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THE REACTION $C^{12}(\alpha, p_0)N^{15}$ *AT 16 TO 26 MeV* α*-PARTICLE ENERGY*

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The excitation curves and angular distributions of protons from the $C^{12}(\alpha, p_0)N^{15}$ reaction have been studied experimentally in the range of α-particle energies from 16 to 26 MeV. The excitation curves have a resonance structure which apparently is related to the mechanism of compound nucleus formation. The angular distributions depend strongly on the α-particle energies. At almost all energies a peak is observed in the differential cross section at large angles. The shape of the angular distributions indicates that direct processes make an appreciable contribution to the reaction mechanism. However, the present theory of direct reactions cannot explain the observed energy dependence of the angular distributions.

IN the last few years a considerable number of investigations have been carried out [1-7] on the reaction $C^{12}(\alpha, p_0)N^{15}$ with formation of the final nucleus in the ground state. In these studies angular distributions of the protons have been measured at the following α-particle energies: 14 [1], 16-19 [2], 20-22 [3,4], 25-38.6 [5], and 42 MeV [6].

The angular distributions agree qualitatively with the stripping and replacement (knock-out) theories [8] only at energies above 33 MeV. At lower energies the reaction is characterized by presence of a sharply expressed peak in the differential cross section at large angles and also by a strong dependence of the proton angular distributions on the α-particle energy. This fact makes it necessary to obtain systematic data on the proton angular distributions from the reaction $C^{12}(\alpha, p_0)N^{15}$ at different α-particle energies.

In the present work we have carried out a detailed study of the excitation functions and angular distributions of protons formed in the $C^{12}(\alpha, p_0)N^{15}$ reaction for α-particle energies from 16 to 26 MeV.[1)]

EXPERIMENTAL TECHNIQUE

The experiments were performed with an external focused beam of α particles accelerated to 26 MeV in the 120 cm cyclotron of the Nuclear Physics Institute at Moscow State University. Variation of the bombarding particle energy was achieved by slowing down the α particles in aluminum foils whose thickness could be changed in steps of 5.65 μ. This corresponds to energy changes of 0.29, 0.35, and 0.41 MeV for α particles of 26, 20, and 15 MeV, respectively. To in-

1) Preliminary results of the study of this reaction have been published previously.[7]

crease the intensity of the beam of particles incident on the target, short-focal-length magnetic lenses were placed between the foils and the target to focus onto the target particles scattered in the aluminum foils. The energy of the initial particles was determined from the secondary proton range with an accuracy of ±0.2 MeV (the function $R_p(E)$ was taken from Sternheimer [9]). The accuracy of the determination of the relative energy of the particles bombarding the target was roughly 0.05 MeV.

The protons produced in the reaction were counted by a telescope of four proportional counters.[10] In the angular distribution and excitation function measurements the background usually did not exceed 1—2%. The regions where the differential cross section is less than 0.1 mb/sr are an exception. In these regions the background was as high as 20—40%.

The target was a lavsan (mylar) polyester film ($C_{10}H_8O_4$) of thickness 10μ. If we take into account that the target was placed at an angle of 45° to the beam, this thickness corresponds to energy losses of 0.4 and 0.6 MeV for α particles of 26 and 15 MeV, respectively. The α-particle energy spread due to slowing down in the foils did not exceed the energy loss in the target.

Absolute cross section values were not specifically determined in this work but were obtained by comparison of the angular distributions with the data of other authors.[2,4,5]

EXPERIMENTAL RESULTS

The excitation functions of the reaction $C^{12}(\alpha, p_0)N^{15}$ with formation of the final nucleus in the ground state were measured for eleven different proton emission angles (Fig. 1). The measurements were made in the α-particle energy region from 15.5 to 26.3 MeV for all the angles except $\theta_{c.m.}$ = 19° and 30°, for which measurements were made down to energies of 21.5 and 18.5 MeV. At lower energies it was impossible to separate the group of protons being studied from the recoil protons produced in the polyester target.

