Experimental reconstruction of primary fragments with kinematical focusing method

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Abstract An experimental method was used to evaluate the primary isotope yields of semi-central collisions in the reaction system ^{64}Zn+^{112}Sn at 40*A* MeV. The characteristic nature of the hot nuclear matter at the time of the isotope formation was studied. The multiplicities of light particles (LPs) associated with intermediate mass fragments (IMFs) were determined experimentally by using a kinematical focusing technique. The primary isotope distributions, reconstructed by a Monte Carlo method, were compared with those of the AMD-Gemini simulations. a_c/T=0.11 and a_{sym}/T=3.34 were extracted from the reconstructed primary fragments yield. These are consistent with those of the primary fragments of the AMD simulation.

Key words Kinematical focusing, Coulomb parameter, Symmetry parameter, Primary fragments

1 Introduction

In heavy ion collisions, it is very important to understand the properties of nuclear matter under extreme conditions. However, because of the secondary sequential cooling processes the experimentally observed fragments are not usually the same as those at the time of the fragment formation in an early stage of the reaction. Many different models have been proposed in order to explain the observed fragment production. However, the situation is still not clear from both the theoretical and experimental perspectives. Therefore, it is very desirable to extract, directly from the experimental data if possible, information on fragments at the time of fragment formation. In order to reconstruct the primary fragment distribution experimentally, a fragment-particle correlation technique based upon the kinematical focusing method was used to detect the light particles (LPs) associated with intermediate mass trigger fragments (IMFs). 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. The detector setup is the same as that in Refs.[1,2].

2 Data analysis

To extract the multiplicity of LPs associated with triggered IMFs, it is important to determine the background of uncorrelated LPs from other sources. By kinematical focusing, the LPs associated with the triggered IMF are observed as an excess in their velocity or energy spectra above the yields of uncorrelated LPs. The excess increases as the opening angle between the IMF and each LP decreases because of the kinematical focusing along the IMF direction. In the actual analysis, the uncorrelated background was determined experimentally using the spectral shape of LPs triggered by Li isotopes and assuming very few associated secondary LCPs from these isotopes[1,3,4].

A moving source parameterization was used to determine the multiplicities of LPs associated with IMF[5,6]. The parent nucleus of the associated LPs is assumed to be a surface-type emitting source emitting LPs isotropically in the parent rest frame. Therefore the LP emission can be described by a surface Maxwellian distribution which can be written as

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$$\left[\frac{d^2\sigma}{d\Omega dE}\right]=\frac{M}{4\pi T^2}(E-E_c)\exp\left[-(E-E_c)/T\right]. \quad (1)$$

Here M is the multiplicity of LPs associated with the triggered IMF. T is the temperature of parent source. E_c is the minimum Coulomb barrier energy of the particle. The spectra are transformed to the laboratory system using

$$\left[\frac{d^2\sigma}{d\Omega dE}\right]_{\text{lab}}=\left[\frac{E_{\text{lab}}}{E^{'}}\right]^{1/2}\left[\frac{d^2\sigma}{d\Omega dE}\right]_{E=E^{'}},$$

where

$$E^{'}=E_{\text{lab}}+\frac{1}{2}mv_s^2-(2E_{\text{lab}}mv_s^2)^{1/2}\cos\theta.$$

Here, E_{lab} is LPs energy, v_s is the velocity of the parent source and θ is the opening angle between the LP and the triggered IMF.

Figure 1 shows the extracted mean multiplicities of LPs in the ^{64}Zn+^{112}Sn reaction at 40*A* MeV as a function of the trigger IMF mass number *A*. The different colors or symbols correspond to the average multiplicities of isotopes with different atomic number *Z*. The multiplicity of ^{3}He was not determined in this experiment because of poor statistics. The errors in Fig.1 are from the systematic errors for the moving source fit and they are evaluated as 10%.

