New measurements of the properties of neutron-rich projectile fragments

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Abstract. Two new experiments were carried out at the NSCL to explore the details of the linear moment and excitation energy distributions of projectile fragmentation production. In the first experiment the full linear momentum distributions of fragments from the reaction of a $^{76}$Ge beam with beryllium and gold targets were measured in the S800 spectrometer. The results indicate a strong contribution of “far side” or attractive scattering to the near-projectile products with the gold target. In the second experiment the excitation energy of primary projectile fragments from peripheral nuclear reactions at intermediate energies was carried out at the NSCL. Sodium, neon and fluorine isotopes produced by the fragmentation of a neutron-rich $^{32}$Mg beam by a beryllium target were observed in a magnetic spectrometer in coincidence with fast neutrons detected using the Modular Neutron Array (MoNA). A new technique based on an analysis of the observed neutron multiplicity distributions was used to estimate the excitation energy and mass of the precursor intermediate products for the first time. A strong correlation between the neutron multiplicity and the total mass loss was observed indicating that large excitation energies were created in the prefragments by the initial collision. These findings are generally consistent with the internuclear cascade model of the collision dynamics but not with macroscopic abrasion-ablation models.

1. Introduction
The study of fragments produced from fragmentation reactions has followed many paths with various observables used to probe the underlying reaction mechanism(s) involved. An overall parameterization of the fragment yields has existed for some time, including recent revisions[1] and provides the basis for the operation of large-scale production facilities but the details of the reaction mechanism have been known to be ambiguous for a long time[2]. Measurements of the fragments linear momentum distributions have been a key tool for examining the reaction mechanism. Distributions of either total momentum or its parallel (longitudinal) component have been measured for fragments produced from the interaction of a wide range of target and projectile combinations. The parallel component of the momentum vector has been extensively measured and modeled, however, the much smaller, equally important, perpendicular component has not been as well studied. Along a similar line, the excitation energy of initial products of the collision are not generally known, moreover, a variety of models have been developed with conflicting predictions that get washed out in the subsequent deexcitation processes.

In the first part of the present work we report measurements of the full momentum distributions of fragments produced by the reactions of a $^{76}$Ge beam at 130 MeV/nucleon with
Be and Au targets. The measurement of both the parallel and perpendicular components of the fragmentation residue momentum for a wide range of fragment species showed that the reactions with heavy targets show significant angular deflection (attractive) as a function of mass loss. The details of this work are contained in a recent publication [3].

In the second part of the present work we report some of the results from the first experiment to determine the excitation energy of primary projectile fragments from peripheral nuclear reactions at intermediate energies. A series of light isotopes produced by the fragmentation of a neutron-rich Mg beam by a beryllium target were observed in coincidence with fast neutrons detected in the Modular Neutron Array (MoNA) [6]. The excitation energy and mass of the precursor intermediate products was obtained from a sophisticated new simulation of the experiment for fragments with mass losses, ∆A, between 3 and 10. A strong correlation between the neutron multiplicities and the total mass loss was observed and the bulk of the mass loss was found to occur in the evaporative stage of the overall reaction.

2. Linear Momentum Measurement

The linear momentum experiment was performed by fragmenting a stable beam at the NSCL. The spread of the primary 76Ge primary beam at 130 MeV/nucleon from the Coupled Cyclotron Facility was measured with the A1900 fragment separator to be ≤0.10%. The 76Ge beam was reacted with either of two targets, 99.8 mg/cm² 9Be or 50.73 mg/cm² 197Au, placed at the target position of the S800 spectrometer. The forward-focused projectile-like fragments entered the large acceptance of the spectrometer and were uniquely identified using a combination of detectors in the focal plane. The full momentum vector was reconstructed on an event-by-event basis for a wide range of fragment species produced in the projectile fragmentation reaction. Position information from the cathode readout drift chambers (CRDCs) in the focal plane detection system was combined with trajectory reconstruction through the spectrometer using the COSY INFINITY ion-optical code to reconstruct both the longitudinal and transverse momentum distributions at the target position. To minimize error from events with trajectories near the physical limits of the spectrometer, the acceptance was limited to ±4.07% in momentum in the longitudinal direction and ±52.2 mrad in the transverse direction. Several magnetic rigidity Bρ settings of the S800 were used to collect the majority of the fragments produced in these reactions. The full parallel momentum distributions were reconstructed by combining the data obtained in each magnetic rigidity setting. Examples of the distributions of the perpendicular momentum are shown in Fig. 1 observed with the two targets. The parallel momentum of each fragment was measured as well as the average parallel momentum transfer of each fragment.

