Single-Nucleon Transfer Reactions of F^{19}, O^{16}, N^{14}, and C^{12}†

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(Received August 30, 1960)

Results on the angular distribution of single-neutron stripping products are presented. Beams of F^{19}, O^{16}, N^{14}, and C^{12} having an energy of 10 Mev per nucleon, and beams of O^{16} at lower energies were used in conjunction with a rhodium target. The relative contribution of tunneling and grazing transfer processes is discussed. The form of the angular distributions of products originating from the tunneling mechanism is very similar in all systems, although the magnitude of the F^{19} cross section is unexpectedly large. The cutoff distance for closest approach in a tunneling event is found to correspond to the cutoff for elastic scattering.

IN the course of studies of grazing reactions of complex nuclei, as reported in the preceding paper,[1] data were obtained on single-nucleon as well as multinucleon transfer processes. Since single-nucleon transfer is currently of interest, particularly in connection with the nucleon tunneling mechanism,[2,3] this information is briefly presented and discussed here.

Results obtained include angular distributions of products resulting from the loss of a single neutron from C^{12}, N^{14}, O^{16}, and F^{19}. Bombarding energies were varied from 80 Mev to 160 Mev for O^{16} and were 10 Mev per mass unit for the other projectiles. A 7.35-mg/cm² rhodium target was used in all experiments. The experimental arrangement and method, and the accuracy obtainable have been described in the preceding paper.[1]

The angular distributions of the products—C^{11} from C^{12}, O^{15} from O^{16}, etc.—are plotted as differential cross sections in Figs. 1, 2. The peak at small angles in all the distributions corresponds to the strong forward peak observed for multinucleon transfer products.[1] It may, therefore, be taken to result from grazing collisions (as discussed in the preceding paper) in which only a single neutron is transferred. The peak at larger angles is similar to that obtained in previous work on single-nucleon transfer from N^{14}.[2,4] It has been

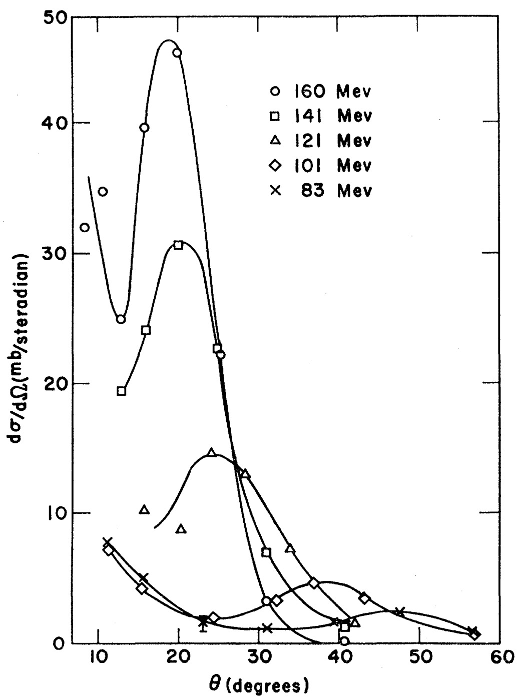

FIG. 1. Differential cross sections with respect to the solid angle ($d\sigma/d\Omega$) at various bombarding energies for the loss of a single neutron from an O^{16} projectile on a Rh target.

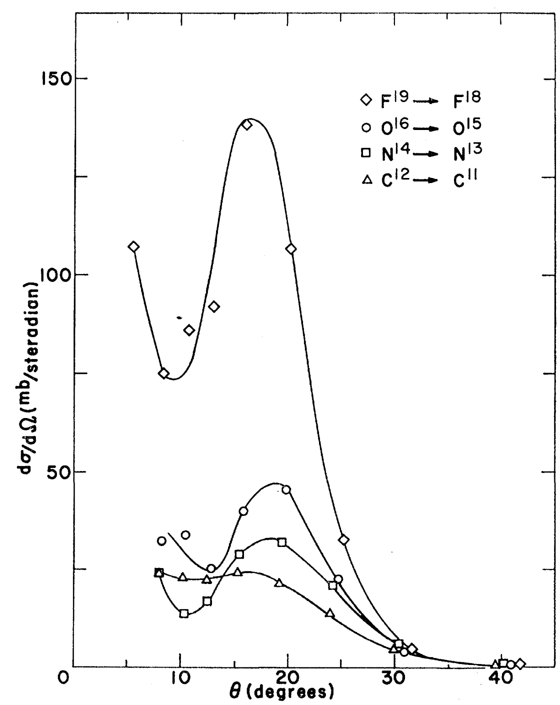

FIG. 2. Differential cross sections with respect to the solid angle ($d\sigma/d\Omega$) for the loss of a single neutron from several beams with bombarding energies of 10 Mev per mass unit on a Rh target.

