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Some energy levels in P(30) observed in radiative capture by Si(29) of protons with energies from 1420 to 2160 keV

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eliminate it. Furthermore, the quality of the fits was not improved; instead, it was worsened at the highest energies. This is not surprising, since the set C geometry was determined without this additional potential.[1] Parameter searches on the five highest energies, with r_{0S} kept fixed at 1.18 F and α at 0.5×10^{-39} cm^3, yielded different sets of geometrical parameters from those obtained in the previous section where α was zero.

We did not attempt a more extensive fitting of the data by using the polarizability potential, since we felt that incorporating virtual excitations of the deuteron without in some manner treating the electric breakup of the deuteron would be inconsistent. At present, there is no simple treatment of the electric breakup of the deuteron in a formalism which can be easily incorporated in an optical-model calculation. Possibly a long tail, which might simulate the deuteron breakup, could be added to the imaginary part of the optical potential. However, we feel that some theoretical justification should be given to the shape and strength of this imaginary potential, because the lack of structure in the angular distribution would certainly allow a wide range of shapes and strengths on a purely phenomenological basis.

V. CONCLUSIONS

The data presented in this paper may show evidence for some effects of the nuclear electric field on the deuteron during elastic scattering from nuclei. Since the departure from Rutherford scattering is many times larger than that expected from the electric polarizability of the deuteron alone, we must conclude that nuclear interactions still dominate the elastic scattering even at the lowest energies of our measurements. The lack of structure of the deuteron elastic-scattering angular distributions at low energies is a very serious handicap to a phenomenological analysis of the data. We feel that more theoretical attention should be given to the electric breakup of the deuteron before any meaningful optical-model analysis of the data can be extended to low deuteron bombarding energies.

ACKNOWLEDGMENTS

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Some Energy Levels in P^{30} Observed in Radiative Capture by Si^{29} of Protons with Energies from 1420 to 2160 keV*

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The excitation function for the $Si^{29}(p,\gamma)P^{30}$ reaction has been experimentally determined in the proton energy range from 1420 through 2160 keV. Unreported resonances in this reaction have been identified at 1975, 2033, 2075, and 2117 keV with estimated errors of ±4 keV, corresponding to energy levels in P^{30} at 7.49, 7.55, 7.59, and 7.63 MeV. Gamma spectra at these resonances are obscured by contaminant radiation but suggest complex decay schemes. Double angular-correlation measurements have been made at the 1470-keV resonance indicating a resonance-level spin of 2+, or less probably, 2−. The level at 4.50 MeV in P^{30} is shown to probably have a spin of 2+ or, less probably, 3+; these spin values are in disagreement with the 0+ that has been predicted for this level.

I. INTRODUCTION

THE results of a study of the $Si^{29}(p,\gamma)P^{30}$ reaction, herein reported, consist of two parts. The first consists of observations of the excitation function between 1420 and 2170 keV and, in particular, of four resonances which have been found at the proton energies: 1975, 2033, 2075, and 2117 keV. The second reports on a double γ-γ angular-correlation experiment at the 1470-keV resonance.

Previous investigations of this reaction were summarized in the compilation of Endt and Van der Leun.[1] Recent investigators have been Baart *et al.*[2], Moore[3], and Ejiri *et al.*[4]

II. EXPERIMENTAL PROCEDURE

The 2-MeV Van de Graaff accelerator at the U. S. Naval Postgraduate School was used to bombard isotopically enriched SiO_2(91.8% Si^{29}; 7.8% Si^{28}; 0.30 Si^{30}) purchased from the Oak Ridge National Laboratory. Targets of 5- to 8-keV thickness for 2-MeV protons were produced by vacuum plating enough high-purity

* Research work supported in part by the U. S. Office of Naval Research.
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[1] P. M. Endt and G. Van der Leun, Nucl. Phys. **34**, 151 (1962).
[2] E. E. Baart *et al.*, Proc. Phys. Soc. (London) **79**, 237 (1962).
[3] R. A. Moore, Ph.D. thesis, University of Kansas, 1963 (unpublished).
[4] H. Ejiri *et al.*, Nucl. Phys. **51**, 470 (1964).

gold on thick copper backings to stop incident protons, and then vacuum depositing the target material on this backing. These backings, when appropriately cooled, conducted away heat fast enough to allow higher target beam intensity than possible with the usual tantalum sheet backing and also showed somewhat less contamination by F^{19}. Gamma rays from the reaction were measured by a scintillation crystal spectrometer constructed for this experiment. This system employed two cylindrical 3-in.×3-in. NaI(Tl) crystals with 9% resolutions for 0.662-MeV gamma rays. The scintillation detectors were mounted on a correlation table with the fixed detector axis at 270° relative to the proton beam when viewed from above, and with the other detector movable in the horizontal plane containing the beam. The rest of the spectrometer consisted of a slow-fast coincidence system, a pulse adder[5] used to obtain sum-coincidence spectra,[6] and an RCL 128-channel pulse-height analyzer.

Analysis of the data was programmed for and performed on a CDC-1604 computer. In this analysis a least-squares fitting technique was used to analyze gamma spectra, and correlation coefficients were computed using the method of Rose.[7] A digital graph-plotter output mode of the computer was utilized to produce contour plots[8] of correlation coefficients against mixing parameters.

