Inelastic Proton Scattering from Phosphorus and Zinc*

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Inelastic proton spectra from targets containing phosphorus and zinc have been studied at bombarding energies of 3.72 and 4.66 Mev using a double-focusing spectrometer. Proton groups have been observed corresponding to levels in P^{31} at 1.264±0.004, 2.230±0.005, 3.134±0.006, and 3.292±0.005 Mev. Excitation curves for these four inelastic groups measured in the region of E_p=4.55 to 4.70 Mev show the same general resonant structure, although differing in detail. At E_p=4.66 Mev, no additional groups from P^{31} were observed for the excitation region 0 to 1.26 Mev with an intensity greater than 2% of the intensity of the first excited state group.

Four inelastic proton groups were observed from zinc. From a comparison with the known level schemes of the zinc isotopes, three of these groups were assigned to the following isotopes: Zn^{64}, 0.991±0.005 Mev; Zn^{66}, 1.038±0.005 Mev; and Zn^{68}, 1.078±0.005 Mev. The remaining group with $Q=-1.802\pm0.005$ Mev remains unassigned.

I. INTRODUCTION

IN a previous publication,[1] an investigation of the levels of P^{31} from 0 to 1.43-Mev excitation by magnetic analysis of the $P^{31}(p,p')P^{31}$ reaction at a bombarding energy of 3.055 Mev was reported. Recently, there have been investigations of the $Si^{30}(p,\gamma)P^{31}$ reaction,[2] whose interpretation would be aided by a more complete knowledge of the level scheme of P^{31}. Accordingly, a survey for P^{31} levels from the $P^{31}(p,p')$ reaction has been extended to 3.55-Mev excitation, by the use of higher bombarding energies of 3.72 and 4.66 Mev. In order to detect inelastic proton groups of low intensity, the continuous proton background for the magnetic spectrometer has been considerably reduced. Preliminary reports of these measurements have been presented.[3]

II. EXPERIMENTAL PROCEDURE

For the present investigation, protons of energies 3.69 to 4.71 Mev were provided by the Office of Naval Research-Bartol Van de Graaff accelerator. Charged particles emitted from the target at a median angle of 91.36±0.15° were analyzed by a 180° double-focusing magnetic spectrometer, and detected by a NaI crystal 1 mm thick. A more complete description of the experimental arrangement has been given elsewhere.[1,4]

The primary energy calibration of the magnetic spectrometer was provided by Po-alpha particles, for which Wapstra's momentum value of 331.65±0.06 kilogauss-cm[5] was assumed. Additional calibrations were obtained from the analysis of proton groups elastically scattered from targets of gold or zinc phosphide at bombarding energies corresponding to the $Li^7(p,n)Be^7$ and $F^{19}(p,n)Ne^{19}$ thresholds, and to the 3.246-Mev resonance for the production of 1.26-Mev γ radiation from the $P^{31}(p,p')$ reaction.[6] Further checks have been provided from determinations of several groups from the $Al^{27}(p,\alpha)Mg^{24}$ and $Al^{27}(p,p')Al^{27}$ reactions,[4] which compared favorably with the results of other workers.

The resolution used for most of the investigation corresponded to 0.14% in momentum. However, most of the observed groups had half-widths which exceeded 0.2%, because of the contributions due to target thickness and the 2° acceptance angle of the spectrometer. The method of analysis used to translate the observed momentum profiles of reaction groups into energy determinations has been outlined elsewhere.[1,4] In this experiment, some additional procedures were necessary. First, in the case of protons elastically scattered from zinc, the elastic groups from the various zinc isotopes were not resolved. In order to obtain accurate energy determinations, the observed momentum profiles were compared to composite curves. These curves were composed from momentum profiles for protons elastically scattered from each isotope, with the proper half-widths and energy spacings, assuming that their maxima were in the ratios of the isotopic abundances. Second, in order to observe weak inelastic groups with energies below 1.5 Mev, it was necessary to increase the aperture of the detector slit from 1.9 to 3.8 mm, which changed the resolution from 0.14 to 0.27%. From observations of the momentum profiles of Po-alpha groups for the two apertures of the detector slits, it was possible to determine the corrections to be applied to the momentum profiles of the inelastic proton groups observed using the larger aperture.