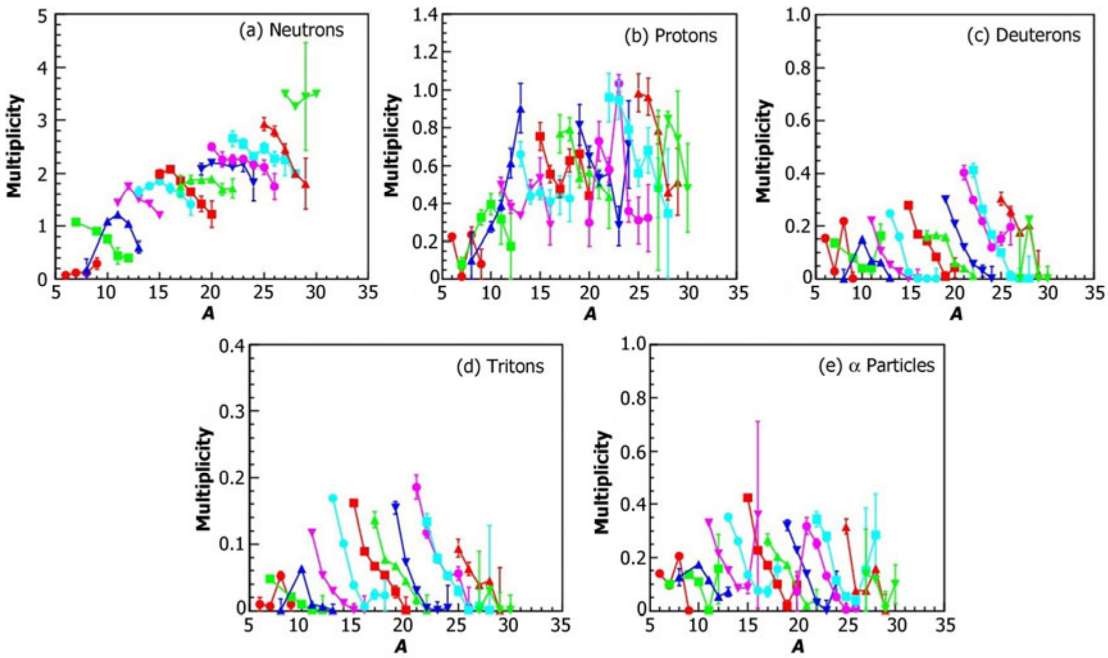

Fig.1 (Color online) Extracted average secondary multiplicities of light particles (n, p, d, t, α) in the ^{64}Zn+^{112}Sn reaction at 40*A* MeV as a function of the trigger IMF mass number *A*. Isotopes with the same *Z* number are connected to each other by lines.

Figure 2 shows the comparison between the experimental mean neutron multiplicities and those obtained from the GEMINI simulation assuming different excitation energies of the parent nuclei versus the associated IMF charge number *Z*. One can see that the average neutron multiplicities of the GEMINI simulation are close to the experimental ones when the excitation energy is around 2 to 3*A* MeV.

A Monte-Carlo method was used to reconstruct the primary fragment distribution, employing the experimentally observed mean multiplicities in Fig.1 and decay widths from GEMINI simulations, combined with the experimental (secondary) fragment yield distributions[7]. Based on results in Fig.2, the

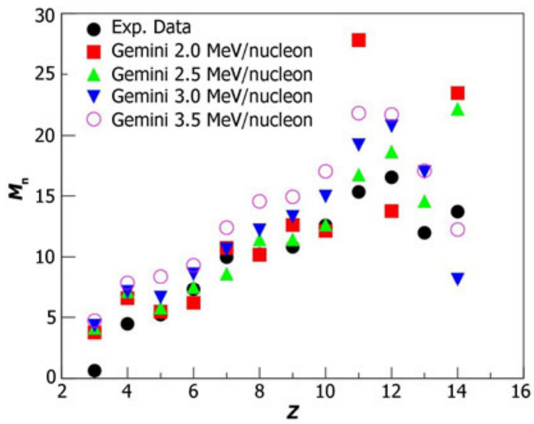

Fig.2 (Color online) Comparison between mean neutron multiplicities *vs.* the associated IMF charge number *Z* obtained from the GEMINI simulation with different excitation energies of parent nuclei as shown in the figure. The experimental results are shown by dots.

reconstruction was made using the excitation energy 2.5*A* MeV. In Fig.3, the experimental isotope distribution (a) and the reconstructed one (b) are shown in 2D plots of charge number *Z* against neutron number *N*. Comparing the width of neutron number *N* distribution for a given *Z* in Figs.3(a) and (b), one can see that the distribution of reconstructed fragments is significantly broader than that of the experimental one. Fig.4 shows the isotopic distributions of the reconstructed primary fragments as well as those of the AMD primary fragments as a function of fragment mass number *A*. As shown in Fig.4, the reconstructed primary distributions are well reproduced by those of the AMD simulation.

