Residue Coulomb interaction among isobars and its influence in symmetry energy of neutron-rich fragment

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The residue Coulomb interaction (RCI), which affects the results of symmetry energy of neutron-rich nucleus in isobaric yield ratio (IYR) methods, is difficult to be determined. Four RCI approximations are investigated: (1) the M1–RCI adopting the $a_c/T$ (the ratio of Coulomb energy coefficient to temperature) determined from the IYR of mirror-nuclei fragment; (2) the M2–RCI by fitting the difference between IYRs; (3) the M3–RCI by adopting the standard Coulomb energy at a temperature $T = 2\text{MeV}$; and (4) neglecting the RCI among the three isobars. The M1–, M2– and M3–RCI is found to no larger than 0.4. In particular, the M2–RCI is very close to zero. The effects of RCI in the $a_{sym}/T$ of fragment are also studied. The M1– and M4–$a_{sym}/T$ are found to be the lower and upper limitations of $a_{sym}/T$, respectively. The M2–$a_{sym}/T$ overlaps the M4–$a_{sym}/T$, which indicates that the M2–RCI is negligible, at the same time the RCI among the three isobars can be neglected. A relative consistent low values of M3–$a_{sym}/T$ ($7.5 \pm 2.5$) are found in very neutron-rich-isobars.

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I. INTRODUCTION

The study of nuclear symmetry energy (NSE) has continuously attracted attention because of its importance in nuclear physics and astrophysics. Lots of theoretical and experimental methods are proposed to investigate the NSE of nuclear matters from sub-saturation to supra-saturation densities, which can both be produced in heavy-ion collisions (HICs) 1. Among the various observable to study NSE — such as flow 2, emission of light particles ($n, p$ and the ratio between them) 3 5, isospin diffusion 4, neutron-skin thickness 5, isoscaling (for colliding source or fragments) 6 21, or m-scaling 22–24, isobaric yield ratio (IYR) 24 29, etc. — the IYR methods have attracted much attention recently 23 37. In IYR, parameters depending only on the mass of fragment can be neglected, which makes the IYR methods possible to study the symmetry energy of neutron-rich fragment specifically. In some similar isobaric analysis, the symmetry energy of nucleus (including the volume symmetry energy and surface symmetry energy) has also been investigated 38 40.

Different to the uniform value of parameter in mass formula, the symmetry-energy coefficient ($a_{sym}$) of nucleus or fragment in isobaric methods becomes nonuniform, and depends on the neutron-excess ($I = N - Z$) and mass number $A$. 26 32 35 38 40. $a_{sym}$ is found to decrease with increasing $I$ in isobaric chains 40, and similar phenomena is also shown in fragments produced in HICs 20 32 34. The difference between $a_{sym}$ (or $a_{sym}/T$) of isobars is found to decrease when the nucleus (fragment) becomes more neutron-rich. In particular, $a_{sym}$ ($a_{sym}/T$) of nucleus (fragment) with large neutron-excess is found to be very similar 33 40 41. It is also shown that the volume-symmetry-energy coefficient ($b_v$) and the surface-symmetry-energy coefficient ($b_s$) both decrease with increasing $I$, but tend to be very similar in the very neutron-rich nucleus (when $I > 13$) 40.

In IYR methods to determine the symmetry energy of fragment, the residue Coulomb interaction (RCI) between isobars is also difficult to be known due to the difficulty to separate the temperature and energy terms contributing to free energy. In previous works, the standard Coulomb term is used to calculate RCI 38–40, or the value of $a_c/T$ (the ratio of Coulomb energy coefficient to temperature) for mirror nuclei [IYR(m)] is used as an approximation for more neutron-rich fragments. For examples, the value of $a_c/T$ is determined from the scaling between the IYR(m) and the $Z/A$ of the reaction systems in a series of reactions, and $a_c/T$ is used for the $I = 3$ fragments 20. Though $a_c/T$ can also be fitted from IYR(m) in a single reaction 27 33 34, it is supposed to be influenced by the volume or mass of projectile 42. But it is also suggested that the volume dependence of $a_c/T$ disappears in the reactions induced by neutron-rich projectiles 37. The different RCI approximations request the comparison between them, and the study of the RCI effects in the resultant symmetry energy of neutron-rich fragment is also required, which will be focused on in this article. The article is organized as follows: Sec. I II describes the IYR method and the approximations of the RCI; Sec. III discusses the results of the different RCIs and their effects in the symmetry energy of fragment in measured reactions; Sec. IV presents the summary of the article.
II. MODEL DESCRIPTION

In free energy based theories, the yield of fragment is determined by its free energy, the property of colliding source, temperature, etc. in HICs above the Fermi energy [24, 43–45]. In a modified Fisher model (MFM), the free energy of a cluster (fragment) equals its binding energy at nonzero temperature, which includes the contribution of entropy [45]. This makes the IYR method can conveniently determine the symmetry energy of fragment. The description of IYR methods can be partly found in Refs. 24, 44. For a better understanding of the methods, first we briefly describe the IYR methods in MFM. Then the methods dealing with RCI will be intensively described.