† Contribution Number 1639 of Sterling Chemistry Laboratory.
[1] R. Kaufmann and R. Wolfgang, preceding paper [Phys. Rev. **121**, 192 (1961)].
[2] J. A. McIntyre, T. L. Watts, and F. C. Jobes, Phys. Rev. **119**, 1331 (1960).
[3] G. Breit and M. E. Ebel, Phys. Rev. **103**, 679 (1956).
[4] H. L. Reynolds and A. Zucker, Phys. Rev. **101**, 166 (1956);

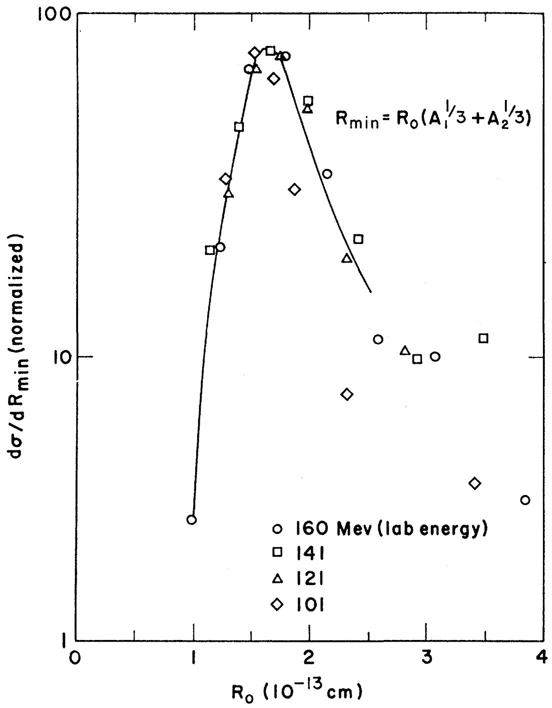

FIG. 3. Differential cross sections with respect to the distance of closest approach ($d\sigma/dR_{\min}$) are plotted as a function of the separation parameter R_0 for the system O^{16}+Rh. All curves are normalized to peak at the same height.

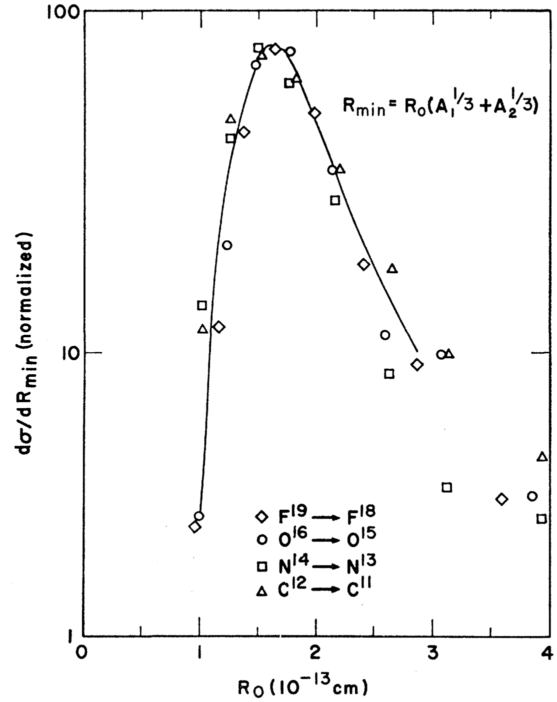

FIG. 4. Differential cross sections with respect to the distance of closest approach ($d\sigma/dR_{\min}$) are plotted as a function of the separation parameter R_0. Several beams were used at bombarding energies of 10 Mev per mass unit. All curves are normalized to peak at the same height.

ascribed to tunneling[3] or virtual state excitation.[5] Mechanisms of this nature, in which the Coulomb barrier is not penetrated, may be termed barrier processes. They predict the observed increase in peak angle as the bombarding energy is decreased (see Fig. 1).

