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INCOMPLETE MOMENTUM TRANSFER IN PERIPHERAL
HEAVY ION COLLISIONS AT 20 MEV/A

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Abstract:

Projectile residues have been studied in coincidence with fragments resulting from fission of the target residue for reactions induced by 315 MeV $^{16}$O ions on a $^{238}$U target. A kinematical analysis shows that the forward linear momentum transferred to the target nucleus is significantly smaller than that expected for simple transfer reactions, but larger than that expected for pure projectile fragmentation processes.
At energies of only a few MeV/A above the Coulomb barrier, peripheral heavy ion collisions have been shown to be mainly two body reactions followed by the subsequent decay of the primary reaction products by particle emission or fission.\textsuperscript{1-3} At relativistic energies (E/A $\geq$ 200 MeV/A), on the other hand, peripheral reactions are largely associated with a projectile fragmentation process in which the target nucleus acts as a mere spectator to which only a small amount of momentum is transferred.\textsuperscript{4} Until now, however, the momentum transfer to the target residue has not been directly measured for heavy ion reactions above 10 MeV/A. In this letter we report the first such measurement for the reaction \textsuperscript{16}O + \textsuperscript{238}U at about 20 MeV/A.

The experiment was performed at the 88-inch cyclotron of the Lawrence Berkeley Laboratory. Targets consisting of 200 $\mu$g/cm$^2$ UF$_4$ on a 50 $\mu$g/cm$^2$ carbon backing were bombarded by \textsuperscript{16}O$^{6+}$ ions of 315 MeV. Projectile-like reaction products were identified with a solid state $\Delta E$-$\Delta E$-E telescope (27 $\mu$m, 70 $\mu$m and 3 mm thicknesses, respectively) at the laboratory angle of 15°. Coincident fragments resulting from fission of the target residue were detected by two position sensitive solid state detectors, arranged in the geometry shown in Fig. 1. The data were recorded event-by-event on magnetic tape and analyzed off-line. For each event an iterative procedure was used to correct for post fission neutron evaporation and for pulse height defects in the fission detectors. Gates were placed on various element numbers and energies of the projectile residues and a kinematical analysis was carried out for each event in order to extract distributions of momentum components parallel to the beam momentum $p_1$. 
The momentum transferred to the target residue can be expressed as

\[ \mathbf{p}_R = \mathbf{p}_A + \mathbf{p}_B \]  

(1)

where the indices R, A and B denote the target residue and the two primary fission fragments, respectively. Projection of the vectors of Eq. 1 onto the direction perpendicular to \( \mathbf{p}_R \) gives the relation

\[ \frac{M_A}{M_B} = \frac{E_B \sin^2 (\theta_B + \theta_R)}{E_A \sin^2 (\theta_A - \theta_R)} \]  

(2)

projection onto the direction perpendicular to \( \mathbf{p}_A \) gives

\[ p_R^2 \sin^2 (\theta_A - \theta_R) = \frac{2E_B (M_A + M_B) \sin^2 (\theta_A + \theta_B)}{1 + M_A/M_B} \]  

(3)

or with Eq. 2,

\[ p_R^2 = \frac{2(M_A + M_B) E_A E_B \sin^2 (\theta_A + \theta_B)}{E_B \sin^2 (\theta_B + \theta_R) + E_A \sin^2 (\theta_A - \theta_R)} \]  

(4)

Here, the momenta \( p \), the energies \( E \), and the angles \( \theta \) refer to the laboratory frame of reference (see also Fig. 1). The quantities \( E_A, E_B, \theta_A \) and \( \theta_B \) are determined experimentally. Eqs. (2) and (4), therefore, contain four unknown quantities \( (M_A, M_B, p_R, \theta_R) \), leaving two parameters undetermined.

One degree of freedom can be removed by assuming that \( M_A + M_B \) is equal to the mass of the target nucleus. This introduces only a small uncertainty and it was verified that the final results are not very sensitive to this assumption.
The remaining degree of freedom cannot be removed on an event by event basis. It is this uncertainty which prevents a precise determination of the momentum components perpendicular to the beam direction. However, it is still possible to determine $p_R$, the component of the recoil momentum parallel to the beam axis, with good accuracy. This can be understood by noting that the experimental setup was such that $\theta_A \approx 90^\circ$. With Eq. 3, this gives $p_R = p_R \cos \theta_R \approx p_R \sin (|\theta_A - \theta_R|)$. Therefore, the main uncertainty in the determination of $p_R$ arises from its dependence on the mass ratio $M_A/M_B$ (which is not very well determined because of its dependence on $\theta_R$). This uncertainty is, however, rather small for the kinematic conditions encountered in this experiment.