In MFM the yield of a fragment with mass A and neutron-excess I, $Y(A, I)$, is given by [24, 45]

$$Y(A, I) = C A^{-r} \exp \left\{ (W(A, I) + \mu_n N + \mu_p Z) / T \right\}$$

$$+ N \ln(N/A) + Z \ln(Z/A),$$

(1)

where $C$ is a constant; $A^{-r}$ originates from the entropy of fragment; $\tau$ is independent of fragment size, but is nonuniform in different reactions [45, 46]. $\mu_n$ and $\mu_p$ are the neutron and proton chemical potentials, respectively; $T$ is the temperature, and $W(A, I)$ is the free energy of a cluster at $T$, which equals the binding energy of the cluster. At a given $\rho$ and $T$, $W(A, I)$ can be parameterized as the Weizsäcker-Bethe form mass formula [47],

$$W(A, I) = a_v (\rho, T) A - a_s (\rho, T) A^{2/3} - E_c (\rho, T)$$

$$- a_{\text{sym}} (\rho, T) I^2 / A - \delta (N, Z),$$

(2)

where the indices $v, s$, and $\text{sym}$ represent the volume-, surface-, and symmetry- energy, respectively. $E_c (\rho, T)$ represents the Coulomb energy (assuming a spherical expansion, at low densities the Coulomb energy decreases as $\rho^{1/3}$). The coefficients contain contributions both from the binding energy and the entropy of the cluster due to nonzero $T$ [12]. For simplification, $a_v (\rho, T)$ is written as $\tilde{a}_c (i)$ represents the different indices).

Inserting Eq. (2) into Eq. (1), the IYR between isobars differing by 2 units in $I$, $R(I+2, I, A)$, can be defined as,

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

$$= \exp \left\{ W(I+2, A) - W(I, A) + (\mu_n - \mu_p) \right\} / T$$

$$+ S_{\text{mix}} (I+2, A) - S_{\text{mix}} (I, A)),$$

(3)

where $S_{\text{mix}} (I, A) = N \ln(N/A) + Z \ln(Z/A)$. Assuming that $a_v, a_s, \mu_n$, and $\mu_p$ for the I and I+2 isobars are the same, inserting Eq. (2) into Eq. (3), and taking logarithm of the resultant equation, one gets the IYR for odd-I isobars,

$$\ln[R(I+2, I, A)] - \Delta I = \left[ \Delta \mu - 4 a_{\text{sym}} (I+1) / A \right.$$

$$- \Delta E_c (I+2, I, A) / T, \right.$$  

(4)

where $\Delta I = S_{\text{mix}} (I+2, A) - S_{\text{mix}} (I, A)$; $\Delta E_c (I+2, I, A) = E_c (I+2) - E_c (I)$; $\Delta \mu = \mu_n - \mu_p$, $Z$ is the charge numbers of the reference nucleus $(A, I)$. The pairing energy in Eq. (1) is avoided in the odd-I isobars. It is hard to know $\Delta \mu$, $a_{\text{sym}}$, $\Delta E_c$, and $T$ exactly, because of the difficulty to separate them in the ratios. $\Delta \mu$ is assumed to change slowly in the reactions, thus $\Delta \mu / T$ can be the same in $R(I+2, I, A)$ and $R(I, I-2, A)$. Then $\Delta E_c / T$ is the retained term that affects $a_{\text{sym}} / T$ in the IYR methods. Taking the difference between the neighboring IYRs,

$$\ln[R(I, I-2, A)] - \ln[R(I+2, I, A)] - \Delta_{21}$$

$$= 8 a_{\text{sym}} (AT) - \Delta E_{c21} / T, \right.$$  

(5)

where $\Delta_{21} = \Delta_{I-2} - \Delta_I$, and $\Delta E_{c21} = \Delta E_c (I, I-2, A) - \Delta E_c (I+2, I, A)$ is the RCI among the $(I+2, A)$, $(I, A)$ and $(I-2, A)$ isobars. Since $\Delta E_{c21} / T$ can be viewed as one parameter, it is also called as RCI between IYRs, and it is the parameter that will be focused on in this article.