Figure 2 shows the dependence of the differential cross section on the proton emission angle for different α-particle energies, as obtained from the measured excitation functions. To determine the total cross sections we integrated the angular distributions for 31 values of α-particle energy. For energies below 21.5 MeV in the small-angle region at which measurements were not made, we used the data of other authors.[2,3] Figure 3 shows the dependence of the total cross section on the α-particle energy, and also the

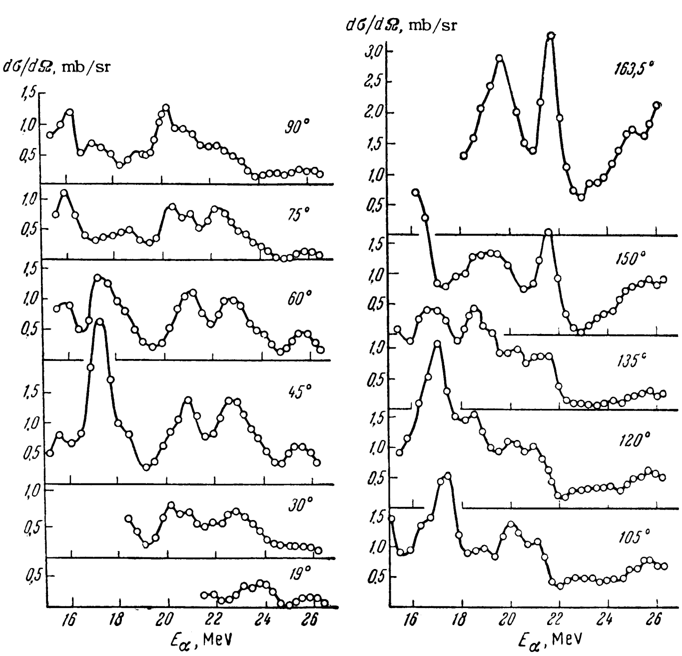

FIG. 1. Excitation functions for the reaction $C^{12}(\alpha, p_0)N^{15}$ for different angles θ_{cm} (in the center-of-mass system). The statistical errors and the errors associated with the background do not exceed the size of the points.

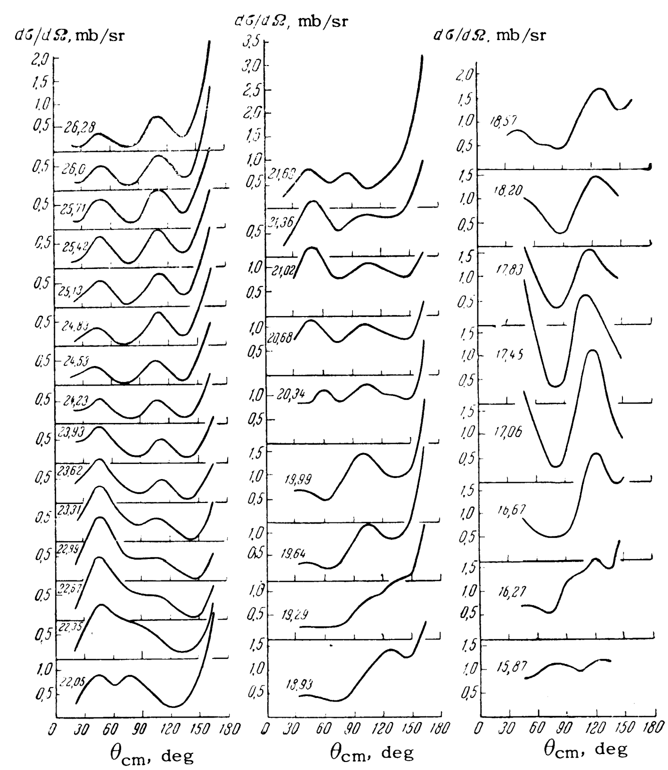

FIG. 2. Variation of the differential cross section with angle θ_{cm} for different energies E_α (in the laboratory system) indicated near the corresponding curves.

