Reactions of 336-MeV ^{32}S with In†

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(Received 8 December 1975)

The cross section for evaporation residues produced in the complete-fusion reactions of 336-MeV ^{32}S with In has been measured. After correction for the heavy residues formed in transfer reactions, the evaporation-residue cross section is found to be 530 ± 150 mb, which corresponds to a "sharp-cutoff" angular momentum for evaporation residues of $(72 \pm 9)\hbar$. This result is discussed in terms of various theoretical models.

[NUCLEAR REACTIONS evaporation residues In(^{32}S, Tb), $E = 336$ MeV; measured $\sigma(E, \theta)$; σ for evaporation residues; discussed in terms of models.]

I. INTRODUCTION

The cross section for complete fusion in reactions between heavy nuclei is among the more interesting measurements that may be made in the study of the dynamical behavior of nuclear matter. Such measurements are conveniently parametrized in terms of a sharp-cutoff model in which it is usually assumed that all partial waves in the entrance channel up to some critical value l_{cr} lead to complete fusion of the projectile and target, while the higher partial waves lead to either other inelastic or elastic processes. It should be mentioned in this connection that recent experimental results with heavier projectiles, such as Kr, have led to the speculation that the lowest partial waves do not lead to complete fusion and thus there is a window in l space ranging from some nonzero l value up to l_{cr} that leads to complete fusion.[1] There is as yet no unambiguous experimental support for this conjecture. In any event, it is well established that l_{cr} depends primarily on dynamical processes in the entrance channel rather than the equilibrium properties of the composite system of target plus projectile.[2,3] Nevertheless, the equilibrium properties of the composite system do possibly provide information on an upper limit to l_{cr} and it is this topic to which the present work is addressed.

It is usually assumed that complete fusion in a heavy-ion reaction is essentially synonymous with compound-nucleus formation and the exit channel is either fission or the evaporation of small particles. Thus, either fission products or what have come to be called evaporation residues are the expected result of complete-fusion reactions and measurements of complete-fusion cross sections entail the measurement of the cross section for these two processes. It is possible that precompound particle emission also contributes to the deexcitation in the complete-fusion reaction; no persuasive evidence yet exists that this is a significant process in heavy-ion reactions. If, then, complete fusion is taken as synonymous with compound-nucleus formation, the question arises as to whether the spin of the compound nucleus at which the fission barrier vanishes is an upper limit to l_{cr}. It should be reemphasized immediately that this would be an upper limit only; as mentioned previously, l_{cr} depends upon dynamical processes in the entrance channel which determine the angular momentum at which transfer processes become more important than complete fusion. Nonetheless, it is possible that there may be particular systems for which the angular momentum at which transfer processes begin to dominate exceeds that at which the fission barrier vanishes.

For these particular systems, if they exist, it is not obvious what would be observed from entrance channels with angular momenta exceeding that at which the fission barrier vanishes for the corresponding compound nucleus. The whole concept of a fission barrier depends upon an equilibrium configuration being attained by the composite system. The entrance channel, though, is to be found in a very different part of the potential-energy landscape from the fission pass and considerable relaxation time may be involved before the composite system becomes a compound nucleus and "realizes" that there is no fission barrier.

Consequently, it is still an open question whether complete fusion can occur at angular momenta exceeding that at which the fission barrier vanishes and, further, what is to be expected in the exit channel from such an interaction. There have been a few recently published experimental results for the reactions between Ar and targets ranging from Ag to I which may provide some information on this point.

The liquid-drop-model study of Cohen, Plasil, and Swiatecki[4] suggests that the fission barrier vanishes at a spin of 80 to 85$\hbar$ for the compound nuclei that would be formed in these systems. The investigation of Gauvin, Le Beyec, and Porile[5] on the reactions of Ar with ^{118}Sn, ^{121}Sb, and ^{127}I lead to values of l_{cr} up to around 140 and values of l_{er} around 100 for just the evaporation-residue exit channel by itself if the fission contribution to complete fusion is ignored. The cross sections in this work are based on the assay of α particles emitted from radioactive products and the authors caution that there can be significant errors caused by the paucity of precise decay-scheme information on these highly neutron-deficient products. Gutbrod *et al.*[6] and Plasil,[7] from measurements of fission and evaporation-residue cross sections by means of a counter-telescope system, have reported an l_{cr} of about 111 from complete fusion in the reaction of 288-MeV Ar with ^{109}Ag. The limiting value for just the evaporation residues ($l_{er} < l_{cr}$) in their work is about 80.

