Gamma Rays from the Proton Bombardment of Phosphorus*

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The yield of gamma rays from the proton bombardment of phosphorus has been obtained for proton energies from 0.4 to 2.0 Mev. There are seen in this region nineteen resonances, corresponding to energy levels in S^{32} at energies from 9.295 to 10.775 Mev. The energy spectra of the gamma rays emitted at several of the resonances have been obtained and interpreted in terms of levels in the residual nucleus S^{32}. The spectra indicate that a 3.8-Mev gamma ray is present; from a tentative assignment of it to the second excited state to ground state transition there follows the result that the second excited state of S^{32} has $J=1$, even parity.

A. INTRODUCTION

IN earlier work, the yield of capture gamma rays from the proton bombardment of phosphorus has been obtained in the energy region from 0.34 to 1.0 Mev with the use of thick targets and several resonances have been noted.[1-3] Thin-target resonances have been reported[4-8] for proton energies from 0.5 to 2.5 Mev. A study of the angular distribution of the gamma rays has given information on the spin and parity of several of the highly excited levels of S^{32}.[9]

The object of this investigation was to determine some of the properties of the low-lying levels of S^{32}.

B. EXCITATION CURVE

In the present work, water-cooled thin targets of zinc phosphide prepared by evaporation were used. The gamma rays were detected with a scintillation counter incorporating a cylindrical 1-in.$\times 1\frac{1}{2}$-in. diameter NaI(Tl) crystal which was placed 1 cm from the target on the beam axis. The amplifier discriminator was set to accept pulses due to gamma rays of energies above 1 Mev, except above $E_p=1.63$ Mev, where the discriminator level was set at 2 Mev. Below 0.75 Mev the hydrogen molecule-ion beam was used; the two portions of the curve have been normalized by overlapping sections. Figure 1 shows the excitation curve and Table I gives the resonance energy values after correction for the target thickness. The energy scale was calibrated with reference to several well-known lithium, fluorine, and sodium (p,γ) resonances. The resonance width was 8.5 kev at the 1.232-Mev resonance, as determined from a thick target excitation curve. Using this value, the thickness of the thin target at this resonance is determined to be 10.5 kev. Upon allowing for the variation of the target thickness with proton energy, it is possible to compute the level widths at many of the resonances; these are listed in Table I. A weak resonance at 0.722 Mev appears also in the bombardment of a zinc sulfide target and is not attributed to phosphorus. A small trace of aluminum as a contaminant gives rise to the resonances at 0.994 and 1.373 Mev; at other energies the aluminum resonances are of insignificant size.

The energy difference between $(P^{31}+H^1)$ and S^{32} has been taken as 8.855 Mev[10] and the excitation energies of the levels in S^{32} have been calculated; they appear in column 3 of Table I.

C. GAMMA-RAY SPECTRA

A detailed study has been made of the energy spectra of the gamma rays emitted at several of the stronger

TABLE I. Gamma-ray resonances in the proton bombardment of phosphorus. The resonant proton energies have been corrected for target thickness and the excitation energies of the S^{32} levels are based on a Q-value of 8.855 Mev. The error in the resonant energies is estimated as ± 0.010 Mev.

Resonant energy E_p(Mev)	Γ(kev)	Excitation energy S^{32}(Mev)
0.454	34	9.295
0.540	···	9.378
0.646	17	9.481
0.813[a]	15	9.643
0.893	9	9.720
1.034	<5	9.857
1.069	6	9.891
1.101	···	9.922
1.124	5	9.944
1.227	9	10.044
1.395	15	10.206
1.428	12	10.238
1.470	6	10.279
1.517	14	10.325
1.560	7	10.366
1.586	5	10.391
1.876	···	10.672
1.901	···	10.697
1.961	···	10.755

[a] Paul *et al.*[9] have found two resonances here; one at 0.816 Mev which is resonant for 7.5-Mev gamma rays and one at 0.825 Mev which is resonant for 10-Mev gamma rays.

