed of five lines at 4.272 MeV $-2mc^2$, 4.351 MeV$-2mc^2$, 4.425 MeV$-2mc^2$, 4.560 MeV$-2mc^2$, and 4.751 MeV$-2mc^2$. With the exception of the 4.425 MeV$-2mc^2$ line, these can be uniquely identified as transitions from the resonance to the 3.02-, 2.94-, 2.72-, and 2.54-MeV levels, respectively. The 4.425 MeV$-2mc^2$ line requires special comment. This line, and a strong line observed at 2.865 MeV $-2mc^2$, have roughly the energies expected from a Res.$\rightarrow 2.84 \rightarrow 0$ cascade proposed by Moore.[6] However, a careful measurement of the energies of these lines (see inset in Fig. 10) shows instead that they must be the two members of a cascade through the level at 4.421 ± 0.010 MeV.[21] This is the first observation

[20] The existence of the $4.62 \rightarrow 2.94$ and $4.62 \rightarrow 1.97$ transitions were brought to our attention by Dr. Solveig Bergstrom, who observed them in a study (unpublished) of the 1686-keV resonance in the $Si^{29}(p,\gamma)P^{30}$ reaction. They are also observed at the 1686-keV resonance in the present study.

[21] The inverted order for this cascade would imply that the level observed at 2.839 ± 0.010 MeV by Endt and Paris (Ref. 2) lies instead at 2.865 ± 0.004 MeV—a discrepancy of three times the error quoted for the results of the $S^{32}(d,\alpha)P^{30}$ measurements.

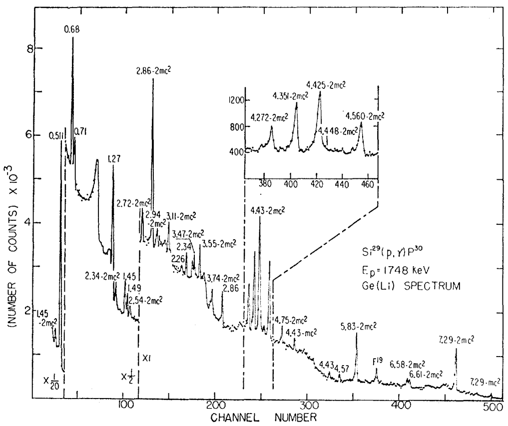

FIG. 10. γ-ray spectrum of the E_p = 1748-keV resonance obtained with the Ge(Li) detector and a dispersion of 13.4 keV/channel. The inset shows a portion of the spectrum obtained with a dispersion of 4.36 keV/channel. The expected position of the two-quantum escape peak corresponding to a previously reported Res.→2.84 transition is indicated by the arrow at 4.448 MeV $-2mc^2$ in the inset.

of the 4.42-MeV level by the proton-capture reaction. No transitions other than to the ground state were observed from the 4.42-MeV level. There is no evidence for a 3.02→0 transition which has been reported by other workers. It is difficult with the present data to determine whether transitions other than 2.72→0 occur from the 2.72-MeV level. However, it can be estimated that such transitions must account for less than about 20% of the decay of the 2.72-MeV level. This is the only resonance studied in which transitions from the resonance level to both members of the doublet near 0.7 MeV were observed. (They are both weak, which probably accounts for their not being observed by Moore.) Also, this is the only resonance observed to decay to the 3.74-MeV level. This level appears to decay only to the ground state.

The decay scheme of the 1748-keV resonance provides a special opportunity to search for transitions from the 1.45-MeV level to members of the 0.7-MeV doublet. The resonance decays with relative intensity 14% to the 1.45-MeV level, but with a total of only 3.5% to the members of the doublet. Spectra from a 5-in.×5-in. NaI(Tl) detector were recorded in coincidence with pulses from two windows in a spectrum from the 8-in.×8-in. detector. One window was adjusted to accept only pulses from a region containing the photopeak of the 5.83-MeV, Res.→1.45 transition. The other window of equal width was set at an energy slightly higher than the photopeak in order to compensate partially for the effects of the Res.→(0.68,0.71) transitions. From the resulting data, it can be estimated that the intensity of 1.45→0.68 and 1.45→0.71 transitions must each be less than 3% of the crossover transition to the ground state.

TABLE I. Properties of resonance levels studied in the $Si^{29}(p,\gamma)P^{30}$ reaction. The excitation energies E_x are based upon a reaction Q value of 5.597±0.003 MeV (see text). The strength $(2J+1)\Gamma_\gamma\Gamma_p/\Gamma$ of the 695-keV resonance, which was otherwise not studied in this work, was found to be 0.86±0.13 eV.