From the above data it would appear that the angular momentum at which the fission barrier is calculated to vanish may not have a limiting effect on l_{cr}. And, more surprising, l_{er} may not necessarily seem to be strongly affected. Although, as mentioned before, Gauvin *et al.*[5] state that there may be significant error in their results because of decay-scheme uncertainties.

In this context, we report here a measurement of the cross section for the formation of evaporation residues in the reactions of 336-MeV ^{32}S with natural isotopic In by means of a standard ΔE-E counter-telescope technique. In this measurement, particular attention was paid to the correction for heavy residues from various transfer reactions that can be confused with evaporation residues from complete-fusion reactions with this experimental technique.

II. EXPERIMENTAL METHODS AND RESULTS

A. Measurement of heavy-residue cross section

The In target was made by evaporation of natural In onto a 10-μg/cm^2 carbon foil. The target thickness of 514 ± 20-μg/cm^2 was determined by weight and verified by measuring elastic scattering cross sections using ^{16}O and ^{32}S beams.

The target was irradiated with the full-energy sulfur beam (10.5 MeV/nucleon) at the now-deceased Yale HILAC at a time average beam current of about 0.25 nA. The products of the reactions were detected with a counter telescope which consisted of a proportional counter (ΔE) followed by a 500-μm Si(Li) surface-barrier detector (E-ΔE). The ΔE detector had a 0.32-μm parylene-C window. The pressure was maintained at 50 Torr, which corresponded to a gas thickness of 200 μg/cm^2.

The beam was defined by a 1.59-mm diameter collimator at the entrance to the scattering chamber. One of three detector collimators of diameter 1.59, 3.18, and 4.77 mm were used according to the angle of the detector. These collimators defined the particle-acceptance geometry with a telescope-to-target distance of 14.6 cm. The beam axis in the scattering chamber was located to within $\pm 0.15^\circ$ by measuring the Rutherford scattering cross section of Au on both left and right sides of nominal zero degrees.

To minimize dead-time and pileup problems, the beam intensity was controlled such that at most two events were measured per 2000-μsec beam pulse. Signals from the detectors were processed by conventional electronics and stored on magnetic tape. Depending upon the angle of observation, differential cross sections were calculated by using beam-current integration, a monitor detector calibrated with the current integrator, or normalization to the Rutherford scattering cross section. There was excellent agreement between the first and third methods at those angles where they could be employed simultaneously. In general, the error in the results was due mainly to counting statistics, although at small angles the angular uncertainty became dominant.

Figure 1 shows a typical ($\Delta E, E$-ΔE) spectrum. The region labeled A indicates heavy-residue products, the fission region is indicated by B, the elastic scattering is found in region C, while D indicates the transfer-product region. The heavy residues lie in the energy range of 30 to 95 MeV after correction is made for energy losses within the target and ΔE detector as well as the pulse-height defect.[8]

The laboratory angular distribution, $d\sigma/d\Omega$ vs θ, of the heavy residues is given in Fig. 2, while $d\sigma/d\theta$ is given in Fig. 3. Integration beneath the curve presented in the figure results in a cross section of 840 ± 90 mb where the error includes only the statistical error due to the finite number of counts. The validity of the curve and in particular the extrapolation to 0° will be examined in Sec. III.

B. Contribution of transfer reactions to heavy residues

As seen in Fig. 1, the energies of the heavy residues are such that they are on the rapidly rising part of the stopping-power curve and accordingly it is not possible to identify their atomic numbers in this experiment. This means that it is not possible to distinguish directly between heavy residues which are evaporation residues from complete fusion and those heavy residues that result from transfer reactions. Thus, in order to obtain the cross section for the formation of evaporation residues, correction must be made for the contribution of transfer reactions to the heavy-residue cross section.

The energy spectrum of the light transfer products in area D of Fig. 1 extends, as usual, continuously from an upper limit for quasielastic process in which the particles in the stripping product behave like a spectator down to a lower limit variously called quasifission, deep inelastic, relaxed, or strongly damped, which is essentially determined by the Coulomb repulsion between the separating fragments. If the primary process is assumed to involve a two-body breakup, then each of these light transfer products will have a corresponding heavy partner which, depending upon its angle and energy of emission, can make a contribution to the measured heavy-residue cross section in region A. Thus, in order to obtain the evaporation-residue cross section one must subtract from 840 ± 90 mb the contribution of the heavy transfer products to the events in region A. This

