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# *ANGULAR DISTRIBUTIONS FOR SOME (d, p) REACTIONS*

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Angular distributions for some of the proton groups from (d, p) reactions on silicon, phosphorus, sulfur, and chlorine were found for 4 Mev deuterons. The results show that when nuetrons with $\ell = 2$ are captured, the maximum in the differential cross section is shifted toward smaller angles from the position of the maximum as given by the Butler theory. A comparison of the angular distributions shows that there is an appreciable effect on the shape of the distribution from the interference between the processes of stripping and compound nucleus formation.

THE angular distribution which was found[1] for the long range protons from the stripping reaction $S^{32}(d, p)S^{33}$ with 4-Mev deuterons was different from the angular distributions of the long range protons from the $P^{31}(d, p)P^{32}$ and $Cl^{35}(d, p)Cl^{36}$ reactions[2,3] for the same deuteron energy. One would have expected that the shapes of the angular distributions would be similar for all three reactions. In the first place, in all three cases the neutron is captured in a $1d_{3/2}$ state, i.e., $\ell = 2$. This follows from the shell model and is confirmed by studies of the stripping reaction for deuteron energies around 8 Mev.[4-6] Secondly, all the fundamental parameters characterizing the three reactions — charge, mass, and nuclear radius, as well as the Q value, are approximately the same (cf. below).

The present paper gives the results of additional studies of these three reactions. In addition we give the angular distributions for two long-range proton groups from the $Si^{28}(d, p)Si^{29}$ reaction with 4-Mev deuterons, as well as the angular distribution of the proton group from $S^{32}(d, p)S^{33}$ in which the final nucleus is left in its ground state. The last group was observed with 1.3 and 2.2 Mev bombarding energy.

## EXPERIMENTAL METHOD

The proton angular distributions were studied using NIKFI-Ia2 thick-layered photoplates; all the particulars of the experiment have been previously described.[7] We should add only that the absolute value of the deuteron energy was known to ± 3%, while the energy spread of the beam did not exceed 30 kev.*

PbS, $Zn_3P_2$, and $BaCl_2$ were used for preparing the targets. These compounds were evaporated onto a gold leaf backing. In the case of sulfur, an additional irradiation at 4 Mev was made after the main irradiations at 4.0, 2.2, and 1.3 Mev. The ratio of the cross sections found in the check series to those in the main series was 0.84, so apparently as a result of deuteron bombardment the number of sulfur atoms in the target had decreased somewhat.

The silicon target was prepared by evaporating coarse-grained silicon from a tungsten helix. In this case the backing was a polystyrene film. Since its thickness was not known, we were unable to determine the absolute value of the $Si^{28}(d, p)Si^{29}$ reaction cross section. Another defect of the polystyrene backing is that the spectrum measurement is made somewhat more difficult because of the presence of a proton group from the $C^{13}(d, p)C^{14}$ reaction.

Purified reagents were used in all cases for preparing targets. No protons were observed from impurities.

## EXPERIMENTAL RESULTS

The observed angular distributions are given in Figs. 1 — 8, in which the abscissa gives the angle in the center of mass system, and the ordi-

*This value of the spread comes from measurements by G. F. Timushev, carried out at the same cyclotron using a precision magnetic spectrometer, under conditions similar to ours.

nate is the differential cross section in millibarns per steradian. For the case of silicon, (Figs. 1 and 5), the differential cross sections are given in relative units, with the same scale on both figures. The errors indicated on the figures are statistical errors. (Errors not associated with statistical fluctuations are, in any case, less than 10%, cf. Ref. 7.)

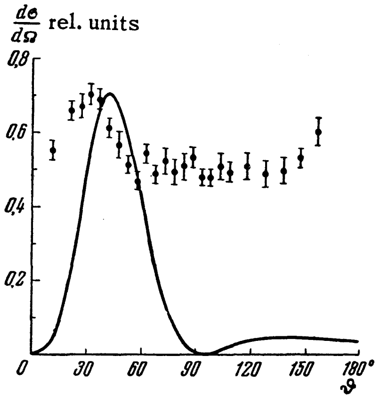


FIG. 1. Silicon reaction. $Si^{29}$ excitation energy = 1.28 Mev; $l$ = 2.

