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Abstract

An improved method is proposed for the extraction of the symmetry energy coefficient relative to the temperature, asym/T, for the heavy-ion reactions near the Fermi energy region, based on the modified Fisher Model (MFM). This method is applied to the primary fragments of the Anti-symmetrized Molecular Dynamics (AMD) simulations for the reactions of 40Ca + 40Ca at 35 MeV/nucleon. The density and the temperature at the fragment formation stage are extracted using a self-consistent method.

Full Text

Preamble

Symmetry Energy Extraction from Primary Fragments in Intermediate Heavy-Ion Collisions

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Abstract. An improved method is proposed for extracting the symmetry energy coefficient relative to temperature, a_{sym}/T, for heavy-ion reactions near the Fermi energy region, based on the modified Fisher Model (MFM). This method is applied to the primary fragments from Anti-symmetrized Molecular Dynamics (AMD) simulations of ^{40}Ca + ^{40}Ca reactions at 35 MeV/nucleon. The density and temperature at the fragment formation stage are extracted using a self-consistent method.

Keywords: Intermediate energy heavy ion reactions, Symmetry energy, Density, Temperature, Modified Fisher model, Self-consistent method

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Introduction

The symmetry energy term in the nuclear equation of state (EOS) intimately relates to numerous dynamical processes in nuclear reactions, structural characteristics of nuclei, and astrophysical phenomena [**?**]. Investigations of symmetry energy, particularly its density dependence, have been conducted through many observables such as isotopic ratios [**?**], isospin diffusion [**?**], neutron-proton emission ratios [**?**, **?**], giant monopole resonance [**?**], pygmy dipole resonance [**?**], giant dipole resonance [**?**], collective flow [**?**], and isoscaling [**?**]. In our recent works, we utilized isotopic yields to extract the symmetry energy coefficient relative to temperature, a_{sym}/T, within the framework of nuclear phase transition theory [**?**]. Along this line, a_{sym}/T was extracted using m-scaling [**?**] and isobaric yield ratios [**?**]. Ono et al. also independently introduced a generalized free energy, $K(N, Z)$, and extracted a_{sym}/T values from their quadratic distributions [**?**]. In this method, for a given Z, all contributions from the volume, surface, Coulomb, and pairing terms in the free energy are squeezed into an N-proportional term and a constant, $\xi(Z)N + \eta(Z)$, as a coarse approximation.

While temperature is one of the key variables characterizing nuclear reactions, determining the temperature of hot nuclear matter in a dynamical process is very difficult. Several nuclear thermometers have been proposed [**?**], including the slope of energy spectra [**?**, **?**], momentum fluctuations [**?**, **?**], double isotope yield ratios [**?**], and excited state distributions [**?**]. However, they may not be generally applicable in all circumstances, and even for a given system the extracted temperature values from these thermometers may differ considerably from each other [**?**]. In our recent work, temperature was evaluated from a $(\mu_n - \mu_p)/T$ analysis, but no density determination was possible [**?**]. In another recent work, the isotopic yield ratio method was applied to extract a_{sym}/T values from experimentally reconstructed primary fragment yields. These ratios were compared to those calculated from AMD primary generated fragment yields obtained using Gogny interactions with different density dependencies of the symmetry energy [**?**, **?**]. In the analysis, we found that the extracted a_{sym}/T

values change according to the interactions used. From this dependence on interaction, the density, symmetry energy, and temperature at the time of fragment formation were determined in a self-consistent manner.

In this article, an improved method is used to extract the a_{sym}/T values. In the improved method, all available isotope yields are employed. The improvement is made possible by taking into account the mass-dependent temperature [**?**] in the free energy in an iterative manner. Using the self-consistent method, the density and temperature at the time of fragment formation are carefully determined from the obtained a_{sym}/T values from different interactions with different density dependencies of the symmetry energy term: the standard Gogny interaction which has an asymptotic soft symmetry energy (g0), the Gogny interaction with an asymptotic stiff symmetry energy (g0AS), and the Gogny interaction with an asymptotic super-stiff symmetry energy (g0ASS) [**?**, **?**]. Our present analyses are conducted within the framework of AMD.

