Vol 14 No 8, August 2005
1009-1963/2005/14(08)/1549-05
Chinese Physics
© 2005 Chin. Phys. Soc.
and IOP Publishing Ltd

Several observables sensitive to the symmetry energy in heavy-ion collisions induced by high energy radioactive beams*

Yong Gao-Chan(雍高产)[a)b)], Li Bao-An(李宝安)[c)], and Zuo Wei(左 维)[a)b)]

[a)] *Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China*
[b)] *Graduate School, Chinese Academy of Sciences, Beijing 100039, China*
[c)] *Department of Chemistry and Physics, Arkansas State University, State University, Arkansas 72467-0419, USA*

(Received 12 January 2005; revised manuscript received 3 March 2005)

Using an isospin- and momentum-dependent hadronic transport model, effects of the symmetry energy on several observables in heavy-ion collisions induced by radioactive beams at intermediate energies are studied. It is found that rapidity distribution of the isospin asymmetry of nucleon emissions, transverse momentum distribution of the ratio of free neutrons to protons at mid-rapidity, kinetic energy distribution of the ratio of π^-/π^+ as well as evolution of the isospin fractionation are all sensitive to the symmetry energy.

Keywords: momentum dependence, hadronic transport model, symmetry energy
PACC: 2570

A major goal of isospin physics is to obtain a better understanding of properties of asymmetric nuclear matter, in particular, the isospin dependance of nuclear equation of state. (EOS).[1] Thanks to the hard work of many physicists for almost three decades the EOS of isospin symmetric nuclear matter is now relatively well determined by studying giant resonances and flow in heavy-ion collisions.[2] The new challenge is to extract information about the EOS of isospin asymmetric nuclear matter, specifically the density dependence of nuclear symmetry energy.[1,2] Besides the general interest in nuclear physics, the EOS of asymmetric nuclear matter at high densities is also of crucial importance in many astrophysical processes, especially in connection with the structure and dynamical evolution of neutron stars.[3] For example, the EOS of asymmetric nuclear matter is a fundamental input for the neutron star structure model (Tolman–Oppenheimer–Volkoff (TOV) equation) and the critical density for the direct cooling process is determined uniquely by the density dependence of symmetry energy. Although recently considerable progress has been made in determining the low-density part of the symmetry energy,[4] much more work is still needed to probe the symmetry energy at high densities. A critical task is to find experimental observables that are sensitive to the symmetry energy. A number of such observables have been identified already, such as the free neutron/proton ratio,[5] the isospin fractionation,[6−10] the neutron–proton transverse differential flow,[11−13] the neutron–proton correlation function,[14] the isospin diffusion,[15,16] the proton differential elliptic flow[17] and the π^-/π^+ ratio.[18]

In Ref.[19], it has been shown that the momentum dependence of the symmetry potential affects many experimental observables. In the present paper, we report our investigations on several observables by adopting various momentum-dependent symmetry potentials proposed in Ref.[20]. We concentrate on the central reaction of ^{132}Sn + ^{124}Sn at a beam energy of 400 MeV/nucleon.

*Project supported by the Knowledge Innovation Program of the Chinese Academy of Sciences (Grant No KJCX2-SW-N02), the State Key Development Program of Basic Research of China (Grant No G2000077400), the National Natural Science Foundation of China (Grant No 10235030), the Key Pre-research Program of the Ministry of Science and Technology of China (Grant No 2002CCB00200), and the K. C. Wong Education Foundation, Hong Kong. Li Bao-An is supported in part by the National Science Foundation Grants (Grant Nos PHY0243571 and PHY0354572).

Our study is based on the isospin- and momentum-dependent hadronic transport model IBUU04.[21] In this model, besides nucleons, Δ and N^* resonances as well as pions are included. The initial neutron and proton density distributions of the projectile and target are obtained by using the relativistic mean field theory. The experimental free nucleon–nucleon scattering cross sections are used. The total and differential cross sections for all other particles are taken either from experimental data or obtained by detail balance formula. The isospin-dependent phase-space distribution functions of the involved particles are solved by using test-particles method numerically, and the isospin dependence of Pauli block for fermions has also been considered (for details see Refs.[5,19–22]). The single nucleon potential adopted in the present calculations is the momentum-dependent potential proposed recently in Ref.[20]:

