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

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 (a_{sym}) at zero temperature (T) and a_{sym}/T at nonzero temperature in the measured 1A GeV ^{124,136}Xe+Pb reactions. T of fragment is obtained from the ratio of its a_{sym} to a_{sym}/T. The results show that, for fragment with the same neutron-excess (I=N–Z), the heavier the fragment is, the higher T it has, and T tends to saturate around 1 MeV for the 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

1 Introduction

Depending on both the density and temperature of nuclear matter, the nuclear symmetry energy (NSE) is very important not only in nuclear physics but also astrophysics. On the density dependence of NSE, several probes were used to study NSE theoretically and experimentally[1-14]. Many works have been performed on NSE of the supra-saturate nuclear matter in the hot emitting source of heavy-ion collisions (HIC)[1,2]. However, the NSE results show a large difference ranging from soft to stiff one, especially for high density nuclear matter. This necessitates further theoretical efforts on constraining the symmetry energy.

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

The non-zero temperature of symmetry energy coefficient to temperature (a_{sym}/T) of neutron-rich fragment in HIC has been investigated using the IYR method in the framework of a modified Fisher model[9-12]. Previously, we reported the symmetry energy coefficient of nucleus at T=0, the surface-symmetry energy coefficient (a_{sym}) and the volume-symmetry energy coefficient[13]. Based on the results in Refs.[11,13], we will extract the temperature of the measured fragments in the 1A GeV ^{124,136}Xe+Pb reactions[26].

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* Corresponding author. *E-mail address:* machunwang@126.com

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2 Theoretical method

The theoretical deduction is performed in 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 the a_{sym}/T of the neutron-rich fragment in Refs.[11,12] is slightly changed to Eq.(1):

$$\frac{a^{*'}_{\mathrm{sym}}}{AT}=\frac{1}{2}\{\ln R(I,I-2,A)-\ln R(I+2,I,A)+\Delta E_c-\Delta_{I-2}+\Delta_I\}, \quad (1)$$

where I=N–Z, $a^{*'}_{\mathrm{sym}}=4a'_{\mathrm{sym}}$, and the prime means that the results are for the fragment; R is the yield ratio between the isobars differing 2 in I; $\Delta E_c=E_c(I)-E_c(I-2)$ is the difference between the Coulomb energy of the isobars; Δ_{I-2} and Δ_I are the mixing term of N and Z of the isobars related $[\Delta_I=(N_{I+2}/A)+Z_{I+2}\ln(N_{I+2}/A)-N_I\ln(N_I/A)-Z_I\ln(N_I/A)]$. In Eq.(1), T can hardly be known directly, and the term of $\alpha^{*'}_{\mathrm{sym}}/AT$ 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):

$$\frac{a^{*}_{\mathrm{sym}}}{A}=[B(I)-B(I+2)+\Delta E_c]/(I+1), \quad (2)$$

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:

$$T=\frac{a^{*}_{\mathrm{sym}}}{A}\Big/\frac{a^{*'}_{\mathrm{sym}}}{AT}. \quad (3)$$

Therefore, the a_{sym}~T correlation can be investigated.

3 Results and discussion

In Fig.1, the $\alpha^{*'}_{\mathrm{sym}}/AT$ of the fragments in the 1A GeV ^{124,136}Xe+Pb reactions and $\alpha^{*'}_{\mathrm{sym}}/AT$ of the corresponding T=0 nuclei are plotted. Due to the effect of the nonzero temperature, there is large difference between the values of $\alpha^{*'}_{\mathrm{sym}}/AT$ and $\alpha^{*}_{\mathrm{sym}}/A$, especially in fragments which have relative small mass.