The angular distributions for phosphorus and chlorine (Figs. 2 and 4) are based on the same experimental material as in Ref. 3, but the plates were examined again with appreciably greater accuracy. We also checked the calibration of the integrator (by elastic deuteron scattering on gold) and the target thickness. The check showed that the phosphorus reaction cross section is approximately twice as large as that given in Ref. 3.* We should mention that, in the case of phosphorus, at large angles we are able to separate the proton group from the $Zn^{64}$(d, p)$Zn^{65}$ reaction in which the final nucleus is left in the ground state. At small angles this proton group cannot be separated from the protons from the phosphorus reaction. Thus the results for phosphorus (Fig. 2) at small angles were obtained under the assumption that the distribution of the protons from the $Zn^{64}$(d, p)$Zn^{65}$ reaction is isotropic and that the differential cross section is 0.25 mbn/sterad.

For chlorine, in addition to the main measurements whose results are given in Fig. 4, we also made some additional measurements. In this case the plates were placed at a smaller number of angles and fewer tracks were measured on each plate than for the main series. However, the shapes of the angular distributions and the absolute total cross sections were practically the same for both cases.

Table I gives the values found for the total cross sections for formation of the various proton groups. The absolute cross sections are determined to 30 — 40% (the uncertainty in the relative cross sections for sulfur is considerably smaller). For silicon we give only the relative cross sections for formation of the two proton groups.

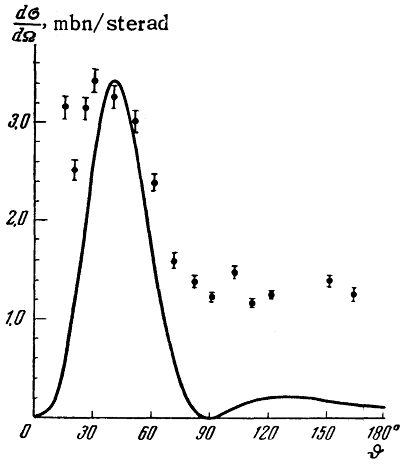


FIG. 2. Phosphorus reaction. $P^{32}$ ground state and first excited state (0.077 Mev); $l$ = 2

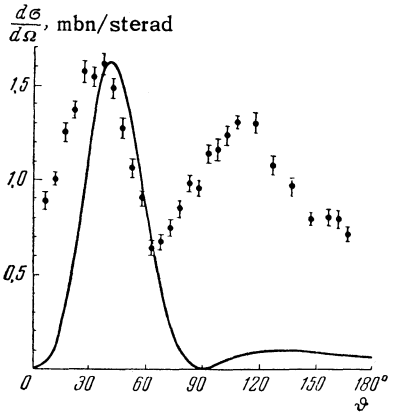


FIG. 3. Sulfur reaction. $S^{33}$ ground state; $l$ = 2.

## DISCUSSION OF RESULTS

In addition to the experimental results, Figs. 1 — 8 give the angular distributions calculated from the Butler theory;[8] the nuclear radius, in accordance with Holt and Marsham, is taken as $R = (1.7 + 1.22\,A^{1/3}) \times 10^{-13}$ cm.

Let us first look at the angular distributions found for the first excited state of $Si^{29}$, for the close doublet of $P^{32}$ and for the ground states of $S^{33}$ and $Cl^{36}$ (Figs. 1 — 4). In these cases the neutron is captured into a $1d_{3/2}$ state, i.e., with orb-

*The ordinates of all figures in Ref. 3 for phosphorus should therefore be multiplied by 2.