$$\begin{aligned} U(\rho,\delta,\boldsymbol{p},\tau) =& A_u(x)\frac{\rho_{\tau'}}{\rho_0} + A_l(x)\frac{\rho_\tau}{\rho_0} \\ &+ B(\frac{\rho}{\rho_0})^\sigma(1-x\delta^2) \\ &- 8x\tau\frac{B}{\sigma+1}\frac{\rho^{\sigma-1}}{\rho_0^\sigma}\delta\rho_{\tau'} \\ &+ \frac{2C_{\tau,\tau}}{\rho_0}\int \mathrm{d}^3\boldsymbol{p}'\frac{f_\tau(\boldsymbol{r},\boldsymbol{p}')}{1+(\boldsymbol{p}-\boldsymbol{p}')^2/\Lambda^2} \\ &+ \frac{2C_{\tau,\tau'}}{\rho_0}\int \mathrm{d}^3\boldsymbol{p}'\frac{f_{\tau'}(\boldsymbol{r},\boldsymbol{p}')}{1+(\boldsymbol{p}-\boldsymbol{p}')^2/\Lambda^2}, \quad (1) \end{aligned}$$

supplemented with the Coulomb potential for protons. In the above equation, $\delta \equiv (\rho_\mathrm{n}-\rho_\mathrm{p})/(\rho_\mathrm{n}+\rho_\mathrm{p})$, $\tau = 1/2(-1/2)$ for neutron (proton) and $\tau \neq \tau'$(baryon resonances are divided into neutrons and protons), $\sigma = 4/3$, $f_\tau(\boldsymbol{r},\boldsymbol{p})$ is the phase-space distribution at coordinate $\boldsymbol{r}$ and momentum $\boldsymbol{p}$. The parameters $A_u, A_l, B, C_{\tau,\tau}, C_{\tau,\tau'}$ and Λ are set by reproducing the momentum-dependent $U(\rho,\delta,\boldsymbol{p},\tau)$ predicted by the Gogny–Hartree–Fock and/or the Brueckner–Hartree–Fock calculations, the saturation properties of symmetric nuclear matter and the symmetry energy of 30MeV at a normal nuclear matter density. The compressibility of symmetric nuclear matter at a normal density is set to be 211MeV. Specifically, the parameters $A_u(x)$ and $A_l(x)$ depend on x and they are given by

$$A_u(x) = -95.98 - \frac{2B}{\sigma+1}x, \quad (2)$$

$$A_l(x) = -120.57 + \frac{2B}{\sigma+1}x, \quad (3)$$

where $B = 106.35$MeV. $\Lambda = p_\mathrm{F}^0$ is the nucleon Fermi momentum in symmetric nuclear matter, $C_\mathrm{unlike} = -103.4$MeV and $C_\mathrm{like} = -11.7$MeV. The C_unlike and C_like terms are responsible for the momentum-dependent interactions of a nucleon with unlike and like nucleons in nuclear matter. The parameter x is introduced to mimic various density-dependent symmetry energies $E_{sym}(\rho)$ predicted by microscopic and phenomenological many-body approaches. The isoscalar part ($(U_\mathrm{n}+U_\mathrm{p})/2$) of the single nucleon potential is shown[19,22] to be in good agreement with that of the variational many-body calculations[23] and the isovector part ($(U_\mathrm{n}-U_\mathrm{p})/2\delta$) turns out to be consistent with the experimental Lane potential.[24] It is seen that in this single particle potential the momentum dependences of both the isoscalar and isovector (symmetry) potentials are consistently taken into account.

The effective mass of nucleon is an important input in a transport model. In terms of the single particle potential $U(\rho,\delta,\boldsymbol{p},\tau)$, in the present model the effective mass of nucleon is defined as[25]

$$\frac{m_\tau^*}{m_\tau} = \left[1+\frac{m_\tau}{p}\frac{\mathrm{d}U}{\mathrm{d}p}\right]^{-1}_{p_\mathrm{F}^\tau}. \quad (4)$$

It is found that the effective mass of neutron is higher than that of proton and the difference between them increases with both the density asymmetry and the isospin asymmetry of the medium.