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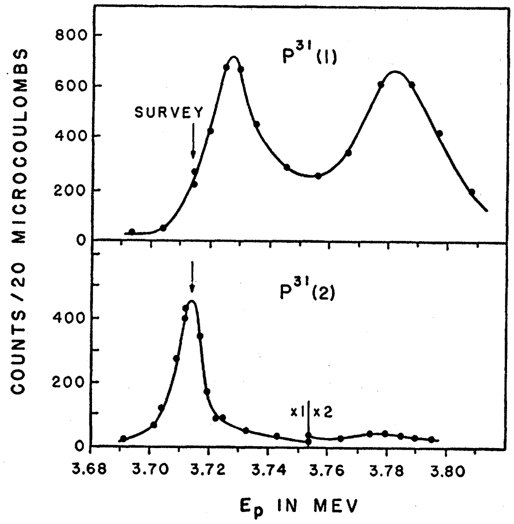

FIG. 1. Excitation curves for the $P^{31}(p,p')P^{31}$ groups corresponding to the first two levels of P^{31}, obtained by using an 11-kev Zn_3P_2 target, at $\theta=91.4°$.

III. RESULTS AND DISCUSSION

$P^{31}(p,p')P^{31}$ Reaction

In the previous investigation,[1] the yield of the inelastic proton group corresponding to the first excited state of P^{31} [designated as $P^{31}(1)$] was found to exhibit pronounced resonances, in particular at bombarding energies of 3.58, 3.73, and 3.78 Mev. Because of this resonant behavior, it was necessary to choose judiciously the bombarding energy for a survey of inelastic proton groups. In order to arrive at a reasonable choice, the yields of the inelastic groups corresponding to excited states of P^{31} at 1.264 and 2.230 Mev were measured for bombarding energies from 3.69 to 3.81 Mev, as shown in Fig. 1. For these measurements, an 11-kev target of zinc phosphide evaporated onto Formvar strengthened by gold was used. The energy scale shown in Fig. 1 has been corrected for target thickness, and is considered to be accurate to ±5 kev. In this region, the yield of the $P^{31}(2)$ groups is markedly different from that of the $P^{31}(1)$ group, having a pronounced resonance at 3.714 Mev ($\Gamma<10$ kev), 14 kev lower than the 3.73-Mev resonance for the $P^{31}(1)$ group. As indicated by the arrows in Fig. 1, a bombarding energy of 3.720 Mev corresponding to the maximum of the 3.714-Mev resonance, was chosen for a survey. The results of this survey are shown in Fig. 2, covering a region of excitation of P^{31} from 0 to 2.3 Mev. The small rise at a proton energy of 2.6 Mev was attributed to the presence of inelastic groups from zinc, as indicated. In addition to the $P^{31}(1)$ and $P^{31}(2)$ groups, no other inelastic groups from P^{31} were observed with an intensity greater than 7% of the intensity of the $P^{31}(1)$ group at this bombarding energy. As compared with the previous investigation,[1] the continuous background has been reduced by a factor of about 5, which has been attributed to the use of an improved collimating system for the bombarding beam.[4]

In order to extend the search for P^{31} levels above 2.3-Mev excitation, it was necessary to increase the bombarding energy. Again, in order to select a favorable bombarding energy for surveying, the yields of the $P^{31}(1)$ and $P^{31}(2)$ groups were measured over a limited region, $E_p=4.53$ to 4.71 Mev, as indicated in Fig. 3, using a 10-kev target. The energy scale shown in Fig. 3 has also been corrected for target thickness, and is considered to be accurate to ±6 kev. In this region, the excitation curves for the $P^{31}(1)$ and $P^{31}(2)$ groups are similar, although the relative intensities and positions of the resonances differ to some extent. Since the yield of both groups was a maximum in the vicinity of 4.655 Mev, a bombarding energy of 4.660 Mev, corresponding to this maximum, was chosen for a survey. The results of this survey are shown in Fig. 4, covering a region of excitation of 0 to 3.55 Mev. For proton energies below 1.5 Mev, the aperture of the detector slit was increased by a factor of two. A corresponding decrease of the continuous background in this region by

