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$C^{13}(He^3,\alpha)C^{12}$ Angular Distributions at 4.5 Mev

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The angular distributions of the α-particle groups from the $C^{13}(He^3,\alpha)C^{12}$ reaction which leave the C^{12} nuclei in the ground and first excited states have been measured at a bombarding energy of 4.5 Mev. The angular distributions have been fitted with Legendre polynomial expansions. In order to fit the data within the experimental uncertainties it was necessary to include polynomials up to the eighth degree in these expansions. It appears unlikely that the angular distributions can be accounted for on the basis of compound-nucleus type of reaction. Although the usual concept of a pickup type reaction also encounters difficulties in attempting to account for this reaction, theoretical calculations based on this type of process have been compared with the experimental results. Other possible mechanisms by which this reaction may take place are suggested.

RECENT measurements[1] of the differential cross sections for the $C^{13}(He^3,\alpha)C^{12}$ reaction at a bombarding energy of 2.00 Mev have indicated that the yields of α-particle groups exhibit a rather complicated behavior as a function of angle. Since the effect of the Coulomb interaction on any type of direct process is expected to be rather large at this bombarding energy, it was decided to measure the angular distributions of these α particles at a higher bombarding energy in order to facilitate the determination of the mechanism by which this reaction proceeds.

The Naval Research Laboratory 5-Mv Van de Graaff accelerator was used to accelerate singly-ionized He^3 particles to an energy of 4.5 Mev. The remaining experimental details are identical to those in the preceding paper[1] except that the absolute cross sections were not measured.

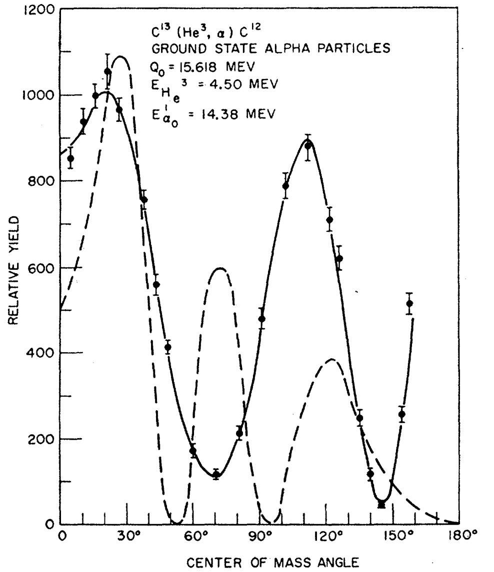

FIG. 1. The angular distributions for the α-particle from the $C^{13}(He^3,\alpha)C^{12}$ reaction which leave C^{12} in the ground state. Q_0 is the ground-state Q value for this reaction, E_{He^3} is the bombarding energy, and E_{α_0}' is the energy of the ground-state α-particles in the center-of-mass system.

The angular distributions for the α particles from the $C^{13}(He^3,\alpha)C^{12}$ reaction which leave C^{12} in the ground state and first excited state are given in Fig. 1 and Fig. 2. The uncertainties indicated in these figures include the statistical uncertainty of the number of tracks counted, the uncertainty in the measurement of the solid angles of the cameras, and an estimated counting uncertainty of one percent.

The solid lines in the above figures represent the least-squares Legendre polynomial fits to these data. In order to fit these data within the experimental uncertainties, it was necessary to include polynomials of the eighth degree in these expansions. The coefficients of the Legendre polynomials in these expansions are tabulated in Table I. The constants C in this table are proportional to the total cross sections and may be used to determine the relative yields of the two groups of α particles.

If the angular distributions of the α particles obtained at a bombarding energy of 4.5 Mev are compared with those observed at 2.00 Mev,[1] an interesting similarity is observed, particularly for the ground-state α-particle group. This similarity suggests that the angular distributions at 4.5 Mev may possibly result from a gradual evolution of the angular distributions at 2.00 Mev. Preliminary measurements of the yield curves for the ground-state α-particle group at 7, 30, 60, and 120 degrees in the region of bombarding energy in extending from 1.8 to 3.8 Mev indicate that the angular distribution of this group changes slowly with energy. The yields at all angles increase rapidly with energy (about a factor of 10 in this energy interval); however, these yield curves appear to exhibit several points of inflection in this region of energy. It is not yet possible to determine whether these points of inflection are due to some sort of resonance phenomenon or to changes in the angular distributions.

It appears that it would be difficult to account for the experimental observations of the $C^{13}(He^3,\alpha)C^{12}$ reactions solely on the basis of a compound nucleus model for the interaction. If a mechanism could be

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[1] H. D. Holmgren, preceding paper [Phys. Rev. 106, 100 (1957)].

