

# Re-visit the N/Z ratio of free nucleons from collisions of neutron-rich nuclei as a probe of EoS of asymmetric nuclear matter

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## Abstract

The N/Z ratio of free nucleons from collisions of neutron-rich nuclei as a function of their momentum is studied by means of Isospin dependent Quantum Molecular Dynamics. We find that this ratio is not only sensitive to the form of the density dependence of the symmetry potential energy but also its strength determined by the symmetry energy coefficient. The uncertainties about the symmetry energy coefficient influence the accuracy of probing the density dependence of the symmetry energy by means of the N/Z ratio of free nucleons of neutron-rich nuclei.

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Following the establishment of radioactive beam facilities at many laboratories of different countries, the experimental studies on the equation of state (EoS) for asymmetric nuclear matter become possible. As is well known that the EoS for asymmetric nuclear matter is one of the most important input for astrophysics.

The EoS for asymmetric nuclear matter can be approximately expressed as

$$e(u, \delta) = \frac{\epsilon(u, \delta)}{\rho} = e_0(u) + e_{sym}(u)\delta^2, \quad (1)$$

where  $u = \rho/\rho_0$ ,  $\delta = (\rho_n - \rho_p)/\rho$ ; and  $\epsilon(u, \delta)$  is the energy density;  $e_0$  is the energy per nucleon for symmetric nuclear matter and  $e_{sym}$  is the bulk symmetry energy. There exist large uncertainties for the  $e_{sym}$ , especially, its density dependence. The symmetry energy at saturated normal density, i.e. the symmetry energy coefficient, is not well constrained [1]. The empirical value is  $30 \pm 4$  MeV. The theoretically predicted values are rather different from different approaches, its value is about 27-38 MeV by non-relativistic Hartree-Fock approach [2], 35-40 MeV by relativistic mean field approach [3–5], 31 MeV by Brueckner-Hartree-Fock (BHF) theory [6], 28.7 MeV by extended BHF theory [7], 26-34 MeV by relativistic BHF [8–10], 28.1 MeV by Brueckner-Bethe-Goldstone approach [11], *et al.* Furthermore, a recent study has shown that the symmetry energy coefficient increases as the isospin asymmetry increases and the increasing slope is quite different for different versions of Skyrme force [12]. At the same time, we find rather different values are used in the applications, for example, some authors [13,14] have adopted values of 29 MeV and 31 MeV in the different IQMD model calculations, whilst others [15,16] used 30 MeV and 35 MeV, respectively, in the framework of the IBUU model. 32 MeV was used in the stochastic Boltzmann-Nordheim-Vlasov (BNV) calculations [17], and 23.4 MeV was used in [18,19], *et al.*

The value of the symmetry energy coefficient  $a_{sym}$ , which can be related to the strength of the symmetry potential energy  $C_S$  as

$$a_{sym} = \frac{C_S}{2} + \frac{\epsilon_F^0}{3} \quad (2)$$

if we write the symmetry potential energy part in the form of

$$v_{sym} = \frac{C_S}{2}F(u), \quad (3)$$

where  $F(u)$  gives the density dependence of symmetry potential energy. One can see from expressions 2) and 3) that the divergence of the values of  $a_{sym}$  means the uncertainties about the strength of the symmetry potential energy. We have studied the influence of the different  $C_S$  on the isospin distribution of the emitted nucleons, intermediate mass fragments, and light charged particles and we have found this influence is obvious [20], while the quantity concerned the most for the isospin dependent part of EoS is its density dependence, which is one of the most important input for the astrophysics. This has inspired people to find more sensitive observable in order to pin down the form of the density dependence of the EoS of the asymmetric nuclear matter. These works usually adopted a fixed value of  $C_S$  and then test the sensitivity of the proposed sensitive observable to the different forms of the density dependence of the symmetry potential energy term without checking the influence of the strength of the symmetry potential. The aim of this paper is to study how the existing uncertainties concerning the  $a_{sym}$  influence the sensitivity of the proposed sensitive observable to the form of the density dependence of the symmetry energy term. In this work, we mainly concentrate on the momentum distribution of N/Z ratio of emitted nucleons in neutron rich heavy ion collisions at energies ranging from several tens to 100A MeV since it has been proposed as a very sensitive observable to the form of the density dependence of the EoS of asymmetric nuclear matter [21].