III. RESONANCES

The excitation function for $Si^{29}(p,\gamma)P^{30}$ as measured by gamma-ray yield is shown in Fig. 1, and as measured by gamma-gamma coincidence yield in Fig. 2. A coinci-

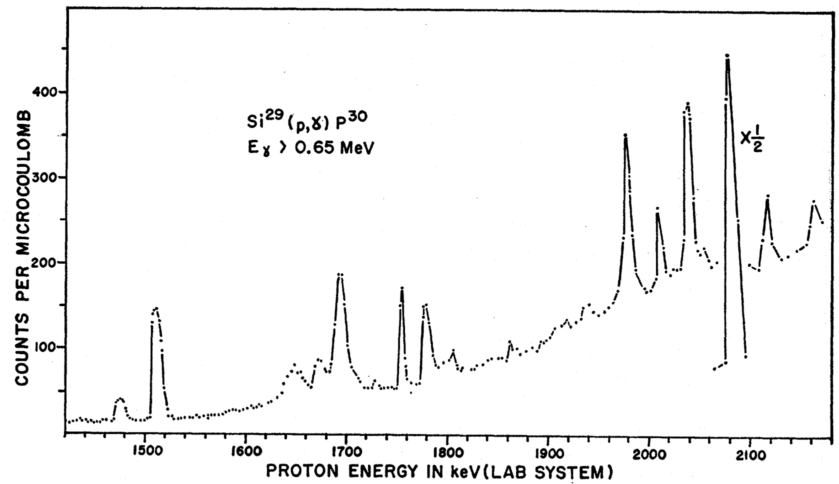

FIG. 1. Yield of gamma rays over 0.65 MeV in energy. Statistical uncertainties are smaller than the sizes of the experimental points. Background (see text) counts have been subtracted.

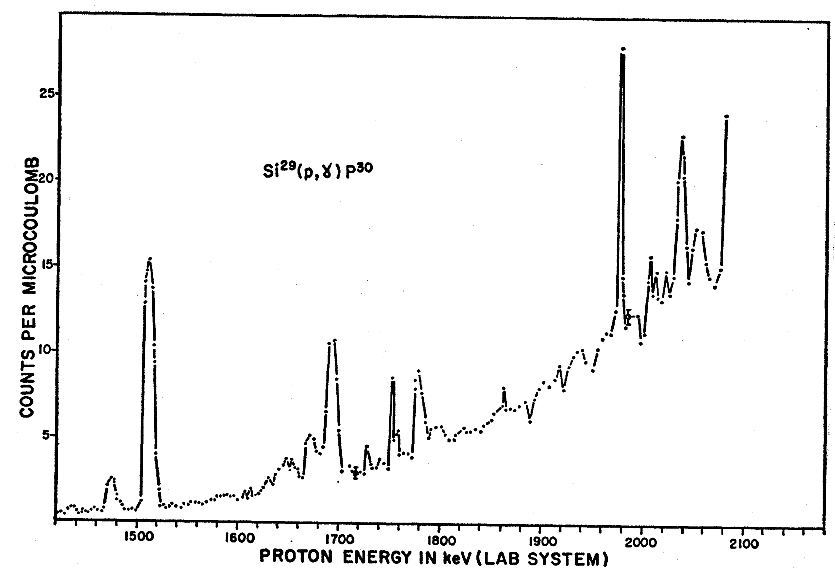

FIG. 2. Gamma-gamma coincidence yield. Background (see text) counts have been subtracted.

[5] J. Kantele and R. W. Fink, Nucl. Instr. Methods **15**, 69 (1962).
[6] A. M. Hoogenboom, Nucl. Instr. Methods **3**, 57 (1958).
[7] M. E. Rose, Phys. Rev. **91**, 610 (1953).
[8] H. E. Gove, in *Nuclear Reactions*, edited by P. M. Endt and M. DeMeur (North-Holland Publishing Company, Amsterdam, 1959), Vol. I.

dence resolving time of 25 nsec was used when measuring gamma-gamma coincidence yield of the reaction in order to reduce accidental coincidence counts to under one per cent of the coincidence counts. An integral discriminator setting of 0.65 MeV in each channel excluded annihilation radiation arising from positron decay of P^{30} while accepting the full energy peaks of the 0.68- and 0.71-MeV radiations which de-excite the first two excited states in P^{30}. This choice of discriminator setting also eliminated coincidence counts arising from cross talk between crystals associated with Compton scattering and pair-production events. Counting errors due to pile-up were not significant. The 7-μA proton beam was collected by a current integrator, which closed a beam shutter and stopped counters after collection of 84 μC at each energy step of approximately 3 keV. Background counts were made every 50 keV with the beam intercepted by a shutter in the beam tube outside the shielded target area.

The energies at which resonances are observed are listed in Table I, together with some of the results which have been obtained at proton energies below 1900 keV by other investigators. In arriving at the uncertainties of 0.20% in the values of the resonance energies, consideration has been given to errors arising from instability and inhomogeneity of the field of the analyzing magnet, the proton beam spread, possible surface contaminants, calibration drift, and the 0.5-keV estimated error for the 992-keV aluminum calibration point.[9]

The four resonances above 1900 keV, which have not previously been reported, were examined carefully to ensure that radiative capture by Si^{29} was being observed.

TABLE I. Resonances observed in the $Si^{29}(p,\gamma)P^{30}$ reaction E_p from 1450 to 2170 keV.

This work	Green[a]	Seagondollar[b]	Tsytko[c]	Wild[d]	Remarks
1470	1479	1479		1470	
1506	1515	1512		1505	
1637	1648	1643	1635	1638	
(1646)		(1653)	(1647)	(1650)	Si^{28}
1667	1671		1663	{1665 1670	
1688	1692	1693	1680	1685	
(1726)					weak
1752	1752	1752		1749	
1775	1777	1775		1772	
(1803)	1811			1808	
1860	1857			1852	
(1933)					weak
1975					
(2007)					Si^{30}
2033					
2075					
2117					
(2159)					not identified
±0.20%	±2	±2		±3	Errors

[a] N. K. Green and R. F. Wiseman, M.S. thesis, U. S. Naval Postgraduate School, 1958 (unpublished).
[b] L. W. Seagondollar *et al.*, Phys. Rev. 120, 251 (1960).
[c] S. P. Tsytko and Iu. P. Antuf'ev, Zh. Eksperim. i Teor. Fiz. (USSR) 30, 1171 (1956) [English transl.: Soviet Phys.—JETP 3, 993 (1957)].
[d] U. P. Wild, M.S. thesis, University of Kansas, 1962 (unpublished).