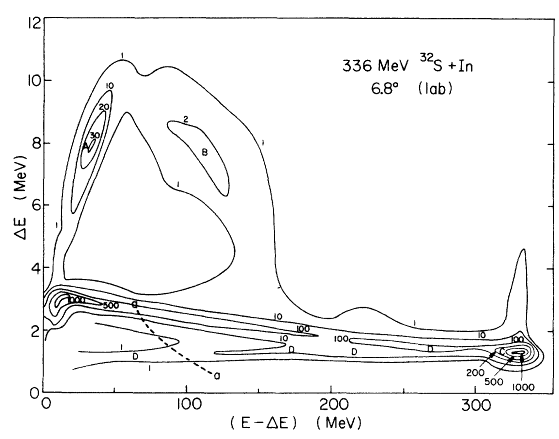

FIG. 1. Contour diagram of ΔE vs E-ΔE obtained in detector-telescope system at 6.8° in the laboratory. Region A contains heavy residues; region B contains fission products; region C contains elastic scattering; and region D contains light transfer products. Light transfer products to the left of the dotted line aa will have heavy complements that contribute to region A at some other angle.

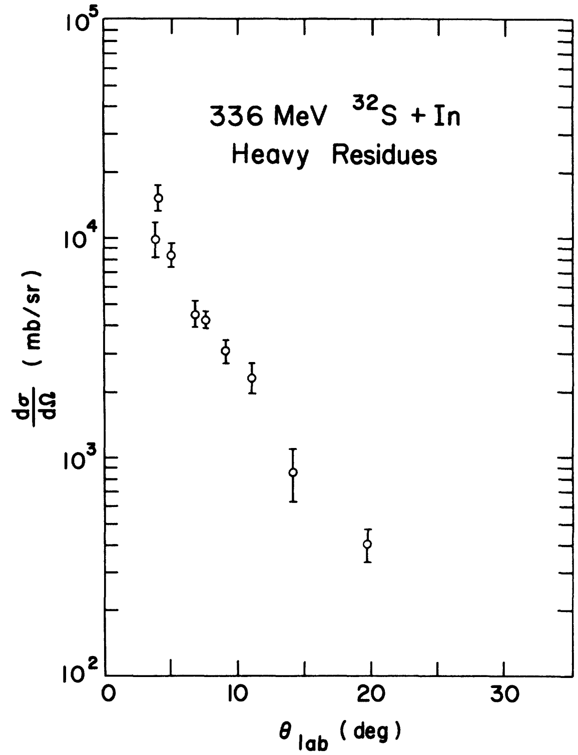

FIG. 2. Angular distribution of heavy residues in the laboratory system.

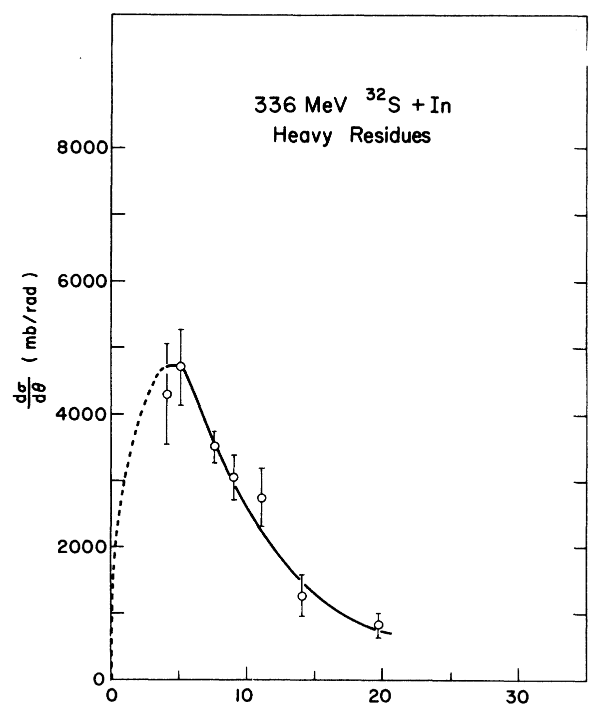

FIG. 3. Angular distribution of heavy residues in the laboratory system.

correction was estimated from the application of two-body kinematics to the energy and angular distributions of the light transfer products (after correction for the evaporation of particles from them). For example, those light transfer products to the left of the dotted line *aa* in Fig. 1 will have complementary heavy partners with energies greater than 30 MeV emitted at an angle less than 20° in the laboratory. Figure 4 shows the angular distribution of all light transfer products with partners which contribute to the measured heavy-residue cross section. The kinematics lead to the conclusion that these light transfer products must have a mass less than about 27. Integration of the results in Fig. 4 under the condition that $d\sigma/d\theta$ approaches 0 as θ approaches 0 leads to a cross section of 310 ± 120 mb. This leaves 530 ± 150 mb as the cross section for the production of evaporation residues from compound nucleus formation. If, as a first approximation, it is assumed that all partial waves up to l_{er} give rise to complete fusion followed by the evaporation of only small particles and that higher partial waves lead to other process including complete fusion followed by fission, the value of l_{er} may be obtained from the expression

$$\sigma_{er} = \pi \lambda\!\!\!^{-2}(l_{er}+1)^2 ,$$

which yields $l_{er} = 72 \pm 9$.

