Cross Section and Angular Distribution of Products in "Quasifission" Reactions Induced by 525-MeV ^{84}Kr Ions on a ^{209}Bi Target

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We observed "quasifission" events (or "incomplete fusion" events) in the bombardment of ^{209}Bi by 525-MeV ^{84}Kr ions. By a simple method, the angular distribution of these events has been obtained. Its maximum value appears around 65° lab, i.e., ~95° c.m. The integrated cross section for this reaction is 500 mb, more than $\frac{1}{2}$ of the total reaction cross section. No symmetric fission coming from a complete fusion nucleus has been observed, and it seems that the "quasifission" reaction occurs instead of complete fusion, as was previously observed at 500 MeV bombarding energy.

Much interest has been aroused recently by unexpected products observed in reactions induced by different heavy ions and called "very inelastic transfer products,"[1,2] "fissionlike events,"[3] or "incomplete fusion events."[4] It is not clear whether they are all due to the same mechanism or not, but in any case it seems they are related to the viscosity of nuclear matter and to frictional forces exerted between the two nuclei, which concert a great deal of the kinetic energy into excitation energy during the short time of the interaction.

For heavy targets and for heavy ions up to argon, it has been observed that the complete fusion cross section is always a very important part of the reaction cross section.[4] By extrapolating these data and taking into account the limiting values of the orbital angular momenta involved in the reactions, it was expected that complete fusion would also be an important part of the total reaction cross section when the projectile is as heavy as krypton. Since all the fusion nuclei undergo fission, the complete fusion cross section was measured via the binary-fission cross section and, contrary to expectations, was found to be very low.[4,5] A possible interpretation is the existence of a fusion barrier which may be higher than the interaction barrier.[4,6]

In the same experiments, a new kind of reaction was observed, which seems to occur instead of complete fusion; therefore we called it "incomplete fusion," but the name "quasifission" is perhaps better. The features of these reactions are as follows: (1) Two products are detected whose masses are near the mass of Kr or the mass of the target nucleus. (2) Their kinetic energy in the center-of-mass system has the value calculated for Coulomb repulsion between the two fragments, assuming the distance for scission as in normal fission. However, it must be recalled that, up to now, the masses have not been directly measured but were calculated from the laboratory energies of the two products by assuming a full momentum transfer from the projectile to the system target plus projectile.

With respect to this absence of binary fission following complete fusion and the observation of quasifission, the main questions which must receive experimental answers are the following: How do the cross sections vary with the bombarding energy? What is the angular distribution of the quasifission events? What happens for projectiles between Ar and Kr?

In the experiments reported here, we tried to obtain information on the first and second questions by bombarding a ^{209}Bi target with 525-MeV ^{84}Kr ions. The experimental setup has been described elsewhere.[7,8] Three surface-barrier detectors X, Y_1, and Y_2 were used. X is located at a fixed angle of 55°, which corresponds to about 90° for the direction of emission of a fragment in a symmetric fission from the fusion nucleus. Y_1 and Y_2 have an angular width of 10° in the reaction plane, and are moved step by step every 10 deg so that the whole angular correlation of fragments is covered in a few measurements. The angular widths in the plane perpendicular to the reaction plane are such that all the coincident fragments are detected even if evaporation of particles produces a noncoplanar correlation.

In Fig. 1(a) is displayed a two-dimensional energy spectrum of the correlated events. Measurements were added with θ_Y varying from 19 to 79°. The first observation is the absence of fission fragments of equal energies, which should

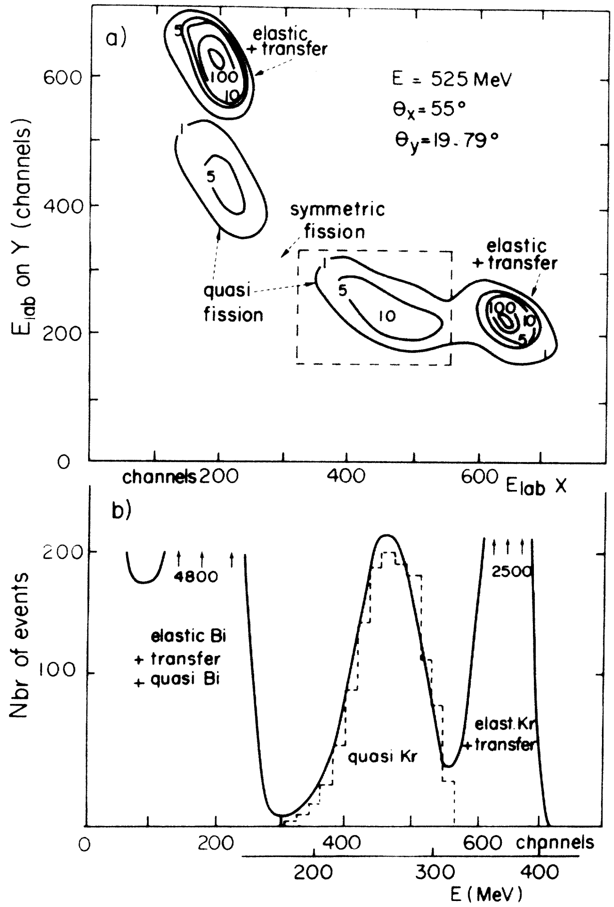

FIG. 1. (a) Two-dimensional distribution (curves of equal numbers of events) of correlated laboratory energies in detectors *X* and *Y*. (b) Solid line, energy spectrum of all particles (correlated or not) received by the *X* detector; dashed line, projection on the *X* axis of the quasifission events enclosed in the rectangle of (a).