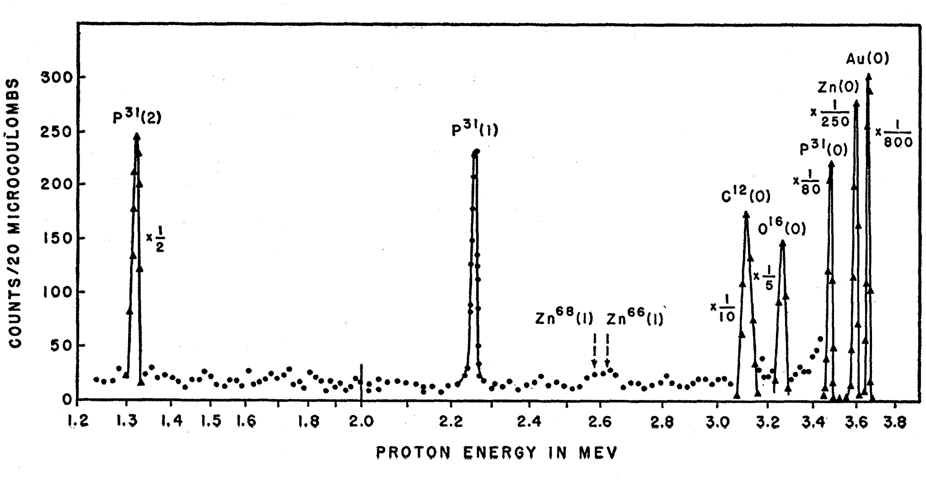

FIG. 2. Proton groups from an 11-kev Zn_3P_2 target at $E_p=3.720$ Mev, $\theta=91.4°$.

a factor of two was achieved by shielding the NaI detector from neutrons, produced mainly in the beam collector.

As indicated in the survey of Fig. 4, two additional groups, (3) and (4), attributed to the $P^{31}(p,p')$ reaction were clearly observed. These groups did not appear when targets of zinc or gold on Formvar were substituted for the zinc phosphide target. To obtain a more definite identification, the yields of the $P^{31}(3)$ and $P^{31}(4)$ groups were measured in the same region of bombarding energy, as shown in Fig. 3. The choice of bombarding energy proved to be a fortunate one, since there are resonances for both groups near this energy. The general similarity of the excitation curves of the four inelastic groups indicates that the identification of the $P^{31}(3)$ and $P^{31}(4)$ groups is correct. An independent identification has been made recently by Endt and Paris,[7,8] by observing their energy shift with angle at $E_p=7.04$ Mev. They also observed two additional groups, corresponding to levels in P^{31} at 3.414 and 3.508 Mev, which are included in the region of excitation covered by this present survey. In Fig. 4, a dashed curve indicates the expected position for their $P^{31}(5)$ groups, showing that this group was not of sufficient intensity to permit a positive identification or energy determination in this present survey. Similarly, the group corresponding to the 3.508-Mev level should appear at a proton energy of 0.95 Mev, but is too low in intensity to be observed.

In Table I are listed the excitation energies for the first four levels of P^{31} obtained from this investigation, from a weighted average of from 3 to 11 determinations. Comparison with the results of Endt and Paris[7] indicates excellent agreement. From the survey of Fig. 4 at $E_p=4.66$ Mev, no inelastic groups which could be assigned to P^{31} were observed in the excitation region of 0 to 1.26 Mev, with an intensity greater than 2% of the intensity of the $P^{31}(1)$ group. This result is in agreement with all recent work[2,6,7,9] concerning the level scheme of P^{31}; i.e., that there has been no confirmation of earlier reports[10] of the levels at 0.4 and 0.9 Mev, and that they most probably do not exist. In Fig. 5 are shown the levels of P^{31} known at present up to 7 Mev. A level at 3.4-Mev excitation reported from the $Si^{30}(d,n)P^{31}$ reaction[11] would appear to represent an unresolved combination of the four levels now known in the region of 3.1- to 3.5-Mev excitation. In addition to these levels, two higher levels have been found at 3.76 and 4.04 Mev from a study of the $Si^{30}(p,\gamma)P^{31}$ reaction.[12] The spin and