For the analysis of the data we write the total momentum $\vec{p}$, as the sum of the momenta of the projectile residue ($\vec{p}_3$), the fissioning nucleus ($\vec{p}_R$) and the "missing momentum" $\vec{p}_m$ (see Fig. 1):

$$\vec{p}_1 = \vec{p}_3 + \vec{p}_R + \vec{p}_m.$$

(5)

The range of values of $\theta_m$, the angle of the "missing momentum" with respect to the beam direction, can be assessed by making the following observation: For peripheral reactions at 20 MeV/A, energetic light particles are mainly emitted into a rather narrow angular interval into the forward direction. These particles are expected to carry a significant part of the "missing momentum" $\vec{p}_m$. We therefore chose the constant value of $\theta_m = 0$. This choice was also justified by using different constant values of $\theta_m$ and calculating the resulting mass asymmetry $c(\theta_m) = (M_B - M_A)/(M_A + M_B)$, averaged over all events within a given gate.
By requiring that \( \epsilon(\theta_m) \) is consistent with the value that is expected for
the average kinematic situation corresponding to that gate, one
finds that the average value of \( \theta_m \) lies in the angular interval of
\(-30^\circ < \theta_m < +30^\circ\). The dependence of our result on variations of \( \theta_m \)
within this interval has been included in the errors of Fig. 3.

With the direction of the missing momentum fixed at \( \theta_m = 0 \), the
parallel momentum components were calculated for each event.
The resulting distributions (summed over all energies) of \( p_m \)
are shown in Fig. 2 for different projectile residues. For
the purpose of orientation, the missing momenta corresponding to the
extreme limit of pure projectile fragmentation, have been marked by arrows.
They were calculated as \( p_m = p_1 (M_1 - M_3) / M_1 \) which corresponds to the
assumption that the undetected fragment of mass \( M_1 - M_3 \) has the beam
velocity. The other extreme situation of a pure transfer reaction
corresponds to \( p_m = 0 \) and is marked by the dashed vertical lines in the
figure. With decreasing atomic number of the coincident projectile
residue the centroids of the \( p_m \) distributions increase. In no case,
however, do they agree with either of the extreme situations of transfer or
fragmentation. Moreover, from the widths of the \( p_m \) distributions one
can rule out the possibility that these distributions are due to a
simple superposition of pure transfer and pure fragmentation processes.
Rather it appears that we are confronted with an intermediate type
of reaction. It should be noted that part of the widths of the \( p_m \)
distributions is due to the smearing of the fission angles by neutron
evaporation. The mean fission angles and mean \( p_m \) however, are not
affected by isotropic neutron evaporation.
To obtain more information, we set gates on different energy bins for the projectile residues and determined, for each gate, the average parallel momenta of the outgoing projectile and target residues, $<p^\parallel_R>$ and $<p^\parallel_3>$. The resulting relation between $<p^\parallel_R>$ and $<p^\parallel_3>$ is shown in Fig. 3. For the purpose of orientation, the two-body transfer limit, $p_{tr} = p_1 - p_3$, is shown by the solid line. The average missing momentum $<p^\parallel_m>$ can be read off this figure as the distance of the actual values of $<p^\parallel_R>$ from this line: $<p^\parallel_m> = p_{tr} - <p^\parallel_R>$.

For low momenta (i.e. low kinetic energies) of the outgoing projectile residues the average missing momentum becomes a substantial fraction of the beam momentum. More surprisingly, however, is the observation of an approximately linear dependence of $<p^\parallel_R>$ on $<p^\parallel_3>$, which shows that $<p^\parallel_R>$ is about 65% of the momentum transfer expected for a transfer reaction. This linear dependence on $<p^\parallel_3>$ is significantly more pronounced than any remaining dependence on the atomic number of the projectile residues. The extreme situation of pure projectile fragmentation where the target nucleus acts as a mere spectator corresponds to $p_R = 0$. The average kinematic situation observed experimentally cannot be explained by a simple superposition of pure transfer and fragmentation processes (see discussion of Fig. 2). Rather the reaction appears to be dominated by an intermediate process which is observed for a large dynamic range of energies and atomic numbers of the outgoing projectile residues. From the rather unique dependence of this process on the parallel momentum of the projectile residue and the forward direction of the missing momentum ($|\theta_m| \leq 30^\circ$), it appears that
the mechanism of momentum transfer and energy dissipation at projectile energies of about 20 MeV/A is closely connected with the fast emission of a "jet" of particles preferentially into the forward direction.

To summarize, we have shown that for peripheral reactions induced by $^{16}$O ions of about 20 MeV/A the momentum transferred to the target residue is intermediate between the calculated momentum transfer for the extreme cases of a two body transfer reaction and a projectile fragmentation reaction. The measurement of the projectile energy dependence of this process should yield additional important information on the change in the reaction mechanism from deeply inelastic and quasi-elastic reactions at low energies to fragmentation reactions at higher energies.

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FOOTNOTES AND REFERENCES

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FIGURE CAPTIONS

Fig. 1 Schematic diagram of experiment and relevant momentum vectors.

Fig. 2 Distributions of the missing parallel momentum $p_m^\parallel$ for different projectile residues.

Fig. 3 Dependence of the average parallel recoil momentum $<p_R^\parallel>$ on the average parallel momentum $<p_3^\parallel>$ of the projectile residue. The error bars include statistical errors and an estimate of the uncertainty due to the choice of $\Theta_m$. 
Fig. 1
Fig. 2
\[ \langle p_R^\| \rangle / p_1 \]

\[ p_R^\| = 0.65 (p_1 - p_3^\|) \]

\[ \text{TWO-BODY TRANSFER REACTIONS} \]

\[ \text{Li, C, Be, N, B} \]

\[ ^{16}\text{O} + ^{238}\text{U}, \ 315 \text{ MeV} \]
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