be issued from a complete-fusion nucleus. Although the center-of-mass kinetic energy available above the interaction barrier is around 58 MeV, as opposed to the 42 MeV when the bombarding energy was 500 MeV, the cross section for this process is no greater. This result does not support the idea of a fusion barrier higher than the interaction barrier, unless this fusion barrier is much higher.[6]

When the events of Fig. 1(a) are transformed into the center-of-mass system, one obtains a distribution for mass versus total kinetic energy similar to those shown in Refs. 4 and 7. In Fig. 1(a), each of the two high mountains corresponds to elastic, inelastic, and quasielastic transfer reactions (for the right-hand mountain a high-energy scattered Kr ion or a transfer product close to Kr was received by the X detector and the low-energy scattered Bi or transfer product close to Ni was received by the Y detector; and vice-versa for the left-hand mountain). Near each of these mountains, but separated from them, are the two hills of "quasifission" events. Their cross section is 90 mb/sr, slightly more than the 70 mb/sr observed at the same angle with 500-MeV Kr on the same target.[7] No quasifission events have been missed since their angular correlation is restricted to θ_Y between 39 and 59°.

The angular distribution of these events can, of course, be obtained by moving the X detector and repeating, for each value of θ_X, the series of measurements at different values of θ_Y which are necessary to cover the whole angular correlation of coincident events. But this would consume too much machine time with the presently available Kr-beam intensity. The following observation will allow us to obtain the angular distribution of the light quasifission products without making any additional measurement. In Fig. 1(b), the solid line (called the total spectrum) is the energy distribution of all the particles received by the X detector at 55° during one measurement, *whether these particles are in coincidence with a particle on the Y detectors* or not. The peak at the highest energy (around channel 630) is due to scattered Kr ions and quasielastic transfer products close to Kr; a second, smaller, peak appears around channel 470; the third peak is mainly due to scattered Bi nuclei and transfer products close to Bi; the low-energy part of the spectrum, below channel 100, is due to particles of relatively low energies or very energetic light particles which leave only part of their kinetic energy in the X detector which is only 100 μm thick. The dashed-line histogram is the distribution of the energies in the X detector for the events attributable to quasifission reactions which appear in the dashed-line rectangle of Fig. 1(a) (measured at 55°). These energies are then those of the quasifission products whose masses are close to 84, and we call them "quasi-Kr." This histogram and the second peak of the total spectrum are identical in shape and in height within the limits of statistical error.

This observation leads us to make the hypothesis that in the energy distribution *of all the particles received by a single detector*, the peak which appears between the peaks due to scattered Kr and Bi ions is due to quasi-Kr, even if the

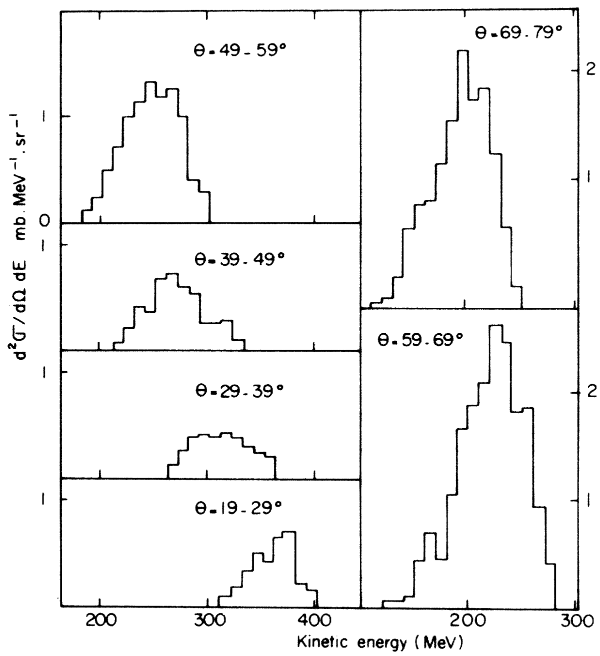

FIG. 2. Energy distributions of the quasi-Kr products observed between 19–29° and 69–79°. Because of some admixture of the other peaks in the energy spectra, the edges of these peaks are subject to errors [see Fig. 1(a), mostly for the 19–29° spectrum.

angle of detection is different from 55°. At angles close to 55°, this hypothesis is surely correct and this will allow us to obtain the slope of the angular distribution of quasi-Kr around 55°. At angles far from 55°, one can imagine that reactions other than complete fusion or transfer reactions give some products which have the same energy as the quasi-Kr, but so far we have no indication of the existence of such reactions. By using this hypothesis, it is sufficient to take the intermediate peaks on the energy spectrum measured at different angles in order to obtain the angular distribution. No supplementary measurement is necessary, since the Y detectors have been moved from 19 to 79° and the energy spectra of all the impinging particles have been recorded. The results for the six angles are shown in Fig. 2. A contribution from the two other peaks had to be subtracted and this produces an uncertainty in the edges of the spectra.

