branch of Cu^{62}. The multipolarity of the 42 keV has been assigned as $M1$ from the following considerations: The lifetime measurement of the 42-keV level gives a value which is close to theoretical $M1$ assignment. The 42-keV level is not fed directly in the Zn^{62} decay. This suggests that the spin assignment of 0 or 1 for this state may be excluded, and gives a probable spin value of 2 and even parity. No direct feeding to the excited state at 287 keV has been observed which is also in agreement with the intensity balance of the proposed decay scheme. This suggests that the spin parity assignments of 0+ and 1+ for this level may be excluded. The K-conversion coefficient of the 287-keV transition as measured by Antman *et al.*[4] shows a mixed $M1$-$E2$ transition. A pure $E2$ transition is, however, excluded. Accordingly, the 2+ assignment is the only remaining alternative for the 287-keV state.

In discussing their proposed decay scheme, Antman *et al.*[4] summarized all the information pertaining to each level which had been reported up to that time. The energies of their levels are roughly the same as ours, and the arguments they used to establish these levels are similar to the ones we gave in the section on γ-ray studies. The level at 682 keV is based on the singles as well as on the coincidence of the 245-keV with the 395-keV γ ray. This level has not been reported earlier.

The logft value for the 547-keV and 637-keV levels, as calculated from the intensity balance of the γ rays, is found to be 4.6, which indicates an allowed transition. Since Zn^{62} has a spin of 0 and even parity, the most probable spin of the 547- and 637-keV levels is 0 or 1 with even parity.

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Complete-Fusion Collisions in Heavy-Ion Reactions*

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Cross sections for compound-nucleus formation were experimentally measured for the $O^{16}+Al^{27}$, $Ne^{20}+Al^{27}$, and $O^{16}+Co^{59}$ systems by means of mica track detectors. It was shown that the cross section for compound-nucleus formation (complete fusion) above 100 MeV decreases with increasing energy of the bombarding particles, whereas the reaction cross sections increase slightly. An attempt was made to explain this behavior by considering a sharp cutoff in the spin distribution of the compound nuclei.

INTRODUCTION

It is well known[1,2] that not all of the nuclear reactions induced by heavy ions proceed through the formation of compound nuclei; a considerable part of the reaction cross section is attributed to various direct processes. An interest in measuring the probability of formation of coumpound nuclei in heavy-ion reactions is stimulated by a desire to understand not only the factors governing these reactions, but also the nature of the so-called fragmentation reactions in which light nuclei are emitted in the bombardment of target nuclei by high-energy ($>10^2$ MeV) protons. When these latter reactions are analyzed in terms of the statistical model,[3] it is necessary to know the cross section for compound-nucleus formation and not just the reaction cross section in the inverse channel.

In the present work, thin targets of Al^{27} and Co^{59} were irradiated by O^{16} and Ne^{20} ions at the Yale heavy-ion linear accelerator. Measurements of the complete-fusion cross sections were made using mica detectors.[4,5]

EXPERIMENTAL METHOD AND RESULTS

The use of mica detectors for measuring complete-fusion cross sections can be illustrated by considering the formation of the V^{47} compound nucleus in $Ne^{20}+Al^{27}$ interactions at a beam energy of 150 MeV. In this system the excitation energy is 104 MeV and the emission

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of from perhaps 7 to 10 nucleons is expected, most probably leading to isotopes of K and Ar. A theoretical charge-recoil energy (Z-E) distribution of recoiling nuclei resulting from the evaporation of particles from the moving compound nucleus, estimated by the Monte Carlo method,[6] is shown in Fig. 1. It was assumed in this calculation that particles were emitted isotropically in the moving system; the energy spectra of the emitted particles were those given by the evaporation formalism. It is seen there that if the efficiency limit is correctly established, practically all of the products have an ionization rate higher than the limiting value[7] below which no tracks can be formed, and therefore they are expected to be registered in mica with a 100% efficiency. The possibility of incomplete registration will be discussed later.

Mica, on the other hand, is insensitive to the incident Ne^{20} ions, to Al^{27} recoils resulting from most of the elastic scattering, and to most of the products of possible transfer reactions. Further, those transfer reactions that might register will give track lengths much shorter than those from fusion reactions. Thus, one can measure the fusion cross section by counting the number of tracks formed in mica placed behind the target in the manner illustrated in Fig. 2.

