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Full Text

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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 40A MeV. The characteristic nature of the hot nuclear matter at the time of isotope formation was studied. The multiplicities of light particles (LPs) associated with intermediate mass fragments (IMFs) were determined experimentally using a kinematical focusing technique. The primary isotope distributions, reconstructed by a Monte Carlo method, were compared with those of AMD-Gemini simulations. Values of a_c/T = 0.11 and a_{sym}/T = 3.34 were extracted from the reconstructed primary fragment yields. These are consistent with those of the primary fragments from the AMD simulation.

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

Introduction

The experiment was performed at the K-500 superconducting cyclotron facility at Texas A&M University. Beams of ^{64},^{70}Zn and ^{64}Ni at 40A MeV were used to irradiate targets of ^{58},^{64}Ni, ^{112},^{124}Sn, ^{197}Au, and ^{232}Th. The detector setup was identical to that described in Refs. [1,2].

In heavy ion collisions, understanding the properties of nuclear matter under extreme conditions is of fundamental importance. However, due to secondary decay processes, experimentally observed fragments are not typically the same as those present at the time of fragment formation in the early stage of the reaction. Numerous models have been proposed to explain the observed fragment production, yet the situation remains unclear from both theoretical and experimental perspectives. Therefore, it is highly desirable to extract information about fragments at the time of their primary formation directly from experimental data whenever possible. To reconstruct the primary fragment distribution experimentally, a fragment-particle correlation technique based upon kinematical focusing was employed to detect light particles (LPs) associated with intermediate mass fragment triggers (IMFs).

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2 Data Analysis

To extract the multiplicity of LPs associated with triggered IMFs, it is crucial to determine the background contribution from uncorrelated LPs originating from other sources. Through kinematical focusing, LPs associated with a triggered IMF are observed as an excess in their velocity or energy spectra above the yields of uncorrelated LPs. This excess increases as the opening angle between the IMF and each LP decreases, due to 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 IMFs [5,6]. The parent nucleus emitting the associated LPs is assumed to be a surface-type source emitting LPs isotropically in its rest frame. Therefore, the LP emission can be described by a surface Maxwellian distribution. The spectra are transformed to the laboratory system using the appropriate relativistic transformation equations. Here, E_{lab} is the LP 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 average multiplicities of LPs (n, p, d, t, α) in the ^{64}Zn+^{112}Sn reaction at 40A MeV as a function of the trigger IMF mass number A. Isotopes with the same atomic number Z are connected by lines. The multiplicity of ^{3}He was not determined in this experiment due to poor statistics. The errors shown in Fig. 1 represent systematic uncertainties from the moving source fit, evaluated to be 10%.

[Figure 1: see original paper]

Figure 2 compares the experimental mean neutron multiplicities with those obtained from GEMINI simulations assuming different excitation energies of the parent nuclei, plotted versus the associated IMF charge number Z. The average neutron multiplicities from the GEMINI simulation are in good agreement with experimental data when the excitation energy is approximately 2–3A MeV.

[Figure 2: see original paper]

A Monte Carlo method was employed to reconstruct the primary fragment distribution, utilizing the experimentally observed mean multiplicities from Fig. 1, decay widths from GEMINI simulations, and the experimentally observed secondary fragment yield distributions [7]. Based on the results shown in Fig. 2, the reconstruction was performed using an excitation energy of 2.5A MeV.

Figure 3 presents two-dimensional plots of charge number Z versus neutron number N for both the experimental (a) and reconstructed (b) fragment distributions. Comparing the width of the neutron number distribution for a given Z between Figs. 3(a) and 3(b), it is evident that the distribution of reconstructed fragments is significantly broader than that of the experimentally observed fragments.

[Figure 3: see original paper]

Figure 4 shows the isotopic distributions of reconstructed primary fragments, experimental fragments, and AMD primary fragments as a function of fragment mass number A. As demonstrated in Fig. 4, the reconstructed primary distributions are well reproduced by those from the AMD simulation.

[Figure 4: see original paper]

To study the symmetry energy contribution to fragment production using the yields of reconstructed fragments, the Modified Fisher Model (MFM) from Refs. [8,9] was applied. The detailed methodology can be found in Ref. [2]. In this model, the yield ratio of two isotopes with I and $I+2$, where $I = N - Z$, can be expressed as:

$$Y(A,I) \propto \exp\left(\frac{\mu_n N + \mu_p Z - a_c \frac{Z^2}{A^{1/3}} - a_{sym}\frac{I^2}{A} + \delta}{T}\right)$$

where $I = (N - Z)$, μ_n and μ_p are the neutron and proton chemical potentials, a_c and a_{sym} are the Coulomb and symmetry parameters, $\Delta\delta$ is the difference in pairing terms between the two isotopes, and $\Delta(I, A)$ is the difference in mixing entropy. For isotopes with $I = -1$ and $I = 1$, the symmetry, pairing, and $\Delta(I, A)$ terms cancel out.

Taking the logarithm of the resultant equation yields:

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

where $R(I + 2, I, A) = Y(A, I + 2)/Y(A, I)$.

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

[Figure 5: see original paper]

In the next step, isobars with $I = 1, 3$ and $I = -1, 1$ were used to extract the symmetry term a_{sym}/T. Note that these isobars are all even-odd nuclei, so the pairing term is zero. Neglecting the small $\Delta(I, A)$ term, the symmetry energy coefficient can be expressed as:

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

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

[Figure 6: see original paper]

The values of the Coulomb and symmetry parameters relative to temperature, a_c/T and a_{sym}/T, obtained from the reconstructed primary fragments differ significantly from those of the experimentally detected fragments and are distributed close to those of the AMD primary fragments, indicating a strong effect of the sequential decay process on the Coulomb and symmetry parameters.

3 Conclusion

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

The extracted value for the reconstructed fragments is $a_c/T = 0.11$, whereas the value for detected fragments is $a_c/T = 0.35$. The calculated a_{sym}/T values show a relatively constant distribution as a function of A, while those for experimentally detected isotopes exhibit significant A dependence. The significant difference in the Coulomb and symmetry parameters relative to temperature between reconstructed primary multiplicities and those of detected fragments indicates a strong effect of the sequential decay process, as discussed in Ref. [10].

References

1. Rodrigues M R D, Wada R, Hagel K, et al. J Phys: Conf Ser, 2011, 312: 082009.
2. Huang M, Chen Z, Kowalski S, et al. Phys Rev C, 2010, 81: 044620.
3. Marie N, Chbihi A, Natowitz J B, et al. Phys Rev C, 1998, 58: 256–269.
4. Hudan S, Chbihi A, Frankland J D, et al. Phys Rev C, 2003, 67: 064613.
5. Hagel K, Wada R, Cibor J, et al. Phys Rev C, 2000, 62: 034607.
6. Wada R, Keutgen T, Hagel K, et al. Phys Rev C, 2004, 69: 044610.
7. Kowalski S. Cyclotron Institute Annual Reports, 2005.

8. Minich R W, Agarwal S, Bujak A, et al. Phys Lett B, 1982, 118: 458-460.
9. Hirsch A S, Bujak A, Finn J E, et al. Nucl Phys A, 1984, 418: 267-287.
10. Chen Z, Kowalski S, Huang M, et al. Phys Rev C, 2010, 81: 064613.

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