E_p (keV)	E_x (MeV)	$(2J+1)\Gamma_\gamma\Gamma_p/\Gamma$ (eV)[a]	J^π	T
730±2	6.303±0.003	0.46±0.07		0[d]
917±2	6.483±0.003	0.49±0.07	1[b]	0[d]
1302±2	6.856±0.003	1.5 ±0.2		0[d]
1470±2	7.018±0.003	0.55±0.08	2[b]	
1505±2	7.052±0.002	4.4 ±0.7	4− [c]	1[c]
1686±2	7.227±0.003	9.1 ±1.4	2[b]	
1748±2	7.287±0.002	8.5 ±1.3		

[a] Measured relative to the value 0.70±0.10 eV given in Ref. 16 for the E_p = 414-keV resonance.
[b] Reference 17.
[c] Reference 18.
[d] Assigned on the basis of decay-scheme properties.

TABLE II. Bound energy levels in P^{30}. The energies derived from the Ge(Li) data are compared with the earlier values of Endt and Paris (Ref. 2) obtained from the $S^{32}(d,\alpha)P^{30}$ reaction.

E_x (MeV±keV) Ref. 2	Present work	J^π; T	References for J^π and T
0	0	1^+; 0	a
0.684±3[a]	0.680±2	0^+; 1	a
0.705±3[a]	0.709±2	1^+; 0	a, b
1.451±10	1.453±2	2^+; 0	b
1.972±10	1.974±2	3^+; 0	b
2.538±10	2.536±2	3^+; 0	b
2.723±10	2.722±2	2^+; 0	a
2.839±10			
2.937±10	2.939±2	2^+; 1	a
3.018±10	3.020±3	1^+; 0	a
3.734±10	3.736±3		
3.836±10			
3.926±10	3.928±4		
4.141±10	4.142±2	2 ; 0	c
4.181±10	4.182±4	2^+; 1	a
4.230±10	4.231±2	4^-; 0	b
4.296±10			
4.342±10			
4.421±10	4.425±3		
	4.468±3	(0); (1)	d
4.501±10	4.501±3	(1); 1	a, d
4.625+10	4.624±2	3^-; 0	b
4.734±10			
4.929±10	4.921±2	3^-; 0	b
5.024±10			
5.200±10			
(5.233±10)			
5.412±10			
5.504±10			
5.598±10			
5.700±10			
5.790±10			

[a] Reference 1.
[b] Reference 18.
[c] Reference 17.
[d] Present work.

B. Resonance Strengths and Level Energies

The results of the strength measurements of the seven resonances studied are given in Table I. Also given in this table are the excitation energies in P^{30} of the resonance states based upon a Q value of 5.597±0.003

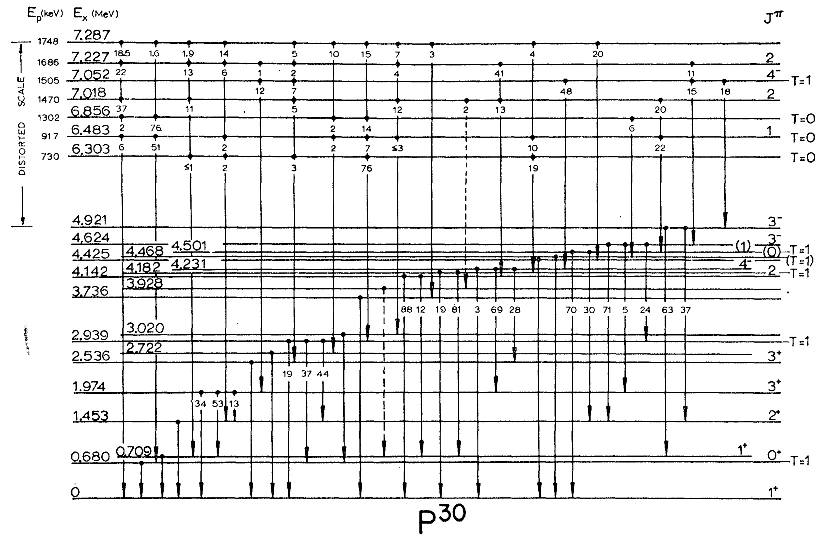

FIG. 11. Decay scheme of resonances and bound levels of P^{30} as determined in the present study. Only those levels observed in the capture reaction are shown. See Table II for a complete listing of the known bound levels and Table III for estimates of errors in the γ-ray branching ratios. The spin-parity assignments shown are taken from Refs. 17 and 18, except those for the 4.468- and 4.501-MeV levels, which are tentatively assigned on the basis of arguments presented in the present paper. See Ref. 1 for further information on spins and parities. The isobaric-spin assignments are from Refs. 2, 5, 18, and the present work. The dashed lines indicate transitions which are probable but not definitely established.

