# Investigation of the ($d$, $p$) Reaction in Phosphorous and Chlorine

I. B. TEPLOV
*Moscow State University*

(Submitted to JETP editor February 24, 1956)
J. Exptl. Theoret. Phys. (U.S.S.R.) 31, 25-30 (July, 1956)

Proton angular distributions are determined for the $P^{31}(d,p)P^{32}$ and the $Cl^{35}(d,p)Cl^{36}$ reactions using thick nuclear photographic plates. The analysis of the observed experimental results permits a number of conclusions to be made regarding the excited states of the residual nuclei.

---

IT is well known that nuclear reactions of the $(d,p)$ or the $(d,n)$ types can proceed either with or without the formation of an intermediate nucleus. In the latter event, it is not the entire deuteron which interacts with the target nucleus, but rather, only one of its nucleons. A distinguishing characteristic of such a reaction mechanism---usually referred to as a stripping process---appears to be the presence of narrowly shaped maxima in the angular distribution of the outgoing particles, the positions of these maxima being characterized by the orbital momentum $l$ with which the nucleon (a neutron for the case of the $(d,p)$ reaction) is captured by the nucleus[1]. Consequently, a comparison of the experimental with the theoretical angular distributions makes possible the determination of a set of physical data for the various states of the residual nucleus. Of special importance is the circumstance that it is possible to investigate the excited states of the atomic nuclei using these methods, and, in particular, to verify the correctness of the shell model description of the properties of the low-lying excited levels.

The purpose of the present work, which was completed in 1954, was to determine the excited level characteristics of the $P^{32}$ and $Cl^{36}$ nuclei by an investigation of the energy and angular distributions of the protons formed in reactions of the $(d,p)$ type in phosphorous and in chlorine. Detailed studies of the angular distributions produced in these proton reactions have not yet been published. Only angular distributions for the formation of residual nuclei in the ground states have been dealt with in several investigations[2-4], it being shown that the transferred orbital momentum in this case is equal to 2. In addition, a brief communication[5] has appeared concerning an investigation of the angular distribution of particles for a number of excited levels of $P^{32}$.

A cyclotron output, consisting of a focussed deuteron beam of energies near 4 mev, was used for studying the reactions. The energy spread in the beam did not exceed 1%, and the absolute value of the average energy was known with an accuracy of 3%. For the case of the $P^{31}(d,p)P^{32}$ reaction a thin layer ($0.16 \pm 0.05$ mg/cm$^2$) of zinc sulfide, deposited on tinsel by evaporation in a vacuum, served as a target. For investigating the $Cl^{35}(d,p)Cl^{36}$ reaction the target was a layer of barium chloride ($0.51 \pm 0.09$ and $0.27 \pm 0.08$ mg/cm$^2$), prepared in the same way. The protons produced in the nuclear reactions were detected with the help of thick-layered photographic plates of type Z-2 (having an emulsion thickness of $100\,\mu$) oriented at various angles to the direction of the incoming deuterons. An aluminum absorber of thickness $320\,\mu$ was inserted between the target and the photographic plates to absorb the elastically scattered deuterons.

**The $P^{31}(d,p)P^{32}$ Reaction.** The distribution of the proton tracks is shown in Fig. 1 for protons emerging from the target at an angle of 20° to the direction of the deuteron beam. The energies of excitation for various states of $P^{32}$ obtained from the histogram are presented in the Table together with the data proceeding from a magnetic analysis of the products of the $P^{31}(d,p)P^{32}$ reaction. The results obtained by these two methods agree well among themselves considering, of course, the poor resolving power of the photographic plate method. In all, 18 photographic plates, exposed at various angles, were processed. Angular distributions obtained from an analysis of all the histograms for four groups of protons are presented in Figs. 2-4, the statistical errors only being indicated. The angle of scattering in the center-of-mass system for the proton is indicated along the abscissa axis, while the differential cross section in millibarns per steradian is along the ordinate axis (it is important to note that the accuracy of the determination of the absolute cross section is very poor---several tens of percent). The isotropic contributions of the angular distributions, obviously corresponding to the formation of the compound nucleus, are separated off by horizontal dashed lines. Curves on these same diagrams are presented which have been calculated using the theoretical formulas of Ref. 1, the values of the orbital momenta being selected so as to achieve optimum agreement between the experimental points and the calculated curves.