There are three major reasons to use AMD as the event generator for this work. First is its capability to reproduce experimental isotope yields. AMD results, such as multiplicity, angular distribution, and energy spectra, have often been compared with experimental data for intermediate energy heavy ion collisions and reproduce them reasonably well [**?**]. In one of our recent works [**?**], the yields of experimentally reconstructed primary hot isotopes were well reproduced by those from AMD simulations. Second is to eliminate the secondary cooling effect. As shown in [**?**, **?**], the sequential decay of primary hot isotopes significantly alters the yield distribution and distorts the information inherent in the primary hot fragment yields. Third is to simplify the initial conditions using zero impact parameter to eliminate the effects of transverse flow and neck emission among others. Thus the AMD events are generated for central collisions ($b = 0$ fm) of ^{40}Ca + ^{40}Ca at 35 MeV/nucleon.

Improved MFM Model and Extraction of a_{sym}/T

In the framework of MFM, the yield of an isotope with mass A and $I = N - Z$ (N neutrons and Z protons) produced in a multifragmentation reaction can be given as [**?**, **?**, **?**]

$$Y(I,A) = Y_0 \cdot A^{-\tau} \exp\left[\frac{W(I,A) + \mu_n N + \mu_p Z + N\ln(\langle MATH_1\rangle) + Z\ln(\langle MATH_2\rangle)}{T}\right]$$

Using the generalized Weizsäcker-Bethe semiclassical mass formula [**?**, **?**], $W(I,A)$ can be approximated as

$$W(I,A) = a_v A - a_s A^{2/3} - a_c\langle MATH_3\rangle$$

$$\delta = \langle MATH_4\rangle - a_{sym}(N-Z)^2(-1)^Z + (-1)^N$$

In Eq. (1), $A^{-\tau}$ and $N\ln(N/A) + Z\ln(Z/A)$ originate from the increases of entropy and mixing entropy at the time of fragment formation, respectively. μ_n (μ_p) is the neutron (proton) chemical potential. τ is the critical exponent. In this work, the value of $\tau = 2.3$ is adopted from previous studies [**?**]. In general, coefficients a_v, a_s, a_{sym}, a_p, and the chemical potentials are temperature and density dependent. In this formulation, a constant volume process at equilibrium is assumed in the free energy, and therefore the term "symmetry energy" is used throughout this work along with Ref. [**?**]. If one assumes a constant pressure at the equilibrium process [**?**], the term "symmetry enthalpy" should be used. Experimentally, whether the equilibrium process takes place at constant pressure or volume cannot be determined, and thus we use "symmetry energy" throughout the paper, keeping in mind this ambiguity [**?**].

In previous analyses [**?**, **?**, **?**, **?**], the temperature in Eq. (1) was assumed to be identical to the temperature of the fragmenting source and treated as a constant for all isotopes. However, as seen below, this temperature turns out to be fragment mass dependent. This mass dependence on temperature was not recognized in previous analyses simply because it was masked by larger error bars. In this improved method, the error bars become small and the mass dependence becomes evident. To account for the mass dependence of temperature in Eq. (1), the temperature T is replaced by an apparent temperature $T(A)$. We attribute this mass dependence to the system size effect as discussed in Section IV. In the improved MFM formulation, this system size effect is empirically realized by reducing the apparent temperature as A increases:

$$T(A) = T_0(1 - kA)$$

where T_0 is the temperature of the fragmenting source and k is a constant quantifying the mass dependence.

To study the density, temperature, and symmetry energy in the fragmenting source, the improved MFM of Eq. (1) is utilized to extract the a_{sym}/T_0 value from available isotope yields. Since a_{sym}/T_0 in Eqs. (1) and (2) depends on five parameters (a_v, a_s, a_c, a_p, and $\Delta\mu$ defined by $\Delta\mu = \mu_n - \mu_p$), the optimization process is divided into three steps to minimize ambiguity for each parameter.