Concerning the form of density dependence of the symmetry potential energy, Prakash and Lattimer has proposed [22,23] as:

$$F(u) = \begin{cases} u \\ u^{1/2} \\ 2u^2/(1+u) \end{cases} . \quad (4)$$

This form can be expressed as a simple one, i.e.,

$$F(u) = \begin{cases} u^\gamma \\ 2u^\gamma/(1 + u^{\gamma-1}) \end{cases} . \quad (5)$$

In Fig. 1 we show  $F(u)$  as a function of reduced density with  $\gamma=0.5, 1.0,$  and  $1.5,$  respectively. The  $\gamma=0.5$  case corresponds to the asy-soft EoS and  $\gamma=1.0$  the asy-stiff EoS,  $\gamma=1.5$  asy-super stiff EoS. From Fig. 1, one sees that the type  $F(u) = 2u^\gamma/(1 + u^{\gamma-1})$  is not too far away from linear density dependence in the densities given in the figure. We then take a simple form, i.e.,  $F(u) = u^\gamma,$  in this work. It has been predicted that  $\gamma$  is about 0.6, based on a many-body theory calculations [24,25], which seems to be supported by the recent experimental observation [18].

Fig. 1

In this paper, we take  $C_S$  to be 27, 35, and 50 MeV (corresponding to the values of symmetry energy coefficient  $a_{sym}$  of 27, 31, and 38 MeV, respectively), which roughly include the range of symmetry energy coefficients predicted by different theories and  $\gamma$  to be 0.5, 1.0, and 1.5. The results with a reduced range of symmetry energy coefficients  $C_S = 37, 40,$  and 45 (corresponding to  $a_{sym} = 32, 34, 36$ ) are also shown. The other parameters of EoS will be shown in Table I. A soft EoS ( $K=200$  MeV) is used in the calculations.

Table I.

The compressibility contributed from symmetry potential can be obtained by,

$$\begin{aligned} K_{sym} &\equiv 9\rho_0^2 \frac{\partial^2 e_{sym}(u)}{\partial^2 \rho} \Big|_{\rho=\rho_0} \\ &= \frac{9}{2}\gamma(\gamma-1)C_S - \frac{2}{3}\epsilon_F^0. \end{aligned} \quad (6)$$

Table II lists the  $K_{sym}$  parameters when  $C_S=27, 35,$  and  $50$  MeV, and  $\gamma=0.5, 1.0,$  and  $1.5.$  It shows that  $K_{sym}$  changes sign from negative to positive when  $\gamma$  increases from 0.5 to 1.5. At the same time,  $K_{sym}$  increases for  $\gamma=0.5$  and decreases for  $\gamma=1.5$  without changing sign when  $C_S$  decreases from 50 MeV to 27 MeV. And these values are well within the wide

range of  $K_{sym}$  from about -400 MeV to +466 MeV predicted by many-body theories [26,27]. Available data of giant monopole resonances does not give a stringent constraint on the  $K_{sym}$  parameter either [28].

Table II.

However, a complementary and perhaps more complete depiction of the isospin dynamics can be obtained from the analysis of the density dependence of the neutron/proton chemical potential,

$$\begin{aligned}\mu_{n/p} &\equiv \frac{\partial \epsilon(u, \delta)}{\partial \rho_{n/p}} \\ &= \alpha u + \beta u^\sigma + \epsilon_F^0 u^{2/3} \\ &\quad + \left[ \frac{C_S}{2} (\gamma - 1) u^\gamma - \frac{1}{9} \epsilon_F^0 u^{2/3} \right] \delta^2 \pm \left[ C_S u^\gamma + \frac{2}{3} \epsilon_F^0 u^{2/3} \right] \delta.\end{aligned}\tag{7}$$

From this equation, we find the difference between neutron and proton chemical potential is

$$\mu_n - \mu_p = 4e_{sym} \rho \delta.\tag{8}$$

This expression indicates that the difference between  $\mu_n$  and  $\mu_p$  depends on both isospin asymmetry and the density. When a more neutron-rich (or deficient) system is chosen, the difference becomes more obvious. Since in the following we will study reactions of  $^{96}\text{Zr} + ^{96}\text{Zr}$  and  $^{132}\text{Sn} + ^{132}\text{Sn}$  in Fig. 2 we show  $\mu_n$  and  $\mu_p$  versus density with  $C_S = 35$  MeV,  $\gamma = 0.5, 1.5$ , and  $C_S = 27$  MeV,  $\gamma = 0.5$  case for these two reactions, respectively. The left panel is for  $^{96}\text{Zr} + ^{96}\text{Zr}$  ( $\delta = 16/96$ ), the right one is for  $^{132}\text{Sn} + ^{132}\text{Sn}$  ( $\delta = 32/132$ ), respectively. Fig. 2 shows that the larger the  $C_S$  is, the larger the difference between  $\mu_n$  and  $\mu_p$  is and accordingly the more neutrons are emitted. Concerning the change of the form of density dependence, when the density is higher than the normal density, the difference between  $\mu_n$  and  $\mu_p$  for asy-stiff and asy-super stiff is larger than that for asy-soft while, when density is lower than normal density, the tendency is just opposite.