[9] J. B. Marion, Rev. Mod. Phys. 33, 139 (1961).

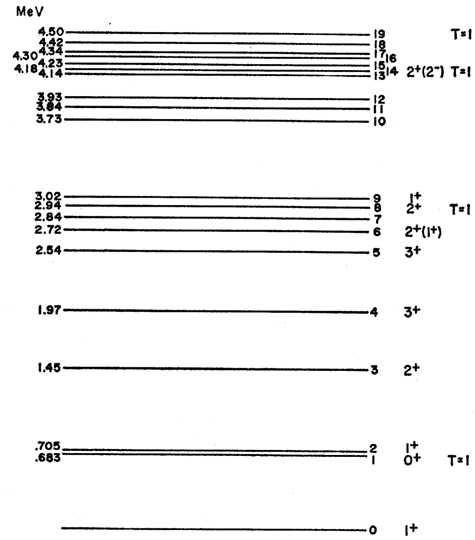

FIG. 3. The lower energy levels in P^{30}. T values are isotopic spins; spin parities in parentheses are less likely alternates.

The intensity and half-life of postbombardment radiation were observed at each resonance point and just off resonance to confirm that the gamma-ray intensity peaks were due to this reaction.

The lower energy levels of P^{30} through which radiative transitions may occur are known from work by previous investigators,[1,2] and are shown in Fig. 3. Gamma-ray spectra were obtained at the four resonances at proton energies of 1975, 2033, 2075, and 2117 keV. Calculation of the corresponding energy levels in P^{30} using a Q value[10] of 5.582 meV leads to values of 7.49, 7.55, 7.59, and 7.63 MeV. Masking radiation from the resonant reaction with the contaminant F^{19} dominates the upper energy region of these spectra so that a detailed analysis of the relatively weaker radiation from the $Si^{29}(p,\gamma)P^{30}$ reaction was not possible. However, the gamma-ray energies and intensities which could be determined with reasonable certainty from stripping and least-squares analysis are given in Table II. The 6–7-MeV gamma rays due to F^{19}, which are omitted in Table II, were included in the least-squares intensity analysis. Also included in Table II are energies of sum-coincidence spectral peaks which were close to energies observed in the singles spectra. The good spectral resolution and discrimination against background radiation, which are obtainable with the sum-coincidence method, proved to be of only nominal assistance in analyzing the gamma-ray spectra. This was due in part to the relative weakness of radiative decay of these resonance levels in comparison with inelastic scattering, and in part due to photomultiplier gain drifts which blurred peaks in the sum-coincidence spectra. However, it is apparent from the large number of low-intensity

[10] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences–National Research Council, Washington 25, D. C.), NRC [60-3-14].

peaks observed in the sum-coincidence spectra at the higher energy resonances that decay schemes from these levels are considerably more complex than decay schemes from the 1752-keV resonance level,[3] where sum-coincidence spectra were recorded for the purpose of comparison.

The strong 1.28-MeV gamma ray observed at 1975, 2033, and 2075 keV is interpreted as de-excitation of the P^{30} compound nucleus by proton reemission to the first excited state of Si^{29} at 1.277 MeV.[1] The high intensity of this gamma ray is convincing evidence that this inelastic scattering process predominates over radiative capture in the gamma-ray yield curve. Rather curiously, however, this gamma ray does not appear in the spectrum at the 2117-keV resonance.

The resonance at 2075 keV lies near the $Si^{28}(p,\gamma)P^{29}$ resonance reported at 2090 keV which has a half-width of 16 keV.[1] The gamma-ray spectrum at this resonance is characterized by a 4.76-MeV radiation to the ground state of P^{29}.[11] It seems probable, therefore, that the 4.70-MeV gamma ray seen in the spectrum at 2075 keV is due to the Si^{28} reaction. The observed intensity is in agreement with this explanation. Although the presence of 2.94-MeV and 2.24-MeV gamma rays in this spectrum suggests a cascade through the level at 2.94 MeV in P^{30}, the 1.45-MeV gamma ray known to occur in this cascade[2] is not seen, and sum-coincidence work has not been able to confirm this possibility. It is possible, however, that the gamma rays due to Si^{29} reactions could be responsible for the anisotropy of the radiation from the 4.76-MeV level in P^{29} which has been observed by Newton,[12] since anisotropy is not expected to result from the spin assignment to this level of $\frac{1}{2}^+$ based on proton scattering experiments.[13]

TABLE II. Gamma-ray intensities at resonance energies of 1975, 2033, 2075, and 2117 keV.

E_p (keV)	Singles spectra[a] E_γ (MeV)	Sum-coincidence[b] E_γ (MeV)	Intensity[c] (quanta/μC)
1975	4.52	4.58	5
	4.19	4.07	2
	3.48	3.40	2
	3.33		2
	3.00	2.99	3
	2.44	2.50	3
	1.28	···	117
2033	5.10	···	8.6
	1.28	···	187.3
2075	7.59	···	14
	4.70	4.85	60
	2.98	2.95	55
	2.26	2.23	55
	1.36	···	303
	1.28	···	1360
2117	5.10	···	2
	2.55	···	3

[a] Error in singles spectra E_γ estimated to be 1%.
[b] Error in sum coincidence E_γ estimated to be 2%.
[c] Error in intensities estimated to be 30%.

[11] K. J. Van Oostrum *et al.*, Nucl. Phys. **25**, 409 (1961).
[12] J. O. Newton, Nucl. Phys. **21**, 529 (1960).
[13] J. Vorona *et al.*, Phys. Rev. **116**, 1563 (1959).

