reaction at 10.5 Mev. This gives a value for the total cross section at this energy of 48±6 millibarns. Table II gives a comparison of the maximum and minimum of the absolute value together with the position of the maximum and minimum of the differential cross-section curve for the $T(d,n)He^4$ reaction and the mirror reaction, $He^3(d,p)He^4$.[2,9] It is apparent that these reactions are closely similar at this bombarding energy, where the effects of coulomb forces are small compared with purely nuclear forces. Since the intermediate nuclei formed by these two reactions differ from each other in that a neutron is substituted for a proton, this comparison suggests the approximate identity of the neutron and proton insofar as purely nuclear forces are concerned at these energies.

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[9] J. C. Allred, LA-981 (unpublished).

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The Gamma-Ray Yield of Phosphorus Bombarded with Protons*

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Protons from a van de graaff generator have been used to bombard P^{31}, and the reaction $P^{31}(p,\gamma)S^{32}$ has been studied. The gamma-ray yield has been measured, as a function of proton energy, in the region between 400 and 1700 kev. Maxima in the gamma-ray yield occur at proton energies of 440, 550, 650, 817, 890, 1067, 1100, 1129, 1162, 1265, 1421, 1458, 1495, 1538, 1583, and 1610 kev. Absorption measurements of the gamma-rays from the strongest resonance, that at 1265 kev, indicate a quantum energy of 12 Mev, which is consistent with the assumption that the compound nucleus decays to the ground state by a single transition.

I. INTRODUCTION

The gamma-rays induced by proton bombardment of phosphorus were first observed by Curran and Strothers,[1] who reported maxima of a thick target excitation curve at proton energies of 460, 580, 700, and 950 kev. They measured the energy of the gamma-rays and concluded that the radiation must be associated chiefly with the reaction

$$H^1+P^{31}\rightarrow S^{32*}\rightarrow S^{32}+h\nu,$$

which has a Q-value of approximately 10.7 Mev. In studying this same reaction, Hole, Holtsmark, and Tangen[2] found three sharp resonances situated at 347, 433, and 530 kev. More recently, Tangen[3] has reexamined these resonances, which he reported at proton energies of 355, 440, and 540 kev. Thick targets were used in these investigations of the proton-capture process in phosphorus, and proton energies above one Mev were not available.

Some work with thin phosphorus targets and proton energies above one Mev was done by Herb[4] and his collaborators, who elected to discontinue this study in favor of other problems. The present authors have made careful runs over the levels studied at Wisconsin and have discovered several new levels. Both thick and thin targets have been bombarded with protons of energies between 400 and 1700 kev, and the gamma-resonances have been studied. Preliminary results of measurements on phosphorus were reported earlier.[5]

In addition to the reaction under consideration, the bombardment of phosphorus with protons may lead to the reaction

$$H^1+P^{31}\rightarrow S^{32*}\rightarrow Si^{28}+He^4,$$

which has a Q-value of approximately 1.8 Mev. The alpha-particles from this reaction have not been observed as yet.

II. EXPERIMENTAL PROCEDURE

The electrostatic generator at the Ohio State University was used as the source of bombarding protons. The voltage stability of the generator depends on corona drain to grounded needle points above the high voltage cap. With large drains the cap voltage is held constant to about $\frac{1}{4}$ percent with respect to rapid fluctuations.

An analyzing magnet located at the grounded end of the accelerating tube separates ions of the desired e/m and energy value from the several types of particles which come down the tube. A variable slit located in the path of the bombarding beam allows protons of

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† AEC Predoctoral Fellow; now at the National Bureau of Standards.

[1] S. C. Curran and J. E. Strothers, Proc. Roy. Soc. (London) A172, 72 (1939).

[2] Hole, Holtsmark, and Tangen, Naturwiss. 28, 668 (1940).

[3] R. Tangen, Kgl. Norske Videnskab. Selskabs Skrifter (1946), NR 1.

[4] R. G. Herb, private communication. The authors are deeply grateful to Professor Herb for suggestions and, especially, for making available the complete results of the preliminary work at Wisconsin.

[5] Grove, Cooper, and Harris, Phys. Rev. 80, 107 and 131 (1950).