C. Fission

From Fig. 1 it can be seen that it is rather difficult to estimate the fission cross section from the data obtained in this experiment. In that figure, fission-product events are found in region *B*, which at the heavy end merges into the tail of the heavy residues in region *A*, and at the light end into the transfer events in region *D*. These mergings have an essentially negligible effect on the heavy-residue cross section because the number of events is relatively small, but are significant to an estimate of the fission cross section. Nevertheless, because of the added interest of knowing the complete-fusion cross section rather than just that for the formation of evaporation residues, an attempt was made to estimate the fission cross section by assuming that it would be given by the cross section for the formation of products with atomic numbers between about 19 and 31. This approach yielded a result of 330 ± 210 mb.

When combined with the previously presented cross section for evaporation residues, there results an estimated complete-fusion cross section of 860 ± 260 mb or an l_{cr} of 92 ± 14 as the estimated sharp-cutoff upper limit to complete fusion.

III. DISCUSSION

In this section we shall examine both the difficulties that are encountered in extrapolating the experimental results to small angles in order to obtain the integrated cross section for heavy residues, and the implications for heavy-ion reactions of those integrated results.

A. Extrapolation of experimental results

It was not possible with the experimental techniques employed here to carry out cross section determinations satisfactorily at laboratory angles smaller than about 4°. This limitation was imposed both by geometrical considerations as well as the rapidly increasing dominance of Rutherford scattering at small angles. Accordingly, as may be seen in Fig. 3, determination of the heavy-residue cross section required extrapolation of the measured cross sections from about 4° down to 0°.

The only unambiguous condition on this extrapolation is that the curve must go through the origin. Further guidance was obtained from a Monte Carlo estimate of the angular distribution particles from the appropriate compound nucleus under the assumption of isotropic particle emission in the moving system of the emitting nucleus.[9] The extrapolated portion of the curve in Fig. 3 was obtained in this fashion.

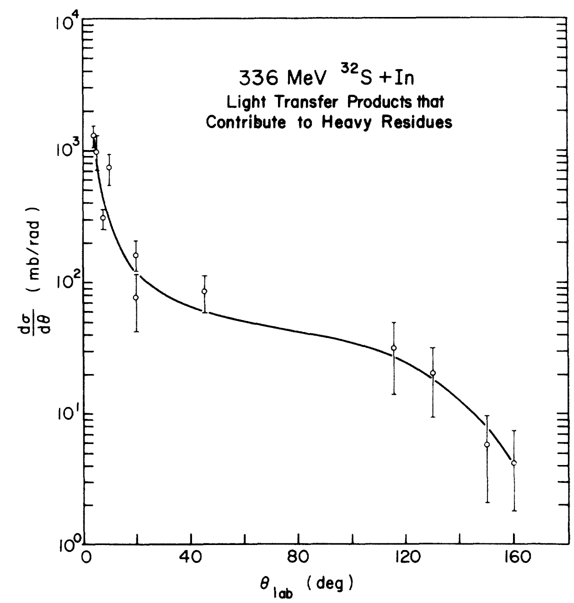

FIG. 4. Angular distribution of light transfer products whose heavy complements contribute to the cross section for heavy residues.

B. Evaporation-residue cross section and the liquid-drop-model limit

The main point of this work was to investigate whether the cross section for the formation of evaporation residues would require incoming partial waves with angular momenta beyond about $84\hbar$ at which the fission barrier is expected to vanish within the framework of the liquid-drop model. The observed cross section with its concomitant sharp-cutoff angular momentum of $(72\pm 9)\hbar$ shows that such high partial waves are not required. This is not to say that all partial waves below $l=72$ lead to nothing but evaporation residues and all those of higher l never do; it is expected that there will be some fission for $l<72$ and evaporation residues for $l>72$. It only means that the evaporation-residue cross section itself does not require anomalously high values of l, as was suggested by some earlier experiments.