The remaining weaker radiations, seen at the four higher resonances, are most probably due to radiative capture by Si^{29}, but the rather large errors, due chiefly to masking contaminant radiation, do not permit more than tentative postulation of decay modes. Gamma rays observed at the 1975-keV resonance suggest cascades through the 4.50-MeV level and through the 4.18-MeV level. No conclusions can be drawn for the 2033-keV resonance. At the 2075-keV resonance the 7.59-MeV radiation is readily recognized as a ground state transition, but the other gamma rays are not identified. Finally, at the 2117-keV resonance, the two radiations observed nicely fit a decay through the 2.54-MeV level which is known to decay 95% to the ground state.[2]

IV. MEASUREMENTS AT 1470 keV

A. General

The double angular-correlation experiment to determine angular distributions of gamma rays at the 1470-keV resonance was performed in order to test a prediction by Thankappan and Pandya[14] that the 4.50-MeV level of P^{30} has a spin parity of 0^+. This prediction was based upon an analysis of the weakly coupled collective model applied to $A=30$ nuclei.

Since the 4.50-MeV level in P^{30} has been shown to be strongly excited at the 1470-keV resonance, this proton energy was a logical choice for angular-correlation measurements which could lead to determination of the spin parity for the level. The resonance is rather weak, so it was decided to take five sets of data to improve the counting statistics and to permit a check of the consistency of results. Each set of data consisted of five spectra taken with the movable detector in the horizontal plane containing the proton beam and set at angles of 0°, 30°, 45°, 60°, and 90° relative to the beam direction as viewed from above. With the 3-in.×3-in. movable detector positioned with its face 4.125 in. from the target, runs were made using a 7-μA beam for counting times of approximately one hour at each angular setting. The same target was used for each set of runs, and the order of the angular settings was varied in different sets so as to minimize differences in the gamma-ray spectra due to any contaminant buildup or target erosion. The fixed 3 in.×3 in. detector, positioned at 270° relative to the beam and 4.125 in. from the target, was employed as a monitor counter. Each run was terminated when 30 000 monitor counts had been recorded. A 2-in.×2-in. detector was also used as a secondary monitor counter. The integral discriminator in each monitor channel was adjusted to a valley in the gamma-ray spectrum at 4.75 MeV, so that the effect of gain shifts would be minimized. Before and after each run the discriminator levels were checked and adjusted with the aid of a Co^{60} source, which was precisely and reproducibly located relative to the counters.

[14] V. K. Thankappan and S. P. Pandya, Nucl. Phys. **39**, 394 (1963).

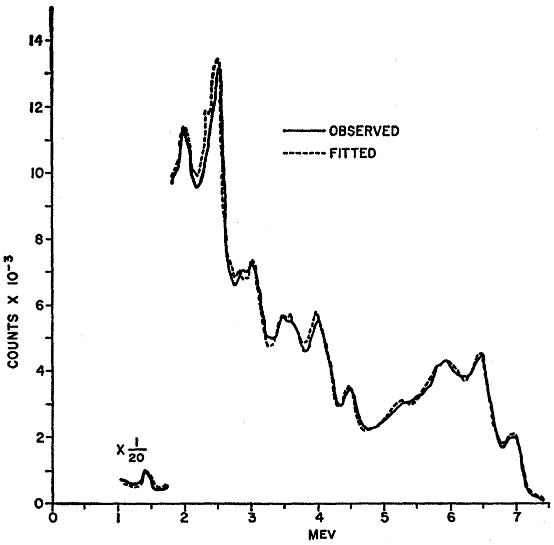

FIG. 4. The gamma-ray spectrum at 1470 keV obtained with movable detector at 90°. The broken line is a synthetic spectrum consisting of the monoenergetic gamma rays observed at this resonance with intensities determined by a least-squares analysis.

The gamma-ray spectrum observed at the 1470-keV resonance with a crystal-face-to-target distance of 0.6 in. and at an observation angle of 90° is shown in Fig. 4. This spectrum has been least-squares fitted by gamma rays with energies required by the decay scheme proposed in Ref. 3. Reanalyses with alternate energy choices in each instance gave a poorer fit in reassurance of the correctness of the decay modes proposed. This decay scheme, with intensities as found in the present analysis, is shown in Fig. 5. (Heavy dots indicate cascades confirmed in Ref. 3 by coincidence spectroscopy.) The branching ratio shown for the 4.50-MeV level is that given in Ref. 2. The assumed correctness of this

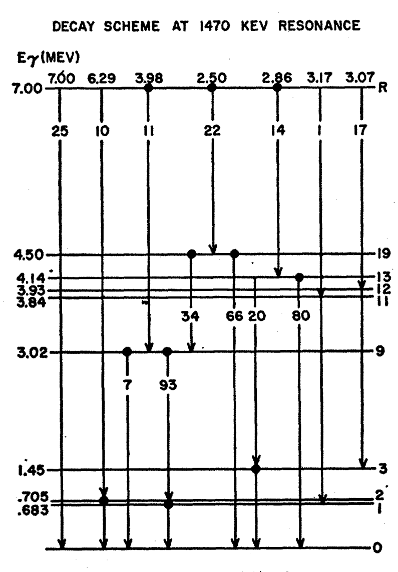

FIG. 5. Decay scheme at 1470-keV resonance.

ratio then requires branching ratios of 93:7 for the 3.02-MeV level and 80:20 for the 4.14-MeV level in order to fit the intensities of gamma rays which have been observed. These ratios are in reasonably good agreement with ratios of 89:11 reported[2] for the 3.02-MeV level and 88:12 reported[3] for the 4.14-MeV level.