Step 1: Optimize $\Delta\mu/T_0$ and a_c/T_0 values from mirror isobars and fix these parameter values.

Step 2: Apply Eq. (1) to isotopes with $N = Z$ using extracted $\Delta\mu/T_0$ and a_c/T_0 values from Step 1. For $N = Z = A/2$ isotopes, the ratio of free energy relative to temperature can be calculated from Eqs. (1) and (2) without the symmetry energy term:

$$\frac{F(A/2, A/2)}{T(A)} = \ln\left[\frac{Y(A/2, A/2)}{Y_0 A^{\tau}}\right] = \tilde{a}_v A - a_s A^{2/3} - a_c \frac{Z(Z-1)}{A^{1/3}} - a_p\delta + \frac{A}{2}(\mu_n + \mu_p)$$

where $\tilde{a}_v = a_v + 1$. The value of $\ln[Y(A/2, A/2)A^\tau]$ on the right side can be calculated from simulated or experimental values when the τ value is fixed. Non-zero values show the deviation of the mass distribution of $N = Z$ isotopes from the power law distribution determined by the critical exponent [**?**]. When other τ values are used, the parameter values change accordingly. To eliminate the constant Y_0, all isotope yields are normalized to the yield of ^{12}C [**?**, **?**, **?**]. For the first round with $k = 0$, the renormalized values of $-F(A/2, A/2)/T_0$ from AMD events with the g0 interaction are plotted as a function of isotope mass A using solid points in Fig. 2(a). The values of $\tilde{a}_v/T_0$, a_s/T_0, and a_p/T_0 are used as free parameters to fit the given $-F(A/2, A/2)/T_0$ values, employing Eq. (5). A typical search result is shown by open circles in Fig. 2(a) for the case of the g0 interaction. Similar quality results are obtained for events generated using the g0AS and g0ASS interactions.

One should note that the value of a_p/T_0 makes a small contribution evident as staggering in the $-F(A/2, A/2)/T_0$ vs. A plot. Therefore, the essential free parameters in this step are $\tilde{a}_v/T_0$ and a_s/T_0. The extracted parameter values are summarized in Table 1 for the first round ($k = 0$) and the final round ($k = 0.007$).

Step 3: Using extracted parameters from Steps 1 and 2, a_{sym}/T_0 values are extracted from all available isotopes. Comparing the extracted a_{sym}/T_0 values with three different interactions, the density of the fragmenting source is extracted. Using this density, the symmetry energy coefficient a_{sym} for each interaction is determined. The temperature is then calculated as the ratio of a_{sym} to a_{sym}/T_0.

It is expected that if the k value is properly selected (meaning the mass dependence is well considered), a constant T_0 will be obtained. Since the k value is small as seen below, we perform the optimization of parameter k iteratively. In the first round, $k = k_1 = 0$ is set in $T(A) = T_0(1 - kA)$ and the temperature is calculated as a function of A using Steps (1)-(3). From this plot, a new k value, $k = k'_1$, is extracted from the slope. In the second round, $k = k_2 = k_1 + k'_1$ is used for Steps (1)-(3) and a new k value, $k = k'_2$, is extracted. If $k'_2 \approx 0$ within a given error range, the iteration stops and the k_2 value is fixed as the mass-dependent parameter of the apparent temperature and the T_0 value is determined. Otherwise, the iteration continues.

