Energetic Particle Emission and Linear Momentum Transfer in Central Collisions induced by 32.5 MeV/nucleon $^{18}\text{O} + ^{238}\text{U}, ^{197}\text{Au}^\dagger$

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1. Introduction

The amalgamation of two heavy-ions to form a highly excited nucleus and its subsequent modes of de-excitation have been active areas of research in nuclear physics for many years. At low bombarding energies ($E_{\text{Beam}} \leq 10$ MeV/nucleon), complete fusion, characterized by full linear momentum transfer (LMT) and equilibration in all degrees of freedom, is a predominant mechanism for central collisions. Further increase of the bombarding energy induces a variety of related processes generally referred to as incomplete fusion. There are many interesting questions concerning these processes, such as :

- the maximum excitation energy and angular momentum of the primary nucleus thus formed,
- systematics and global behavior of LMT,
- dynamics responsible for the missing momentum,
- exotic decay modes of the parent nucleus at high excitation energy,
- transition from binary to multi-fragmentation processes, etc.

Complicated and ambiguous as it may seem, incomplete fusion is a dominating mechanism in central collisions between 40-100 MeV/nucleon. A detailed study of this phenomenon is therefore essential in understanding heavy-ion reaction mechanisms in the intermediate energy regime.

The systematic behavior of LMT for central collisions has been well established in the literature^{1,2}. Generally speaking, incomplete fusion becomes significant when the bombarding energy exceeds 5 MeV/nucleon above the reaction barrier and increases quickly with increasing $v_{\text{loc}} (\equiv [(E_{\text{cm}} - V_B)/2\mu]^{1/2})$. A detailed discussion of the systematics can be found in

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Morgenstern *et al.*¹ and Viola *et al.*².

The present talk will discuss results of an experiment addressing the question of reaction mechanisms responsible for missing LMT, by studying the correlations between fusion-like products and other emitted energetic fragments.

2. Mechanisms for incomplete LMT in central collisions

In an incomplete fusion event, the parent nucleus does not carry the full linear momentum brought in by the projectile. This can either be due to partial capture of the projectile in a binary reaction (e.g. breakup-fusion), or, even though capture is complete and an intermediate mono-nucleus system is formed, precompound emission occurs before all degrees of freedom of the composite system are equilibrated.

There have been suggestions that the major mechanism for incomplete fusion is nucleon-nucleon scattering, where particles with local velocity larger than the characteristic fermi velocity of the composite nucleus are emitted prior to thermalization. This process is predicted by several theoretical models such as the promptly-emitted-particle (PEP) mechanism and its variations. On the other hand, similar processes could also be described by more conventional binary transfer reactions where the mean field and structural properties of the nucleus play important roles. Recent studies for light systems³ have indicated that this is the major mechanism for incomplete fusion at low energies, $\sim 7\text{MeV/nucleon}$. It should be noted, however, that the direct transfer of a cluster with mass $\sim A_{\text{PROJ}}$ to continuum states of the target nucleus is not a trivial process from the viewpoint of conventional heavy-ion DWBA theories and has still to be established. The relative importance of these two mechanisms at higher bombarding energies is still an open question.

Which of these apparently different mechanisms are responsible or more important for incomplete fusion ? One possible way to differentiate between them is by looking at the detailed properties of the emitted energetic fragments and their correlation with the fusion-like products. Specifically, in the breakup-fusion picture one expects to see a wide spectrum (masses may range from 1 to A_{PROJ}) of energetic ($\sim$ beam velocity) projectile remnants emerging from the reaction with their momenta strongly correlated to the decay products of the parent nuclei (residues or fission fragments). The missing linear momentum is mostly carried away by a *single* nuclear cluster in this case, due to the binary nature of this mechanism. On the other hand, if PEP is the dominating process, the energetic particles in coincidence with central fission products will mostly be nucleons and the missing linear momentum would be shared among them. These differences should be evident from experimental momentum-balance and fast-particle-multiplicity correlation data.

3. Experiment

One can determine whether a collision is central or peripheral by measuring the amount of linear momentum that is transferred from a projectile to the primary composite nucleus. For non-fissile systems, kinematic properties of the evaporation residues (e.g., the velocity distributions) are usually used to deduce the initial LMT. For heavy and fissile systems, the same quantity could be obtained from the relative opening angle between the two emerging fission fragments (the folding-angle method). Due to the high excitation of the parent nucleus, the fragments are generally not in-plane with the beam-axis. The folding angle Θ_{12} , in this case, is defined as the angle between the projection of the position vector of one fragment onto the reaction plane defined by the position vector of the other fragment and the beam-axis.

The reactions studied were $^{16}\text{O} + ^{238}\text{U}$ and ^{197}Au at $E_{\text{cm}} = 487$ and 481 MeV respectively at the LBL 88-Inch Cyclotron. The experiment was designed to detect fission fragments, projectile-like fragments, and light charged-particles in two-fold and higher-fold coincidences.