Irradiations of from 1×10^{-8} to 3×10^{-8} C were employed in order to keep the track densities in the convenient region of the order of 10^5 tracks cm^{-2}. The number of counts under the elastic peak in the monitor detector was of the order of 5000 in each irradiation.

The targets used in this work were in the range of 0.1 to 0.3 mg/cm^2. The beam intensities were determined by a monitor detector which measured the elastic scattering from a thin gold foil. The monitor, in turn, was calibrated with the use of a Faraday cup with no mica present.

Natural muscovite etched in concentrated hydrofluoric acid was used in all experiments. Etching conditions were investigated with samples of mica previously exposed to fission fragments from a Cf^{252} source, and were finally optimized by studying tracks in mica from the $Ne^{20}+Al^{27}$ system at a beam energy of 140 MeV. The effect of etching time on the appearance of tracks was similar for fission fragments and for recoils: After the tracks became visible under the microscope (10-min etching time), their number remained constant while their diameters grew with increased etching time. Etching for more than 1 h resulted in transformation of the tracks into characteristic diamond-shaped figures, very easy to count, but indistinguishable from other defects on the surface of the mica. To combine ease of counting with reliable identification, we have used etching times of 20–30 min, at which time all the tracks still had cylindrical shapes.

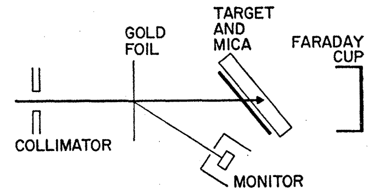

FIG. 2. Schematic diagram of experimental arrangement.

In order to reduce the background from nuclear reactions induced by the beam in mica, homogeneous crystals of mica thicker than the ranges of the projectiles were used. With these detectors, only those tracks which intersected the surface of the crystal could be attacked by the acid and thereby seen in the microscope. The same result can be obtained with thin mica by etching with a drop of acid deposited on the front surface only. Irradiations of mica without a target present showed that the background corrections were usually less than 3%.

The efficiency of the method was checked by measuring the differential cross section of fission from $Au^{197}+Ne^{20}$ at 202 MeV at a laboratory angle close to 30°. Our results, 230 mb/sr, is in reasonable agreement with the fission cross sections measured by other methods.[8]

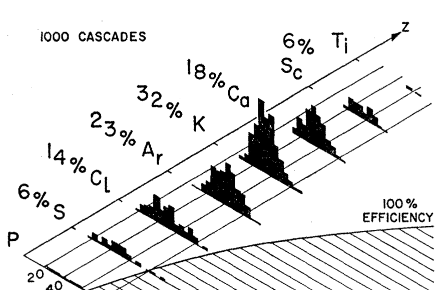

FIG. 1. Theoretical charge Z and kinetic-energy E distribution of recoiling nuclei resulting from the fusion of Al^{27} with Ne^{20} ions of 150 MeV. Products outside of the shaded area are registered in mica with a 100% efficiency.

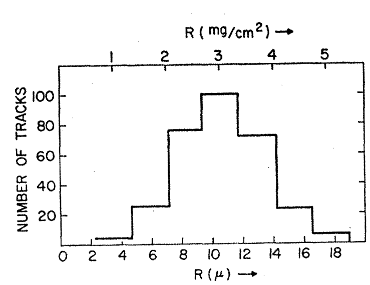

FIG. 3. Distribution of track lengths in mica of fragments from Al^{27}+140-MeV Ne^{20}. The upper scale is in mg cm^{-2} while the lower is in microns. This distribution was obtained with an aluminum target of 0.20 mg/cm^2, after 15 min of etching.

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TABLE I. Experimental complete-fusion cross sections.

Target	Beam	E_1 (MeV)	σ_{fu} (mb)	σ_R (mb)	σ_{fu}/σ_R	$J_{cr}(\hbar)$
Co^{59}	O^{16}	161	740±100	1900±70[b]	0.39	44
		119	1010±150	1750[a]	0.58	44
Al^{27}	O^{16}	161	500±100	1790±60[b]	0.28	26
		126	815±120	1620±90[b]	0.50	31
		105	1200±180	1540±90[b]	0.78	35
		87	1550±250	1420±100[b]	1	>38
	Ne^{20}	198	380±100	1714[a]	0.22	27
		140	600±12(	1632[a]	0.37	29
		87	$\sigma>1000$	1350[a]	>0.74	>30

[a] Calculated with the optical model using parameters given in Ref. 9.
[b] From Ref. 10.