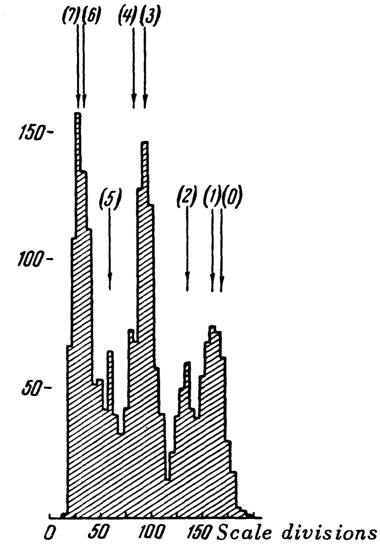


FIG. 1. Spectrum of protons emitted at an angle of 20° to the deuteron beam for the $P^{31}(d,p)P^{32}$ reaction. The divisions of the microscope ocular scale are indicated along the abscissa (1 division = $1.41\mu$).

Comparison of the experimental with the theoretical angular distributions indicates that it is possible to explain satisfactorily the observed results, provided that it is assumed that the transferred orbital momentum is equal to 2 for the case in which $P^{32}$ is formed in the ground state (in agreement with the results of Refs. 2 and 3), and 0 for state (2). The angular distribution of the groups of protons corresponding to levels (3) and (4) can be explained by assuming that two orbital momenta, 0 and 3, contribute. Evidence in favor of the orbital momentum 0 corresponding to level (3) and the orbital momentum 3 to level (4) is given by the form of the peak of this group of protons on certain histograms, that of Fig. 1, for example. It is not possible to give any definite value at all for the orbital momentum of group (5), since the angular distribution of this group is practically isotropic (within limits of an average error of ±7%). In the Table are listed all the values obtained for the orbital momenta together with the parities and possible spin values of the observed nuclear levels ($|J_0 + 1 + s_n|_{min} \leq J \leq J_0 + l + \frac{1}{2}$, where $J_0$ is the spin of $P^{31}$, equal to $\frac{1}{2}$).

It is known from other evidence that the spin of the ground level of $P^{32}$ is 1. Comparing the relative intensities obtained by the method of magnetic analysis[6] for the proton groups corresponding to capture by levels (0) and (1), it can be concluded that the spin of level (1) is equal to 2[7]. From the point of view of the nuclear shell model both of these levels correspond to the state $1d_{3/2}$ of the last neutron.

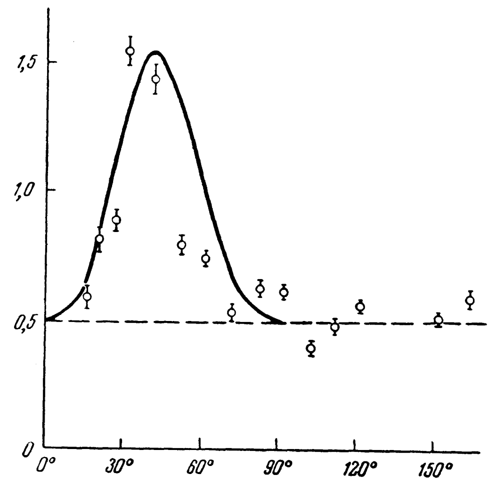


FIG. 2. Angular distribution of protons for the nuclear states (0–1) of $P^{32}$. The solid curve is plotted for $l = 2$.