The most conspicuous feature of Fig. 2 is the high cross section for the formation of F^{18} from F^{19} (total cross sections given in Table II of the preceding paper). This is not well understood. It may well be connected with the binding energy of the last neutron, which is lower for F^{19} than it is for O^{16} or C^{12}. In that case, however, the low yield of N^{13} becomes anomalous, since the last neutron is bound about equally strongly in F^{19} and N^{14}. Possibly the yield of N^{13} is diminished because the excited levels of this species are unstable with respect to particle emission. The fact that F^{19} has two rather loosely bound neutrons, as opposed to N^{14} with only one, may also be important.

It is difficult to determine the relative importance of tunneling and grazing contact mechanisms from the differential cross sections given in Figs. 1 and 2, since the area under the curves is not proportional to the cross section. A more useful representation of the data is to give cross sections as a function of the distance of closest approach. If it is assumed that the projectiles follow Rutherford trajectories, products detected at a scattering angle, θ, will have a minimum center-to-center separation from the target, $R_{\min}$, as given by the Rutherford scattering formula:

$$R_{\min}=\frac{Z_1Z_2e^2}{2T_{\text{c.m.}}}[1+\csc(\theta/2)]. \tag{1}$$

The data in Figs. 1 and 2 may then be transformed as suggested by McIntyre[2]:

$$\frac{d\sigma}{dR_{\min}}=\frac{d\sigma}{d\Omega}\frac{d\Omega}{d\theta}\frac{d\theta}{dR_{\min}}, \tag{2}$$

where Ω represents the solid angle. The factor $(d\sigma/dR_{\min})$ is obtained by differentiation of Eq. (1). $R_{\min}$ may be expressed in terms of the mass numbers of the projectile and target, A_1 and A_2, and the reduced reaction radius, R_0:

$$R_{\min}=R_0(A_1^{\frac{1}{3}}+A_2^{\frac{1}{3}}). \tag{3}$$

Plots of $(d\sigma/dR_{\min})$ vs R_0 are given in Figs. 3 and 4. All curves are normalized to the same maximum value.

The relative importance of the tunneling and grazing contact mechanisms may now be examined. Particles which do not follow a Rutherford trajectory give fictitious values of R_0. Thus, products of grazing reactions, because of their forward angular distributions, yield

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[5] G. Breit and M. E. Ebel, Phys. Rev. **104**, 1030 (1956).

large apparent values of R_0, although, of course, their actual approach is so close that the nuclear surfaces overlap. An appreciable part of the cross sections for very large apparent distances of closest approach are thus due to grazing reactions.

As the energy is decreased to near 100 Mev, the cross section at large apparent R_0 values, as shown for O^{16} in Fig. 3, decreases very rapidly. Despite large experimental errors in this region, the effect seems to be real. A similar decrease was first observed by McIntyre, Watts, and Jobes[2] with the system N^{14} on Au. This effect is to be expected since, in the vicinity of 100 Mev, the cross section for grazing contact transfer drops off much more rapidly with decreasing energy than does that for tunneling.[1] A comparison of reactions of different projectiles (Fig. 4) shows a similar structure. Of the beams used, C^{12} has the highest last neutron binding energy, and so contact transfer should be most important relative to transfer by some barrier process such as tunneling or virtual state excitation. This shows up in Fig. 4 as a relatively large cross section at large R_0. The same effect causes a peak near zero degrees (or a shallow minimum between the two peaks) in Fig. 2. In order of binding energies of the last neutrons, the curves at large R_0 in Fig. 4 should be in the order C^{12} highest, then O^{16}, and then N^{14} and F^{19} about equal. This is roughly the order observed experimentally, though experimental accuracy is not sufficient to make this conclusion certain.

Apart from these effects at high R_0, due to grazing transfer, the shapes of the curves for all systems are remarkable for their similarity. Within experimental error, they are all superimposable. This indicates that, except for its magnitude, the barrier mechanism is virtually identical in all systems.