TABLE I. Coefficients of Legendre polynomial expansion of differential cross section for each group of α-particles in the reaction $C^{13}(He^3,\alpha)C^{12}\cdot E_{He^3}=4.5$ Mev. $\sigma(\theta)=C\{P_0+a_1P_1+\cdots\}$. C is proportional to the total cross section.

	C	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8
α_0	504	+0.04	+0.36	+1.01	+0.55	−1.28	+0.49	−0.41	−0.03
α_1	855	−0.43	+0.59	+0.14	−0.41	−0.26	+0.26	+0.17	+0.07

devised on the basis of the compound nucleus model to produce the observed angular distributions at 2.00 and 4.5 Mev, it is not easy to understand how such a mechanism could yield theoretical angular distributions which would change slowly with energy. It is likely that any mechanism which would yield angular distributions as complex as those observed would depend mostly on the properties of only a few levels rather than on collective properties of many levels and thus would be expected to be strongly energy dependent.

One of the simplest direct-process models for this reaction is one in which the loosely bound neutron in the C^{13} nucleus is picked up by the He^3 particle. The dashed line in Fig. 1 represents a naive theoretical angular distribution calculated on the basis of this type of process. These calculations are similar to those of Newns[2] for (d,t) reactions. If one employs a wave function of the type used by Rarita and Present[3] for the α particle,

$$\psi_\alpha = N\exp(-\beta^2 \textstyle\sum_{ij} R_{ij}^2),$$

the angular distribution due to a single angular momentum L may be expressed as

$$\phi(\theta)=M_L\exp\left(\frac{-k_\alpha^2}{6\beta^2}\right)\left[\frac{\partial j_L(Kr)}{\partial r}-\frac{j_L(Kr)}{h_L^1(kr)}\frac{h_L^1(kr)}{\partial r}\right]_{R_0}^2,$$

where

$$\bar{k}_\alpha=\bar{k}_3-\tfrac{3}{4}\bar{k}_4,$$

$$\bar{K}=\bar{k}_4-(M_I/M_f)\bar{k}_3,$$

and

$$k=i\left[\frac{2}{\hbar^2}\left(\frac{M_IM_d}{M_f}\right)(Q+\epsilon_3)\right]^{\frac{1}{2}},$$

k_3 and k_4 being the wave numbers of the He^3-particle and the α particles in the center-of-mass system. R_0 is the usual radius of interaction in this type of reaction and may be expected to be somewhat smaller than in the case of deuteron reaction due to the larger binding energy per nucleon in the α particle. β is a quantity which is related to the radius of the alpha particle. M_I, M_f, and M_d are the masses of the target nucleus, residual nucleus, and deuteron. ϵ_3 and Q are the binding energies of a proton in He^3 and Q value for the reaction. The M_L factor contains various terms which are not functions of the angle. Among these terms are those quantities which depend upon the target and final nuclei wave functions.

When one uses the above expression for the angular distribution, it is not possible to match the positions of all the experimental maxima and minima by varying the parameter R_0. A value of $R_0=5.3\times10^{-13}$ cm seems to produce about as good a fit as possible, giving more weight to the low-angle maximum and minimum. This failure of the theoretical expression may not be very serious, since the inclusion of Coulomb interactions and the nuclear interaction of the outgoing particle would shift the position of these maxima and minima. A far more important failure of this expression is the small yield at large angles which is due to a fundamental limitation of this model. This type of direct reaction requires that the neutron, which participates in the interaction, transfer the amount of momentum from the target nucleus to the incoming He^3 particle necessary to change this He^3 particle into the observed α particle. Since the Q value for the ground-state transition in this reaction is rather large ($Q_0=15.618$ Mev), the momentum transferred for the α particles observed at high angles is very large. At a bombarding energy of 4.5 Mev, for the ground-state α particles emitted at 180 degrees, the momentum transferred corresponds to a neutron with a kinetic energy of about 120 Mev in the center-of-mass system or an internal momentum in the α-particle equivalent to a kinetic energy of 80 Mev. The existence of such large values of momentum seems quite improbable for any reasonable α-particle wave