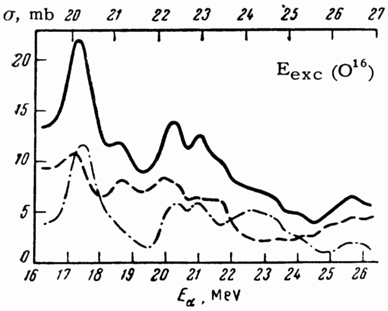

FIG. 3. Total cross section (solid curve) and cross sections for the forward (dot-dash curve) and backward (dashed curve) hemisphere, as a function of energy E_α.

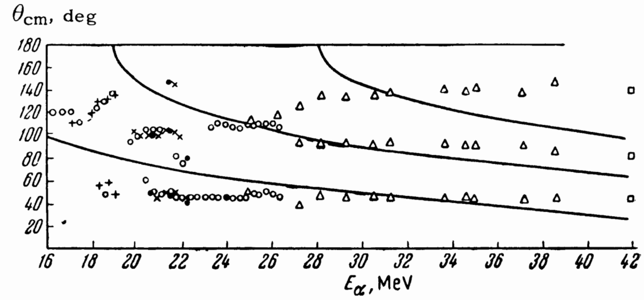

FIG. 4. Position of the peaks in the proton angular distributions as a function of α-particle energy: o – present work, + – data of Priest et al.,[12] • – data of Kondo et al.,[3] × – data of Yamazaki et al.,[4] △ – data of Nonaka et al.,[5] □ – data of Lieber et al.[6] The solid lines correspond to the peak locations calculated from the stripping theory for R = 6.5 F.

cross sections calculated separately for the forward and backward hemispheres.

Our results are in good agreement with the angular distributions obtained by Priest et al.,[2] Yamazaki et al.,[4] and Nonaka et al.[5] and with the excitation function measured by Priest et al.[2] for $\theta_{lab} = 31.8°$ (in comparison with the curve for $\theta_{c.m.} = 45°$). In those energy regions where a comparison can be made, the behavior of the total cross section as a function of energy also is in satisfactory agreement with the data of other authors.[2,4]

DISCUSSION OF RESULTS

Our results together with those of Nonaka et al.[1] and Lieber et al.[6] permit tracing the energy dependence of the proton angular distributions from the $C^{12}(\alpha, p_0)N^{15}$ reaction from 16 to 42 MeV. In analyzing these results our attention is drawn to the diffraction nature of the angular distributions and the resonance structure of the excitation functions.

Let us discuss in more detail the angular distributions obtained and their variation with α-particle energy (Fig. 2). First of all we must mention the presence of the rise in the differential cross section at small angles for $E_\alpha < 18$ MeV and at large angles for $E_\alpha > 18$ MeV. The location of the peaks for other bombarding particle energy values from 16 to 42 MeV is shown in Fig. 4. The peak at about 45° is observed at practically all energies above 18 MeV. The peak at 100—110° present in the angular distributions for E_α from 19.5 to 26 MeV splits at an energy of 26—27 MeV into two peaks located at about 90° and 140°, whose position does not change up to 42 MeV.

The regularity in the location of the peaks in the angular distributions indicates that direct processes make an important contribution to the reaction mechanism. However, the theory of direct nuclear interactions with plane waves [8] cannot explain the behavior of the differential cross section even at small angles. Figure 4 also shows the position of the peaks calculated on the basis of stripping theory for R = 6.5 F. It is obvious that for a constant value of the parameter R the position of the peaks over a wide energy range cannot be reconciled with experiment. For example, for the peak to remain at 45°, the parameter must be increased from 5.6 to 8.2 F as E_α is decreased from 42 to 19 MeV.

For α-particle energies greater than 28 MeV the height of the peaks in the angular distribution decreases with increasing angle,[5,6] in agreement with both the stripping and knock-out theories. At lower energies this regularity disappears, and in a number of cases an increase in the height of the peaks is even observed with increasing angle (for example, in the region $E_\alpha = 24$—26 MeV). This angular distribution shape cannot be explained by the stripping or replacement theories with plane waves.