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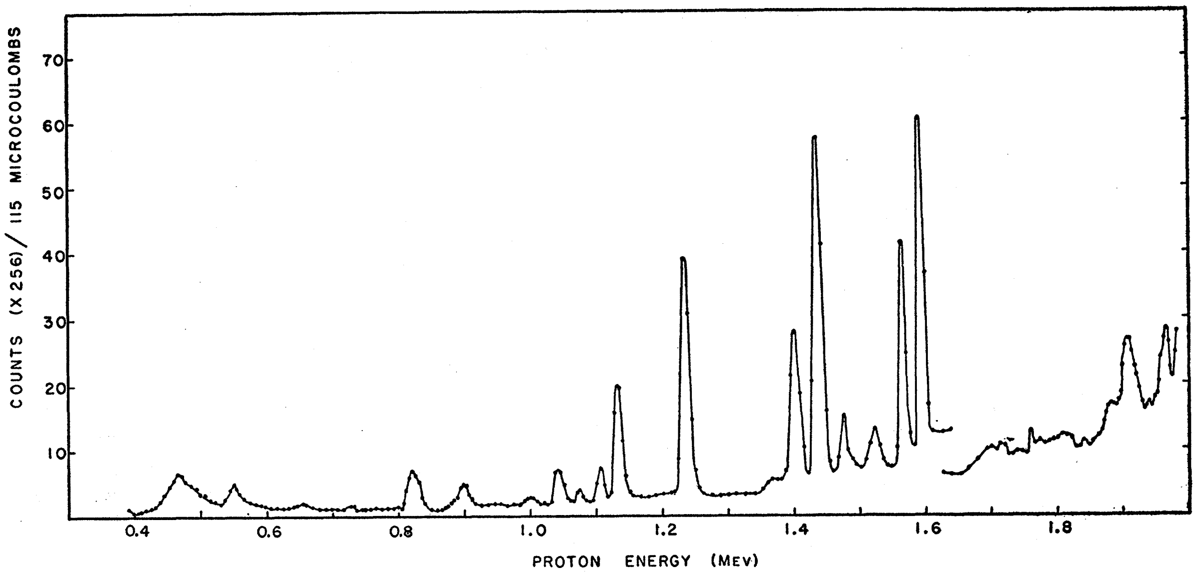

FIG. 1. Excitation curve of the gamma rays from proton bombardment of phosphorus. Below 1.63 Mev, the discriminator level was set to accept pulses due to gamma rays of energy greater than 1.0 Mev; above, greater than 2.0 Mev.

resonances in an attempt to learn more about the low-lying levels of S^{32}. The spectra have been obtained using both a cylindrical 1-in.$\times 1\frac{1}{2}$-in. diameter NaI(Tl) crystal and a cylindrical 3-in.$\times$3-in. diameter NaI(Tl) crystal with a twenty-channel differential-pulse-height analyzer.

Figure 2 displays a typical pulse-height spectrum obtained at the prominent 1.227-Mev resonance; the 1-in.$\times 1\frac{1}{2}$-in. diameter crystal was utilized. The energy scale was established using the 1.33-Mev gamma ray from Co^{60} and for comparison purposes the spectra due to ThC″ (2.62 Mev), $B^{11}(p,\gamma)C^{12}$ (4.43 Mev), and $F^{19}(p,\alpha\gamma)O^{16}$ (6.14 Mev) are shown. It is possible to identify a strong 2.25-Mev gamma ray by "escape 2", "escape 1", and "total energy" peaks, and others of energy 7.5 and 10 Mev (latter not shown). Above 2.25 Mev there are several peaks spaced approximately 0.5 Mev apart and it is difficult to make energy assignments. However, it does seem reasonable that there might be a 3.8-Mev gamma ray. Figure 3 is the spectrum taken at the same resonance with the use of the 3-in.$\times$3-in. diameter crystal; there is shown also the response due to 2.62- and 4.43-Mev radiation. It will be noted that as compared to the smaller crystal the

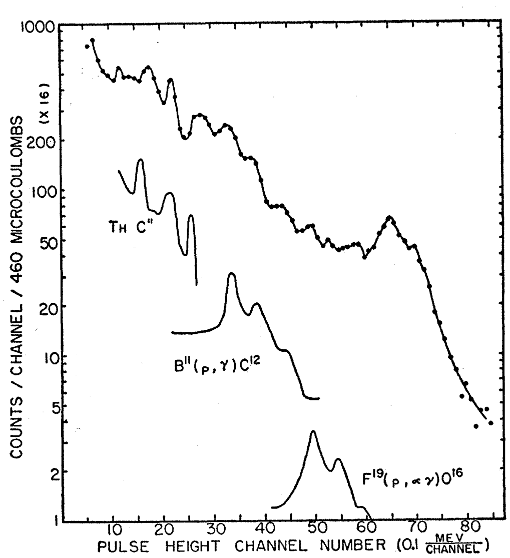

FIG. 2. Pulse-height spectrum due to the gamma rays from proton bombardment of phosphorus at the 1.227-Mev resonance. A cylindrical 1-in.$\times 1\frac{1}{2}$-in. diameter NaI(Tl) crystal was used.