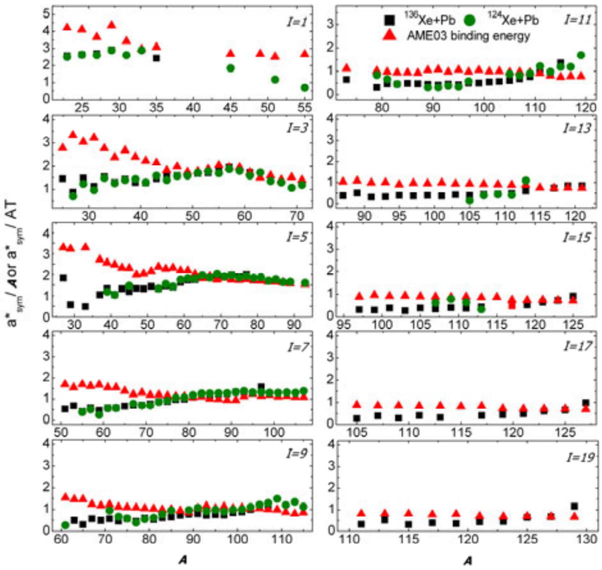

Fig.1 (Color online) The value of $\alpha^{*'}_{\mathrm{sym}}/AT$ of fragment in the 1A GeV ^{136}Xe+Pb (the squares) and ^{124}Xe+Pb (the circles) reactions[26], and the value of α_{sym}/A of nucleus (the triangles) from the binding energy (the data taken from the AME03[28]).

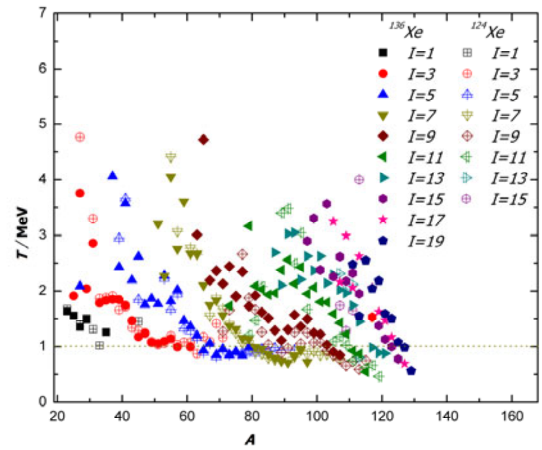

Fig.2 (Color online) The values of T for the fragments in the 1A GeV ^{124}Xe+Pb (crossed open symbols) and the ^{136}Xe+Pb (solid symbols) reactions. I and A are the neutron-excess and the mass number of the fragment, respectively.

Taking the ratio of $\alpha^{*'}_{\mathrm{sym}}/AT$ and $\alpha^{*}_{\mathrm{sym}}/T$ of the fragments according to Eq.(3), the values of T related to the fragments can be determined. The obtained T of fragments are plotted in Fig.2. For the nuclei having same I, T decreases with increasing mass, especially for fragments of which less nucleons being abraded from the projectile and are mostly produced in peripheral reactions[24,29,30]. The results show that, in the two Xe reactions, T of the same fragment has very little difference, except the fragment of small A in the same I nucleus-chain. It should be noted that, in models which predict the yield of fragment, the temperature is usually set as a constant, which will result in the disagreement between the theoretical and experimental yield. The variation of T of fragments shown in this work indicates that T changes with the fragment in theoretical calculation.

After the fragment temperature is separated from the $\alpha^{*\prime}_{\rm sym}/AT$ results, by using the ($\alpha^{*\prime}_{\rm sym}/AT$)/($\alpha^{*\prime}_{\rm sym}/A$) ratio of the fragments, it is interesting to see how $a_{\rm sym}/T$ depends on T as shown in HIC[9-12,31]. The correlation between $a_{\rm sym}/T$ and the obtained T of the fragment is plotted in Fig.3. Relative similar distributions of $a_{\rm sym}/T$~T correlations of fragments with different I are observed. For the measured fragments, $a_{\rm sym}/T$ decreases with increasing T. Generally, the symbols of larger $a_{\rm sym}/T$ are for the larger mass fragments, and the symbols of larger T values represent the smaller mass fragments in the same I chains.