According to microscopic investigations,[26] the equation of state (EOS) for isospin asymmetric nuclear matter can be expressed as

$$E(\rho,\delta) = E(\rho,0) + E_\mathrm{sym}(\rho)\delta^2 + \mathcal{O}(\delta^4), \quad (5)$$

where $\delta = (\rho_\mathrm{n}-\rho_\mathrm{p})/(\rho_\mathrm{n}+\rho_\mathrm{p})$ is the isospin asymmetry parameter, $\rho = \rho_\mathrm{n}+\rho_\mathrm{p}$ is the baryon density, and ρ_n and ρ_p are the neutron and proton densities, respectively. $E(\rho,0)$ is the energy per nucleon of symmetric nuclear matter, and $E_\mathrm{sym}(\rho)$ is the symmetry energy. For a given value x, one can readily calculate the symmetry energy $E_\mathrm{sym}(\rho)$ as a function of density from the single particle potential Eq.(1). The results are shown in Fig.1. It is seen that the density-dependent symmetry energy at high densities ($\rho > \rho_0$) becomes stiffer and stiffer as the parameter x goes from x=1 to x=–2. With this choice the density-dependent symmetry energy samples a wide range of the theoretical predictions.

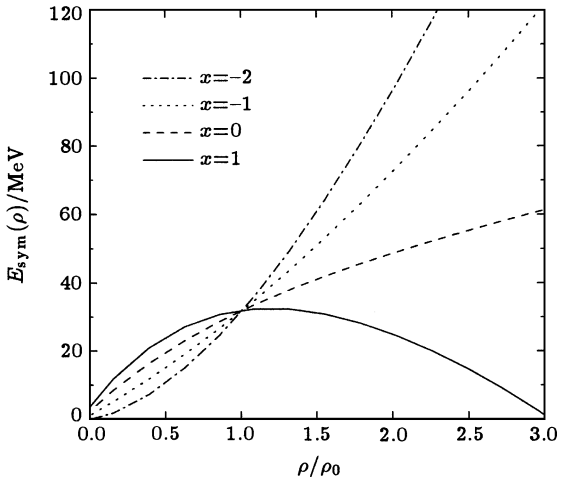


Fig.1. Density dependence of nuclear symmetry energy with different values of parameter x in Eq.(1).

Knowledge about the maximum baryon density is important for the study of the nuclear EOS. Shown in Fig.2 is the central baryon density as a function of time in the reaction of ^{132}Sn +^{124} Sn at a beam energy of 400MeV/nucleon and an impact parameter of 1 fm with various symmetry energies. It is seen that the maximum baryon density reached is about 2 times normal nuclear matter density. Secondly, because the symmetry energy is relatively small compared to the EOS of symmetric nuclear matter around this density, the compression is rather insensitive to the symmetry energies. Although the EOS of symmetric nuclear matter dominates the reaction dynamics, there are still many observables that are sensitive to the symmetry energy.

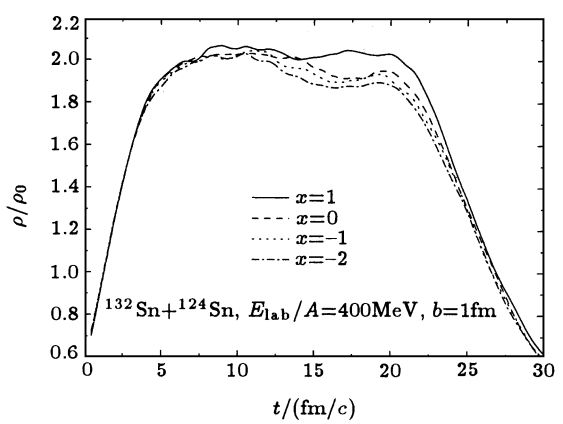


Fig.2. Evolution of central baryon density with various symmetry energies in the reaction of ^{132}Sn+^{124}Sn at E_{beam}/A=400MeV and an impact parameter of 1fm.