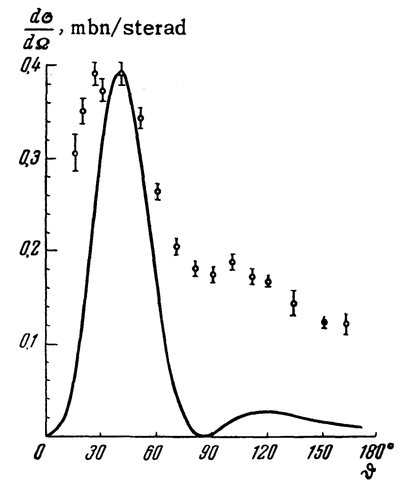


FIG. 4. Chloride reaction. $Cl^{36}$ ground state; $l = 2$.

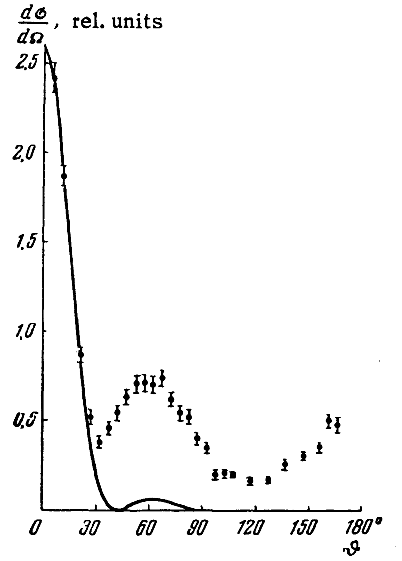


FIG. 5. Silicon reaction. $Si^{29}$ ground state; $l = 0$.

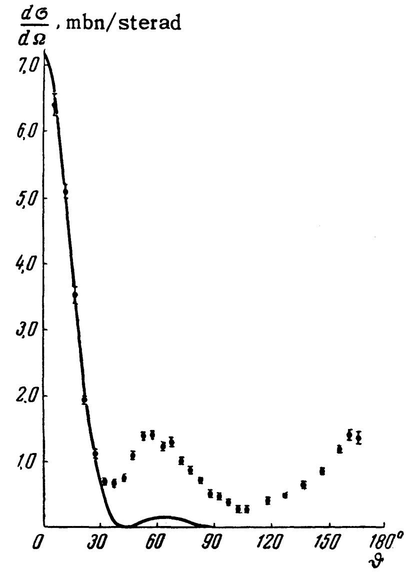


FIG. 6. Sulfur reaction. $S^{33}$ excitation energy = 0.84 Mev; $l = 0$

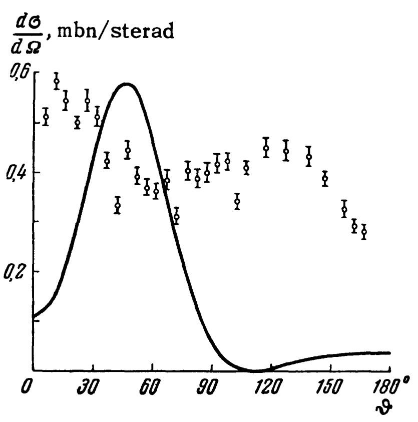


FIG. 7. Sulfur reaction. $S^{23}$ ground state; $l = 2$; deuteron energy = 2.2 Mev.

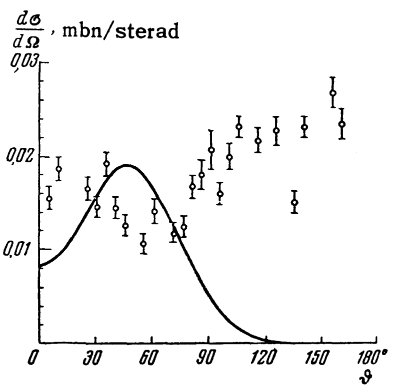


FIG. 8. Sulfur reaction. $S^{33}$ ground state; $l = 2$; deuteron energy = 1.3 Mev

