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Energy Dependence of Quasifission

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Quasifission reactions induced by 443-MeV ^{63}Cu ions on ^{197}Au are studied and compared with results at 365 MeV. The initial relative motion is completely damped in both cases. At the higher energy, the angular distribution is broader and peaked further forward, and the complete-fusion component is larger. Near the grazing angle partially damped events are observed in addition to quasifission.

The study of heavy-ion–induced quasifission,[1-3] also referred to as strongly damped collisions,[4] is of great current interest. Experimental results exist for bombarding ions from Cu to Kr and for targets from W to Bi, but data for the same system at two different bombarding energies are very limited.[1,4,5] The purpose of this work is to study quasifission induced by 443-MeV ^{63}Cu ions incident on a ^{197}Au target, and to compare the results with those obtained for the same system at 365 MeV.^{3}

The known features of a typical quasifission reaction are as follows. The mass distribution is peaked near the masses of the target and of the projectile. The fraction of the mass distribution located at symmetry is relatively small. The fragment kinetic energies are characteristic of the Coulomb repulsion of fission fragments. The angular distributions are peaked in the vicinity of the grazing angle.

The primary aim of this work was to answer the following questions: (a) Is the fragment kinetic energy in quasifission independent of the bombarding energy? That is, is the initial relative motion completely damped? (b) As one moves higher above the interaction barrier, does the angular distribution tend to look more like those of deep inelastic transfer products from Ar reactions on heavy targets^{6,7} which were obtained relatively high above the interaction barrier? Is there evidence for the onset of nuclear orbiting?^{8}

Beams of 443-MeV ^{63}Cu ions were obtained from the ALICE facility at Orsay. The experimental method was identical to that used in the 365-MeV work.^{3} The energy of each fragment was measured with a surface-barrier detector simultaneously with its velocity. The fragment mass was thus obtained directly and the detection of the fragment partner was not necessary.

The mass distributions obtained at 443 MeV are not as yet analyzed in detail and will be described in a later paper. The general characteristics of the mass distributions of light quasifission fragments are as follows: The peak of the distributions is near the mass of the projectile at an angle close to the grazing angle (68° c.m.), and shifts towards higher masses at angles that are lower than the grazing angle. The width of the distributions increases as the angle decreases from 77° to 8° c.m.

The above characteristics are quite similar to those observed at the lower bombarding energy of 365 MeV.^{3} The most apparent difference at 443 MeV is the higher percentage of products of mass close to half the mass of the total system; they are clearly seen at 90° c.m. where the cross section for quasifission products is small, and may be attributed to fission after complete fusion. The following possibility, however, cannot be ruled out: It is possible that these products result from the quasifission of a composite system which has lived long enough so that almost complete mass equilibration between the two parts of the system has taken place. In such a case the rotation time before scission is large, and the products are observed at large negative angles (see Fig. 1 and discussion below).

Fragment c.m.-kinetic-energy spectra close to the grazing angle (44° lab) and forward and backwards of it (35° and 56° lab) are shown in Fig. 2. It can be seen that at 35° and at 56° there is a clear separation between the quasifission peak and the elastic peak. Such a separation was observed at all angles except near the grazing angle where partially damped events fill in the region between quasifission and elastic events. Since we have observed the partially damped events only at one angle, they must be limited to a rather narrow angular region. At the other angles, the widths of the quasifission peak all lie between 60 and 73 MeV full width at half-maximum, while the average total c.m. kinetic energies (i.e., sum of the energies of both fragments) lie between 201 and 214 MeV. (These values are corrected for neutron emission from the fragments, assuming that the neutrons are emitted from both fragments in proportion to their respective masses). By taking the same shape and location of the quasifission peak at 44° as at the other angles, it is possible to decompose the