Intensities of gamma rays observed in the angular correlation runs are shown in Table III, together with intensities observed in Ref. 3 at 55°. The intensities found in the correlation runs have been averaged over 4π sr by weighting the mean values for each observation angle by the sine of that angle. Because the 1.46-MeV background radiation due to K^{40} was found to be quite strong relative to the 1.45-MeV gamma ray observed in the correlation runs, no attempt was made to analyze the gamma radiation of this or lower energy. Although the

TABLE III. Relative gamma-ray intensities at the 1470-keV resonance.

E_γ (MeV)	Transition	Observed intensity[a]	Decay scheme intensity	b
7.00	$R\rightarrow 0$	25.4	25.4	39.6
6.29	$R\rightarrow 2$	9.6	9.6	6.3
4.50	$19\rightarrow 0$	14.6	14.3	13.2
4.14	$13\rightarrow 0$	10.7	10.7	11.1
3.98	$R\rightarrow 9$	10.5	10.8	7.3
3.45	Not accounted for	2.0	···	4.0
3.17	$R\rightarrow 11$	3.0	1.5	2.0
3.17	$11\rightarrow 1$		1.5	2.0
3.07	$R\rightarrow 12$	19.1	17.6	11.7
3.02	$9\rightarrow 0$		1.2	1.6
2.86	$R\rightarrow 13$	13.7	13.7	13.0
2.69	$13\rightarrow 3$	2.8	2.8	···
2.50	$R\rightarrow 19$	38.8	21.6	20.0
2.50	$12\rightarrow 3$		17.6	11.7
2.34	$9\rightarrow 1$	17.2	16.9	13.4
1.45	$19\rightarrow 9$	Not analyzed[c]	7.3	6.8
1.45	$3\rightarrow 0$	Not analyzed[c]	20.3	11.7
0.71	$2\rightarrow 0$	Not analyzed	9.6	21.8
0.68	$1\rightarrow 0$	Not analyzed	18.4	

[a] Relative intensities shown are also approximate absolute intensities in quanta per μC.
[b] R. A. Moore, Ph.D. thesis, University of Kansas, 1963 (unpublished).
[c] An intensity of approximately 34 is indicated for the 1.45-MeV radiation by observations at 90° with 0.6-in. crystal-face-to-target distance.

background radiation subtracts out, the statistics of the remaining counts do not allow extraction of significant information. The observed intensities are seen to agree reasonably well with those of Ref. 3 except for the 7.00-MeV radiation which is found to be considerably weaker in the present work. Since the experimental intensities are based upon reported values of intrinisc peak efficiencies[15] rather than an absolute spectrometer calibration, this discrepancy is not considered significant.

The correlation-function coefficients which have been found in this experiment are given in Table IV. These are the usual coefficients used to define the correlation function[16] as a finite series of even Legendre poly-

[15] N. H. Lazar, IRE Trans. Nucl. Sci. **NS-5**, 138 (1958).
[16] L. C. Biedenharn, in *Nuclear Spectroscopy*, edited by F. Ajzenberg-Selove (Academic Press, Inc., New York, 1960), Part B.

nomials

$$W(\theta)=\sum_{\nu=0}^{\nu_{\max}} A_\nu P_\nu(\cos\theta).$$

The values given are weighted means of those found in each of the five sets of data taken. The chi-square values for each correlation coefficient have been calculated and show the different sets to be consistent, under the acceptance requirement that the cumulative chi-square probability be equal to or less than 0.9.

The intensity analysis was performed both by subtracting background radiation analytically and by subtracting off-resonance background; essentially the same results were obtained in both cases.

The most obvious feature of the data is the anisotropy of the 4.50-MeV gamma ray, which is incompatible with a spin of zero for this level. It is also noteworthy that the 4.50-MeV gamma ray is the only radiation to show a statistically significant $P_4(\cos\theta)$ term. Figure 6 shows the correlation-coefficient values for this

TABLE IV. Double angular-correlation coefficients at 1470-keV resonance.[a]

E_γ (MeV)	P_2 highest term A_2/A_0	Std. dev.	P_4 highest term A_2/A_0	Std. dev.	A_4/A_0	Std. dev.
7.00	−0.42	0.02	−0.43	0.03	0.05	0.03
6.29	−0.47	0.05	−0.47	0.06	0.01	0.06
4.50	0.09	0.02	0.11	0.02	−0.07	0.03
4.14	−0.09	0.04	−0.08	0.04	−0.01	0.05
3.98	−0.35	0.05	−0.37	0.06	0.02	0.07
3.45	0.03	0.22	...	...	...	...
3.17	−0.09	0.16	...	...	...	...
3.07–3.02	−0.04	0.07	...	...	...	...
2.86	0.31	0.03	0.32	0.04	−0.03	0.05
2.69	0.39	0.14	0.50	0.15	−0.31	0.19
2.50	−0.22	0.02	−0.24	0.02	0.03	0.02
2.34	−0.24	0.03	−0.26	0.03	0.06	0.04

[a] Coefficients shown are corrected for finite angular resolution of detector.

gamma ray obtained from each set of data. In this figure M denotes mean values and C denotes values obtained by combining intensities from each data set before computing coefficients. Figure 7 shows the fit to the Legendre series, both with and without P_4 terms. Although the existence of the P_4 term is not incontrovertible, it permits a markedly better fit to the data and gives a smaller value of the parameter ϵ, defined by Rose,[7] which serves as a guide to the appropriate number of terms which should appear in the Legendre series.

In order to deduce spin-parity values it is necessary to examine the possible particle- and radiation-mixing ratios for this reaction. The notation used herein to refer to these mixing ratios is as follows: δ_1=proton-partial-wave mixing ratio; δ_2= the multipole mixing ratio of an intermediate unobserved gamma ray; δ_3= the multipole mixing ratio of an observed gamma ray; δ_4= channel-spin mixing ratio. Each ratio is that of the higher angular momentum (or multipolarity) matrix element to the lower.

