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# Transfer and Fragmentation Reactions in $^{16}O$ + CsI at 16.4 MeV/n*

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ABSTRACT

A streamer-chamber particle-telescope system has been used to observe ejectile charge, energy, and associated charged particle multiplicity in the reaction of $^{16}O$ + CsI at 16.4 MeV/n. The measurement provides relative probabilities for transfer and projectile fragmentation as a function of ejectile charge, and spectra for the heavy ejectiles from transfer and fragmentation events. The results show that the interaction energy of 16.4 MeV/n is near the threshold for fragmentation reactions in heavy-ion collisions.

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The basic mechanism of peripheral heavy-ion reactions appears to change between 10 and 100 Mev.[1,2] At lower energies one observes mostly mass transfer, and some forms of projectile breakup. The inclusive energy spectra of the heavy-ion ejectiles are narrow, with reduced momentum widths of $\sim$40 Mev/c.[2] At energies above 100 MeV/n the reaction mode is predominately projectile fragmentation, and the spectra have broadened to the same reduced momentum width[3] (80 MeV/c) as that observed at 2 GeV/n. It is likely that the characteristics of the inclusive heavy-ion singles spectra between these energies are due largely to the change from one dominant reaction type to another. We have begun to investigate this transition experimentally in order to find its cause and to uncover its effects on the spectra of the reaction products. Our approach has been to measure the total charged particle multiplicity of a heavy-ion reaction with a $4\pi$ detector and thus separately identify and study the transfer and fragmentation events. This is the first experiment at an energy in the transition region in which the complete reaction multiplicity has been explicitly determined.

We observed the reaction of $^{16}O$ + CsI at 16.4 MeV/n with a hybrid streamer chamber[4] triggered by solid state telescopes. The telescopes measured ejectile charge and energy, while the streamer chamber recorded the $4\pi$ event multiplicity. The use of a heavy target prevented the recoil from being observed and also minimized

charged particle evaporation. This insured that, for most events, all of the observed charged particles were from the projectile.

A thick (49 mg/cm$^2$ ) target of pressed CsI powder was located inside the chamber, and a 315 MeV $^{16}$O beam was extracted from the LBL 88-Inch Cyclotron; after energy losses in the windows, chamber gas, and target this provided an interaction energy of 17.8 - 14.9 MeV/n. The entire fiducial volume was viewed by one camera mounted normal to the reaction plane. Outside of the chamber three Si(Li) particle telescopes were positioned at angles of 12.5$^\circ$ , 17.5$^\circ$ , and 24$^\circ$ . The chamber was triggered by any of the three telescopes, and the $4\pi$ charged particle track image photographed; simultaneously the data from the telescope were recorded on magnetic tape with the identifying event number of the photograph. For the purposes of discussion, the reaction events will be divided into two groups according to their charged particle multiplicity. The target-like recoil is too heavy to be detected. Therefore events with a track multiplicity of one (M=1) correspond to two charged particles in the final state; these events are identified as transfer. Events with multiplicity $M \geqslant 2$ have three or more body final states, and include both fragmentations and statistical evaporation.

We first examined the multiplicity data to determine if we were observing a significant number of both transfer and

fragmentation events. It was necessary to first separate target-related evaporation tracks from the projectile-related charged particles in order to identify fragmentations. It was assumed that target related evaporation is isotropic in the lab frame, and that all projectile fragments go into a forward cone. The frequency of backward-going tracks is then approximately one-half of the total frequency of target-related evaporations. The multiplicity distributions were corrected accordingly.

Table I summarizes the event multiplicities as a function of the trigger particle's charge. (The total number of backward tracks observed for each ejectile is included in the table to indicate the frequency of target evaporations.) The M=1 events are assumed to be transfers. Because the $M \geqslant 2$ events have had backward tracks subtracted, they must be projectile fragmentations rather than massive transfers followed by evaporation from the heavy recoil. These fragmentations account for approximately 30% of all events.