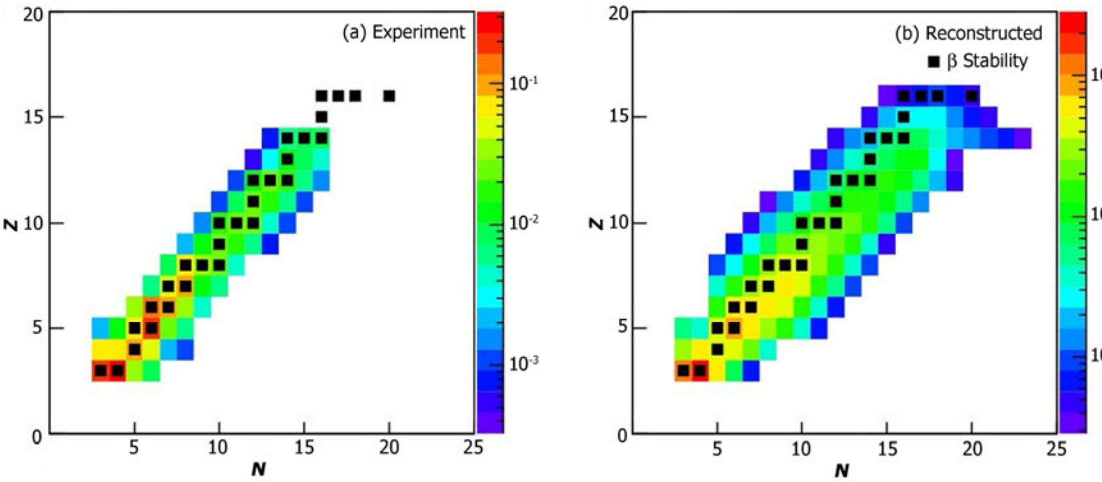

Fig.3 (Color online) Plots of charge number *Z vs.* neutron number *N* for both experimental (a) and reconstructed (b) fragments. The black solid squares represent the beta stable nuclide.

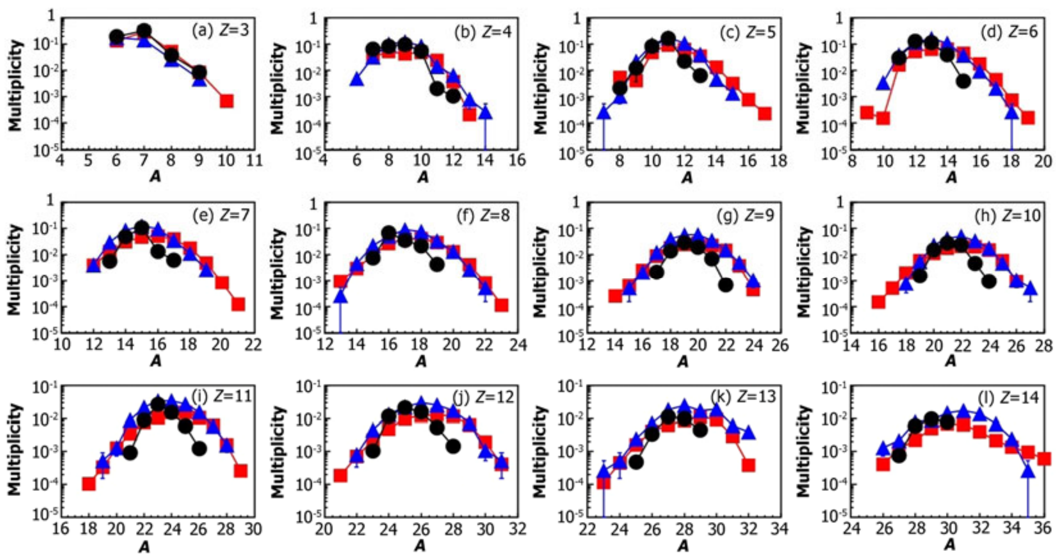

Fig.4 (Color online) Isotopic distribution of reconstructed primary (red squares), experimental (black circles) as well as the AMD primary (blue triangles) fragments as a function of fragments mass number *A*.

Using the yield of the reconstructed fragments to study the symmetry energy contribution to the fragment production, the Modified Fisher Model (MFM) of Ref.[8,9] is used. The detailed method can be found in Ref.[2]. In the model the yield ratio is of two isotopes with *I* and *I*+2, where *I*=*N*–*Z*, can be given by:

$$\begin{aligned} R(I+2,I,A) &= Y(A,I+2)/Y(A,I) \\ &= \exp\left\{\left[\mu_n-\mu_p+2a_c(Z-1)/A^{1/3} -4a_{\rm sym}(I+1)/A-\Delta\delta\right]/T+\Delta(I,A)\right\}, \end{aligned} \tag{2}$$

where $I=(N-Z)$, μ_n and μ_p are the neutron and proton chemical potential. a_c and $a_{\rm sym}$ are the Coulomb and symmetry parameters. $\Delta\delta$ is the difference of the pairing terms of two isotopes. $\Delta(I, A)$ is the difference of the mixing entropy.

For the isotopes with $I=-1$ and 1, the symmetry, pairing and $\Delta(I, A)$ terms in Eq.(2) drop out. Taking the logarithm of the resultant equation, one can get

$$\ln\left[R(1,-1,A)\right]=2\frac{a_c}{T}(Z-1)A^{-1/3}+\frac{\mu_n-\mu_p}{T}. \quad (3)$$

In Fig.5, the values of $\ln[R(I+2, I, A)]$ for $I=-1$ are plotted for the detected and reconstructed fragments as a function of fragment mass number A. The $(\mu_n-\mu_p)/T$ and a_c/T are used as fitting parameters in Eq.(3), which gives $a_c/T=0.11$ for the reconstructed primary fragments. The AMD simulation gives the value of 0.17 for the primary fragments[2]. These values are much smaller than that of the experimental data[2], which gives $a_c/T = 0.35$.