A typical distribution of track lengths found for the $Ne^{20}+Al^{27}$ system is shown in Fig. 3. It was assumed that all tracks with $R>3\ \mu$ were produced by complete-fusion events. The absence of very short tracks confirms that the contribution of transfer reactions to the formation of tracks was negligible.

The situation might be more delicate for heavier systems such as $O^{16}+Co^{59}$, which was studied in this work with a Co^{59} target of 0.23 mg/cm^2. In this case, a transfer of only one nucleon with sufficient linear momentum, or even a simple scattering of O^{16} at a large angle, might form a detectable product. For this reason, only an upper limit to the complete-fusion cross section can be evaluated for this system from the number of tracks in mica. It is remarkable, however, that the observed distribution of track lengths at an O^{16} beam energy of 165 MeV still has a maximum close to $6\ \mu$. That the number of very short tracks was not excessively large indicates that even for the above system noncompound tracks did not exceed 20% of the total. This is consistent with the small cross sections for elastic scattering at large angles.[9]

For the light systems, such as $O^{16}+Al^{27}$, while one has no problem with possible contribution from direct reactions, *a priori* it was not certain that at the highest bombarding energies some recoil products were not too light to be registered in mica. In order to check if a large error resulted from the possible incomplete registration, an additional experiment was performed with the $Al^{27}+O^{16}$ system at 161 MeV, in which a glass detector was used instead of mica. Within the experimental error of ±15%, the cross section measured with glass was found to be the same as in mica. Knowing that glass is less sensitive than mica,[4] it was concluded that no very large error resulted from incomplete registration.

The cross sections of complete-fusion events σ_{fu} for the systems studied in this work at several beam energies E_1 are given in Table I along with the reaction cross sections measured by Wilkins and Igo.[10] The experimental errors include the uncertainties from the measurements of the total number of tracks, the thicknesses of the targets, and the number of beam particles in each irradiation. The largest contribution to the experimental error, especially when the recoil ranges are short, came from the personal factor involved in deciding whether a particular dark point on the mica surface was a real recoiling track or just some kind of mechanical defect. This error was estimated to be from 10–15% on the basis of the range distribution and by comparing the results obtained by different scanners with the same plates.

Two separate irradiations were performed on the $O^{16}+Al^{27}$ system at the maximum energy of 161 MeV and the difference in the cross sections from these irradiations, as determined by the same scanner, was of the order of 10%. The same errors were usually observed when the same sample was studied by different scanners.

As mentioned above, the actual complete-fusion cross section in the $O^{16}+Co^{59}$ system might be up to 20% lower than shown in Table I because of the uncertainty about the origin of the very short tracks.

In addition to cross sections, the angular distribution of the recoils from the $Ne^{20}+Al^{27}$ system at the energy $E_1=198$ MeV has been investigated with small mica detectors placed 13 cm from the target at angular intervals of 5°. It was found that at least 95% of the recoiling nuclei are emitted within an angle of less than 25° with respect to the incident beam. This is consistent with what one would expect: The evaporation of one nucleon of 4 MeV, for example, can modify the initial direction of the heavy residual by as much as 1.8°; the total deviation results from the random combination of all of these individual recoils.

DISCUSSION

1. Experimental Method

Complete-fusion cross sections were computed from the number of tracks assuming that recoil nuclei from complete-fusion reactions are registered in mica with an efficiency of 100%. Unfortunately, the validity of this assumption can be put in doubt, especially for the lightest system $O^{16}+Al^{27}$. The main source of doubt results from the imprecision with which the critical ionization rate in mica is known. The cutoff line on Fig. 1 was drawn according to that indicated by Fig. 1 of Ref. 7. There is a chance, though, that the real limit of 100% efficiency is closer to the circle points given in Fig. 1 of Ref. 7, corresponding to a shift of our cutoff line in Fig. 1 by perhaps as much as 40 MeV toward low energies. More independent experiments are necessary in order to determine the limit of 100% efficiency in mica before the interpretation of tracks in mica made in this work is completely justified. However, in spite of this possible difficulty, there is a number of indications that the incomplete registration of recoils is not re-

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sponsible for the fact that the complete-fusion cross sections are observed to be much smaller than σ_R and to decrease with an increase in bombarding energy.

