Neutron multiplicity from primary hot fragments produced in heavy ion reactions near Fermi energy

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Abstract. In order to reconstruct the yields of the primary hot fragments at the time of their formation, the neutron multiplicity associated with intermediate mass fragments (IMFs) was determined experimentally using the kinematical focusing of light particles emitted along the direction of each IMF. The reaction system \(^{64}\text{Zn} + ^{112}\text{Sn}\) has been studied at 40 A MeV. IMFs were isotopically identified with Z up to 18. Neutrons were measured at 16 angles around the direction of the IMFs. The extracted neutron multiplicities are in good agreement with those calculated AMD+Gemini simulations.

1. Introduction

In intermediate heavy ion collisions, the composite system of the projectile and target nuclei is compressed and excited at an early stage of the reaction. This hot-dense nuclear system expands and can break into fragments by a multifragmentation process. In general the process can be divided into stages: the dynamical compression and expansion, the formation of fragments, and finally the separation and secondary cooling by evaporation. At the time of the fragment formation, especially for the intermediate mass fragments (IMFs) with \(3 \leq Z \leq 20\), their characteristic properties, such as excitation energy and isotopic distributions, are governed by the characteristics of the break-up source, such as the temperature, density and N/Z ratio. Therefore IMFs may provide a unique probe to study the reaction mechanism and hot nuclear matter properties. However most of IMFs experimentally measured are not primary products but are the final (secondary) products, observed after the cooling down through a sequential particle decay process. The secondary decay process will alter the mass and charge distribution of the IMFs. Some model simulations predict significant changes of the isotope distributions between the primary and secondary IMFs. For example, in figure 1 the results for carbon isotope yield distribution calculated for the reaction \(^{64}\text{Zn} + ^{96}\text{Mo}\) at 47 MeV/nucleon are compared using two different model simulations: an Anti-symmetrized molecular dynamics model (AMD) and a simultaneous multifragmentation model (SMM). The multiplicities are shown as a function of neutron...
number for the primary hot fragments on the left and for the secondary cold fragments on the right. In both cases significant differences are predicted between the primary and secondary fragment isotope distributions. Note that, although the cold fragment multiplicity distributions are in reasonable agreement in the two model simulations, the primary hot fragment multiplicity distributions are quite different. This suggests that the information of the characteristic nature of the emitting source may be significantly modified by the secondary decay process.

![Figure 1](image)

**Figure 1.** Multiplicity of carbon isotopes as a function of neutron number for the primary hot fragments on the left, and for the secondary cold fragments on the right. Results predicted by AMD (circles) and SMM (squares) model simulations are shown for $^{64}$Zn + $^{94}$Mo at 47 A MeV.

Experimentally excitation energies of the primary fragments were evaluated by studying the light charged particle multiplicities associated with a given IMF [1,2]. By comparing measured light charged particle multiplicities to those of a statistical decay calculation, excitation energies of 2 to 3.5 A MeV for fragments with $3 \leq Z \leq 30$ were determined for the Xe+Sn reactions in the incident energy range between 32 to 50 A MeV. These values are consistent with those calculated in the AMD simulations shown above [3].

In our previous works, the primary fragment distributions were empirically reconstructed from the observed IMF isotope distributions, based on the Modified Fisher Model [4-6]. In the analysis, the observed isotope yields were corrected for the secondary decay effects. The effects of the secondary decay process on the symmetry and pairing energy terms were taken into account. The corrected mass distributions showed a power law distribution and, by comparing to a simple statistical model, they indicated that the primary IMF mass distribution exhibits a power law behavior with an exponent value of 2.3, which suggests that the emitting source is at a critical point when the fragments are formed.

It is desirable to reconstruct the primary hot fragment distributions directly from all light particle multiplicities associated with de-excitation from a primary IMF. This requires measurement of the associated neutrons and charged particles for each IMF. For neutrons the determination is more difficult than for charged particles in [1,2], since there is no Coulomb peak. In addition the numbers of neutrons evaporated from the individual primary IMFs are much smaller relative to the total number of neutrons emitted. In the present work we have used kinematical focusing techniques which are described in detail in the next section. In this report we focus on the neutron multiplicity measurements for each IMF. The extraction of the neutron and charged particle multiplicities is underway.

