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Constraints on nucleon effective mass splitting with heavy ion collisions

Yingxun Zhang [a,*], M.B. Tsang [b], Zhuxia Li [a], Hang Liu [c]

[a] China Institute of Atomic Energy, P.O. Box 275 (10), Beijing 102413, PR China
[b] National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824, USA
[c] Texas Advanced Computing Center, University of Texas, Austin, TX 78758, USA

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ABSTRACT

A new version of the improved quantum molecular dynamics model has been developed to include standard Skyrme interactions. Four commonly used Skyrme parameter sets, SLy4, SkI2, SkM* and Gs are adopted in the transport model code to calculate the isospin diffusion observables as well as single and double ratios of transverse emitted nucleons. While isospin diffusion observables are sensitive to the symmetry energy term, they are not very sensitive to the nucleon effective mass splitting parameters in the interactions. Our calculations show that the high energy neutrons and protons and their ratios from reactions at different incident energies provide a robust observable to study the momentum dependence of the symmetry potential which leads to the effective mass splitting. However the sensitivity of effective mass splitting effect on the double n/p yield ratios decreases with increasing beam energy, even though high energy protons and neutrons are produced more abundantly at high beam energy. Our calculations show that the optimum incident energy to study nucleon effective masses is between 100–200 MeV per nucleon.

For nuclear matter with unequal number of neutrons and protons, the energy of the system is reduced by approximately the square of the differences in the proton and neutron densities divided by the total density. Such reduction in energy is called the nuclear symmetry energy which also appears in the nuclear binding energy of the liquid drop model. Thus the symmetry energy is of fundamental importance in our understanding of nature's asymmetric objects including neutron stars as well as heavy nuclei with very different number of neutrons and protons. Theoretical predictions on the symmetry energy have large uncertainties [1,2]. This stimulates a lot of efforts in the nuclear physics communities to provide experimental constraints on the density dependence of symmetry energy. Observables used to constrain the symmetry energy range from isospin diffusions, yield ratios of emitted nucleons, isoscaling and flow of light charged particles in heavy ion collisions (HIC) [2–16], to experiments that measure nuclei properties such as neutron skin [17–19], Pygmy Dipole Resonance [20–22], masses of Isobaric Analog States [23], and nuclei masses [24,25]. Only recently, a consistent picture on the symmetry energy at saturation density, S_0, and its slope, L has been obtained [7,26]. The slope $L = 3\rho_0\, dS(\rho)/d\rho|_{\rho=\rho_0}$ where $S(\rho)$ is the density dependence of the symmetry energy is related to the pressure of pure neutron matter at saturation density. Initial results from astrophysical measurements seem to favor much lower L values [27] than other experimental constraints. However, extraction of the radii from neutron stars is not settled and the latest results are more consistent with the heavy ion collision results [28].

Another source of uncertainties in the theoretical description of the symmetry energy comes from the momentum dependence of the symmetry potential. Inside a strongly interacting medium as in the description of nuclear matter, the momentum dependence of symmetry potential may lead to different values of the neutron/proton effective masses. The knowledge of the difference, also known as the nucleon effective mass splitting, is important for understanding not only level density of single particles, isovector Giant Dipole Resonance in nuclear structures and spectra of emitted particles in nuclear reactions but also many critical issues in astrophysics, such as heat capacity of matter, the neutron and proton chemical potential and their fraction [29,30,2,31–37]. There have been some efforts on constraining the nucleon effective mass splitting by analyzing the symmetry potential $U_{sym}(\rho_0, E)$ using nuclei optical potential data [2,33,38]. In that study, $m_n^* > m_p^*$ is found to be valid around normal density and Fermi momentum. However, other theoretical predictions including Relativistic Hartree

* Corresponding author.
E-mail address: zhyx@ciae.ac.cn (Y. Zhang).

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Table 1
Corresponding saturation properties of nuclear matter in, SLy4, SkI2, SkM*, and Gs Skyrme parameters. All entries are in MeV, except for ρ_0 in fm^{-3} and the dimensionless effective mass ratios for nucleon, neutron and proton. The effective mass for neutron and proton are obtained for isospin asymmetric nuclear matter with $\delta = 0.2$.