TABLE I

| Reaction | Deuteron energy Mev | Excitation energy Mev | $l$ | σ, mbn |
|---|---|---|---|---|
| $Si^{28}(d, p)Si^{29}$ | 4.0 | 0 | 0 | $\sigma_0$ |
| $P^{31}(d, p)P^{32}$ | 4.0 | 1.28 | 2 | $0.16\sigma_0$ |
| $S^{32}(d, p)S^{33}$ | 4.0 | 0+0.077 | 2 | 22.6 |
| | 4.0 | 0 | 2 | 13.4 |
| | 2.2 | 0 | 2 | 5.25 |
| | 1.3 | 0 | 2 | 0.23 |
| | 4.0 | 0.84 | 0 | 11.0 |
| $Cl^{35}(d, p)Cl^{36}$ | 4.0 | 0 | 2 | 2.9 |
| $Zn^{64}(d, p)Zn^{65}$ | 4.0 | 0 | — | 3.2 |

ital angular momentum $l = 2$. All four experimental angular distributions show the main feature of the stripping reaction, the presence of a maximum at small proton angles. But a more detailed comparison shows that there are differences between the experimental and theoretical angular distributions which are common to all four cases. These are, first, the presence of an appreciable "background" (i.e., some differential cross section at the minima of the angular distributions); secondly, there is a shift of the principal maximum toward smaller angles compared with the curve calculated from the Butler theory. The occurrence of an appreciable background or, as it is sometimes called, an isotropic part of the angular distribution, is almost always observed with low energy deuterons. It might be attributable to compound nucleus formation. It is entirely possible that it is partially due to the stripping process itself, as is shown by computations of Tobocman and Kalos[10] which include Coulomb and nuclear interactions. As for the shift of the main maximum toward smaller angles, such a shift was already observed in our work[7] in which we studied the potassium and calcium reactions with 4-Mev deuterons. There is also a shift of the maximum in the results of Shapiro[11] for the $Na^{23}(d, p)Na^{24}$ reaction with 3-Mev deuterons.

Thus we may assume that the shift of the characteristic stripping maximum toward smaller angles from the position as computed on the Butler theory is not accidental, at any rate for deuteron energies somewhat below the Coulomb barrier. This result is somewhat unexpected, since the Coulomb interaction should shift the maximum in the opposite direction. Therefore the shift toward 0° shows that nuclear interaction plays an important role in the stripping process. It would seem that the presence of such a shift should be borne in mind when selecting a method of description of the nuclear interaction in calculations of angular distributions according to the formula of Tobocman and Kalos.[10]

TABLE II

| Reaction | Excitation energy of final nucleus, Mev | Q, Mev | Target nucleus | | Effective Height of Coulomb barrier, Mev | Excitation energy of intermediate nucleus, Mev |
|---|---|---|---|---|---|---|
| | | | $Z$ | $N$ | | |
| $Si^{28}(d, p)Si^{29}$ | 1.28 | 4.97 | 14 | 14 | 4.74 | 15.5 |
| $P^{31}(d, p)P^{32}$ | 0+0.077 | 5.70 | 15 | 16 | 4.88 | 19.0 |
| $S^{32}(d, p)S^{33}$ | 0 | 6.42 | 16 | 16 | 5.14 | 15.2 |
| $Cl^{35}(d, p)Cl^{36}$ | 0 | 6.30 | 17 | 18 | 5.27 | 19.0 |

As already remarked, the fundamental parameters describing the reactions are closely equal for silicon, phosphorus, sulfur, and chlorine, which occupy neighboring positions in the periodic table (cf. Table II). Thus, independently of whether we include Coulomb and nuclear interactions in the calculations, the theoretical angular distributions should be alike for all four cases. But it is apparent from Figs. 1 — 4 that only for phosphorus and chlorine are the shapes similar to one another. In the case of sulfur (Fig. 3), a very sizeable secondary maximum is observed (around 115°) in the angular distribution; in the case of the silicon reaction (Fig. 1), the very small height of the main maximum compared to the isotropic part is striking. None of the known theories of the stripping reaction can explain such differences. One can, of course, assume that the nuclear interactions depend essentially on the nucleon configuration in the initial nucleus, but it is more natural to explain the observed differences in terms of the effect of the mechanism of compound nucleus formation. Such an explanation is the more plausible, since Lee and Schiffer[12] recently observed a resonance structure in the excitation curve of the $Ca^{40}(d, p)Ca^{41}$ reaction (in which they found 30 resonances in the range of deuteron energies from 1.50 to 4.22 Mev), and Nemilov and Litvin,[13] in their investigation of the ratio of yield of various proton groups from the reaction $Si^{28}(d, p)Si^{29}$ at fixed angle for the emerging protons, found several sharp resonances separated by about 0.5 Mev. One can try to check whether the resonances found by Nemilov and Litvin are actually caused by the mechanism of formation and breakup of the compound nucleus. The basis of such a test is the fact that, according to stripping theory,* the ratio of the differential cross sections for two neighboring levels should be a function of the quantity