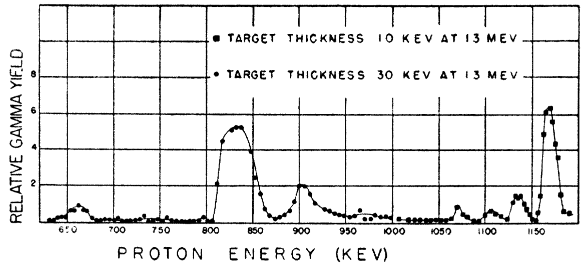

FIG. 1. Relative gamma-ray yield from P^{31} bombarded with protons of energies between 600 and 1200 kev.

only a few kilovolts energy spread to pass through and strike the target. Under favorable conditions, 1.5 μamp pass through this slit. The current in the coils of the magnet is determined by measuring the voltage drop across a one-ohm standard resistance with a Leeds and Northrup Type *K* potentiometer. It is found that the magnet current is a very reliable means of measuring the generator voltage because of its sensitivity and reproducibility. The magnet current was calibrated in terms of the accelerating potential from the accurately known resonances in lithium and fluorine at 440 and 873.5 kev as determined by Herb, Snowdon, and Sala.[6] The magnet current was always increased during the course of a run, after which it was increased to a fixed large value and then decreased zero. Usually, steps of 1.25 mamp were taken, which corresponds to about a 2 kev step at 1 amp. Resonance maxima were reproducible to about 3 kev on independent runs.

With a single Geiger tube placed 9.5 mm from the target an effective relative solid angle of 0.128 was obtained. With this counting geometry, the efficiency of the Geiger tube was determined for the 17 and 6.2 Mev quanta of lithium and fluorine, respectively, from the known cross sections of these resonances.[7] The charge collected on the target was recorded by a thyratron current integrator and mechanical recorder and the concomitant number of gamma-rays counted was recorded by a scale-of-4096 scaler and a mechanical recorder.

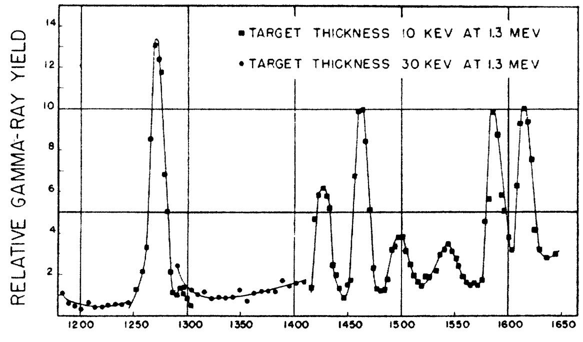

FIG. 2. Relative gamma-ray yield from P^{31} bombarded with protons of energy between 1200 and 1650 kev.

Phosphorus targets were prepared by vacuum evaporation of zinc phosphide and calcium phosphide on five mil tantalum disks. Zinc phosphide targets of 75, 40, 30, and 10 kev thicknesses at 1.3 Mev, as well as thick targets, were bombarded. These targets were very durable and showed no appreciable deterioration during the time they were used. Several thin calcium phosphide targets were also prepared and bombarded; these targets were somewhat less stable.

III. EXPERIMENTAL RESULTS

The excitation curves resulting from the proton bombardment of zinc phosphide are shown in Figs. 1 and 2. The yield from a target of about 30-kev thickness at 1.3 Mev is shown in the energy region below 1.0 Mev and in the low yield regions around 1.2 and 1.35 Mev. A target of 10-kev thickness at 1.3 Mev (87 $\mu g/cm^2$) was used for the energy region above 1.0 Mev to get better resolution of the resonance levels. Proton excitation energies of 650, 817, 890, 1067, 1100, 1129, 1162, 1265, 1421, 1458, 1495, 1538, 1583, and 1610 kev have been assigned to the observed resonance levels. These resonance energies are believed to be not more than 15 kev in error with respect to the absolute voltage scale. In addition to the resonances shown, the levels at 440- and 540-kev bombarding energy were observed. At most points on these resonances, over 1000 Geiger counts were taken.

The data plotted have been corrected only for the background not associated with the ion beam. At off-resonance points the Geiger counting rate was of the same order of magnitude as this background counting rate, so that the difference of the two rates gives rise to large percentage variations. The statistical fluctuations of these off-resonance regions are to be distinguished from the less intense levels which were always indicated in data from other thin targets as well as from thick targets. The excitation curve obtained from the bombardment of thin calcium phosphide targets showed the presence of all the levels observed from zinc phosphide.

A check of the gamma-ray yield from targets of tantalum, zinc, and calcium oxide was made. Tantalum gave a very small yield which increased slowly with proton energy. The yield from the zinc and calcium oxide targets was much greater than that from the tantalum, but there was no indication that any of the reported resonances could be attributed to zinc or to calcium.