The following discussion is based on the observation that if the probability of capture of the neutron into some excited level is comparable with the probability of capture into the ground state, then this excited level is formed by one particle excitation. If the capture probability for some level is considerably less than for the ground level, then the excited level which is formed involves excitation of the initial nucleus. As theory shows[1], the probability of neutron capture into a given state is proportional to $\sigma(\theta)f(E_d, E_p, \theta)/(2J + 1)$, where $f$ is a known function of the angle and the deuteron and the proton energies, and $\sigma$ is the differential cross section for the process. The capture probability of the neutron (in relative units) obtained in this manner is

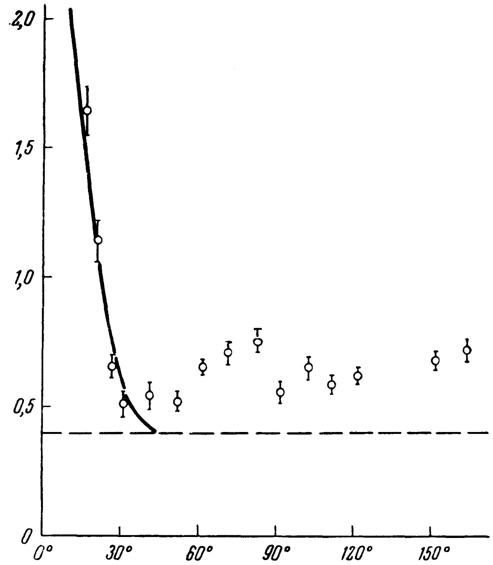


FIG. 3. Angular distribution of protons for the nuclear state (2) of $P^{32}$. The solid curve is plotted for $l = 0$.

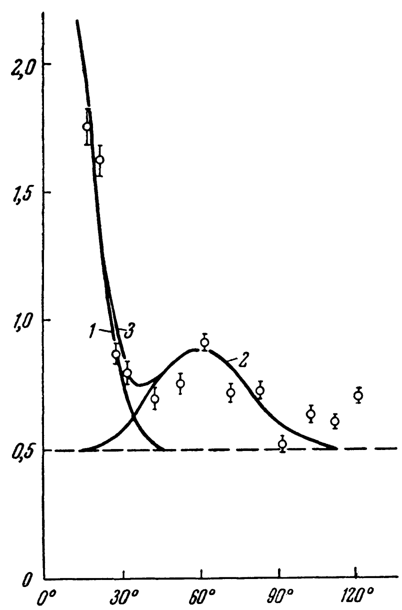


FIG. 4. Angular distribution of protons for the nuclear states (3–4) of $P^{32}$. Curves *1*, *2* and *3* are plotted for $l = 0$, 3 and 0 + 3, respectively.

indicated in one of the columns of the Table, the calculation for the doublet (0)–(1), making use of the fact that the spin of the ground state is 1 and the spin of state (1) is 2. The capture probability for excited states is evaluated for each allowable value of $J$. As is seen from the Table, level (4) corresponds to one particle excitation, namely, to the state $1f_{7/2}$ of the last neutron, while levels (2) and (3) are associated with excitation of the initial nucleus. If this interpretation is correct, then the number of possible values for the spin of state (4) is limited, since the combination of the proton in the state $2s_{1/2}$ and the neutron in the state $1f_{7/2}$ can only lead to the values 3 and 4 for the spin. The circumstance that several of the low-lying states of $P^{32}$ can be described with the help of the shell model is quite understandable, since in this nucleus the last neutron alone occupies the new level.

It should be noted that the values of the orbital momenta for the excited nuclear states of $P^{32}$ obtained in the present work are different from those communicated in Ref. 5. In agreement with the data presented there, however, the angular distributions of the proton groups for the formation of the nucleus in states (2), (3) and (4) are describable using a mixture of $l = 0$ and $l = 2$. No estimate of the degree of certainty of these results can be made at the present time, inasmuch as a detailed description of the experiments has not yet been published.

**The $Cl^{35}(d,p)Cl^{36}$ Reaction.** The nuclear level scheme of $Cl^{36}$ obtained as the result of analyzing the distribution of proton tracks in photographic plates is presented in Fig. 5. In the same figure are indicated the level scheme determined from the $\gamma$–ray energies for the $(n,\gamma)$ reactions[7], as well as the levels found by Innis[8], who investigated the $Cl^{35}(d,p)Cl^{36}$ reaction (see also Ref. 9).