The details of Steps (1)-(3) are first described below for a given k value. In Step (1), following Ref. [**?**], the isotope yield ratio between isobars with $I + 2$ and I, $R(I + 2, I, A)$, is utilized:

$$R(I{+}2, I, A) = \frac{Y(I+2, A)}{Y(I, A)} = \exp\left\{ \frac{\mu_n - \mu_p + 2a_c(Z-1)/A^{1/3} - 4a_{sym}(I+1)/A - \delta(N+1, Z-1) - \delta(N, Z}{T_0(1-kA)} \right.$$

where $Y(I, A)$ is the yield of isotopes with I and A, and $\Delta(I + 2, I, A) =$

$S_{mix}(I+2,A) - S_{mix}(I,A)$. When the above equation is applied for a pair of mirror nuclei of odd mass isotopes with $I = -I$ and I, the symmetry energy term, pairing term, and mixing entropy terms drop out, yielding:

$$\frac{\ln[R(I,-I,A)]}{I} = \frac{\Delta\mu + a_c(A-1)/A^{1/3}}{T_0(1-kA)}$$

For all available mirror isobars, $\Delta\mu/T_0$ and a_c/T_0 are optimized using Eq. (4). The $\ln[R(I,-I,A)]/I$ values and fit result for $k = 0$ are shown in Fig. 1.

In Step (3), Eq. (1) is applied to yields of all isotopes with $N = Z$ and $N \neq Z$. From Eq. (1), a_{sym}/T_0 and $\Delta\mu/T_0$ values can be related to the modified free energy $\Delta F(N,Z)$:

$$\Delta F(N,Z) = \frac{F(N,Z)}{T(A)} - \frac{F(A/2,A/2)}{T(A)} = \frac{a_{sym}(N-Z)^2}{T_0(1-kA)} + \frac{\Delta\mu(N-Z)}{T_0(1-kA)}$$

where $F(N,Z)/T(A)$ is the free energy relative to temperature, subtracted by calculated contributions of the volume, surface, Coulomb, and pairing terms using parameters from Table 1. Resultant values are shown by symbols in Fig. 2(b). They exhibit quadratic relationships with minimum values close to zero. The minimum values are at or near $N = Z$ isotopes and therefore reflect approximately the difference between data and fitting points in Fig. 2(a). In this step, a_{sym}/T_0 and $\Delta\mu/T_0$ values are optimized. Since $\Delta\mu/T_0$ values are extracted from Step (1), optimization is made around values in the fifth column of Table 1 within a small margin. The a_{sym}/T_0 values are extracted from the quadratic curvature of the isotope distribution for each given Z and plotted in Fig. 2(c) separately for g0, g0AS, and g0ASS interactions. As seen for the first round with $k = 0$, the extracted a_{sym}/T_0 values increase as Z increases in all cases, and they more or less parallel each other.

Self-Consistent Determination of Density and Temperature

To determine the density and temperature at the time of fragment formation, the parallel behavior of observed a_{sym}/T_0 values in Fig. 2(c) is utilized. As suggested in Ref. [**?**], the observed differences are attributed to the difference in symmetry energy at the density at the time of fragment formation. The ratios between g0/g0AS and g0/g0ASS of a_{sym}/T_0 for the first round are shown in Fig. 3(a). The ratios show flat distributions as a function of Z for both cases. The extracted average ratio values are shown by lines in the figure and given in the first column of Table 2.

In Fig. 3(b), the symmetry energy coefficient is plotted as a function of density for the three interactions used in calculations, and in Fig. 3(c) their ratios $R_{sym} = a_{sym}(g0)/a_{sym}(g0AS)$ and $R_{sym} = a_{sym}(g0)/a_{sym}(g0ASS)$ are plotted.

Using ratio values determined from Fig. 3(a) and the density dependence of R_{sym} values in Fig. 3(c), the implied densities of fragmenting sources are indicated by shaded vertical areas in Fig. 3(c). The extracted density values for each case are given in the second column of Table 2.

Assuming that nucleon density should be the same for the three different interactions used, the nucleon density of the fragmenting source is determined from the overlap of extracted values. This assumption is reasonable for central collisions because nucleon density is mainly determined by the stiffness of the EOS and not by the density dependence of the symmetry energy term. From the overlapped density area in Fig. 3(c), $\rho/\rho_0 = 0.67 \pm 0.02$ is extracted as the density at the time of fragment formation. Using this density value, corresponding symmetry energy values at that density are extracted for the three different interactions from Fig. 3(b) and given in the third column of Table 2.