Fig. 2

The single particle symmetry potential can be written as

$$\begin{aligned}
v_{sym}^{n/p} &= \frac{\partial(v_{sym}(u,\delta)\rho)}{\partial\rho_{n/p}} \\
&= \frac{C_S}{2}[\pm 2u^\gamma\delta + (\gamma - 1)u^\gamma\delta^2],
\end{aligned} \tag{9}$$

where  $v_{sym}(u, \delta)$  represents the symmetry potential energy per nucleon. One can see from Eq. 9 that the symmetry potential is repulsive for neutrons and attractive for protons. So the effect of the symmetry potential is to make more free neutrons and less free protons. The first term in the bracket gives major contribution. And for the  $\delta^2$  term in the bracket, its sign depends on whether  $\gamma$  is less than 1 or not. It reduces the repulsive force for neutrons and increases the attractive force for protons for  $\gamma < 1$  case and opposite for  $\gamma > 1$  case and consequently the  $\delta^2$  term may reduce the effect of first term slightly. Furthermore the tendency of  $u^\gamma$  factor is different for  $\gamma < 1$  and for  $\gamma > 1$  as density increases from sub-normal to above-normal densities; at the sub-normal density the repulsive force for neutrons is stronger when  $\gamma < 1$  than that when  $\gamma > 1$  and for the above-normal density, it is just opposite. And therefor one expects that the N/Z ratio of emitted nucleons in collisions of neutron-rich nuclei with  $\gamma < 1$  is over with the  $\gamma > 1$  case. As for the change of the strength of  $C_S$ , it is simply that the larger the  $C_S$  is the higher the N/Z ratio of emitted nucleons is. Our numerical results clearly show all these tendencies.

From Eq. 9 we obtain the time evolution of  $\vec{r}_i$  and  $\vec{p}_i$  contributed by symmetry potential term

$$\dot{r}_{i=n/p}^{sym} = 0, \tag{10}$$

$$\begin{aligned}
\dot{p}_{i=n/p}^{sym} &= -\frac{C_S}{2\rho_0}[2 \pm 4(\gamma - 1)u^{-1}\delta + (\gamma - 1)(\gamma - 2)u^{-2}\delta^2]u^{\gamma-1}\partial\rho_{n/p} \\
&\quad + [-2 + (\gamma - 1)(\gamma - 2)u^{-2}\delta^2]u^{\gamma-1}\partial\rho_{p/n}.
\end{aligned} \tag{11}$$

The isospin dependent quantum molecular dynamics model (IQMD) is used in the calculations [14] and the construction of clusters is in terms of the conventional coalescence model [29], in which particles with relative momenta smaller than  $P_0$  and relative distances smaller than  $R_0$  are considered to belong to one cluster. In this work  $R_0$  and  $P_0$  are taken to be 3.5 fm and 300 MeV/c, respectively, following [30]. In addition, only the cluster with reason-

able proton number  $Z$  and neutron number  $N$  is selected in order to get rid of nonphysical clusters.

The secondary deexcitation of primary hot fragments is not taken into account in the present calculations. This should not change the general conclusion of this work.

First let us study the influence of the different forms of  $F(u)$  on the  $N/Z$  ratio when  $C_S$  value is taken as a fixed value, i.e.,  $C_S = 35$  MeV. Fig. 3a) and 3b) show the ratio of emitted neutron numbers and proton numbers versus their momentum for reactions of  $^{132}\text{Sn}+^{132}\text{Sn}$  at 50A MeV (Fig. 3a)) and 100A MeV (Fig. 3b)) calculated with  $F(u)$  being to be the form of  $u^{1/2}$ ,  $u$ , and  $u^2$ . Different characters denote calculation results obtained with different form of  $F(u)$  and the lines are shown just for guiding the eyes. The case for reactions of  $^{132}\text{Sn}+^{132}\text{Sn}$  at  $E = 50A$  MeV has been calculated in Ref. [21]. Here, for simplicity, the impact parameter  $b = 2$  fm is chosen for central collisions. From Fig. 3, the obvious dependence of the  $N/Z$  ratio of free nucleons on the form of  $F(u)$  is seen, especially for the  $N/Z$  ratio of the energetic neutrons from reactions of  $^{132}\text{Sn}+^{132}\text{Sn}$  at  $E = 50A$  MeV case. The  $N/Z$  ratio of free nucleons with asy-soft case ( $F(u) = u^{1/2}$ ) is much higher than those with the asy-stiff ( $F(u)=u$ ) and asy-super stiff ( $F(u)=u^2$ ) cases, which is in agreement with our expectations. However, our results are not as pronounced as that obtained in [21] though the general trend is the same, which may due to the model dependence.