Our measurements are found to be in satisfactory agreement with the results of these investigations as a result of our success in resolving all groups of protons corresponding to the known nuclear levels. The only exception is the 5.57 mev level, since in this case the protons corresponding to it are masked by the protons from the $O^{16}(d,p)O^{17}$ reaction. Groups (1) and (12), which previously have been unobserved, have very weak intensities and, possibly, are associated with the existence of foreign admixtures in the target.

Angular distributions were plotted for ten groups of protons, two of which are shown in Figs. 6 and 7. The orbital angular momentum values obtained by the comparison of the experimental results with the theoretical curves are indicated in Fig. 5 for all the levels for which angular distributions were plotted. In those cases in which the magnitude of the orbital momentum is not reliably

TABLE. Excited nuclear levels of $P^{32}$.

| Level No. | Energy of excitation: Result of magnetic analysis in mev | Energy of excitation: isotropic distribution in mev | Characteristics of the residual states: $l$ | Parity | $J$ | Probability of neutron capture | State |
|---|---|---|---|---|---|---|---|
| (0) | 0 | | | | | | $1d_{3/2}$ |
| (1) | 0,077 | 0 | 2 | + | 1; 2; 3 | 7.9 | $1d_{3/2}$ |
| (2) | 0,515 | 0,48 | 0 | + | 0; 1 | 2.3; 0.8 | |
| (3) | 1,154 | 1,24 | 0 | + | 0; 1 | 3.8; 1.3 | |
| (4) | 1,316 | | 3 | − | 2; 3; 4 | 12.0; 8.6; 6.7 | $1f_{7/2}$ |
| (5) | 1,750 | 1.84 | Present work | | | | |
| (6) | 2,177 | 2,23 | | | | | |
| (7) | 2,227 | | | | | | |

determined--that is, whenever the agreement of the theoretical curve with the experimental points is not sufficiently good---a question mark has been placed opposite the dubious value. The parity and the allowed values of the spin $J$ for the nuclear states of $Cl^{36}$ observed in the reaction are indicated in the last two columns of Fig. 5. The re-

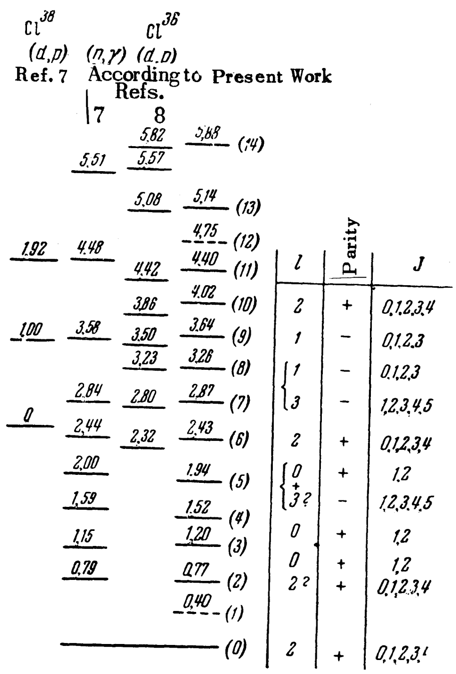


FIG. 5. Nuclear level diagram for $Cl^{36}$.

sults obtained for the longest track group agree with the published data[4]. The analysis which can be carried out for the case of the $Cl^{35}(d,p)Cl^{36}$ reaction, using the probability of neutron capture, does not lead to definite results, as is fully apparent, since the presence of levels with clearly

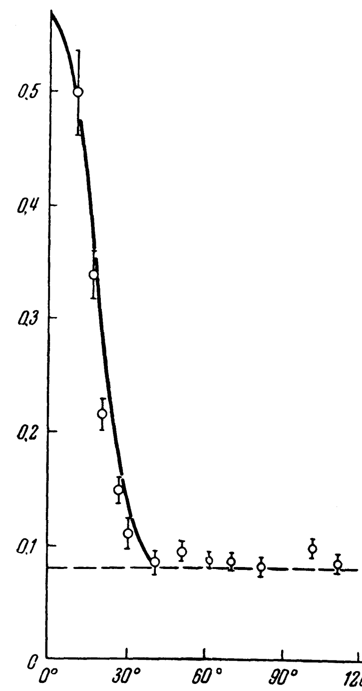


FIG. 6. Angular distribution of protons, corresponding to state (4) of the nucleus $C^{36}$. Solid curve: $l = 0$.

manifested one particle excitation is not to be expected in $Cl^{36}$.