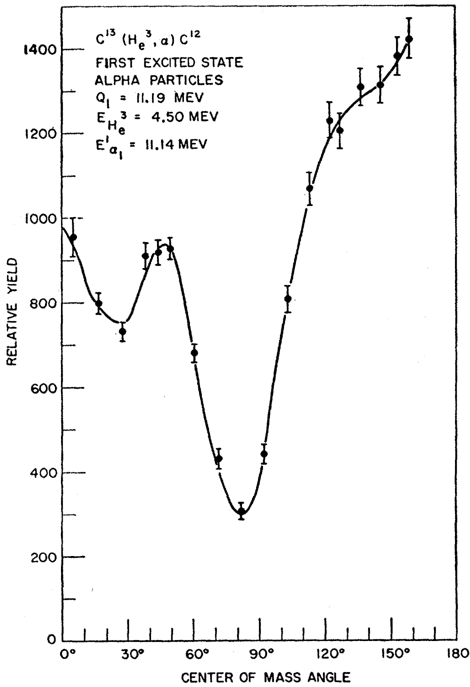

FIG. 2. The differential cross sections for the first excited state α particles from the $C^{13}(He^3,\alpha)C^{12}$ reaction. Q_1 is the Q value for this reaction when C^{12} is left in the first excited state, E_{He^3} is the bombarding energy, and E_{α_1}' is the energy of the first excited state α particles in the center-of-mass system.

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[2] H. C. Newns, Proc. Phys. Soc. (London) A65, 916 (1952).

[3] W. Rarita and R. D. Present, Phys. Rev. 51, 788 (1937).

function. Even by choosing an extremely large value of $\beta(\beta=1\times10^{13}\ \mathrm{cm}^{-1})$ the yield at high angles is far too small. By including the Coulomb interaction into the theory it may be possible to increase the theoretical yields at high angles; however, it does not seem likely that this effect would be sufficient to account for the observed yields at these angles. In addition to the problem of the momentum transfer, the probability of the α particle existing as a He^3 particle plus a neutron is expected to be very small due to the large binding energy of the α particle.

Other types of direct processes have been suggested for this reaction but as yet no theoretical calculations have been performed employing these models. One of these processes may be thought of as stripping an α particle off the initial C^{13} nucleus. Another process, which is somewhat similar, is one in which the He^3 particle collides with an α-particle subunit of the C^{13} nucleus. The α particle is then ejected and the He^3 particle is scattered into the residual nucleus. This process is similar to the direct surface interactions suggested by Austern *et al.*[4]; however, the simple expression for the angular distribution, $|j_L(KR)^2|$, predicted by this theory is not able to reproduce the observed positions of the maxima and minima. This expression also is unable to account for the measured relative intensities of the maxima.

The rather rapid increase in yield with bombarding energy may seem to favor the compound nucleus mechanism; however, for this reaction it is possible that the yield due to a direct process would also increase rapidly with bombarding energy. As the bombarding energy is increased, the momentum transferred by the neutron in a pickup type of reaction decreases for α particles emitted in the forward direction; thus, if the momentum distribution of the neutron in the α particle is changing rapidly in this region, the yield in the forward direction would also be expected to change rapidly with energy. This does not account for the increase in yield at large angles; however, if the reaction proceeds by another type of direct process, the yield at large angles may also change rapidly with energy due to the effect of the increased center-of-mass motion reducing the required amount of internal momentum of the interacting particle at the time of collision. In addition, the Coulomb interaction undoubtedly affects the yield of a direct process in this region of bombarding energy.

On the basis of almost any type of direct process, considerations of the momentum transfer for positive Q reactions indicate that the yield of α particles which leave the C^{12} nucleus in an excited state should be larger than the yield of those which leave the C^{12} nucleus in the ground state, since transitions to the excited state require less transfer of momentum. For a pickup process, however, the M_L factor in the cross section probably decreases rapidly with the energy of excitation of the level, because it must contain a term which depends upon the amplitude of the excited state wave function of the C^{12} nucleus contained in the ground-state wave function of the C^{13} nucleus. This limitation may be less important in other types of direct processes. In any case, the M_L factors or their analogs in other direct processes are probably not strongly dependent upon the bombarding energy; thus, the dependence of the ratio of the yields on the bombarding energy is determined mainly by the factors which depend upon the momentum transfer. Since the rate of decrease of momentum transfer in the direction of the theoretical maximum yield is smaller for an excited state transition than for the ground state transition, the ratio of the yields should be expected to decrease with increasing bombarding energy. Although the experimental observations exist for only the first excited state and the ground-state α-particle groups, they are more consistent with the predictions of a direct process theory than with those determined from a compound nucleus model on the basis of barrier penetrability arguments.

On the basis of the present experimental observations and the existing theories, it is not possible to determine the exact nature of the interaction; however, it is hoped that improved experimental techniques and theoretical developments will lead to the determination of the mechanism of this interaction.

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[4] Austern, Butler, and McManus, Phys. Rev. **92**, 350 (1953).