$$k = |\mathbf{k}_d - (M_i/M_f)\,\mathbf{k}_p|.$$

Here $\mathbf{k}_d$ and $\mathbf{k}_p$ are the wave vectors of the deuterons and proton in the center of mass system, $M_i$ and $M_f$ are the masses of the initial and final nucleus. The magnitude of k depends on the angle of emergence of the proton and the energy of the

*This holds for the Butler theory and apparently remains approximately true for more complicated theories.

deuteron. Therefore, in the stripping theory there should be a unique relation between the shape of the angular distribution and the shape of the differential excitation curve. This is, of course, not the case for the reaction mechanism associated with compound nucleus formation. The solid curve in Fig. 9 shows the curve obtained by Nemilov and Litvin for the ratio of the yields of the $p_1$ and $p_0$ proton groups at an angle of 109° for the emerging protons, as a function of deuteron energy. The dashed curve in the same figure shows the same ratio as found from our measured angular distributions for the $p_1$ and $p_0$ proton groups from the $Si^{28}(d, p)Si^{29}$ reaction (Figs. 1 and 5). The shift from angles of emergence of the protons to deuteron energies was made on the assumption that the reaction goes only via stripping.

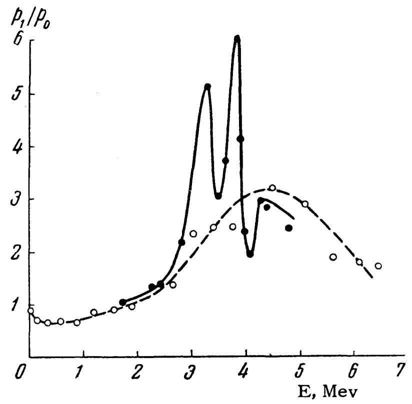


FIG. 9. Energy dependence of the ratio of yields of proton groups $p_1$ and $p_0$, at a proton angle of 109°, from the $Si^{28}$ (d, p) $Si^{29}$ reaction. The points are the data of Nemilov and Litvin;[13] the open circles are the results obtained from the angular distributions (Figs. 1 and 5).

Comparison of the two curves of Fig. 9 shows that the sharp peaks cannot be due to the stripping process, since the curve computed from the angular distributions shows no such narrow maxima. Consequently the different shapes of the angular distributions for the cases in which the neutron is captured into a $1d_{3/2}$ state are apparently explained by the effect of the mechanism of compound nucleus formation with subsequent emergence of the proton, in which a change in the interference term obviously plays the principal role. From this point of view, it is easy to explain the marked change in the shape of the angular distribution from the sulfur reaction for decreasing deuteron energy (Figs. 7 and 8, and also Fig. 1 of Ref. 1).

So for target nuclei with charge $Z \leq 20$ and deuteron energies less than or equal to the height of the Coulomb barrier, the angular distributions of protons from (d, p) reactions as computed from the Butler formula may be strongly distorted, first because of nuclear and Coulomb interaction between the particles participating in the reaction and, secondly, because of interference between the stripping process and the process which occurs via compound nucleus formation. The first cause leads to a shift of the main maximum in the angular distribution toward smaller angles, and this shift may be very large [for example, for the case of the $Ca^{40}(d, p)Ca^{41}$ reaction with 2.2-Mev deuterons, cf. Ref. 7]. The second cause apparently produces an increase in the isotropic part of the angular distribution and also affects the relative size of the main and secondary maxima.

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