As we have already pointed out, a peak in the differential cross section in the neighborhood of 180° is characteristic of the $C^{12}(\alpha, p_0)N^{15}$ reaction. Of the direct processes usually considered, only heavy-particle stripping in the plane-wave approximation leads to a rise of the differential cross section in the large-angle region, and this only to a curve flatter than that found experimentally. Honda et al.[11,12] have made detailed calculations of this process for the $C^{12}(\alpha, p_0)N^{15}$ reaction and concluded that the behavior of the differential cross section in the large-angle region for various energies can be explained by heavy-particle stripping. However, the systematic experimental data obtained in the present work do not confirm this conclusion. In fact, the excitation

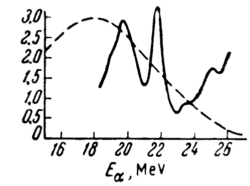

FIG. 5. Excitation functions measured experimentally and calculated from the heavy-particle stripping theory[11] for the reaction $C^{12}(\alpha, p_0)N^{15}$ for $\theta_{cm} = 163.5°$, The calculation was made for $l_\alpha = 2$, $l_p = 1$, $R_\alpha = 5.2$ F, $R_p = 4.0$ F, $\{\theta_{l_p j_p} O_\alpha \Theta_{l_\alpha}\}^2 = 2.1$ (notations of Honda and Ui[11]).

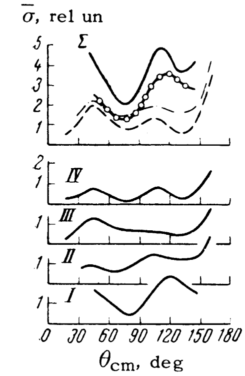

FIG. 6. Angular distributions of secondary protons, averaged over intervals of width 2.5, 5, and 10 MeV: I – for the interval 16.25 to 18.75 MeV; II – 18.75 to 21.5 MeV; III – 21.5 to 23.75 MeV; IV – 23.75 to 26.25 MeV. I + II – solid curve with points; II + III – dot-dash curve; III + IV – dashed curve; I + II + III + IV = Σ – solid curve.

functions for $\theta_{c.m.} = 163.5°$ measured by us and calculated from the formulas of Honda et al. with parameters taken from their work do not agree, even if we disregard the narrow peaks in the excitation function (Fig. 5). To explain the experimental angular distributions it is necessary to assume that the parameters R_t, R_α, R_p, and the relative contributions of stripping and heavy-particle stripping depend on energy.

In addition to heavy-particle stripping, there are other possible explanations for the rise in the differential cross section in the large-angle region. We may take into account the distortions in stripping [13] and heavy-particle stripping,[14] use p and d phases in αp scattering in the replacement theory,[15] or consider more complex direct processes described by Feynman diagrams.[16] As an example we can cite the direct process with a local interaction,[17] which is described by a four-vertex Feynman diagram.

Let us now consider the excitation functions. The energy dependence of the total and differential cross sections has a clearly expressed resonance nature, the total cross section decreasing with increasing α-particle energy (Figs. 1 and 3). It is natural to assume that the resonance structure is connected with formation of an intermediate nucleus.

If we assume that the principal mechanism of the reaction is the formation of a compound nucleus and that a number of states correspond to each resonance, then, according to Ericson,[18] the angular distributions averaged over a sufficiently wide energy interval (considerably exceeding the width of the "fluctuations") should be symmetrical with respect to 90°. However, this symmetry is not observed for the $C^{12}(\alpha, p_0)N^{15}$ reaction (Fig. 6). In the averaged angular distributions there is also a peak at large angles, which is larger than the peak in the forward hemisphere.