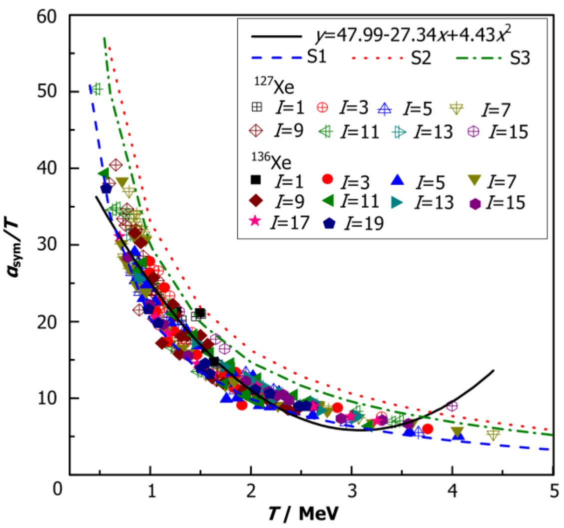

Fig.3 (Color online) The correlations between $a_{\rm sym}/T$ and T of the fragments in the 1A GeV ^{124}Xe+Pb (crossed open symbols) and the ^{136}Xe+Pb (solid symbols) reactions. The solid line represents the fitting results using the y=a+bx+cx^2 function. The other lines (labeled as S1–S3) represent the values of ^{117}Cs according to Eq.(5) with different b_v and b_s at T=0.

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

$$E_{\rm sym} = (b_v + 0.42T^2)I^2/A - (b_s + 2.06T^2)I^2/A^{4/3}, \quad (4)$$

where b_v and b_s are the volume- and surface-symmetry energy coefficients, respectively. The first and second terms in 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 $a_{\rm sym}/T$ of the fragment is deduced according to

$$a_{\rm sym}/T = E_{\rm sym}A/(I^2T). \quad (5)$$

Figure 3 shows the correlation between $a_{\rm sym}/T$ 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, of which I=15, is calculated using different sets of b_v and b_s (for the S1, S2 and S3 lines in Fig.3, b_s/b_v=1.68). Using such sets of b_v and b_s values, the $a_{\rm sym}/T$ of nucleus depends very little on the b_v values (result not shown). The T was varied from 0.04 MeV to 5 MeV in the calculation. In S1 (dash line), b_v=19.69 MeV was suggested in Ref.[15]. In S2 (dot line), b_v=32 MeV accords to the finite-range liquid-drop (FRLD) model[13]. In S3 (dash-dot line), the b_v is simply changed to 29 MeV to see the effect of b_v and b_s parameters. All the S1–S3 results can well reproduce the trend of the experimental $a_{\rm sym}/T$~T correlation. The result of S1 shows that the suggested b_v in Ref.[15] agrees with the $a_{\rm sym}/T$ of ^{117}Cs, while the S2 according to FRLD and S3 overestimate the experimental data. The calculated $a_{\rm sym}/T$ verifies the T^2 dependence of the symmetry energy of finite nucleus, however, for a specific nucleus, proper values of b_v and b_s should be used.

A simple fitting using the y=a+bx+cx^2 function was performed to see how $a_{\rm sym}/T$ depends on the temperature, and from the fitting we have a=47.99, b=–27.34 and c=4.43. The bx term in the fitting function term 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 to the opposite direction of the experimental data, which indicates that T^2 dependence of the symmetry energy is only valid in the relative low temperature (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. It is also instructive for other models based on the free energy. By analyzing the yield of the fragment produced in the 1*A* GeV ^{124}Xe+Pb and ^{136}Xe+Pb reactions measured at GSI, the symmetry energy coefficient of fragment is found to be modified in different degrees by the temperature in HIC. T of fragment is determined by the ratio of its symmetry energy coefficient at T=0 and nonzero T in HIC. The dependence of a_{sym}/T on T is shown. All these verify the T^2-dependence of the symmetry energy of finite nucleus at low temperature, with a proper setting of b_v and b_s.

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