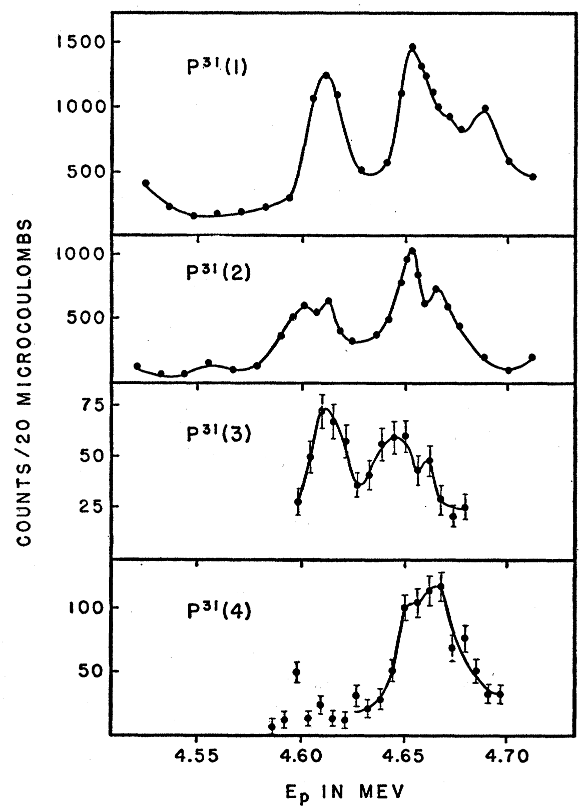

FIG. 3. Excitation curves for the $P^{31}(p,p')P^{31}$ groups corresponding to the first four levels of P^{31}, using a 10-kev Zn_3P_2 target, at $\theta=91.4°$.

parity assignments indicated in Fig. 5 originate from investigations of the $Si^{30}(p,\gamma)P^{31}$ reaction.[2,8]

In Fig. 5, the presently known level scheme for P^{31} (up to 7-Mev excitation) is compared to that of S^{31}, obtained from a recent investigation of the $P^{31}(p,n)S^{31}$ reaction.[13] Again, because of the low resolution inherent in the photographic detection of neutron groups, a structure corresponding to six levels in P^{31} from 3.1- to 4.0-Mev excitation could not be completely resolved in their experiment, although the authors did indicate the possible presence of a neutron group corresponding to a level at about 3.6 Mev, in addition to the level at 3.35±0.20 Mev. Hence, within the limitations of our

TABLE I. Energy levels of P^{31} (in kev) from $P^{31}(p,p')P^{31}$.

P^{31}	Present results	Endt and Paris[a]
(1)	1264±4	1267±5
(2)	2230±5	2235±5
(3)	3134±6	3131±5
(4)	3292±5	3292±5
(5)	...	3414±5
(6)	...	3508±5

[a] See reference 7.