In order to explain the resonance structure of the excitation curves and the strong energy dependence of the angular distributions, it is sufficient to assume that each peak in the excitation function corresponds to one or two states of the intermediate nucleus O^{16} with a different parity. Blieden [19] showed that if two levels of the O^{16} nucleus contribute to the mechanism of forming the compound nucleus, the difference in the angular distributions obtained experimentally and predicted by the stripping theory can be explained.[2)] However, since the rise of the differential cross section on approaching 180° is characteristic of almost the whole energy range studied in the present work, it is improbable that this rise is due only to interference.

Figure 7 shows the level scheme of O^{16} for excitation energies from 19 to 27 MeV, constructed from the data on total cross sections of reactions in which one of the channels is $C^{12} + \alpha$. (In such reactions levels can be excited with quantum numbers 0^+, 1^-, 2^+, 3^-, etc.) The position of the levels was determined from the assumption that each peak in the excitation curve corresponds to one level in the intermediate nucleus. The level locations obtained from different reactions are in good agreement. This indicates that the resonance structure of the excitation curves is related to the mechanism of intermediate nucleus formation.

It must be noted that comparison of the level locations based on the peaks in the excitation curves for the differential cross sections at specific proton emission angles rather than those for the total cross section can introduce errors, since the position of the peaks depends on the angle of observation even for a single reaction. For example, for the reaction $C^{12}(\alpha, p_0)N^{15}$ (Fig. 1), only the

2)Use of the Blieden formula for the angular distribution, which takes into account interference of two states, is accurate for (α, p) reactions if the final nucleus has quantum numbers $\frac{1}{2}^+$. For the reaction $C^{12}(\alpha, p_0)N^{15}$, where the parity of the final state is negative, the formula will contain not three but seven parameters.

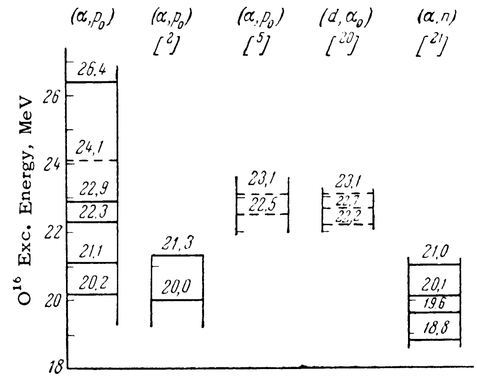

FIG. 7. Level scheme of the intermediate nucleus O^{16} in the excitation region 19 – 27 MeV, obtained from total cross section data of the present work and from other authors. The energy regions investigated are indicated by the vertical lines; the dashed lines indicate levels which are not clearly expressed.

position of the 21.0 and 25.6 MeV peaks (corresponding to excitation energies of 22.9 and 26.4 MeV) is almost independent of angle. It is possible that the constancy in the position of these peaks is an indication that only one level of the intermediate nucleus contributes appreciably to the reaction. In particular, we would expect that the level corresponding to an α-particle energy of 25.6 MeV has quantum numbers 0^+, since the angular distribution changes hardly at all in the vicinity of this state.

CONCLUSIONS

An analysis of the experimental data obtained in the present work shows that in the α-particle energy region investigated three processes contribute appreciably to the mechanism of the $C^{12}(\alpha, p_0)N^{15}$ reaction: 1) the stripping or knockout process; 2) the direct process, which is characterized by peaks in the large-angle region; 3) the process of compound nucleus formation. The diffraction nature of the angular distributions can be explained by the direct processes, and the resonance nature of the excitation function by compound nucleus formation. It must be emphasized that the features noted are characteristic not only of the $C^{12}(\alpha, p_0)N^{15}$ reaction but are observed also for other (α, p) and (p, α) reactions in the same energy region, for example, for the reaction $F^{19}(p, \alpha_0)O^{16}$, which has been investigated in detail by Warsh, Temmer, and Blieden.[22]

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Note added in proof (December 28, 1964). Mikumo[23] has measured the total cross section for the reaction $N^{15}(p, \alpha_0)C^{12}$ as a function of proton energy from 7 to 15 MeV (O^{16} excitation energy from 18.5 to 26.3 MeV). These data are in good agreement with the results of the present work (see Fig. 3).

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