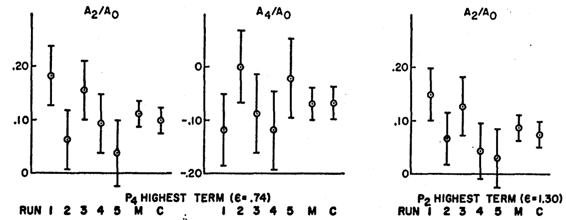

FIG. 6. Experimental angular-distribution coefficients for the 4.50-MeV gamma ray observed at the 1470-keV resonance. The smaller value of ϵ (defined in Ref. 7) suggests the correct analysis includes a $P_4(\cos\theta)$ term (left).

For the $Si^{29}(p,\gamma)P^{30}$ and $Si^{29}(p,x\gamma)P^{30}$ (intermediate unobserved) reactions, the correlation coefficients A_2/A_0 and A_4/A_0 are describable as functions of a maximum of three mixing ratios. Level curves, or contours, of constant A_i/A_0 values may be plotted against any two of the mixing ratios. Actually, the arctangents of the mixing ratios are used as variables for convenience, since they remain finite (e.g., see Fig. 8). If a third mixing ratio appears, changing its value changes these contour plots only to the extent of changing the A_i/A_0 values for all contours by a multiplicative constant.

In the following discussion it will be assumed that only $E1$ radiation or $E2/M1$ mixtures are likely to be observed for transitions from levels of several MeV. This simplifying assumption is based upon transition probabilities estimated from the independent-particle model and[17] is commonly made in analysis of gamma radiation following proton capture in light and intermediate nuclei. Although suppression or inhibition of

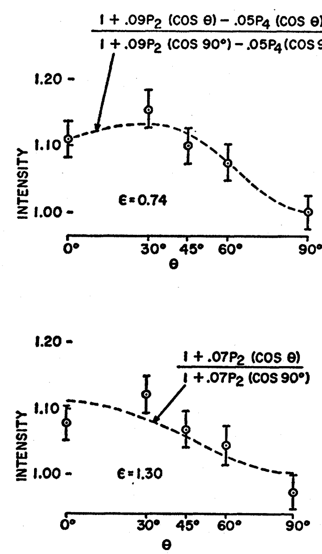

FIG. 7. Fits of combined experimental distribution data for the 4.50-MeV gamma ray to Legendre series with $P_4(\cos\theta)$ term (upper) and without $P_4(\cos\theta)$ term (lower). Neither coefficients nor data are corrected for finite solid angles subtended by the detectors. Intensities are normalized to fitted curve at 90°.

[17] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley & Sons, Inc., New York, 1953).

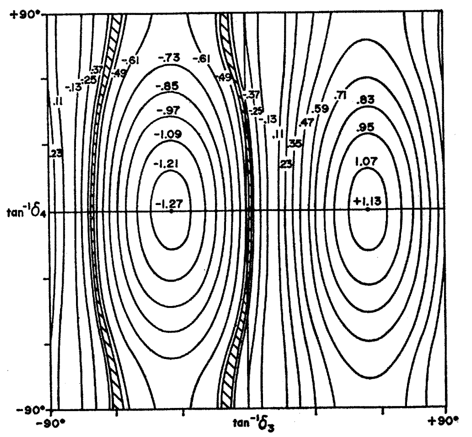

FIG. 8. Contour plot of A_2/A_0 for $2+ \to 1+$ transition plotted against inverse tangents of channel-spin mixing ratio (δ_4) and the $E2/M1$ multipole mixing ratio (δ_3). See text for discussion of shaded areas.

dipole radiation is possible because of the isotopic spin selection rule, $\Delta T = \pm 1$ for self-conjugate nuclei,[18] there are an adequate number of lower levels of both $T=0$ and $T=1$ in P^{30} so that the resonance level can decay by either $E1$ or $E2/M1$ radiation without violating this rule.

In analyzing the experimental correlation coefficient values, tables from Ref. 3 have been quite helpful. This reference tabulates the maximum and minimum values which may be assumed by A_2/A_0 and A_4/A_0 for a variety of postulated spin sequences.

B. Resonance-Level Spin Parity

The observed A_2/A_0 terms of about -0.40 for the 7.00-, 6.29-, and 3.98-MeV gamma rays, which all proceed to known $1+$ levels, are found to be most useful in determining the spin parity of the resonance level. Among possible values through 4 for this level, it is found that only $1+$, $2+$, and $2-$ can lead to the A_2/A_0 coefficient measured for the 7.00-MeV ground-state transition. The same conclusion is supported by the A_2/A_0 values observed for the 6.29- and 3.98-MeV radiations.

The contour plot for the $1+ \to 1+$ transition shows that a *d-s* proton-angular-momentum mixing ratio of over 0.90 is required to produce the observed A_2/A_0 value for the 7.00-MeV gamma ray. Since the relative penetrability of *d* waves to *s* waves is about 3×10^{-2}, such a mixture is not a likely choice. The A_4/A_0 term observed for the 4.50-MeV radiation supports this conclusion, since A_4/A_0 terms do not result from resonance spins smaller than 2. Finally, the value of A_2/A_0 observed for the 2.34-MeV radiation will be shown to be incompatible with a $1+$ resonance level spin. This radiation proceeds to the known $0+$ level at 0.68 MeV from the known $1+$ level at 3.02 MeV. The 3.02-MeV level is fed more than 50% from the resonance level and, secondarily, by the intermediate 1.48-MeV radiation from the 4.50-MeV level. The A_2/A_0 value, observed for this primary 3.98-MeV feeder, restricts the ranges δ_1 and δ_2 for the cascade from the resonance level to the 0.68-MeV level *via* the level at 3.02 MeV. When these ranges are delineated on a contour plot for a $1+ \to 1+ \to 0+$ transition, it is found that A_2/A_0 for the second radiation is restricted to a range between -0.01 and $+0.24$. By an extension of[16] the formalism for intermediate-unobserved cascades, it is possible to calculate the angular distribution coefficients for the 2.34-MeV radiation in the triple cascade from the resonance level to the 0.68-MeV level through the 4.50-MeV level and the 3.02-MeV level. It is found that for a $1+$ resonance level, the minimum possible value of A_2/A_0 occurs if the 4.50-MeV level has a spin of 2. This minimum value has been calculated to be -0.175. Thus, a $1+$ resonance level leads to a minimum possible value for A_2/A_0 of about -0.093. Comparing this with the observed value of -0.24 ± 0.03 for the 2.34-MeV gamma ray, $1+$ can be ruled out as a possible spin parity of the resonance level.