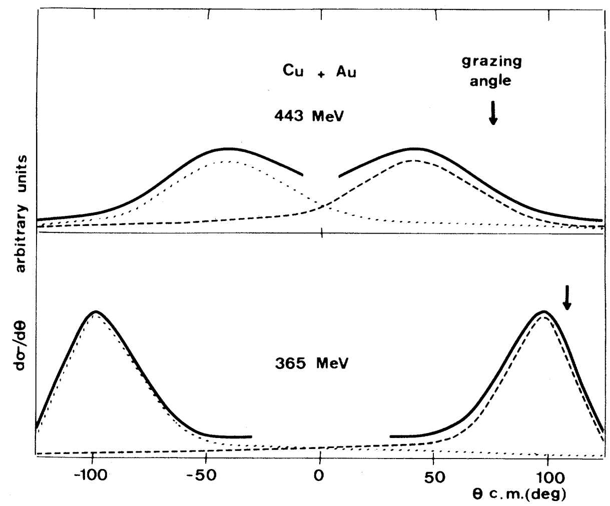

FIG. 1. Possible decomposition of observed angular distributions (solid curves) into positive and negative components. The dashed and dotted curves represent angular distributions (including negative angles) which could account for the observed distributions. At 365 MeV the contribution from negative angles shown here is the maximum that is compatible with the data, but the results can also be understood without assuming a contribution from negative angles. At 443 MeV, a contribution from negative angles is necessary for an understanding of these data.

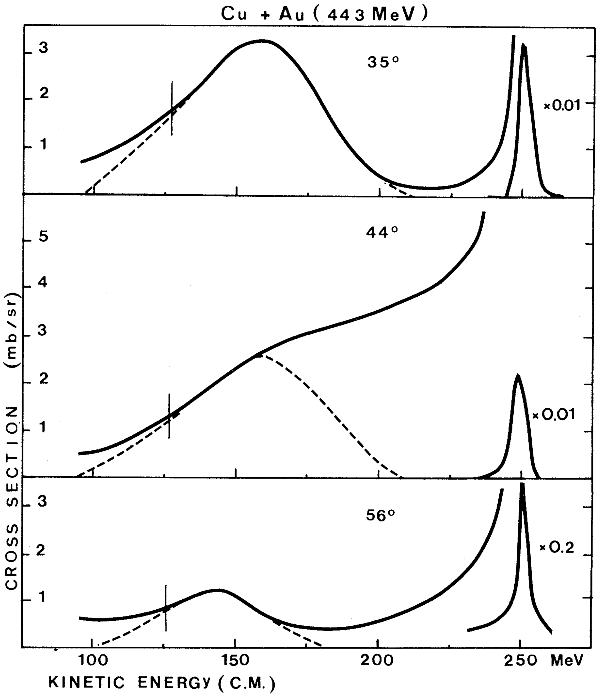

FIG. 2. Center-of-mass kinetic energy distributions of the light products detected at angles forward of the grazing angle (35° lab), close to it (44°), and backward of it (56°). The corresponding average center-of-mass angles (for the quasifission products) are 48°, 62°, and 77°. The solid curves give the total distribution, and the dashed curves the quasifission component (see text). At 44° lab the quasifission component was obtained by assuming a shape and position consistent with the quasifission peaks at 35° and 56°.

events at 44° into quasifission (completely damped) and partially damped events as shown in Fig. 2.

The overall average fragment total kinetic energy (207± 5 MeV) is equal to that observed at a bombarding energy of 365 MeV: 206± 5 MeV. Both values were obtained in the same experiment (they should be compared with the value of 200± 5 MeV obtained in an earlier run at 365 MeV[3] for an indication of the absolute experimental accuracy). Thus quasifission involves complete damping of the initial relative motion regardless of the bombarding energy; this confirms earlier results for ^{209}Bi + Kr.[1,4]

The angular distribution of light quasifission products is shown in Fig. 3. When the differential cross section is expressed in units of solid angle, the angular distribution is forward peaked [Fig. 3(a)]. If, however, we consider the cross section integrated over the azimuthal angle ($d\sigma/d\theta$), the angular distribution has a broad peak at

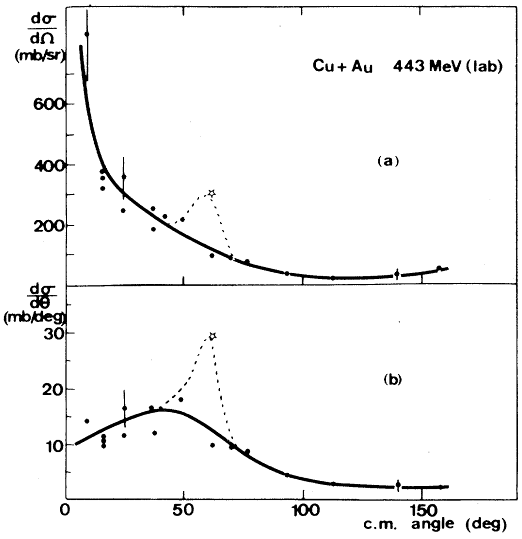

FIG. 3. Angular distributions of light products in the center-of-mass system: (a) $d\sigma/d\Omega$ and (b) $d\sigma/d\theta$ [i.e., the curve of (a) multiplied by sinθ]. The solid curves are for quasifission (and fission) products only; the dotted curves include partially damped events (see text). For the meaning of the open star, see text.