The $M \geqslant 2$ events are confirmed to be projectile fragmentations by a comparison of the energy spectra for the two components. The mean energies of the separated spectra for M=1 and $M \geqslant 2$ are summarized in Table II. For each ejectile charge the mean energy for $M \geqslant 2$ is 10 - 20 MeV less than the mean energy for M=1. These differences in energy are not trivially due to differences in

ejectile masses for the two components - for each Z greater than Be the mean ejectile masses for M=1 and M $\geqslant$2 agree to within 0.1 AMU. We conclude that these data reveal a real difference in the energetics of the M=1 and M $\geqslant$2 events. This difference is consistent with the M $\geqslant$2 events being projectile fragmentation reactions. To show this, consider the following possible fragmentation mechanisms:

1) direct projectile fragmentation,
2) inelastic excitation of $^{16}O$ to levels above the particle threshold ( $^{16}O \rightarrow {}^{16}O^{*} \rightarrow {}^{12}C + {}^{4}He$).
3) stripping reactions leaving the projectile fragment above the particle threshold ( $^{16}O \rightarrow {}^{12}C^{*} \rightarrow {}^{11}B+p$),
4) pickup reactions to states above the particle threshold ( $^{16}O \rightarrow {}^{19}F^{*} \rightarrow {}^{11}B+X$).

It is most likely that the pickup mechanism would produce events with M $\geqslant$3 through emission of alphas and protons. Because most of our higher multiplicity events are M=2, we relegate such pickup reactions to a minor role.

The ejectiles for the transfer events are observed to have nearly beam velocity (Table II), which is consistent with earlier data[1] and with semiclassical theories of angular momentum matching.[7] This velocity defines a Q-value for the M=1 events. If we assume that the M=2 events are either direct projectile

breakups, or breakups of projectile residues from stripping reactions, we may then calculate similar Q-values for these events. With the further assumption that the breakups occur at threshold and isotropically in the projectile or projectile fragment frame, this Q-value calculation predicts that the mean energies of the M=1 and $M \geqslant 2$ events should differ by the amounts shown in Table II. The calculated differences are in full agreeement with the data.

On the other hand, the observation of M=1 ejectiles at velocities less than or equal to beam velocity indicates Q-values of at least -15 to -150 MeV for A=1 to A=10 transfers. It is unlikely that an additional excitation of 10 - 20 MeV in the heavy recoil would be necessary or sufficient to cause it to begin evaporating charged particles. Therefore the 10 - 20 MeV difference in mean energies does not appear to be consistent with the $M \geqslant 2$ events being massive transfers followed by evaporation from the heavy recoil.

The $M \geqslant 2$ events have been identified as fragmentation reactions by two independent observations. The multiplicity data therefore show that the interaction produces a significant number of both transfers and projectile fragmentations for each ejectile charge, confirming that the transition is underway.

We have endeavored to find evidence in the cross-sections for the cause of the transition from transfer to fragmentation. Our

measurement has provided only relative cross-sections. Nevertheless, these data are consistent with a model in which a limiting angular momentum for transfer causes the onset of fragmentation.

To obtain the relative cross-sections for each ejectile charge the angular distributions of the M=1 and $M \geqslant 2$ events were fit with a function of the form $(e^{-\theta/\alpha})/\sin\theta$ and integrated over angle. Figure 1a shows the relative inclusive cross-sections and the relative cross-sections for transfer, normalized to the yield of nitrogen ejectiles. We now combine these data with the results of previous measurements at other energies. Figure 1b summarizes the relative inclusive cross-sections, normalized to a nitrogen ejectile, for the reactions of $^{16}O$ + (Zr,Au,Pb) at 8.8 and 19.7 MeV/n.[1] The data at 8.8 MeV/n have been well reproduced by an incomplete fusion calculation which assumes only binary reactions.[5] We may thus assume that nearly all of the events at 8.8 MeV/n, excluding ( $^{16}O^{*} \rightarrow {}^{12}C + {}^{4}He$), are transfer reactions. As the interaction energy increases, the relative inclusive strength of the lighter ejectile channels increases. The same incomplete fusion calculation applied at 19.8 MeV/n significantly underpredicts the inclusive yields of ejectiles with $A<12$. However, comparison with Figure 1a shows that the transfer components of the cross-sections at 8.8 and 16.4 MeV/n are quite

similar, indicating that the increased inclusive strength in the lighter ejectile channels is principally in the form of fragmentation reactions, and that these fragmentation reactions begin somewhere between 10 and 15 MeV/n.