The results for the width of each fragments parallel distribution are presented in Fig. 2 as a function of the total observed mass loss: ∆A = Aprojectile − Afragment from interaction with both the 9Be and 197Au targets. The data clearly indicate that there is no significant difference between the two targets. The two data sets overlap so well that the 70 isotopes that were observed in both cases cannot be distinguished by parallel distribution values alone.

The widths extracted for the perpendicular momentum distributions of fragments produced from the 9Be target as well as those for fragments with mass ≤69 produced from the 197Au target that were found to be peaked at zero momentum (0° in scattering angle) are shown in Fig. 3. The widths of the perpendicular momentum distributions presented in Fig. 3 are compared to the empirical description developed by Van Bibber et al. [4] that adds a term to the definition of parallel width by Goldhaber [5] to include a contribution from the orbital deflection of the projectile by the target in addition to the intrinsic nucleon motion of the fragment that generates the longitudinal width.

The fragments with ∆A<20 from the gold target clearly diverge from this simple description.
Figure 1. Examples of the perpendicular momentum distributions observed for fragments obtained with a beryllium target (left) with those observed with a gold target (right) as a function of total mass loss.

from Van Bibber, see Fig. 1, and the measured perpendicular distributions for those fragments with $70 \leq A \leq 74$ have a peak just below the momentum value corresponding to the grazing angle. The observed peak shifts systematically to zero as the fragment mass decreases, and then the width of the distribution decreases toward the values found for the $^9$Be target. The interplay of the Coulomb and nuclear potentials that leads to this behavior was explored with a simple calculation of the classical deflection angle as a function of impact parameter. The observed scattering angle corresponds to two values of the impact parameter that are larger than the sum of the two nuclear radii. The larger of the two calculated impact parameters corresponds to a scattering angle due to the Coulomb potential alone along a trajectory in which the projectile enters and exits on the “same side” of the target. On the other hand, the smaller impact parameter corresponds to scattering due to the nuclear plus Coulomb potentials along a
trajectory in which the projectile enters and exits on the “far side” of the target and is deflected through zero degrees. The impact parameter values associated with Coulomb scattering have a large separation between the projectile and target which would preclude the necessary overlap of nuclear density for producing the observed fragment species. On the other hand, the calculated impact parameter which comes from the nuclear plus Coulomb scattering scenario decreases slightly with increasing mass loss and is very close to the sum of the radii.

Figure 2. Variation of the widths of the longitudinal momentum distributions as a function of mass loss.

Figure 3. Variation of the widths of the perpendicular momentum distributions as a function of mass loss.

3. Excitation Energy Measurement

A primary beam of $^{48}$Ca at 140 MeV/u was reacted with a 1316 mg/cm$^2$ $^9$Be target at the NSCL to produce the neutron-rich $^{32}$Mg beam at 86.0 MeV/nucleon with a momentum spread of 0.5%, and a rate of $\sim$1200 /s, and purity of 95%. The $^{32}$Mg beam was delivered to a 1.27 mm thick $^9$Be target in the sweeper magnet system and the individual beam particles were identified by time-of-flight from the A1900 separator. The unreacted beam and charged nuclear reaction products were then bent clockwise (from above) by a large superconducting, 3.8 T magnet with a vertical gap of 14 cm and a bending angle of 43°. The standard suite of detectors behind the magnet was used to measure charged particle trajectories and provide particle identification. Three settings of the magnetic rigidity (3.75, 3.15, and 2.97 Tm) were used in the present work to provide the desired range of sodium, neon and fluorine isotopes. Neutrons were detected in coincidence with the charged fragments using the Modular Neutron Array [6].

Neutrons detected in the present experiment could result from interactions with the target or subsequent evaporation from the excited precursor fragment. Neutrons emitted from the precursor fragment should be isotropic in their center-of-mass frame that results in a distribution centered approximately on the beam energy per nucleon. An example of the neutron kinetic energy distribution for neutrons detected in coincidence with $^{26}$Ne fragments is shown in Fig. 4. The observed distribution is roughly Gaussian, with a slight asymmetry favoring lower energies. This indicates that the majority of neutrons detected are from evaporation, with only a small contamination from neutrons removed in the first (fast) step of the reaction.