The angular distribution in the laboratory system is obtained by summing these spectra and is shown in Fig. 3. The errors are mainly due to the decomposition of the peaks. The main feature is the increase of $d\sigma/d\Omega$ with the angle from 25° up to 65°; after 65°, $d\sigma/d\Omega$ seems to decrease but unfortunately no further measurements have yet been made. The shape is quite different from the $1/\sin\theta$ form which characterizes the angular distribution of fission fragments. It is rather similar to the angular distribution of quasielastic transfer products, but the maximum is not at the grazing angle (~75°). We have transformed the cross section to the center-of-mass of the projectile-plus-target system. We simply used the average angle and energy of each spectrum in Fig. 2, and assumed that the average mass of the quasi-Kr ions is 84. The result is also shown in Fig. 3. It seems to have its maximum value near 90°. This has to be confirmed by measurements at larger angles. The value of 90° could be fortuitously due to the values of the bombarding energy and the projectile and target masses

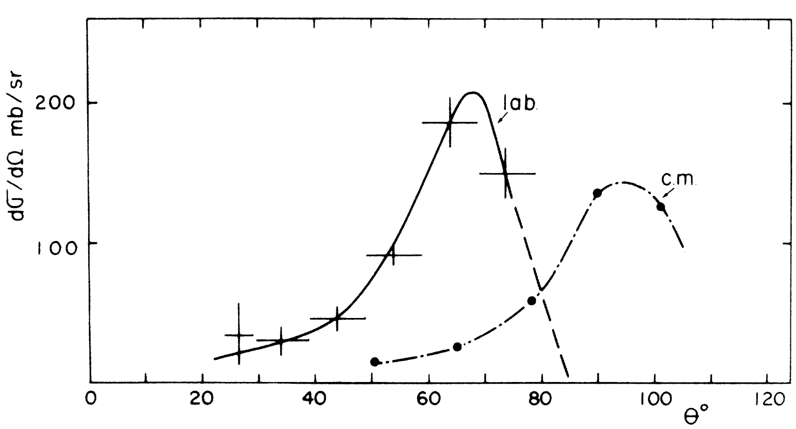

FIG. 3. Angular distributions of the quasi-Kr products in the lab (solid curve) and c.m. (dot-dashed curve) systems. The curves are drawn as a visual aid. The errors are mainly due to the decomposition of the peaks in the energy spectra.

or due to a characteristic of the mechanism independent of this set of values.

After extrapolating $(d\sigma/d\Omega)_{\rm lab}$ at larger angles, as indicated by the dashed line in Fig. 3, the integrated cross section for the production of quasi-Kr is about 500 mb. It is a large part of the reaction cross section (calculated value 870 mb), and this seems to confirm the idea that the quasifission reactions occur instead of the complete-fusion reactions. One should remember, however, that the method used for the angular distribution is based on a hypothesis which is reasonable but not entirely proved for angles far away from 55°.

More work—with more intense beams if possible—has to be done in order to get more detailed information on the features of the quasifission reactions induced by Kr ions. Nevertheless we hope the indications we have obtained will stimulate theoretical work which is now underway for understanding the reaction mechanism. In particular, the angular distribution should help in deciding among the various pictures for the potential energy between the two nuclei which can be considered in order to explain the quasifission reactions.[8]

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Note added.—We have recently made angular-distribution measurements at large angles. The maximum at 65° has been confirmed but the descent above 80° is not as steep as the dashed curve on Fig. 3: At 120° the cross section has decreased down to 4 mb/sr.

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Nuclear Shock Waves in Heavy-Ion Collisions

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It is shown that nuclear matter is compressed during the encounter of heavy ions. If the relative velocity of the nuclei is larger than the velocity of first sound in nuclear matter (compression sound for isospin $T=0$), nuclear shock waves occur. They lead to densities which are 3–5 times higher than the nuclear equilibrium density ρ_0, depending on the energy of the nuclei. The implications of this phenomenon are discussed.

The possibility of compression of nuclear matter in nucleus-nucleus collisions in one of the most interesting aspects of heavy-ion physics. It has been discussed earlier in connection with the sudden nucleus-nucleus potentials[1] and their energy dependence,[2] which seems to confirm the experimentally deduced heavy-ion potentials of the Yale group.[3] These earlier considerations are valid as long as the relative heavy-ion velocity v_r does not exceed the velocity of first sound in nuclear matter c_s; i.e., for $v_r < c_s$. Here the first sound is an isospin $T=0$ compression wave while the second sound describes an isospin $T=1$ wave where a proton-neutron separation travels in constant nuclear matter density $\rho_0 = \rho_p + \rho_n$.[4]

In order to study local compression effects for