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Onset of nonequilibrium phenomena in fusionlike processes for ^{16}O-induced reactions

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We have measured velocity spectra of evaporation residues from the reactions $^{16}O+Al$, Ca, and Ni at bombarding energies of 8.8, 13.6, and 19.6 MeV/nucleon. Comparison with statistical model predictions shows clear evidence for the onset of incomplete momentum transfer at about 5 MeV/nucleon above the interaction barrier. To first order, the results are similar for all targets, suggesting that the missing momentum is mainly associated with the projectile. The fraction of transferred linear momentum appears to decrease linearly with increasing relative velocity of the colliding nuclei at the barrier.

[NUCLEAR REACTIONS $^{16}O+Al$, Ca, Ni. $E(^{16}O)=8.8$, 13.6, and 19.6 MeV/nucleon. Measured residue velocity distributions. Deduced linear momentum transfer.]

At bombarding energies not too far above the interaction barrier, the complete fusion of heavy ions to form an equilibrated compound nucleus comprises a dominant part of the total reaction cross section. Further increase of the bombarding energy induces reactions that approximate fusion but exhibit nonequilibrium features. In such cases, it is generally believed that only a part of the projectile or target fuses with the other partner, while the remaining part is emitted presumably at an early stage of the collision and prior to the thermalization of the composite system. Such fusionlike processes, well known for heavy systems, have been referred to variously as preequilibrium emission,[1] incomplete fusion,[2] or massive transfer,[3] etc. The present experiment was undertaken to extend such studies into the lighter mass region ($A_{CN}\leq 80$), where the importance of incomplete fusion has been suggested[4–6] but is not as well documented.

Previous studies have emphasized the observation of forward-peaked, fast light particles (n, p, d, α) with velocities near to or greater than the beam velocity, sometimes in coincidence with the residual-like fragments.[2,3,5,6] It follows that the onset of such a phenomenon should also be reflected in a reduced average velocity of the associated heavy residues.[7] Measurements of fission fragment angular correlations have demonstrated such an effect for reactions involving a heavy fissile compound nucleus.[8] This technique is not applicable to lighter systems, however, and has necessitated the introduction of a different experimental approach, one in which the average velocity (or the linear momentum) of the residues is measured directly and compared with evaporation model predictions. Deviations of the observed velocity centroid and/or spectrum shape may be interpreted in terms of reaction mechanisms other than complete fusion followed by equilibrium decay. Similar measurements based on this technique have been reported recently[9] or are in progress.[10,11]

The experiment was performed at the 88-inch Cyclotron of the Lawrence Berkeley Laboratory at ^{16}O bombarding energies of 8.8, 13.6, and 19.6 MeV/nucleon. The energies were chosen to cover the region where one expects to see predominantly complete fusion (8.8 MeV/nucleon) as well as regions where nonequilibrium phenomena can be important (13.6, 19.6 MeV/nucleon). Conventional time-of-flight techniques were used to measure the velocity of the residual nuclei. The start signal was obtained from a channel plate detector with a thin carbon conversion foil ($\sim 20\ \mu g/cm^2$) in a 45° geometry.[12] A 900 mm^2, 100 μm thick Si surface barrier detector (offset by 15° to the flight path in order to minimize geometrical path differences) provided the stop signal as well as energy information. The flight path was 1.8 m long. Natural calcium and aluminum, as well as ^{60}Ni targets with thickness of ~ 235, 215, and 180 $\mu g/cm^2$, respectively, were used. Masses up to about 50 u could be resolved [Fig. 1(a)], which was adequate except for the $^{16}O+^{60}Ni$ reaction. In the latter case, results were obtained from summed mass bins instead of from individual masses. The evaporation residues were measured at forward angles from 5° to 20°.

An important aspect of the experiment was to establish an accurate absolute calibration for the velocity. This was done by measuring the elastic scattering of 1.5 MeV/nucleon ^{40}A ions which have mass and velocity similar to those of the residual nuclei produced in the reactions studied. Energy losses in the target and the channel plate foils were corrected on an event-by-event basis in generating the final velocity spectra.

For decay processes symmetric about 90° in the rest frame of the emitter, the velocity dependence of the quantity $F(v) \equiv (1/v^2) d^2\sigma/dv d\Omega$ is expected to be a Gaussian centered at $V_{c.m.}\cos\theta$, where v is the velocity of the residues in the laboratory, θ is the laboratory detection angle, and $V_{c.m.}$ is the velocity of the center of mass.[13] This relation has been verified with Monte Carlo evaporation model calculations. Figure 1(b) shows a spectrum of $N(v)/v^2$, which is proportional to $F(v)$, for residues of mass 43 detected at 5° for 13.6 MeV/nucleon ^{16}O + ^{40}Ca.

The centroid $\bar{v}$ of $N(v)/v^2$ for each mass and angle has been determined both by numerical evaluation of the spectrum centroid and by fitting a Gaussian function to the spectrum. These two methods agreed to within about 3%. The results for ^{16}O + ^{40}Ca are compared with those expected for full momentum transfer in Figs. 2(a)–2(c). The measured centroids have been divided by $\cos\theta$ for this comparison. The histograms in Fig. 2 show the relative mass yield at 5° at the three bombarding energies.

It is clear that the quantity $\bar{v}/\cos\theta$ depends only weakly on the residual mass and the scattering angle. The deviations from $V_{c.m.}$, averaged over all masses and angles, are also indicated in the figure. The deviations increase wtih bombarding energy. If one assumes, for illustration, that a particle of mass Δm escapes at 0° with the beam velocity before thermal equilibrium is reached, the deviations in Fig. 2 would correspond to $\Delta m = 0.9$, 2.1, and 3.8 u at $E = 8.8$, 13.6, and 19.6 MeV/nucleon, respectively. The results obtained with ^{27}Al and ^{60}Ni targets exhibit the same qualitative features.

