Temperature and symmetry energy of neutron-rich fragments in the 1A GeV 124,136Xe+Pb reactions postprint

Authors: MA Chunwang, QIAO Chunyuan, WANG Shanshan, LU Fangmei, CHEN Li, GUO Meiting

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Full Text

Preamble

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MA Chunwang*
QIAO Chunyuan, WANG Shanshan, LU Fangmei, CHEN Li, GUO Meiting

Institute of Particle and Nuclear Physics, Henan Normal University, Xinxiang 453007, China

Abstract

In this work we study the symmetry-energy coefficient of neutron-rich nuclei and the temperature dependence of nuclear symmetry energy at low temperatures. An isobaric method is used to extract the symmetry-energy coefficients of neutron-rich nucleus (asym) at zero temperature (T) and asym/T at nonzero temperature in the measured 1A GeV ^{124,136}Xe+Pb reactions. The temperature of fragments is obtained from the ratio of its asym to asym/T. The results show that, for fragments with the same neutron-excess (I=N−Z), the heavier the fragment is, the higher temperature it has, and temperature tends to saturate around 1 MeV for large mass fragments. It is also shown that the more neutron-rich the isobar is, the higher temperature it has. The T^2 dependence of symmetry energy of finite nucleus at low temperatures is verified by the extracted results.

Key words: Temperature, Symmetry energy, Isobaric yield ratio, Neutron-rich nucleus

Introduction

The nuclear symmetry energy (NSE), which depends on both the density and temperature of nuclear matter, is critically important not only in nuclear physics but also in astrophysics. Regarding the density dependence of NSE, several probes have been used to study it theoretically and experimentally [1-14]. Many works have focused on NSE of supra-saturate nuclear matter in the hot emitting source of heavy-ion collisions (HIC) [1,2]. However, the NSE results show large differences ranging from soft to stiff behavior, particularly for high-density nuclear matter. This necessitates further theoretical efforts to constrain the symmetry energy.

On the temperature dependence of NSE, some theoretical work indicates a T^2-dependence of the symmetry energy of finite nuclei [15]. Compared with the various thermometers for the colliding source in HIC constructed from emitted light particles [16-21], the thermometer for heavy fragments in HIC has not been fully investigated. In HIC, the measured fragments should not be at high temperature. Albergo et al. [16] used the isotopic thermometer to extract the temperature of heavy fragments, and the temperatures they obtained for heavy fragments were lower than those for light particles [22,23]. The recent isobaric yield ratio (IYR) thermometer for heavy fragments also indicates low temperatures for heavy fragments [24,25]. In this article, we present a new thermometer for heavy fragments using IYR and employ it to investigate the temperature of fragments produced in the 1A GeV ^{124,136}Xe+Pb reactions.

The non-zero temperature symmetry energy coefficient to temperature (asym/T) of neutron-rich fragments in HIC has been investigated using the IYR method within the framework of a modified Fisher model [9-12]. Previously, we reported the symmetry energy coefficient (asym) and the volume-symmetry energy coefficient [13]. Based on these results [11,13], we now extract the temperature of measured fragments in the 1A GeV ^{124},^{136}Xe+Pb reactions [26].

2 Theoretical Method

The theoretical deduction is performed within the framework of the modified Fisher model, which relates the yield of a fragment to its free energy at temperature T [27]. The formula used to determine asym/T of neutron-rich fragments in Refs. [11,12] is slightly modified to Eq. (1):

$$R I I {ln (, + Δ - Δ , and the prime means that where I=N−Z, the results are for the fragment; R is the yield ratio between the isobars differing by 2 in I; ΔEc=Ec(I)–Ec(I–2) is the difference between the Coulomb energy of the isobars; ΔI-2 and ΔI are the mixing terms of N and Z of the isobars related [ΔI=(NI+2/A)+ZI+2ln(NI+2/A)-NIln(NI/A)-ZIln(NI/A)]. In Eq. (1), T can hardly be known directly, and the term asym/AT should be viewed as one parameter.

For the zero-temperature finite nucleus, the symmetry energy coefficient can be determined using the isobaric method [13] as Eq. (2):

$$[/ (where B(I) and B(I+2) are the binding energy of the isobars [28]. In Eqs. (1) and (2), we take the same form of Coulomb energy of the nucleus as in Ref. [13].

Using Eqs. (1) and (2), the temperature of fragments in HIC can be determined as:

$$T = \frac{\text{asym}}{\text{asym}/T}$$

Therefore, the asym~T correlation can be investigated.