The curves for all particles having 10 Mev per nucleon (Fig. 4) show a maximum at $R_0=1.65$ f.[6] At energies near the Coulomb barrier the peak for O^{16} appears at slightly smaller values of R_0 (Fig. 3). This is in good agreement with the value of 1.55 ± 0.05 f obtained by McIntyre[2] for a N^{14} beam and a gold target at energies just above the Coulomb barrier. Such a decrease in R_0 at the Coulomb barrier may be ascribed to the decreasing importance of the grazing contact mechanism (which contributes mainly to the cross section at large apparent R_0) at low energies.

It is interesting to compare these results with data from elastic scattering experiments. Elastic scattering data are often plotted as the experimental cross section divided by the Rutherford cross section. The elastic scattering radius is then taken as the radius at which the experimental cross section drops to $\frac{1}{4}$ the Rutherford cross section. Hubbard and Merkel[7] have suggested that single-neutron transfer data may also be plotted as the ratio of experimental to theoretical cross sections, and the single-neutron transfer radius taken as the point at which this ratio is $\frac{1}{4}$. The theoretical single-nucleon tunneling cross section should increase approximately exponentially as the distance of closest approach decreases.[3] This behavior is observed experimentally at energies just above the Coulomb barrier in this work and in that of McIntyre.[2] (At higher energies this behavior is distorted somewhat due to the contribution from grazing contact transfer.) If the exponential part of the low-energy curve in Fig. 3 is extrapolated from large to small R_0, and this is taken as the theoretical estimate of the tunneling cross section, then the point at which the ratio of experimental to theoretical cross sections is $\frac{1}{4}$ corresponds to an R_0 of about 1.45 f. This is in agreement with the results of Hubbard and Merkel.[7] It is also about the same radius as is obtained from elastic scattering, data.[8]

This radius, $R_0=1.45$ f, represents the distance at which the incident particle comes so close to the target nucleus that the nuclear attractive potentials overlap. At this distance the tunneling mechanism becomes meaningless and other processes, particularly grazing transfer, become dominant. The fact that the cutoff distance as calculated using tunneling theory is the same as the similar cutoff for elastic scattering, provides support for the tunneling hypothesis. It also implies that transfer of a neutron through the Coulomb barrier causes no significant deviation from a trajectory determined by purely Coulombic interaction.

ACKNOWLEDGMENTS

The authors are most grateful to J. McIntyre, both for permitting the use of his counting and for his interest in the work. The help of the heavy ion accelerator staff in making these studies possible is gratefully acknowledged.

[6] Interpretation of the value of R_0 at the peak as the characteristic reduced radius for nucleon transfer is not unambiguous. Equation (1) is correct for an elastic scattering event, but if a neutron is transferred, the lighter residue will be deflected more by the Coulomb field of the target than the original projectile. If it is assumed that transfer takes place at the moment of closest approach and that the velocity of the projectile is not changed during the transfer, Eq. (1) may be improved by replacing $2T_{\text{c.m.}}$ by $T_{\text{c.m.}}+T_{\text{c.m.}}'$, where $T_{\text{c.m.}}$ is the kinetic energy of the incident projectile and $T_{\text{c.m.}}'$ is that of the observed residue, both in the center-of-mass system. This modification will shift the peaks of Figs. 3 and 4 by about 0.05 f to larger values of R_0. After this correction is made, the peak in Figs. 3 and 4 should represent the distance at which most reactions take place. To correct this to the distance at which transfer is most probable, the probability of finding a projectile at a given distance must be considered. This can be approximated by dividing the value of $(d\sigma/dR_{\text{min}})$ by R_{min} at each point (i.e., plot $d\sigma/R_{\text{min}}dR_{\text{min}}$ vs R_{min} or R_0). The result is a shift of the peak of the curves to smaller R_0 by about 0.05 f to 0.1 f. The corrections for the added deflection of the lighter product and for the probability of finding a particle at a given distance nearly cancel, and the most probable reduced radius for transfer is at $R_0=1.65$ f.

[7] E. L. Hubbard and G. Merkel, Proceedings of Second Conference on Reactions Between Complex Nuclei, Gatlinburg, Tennessee, 1960, edited by A. Zucker, E. C. Halbert, and F. T. Howard (John Wiley & Sons, New York, 1960), p. 25.

[8] J. A. McIntyre, S. D. Baker, and T. L. Watts, Phys. Rev. **116**, 1212 (1959). M. L. Halbert and A. Zucker, Nuclear Phys. (to be published).