2. Experimental Procedures

The experiment was performed at the K-500 superconducting cyclotron facility at Texas A&M University. $^{64,70}$Zn and $^{64}$Ni beams were used to irradiate $^{58,64}$Ni, $^{112,124}$Sn, $^{197}$Au, and $^{232}$Th targets at 40 A MeV. Intermediate mass fragments (IMFs) were detected by a detector telescope placed at $\theta_{\text{lab}} =$
20°. The telescope was consisted of four Si detectors. Each Si detector was the effective area of 5 \times 5 cm. The nominal thicknesses were 129, 300, 1000, and 1000 \mu m. All Si detectors were segmented into four sections and each quadrant had a 5° opening angle in polar angle. Therefore, the energies of the fragments were measured at two polar angles of the quadrant detector, namely, \( \theta_{lab} = 17.5° \pm 2.5° \) and \( \theta_{lab} = 22.5° \pm 2.5° \). Typically, six to eight isotopes for atomic numbers Z up to Z = 18 were clearly identified with the energy threshold of 4–10 A MeV, using the \( \Delta E - E \) technique for any two consecutive detectors [5]. The \( \Delta E - E \) spectrum was linearized empirically. Mass identification of the isotopes was made using a range-energy table [7].

In order to determine the light particle multiplicities associated with the observed IMFs, a kinematical focusing technique was employed. When a particle is emitted from an IMF of a velocity of \( v_{IMF} \), the particle tends to be emitted in a cone along the direction of the IMF. The opening angle of the cone depends on the velocity of the particle relative to that of the IMF. The smaller the particle velocity, the sharper the kinematical focusing. When the particle velocity becomes larger than that of IMF, the focusing is weaker and the particle can be emitted in 4\( \pi \) direction. In Fermi energy heavy ion collisions, light particles are emitted at different stages and from different sources. The particles not emitted from the trigger IMF are called uncorrelated particles and those from the IMF are called correlated ones. One should note that the majority of particles are uncorrelated ones in agreement with results of AMD-Gemini simulations.

In order to observe the light particles, two sets of light particle detectors were used. For the light charged particles (LCPs) 16 single-crystal CsI(Tl) detectors of 3 cm thickness were set around the target at angles between \( \theta_{lab} = 27° \) and 155°, tilted 30° from the reaction plane in the azimuthal angle to avoid shadowing the neutron detectors described below. The light output from each detector was read by a photomultiplier tube. The pulse shape discrimination method was used to identify p, d, t, h, and \( \alpha \) particles. The energy calibrations for these particles were performed using Si detectors (50–300 \mu m) in front of the CsI detectors in separate runs. For neutrons 16 detectors of the Belgian-French Demon neutron detector array were set along the direction of the telescope. Demon detectors utilize of a cell, 20 cm long with a diameter of 16 cm, that contains 4.5 liters of liquid scintillator. The detectors were positioned in plane to and perpendicular to the reaction plane, distributed at the opening angle between the telescope and Demon detector, \( 15° \leq \theta_{lab} \leq 160° \). The \( n-\gamma \) discrimination was obtained by a pulse shape analysis using a comparison of the slow component of the light output to the total light output. The Demon detection efficiency was newly calculated, using a GEANT simulation based on existing cross section data [8,9]. The extracted neutron multiplicity for \( ^{64}\text{Zn} + ^{112}\text{Sn} \) at 40 A MeV in this experiment was in good agreement with that extracted from the NIMROD detection system [10] in a separate run, where the average neutron multiplicity is determined by the neutron ball. The whole analysis for different light particles and different reaction systems is also underway and in the following we focus on the neutron multiplicity of the \( ^{64}\text{Zn} + ^{112}\text{Sn} \) reaction at 40 A MeV.