3 Results and Discussion

In Fig. 1, the values of asym/AT for fragments in the 1A GeV ^{124},^{136}Xe+Pb reactions and asym/A for the corresponding T=0 nuclei are plotted. Due to the effect of nonzero temperature, there is a large difference between the values of asym/AT and asym/A. Taking the ratio of asym to asym/T of the fragments according to Eq. (3), the values of T related to the fragments can be determined. The obtained temperatures of fragments are plotted in Fig. 2. For nuclei having the same I, T decreases with increasing mass, especially for fragments from which fewer nucleons are abraded from the projectile and which are mostly produced in peripheral reactions [24,29,30]. The results show that, in the two Xe reactions, the temperature of the same fragment has very little difference, except for fragments of small A in the same I nucleus-chain. It should be noted that in models which predict fragment yields, the temperature is usually set as a constant, which results in disagreement between theoretical and experimental yields. The variation of fragment temperatures shown in this work indicates that T changes with the fragment in theoretical calculations.

After separating the fragment temperature from the asym/AT results using the ratio of asym to asym/T, it is interesting to see how asym/T depends on T as shown in HIC [9-12,31]. The correlation between asym/T and the obtained temperature of the fragment is plotted in Fig. 3. Relatively similar distributions of asym/T~T correlations for fragments with different I are observed. For the measured fragments, asym/T decreases with increasing T. Generally, the symbols of larger asym/T correspond to larger mass fragments, and the symbols of larger T values represent smaller mass fragments in the same I chains.

The temperature dependence of the symmetry energy of the fragments can be discussed as follows. Based on the Skyrme interaction (SKM) density-functional theory, the relationship between the symmetry energy and low temperature of the finite nucleus (A,I) was proposed as Eq. (4) [15]:

$$\mathrm{asym}(T) = bv\left(1 - \frac{T^2}{bv^2}\right) + bs\left(1 - \frac{T^2}{bs^2}\right)A^{-1/3}$$

where bv and bs are the volume- and surface-symmetry energy coefficients, respectively. The first and second terms on the RHS of Eq. (4) correspond to the volume symmetry energy and the surface symmetry energy of the (A, I) nucleus, respectively. The symmetry energy of the fragment at T is calculated, and the value of asym/T of the fragment is deduced according to asym/T = asym(T)/T.

Figure 3 [Figure 3: see original paper] shows the correlation between asym/T and T of the fragments in the 1A GeV ^{124}Xe+Pb (crossed open symbols) and the ^{136}Xe+Pb (solid symbols) reactions. The symmetry energy of the ^{117}Cs nucleus, which has I=15, is calculated using different sets of bv and bs (for the S1, S2 and S3 lines in Fig. 3, bs/bv=1.68). Using such sets of bv and bs values, the asym/T of nucleus depends very little on the bv values (result not shown). The temperature was varied from 0.04 MeV to 5 MeV in the calculation. In S1 (dash line), bv=19.69 MeV was suggested in Ref. [15]. In S2 (dot line), bv=32 MeV accords with the finite-range liquid-drop (FRLD) model [13]. In S3 (dash-dot line), the bv is simply changed to 29 MeV to see the effect of bv and bs parameters. All the S1–S3 results can well reproduce the trend of the experimental asym/T~T correlation. The result of S1 shows that the suggested bv in Ref. [15] agrees with the asym/T of ^{117}Cs, while S2 according to FRLD and S3 overestimate the experimental data. The calculated asym/T verifies the T^2 dependence of the symmetry energy of finite nucleus; however, for a specific nucleus, proper values of bv and bs should be used.

A simple fitting using the $y=a+bx+cx^2$ function was performed to examine how asym/T depends on temperature, yielding a=47.99, b=–27.34 and c=4.43. The bx term in the fitting function cannot be omitted due to the complicated dependence of nuclear symmetry energy on A and I according to Eq. (4). In Fig. 3, when T is larger than ~3.5 MeV, the fitting result deviates from the experimental results, and the trend of the fitting result goes in the opposite direction of the experimental data, which indicates that T^2 dependence of the symmetry energy is only valid in the relatively low temperature region (for example, lower than 5 MeV). Actually, if the system temperature is larger than 5 MeV, the liquid-gas transition happens and the finite nucleus becomes unstable.

4 Conclusion

In conclusion, an IYR method is proposed to separate the energy part and temperature part of parameters obtained in the framework of a modified Fisher model. This approach is also instructive for other models based on free energy. By analyzing the yield of fragments produced in the 1A GeV ^{124}Xe+Pb and ^{136}Xe+Pb reactions measured at GSI, the symmetry energy coefficient of fragments is found to be modified to different degrees by the temperature in HIC. The temperature of fragments is determined by the ratio of its symmetry energy coefficient at T=0 and nonzero T in HIC. The dependence of asym/T on T is demonstrated. All these verify the T^2-dependence of the symmetry energy of finite nucleus at low temperature, with proper setting of bv and bs.

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