[7] P. M. Endt and C. H. Paris, Massachusetts Institute of Technology Annual Progress Report, 1956 (unpublished), p. 105, and private communication.
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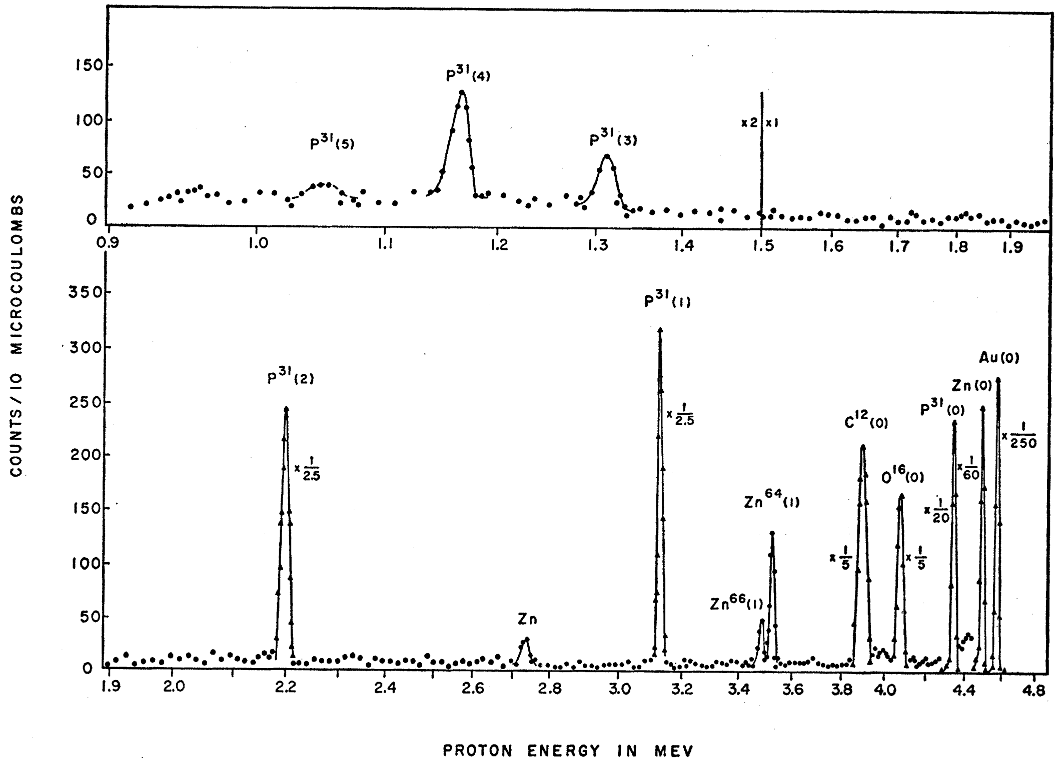

FIG. 4. Proton groups from a 10-kev Zn_3P_2 target at $E_p=4.66$ Mev, $\theta=91.4°$.

present knowledge, the level schemes of the mirror nuclei P^{31} and S^{31} appear to be identical.

$Zn(p,p')Zn$ Reaction

In the survey of Fig. 3, three inelastic proton groups were observed, which have been attributed to the zinc

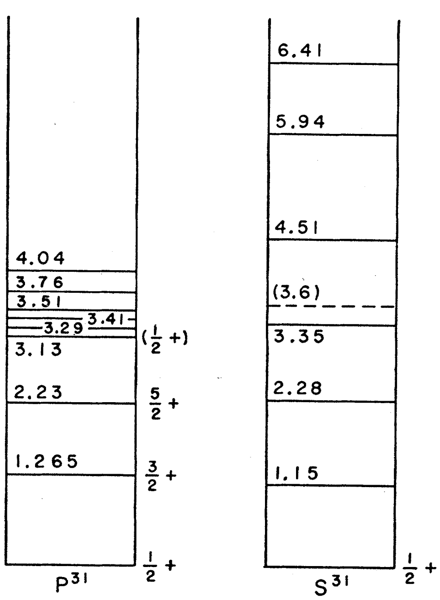

FIG. 5. Energy levels of P^{31} and S^{31} up to 7-Mev excitation.

contained in the zinc phosphide target. In order to identify these groups, a similar survey was made at the same bombarding energy of 4.66 Mev, using a target of zinc on Formvar, 11 kev thick for the $Zn(p,p)$ group. The results of this survey covering a region from 0 to 1.91-Mev excitation, are shown in Fig. 6. The three groups appear with increased intensity as expected, and in addition, a fourth group of low intensity is observed at a proton energy of 3.45 Mev. None of these groups were observed from a target of gold on Formvar, eliminating possible contaminants in the Formvar backing. From a comparison with the known levels of the Zn isotopes, three of the groups have been assigned to the first excited states of Zn^{64}, Zn^{66}, and Zn^{68}, as indicated. By observing these three groups at a bombarding energy of 3.72 Mev, the assignment of these groups to zinc was verified.