Shown in Fig.3[27] are the rapidity distributions of δ_{free} with various symmetry energies. $\delta_{free} \equiv (N_n - N_p)/(N_n + N_p)$, where $N_n(N_p)$ is the multiplicity of free neutrons(protons). Here we consider a nucleon to be free if its local density is less than $\rho_0/8$. As one expects, with stiff symmetry energy the overall isospin asymmetries of free nucleons are significantly higher than that with soft symmetry energy. The δ_{free} at midrapidity is particularly sensitive to the symmetry energy. As the parameter x increases from -2 to 1 the δ_{free} at midrapidity decreases by about a factor of 2. Moreover, the forward–backward asymmetric rapidity distribution of δ_{free} with all four x parameters indicates the apparent nuclear translucency during the reaction. Notice here that for soft symmetry energy the relatively large difference of rapidities of the backward–forward asymmetric isospin asymmetry indicates a larger isospin diffusion velocity. From the concave it is seen that neutrons have larger transit velocities relative to protons.

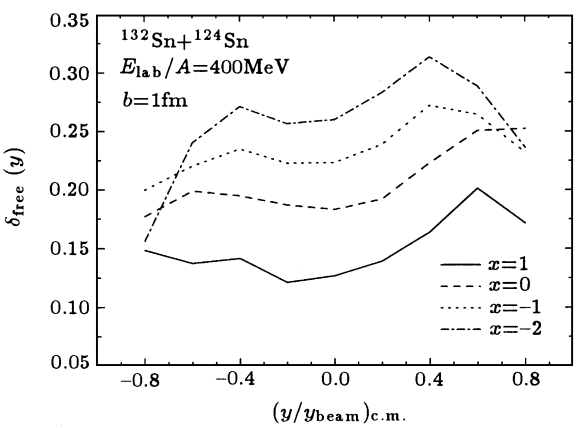


Fig.3. Rapidity distribution of isospin asymmetry of free nucleons with various symmetry energies in the same reaction as that in Fig.2.

Shown in Fig.4[27] are transverse momentum distributions of the ratios of free neutrons to protons at mid-rapidity with the variation of the symmetry energy. Since the general symmetry potential tends to make more/less neutrons/protons to be emitted at high densities, a stronger symmetry potential is expected to lead to a larger ratio of free neutrons to protons as shown in Fig.4. A prominent feature is the increase of the ratios of free neutrons to protons at lower transverse momenta. This is mainly due to Coulomb repulsion which shifts protons from lower to higher transverse momenta. At higher transverse momenta, ratios of free neutrons to protons are lower than those of neutrons to protons of the reaction system (the solid lines indicate the isospin asymmetry of the combined target and projectile system). This is mainly because at higher transverse momenta the momentum dependence of the symmetry potential is to

weaken the strength of the symmetry potential, hence lower ratios of free neutrons to protons are obtained. It is also seen from Fig.4 that the dN_n/dN_p ratios with different x parameters are almost parallel with each other except in the high p_t region.

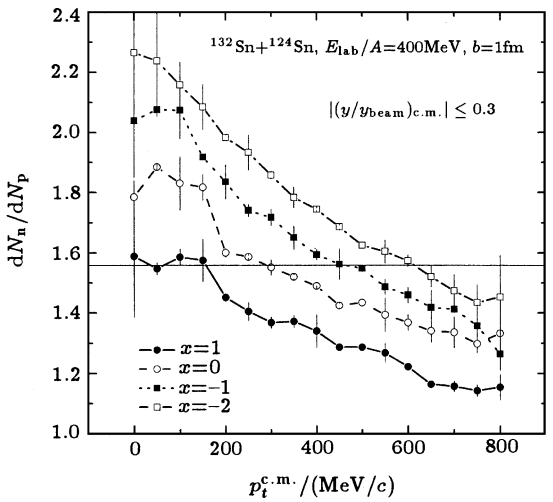


Fig.4. Transverse momentum distribution of the free neutron/proton ratio at mid-rapidity with various symmetry energies in the same reaction as that in Fig.2.

Shown in Fig.5[18] is the kinetic-energy distribution of the π^-/π^+ ratio at freeze-out time. For the positively charged nuclear matter, the Coulomb interaction is attractive for π^- and repulsive for π^+; the negative pions are shifted to relatively low kinetic energies with respect to the positive pions. As a consequence, the magnitudes of the π^-/π^+ ratios are higher at lower kinetic energies with various symmetry energies. Since a stiffer symmetry energy results in a stronger repulsion on neutrons, increasing the stiffness of symmetry energy (x goes from 1 to −2) reduces the number of neutron–neutron collisions in the interaction region and lowers the π^-/π^+ ratio. It is seen that the π^-/π^+ ratio is related inversely to the stiffness of symmetry energy and can serve as a sensitive observable for probing the density dependence of symmetry energy.