For neutron-rich fragment, $a_{\text{sym}} / T$ can be obtained from Eq. (5) as follows [26, 33–35],

$$a_{\text{sym}} / T = 4 \left\{ \ln[R(I, I-2, A)] - \ln[R(I+2, I, A)] \right\}$$

$$- \Delta_{21} + \Delta E_{c21} / T, \right.$$  

(6)

As mentioned above, due to the RCI ($\Delta E_c / T$ or through $a_c / T$) is hard to be known, four approximations are used to deal with RCI in previous works,

(i): $\Delta E_{c21} / T$ or $a_c / T$ is obtained from IYR(m).

The following equation is used to extract the $\Delta E_{c21} / T$ and $\Delta \mu / T$ based on Eq. (5).

$$\text{IYR(m)} = \ln[R(1, -1, A)] = \left( \Delta \mu - \Delta E_c \right) / T, \right.$$  

(7)

The value of $\Delta \mu / T$, at the same time $\Delta E_{c21} / T$ or $a_c / T$ for the mirror nuclei can be determined. Assuming that $a_c / T$ are the same for all the fragments, $\Delta E_{c21} / T$ in Eq. (6) is known [21, 33, 54, 57].

(ii): $\Delta E_{c21} / T$ is determined from the difference between IYRs. Considering the free energy per particle at $T$ and pressure $P$ in MFM, the ratio of free energy to temperature near the critical point can be expanded as [24, 25],

$$\Psi(m_f, A, T, H) / T = \frac{1}{3} a m^2_f + \frac{1}{6} b m^4_f + \frac{1}{5} c m^6_f$$

$$- \frac{4}{3} m + o(m^5), \right.$$  

(8)

where the parameters $a, b$, and $c$ depend on $T$ and $\rho$, and are used for fitting; $m_f = I / A$. $H$ is the conjugate field. The free energy is even in the exchange of $m_f \rightarrow -m_f$, reflecting the invariance of nuclear forces when exchanging $N$ and $Z$. This symmetry is violated by $H$, which arises when the source is asymmetric in chemical composition. $H$ and $m_f$ are related to each other through the relation $m_f = \frac{H}{2}$. The Coulomb energy for large Z nucleus can be written as,

$$E_c / A = 0.77 Z^2 A^{2/3} = \frac{0.77}{4} (1 - m_f)^2 A^{2/3},$$

(9)
Adding this term to the free energy $\Psi/T$, a quadratic and linear term in $m_f$ are introduced, which modify the symmetry energy coefficient and $H$. Also a term independent on $m_f$ is introduced. The RCI is relevant only in the calculation of $a_{sym}/T$ for the large mass fragments in the IYR method, thus the $a(m^4)$ terms are negligible. At the same time, $(1/A^2) \propto m^2$. According to Eq. (3), the fit of the quantity \[ \ln[R(I, I+2, A)]/A \] allows the estimation of the fitting parameters in Eq. (5) and the Coulomb term. The fitting function between the difference of IYRs and RCI is \[ \Delta \ln R/A = a'/A^2 + dA^{2/3}, \] (10) where $\Delta \ln R = \ln[R(I, I+2, A)] - \ln[R(I+2, I, A)]$. $a'$ and $d$ are fitting parameters. The $a_{sym}/T$ of neutron-rich fragments can be obtained as, \[ \frac{a_{sym}}{T} = \frac{A}{8} (\Delta \ln R - \Delta_{21}) - dA^{2/3}, \] (11)

The $dA^{2/3}$ term serves as the RCI.

(iii): $\Delta E_{c21}$ is calculated by adopting $E_C = \frac{3}{2} \frac{Z^2 e^2}{4 \pi \hbar^2} \left[ 1 - \frac{5}{4} \left( \frac{Z}{A} \right)^2 \right]^{2/3} \frac{1}{2 \pi \hbar} \] [33, 40], and using $T = 2$ MeV since a relative low temperature is obtained using similar IYR methods [31, 32]. In this method, the RCI is \[ \Delta E_{c21}/T = [E_c(I - 2) + E_c(I + 2) - 2E_c(I)]/T, \] (12)