MeV for the $Si^{29}(p,\gamma)P^{30}$ reaction. Other properties which we have reported in earlier papers are also listed. The reaction Q value, an average value derived from measurements of γ-ray energies with the Ge(Li) detector, is 5 keV higher than a recently published value of 5.592±0.008 MeV.[22]

With the exception of the members of the doublet at 0.7 MeV, the best previous values for the energies of the bound states of P^{30} result from the $S^{32}(d,\alpha)P^{30}$ measurements of Endt and Paris[2] in which errors of ±10 keV are quoted. It was found that more precise values could be obtained in the present work for many of the bound levels from the Ge(Li) spectra. In many cases the energy of a given level could be determined in several ways by the measurement of the energies of members of cascades which involve the level. In some cases, the values could be determined at several resonances. The final values, after appropriate weighted averages have been determined, are given in Table II along with the previous values. The agreement is seen to be consistently within the quoted errors.

The reaction Q value and P^{30} level energies given in the present paper should be considered to supercede values given recently in a preliminary report[23] in which Doppler-shift corrections were not included.

IV. SUMMARY AND DISCUSSION

The results of the present investigation of properties of levels of P^{30} are summarized in Tables I, II, and III, and in Fig. 11, where the decay modes of all levels observed are represented. It was found in a surprising number of cases in this study that significant changes

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[23] G. I. Harris and A. K. Hyder, Jr., Bull. Am. Phys. Soc. **12**, 73 (1967).

TABLE III. γ-ray transitions between bound levels of P^{30}. $E_x(i)$ and $E_x(f)$ are the excitation energies of the initial and final levels of the transition, respectively. The transition energies E_γ are also listed.

$E_x(i)$ (MeV)	$E_x(f)$ (MeV)	E_γ (MeV)	Relative intensity (%)
0.680	0	0.680	100
0.709	0	0.709	100
1.453	0	1.453	≥96
1.453	0.680	0.773	≲3
1.453	0.709	0.744	≲3
1.974	0	1.974	34±2
1.974	0.709	1.265	53±2
1.974	1.453	0.521	13±2
2.536	0	2.536	≥85
2.722	0	2.722	≥80
2.939	0	2.939	19±2
2.939	0.680	2.259	37±2
2.939	1.453	1.486	44±2
3.020	0	3.020	≤5
3.020	0.680	2.340	≥95
3.736	0	3.736	≥80
3.928	(0.709)	3.219	(100)[a]
4.142	0	4.142	88±4
4.142	0.709	3.433	12±4
4.182	0	4.182	19±3
4.182	0.709	3.473	81±3
4.231	0	4.231	3±1
4.231	1.974	2.257	69±2
4.231	2.536	1.695	28±2
4.425	0	4.425	≥90[b]
4.468	0	4.468	≥80
4.501	0	4.501	70±8
4.501	1.453	3.048	30±8
4.624	1.453	3.171	71±3
4.624	1.974	2.650	5±2
4.624	2.939	1.685	24±3
4.921	0.709	4.212	63±5
4.921	1.453	3.468	37±5

[a] This transition observed, weakly, only at the 1470-keV resonance.
[b] Result depends upon assumed cascade order and the $S^{32}(d,\alpha)P^{30}$ value for the energy of the 2.839-MeV level. See discussion of 1748-keV resonance and Ref. 21.

from previously reported decay schemes were required as a result of the coincidence data and high-resolution Ge(Li) spectra. Revisions in decay schemes were found necessary for the 3.02-, 3.74-, 4.14-, 4.18-, 4.23-, and 4.50-MeV levels and for all seven resonance levels studied. Decay properties of the 4.43-, 4.47-, 4.62-, and 4.92-MeV levels, for which no previous data are available, were also determined. Below $E_x=5$ MeV, only the levels at 2.84, 3.84, 4.30, 4.34, and 4.73 MeV have so far not been observed in the proton-capture reaction. Earlier reports of excitation of some of these levels are shown to be inconsistent with the high-resolution data. In particular, an earlier report[6] that the 2.84-MeV level decays directly to the ground state is now open to question. An unusual result is the discovery at the 1505-keV resonance of a transition to the 1^+ ground state from the 4.23-MeV level which was shown[18] earlier to have $J=4^-$. Although the measurement would be difficult, the lifetime of the 4.23-MeV level would be a very useful check on the character of this level which has been assumed to be a member of the $(2s_{1/2}1f_{7/2})$ configuration.[18] We note, however, that *if* the $E3$, $4.23\rightarrow 0$ transition is enhanced to 10 Weisskopf units, the $E1$, $4.23\rightarrow 1.97$ and $4.23\rightarrow 2.54$ transitions are inhibited by a factor of 1.5×10^{-5} Weisskopf units. These results would not be inconsistent with the empirical distributions of $E1$ and $E3$ transition strengths found in $2s$-$1d$ shell nuclei by Van der Leun.[24]