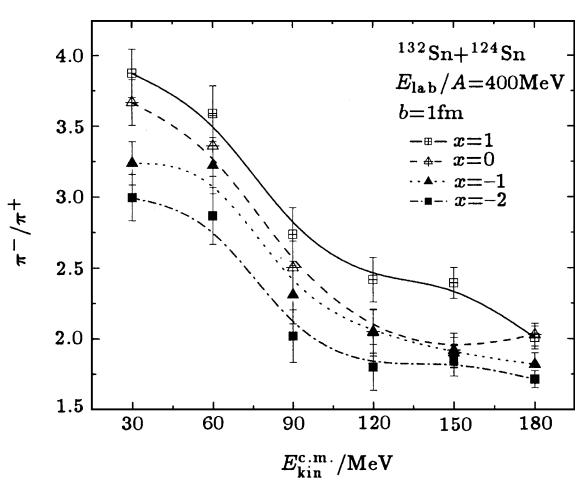


Fig.5. The π^-/π^+ ratio as a function of pion kinetic energy with various symmetry energies in the same reaction as that in Fig.2.

Isospin fractionation refers to the different isospin asymmetries in low and high density regions in nuclear reaction. The strength of isospin fractionation has been found to depend sensitively on the density-dependent symmetry energy.[11] As the stiff symmetry energy enhances the emission of neutrons while suppressing that of protons, the stiffer symmetry energy is expected to lead to a more neutron-rich low density gas (which refers to free nucleons) of nucleons and a more neutron-deficient high density liquid (which refers to bound nucleons) of nucleons, and corresponds to a stronger isospin fractionation. Shown in Fig.6 is the evolution of the isospin fractionation with various symmetry energies in the reaction of ^{132}Sn+^{124}Sn at E_{beam}/A=400MeV and an impact parameter of 1fm. It is seen that ratios of neutrons to protons in gas phase, liquid phase as well as the strength of isospin fractionation $(N_n/N_p)_{gas}/(N_n/N_p)_{liquid}$ are all sensitive to the symmetry energy. The stiff symmetry energy ($x = -2$) corresponds to high ratios of neutrons to protons in the gas phase, low ratios of neutrons to protons in the liquid phase and a larger strength of isospin fractionation, as one expects. At the beginning stage the high ratios of neutrons to protons in

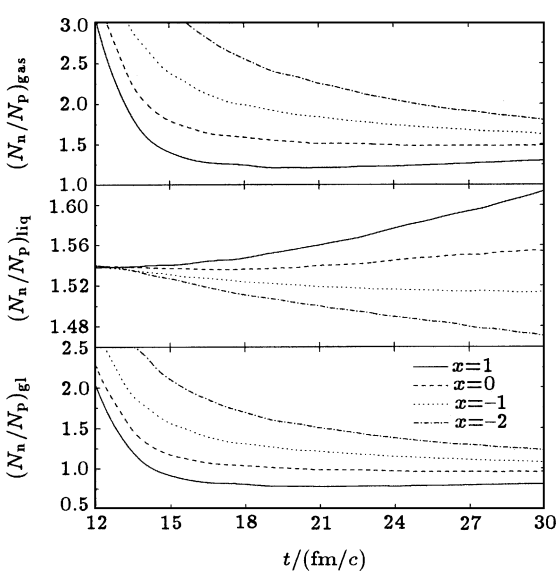


Fig.6. Evolution of the isospin fractionation with various symmetry energies in the same reaction as that in Fig.2.

gas phase are due to the effects of neutron-skins. Other observables that are sensitive to the symmetry energy such as the neutron–proton differential flow and the elliptic flow will be reported elsewhere. With these physical observables, we can probe the stiffness of the symmetry energy by comparing the experimental results with calculations of the transport model. For a new single particle potential used here, the results calculated by the transport model IBUU04 are expected to be more reliable.