(iv): M4: We adopt a new approximation in this article, i.e., the RCI is omitted since it is the difference between three isobars, which is different to the RCI between two isobars and can be supposed to be negligible (the RCI between two isobars depends both on the $m_f^2$ and $m_f$).
the (∆ln Eq. (10) in the three reactions. But the distributions of
9
are calculated according to Eq. (6) using
sym
/2
/2
the parameter a′ includes almost the whole real RCI
relating to the m^2
sym
term, which results in M2–RCI is very small and can be neglected.
It is important to study the effects of RCI in the resultant a_sym/T of neutron-rich fragments. The M1–
M3–a_sym/T are calculated according to Eq. (10) using the corresponding RCI, and the M2–a_sym/T according
to Eq. (11). First, the a_sym/T of fragments in the 98Ni

FIG. 3. (Color online) The RCIs between isobars in the 1A
GeV 136Xe + Pb reaction using the M1–M3 approximations.

III. RESULTS AND DISCUSSION

The yields of fragments in the 140A MeV 58Ni + 9Be reactions, which were measured by Mocko et al. at the
National Superconducting Cyclotron Laboratory (NSCL) in Michigan State University [48], and in the 1A GeV
124,136Xe + Pb reactions, which were measured by Hen-
zelova et al. at the FRagment Separator (FRS), GSI
Darmstadt [49], will be used to perform the analysis.

First, we determine a_c/T from IYR(m) for M1. In
Fig. 1(a), the IYR(m) is plotted (similar results can be
found in Refs. [33, 34, 37]). The form of Coulomb en-
ergy adopted is E_c = a_c Z(Z − 1)/A^{1/3}, and the resultant
fitting function being y = Δµ/T + 2a_c(Z − 1)/(A^{1/3}T)
ing Eq. (7), in which the quantity 2a_c(Z − 1)/(A^{1/3}T) serves as RCI in IYR(m). In Fig. 1(b), the
fitting function is modified to y = Δµ/T + dA^{2/3} due to
(Z − 1)/A^{1/3} ∝ A^{2/3}, and a_c/T is assorted to the parameter d, in which d ∝ A^{2/3} serve as RCI in IYR(m). The
resultant RCIs according to panels (a) and (b) are plotted
in Fig. 1(c), which has a relative little difference of
no larger than 0.2.

Second, d in M2 is determined by fitting the difference
between IYRs according to Eq. (10). In Fig. 2
the correlation between (∆ln R − Δ21)/A and 1/A^2 of fragments
in the 1A GeV 124,136Xe + Pb and 140A MeV 58Ni +
9Be reactions are plotted. The data can be well fitted by
Eq. (10) in the three reactions. But the distributions of the (∆ln R − Δ21)/A ∝ 1/A^2 correlation show different
trend in fragments of the same I in the three reactions,
and the same phenomena also happens in fragments of
different I in the same reaction.

Furthermore, taking the fragments in the 1A GeV
136Xe + Pb reaction as an example, the RCI in the M1–
M3 approximations are compared, which are plotted in
Fig. 3. The values of RCI show that M1 > M3 > M2,
with M1– and M3–RCI are no larger than 0.4, and the
M2–RCI very close to zero. The results verify that in Eq.

FIG. 4. (Color online) The a_sym/T of fragments in the 140A
MeV 58Ni + 9Be reactions. The labels M1 (star), M2 (triangle), M3 (circle), and M4 (square) denote the a_sym/T of fragments using the corresponding RCI.

FIG. 5. (Color online) The same as in Fig. 4 but for the
fragments in the 1A GeV 124Xe + Pb reactions.

FIG. 6. (Color online) The same as in Fig. 4 but for the
fragments in the 1A GeV 136Xe + Pb reactions.
reaction are plotted in Fig. 4 and those of fragments in the $^{124,136}$Xe reactions are plotted in Fig. 5 and Fig. 6 respectively. $a_c/T = 0.55, 0.71$ and 0.52 are used for M1 for the $^{58}$Ni, $^{124}$Xe and $^{136}$Xe reactions is used, respectively. Generally, the M1–$a_{sym}/T$ and M4–$a_{sym}/T$ form the lower and upper limitations of $a_{sym}/T$. The M1–$a_{sym}/T$ being the lower limitation of $a_{sym}/T$ indicates that the direct use of $a_c/T$ from IYR(m) may underestimate the real value of $a_{sym}/T$ in some degree. The M2–$a_{sym}/T$ almost overlaps the M4–$a_{sym}/T$. Since the M2–$a_{sym}/T$ incorporates the $m^2_T$ term of RCI (which is called as the effective symmetry energy [25]), the result also indicates that the $m^2_T$ dependence of RCI is also very small, and the M2– and M4–$a_{sym}/T$ are close to the actual value. Thus the omission of RCI among three isobars is reasonable in determining the coefficient of symmetry energy of neutron-rich fragment using Eq. (4).