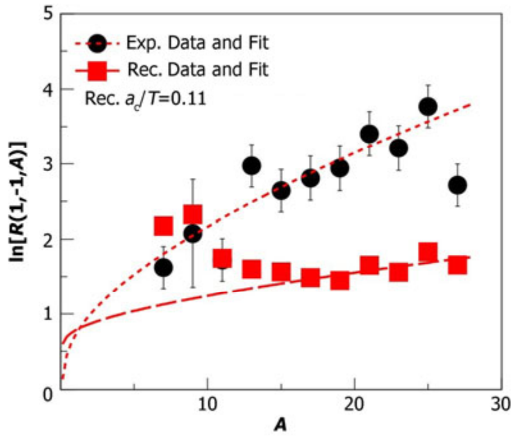

Fig.5 (Color online) $\ln[R(I+2, I, A)]$ for $I=-1$ for the experimental and reconstructed fragments are plotted as a function of fragment mass number A. The closed circles show the results from the detected fragments and solid squares represent the values from the reconstructed fragments. The dashed line is the best fit of the experimental data from Ref.[2]. The long dashed line shows the fit for the reconstructed fragments, using Eq.(3).

In the next step, the isobars with $I=1$, 3 and $I=-1$, 1 were used to extract the symmetry term, a_{sym}/T. Note that the isobars are all even-odd nuclei and therefore the pairing term is 0. Dropping out the small $\Delta(I, A)$ term in Eq.(2), the symmetry energy coefficient term is given as a function of A by

$$a_{sym}/T=-\frac{A}{8}\left\{\ln\left[R(3,1,A)\right]-\ln\left[R(1,-1,A)\right]+2\frac{a_c}{T}A^{-1/3}\right\} \quad (4)$$

In Fig.6, the values of a_{sym}/T, calculated from Eq.(4) using the previously extracted value $a_c/T=0.11$, are plotted as a function of A and compared with the values from the detected fragments. The extracted values from the reconstructed data show a flat distribution as A increases. A mean value of $a_{sym}/T=3.34$ is extracted from the reconstructed fragments. This observation is also consistent with the results derived from the primary fragments of the AMD simulation[2,10].

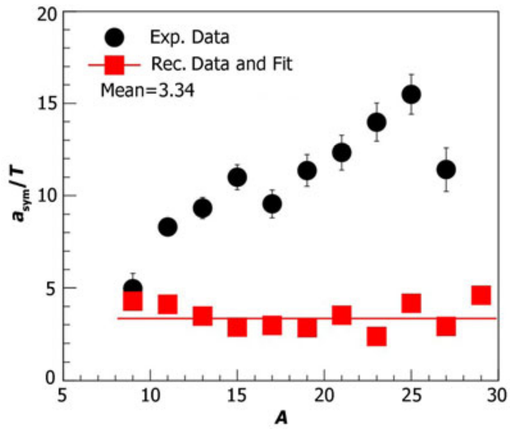

Fig.6 (Color online) Experimental (closed circles) and reconstructed (solid squares) values of a_{sym}/T as a function of fragment mass number A. The solid line is the constant fit for the a_{sym}/T of the reconstructed primary fragments. A mean value of $a_{sym}/T=3.34$ is obtained.

The values of Coulomb and symmetry parameter relative to the temperature, a_c/T and a_{sym}/T, from the reconstructed primary fragments show a significant difference from those of the experimental multiplicities and distribute close to those of the AMD primary multiplicities which indicate a strong effect of the sequential decay process on the Coulomb and symmetry parameter.

3 Conclusion

The primary isotope distribution was reconstructed, employing the experimentally extracted mean associated multiplicities, the widths from the GEMINI simulation and the experimentally observed secondary fragment yield distributions. For the isotope distribution, the reconstructed yields of primary fragments are well reproduced by the yields of the primary fragments from the AMD simulation. The Coulomb and symmetry coefficients in the form of a_i/T are also evaluated for the reconstructed fragments. The extracted value for the reconstructed fragments is $a_c/T=0.11$, whereas the value of detected fragments is

a_c/T=0.35. The calculated a_{sym}/T values show more or less a constant distribution as a function of A, while those of the experimentally detected isotopes show significant A dependence. The significant difference of the Coulomb and symmetry parameter relative to the temperature between the reconstructed primary multiplicities and those of the detected fragments indicate a strong effect of sequential decay process on Ref.[10].

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