Having narrowed the possible resonance spin values to $2+$ or $2-$, the contour plots may be examined for the $2+ \to 1+$ and $2- \to 1+$ transitions, applicable to the 7.00-MeV radiation to the ground state. In the first case, channel-spin mixing may occur, while in the second case, proton partial-wave mixing is permitted. For the $2+ \to 1+$ case, Fig. 8 shows the contour plot with the experimental value of A_2/A_0 for the 7.00-MeV gamma ray delineated thereon by cross hatching. Figure 9 is a similar plot for A_4/A_0. The darker shading in Fig. 9 indicates the superposition of cross hatching on both plots and defines the ranges and combinations of mixing parameters which can give rise to the observed coefficient values. For $\delta_3 \approx 0$ (i.e., $M1$ radiation), δ_4 is constrained to be less than $\approx \tan 50°$. This must not be taken too seriously, however, since the A_4/A_0 contours are widely spaced at the top and bottom boundaries of the permitted region, so that a very slight increase in the error for the experimental A_4/A_0 value would allow δ_4 to range up to 90°. The small region at $\delta_3 \approx \tan(-67°)$ and $\delta_4 \approx \tan 49°$ also fits the observed correlation. The plots for the $2- \to 1+$ case are quite similar to the $2+ \to 1+$ case and show that there is no restriction on *f-p* proton-wave mixing for $\delta_3 \approx 0$ ($E1$ radiation). Two small permitted regions at $\delta_3 \approx \tan 67°$ may be ruled out since they require an $M2/E1$ mixture. An unlikely but small $M2/E1$ mixture with $\delta_3 \approx 0.026$ or greater is required for this transition for the case of resonance formation by pure *p* waves. As will be shown, the $2-$ resonance-level assignment is also less probable than $2+$, based on mixing ratios which are required by experimentally observed coefficients for the 4.50-MeV radiation.

[18] D. H. Wilkinson, in *Nuclear Spectroscopy*, edited by F. Ajzenberg-Selove (Academic Press, Inc., New York, 1960), Part B.

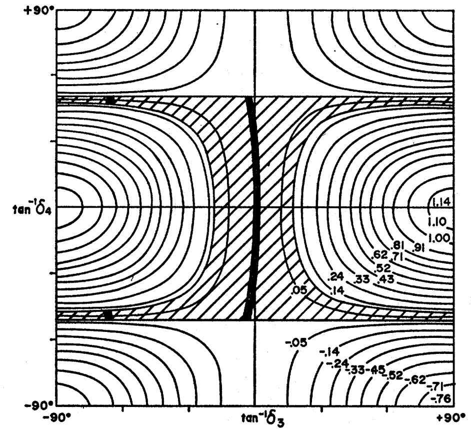

FIG. 9. Contour plot of A_4/A_0 for $2+ \rightarrow 1+$ transition plotted against same variables as in Fig. 8. See text for discussion of shaded areas.

As a result of the above considerations, a spin parity of 2+ is proposed for the resonance level with 2− as a less likely possibility.

C. Cascade Through the 4.14-MeV Level

There are only two cascades which allow cross checking of mixing parameters as a method of eliminating possible spin sequences. These are the cascade through the 4.14-MeV level and that through the 4.50-MeV level, both of which levels have undetermined spins. The cascade through the 4.14-MeV level will be considered first. The existence of an A_4/A_0 term, which has been observed in the distribution of the 4.14-MeV radiation at the 1686-keV resonance,[3] is evidence that this level must have a spin greater than or equal to 2. Of the likely possible spins, 2±, 3±, and 4−, only 2+ and 2− result in the negative value of A_2/A_0 observed for the 4.14-MeV gamma ray. An examination of the contour plots for the four sequences $2\pm \rightarrow 2\pm \rightarrow 1+$ for the cascade through the 4.14-MeV level shows compatibility in all cases with the observed coefficients for the 2.86-MeV gamma ray and the 4.14-MeV gamma ray. For the sequence $2+ \rightarrow 2- \rightarrow 1+$, the parameter δ_4 is constrained to be larger than tan 70°, but the other possible sequences are compatible with a full range of values for either δ_1 or δ_4, as the case may be. The only finding is that, for all cases, the transition from the resonance level to the 4.14-MeV level must be relatively pure dipole radiation. The observed coefficient values for the weak 2.69-MeV gamma ray, which also is believed to de-excite the 4.14-MeV level, are also compatible with all four possible spin sequences with reasonable choices for δ_3.

D. Cascade Through the 4.50-MeV Level

Since no requirements on mixing ratios applicable to this cascade are imposed by transitions already considered, it must be analyzed with no prior restrictions on the mixing ratios. We find, furthermore, that no information is forthcoming from the correlation coefficient of the 2.50-MeV gamma ray resulting from the transition between the resonance level and the 4.50-MeV level, since this radiation is indistinguishable from the 2.48-MeV gamma ray emitted when the 3.93-MeV level decays to the 1.45-MeV level.