To see the evolution of $a_{sym}/T$ in isobars, for a series of isobars in the 1A GeV $^{136}$Xe + Pb reactions, the values of M3–$a_{sym}/T$ are re-plotted in Fig. 7 since the M3–$a_{sym}/T$ is not influenced by the fitting parameters of RCI or the size of the reaction system. The re-plotted isobars are from $A = 57$ to 107 in the step of 10, plus the $A = 51, 91,$ and 111 isobars. For each isobaric chain, $a_{sym}/T$ decreases as the fragment becomes more neutron-rich. But a relative consistent values of $7.5 \pm 2.5$ is found in the neutron-rich fragments for all the plotted isobaric chains, which are shown as the shadowed area.

We will comment on the question raised in the result of $A$ and $I$ dependence of $a_{sym}/T$. Actually, in isobaric method, one can never expect a uniform symmetry energy coefficients except the nuclear have the same neutron and proton density difference which result in the isospin phenomena in HICs. The nuclear density evolves in neutron-rich fragments, thus the isospin effects illustrate. It is discussed to differ the core and surface regions of a neutron-rich nucleus, in which the neutron and proton densities differ evenly while in the surface the neutron and proton densities differ largely [36, 51, 51]. For the neutron-rich nucleus or fragments, we should also expect the evolution of symmetry energy due to the change of proton and neutron density differences. Based on the equilibrium assumption, the symmetry energy of identical source is supposed to be same, and $a_{sym}/T$ of the source obtained should independent on $A$ and $I$. It is revealed that the chemical potential difference between neutrons and protons, which is an important index of symmetry energy (as in isoscaling), is also found to vary little in the central collisions and supports the assumption that the symmetry energy is identical in similar sources [31]. The relative uniform $a_{sym}/T$ is found in prefragments, but is believed to be modified by the decay process and the $A$ and $I$ dependence of $a_{sym}/T$ is observed in the final fragments [15, 24, 33]. It is also know for neutron-rich nucleus, the surface-symmetry-energy and volume-symmetry-energy should be included (the coefficients denoted as $b_s$ and $b_v$, respectively). $b_s$ and $b_v$ can be obtained form $a_{sym}/A$ [34, 40] and for finite temperatures neutron-rich fragments, $b_s$ and $b_v$ of can also be obtained from $a_{sym}/AT$ by assuming the $T^2$ dependence of the coefficients in the mass formula [41], which are both found coincident with the theoretical results.

IV. SUMMARY

In summary, the RCI effects in the $a_{sym}/T$ of fragments in the IYR methods are investigated. Four RCI approximations are investigated: (1) the M1–RCI adopting the $a_c/T$ determined by IYR(m); (2) the M2–RCI by fitting the difference between IYRs based on the free energy of the fragment; (3) the M4–RCI by adopting the theoretical Coulomb energy and an IYR temperature $T = 2$ MeV; and (4) neglecting the RCI among the related three isobars. The M1–, M2– and M3–RCI are found to have relative small values no larger than 0.4. In particular, the M2–RCI is the smallest one in the three RCIs due to it includes only very small part of the actual RCI. The effects of RCI in the $a_{sym}/T$ of fragments are also studied. For fragments in the $^{58}$Ni, and $^{124,136}$Xe reactions, the M1– and M4–$a_{sym}/T$ are found to be the lower and upper limitations of $a_{sym}/T$. Due to the M2–RCI only includes part of the RCI, it enhances the value of M2–$a_{sym}/T$, which should be called as the effective $a_{sym}/T$ [25]. The M4–$a_{sym}/T$ (omitting the RCI), which overlaps the M2–$a_{sym}/T$, indicates that the enhancement of $a_{sym}/T$ in M2 is very small, and the $m^2_T$ dependence of RCI in Eq. (4) should be very small. The omission of RCI among three isobars is verified to be reasonable. It can also be concluded that the M1– and M3–RCI actually underestimate the real value of $a_{sym}/T$ due to the uncer-
tainty introduced by $a_c/T$ and temperature in them. The M3-$a_{sym}/T$ of some isobaric chains are compared, which is found to decreases when the fragment becomes more neutron-rich. Relative consistent value is found in the very neutron-rich fragments, which indicates that the $a_{sym}/T$ of neutron-rich fragments are similar.

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