The primary experimental result from the present work is the neutron neutron-hit (or n-fold) distribution in coincidence with each individual projectile fragments. A decision was made to compare the measured neutron-hit distribution for a single fragment to all of distributions created by simulating the de-excitation of the full range of possible intermediate fragments, each with a wide range of excitation energies rather than trying to unfold the effect of the MoNA
detector response. The neutron spectra (in the appropriate rest frame) were obtained from the well-known statistical evaporation code PACE [7] and then passed through the detector response calculated with the GEANT4 simulation code including scattering from the sweeper magnet [8]. The neutron interaction cross sections used in GEANT4 were taken from Desesquelles, et al.[9] and ENDF[10]. Each simulated multiplicity distribution from GEANT4 was compared to the experimental data to determine the best-fit precursor nucleus and excitation energy using a \( \chi^2 \) statistic calculated from the difference between the measured and the simulated neutron hit multiplicity distributions. For example, the lower portion of the neutron hit multiplicity distribution in coincidence with \(^{25}\text{Ne}\) fragments is shown in Fig.5 can be compared to the distributions obtained from the statistical de-excitation of all intermediate fragments ranging from \(^{30}\text{Ne}^*\) to \(^{26}\text{Ne}^*\) in 1 MeV steps of excitation energy that were each passed through the response filter of GEANT4 to obtain a hit multiplicity distribution and a single \( \chi^2 \) value. In this example the variation of \( \chi^2 \) for each putative intermediate fragment had a clear minimum and the lowest overall \( \chi^2 \) was found for a \(^{30}\text{Ne}\) prefragment at 42 MeV, although the value for \(^{29}\text{Ne}\) at 23 MeV is only slightly higher. Thus, this analysis attributes the primary production of the observed \(^{25}\text{Ne}\) fragments to \(^{30}\text{Ne}^*\) at an excitation energy of 42 MeV, meaning that only two protons were removed in the first step of the reaction and that five neutrons were evaporated in the second step leading to the observed product \(^{25}\text{Ne}\).

This analysis was extended to all of the observed fragments. The variation of the extracted excitation energy with total change in mass number \( \Delta A = A_b - A_f \), see Fig.6, was found to be linear for \( Z=9, 10, \) and \( 11 \), with slopes of approximately 17, 8, and 11 MeV/A, respectively. Even though \( A \) is an important and directly observed quantity, it combines the mass losses in the whole reaction. A more interesting result from the present work is the variation of excitation energy with mass loss in the first step of the reaction, \( \Delta A^* = A_b - A_f^* \), a quantity that is predicted by various models of the reaction. The value of \( A_f^* \) for each observed fragment was taken as the mass number of the precursor fragment with the lowest \( \chi^2 \) in the neutron hit multiplicity analysis described above. The resulting distribution of excitation energy generated and mass removed in the first step of the reaction are shown in Fig.7. The results show the remarkable situation of relatively small mass-loss in the first step of the reaction with the creation of high excitation energies leading to long evaporation chains. For example, the sodium fragments were
The extracted excitation energy, $E^*$, is shown as a function of the total mass loss, $A_b - A_f$, for the reaction products observed in this work. Linear fits are shown for total mass loss in each element.

Examples of the theoretical predictions of the excitation energy, $E^*$, in the intermediate fragment as a function of mass loss in the first step, $\Delta A^* = A_b - A_f^*$, can be compared to the present results in Fig. 7. The abrasion/ablation models have a strong correlation of mass loss and excitation energy that is not supported by the data. Wilson, et al.[11] combine the contribution of the excess surface energy and rescattering of the participant nucleons in the bulk material to create an excitation energy of roughly 3.3 MeV per removed nucleon. Gaimard and Schmidt[12] used a microscopic description that produces the excitation energy by the removal of nucleons bound in a mean-field potential giving 13.3 MeV per nucleon removed. On the other hand, the internuclear cascade model, ISABEL[13], can create a range of excitation energies at small mass losses, a feature that is much more consistent with the data.

4. Summary
The full linear momentum distributions of fragmentation products produced by heavy ion reactions at intermediate energies have been measured for a wide range of fragment masses
from a $^{76}$Ge beam. The parallel momentum transfer and widths of the fragments’ longitudinal distributions were similar to earlier work and followed established empirical descriptions and were independent of target. The widths of the perpendicular momentum distributions, however, could not be described by fragment mass alone. The perpendicular widths of the heaviest products clearly show deflection by the gold target that is consistent with the predictions from a qualitative classical calculation of the deflection angle as a function of impact parameter for opposite-side scattering.

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