This qualitative behavior was predicted by Siwek-Wilczynska, et. al.[6] as arising from a limiting, or critical angular momentum for massive transfer. Their model assumes that the reaction cross-section for fusion and massive transfer preferentially goes into the most massive transfer channel, until the incident cluster's angular momentum exceeds the critical angular momentum at which that cluster can transfer. (The critical $\ell$ corresponds to a limit on the centrifugal force which the cluster may sustain in a bound state of the target.) Those partial waves above the critical $\ell$ are diverted into the next lighter transfer channel. As the interaction energy increases the total reaction cross-section increases, but is shifted toward lighter channels. Eventually the highest partial wave exceeds the critical $\ell$ for all massive transfers, and the remaining cross-section is diverted into fragmentation. At 10 MeV/n all of the heavy-ion transfer channels for $^{16}O$ + CsI are below their critical angular momentum. At 13.4 MeV/n all of the massive transfer channels have reached or exceeded their critical angular momenta. We conclude that we are seeing at 16.4 MeV/n the predicted onset of the fragmentation channel.

This measurement of $^{16}O$ + CsI reaction multiplicities and energy spectra at 16.4 MeV/n has provided explicit data on the transition from transfer to fragmentation in heavy-ion reactions. We have observed both M=1 and M $\geqslant$ 2 events for all heavy ejectiles. The higher multiplicity events have a low incidence of backward-going tracks and a mean energy clearly different from the transfer events. We conclude that we are observing both transfer and fragmentation reactions and are thus in the transition region between these two phenomena. By viewing our data at 16.4 MeV/n in conjunction with published measurements[1] for $^{16}O$ plus other targets at 8.8 and 19.7 MeV/n we find that as the interaction energy increases above $\sim$10 MeV/n the relative cross section for the lighter ejectiles increases due to the onset of fragmentation. This behavior was predicted by Siwek-Wilczynska[6] to occur at $\sim$13.5 MeV/n, on the basis of a limiting angular momentum for massive transfer. Our experiment has thus localized the transition energy range and provided some evidence that it is semiclassical in origin. At this point it becomes essential to make a good measurement of the momentum widths for each ejectile mass and reaction channel, to understand their behavior during the transition.

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Table I. The associated charged particle multiplicities, summed over angle after correction for target evaporations. Also included is the total number of observed backward-going tracks for each ejectile charge.

| $Z_{TRIGGER}$ | MULTIPLICITY 1 | 2 | 3 | 4 | ≥5 | $N_{BACKWARD}$ |
|---|---|---|---|---|---|---|
| 3 | 22 | 60 | 17 | 5 | 0 | 25 |
| 4 | 50 | 23 | 6 | 0 | 0 | 14 |
| 5 | 66 | 45 | 2 | 2 | 0 | 12 |
| 6 | 194 | 85 | 4 | 1 | 0 | 7 |
| 7 | 339 | 16 | 1 | 0 | 0 | 0 |

Table II. The measured mean energies of the M=1 and M > 1 spectra, and a calculation of the mean energy differences based upon the most probable 3-body fragmentation reactions.

| EJECTILE | BEAM VELOCITY | $\langle E \rangle_{M=1}$ (TRANSFER) | $\langle E \rangle_{M \geq 2}$ (FRAGMENTATION) | $\langle E \rangle_{M=1} - \langle E \rangle_{M \geq 2}$ | PROBABLE M=2 MECHANISMS | CALCULATED $\langle E \rangle_{M=1} - \langle E \rangle_{M=2}$ |
|---|---|---|---|---|---|---|
| $^{9}Be$ | 148 MeV | 142±9 MeV | 123±10 MeV | 19±13 MeV | $^{16}O^{*} \rightarrow {}^{9}Be + {}^{7}Be$ | 18.8 MeV |
| B | 180 | 167±7 | 156±8 | 11±10 | $^{15}N^{*} \rightarrow {}^{11}B + {}^{4}He$ | 8.5 |
| | | | | | $^{12}C^{*} \rightarrow {}^{11}B + P$ | 15.1 |
| C | 197 | 206±4 | 197±6 | 9±7 | $^{16}O^{*} \rightarrow {}^{12}C + {}^{4}He$ | 6.5 |
| N | 230 | 226±2 | 215±13 | 11±13 | $^{16}O^{*} \rightarrow {}^{15}N + P$ | 11.3 |

## FIGURE CAPTIONS

Fig. 1. The relative cross-sections for heavy ion ejectiles from reactions of $^{16}O$ + (Zr, CsI, Au, Pb), Integrated over angle and normalized to a nitogen ejectile.