At first glance, even the value of $l_{er}=72$ may seem high in light of the prediction of Cohen *et al.*[4] that the fission barrier becomes equal to the neutron separation energy (11.2 MeV) at a spin of about $60\hbar$ for the ^{147}Tb compound nucleus that is formed here. The implication is that although fission may dominate neutron emission for compound nuclei with spins above 60, it does not dominate the emission of charged particles–probably mainly α particles. This implication was substantiated by a calculation carried out for us by Plasil[10] which yielded an evaporation-residue cross section of 535 mb when allowance is made for the angular momentum carried away by evaporated particles. In particular, it is found in this calculation that evaporation residues formed from compound nuclei with spins greater than 60 do indeed predominantly involve the emission of charged particles.

C. Complete-fusion cross section

The cross section for complete fusion should be given by the sum of the cross sections for evaporation residues and for fission. As discussed in Sec. II, the fission cross section measured in this experiment is subject to considerable uncertainty. The estimate given there of 330 ± 210 mb corresponds to a cross section for complete fusion of 860 ± 260 mb and a corresponding l_{cr} of 92 ± 14. This result is not seriously inconsistent with the l value of about 80–85 at which the fission barrier is expected to vanish for the ^{147}Tb compound nucleus that is formed here. Hence, within the precision of these measurements, there is no evidence for complete fusion in entrance channels above that where the fission barrier vanishes.

As mentioned in the introduction, the complete-fusion (cf) cross section is generally expected to be governed by dynamical processes in the entrance channel rather than the equilibrium properties of the compound nucleus that is formed. Accordingly, it is of interest to compare the value of $l_{cr}=92\pm 14$ obtained in this experiment with the several attempts to estimate this quantity from entrance-channel dynamics.

Calculations of l_{cr} usually entail consideration of the motion of the two ions that are colliding under the influence of conservative and dissipative forces that arise from their mutual interactions. In detailed calculations such as those of Gross and Kalinowski[11] as well as Bondorf, Sobel, and Sperber[12] the equations of motion are integrated numerically on a computer with the dissipative forces introduced as a friction force acting on the various degrees of freedom that are explicitly considered. While these two sets of authors have not computed the l_{cr} expected for the particular entrance channel investigated here, it is of interest to note that a recent preprint from Gross, Kalinowski, and De[13] give a value of $l_{cr}=102-104$ for the similar system of 300-MeV ^{40}Ar + Sb while Bondorf, Sobel, and Sperber give for this same system values ranging from a low of about 60 for their "weak friction" case to a high of 130 for "strong friction."

The method of Bass[14] for the estimation of l_{cr} includes dissipative forces only implicitly and leads to an $l_{cr}=101$ for the 336-MeV ^{32}S + In.

Finally, Seglie and Sperber[15] recently suggested a very simple model for the calculation of σ_{cf} that depends on the amount of overlap of the interacting ions were they to follow elastic trajectories without a repulsive core to the nuclear potential. Their model gives a calculated $\sigma_{cf}=850$ mb, to be compared with the experimental value of 860 ± 260 mb. It is noteworthy that all of these models give reasonable agreement with the experimental results, though even the most elaborate of them must represent a massive simplification of the complex situation that obtains.

IV. SUMMARY AND CONCLUSIONS

The cross section for the formation of evaporation residues from complete fusion was measured to be 530 ± 150 mb for the reactions of 336-MeV ^{32}S + In, while that for fission was found to be 330 $\pm$ 210 mb. The evaporation-residue cross section corresponds to a sharp-cutoff angular momentum of $(72\pm 9)\hbar$; a value well below the estimate of about $84\hbar$ at which the fission barrier is expected to vanish.

The sum of the cross sections for evaporation residues and for fission, which should be a measure of the cross section for complete fusion, is

860 ± 260 mb. This corresponds to a sharp-cutoff angular momentum of $(92 \pm 14)\hbar$, a value which is not seriously inconsistent with the $84\hbar$ mentioned above. Thus, contrary to the indication from previous investigations of similar systems, there is no strong indication of complete fusion from entrance channels where the fission barrier is expected to vanish.

The complete-fusion cross section that is observed is in agreement with all of the extant theories for which calculations for the particular system examined here exist.

Note added in proof: In a recent investigation, Gauvin, Guerreau, Le Beyec, Lefort, Plasil, and Tarrago[16] also point out that the results in Ref. 5 seem to be too large, and l_{cr} is below the value at which the fission barrier is expected to vanish.

ACKNOWLEDGMENTS

We wish first and foremost to express our deep gratitude to the operating crew of the late heavy-ion linear accelerator at Yale University. We have been fortunate in working with this fine group of people over the past decade. It is a pleasure to record our indebtedness to Dr. M. Blann, Dr. H. Britt, and Dr. F. Plasil for many illuminating and instructive conversations, as well as sharing with us details of their investigations of the similar $^{40}Ar + Ag$ system.

†Work supported by U.S. Energy Research and Development Administration.

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