3. Data Analysis

In order to determine the neutron multiplicity associated with an IMF, it is important to determine the contribution of the uncorrelated neutrons from other sources. The uncorrelated neutrons are emitted from a variety of sources moving along the beam direction. The kinematically focused neutrons are observed as an excess above the uncorrelated ones and they are focused along the IMF direction, depending on the relative velocities of IMF and neutrons. The excess is enhanced at the IMF direction when the neutron velocity is small relative to that of IMF. These characteristics can be expressed by two moving sources, one for the uncorrelated ones, moving along the beam direction, and the other moving in the IMF direction. The uncorrelated source can be a convolution of multiple sources, such as projectile-like, intermediate velocity and target-like sources. However in the actual analysis, in order to reduce the number of free parameters, the uncorrelated sources are replaced by the experimentally observed spectrum from events which are triggered by isotopes with very few associated secondary neutrons. In the previous works of ref. [1,2], we observed that the charged particle multiplicities associated with Li isotopes are very small. We assume, at present, that this is
also true for the neutrons in the reactions studied here. Under this assumption, the uncorrelated spectrum was obtained from the neutron velocity spectrum in coincidence with $^{6}\text{Li}$ in its several velocity windows.

The contribution of the correlated neutrons was determined using a moving source parametrization [11,12]. Assuming that the parent nucleus emits particles isotropically in the parent rest frame and therefore has the same velocity as that of the triggered IMF, the neutron emission can be described by a Maxwellian distribution of a volume type, which is given by

$$\frac{d^2N}{dE_{\text{lab}}d\Omega_{\text{lab}}} = \frac{M_n}{2(\pi T)^{3/2}} \left(E'\right)^{1/2} \exp\left(-\frac{E'}{T}\right)$$

with

$$E' = E_{\text{lab}} - U$$

$$E' = E' - 2 \left(E' - \frac{1}{2} m_n v_{\text{IMF}}^2\right)^{1/2} \cos\theta + \frac{1}{2} m_n v_{\text{IMF}}^2$$

where $M_n$ is the neutron multiplicity associated with the triggered IMF, $T$ is the temperature of the parent nucleus, $U$ is the Coulomb barrier, $v_{\text{IMF}}$ is the IMF velocity and $\theta$ is the open angle between the IMF and the neutron. In figure 2 typical neutron velocity spectra in coincidence with $^{12}\text{C}$ are presented. Top to bottom, the panels present results for different IMF velocity windows and panels from left to right correspond to different opening angles between the IMF and the neutron detectors. The excess neutrons from the $^{12}\text{C}$ are shown by dashed curves, which show bell shapes. In the fit the sum of the uncorrelated neutrons and those from the IMF are fixed to the multiplicity derived from the separate moving source parametrization for the same isotope trigger, which is in good agreement with those observed in the NIMROD measurement in a separate run, as mentioned earlier. The spectra of the excess neutrons in a given row decreases monotonically when the opening angle increases, indicating that the angular distribution along the IMF direction may be peaked at smaller angle than the smallest opening angle of 15° in the experiment. One can also clearly see the shift of the peak towards the higher velocity side from the top to the bottom for a given detector, which is caused by the change of the source velocity for the neutrons. The temperature and the multiplicity for a given IMF are extracted by a $\chi^2$ fit at a time for all available velocity spectra, those in 16 neutron detectors and different IMF velocity windows.

4. Results and Discussion

The present work established the technique to derive the neutron multiplicity from the primary hot fragment, which is essential for the reconstruction of the primary fragments through the experimental secondary distribution. Further data analysis is needed to extract the neutron and charged particle multiplicities, in order to finally perform the reconstruction of primary isotope distributions.

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Figure 2. Neutron velocity spectra in coincidence with $^{12}\text{C}$. Three $^{12}\text{C}$ velocity windows are shown from the top to the bottom. The opening angles are indicated on the second panel. Symbols are the experimental points. The dotted, dashed and continuous line spectra are the uncorrelated spectra from the $^6\text{Li}$ trigger, the excess neutrons from the $^{12}\text{C}$ and the sum of them, respectively.

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