The 4.50-MeV level of P^{30} has been assigned $T=1$ as a result of $S^{32}(d,\alpha)P^{30}$ studies by Endt and Paris.[2] It also appears to have about the correct energy to be the analog of one of the members of the doublet near 3.8 MeV in Si^{30}. The members of this doublet have recently been studied by Smulders,[25] who finds $J=1$ and $J=0$ for the 3.77- and 3.79-MeV levels, respectively. Thus the 4.50-MeV level of P^{30} should have either $J=0$ or 1. The results of attempts[9,17] to measure this spin at the 1470-keV resonance are shown in this work to be questionable because of the discovery of a previously unresolved, competing cascade through the 2.54-MeV level. It appears likely, however, that the 4.50-MeV level is not spin 0, since it is excited by a primary transition from the $J=2$ resonance and it decays partially to the $J=2$, 1.45-MeV level. Thus the 4.50-MeV level is tentatively assigned $J=1$.

A two-step cascade to the ground state was observed at the 1302-keV resonance which could only be explained by the existence of a previously unreported level at 2.388 or at 4.468 MeV. By comparison with the level scheme of Si^{30}, a 2.388-MeV level in P^{30} would have $T=0$. Therefore, there is no apparent reason why it should not have been observed in the $S^{32}(d,\alpha)P^{30}$ data.[2]

[24] C. Van der Leun, in Proceedings of the Symposium on the Structure of Low-Medium Mass Nuclei, edited by L. W. Seagondollar, 1964 (University of Kansas) (unpublished). Also Aerospace Research Laboratories Report No. ARL 65-63, 1965 (unpublished).

[25] P. J. M. Smulders, Phys. Letters **9**, 155 (1964).

TABLE IV. Decay of resonance levels to $T=1$ levels of P^{30}. The relative "reduced" intensity of transitions to $T=1$ levels is listed under $I(T=1)$.

Resonance energy (keV)	$I(T=1)$ (%)
730	98.2
917	96.5
1302	96.7
1470	56.0
1505	0
1686	0
1748	20.2

On the other hand, a 4.468-MeV level has just the right energy to be the "missing" analog of the $J=0$, $T=1$ level at 3.79 MeV in Si^{30}. The $J=0$, $T=1$ level in P^{30} could easily have been unobserved in the $S^{32}(d,\alpha)P^{30}$ reaction because of suppression due both to the violation of isobaric-spin conservation and the spin and parity dependence of the (d,α) reaction. As pointed out by Hashimoto and Alford,[26] only one-third of the states formed in the compound nucleus formed by deuteron bombardment of a spin-zero target are able to decay by α emission to a final $J=0$ level. Thus the cross section for a $J=0$ level can be expected to be reduced by a factor of about $\frac{1}{3}$ from that of neighboring $J\neq0$ levels, independent of isobaric-spin considerations. Following Hashimoto and Alford, we find that a more quantitative calculation based upon the statistical theory of Hauser and Feshbach[27] leads to a ratio of 0.26 for the cross sections of $J=0$ and $J=1$ levels near 4.5 MeV in P^{30} and for the 6-MeV deuteron energy used by Endt and Paris.[2] (We note that the $J=0$, $T=1$ level at 0.680 MeV in P^{30} also appeared very weakly in their data.) We thus propose that the new level required by the data at the 1302-keV resonance lies at 4.468 MeV and that it is the $J=0$, $T=1$ analog of the 3.79-MeV level of Si^{30}. However, measurements to confirm and clarify further the proposed correspondences with the 3.77- and 3.79-MeV levels in Si^{30} are clearly desirable.

The influence of the isobaric-spin selection rule $\Delta T=\pm1$ for $E1$ transitions and the inhibition of $\Delta T=0$ transitions for $M1$ transitions in self-conjugate nuclei appears to be quite pronounced in decay schemes of the resonances at $E_p=730$, 917, and 1302 keV. In order to obtain a quantitative evaluation of the possible influence of isobaric spin in the resonance decay schemes, we have computed for each resonance the fraction of "reduced strengths" of transitions to $T=1$ levels. The reduced strengths were obtained by dividing the relative intensity of each transition by E_γ^{2L+1}. All transitions were assumed to be pure dipole, which is generally consistent with the available information on level spins and multipolarity mixings. The results are shown in Table IV. It can be seen that the lowest three resonances decay almost entirely to the small subset

[26] Y. Hashimoto and W. P. Alford, Phys. Rev. **116**, 981 (1959).

