

## Incomplete fusion reactions measured with the QTS

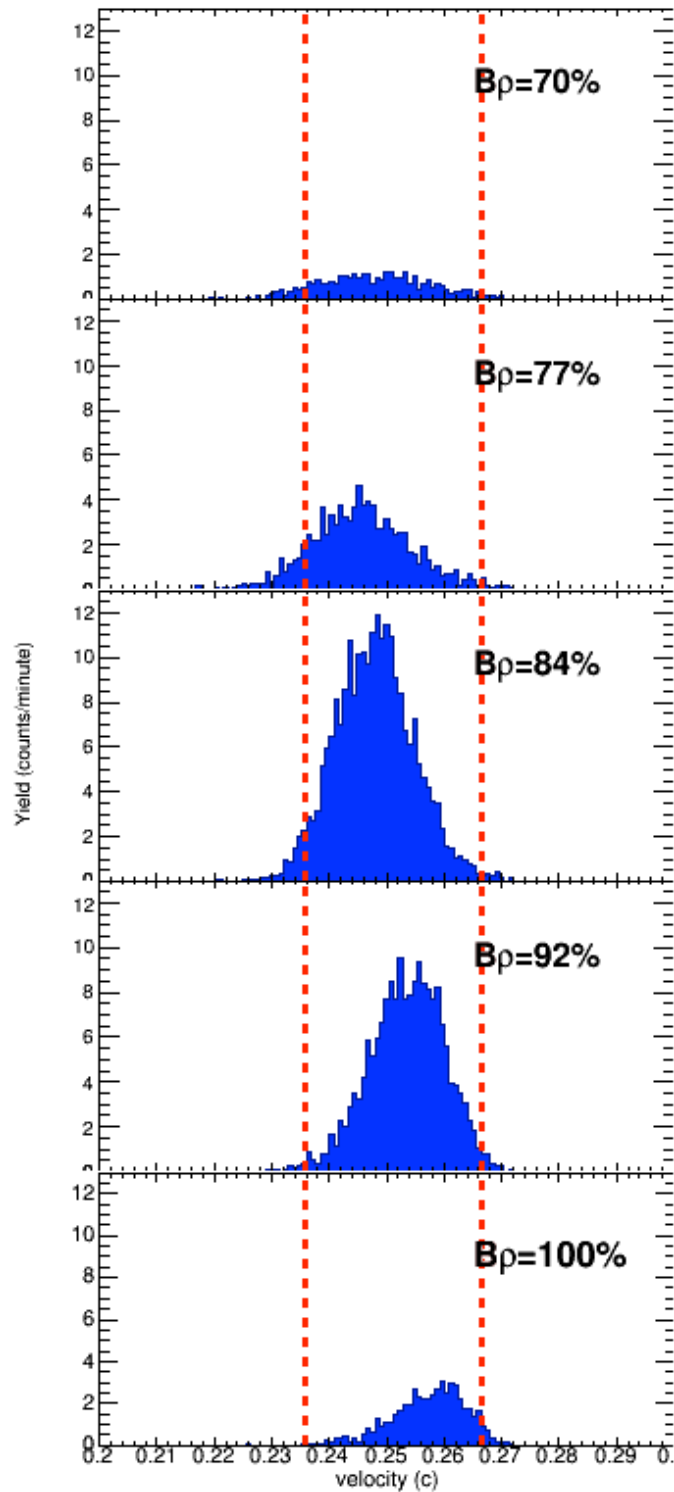
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The first observation of the asymmetry dependence of the caloric curve was recently reported [1-3]. This asymmetry dependence can be verified with improved statistical and systematic uncertainties with a new incomplete fusion experiment. By measuring heavy residues produced in fusion reactions and the coincident light charged particles temperatures and excitation energies can be obtained for excited compound nuclei without reliance on a measurement of the free neutrons.

A short measurement of  $^{86}\text{Kr} + \text{C}$  at 35 MeV/nucleon was performed to validate our understanding of experimental setup and to provide insight into the reaction mechanisms at work. Light charged particles were measured (dE, E) in FAUSTUPS with  $1.6^\circ < \theta < 45^\circ$  and heavy residues were measured (TOF, dE, E) with the Quadrupole Triplet Spectrometer with  $0.9^\circ < \theta < 2.3^\circ$ . For energies at and below the Fermi energy, fusion reactions constitute a significant part of the nuclear cross section. Complete fusion however is only significant at much lower energies; incomplete fusion, a.k.a. massive transfer, dominates above 10 MeV/nucleon [4].