Once the symmetry energy value is determined for a given interaction, the temperature T_0 can be calculated as $T_0 = a_{sym}/(a_{sym}/T_0)$. The extracted T_0 values are shown as a function of Z by open symbols for the first round in Fig. 4. The larger errors of T_0, compared to those in Fig. 2(c), originate from errors of a_{sym} and a_{sym}/T_0 extracted for each interaction, shown in the third column of Table 2 and Fig. 2(c), respectively. The temperature values extracted from the three different interactions agree very well and show a monotonic decrease as Z increases from $\sim$ 5 MeV at $Z = 4$ to $\sim$ 3 MeV at $Z = 18$. From this slope, the extracted temperature as a function of A, $T_0 = 5.5(1 - 0.012A)$, is determined for the first round, assuming $A \sim 2Z$.

The iteration is repeated four times in this work. The same plots as Fig. 2, but with the k value for the fourth (final) round, $k = 0.007$, are shown in Fig. 5, and extracted parameters are also given in Table 1. Very similar quality results to those of the first round with $k = 0$ were obtained, even though optimized parameter values differ considerably between the first round ($k = 0$) and fourth round ($k = 0.007$). The extracted a_{sym}/T_0 values parallel each other and show a rather flat distribution as a function of Z for Z up to 15 in Fig. 5(c). As seen in Fig. 4, where extracted T_0 values are shown by closed symbols as a function of Z for the fourth round with $k = 0.007$, the extracted T_0 values are consistent with 5.5 MeV within error bars. Since T_0 values show a flat distribution as a function of Z, the iteration is stopped at this round and $T_0 = (5.5 \pm 0.2)$ MeV is taken as the temperature of the emitting source.

The extracted parameter values of R_{sym}, density, and symmetry energy for the fourth round are very similar to those of the first round, as shown in Table 2. The values and errors of these parameters are essentially determined by the ratios and their errors of a_{sym}/T_0 values between different interactions, as discussed in Fig. 3(a). These ratio values are stable between the first and fourth rounds, even though optimized parameter values in Table 1 differ considerably between these rounds. The extracted value of the mass-dependent factor k has some errors, but this fact ensures that extracted density, temperature, and symmetry values and their errors in Table 2 are rather stable independent of the choice of

k values within its error bar, when parameters in Table 1 are optimized for the given k value.

The decreasing trend of temperature as A increases is often observed in heavy ion collisions and normally attributed to variations in impact parameter [**?**], with heavier fragments tending to be produced in more peripheral collisions and therefore showing lower temperature. However, in this study all events analyzed are generated in the same class of events: central collisions with $b = 0$ fm. Therefore, we attribute the decreasing trend to different fragment formation processes rather than to the centrality of the events.

Summary

An improved method is proposed for extracting the ratio of the symmetry energy coefficient relative to temperature, $a_{sym}/T(A)$, taking into account the mass dependence of the apparent temperature based on the MFM model. This method is applied to central collisions of AMD events generated for ^{40}Ca + ^{40}Ca at 35 MeV/nucleon. The Gogny interactions g0, g0AS, and g0ASS, with three different density dependencies of the symmetry energy, are employed. As a function of IMF charge Z, the ratios of extracted a_{sym}/T_0 values from different interactions are essentially constant and reflect differences in symmetry energy at that density at the time of fragment formation. Using this correlation, $\rho/\rho_0 = 0.67 \pm 0.02$ is evaluated as the density at the time of fragment formation, and symmetry energy values at that density are extracted for each interaction. The temperature values are then determined as $T_0 = 5.5$ MeV. The apparent temperatures show a monotonic decrease as fragment Z increases, changing from 5 MeV to 3 MeV when Z increases from 4 to 18 due to the system size effect.

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Note: Figure translations are in progress. See original paper for figures.