42° c.m. [Fig. 3(b)]. The solid curves of Fig. 3 are based on completely damped events only. If at 62° c.m. we include partially damped events, then we obtain at that angle the open star of Fig. 3, resulting in the sharp peak in the angular distribution given by the dotted line.

The most interesting aspect of the angular distribution of Fig. 3(b) is the indication that nuclear orbiting is taking place, and that the angular distribution includes substantial contributions from negative angles. This follows from the fact that $d\sigma/d\theta$ at 0° is about 60% of its peak value. A schematic decomposition of the angular distribution into positive and negative angles is shown in Fig. 1. In contrast, the sharp angular distribution at 365 MeV[3] rules out a large contribution from negative angles at this lower bombarding energy.

From an integration of the angular distribution of Fig. 3 (solid line) we obtain a cross section for the sum of fission and quasifission of 1250 ± 150 mb. The calculated total reaction cross section is 1500 mb. In order to separate the quasifission and fission components from each other, a detailed knowledge of the mass distributions is required. Since these are not yet available, we cannot assign a value to the fission cross section (and hence to the upper limit of the complete-fusion cross section), but as was mentioned above, preliminary indications are that it is considerably higher than the value observed at the lower bombarding energy (365 MeV).

The ^{63}Cu bombarding energy of 443 MeV is about 1.4 times the interaction barrier for ^{197}Au. This reaction can be compared with Th + Ar at 288 MeV and with Bi + Kr at 605 MeV also at ~ 1.4 times the interaction barrier.[4] Since the relative energy above the interaction barrier is similar in the three cases, our ^{63}Cu case is expected to be intermediate between the quasifission of Kr + Bi and the deep inelastic transfer from Ar + Th. The angular distribution in the Kr + Bi case is sharply peaked near the grazing angle, while it is more forward peaked in the Ar + Th case.[6] Thus our Cu + Au angular distribution with a broad maximum and a substantial contribution at 0° is ineed intermediate between the distributions obtained with Ar and Kr ions. These considerations indicate that quasifission and deep inelastic transfer processes are the same type of reaction, and that the observed angular distributions of products are determined by the magnitude of the repulsive Coulomb potential compared to the attractive nuclear potential.

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Simple Approximation for Multistep Amplitudes*

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A surface approximation to the multistep amplitude for direct reactions is presented. Within this approximation, the distorted-wave Born-approximation series is summed in closed form, and the result is tested by comparing with exact coupled-reaction-channels calculations for ^{17}O$(p,d,p)^{17}$O and ^{16}O$(d,p,d)^{16}$O. The approximation gives a good representation of the exact results, especially for the ^{16}O$(d,p,d)^{16}$O process which is dominated by strong absorption of the deuteron.

Multistep corrections to the distorted-wave Born approximation (DWBA) are currently of great interest,[1-9] especially in the light of recent observations[10] of direct reactions that cannot be adequately described by the DWBA. The present communication describes a new approximation[11] for the multistep transition amplitude which emphasizes the nuclear surface. For this reason our method may not be well adapted for the description of the dynamics of the interior, which is probably better represented by shell-model states than by asymptotic channels. However, for the rather large class of reactions involving strong absorption, the method appears promising. Conveniently, it requires only ordinary DWBA matrix elements which are easily provided by standard codes. Our method does not address questions of mathematical rigor. Rather, it aims to simplify realistic calculations of multistep contributions to direct reactions in which absorption is an important feature. Although the distorted-wave series has been criticized,[2,3,5,8,12] we use it to illustrate our method, which is also applicable to iterative versions of the coupled-reaction-channels[7] and coupled-integral-equations[2] approaches, as well as to the methods discussed in Refs. 3-5. We hope that our method will facilitate exploratory surveys of possible multistep processes and stimulate identification of dominant indirect mechanisms for any given reaction.

For the reaction $A(a,b)B$, the exact multistep