As an examination of the energy and angular distribution reveals, it is entirely probable that levels of $Cl^{36}$ which cannot be resolved by the photographic plate method exist between levels (7) and (8) and near states (5) and (6). In evidence of this there is, first, the shape of the peaks of these proton groups, second, the very large differential cross section for the production of the protons composing these groups, and, third, the angular distributions for levels (5) and (7) – (8), which can be explained only if it is assumed that two values of the orbital momentum are transferred.

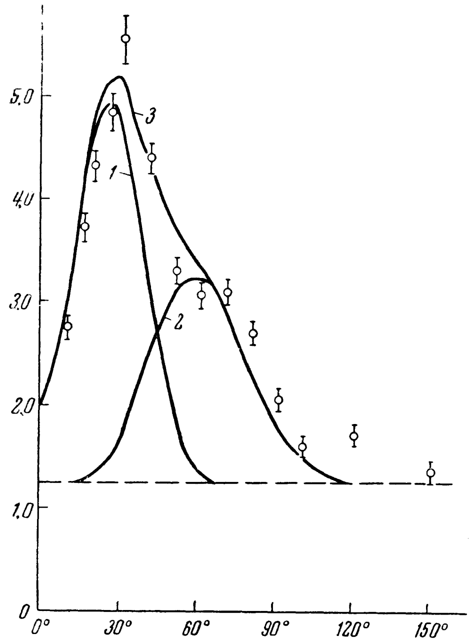


FIG. 7. Angular distribution of protons, corresponding to states (7) - (8) of the nucleus $Cl^{36}$, 1: $l = 1$; 2: $l = 3$, 3: $(l = 1) + (l = 3)$.

It should be noted that in constructing the energy level diagram of $Cl^{36}$ it has been assumed that all of the groups of protons detected belong to the $Cl^{35}(d,p)Cl^{36}$ reaction. Some of the groups, however, could result from a reaction involving the heavy isotope $Cl^{37}$ (25% in a natural mixture). The relative distribution of known[7] energy levels of $Cl^{38}$ is shown in the left portion of Fig. 5.

In conclusion, I wish to express my gratitude to S. S. Vasiliev for his guidance, and to T. N. Markelov for assistance with the work.

*Note added in proof:* After submitting this article for publication, the work of Paris, Buechner and Endt[10] appeared in which the chlorine $(d,p)$ reaction was investigated with the help of a magnetic spectrometer. A series of new nuclear energy levels of $Cl^{36}$ in the range from 2.5 to 4 mev for the excitation energies (that is, in the region of levels (6) – (10)) were discovered, confirming the conclusions of the present article. The existence of level (1) with an energy of excitation 0.40 mev, however, was not confirmed.

1 R. Huby, Prog. Nucl. Phys. **3**, 177 (1953).

2 Parkinson, Beach and King, Phys. Rev. **87**, 387 (1952).

3 C. F. Black, Phys. Rev. **90**, 381 (1953).

4 J. S. King and W. C. Parkinson, Phys. Rev. **88**, 141 (1952).

5 B. B. Kinsey and G. A. Bartholomew, Phys. Rev. **93**, 1260 (1954).

6 Van Patter, Sperdutto, Endt, Buechner, and Enge, Phys. Rev. **86**, 502 (1952).

7 P. M. Endt and I. C. Kluyver, Rev. Mod. Phys. **26**, 131 (1954).

8 W. W. Ennis, Phys. Rev. **82**, 304 (1951).

9 Groshev, Adiasevich and Demidov, *Report on the International Conference on the Peaceful Uses of Atomic Energy*, 1955.

10 Paris, Buechner and Endt, Phys. Rev. **100**, 1317 (1955).

Translated by E. V. Ivash
4