In order measure a nuclear caloric curve, the excitation energy must be known. In incomplete fusion reactions of  $\text{Kr} + \text{C}$ , the excitation energy of the compound nucleus depends to first order on the fraction of the carbon that fuses with the krypton. This fraction also determines the velocity of the compound nucleus to first order. If evaporative cooling of the hot nucleus is isotropic, the average residue velocity for a cohort of events then indicates the average excitation energy.

Measured velocity distributions of heavy residues produced in reactions of  $^{86}\text{Kr} + \text{C}$  @ 35 MeV/nucleon are shown in Fig. 1. These velocities have been corrected for energy loss in all detectors and in the target. The correction is on the order of 5% or less. Each panel represents a different tune of the Quadrupole Triplet Spectrometer (QTS), used to focus a broad but finite range of reaction products across a  $\sim 5.5\text{m}$  flight path. The bottom panel corresponds to the rigidity of the beam, and each other panel to a subsequently lower rigidity. The vertical axis shows the measured counts per minute, which allows immediate comparison of the yield from the five different rigidities. Heavy incomplete fusion residues are dominant around 84% of the rigidity of the beam. In Fig. 1, the upper dashed line indicates beam velocity, and the lower dashed line indicates the velocity a completely fused  $^{86}\text{Kr} + 12\text{C}$  system would have. As the rigidity of the beam decreases from 100%, the velocity centroid initially drops. Around 84%, the centroid finds a peak about two-thirds from  $v_{\text{beam}}$  to  $v_{\text{CF}}$ , and remains there as the rigidity continues to drop. This suggests that more than eight nucleons of the twelve in the carbon target are rarely picked up in fusion with the krypton. This ratio of two thirds hints that alpha cluster structure of the carbon may be relevant in this process.



**FIG. 1.** Velocity distributions measured by time-of-flight. The upper dashed line represents the beam velocity and the lower dashed line corresponds to the velocity of a completely fused  $^{86}\text{Kr} + ^{12}\text{C} = ^{98}\text{Mo}$  compound nucleus. The tune of the triplet selects residues with different magnetic rigidities and thus different velocities.

The width of the velocity distributions shown in Fig. 1 arises first from the number of nucleons picked up from the target. However, once the rigidity of the QTS is low enough that the mean is no longer changing, we are selecting only the fusion events with a single value of the momentum transfer; higher momentum transfer is not produced with appreciable yield at this beam energy. Therefore in this regime, variation in the number of nucleons picked up from the target is not a major cause of the width of the velocity distribution. Second, evaporative particle emission from the compound nucleus causes the heavy residue to recoil, causing significant broadening of the velocity distribution. Neither of these effects precludes the use of the centroid as a measure of the excitation energy. However, it is possible that the fraction of the target that did not fuse will have some energy imparted to it, either internal or translational. This effect would cause a systematic error in the calculation of the excitation of the compound nucleus. However, there is precedent for using the average velocity without correction for energy imparted to the un-fused “pre-equilibrium” nucleons [4, 5, 6].

To determine how a different velocity of the pre-equilibrium nucleons will affect the excitation energy, we can utilize the analytical formula of Bohne [Boh90]. The compound nucleus will be at very small angle, and all of the krypton projectile remains in the compound nucleus. Since we are interested not in an absolute value right now but in how a different velocity of pre-equilibrium nucleons will affect the excitation energy. Taking the extreme limit that maximizes the difference of  $\cos\theta_{TV_P-V_T}$ , there is a 9% difference in the excitation energy if the pre-equilibrium nucleons remain at rest or are boosted to half the residue velocity. Light charged particles boosted to just under this velocity or greater would be measurable, allowing us to constrain this error at the 9% level.

However, it should be considered that the amount of energy imparted to the pre-equilibrium nucleons should not be significantly different between reactions of  $^{86}\text{Kr} + ^{12}\text{C}$  and reactions of  $^{78}\text{Kr} + ^{12}\text{C}$ . Since the goal is to examine relative trends in the caloric curve for systems with different neutron content, an identical shift in the excitation energy of both curves would represent a completely correlated error and thus have no effect on the differences extracted.

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