First of all, even a shift of the cutoff line by 40 MeV toward lower energies would not affect the recoils from the $Co^{59}+O^{16}$ system which have a sufficiently high Z so that they should still be registered with 100% efficiency. (The average range of these recoils in mica is 6 μ; that is, more than 4 times larger than the thickness of the target).

Secondly, if the calculated recoil distribution shown in Fig. 1 is correct, a shift of the cutoff line by 40 MeV toward the low energies would prevent only some 10–15% of the recoils from being recorded; thus it is certainly not enough to account for the difference of the factor of more than 2 between σ_{fu} and σ_R.

Finally, the observation that σ_{fu} for the $O^{16}+Al^{27}$ system at 161 MeV, measured with a glass detector, was the same within experimental error as that measured with mica, shows that partial registration cannot be a serious problem. That this is so follows from the fact that glass is a less sensitive detector than mica[4] and the corresponding 100%-efficiency curve lies above that (E_R shifted to lower values by about 20 MeV) given in Fig. 1. Thus, if the 100%-efficiency curve for mica actually cut substantially through the recoil-spectrum histograms shown in Fig. 1, σ_{fu} measured in glass and mica could not have the same value.

An additional argument indicating that the cutoff line does not cross in the middle of the recoil population comes from the observation that the number of tracks longer than 1 mg/cm^2 does not depend on the etching time for the $Al^{27}+Ne^{20}$ system at 140 MeV. Ions which have a critical ionization rate close to the cutoff region are known to form tracks whose number depends on the etching time.[7,11]

These same arguments can be used in rejecting the possibility that errors in the calculated histograms given in Fig. 1 mask the possibility of a large incomplete registration of recoil nuclei through an underestimation of either the high-energy tail on the recoil spectrum or the number of charged particles emitted.

2. Physical Interpretation

It is not very surprising that the fusion cross section is considerably smaller than the reaction cross section since it is well known that direct transfer reactions are not uncommon in nuclear collisions with heavy ions. It was shown, for instance, that the cross section for several direct reactions is close to 600 mb in the $O^{16}+Al^{27}$ system at a beam energy of 165 MeV.[12]

In general, various theoretical considerations[13] show that compound nuclei with angular momenta above a critical value that depends on the system cannot exist. For instance, liquid-drop-model calculations[14] show that the interaction of Ne^{20} of 150 MeV with an Al^{27} nucleus followed by the formation of a compound nucleus is possible only for impact parameters below some maximum value which thus corresponds to $\sigma_{fu}<\sigma_R$; higher impact parameters produce a rotation such that a stable configuration of the liquid drop would be impossible. The maximum acceptable impact parameter, which determines the ratio of σ_{fu}/σ_R, depends on Z and A of the particular compound nucleus as well as on the bombarding energy. At lower bombarding energies this ratio is expected to approach 1.0, in agreement with our observations (see Table I).

Another approach to the problem of fusion collisions grew out of the earlier work of Kaufmann and Wolfgang.[15] These authors postulated that the complete fusion occurs in peripheral collisions only when the attractive nuclear force is larger than the repulsive Coulomb and centrifugal forces. This point of view was later developed by Kalinkin and Petkov.[16] They present a method for finding the critical value of the angular momentum as a function of the bombarding energy; thus one can obtain the complete-fusion cross section for any system for which this liquid-drop-model approach is reasonable. The results of their calculations depend upon the choice of the nuclear moment of inertia, surface tension, and density. Assuming that the nuclear moment of inertia is identical to that of a rigid body of the same shape, taking the surface tension to be 0.95 MeV/F^2, and considering noncompressible nuclear matter with $r_0=1.3$ F, the authors have shown that the fusion cross section for the $O^{16}+Ni^{58}$ system at 160 MeV is close to the result obtained in this work for the $O^{16}+Co^{59}$ system at the same energy.