Fig. 3

Fig. 3b) shows that for 100A MeV case the dependence of  $N/Z$  ratio of low momentum free nucleons on the form of  $F(u)$  is as strong as that of energetic nucleons, while for 50A MeV case shown in Fig. 3a) only the  $N/Z$  ratio of the energetic nucleons is sensitive to the form of  $F(u)$ . The comparison between Fig. 3b) and Fig. 3a) means that there is an advantage for taking beam energy at 100A MeV to extract the information of the form of  $F(u)$  because the number of low momentum nucleons are much larger than those of energetic nucleons and consequently the value of  $N/Z$  ratio can be measured more accurately.

Now let's study the dependence of the  $N/Z$  ratio of nucleons on the strength of the

symmetry potential energy, which closely related to the symmetry energy coefficient. Fig. 4a) and 4b) show the N/Z ratio of emitted nucleons for reactions  $^{132}\text{Sn}+^{132}\text{Sn}$  and  $^{96}\text{Zr}+^{96}\text{Zr}$  at  $E= 50A$  MeV calculated with  $F(u)=u$  but different  $C_S$  values, namely, with  $C_S = 27$  MeV and 50 MeV. In Fig. 4a) we show the results for central collisions of  $^{132}\text{Sn}+^{132}\text{Sn}$ , and in Fig. 4b) we show the results for peripheral collisions of  $^{96}\text{Zr}+^{96}\text{Zr}$ . These results are similar to our previous work on the central collisions of  $^{96}\text{Zr}+^{96}\text{Zr}$  at 400A MeV [20], in which the sensitivity of the momentum distribution of N/Z ratio of free nucleons to the strength of the symmetry potential energy is also shown but not as pronounced as shown at lower bombarding energies studied in this work. And furthermore, for case of central collisions of  $^{132}\text{Sn}+^{132}\text{Sn}$  at 50A MeV, the dependence of N/Z ratio of energetic nucleons on  $C_S$  is very pronounced, for example, the N/Z ratio of nucleons with momentum of about 300 MeV/c calculated with  $C_S=50$  MeV is about 1.5 times larger than that with  $C_S =27$  MeV. Relatively the N/Z ratio for peripheral reactions of  $^{96}\text{Zr}+^{96}\text{Zr}$  at  $E= 50A$  MeV is reduced but the ratio of  $(N/Z)_{C_s=50}/(N/Z)_{C_s=27}$  is similar with that for central reactions of  $^{132}\text{Sn}+^{132}\text{Sn}$  at 50A MeV. Fig. 4a) and Fig. 4b) show that the influence of strength of symmetry potential energy on th N/Z ratio of free nucleons is as obvious as that of the form of  $F(u)$  shown in Fig. 3a) and Fig. 3b).

Fig. 4

In order to investigate the most pronounced and the least pronounced sensitivity of N/Z ratio to the density dependence of the symmetry potential energy we study the influences of the different combination of both the strength and the form of the density dependence of symmetry potential. We define ratios

$$R_{most} = \frac{N/Z(F(u) = u^{1/2}, Cs = 50)}{N/Z(F(u) = u^{3/2}, Cs = 27)}$$

and

$$R_{least} = \frac{N/Z(F(u) = u^{3/2}, Cs = 50)}{N/Z(F(u) = u^{1/2}, Cs = 27)}$$



Fig. 5 shows the calculation results of the N/Z ratio of emitted nucleons versus their momentum for central collisions of  $^{96}\text{Zr}+^{96}\text{Zr}$  at 50A MeV with  $F(u)=u^{1/2}$ ,  $C_S=50$  and 27 MeV and with  $F(u)=u^{3/2}$ ,  $C_S=27$  and 50 MeV, respectively. The  $R_{most}$  and  $R_{least}$  are shown in the right-top plot. One can see that the  $R_{most}$  is more pronounced, while the  $R_{least}$  is much less pronounced (about unit), than those shown in Fig. 3 and Fig. 4 as well. Fig. 5 tells us that under the influence of the uncertainties of symmetry energy coefficient what sensitivity of the N/Z ratio of emitted nucleons in intermediate energy neutron-rich heavy ion collisions to the form of the density dependence of symmetry potential energy can be obtained.