IV. DISCUSSION OF THE RESULTS

In comparing the data of Fig. 1 with that of Curran and Strothers, it should be noted that they reported the *maxima* of a thick target excitation curve at 700 and 950 kev, while Fig. 1 shows thin target resonances

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[6] Herb, Snowdon, and Sala, Phys. Rev. **75**, 246 (1949).

[7] T. W. Bonner and J. E. Evans, Phys. Rev. **73**, 666 (1948).

at 650, 917, and 890 kev. The level they reported at 950 kev is probably due to the combined contributions of the 817- and 890-kev levels of Fig. 1. Indeed, if the curve is drawn through the 850-kev point in the figure of Curran and Strothers,[1] a definite suggestion of two levels is apparent.

Absorption measurements of the radiation from the 1.265-Mev resonance made with lead, copper, and aluminum absorbers were consistent with a gamma-ray of approximately 12-Mev energy. Since the proton capture process in phosphorus is 10.7-Mev exothermic, a gamma-ray of about 12-Mev energy would be expected if the excited sulfur nucleus decays to the ground state by a single transition.

The efficiency of the Geiger tube was estimated for quanta of 12-Mev energy from the previously determined efficiencies for the lithium and fluorine radiations. From the Geiger counter efficiency, the effective solid angle subtended by the counter, the number of gamma-rays counted per incident proton, and the average number of phosphorus nuclei per unit area of the target, the cross section of the 1.265-Mev resonance was calculated to be 6.4×10^{-28} cm^2. The natural half-width of this level was estimated to be 6.5 kev; this corresponds to a mean life of the excited state of the compound nucleus of approximately 10^{-19} sec.

A comparison of the proton-capture resonance energies for target nuclei which lack one proton of having an even number of alpha-particles shows that there is a similarity between P^{31} and F^{19}. On the other hand, Na^{23} and Al^{27} have progressively denser level spacings. Conceivably, there may be a correlation with the nuclear spin, which is $\frac{1}{2}$ for phosphorus and fluorine, $\frac{3}{2}$ for sodium, and 5/2 for aluminum.

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Microwave Resonance Absorption in Paramagnetic Salts*

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Thirteen paramagnetic salts of the iron group in powdered or crystalline form have been investigated for their resonance absorption at microwave frequencies. Effective g-factors are obtained from the frequencies and magnetic field strengths at which absorption peaks occur. The effects on line shape from dipole-dipole and exchange interactions, and from the crystalline electric field, have been studied.

I. INTRODUCTION

THIS work is intended as a general survey of paramagnetic absorption, at room temperature, in various salts of the iron group, with particular attention to the study of line shapes.

It is well known that the magnetic moments of the iron group are due to electrons of the inner incomplete shell 3*d*. The shapes of 3*d* orbits permit their energies to be perturbed seriously by the electric fields of neighboring atoms or ions. Immersed in a crystal lattice, these ions will then have their orbital degeneracy reduced in accordance with the particular symmetry[1] of the crystalline Stark field. The removal of orbital degeneracy implies that orbital magnetism is quenched, so that the effective magnetic moments of the ions result from spin only. When a dc magnetic field is applied, the lowest Stark level (or, possibly, several closely spaced levels) is split further into Zeeman components. The spacing between these components in a field of several thousand gauss falls in the microwave region. As magnetic dipole transitions of considerable intensity can occur[2] between levels of $\Delta m=\pm1$, m being the magnetic quantum number, the field H_0 for resonance absorption at a given frequency ν is

$$h\nu=|\Delta m g\beta H_0|=|g\beta H_0|, \tag{1}$$

where β is the Bohr magneton, and g is a measure of the effective gyromagnetic ratio.

Actually, the levels have been widened considerably by various interactions between ions. Such interactions, therefore, broaden the absorption line. Besides, they are chiefly responsible for the restoring of thermal equilibrium in the spin system, which in turn makes possible a net absorption when the microwave field is applied. While the phenomenon of spin relaxation is not completely understood, particularly in its relation to

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[*] Some of the equipment used in this study was made available in connection with related work being conducted under a contract between the Geophysical Directorate of the Air Force Cambridge Research Laboratories and The Ohio State University Research Foundation.

[1] H. A. Bethe, Ann. Physik 3, 133 (1929).

[2] C. Kittel and J. M. Luttinger, Phys. Rev. 73, 1621 (1948).