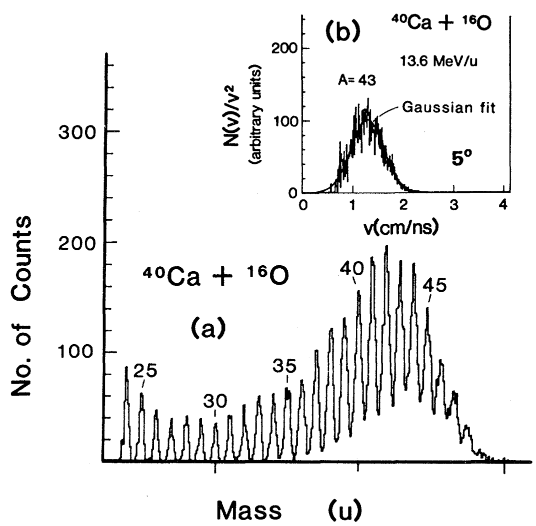

FIG. 1. (a) Partial mass spectrum for ^{16}O + ^{40}Ca at $E_L = 13.8$ MeV/u and $\theta = 5°$ (lab). (b) $N(v)/v^2$ spectrum for $A = 43$. N is the number of counts per unit velocity interval. The curve is a Gaussian fit to the spectrum.

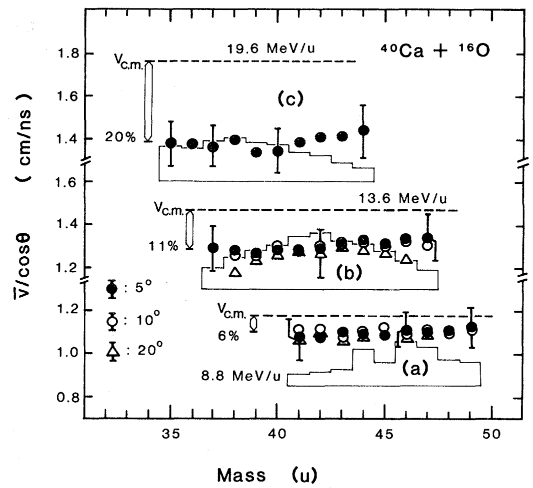

FIG. 2. Comparison of $\bar{v}/\cos\theta$ of the reduced velocity spectra (see text) with the center of mass velocity at (a) 8.8 MeV/u, (b) 13.8 MeV/u, and (c) 19.6 MeV/u. The relative mass yields at 5° are shown by histograms.

The shape of the velocity spectra, mass yield, and angular distribution of the residues may also be compared with a statistical model prediction as was done in Ref. 13. The results of this comparison will be presented elsewhere. In the following, we shall concentrate on the observed, angle-, and mass-averaged velocity centroids which we express as a percentage of the velocity corresponding to full momentum transfer followed by equilibrium decay. This quantity is plotted in Fig. 3 versus the relative velocity of the colliding partners at the interaction barrier ($r_0 = 1.5$ fm). The errors on the data points reflect uncertainties in the velocity calibration, corrections for energy loss in target, and centroid determination. The variation of results obtained at different angles and for different masses is less than the indicated error. Even though there is some dispersion in the data, an apparent systematics is seen to emerge; the amount of transferred momentum, expressed as a percentage of the total available linear momentum, is governed essentially by the relative velocity of the projectile and target nuclei at the barrier. Within errors, the deviations of the averaged centroids from the predictions of full momentum transfer appear to be independent of the target, suggesting that the missing momentum is mainly associated with the ^{16}O projectile.

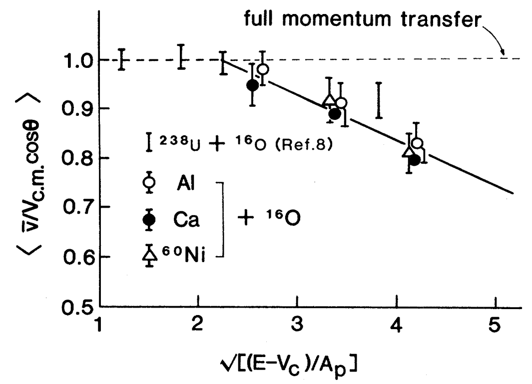

FIG. 3. Systematics of the mean velocities of fusionlike residues, expressed as a percentage of the velocity corresponding to complete momentum transfer. The abscissa is the relative velocity, $(\mathrm{MeV/u})^{1/2}$, of the projectile and target at the interaction barrier ($r_0 = 1.5$ fm). The energy E and Coulomb barrier V_c are evaluated in the laboratory system.

The data also exhibit an approximately linear behavior in the decrease of the fraction of transferred momentum as a function of velocity, as is suggested by the straight line fit to our data points. A similar result has been reported by Viola *et al.*[14] for reactions involving heavier targets. These results suggest a common onset of incomplete momentum transfer in fusionlike reactions at about 5 MeV/nucleon above the interaction barrier. For comparison, also included in Fig. 3 are the results of Ref. 8 obtained from fission fragment correlation measurements using ^{16}O projectiles and a much heavier, ^{238}U target. Except for the highest energy point, which lies two standard deviations above the fitted line, these results are consistent with our systematics and, together, suggest that the relative velocity of the projectile and target at the interaction barrier is a relevant parameter for characterizing incomplete linear momentum transfer in fusionlike processes. The data shown in Fig. 3 are consistent, with there being little or no dependence of the missing momentum on the mass of the target. These simple results, if validated by additional experiments on a wider range of targets, should prove valuable in the evaluation of theories of preequilibrium emission or incomplete fusion.

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