A schematic drawing of the experimental setup is shown in Fig.1.

Fig.1 Schematic of experimental set up

Fig.2 Fragment spectrum obtained from a phoswich detector.

Fig.3 2-dimensional plot of in-plane versus out-of-plane distribution for fission fragments.

Two multi-wire proportional counters (MWPC) were used to detect the folding angle of the fission fragments in the range of 80° to 180° . In addition, there are four fragment telescopes located at forward angles. Two of them are made up of conventional Si detectors ($[\Theta, \phi] = [+6^\circ, 0^\circ]$ and $[0^\circ, -6^\circ]$) while the other two are plastic phoswich detectors (positioned at $[-6^\circ, 0^\circ]$ and $[+14^\circ, 0^\circ]$). The phoswich detectors have a sensitive area of $2.5\text{cm} \times 2.5\text{cm}$, with 1mm-thick fast (NE102) and 750mm-thick slow (NE115) plastic scintillator elements. The combined range is sufficient to stop all $Z=1$ particles of interest. A representative short gate (ΔE) vs. long gate (E) fragment spectrum obtained from the phoswich detector at $[-6^\circ, 0^\circ]$ is shown in Fig.2. One can see that fragments with $1 \leq Z_{\text{FRAG}} \leq 8$ could be identified. For $Z=1$, the p,d,t particles are also resolved.

In order to have a large detection efficiency for energetic light particles in the forward direction, six additional slice phoswich detectors were used. Each detector has a sensitive surface area of $2\text{cm} \times 25\text{cm}$ with position sensitivity along the long dimension. They are positioned at a distance of 24cm away from the target, subtending a combined solid angle of $\sim 0.5\text{sr}$ in the forward cone. Altogether, they cover $\pm 27^\circ$ in-plane and -10° to $+26^\circ$ out-of-plane. The position resolution of these detectors is typically $\sim 0.5\text{cm}$ for 100 MeV α -particles.

The phoswich detectors were calibrated by using proton and α -beams from the cyclotron.

4. Inclusive data : The most probable LMT

Fig.3 shows a 2-dimensional plot of Θ_{12} vs. Φ_{12} for the $^{16}\text{O} + ^{238}\text{U}$ reaction. Due to the high excitation energy of the parent nucleus, the fragments show a significant out-of-plane (Φ_{12}) distribution.

The inclusive folding angle spectrum for the ^{238}U target is shown in Fig.4. There are two broad peaks in the spectrum, one centered at $\Theta_{12} \sim 145^\circ$ and the other at 175° . The first group corresponds to large momentum transfer and is identified with events coming from central collisions. The other one likely originates from peripheral reactions with small LMT. While this latter component is of great interest in studying the energy partition mechanism for quasielastic collisions, we shall concentrate on the central fission group. The peripheral component (small LMT events) diminishes in case of the Au target. This is simply due to the difference in fissility of these two systems.

Also indicated at the abscissa are the most probable Θ_{12} values corresponding to fractional capture of the projectile nucleus, i.e., the initial linear momentum of the fissioning parent nucleus. Our data indicates that the average momentum of the fissioning parent nuclei is only about 75% of the beam for the $^{16}\text{O} + ^{238}\text{U}$ reaction and about 76% for $^{16}\text{O} + ^{197}\text{Au}$.

Fig.4 Inclusive folding angle spectrum.

Fig.5 Correlation between the energetic fragment charge (Z) and fission opening angle

These numbers are consistent with the systematics of LMT for heavy systems.

5. Correlations : Energetic fragments versus Θ_{12}

A plot of the charge of the detected energetic fragment (Z_{FRAG}) versus the fission opening angle Θ_{12} is shown in Fig.5. There are three noticeable regions in this plot :

(A) Binary transfer, the strongly correlated region ($Z=5,6,7$).

There is a very strong and almost linear correlation between the Z of the heavy fragment and Θ_{12} in this region. This is consistent with the interpretation that these fragments are results of binary transfer processes. The heavier the observed beam velocity fragment, the smaller the transferred mass Δm , resulting in a smaller LMT (larger Θ_{12}).

(B) Mutual projectile and target excitation, fission accompanied by sequential-breakup.

In this case, the excitation energy sharing between the projectile and target nuclei is such that the former is excited above its α -particle threshold and the target also receives sufficient excitation to undergo fission. The small LMT implies little or no mass is transferred. The strong yield of energetic α -particles observed in this region suggests the importance of projectile breakup in heavy-ion peripheral collisions. These α -particles are probably coming from the $^{16}\text{O} \rightarrow ^{16}\text{O}^* \rightarrow ^{12}\text{C} + \alpha$ breakup process. They are not likely to be produced in binary transfer because in that case the capture of a ^{12}C cluster will introduce a significant LMT.