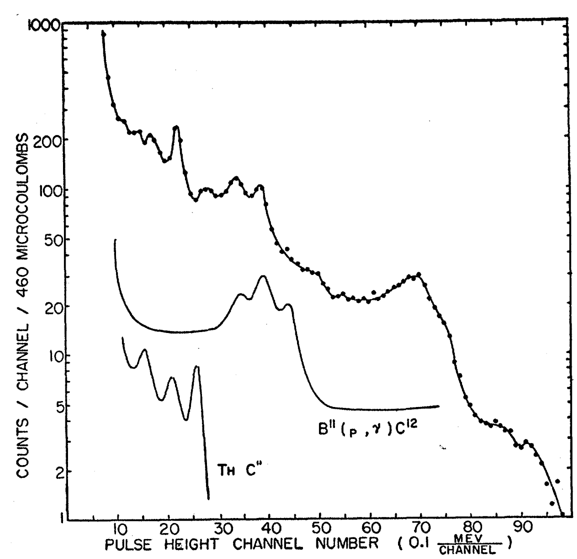

FIG. 3. Pulse-height spectrum due to the gamma rays from proton bombardment of phosphorus at the 1.227-Mev resonance. A cylindrical 3-in.$\times$3-in. diameter NaI(Tl) crystal was used.

TABLE II. Gamma-ray energies and probable assignments at several of the resonances for the reaction $P^{31}(p,\gamma)S^{32}$. "Ex" in each case designates the highest level excited in the S^{32} nucleus.

Resonant energy E_p(Mev)	Gamma-ray energy (Mev)	Probable transition (Refer to Fig. 4)
1.124	7.7 −2.25	Ex−1st −Gnd
	4.3	−3rd −Gnd
	3.8	−2nd−Gnd
1.227	7.7 −2.25	Ex−1st −Gnd
	3.8	−2nd−Gnd
1.395	10	Ex− Gnd
	7.9 −2.25	Ex−1st −Gnd
	5.1	−6th −Gnd
1.428	5.9(?)	−7th −Gnd
	3.6 −2.25	7th−1st −Gnd
1.470	10	Ex− Gnd
	8 −2.25	Ex−1st −Gnd
1.560	8 −2.25	Ex−1st −Gnd
	5.9	−7th −Gnd
	4.3	−3rd −Gnd
	3.8	−2nd−Gnd
	3.6(?)−2.25	7th−1st −Gnd
1.586	8.1 −2.25	Ex−1st −Gnd
	3.8	−2nd−Gnd

2.62-Mev "total energy" peak is more emphasized and the 4.43-Mev "escape 1" peak is now the prominent feature, rather then the "escape 2" peak. Comparison of the two curves establishes the presence of the 2.25-Mev radiation and resolves the intermediate region as principally due to a 3.8-Mev gamma ray. A gamma ray of this energy was reported as accompanying the beta decay of Cl^{32} but the evidence was not conclusive.[11]

A survey of the gamma-ray spectra at several of the resonances shows the presence of certain outstanding gamma rays which may be identified as arising from transitions between known levels. The energy level diagram, Fig. 4, is based on data from inelastic neutron scattering,[12] the $S^{32}(p,p')S^{32}$ reaction,[13] the $P^{31}(d,n)S^{32}$ reaction,[14] and the present report. The gamma-ray energies and assignments are listed in Table II; as the latter are based on the energies primarily, they are not necessarily unique.

D. DISCUSSION

In general, this report of the resonances is in accord with earlier work. The values reported here and those of reference 10 are both about 20 kev lower than those of reference 4 in the 1 to 2-Mev region. During the long bombardments required in this work, the present investigators noted that surface deposits on the target resulted in shifts of resonance energies of this magnitude.