In the survey of Fig. 6, two weak groups which occur between the intense $C^{12}(p,p)$ and $O^{16}(p,p)$ elastic groups are attributed to C^{13} and N^{14}. At energies above the $Zn(p,p)$ group, two elastic groups are observed, which are attributed to traces of contaminants with masses close to those of Ag and Pb. Finally, a weak group assigned to $S^{32}(p,p)$ is observed, which evidently arises from a small amount of sulfur in the Formvar backing, since the same group has appeared in several Massa-

TABLE II. Energy levels of the zinc isotopes (in kev).

	Present results Zn (p,p')	Radioactivity Ga (β^+,γ)[a]	Cu (β^-,γ)[a]	Reactions Cu (p,γ)[b]	Zn $(\alpha,\alpha'\gamma)$[c]
$Zn^{64}(1)$	991±5	970	...	970±10	1000±10
$Zn^{66}(1)$	1038±5	1050±20	1044±10	1040±10	1040±10
$Zn^{68}(1)$	1078±5	1100±20		...	
Zn	1802±5[d]				

[a] See reference 16.
[b] See reference 17.
[c] See reference 18.
[d] For this value, the average atomic weight of zinc of 65.39 was used.

chusetts Institute of Technology surveys.[14] The identification of this group was checked by decreasing the bombarding energy to 3.72 Mev. When similar surveys at $E_p=4.125$ and 4.66 Mev were made using a target of gold on Formvar, two weak proton groups appeared, assigned to elastic scattering from Si^{28} and S^{32}. The presence of these groups prohibited the observation of Coulomb excitation of the 279-kev level in Au^{197}, recently accomplished by Elbek and Bockelman[15] using 6-Mev protons.

In Table II are listed the values for the energy levels obtained in this investigation from a weighted average of four to six determinations. Comparison is made with the level energies obtained by other workers from the following investigations: radioactivity of Ga^{64}, Ga^{66}, Ga^{68}, and Cu^{66},[16] the $Cu^{63}(p,\gamma)Zn^{64}$ and $Cu^{65}(p,\gamma)Zn^{66}$ reactions[17]; and the Coulomb excitation of Zn^{64} (enriched) and Zn^{66} by alpha particles.[18] The assignment of three of the inelastic proton groups observed from natural zinc to the first levels of Zn^{64}, Zn^{66}, and Zn^{68} is based solely on the good agreement of the energy values with the established levels of these zinc isotopes. However, the fourth inelastic group, with $Q=-1.802 \pm 0.005$ Mev, cannot be associated with any level of zinc isotope known at present; hence its assignment must await the use of enriched targets. This Q value is based on the use of the average atomic weight of 65.39 for zinc; and would change to 1.811 Mev if the mass of Zn^{70} were used.

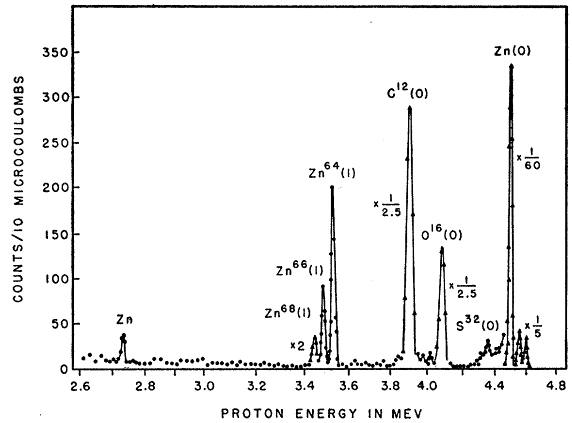

FIG. 6. Proton groups from an 11-kev Zn target at $E_p=4.66$ Mev, $\theta=91.4°$.

Since the primary purpose of the present experiment was the investigation of the level scheme of P^{31}, the survey of inelastic groups from zinc was extended only to 1.91-Mev excitation. However, it did serve to indicate that inelastic proton scattering from nuclei with masses at least up to $A=66$ can be investigated by using a 180° double-focusing spectrometer.

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