(C) Preequilibrium emission and/or massive transfer ($Z=1,2$ fragments).

Generally speaking, the distributions in Θ_{12} corresponding to $Z=1$ and 2 particles are very broad, implying that the emission of energetic $Z=1$ and 2 particles is possible in almost all ranges of impact parameters. According to our previous studies most of the energetic particles with large Θ_{12} (small LMT) originate from the sequential-breakup of the projectile (region B). The portion corresponding to smaller Θ_{12} (large LMT) is presumably due to either massive transfer or pre-compound emission.

6. Linear Momentum Balance

The correlation between the estimated average initial linear momentum of the fissioning parent nucleus, P_{fission} and the longitudinal momentum, P_{FRAG} , of a *single* detected energetic fragment is shown in Fig.6. The linear momentum of the fissioning nucleus is obtained from Θ_{12} by assuming that the missing linear momentum is carried away by particles travelling along the beam direction. Also indicated in the figure is the corresponding beam momentum. The dash-dotted curve connects regions where the yield is more concentrated. One can see that in region (I), the summed momentum approaches the limiting value of the beam. However, the deviation between the trend given by the dash-dotted curve and the beam

Fig.6 Momentum correlation between the fissioning nucleus and a single detected fragment.

Fig.7 Fission opening angle corresponding to different particle multiplicities.

momentum limit becomes larger and larger with increasing LMT to the target. Similar behavior has also been reported by Laville *et al.*⁴. This would indicate that the missing momentum must have been shared by more than one single energetic particle in the large LMT region, in contrast to the simple binary assumption of the massive-transfer mechanism. This would also suggest, in the pre-equilibrium emission interpretation, that several fast particles are emitted prior to the thermalization of the target-like nucleus.

7. Higher multiplicity events

To see how the LMT pattern behaves when two or three more fast particles are emitted in a collision, Fig.7 shows a plot of the Θ_{AB} spectra for different $Z=1$ and 2 particle multiplicities. The $M=1$ curve corresponds to only a single fast light particle being detected in the event. It can be seen that the higher multiplicity curves on the average correspond to larger Θ_{AB} values as expected, since the linear momentum transfer of the fissioning nucleus will be smaller in this case. One can conclude that the deviation of the opening angle from complete fusion increases gradually as the multiplicity of the detected fast particles are increased, consistent with the missing linear momentum being carried away by the energetic particles.

Two fast α -particles in principle could be produced by the sequential break-up of a ^8Be projectile remnant produced by transferring 8-nucleons to the target. In this case, however, the momentum of the fissioning parent should be around the half-capture value, which is not observed. This points to the possibility that some of these α 's are produced by other mechanisms, such as the possible existence of highly excited regions in the composite nucleus (local hot zones).

8. Comparison with precompound emission models

All the observed light particle spectra (p, d, t, α) particle spectra are peaked at energies slightly below the beam velocity and contain relatively high energy components extending close to the fermi velocity limit. Fig.8 shows a proton spectrum observed by a phoswich detector at 6° in the laboratory. One can see that the spectrum peaks at ~ 30 MeV and has a high energy cutoff at about 120 MeV. This latter number corresponds to a proton fermi energy $\epsilon_F \sim 23$ MeV in the projectile frame. To see whether the preequilibrium emission mechanism is responsible for incomplete fusion one can compare the observed nucleon spectra at forward angles with model predictions. Such a comparison has been made for the $^{16}\text{O} + ^{238}\text{U}$ reaction using the master-equation/exciton-model code of Blann *et al.*⁵ (Fig.8). The number of excitons used in the calculation is set equal to 16, the same as the projectile mass. The calculated curve represents time integrated proton yield up to 1.6×10^{-22} s (~ 7 interaction steps for the excitons). Generally speaking, the observed proton spectrum is softer than what

the model predicts. It should be noted that the model also predicts a much larger cross section for preequilibrium neutron emission than for proton emission. Consequently a better test of the role of nucleon-nucleon scattering mechanisms at these energies might be to detect neutrons instead of charged particles.

9. Conclusion

By studying the kinematical correlation between the energetic fragments and the fission opening-angle it was found that the most probable linear momentum transfer in central collisions is only about 75% of the beam momentum for the $^{16}\text{O}+^{238}\text{U}$ and ^{197}Au reactions.

Fig.8 Comparison of the observed proton energy spectrum to precompound model calculation.

The binary massive transfer mechanism appears to be able to account for many of the observed features of the reaction. Even though there are indications that a higher fast particle multiplicity is required to account for the missing momentum in case of large LMT, favoring the interpretation of prompt nucleon emission, the observed experimental proton spectra are softer than those predicted by preequilibrium emission codes. All these probably imply that collisions in this energy domain is still dominated by nuclear mean field dynamics rather than nucleon-nucleon phenomenon.

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