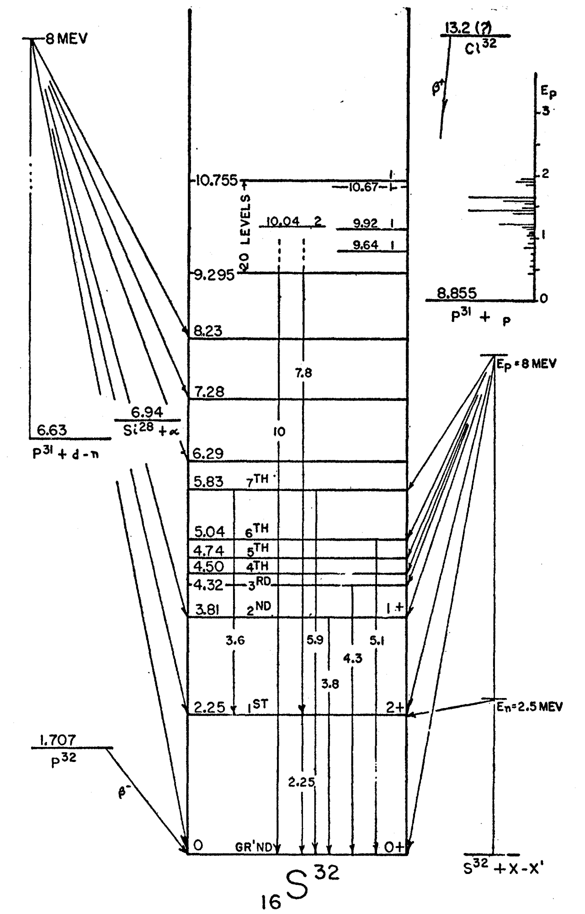

FIG. 4. Energy level diagram of S^{32}. Energy values are in Mev units.

The available evidence indicates that the first excited level of S^{32} comes at 2.25 Mev, and that a gamma ray is emitted in the transition to the ground state level. A (d,n) angular distribution study[14] shows that it is to be designated as 3+, 2+, or 1+ (spin 3, 2, or 1, even parity). It is probably 2+.[9]

The second excited level comes at 3.81 Mev. A gamma ray of this energy has been seen and has been assigned to the transition from this level to the ground level. If such is the case at the 1.227-Mev resonance the 3.8-Mev gamma ray could be preceded in a cascade by a 6.23-Mev gamma ray, which, however, is not seen with sufficiently high intensity for this to be the only cascade path to the 3.81-Mev level. An unfortunate coincidence in the spacing of known levels is present: The 10.044-Mev level (formed at E_p= 1.227 Mev) to the 6.29-Mev level transition could give rise to a gamma ray of 3.75 Mev, if it occurred. If this were the case, the 3.8-Mev gamma ray would not be seen at other resonances, for the initial gamma ray would have its energy altered as

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the excitation energy changes. At the 1.124-, 1.560-, and 1.586-Mev resonances the 3.8-Mev gamma ray is seen again. It seems reasonable to assign it to the second excited level to ground level transition. If the assignment of the gamma ray to the transition from the second excited level to ground level is correct, then the second excited level is to be designated as 1+ as the analysis[14] of the angular distribution of neutrons from the $P^{31}(d,n)S^{32}$ reaction leads to a 1+ or 0+ assignment. The emission of electromagnetic radiation would eliminate the 0+ possibility. However, Huby and Newns[14] point out that this assignment leads to difficulty in the assignment of state configurations, with the second excited state being described as a $(s_{\frac{1}{2}})_1{}^2 (d_{\frac{3}{2}})_0{}^2$, $T=1$, arrangement, which is not expected to appear below about 7-Mev excitation energy in S^{32}.

A 4.3-Mev gamma ray arising at the 1.124-Mev resonance could be emitted in the third excited level to ground level transition. This may be the same gamma ray which has been detected with a magnetic pair spectrometer[15] at an energy of 4.41±0.04 Mev in the $P^{31}+d$ reaction, at deuteron energy 4.6 Mev. If the assignment is correct, then the third excited state does not have a 0+ configuration. This gamma ray is also emitted at the 1.560-Mev resonance.

The 4.50-Mev fourth excited level may be the expected 4+ level occurring at twice the energy of the first 2+ level. The absence of the gamma ray corresponding to the transition to the ground level (4+ to 0+) supports this speculation.

The sixth excited level at 5.04 Mev lies in such a position that a two-step cascade from the 10.206-Mev level ($E_p=1.395$ Mev) would give rise to two gamma rays of nearly the same energy, 5.1-Mev. Such a gamma ray has been detected as a prominent one at this resonance. If the assignment is correct, then for this level also the 0+ designation is excluded. In the $P^{31}+d$ work,[15] a 4.94±0.04 Mev gamma ray has been seen.

At the 1.428-Mev resonance is seen a 3.6-Mev gamma ray which is assigned tentatively to the seventh to first excited level transition; there is some evidence for the presence of 5.8-Mev radiation directly to the ground level. A 5.9-Mev gamma ray observed at the 1.560-Mev resonance may be due to the seventh excited level to ground level transition; at this resonance the competing 3.6-Mev radiation to the first excited level is probably present, but is not resolved in the presence of the 3.8- and 4.3-Mev gamma rays.

At each of the resonances there appeared to be radiation of energy less than 2.25 Mev which could not be resolved in the presence of the higher energy radiation. This supports the assumption, made in making the above assignments, that a great deal of low-energy cascading takes place above about 6 Mev.

E. ACKNOWLEDGMENTS

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