1a) The relative transfer cross-sections, and the relative inclusive cross-sections, for $^{16}O$ + CsI at 16.4 MeV/n.

1b) The relative inclusive cross sections for $^{16}O$ + (Zr, Au, Pb) at 8.8, and at 19.8 MeV/n.[1] (a = Zr, b = Au, C = Pb.)

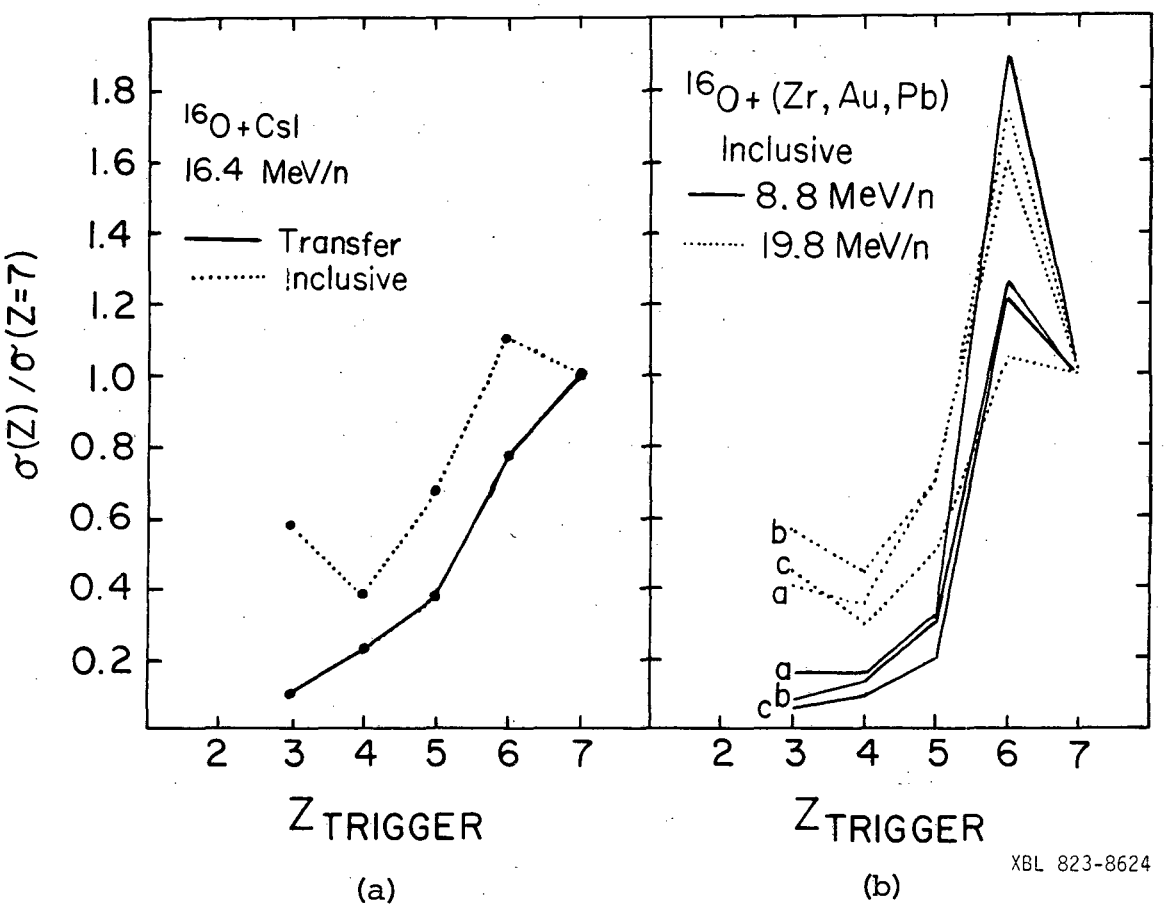
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
σ(Z) / σ(Z=7)
16O + CsI
16.4 MeV/n
Transfer
Inclusive
2 3 4 5 6 7
Z TRIGGER
(a)
16O + (Zr, Au, Pb)
Inclusive
8.8 MeV/n
19.8 MeV/n
b
c
a
a
b
c
2 3 4 5 6 7
Z TRIGGER
(b)
XBL 823-8624

Fig. 1

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