Fig. 5

Recently, a much smaller range of  $32 \text{ MeV} \leq a_{sym} \leq 36 \text{ MeV}$  for symmetry energy at saturation (volume asymmetry) is deduced from the isovector GDR in  $^{208}\text{Pb}$  and the available data of differences between neutron and proton radii in Ref. [31]. It is worthwhile to see how the ratios of  $R_{most}$  and  $R_{least}$  look like with  $32 \text{ MeV} \leq a_{sym} \leq 36 \text{ MeV}$ . Fig. 6 shows the calculation results with  $F(u)=u^{1/2}$ ,  $C_S=45$  and 37 MeV and with  $F(u)=u^{3/2}$ ,  $C_S=37$  and 45 MeV, respectively. The corresponding  $R_{most}$  and  $R_{least}$  with  $C_S=37$  and 45 MeV are also shown in the right-top plot. From this figure, one can find that even with this small range the sensitivities of the N/Z ratio of free nucleons to the density dependence of the symmetry energy is still influenced by the uncertainties of  $a_{sym}$  though the ratio  $R_{least}$  is now larger than one which means the N/Z ratio of free nucleons is enhanced for  $\gamma=0.5$  case. Our study shows that it is urgently needed to have a more precise value of the  $a_{sym}$  in order to get more definite information of the density dependence of the symmetry energy.

Fig. 6

To summarize, in this paper we have studied the sensitivity of the N/Z ratio of free nucleons in collisions of neutron-rich nuclei at energies of 50A MeV and 100A MeV to the form of the density dependence of the symmetry potential energy term and the strength

of the symmetry potential by using IQMD transport model. We have found that the N/Z ratio of free nucleons are sensitive to both the form of the density dependence of the symmetry potential and the strength of the symmetry potential term as well. The results of the influences of the different combinations of both symmetry potential strength and the form of the density dependence of symmetry potential show that the uncertainties of the symmetry energy coefficient largely reduce the sensitivity of the N/Z ratio of free nucleons from collisions of neutron-rich nuclei as a probe of the form of the density dependence of the symmetric energy part. It is urgently needed to have a more precise value of the  $a_{sym}$  in order to get more definite information of the density dependence of the symmetry energy.

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TABLES

TABLE I. Parameters used in calculations.

$\alpha(MeV)$	$\beta(MeV)$	$\gamma$	$\rho_0(fm^{-3})$	$K = (MeV)$	$L(fm)$	$C_{Yuk}(MeV)$
-356	303	7/6	0.168	200	1.45	-5.5

TABLE II. The  $K_{sym}$  of different  $C_S$  and  $\gamma$ .

	$\gamma \setminus C_S (MeV)$	27	35	50
$K_{sym} (MeV)$	0.5	-55.7	-64.7	-81.6
	1.0	-25.3	-25.3	-25.3
	1.5	65.8	92.8	143.4

## FIGURES

FIG. 1. The dependence of  $F(u)$  on  $\gamma$ . The  $\gamma$  value is chosen 0.5, 1.0, and 1.5, respectively.

FIG. 2.  $\mu_n$  and  $\mu_p$  as a function of  $u$  for  $\delta= 16/96$  and  $32/132$  with  $C_S= 35$  MeV,  $\gamma= 0.5, 1.5$ , and  $C_S= 27$  MeV,  $\gamma= 0.5$  cases, respectively.

FIG. 3. The density dependence of N/Z ratio of emitted nucleons versus momentum. The reactions  $^{132}\text{Sn}+^{132}\text{Sn}$  at  $50A$  MeV and  $100A$  MeV are chosen in a) and b), respectively. The different line types are drawn only for guiding the eyes, as well as those in the next figures. The ratio of N/Z with  $\gamma = 0.5$  and  $1.5$  is shown in their right-top plots, respectively.

FIG. 4. The dependence of N/Z ratio of emitted nucleons on symmetry potential strength as a function of momentum. Hereinto a) chooses  $^{132}\text{Sn}+^{132}\text{Sn}$  reaction in central collisions, b) chooses  $^{96}\text{Zr}+^{96}\text{Zr}$  reaction in peripheral collisions, respectively. The ratio of N/Z with  $C_S = 50$  MeV and  $27$  MeV is shown in their right-top plots, respectively.

FIG. 5. The N/Z of nucleons versus momentum in central collision  $^{96}\text{Zr}+^{96}\text{Zr}$  at  $50A$  MeV with different symmetry potential:  $C_S= 27$  and  $50$  MeV when  $\gamma= 0.5$  and  $1.5$ . The  $R_{most}$  and  $R_{least}$  (see text) are shown in the right-top plot.

FIG. 6. The same as in Fig. 5 with different symmetry potential. Here  $C_S= 37$  and  $45$  MeV are chosen.