This class of interpretation suggests that the trend of our experimental results be discussed in terms of the maximum acceptable angular momentum that leads to compound-nucleus formation or complete fusion. Assuming that there is some limiting value J_{cr}, above which no compound nuclei can be formed and that below this value a penetration of the nuclear surface is equivalent to the formation of compound nuclei, one can calculate the complete-fusion cross section σ_{fu} as

$$\sigma_{fu}=\sum_{J=0}^{J_{cr}}\sigma(J).$$

The quantity $\sigma(J)$ is the cross section for inelastic interactions with total angular momentum J as calculated, for example, with the optical model. The values of

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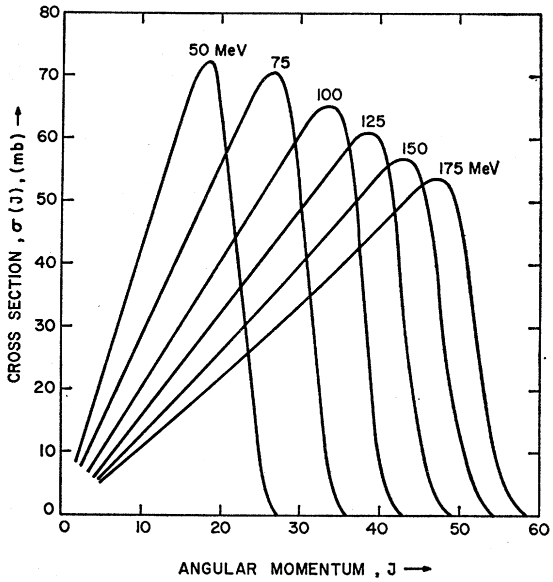

FIG. 4. Initial calculated spin distribution $\sigma(J)$ for the $Al^{27}+O^{16}$ system at six different beam energies. The optical-model parameters given in Ref. 9 were used in the calculation, except that the half-density parameter r_0 was taken as 1.20 rather than 1.26.

$\sigma(J)$ for $O^{16}+Al^{27}$ system, calculated in the usual way[17] from the optical-model transmission coefficients, are shown in Fig. 4. These calculations were performed using the Saxon-Woods optical-model potential with the same parameters as used by Auerbach and Porter.[9] The reaction cross section results from the summation of $\sigma(J)$ over all values of J; complete fusion is taken to occur only at $J<J_{cr}$.

After finding $\sigma(J)$ distributions for all the systems studied in this work, it was easy to calculate the ratios of σ_{fu}/σ_R as a function of the parameter J_{cr}, and thus to determine J_{cr} on the basis of the experimental data. For instance, the ratio of experimental cross sections σ_{fu}/σ_R for the $O^{16}+Al^{27}$ system at the beam energy of 126 MeV led to a value of $J_{cr}=31\pm5$, which is smaller than $J_{max}\simeq50$. The values of J_{cr} estimated in this fashion are given in the last column of Table I.

This approach of using optical-model transmission coefficients in the estimation of J_{cr} is doubtless an oversimplification. A recent investigation by Beringer[18] has shown an increase in the Coulomb barrier caused by the deformation of two nuclei as they approach each other. This effect, though, is expected to be more important in the energy region below that considered in the present study.

The possibility that the spin distribution of compound nuclei is not identical to the spin distribution $\sigma(J)$ in the entrance channels carries significant implications for many nuclear processes. In particular, the energy dependence of the ratio of formation cross sections of isomeric pairs with a large spin difference should be very sensitive to the original spin distribution of the compound nuclei. An investigation of this effect was undertaken by Bredel *et al.*,[19] who studied the energy dependence of the relative yields of the isomers Sc^{44m} and Sc^{44} produced in the reactions of $Ne^{20}+Al^{27}$. From the analysis of the experimental results, it was concluded that "the scandium isotopes are produced in the reactions which have collision parameters corresponding to angular momenta less than $25\hbar$." This is very close to the values of J_{cr} in Table I.

The decrease in σ_{fu}/σ_R with increasing bombarding energy in heavy-ion reactions has been observed in other investigations. On the basis of the assumption that *all* inelastic interactions between heavy ions and uranium result in fission,[20] Sikkeland *et al.*[21] have determined σ_{fu} and σ_R for the $O^{16}+U^{238}$ system through measurements of the angular correlations of the fission fragments. They found that the ratio σ_{fu}/σ_R decreases from ~0.97 to ~0.84 when the beam energy increases from 110 to 165 MeV. A decrease in the fusion cross section with increasing bombarding energy was also deduced from the observation of tracks from the interaction of a 200-MeV Ne^{20} beam with the light components (CON) of nuclear emulsions.[22]

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