For a resonance-level spin parity of either 2+ or 2−, and under the hypothesized restriction to $E1$ and $E2/M1$ radiative transitions, it is found that the possible spin sequences compatible with the observed values of the correlation coefficients are $2- \rightarrow 2+ \rightarrow 1+$, $2+ \rightarrow 3+ \rightarrow 1+$, and $2+ \rightarrow 2+ \rightarrow 1+$. (A spin parity of 1+ or 1− for the 4.50-MeV level is also possible if the P_4 terms are spurious, but spin zero is ruled out in any case.) Of the three possibilities, the $2- \rightarrow 2+ \rightarrow 1+$ sequence is least likely. The appropriate contour plots show that this sequence, for the cascade through the 4.50-MeV level, requires an f to p wave mixing parameter of over 0.10 with a large $E2/M1$ mixing ratio of nearly 12.0. For a $2+ \rightarrow 3+ \rightarrow 1+$ sequence, it is found that an $E2/M1$ ratio of over 1.7 is required for the 4.50-MeV radiation in order to fit the data. Because large $E2/M1$ mixing parameters are not commonly seen in the lighter nuclei, this sequence, though more likely than $2- \rightarrow 2+ \rightarrow 1+$, is not as probable as a $2+ \rightarrow 2+ \rightarrow 1+$ sequence. For the $2+ \rightarrow 2+ \rightarrow 1+$ sequence, contour plots show that for an assumed channel-spin mixing ratio of zero, an $E2/M1$ mixing ratio of 0.27 will fit the observed coefficients for the 4.50-MeV gamma ray with a considerable latitude permitted for δ_2. Alternate choices for δ_4 will also permit acceptable choices of mixing parameters for this sequence though, in general, δ_2 and δ_3 will be required to be larger.

Summarizing, the 4.50-MeV level is found to have a spin of 2+ or 3+ under the assumptions which have been made, with 2+ being more probable.

E. Comparison with Other Results

Concurrently with the present work, an investigation of triple angular correlations at the 1470-keV resonance was undertaken at Wright-Patterson Aeronautical Laboratories. The angular distribution of the 7.00-MeV gamma ray was also examined in this experiment. An A_2/A_0 value of -0.38 ± 0.02 was observed for this gamma ray, in good agreement with the value shown in Table IV. Preliminary results of this experiment indicated restriction of the resonance-level spin to a value of 1 or 2 and show that a zero spin for the 4.50-MeV level is not compatible with such a restriction.[19] It is to be hoped that the complete analysis of this work will lead to a firmer indication of the spin parity of the 4.50-MeV level, since the 2+ (3+) value proposed herein depends upon the somewhat debatable A_4/A_0 term

[19] G. I. Harris, R. A. Moore, and D. D. Watson (private communications).

observed, and upon the hypothesis that only $E1$ or $E2/M1$ radiation is present.

F. $T=1$ Character of the 4.50-MeV Level

The prediction of 0+ for the spin parity of the 4.50-MeV level is based on the premise that this level is the $T=1$ analog of the 3.80-MeV level of Si^{30} in the isotopic-spin-multiplet formalism. A spin of 0 has been suggested for the 3.80-MeV level in Si^{30}, based on observations of cascade gamma rays following the $Si^{30}(p,p')Si^{30}$ reaction.[20] A spin of 0+ results also from calculations made by Thankappen and Pandya of collective vibrational states in a weakly coupled collective model of the nucleus.[14] The spin of the 4.50-MeV level in P^{30} is thus expected to be zero, both on experimental and theoretical grounds. The finding of nonzero spin for this level then appears to be good evidence that either the level is complex (e.g., a doublet), or that it is not the isotopic-spin-multiplet analog of the 4.80-MeV state in Si^{30}, as has been accepted. Some evidence has been reported that the 3.80-MeV level in Si^{30} is a doublet, based upon observations of protons from the reactions $Si^{28}(t,p)Si^{30}$ and $Si^{30}(p,p')Si^{30}$.[21,22] It is possible, therefore, that an analogous 4.50-MeV level in P^{30} is a doublet, although no other evidence suggests this. The other possible explanation is that a nearby level in P^{30}, such as that at 4.42 MeV, may be the $T=1$ level rather than the 4.50-MeV level. This does not appear unlikely, since the $T=1$ character attributed to the 4.50-MeV level is a probable, rather than a firm assignment, which was deduced from the investigation of the $S^{32}(d,\alpha)P^{30}$ reaction by Endt and Paris.[23] It is based upon a correction of the 3.80-MeV level in Si^{30} for the Coulomb energy and neutron-proton mass difference, which yields a predicted energy of 4.47 MeV for the excitation energy in the P^{30} nuclide. The assignment is strengthened by the fact that the alpha-particle group from $S^{32}(d,\alpha)P^{30}$, corresponding to a residual excitation in P^{30} of 4.501 $\pm$0.010 MeV, has only about half the intensity of neighboring groups. This has been interpreted as being due to operation of the selection rule conserving isotopic spin in this reaction.

On the basis of the energy predicted for the $T=1$ level in P^{30}, the 4.42-MeV level is seen to be nearly as likely a candidate as the 4.50-MeV level, particularly since the energy prediction is not expected to be exact. Similarly, in the T conservation argument, the observed lower intensity of the alpha group for the 4.50-MeV level can hardly be considered conclusive evidence of the $T=1$ character of the level, since some $T=0$ levels are associated with alpha-particle groups of even lower intensity (e.g., the 3.84-MeV level). Unfortunately, the 4.42-MeV level in P^{30} is not known to be excited in radiative capture, so that spin parity of this level will probably have to be determined from a different reaction.

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[20] C. Broude and H. E. Gove, Bull. Am. Phys. Soc. **5**, 248 (1960).
[21] S. Hinds *et al.* (private communication reported by Ref. 1).
[22] R. E. White, Phys. Rev. **119**, 767 (1960).
[23] P. M. Endt and C. H. Paris, Phys. Rev. **110**, 89 (1958).