[27] W. Hauser and H. Feshbach, Phys. Rev. **87**, 366 (1952).

of $T=1$ levels of P^{30}. Thus they can with considerable confidence be assigned $T=0$, and there appears to be only a small amount of $T=1$ contamination. The 1470- and 1748-keV resonances appear to have considerable isobaric spin mixing. It has already been argued[18] that the 1505-keV resonance has $T=1$; however, the result $I(T=1)=0$ neither confirms nor contradicts that conclusion because of the high-resonance spin (4^-). The value of $I(T=1)$ for the 1686-keV resonance can be considered as weak evidence in favor of a $T=1$ assignment for this resonance, since $J_r=2$, and thus no strong spin-dependent inhibitions appear in transitions to the known low-lying $T=1$ levels.

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Levels of Si^{29} below 4.1-MeV Excitation Energy

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The states of Si^{29} at 1.28-, 2.03-, 2.43-, 3.07-, 3.62-, and 4.08-MeV have been studied using the particle-γ angular-correlation method of Litherland and Ferguson. The $Si^{28}(d,p)Si^{29}$ reaction was used to populate the levels of Si^{29} at several bombarding energies in the neighborhood of 3 MeV. Charged particles were detected near 180° with respect to the incident-beam direction in a solid-state annular counter, and γ radiation was detected in a 10.2×10.2 cm NaI(Tl) crystal at angles between 0° and 90° relative to the incident-beam direction. The p-γ coincident data were stored in a 2-parameter pulse-height analyzer. γ-ray branching ratios derived from these data are presented for the levels mentioned above. In addition to an independent confirmation of the spin assignments $\frac{3}{2}$, $\frac{5}{2}$, and $\frac{3}{2}$ for the Si^{29} levels at 1.28-, 2.03-, and 2.43-MeV, respectively, an assignment $J=\frac{7}{2}$ for the 3.62-MeV level and a most probable assignment $J=\frac{5}{2}$ for the 3.07-MeV level are established. For the 4.08-MeV level, $J\geq\frac{3}{2}$. Some γ-ray mixing ratios are also presented, and an upper limit for the mean lifetime, $\tau_m\leq 90^{-8}$ sec, was obtained for all the levels studied.

I. INTRODUCTION

THE collective-model descriptions[1,2] of nuclei in the s-d shell have had rather good success near $A=25$; however, this picture does not appear to represent nuclei with Z or $N=15$ quite as well.[2] Core-deformation effects may be of more importance for these nuclei as the sign of the nuclear deformation appears to change around $A=28$. More extensive experimental information about Si^{29}, including spin assignments to the levels in the neighborhood of 3.5 MeV, their γ-ray decay modes, and multipole admixtures in these γ-ray transitions would be of value for comparison with model predictions. Earlier work on Si^{29} is summarized in the compilation of Endt and van der Leun.[3] The location of the levels of Si^{29} has been ascertained using magnetic analysis of charged reaction products, and differential cross-section studies of the $Si^{28}(d,p)Si^{29}$ reaction have assigned l_n values to several of the low-lying levels. Experimental investigations of the γ-ray decay of the low-lying levels of Si^{29} include the $Si^{29}(p,p'\gamma)$ work of Bromley *et al.*[4] and the $Mg^{26}(\alpha,n)Si^{29}$ study of Litherland and McCallum.[5]

A measurement of the spin of the 3.07-MeV level is interesting for comparison with the $J=\frac{3}{2}$ assignment suggested[6] by a study of the J dependence of the $Si^{28}(d,p)Si^{29}$ differential cross section. The 3.62-MeV level is thought[3] to be a single-particle $1f_{7/2}$ level, and a direct measurement of the spin of this level is important. Especially interesting is a comparison of the levels of Si^{29} with corresponding levels of P^{29}, particularly with the recently explored[7] 4.08-MeV level of P^{29}. The spins of the Si^{29} levels at 1.28-, 2.03-, and 2.43-MeV excitation energy have been well established[3]; our work provides an independent check of these assignments. Perhaps of some interest, too, is a comparison of this experiment with the experiment of Litherland and McCallum[5]; both experiments utilize the same method,

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[2] J. P. Davidson, Rev. Mod. Phys. **37**, 105 (1965). J. P. Davidson, in Proceedings of the Lawrence (Kansas) Symposium on the Structure of Low–Medium Mass Nuclei, 1964 (unpublished).

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