To summarize, we have analysed several observables that are sensitive to the symmetry energy in the reaction of ^{132}Sn $+^{124}$ Sn at a beam energy of 400MeV/nucleon and an impact parameter of 1fm within a framework of isospin- and momentum-dependent hadronic transport model. It is found that the rapidity distribution of the isospin asymmetry of nucleon emissions, transverse momentum distribution of the ratio of free neutrons to protons at mid-rapidity, kinetic energy distribution of the ratio of π^-/π^+ as well as the evolution of isospin fractionation are all sensitive to the symmetry energy. With these observables sensitive to the symmetry energy, we can constrain the stiffness of symmetry energy at high densities.

References

[1] Li B A and Schröder W Udo 2001 *Isospin Physics in Heavy-Ion Collisions at Intermediate Energies* (New York: Nova Science) p1

[2] Danielewicz P, Lacey R and Lynch W G 2002 *Science* **298** 1592

[3] Kutschera M 1994 *Phys. Lett.* B **340** 1
Prakash M *et al* 1997 *Phys. Rep.* **280** 1
Lattimer J M and Prakash M 2001 *Astrophys J.* **550** 426

[4] Tsang M B *et al* 2004 *Phys. Rev. Lett.* **92** 062710
Chen L W, Ko C M and Li B A 2005 *Phys. Rev. Lett.* **94** 32701

[5] Li B A, Ko C M and Ren Z Z 1997 *Phys. Rev. Lett.* **78** 1644
Li B A 2003 *Phys. Rev.* C **69** 034614

[6] Li B A and Ko C M 1997 *Nucl. Phys.* A **618** 498

[7] Baran V, Colonna M, Toro M Di and Larionov A B 1998 *Nucl. Phys.* A **632** 287

[8] Xu H S *et al* 2000 *Phys. Rev. Lett.* **85** 716

[9] Tan W P *et al* 2001 *Phys. Rev.* C **64** 051901(R)

[10] Baran V, Colonna M, Toro M Di, Greco V, Zielinska-Pfabé M and Wolter H H 2002 *Nucl. Phys.* A **703** 603

[11] Li B A 2000 *Phys. Rev. Lett.* **85** 4221

[12] Greco V, Colonna M, Toro M Di and Matera F 2003 *Phys. Rev.* C **67** 015203

[13] Scalone L, Colonna M and Toro M Di 1999 *Phys. Lett.* B **46** 19

[14] Chen L W, Greco V, Ko C M and Li B A 2003 *Phys. Rev. Lett.* **90** 162701
Chen L W, Greco V, Ko C M and Li B A 2003 *Phys. Rev.* C **68** 014605

[15] Chen L W, Ko C M and Li B A 2004 *Phys. Rev.* C **69** 054606

[16] Shi L and Danielewicz P 2003 *Phys. Rev.* C **68** 064604

[17] Li B A 2001 *Phys. Rev.* C **64** 054604

[18] Li B A 2002 *Phys. Rev. Lett.* **88** 192701
Li B A 2002 *Nucl. Phys.* A **708** 365
Li B A, Yong G C, Zuo W 2005 *Phys. Rev.* C **71** 014608

[19] Li B A, Das C B, Gupta S Das and Gale C 2004 *Nucl. Phys.* A **735** 563

[20] Das C B, Gupta S Das, Gale C and Li B A 2003 *Phys. Rev.* C **67** 034611

[21] Li B A, Ko C M and Bauer W 1998 *Int. J. Mod. Phys.* **E7** 147

[22] Li B A 2004 *Phys. Rev.* C **69** 064602

[23] Wiringa R B 1998 *Phys. Rev.* C **38** 2967

[24] Lane A M 1962 *Nucl. Phys.* A **35** 676

[25] Jeukenne J P, Lejeune A and Mahaux C 1976 *Phys. Rep.* **25** 83

[26] Zuo W, Bombaci I and Lombardo U 1999 *Phys. Rev.* C **60** 024605
Zuo W, Lejeune A, Lombardo U and Mathiot J F 2002 *Nucl. Phys.* A **706** 418
Zuo W, Lejeune A, Lombardo U and Mathiot J F 2002 *Eur. Phys. J.* A **14** 469

[27] Li B A, Yong G C and Zuo W 2005 *Phys. Rev.* C **71** 044604