Para.	ρ_0	E_0	K_0	S_0	L	K_{sym}	m^*/m	m_n^*/m	m_p^*/m
SLy4	0.160	−15.97	230	32	46	−120	0.69	0.68	0.71
SkI2	0.158	−15.78	241	33	104	71	0.68	0.66	0.71
SkM*	0.160	−15.77	217	30	46	−156	0.79	0.82	0.76
Gs	0.158	−15.59	237	31	93	14	0.78	0.81	0.76

Fock calculations [39] suggest that at higher energy, $m_n^* > m_p^*$ change to $m_n^* < m_p^*$. Similar behaviors have also been found in Skyrme/Gogny–Hartree–Fock predictions on $U_{sym}(\rho, E)$ [40].

At high incident energy, HIC can create "excited nuclear matter" above the normal density and nucleon momentum distribution far from the Fermi momentum for violent nucleon–nucleon collisions. To explore the effective mass splitting issues, we calculate the yield ratios of neutrons and protons emitted from HIC over a range of incident energies. In this paper, we explain how to constrain both the symmetry energy and nucleon effective mass from heavy ion collisions using transport model. Specifically, we incorporate Skyrme effective nucleon–nucleon interaction (or energy density functional) that has been used to describe nuclear structure properties [41] in the Improved Quantum Molecular Dynamics (ImQMD) code. The constraints on the symmetry energy obtained with the new code are consistent with previous studies. Furthermore, our study suggests that nucleon yields from heavy ion collisions are sensitive to nucleon mass splitting at beam energy as low as 50 MeV per nucleon even though the optimum energy to study this effect is found to be around 100–200 MeV per nucleon, within the realms of current and future rare isotope beam facilities.

In most transport models, the nucleon energy density can be written as the local term and momentum dependent interaction term (MDI term) as

$$u = u_{loc} + u_{md} \tag{1}$$

However, u_{loc} in most transport codes adopts the Skyrme like energy density, $\frac{\alpha}{2}\frac{\rho^2}{\rho_0} + \frac{\beta}{\eta+1}\frac{\rho^{\eta+1}}{\rho_0^\eta} + S(\rho)\delta^2\rho$, while u_{md} is often obtained by fitting the effective mass and energy dependence of the real part of the optical potential [42–44]. Most of these interactions used in transport models successfully describe the HIC observables, but few of them were used to study the nuclear structure. Exceptions are inclusion of the Gogny finite range interactions in the Asymmetrized Molecular Dynamic (AMD) and the IBUU04 codes [6,12]. In this paper, we modified the nucleon potential part of the Improved Quantum Molecular Dynamics (ImQMD05) code [45] to that derived from the real Skyrme potential energy density (without spin–orbit term) by including the energy density of isospin dependent Skyrme-like MDI as

$$\begin{aligned} u_{md} &= u_{md}(\rho\tau) + u_{md}(\rho_n\tau_n) + u_{md}(\rho_p\tau_p) \\ &= C_0 \int d^3p\, d^3p'\, f(\vec{r},\vec{p}) f(\vec{r},\vec{p}')(\vec{p}-\vec{p}')^2 \\ &\quad + D_0 \int d^3p\, d^3p' \big[f_n(\vec{r},\vec{p}) f_n(\vec{r},\vec{p}')(\vec{p}-\vec{p}')^2 \\ &\quad + f_p(\vec{r},\vec{p}) f_p(\vec{r},\vec{p}')(\vec{p}-\vec{p}')^2 \big] \end{aligned} \tag{2}$$

where $f(\vec{r},\vec{p})$ is the nucleon phase space density, and $f(\vec{r},\vec{p}) = \sum_i \frac{1}{(\pi\hbar)^3} \exp[-(\vec{r}-\vec{r}_i)^2/2\sigma_r^2 - (\vec{p}-\vec{p}_i)^2/2\sigma_p^2]$ in QMD approaches. The coefficients C_0 and D_0 can be determined with following relationship,

$$C_0 = \frac{1}{16\hbar^2}\big[t_1(2+x_1) + t_2(2+x_2)\big] \tag{3}$$

$$D_0 = \frac{1}{16\hbar^2}\big[t_2(2x_2+1) - t_1(2x_1+1)\big] \tag{4}$$

For nuclear matter at zero temperature, $f_q = \frac{2}{(2\pi\hbar)^3}\theta(p - p_F^q)$, $q = n, p$. Eq. (2) can be calculated analytically, and it is equal to $A_0\rho\tau + B_0(\rho_n\tau_n + \rho_p\tau_p)$ (the same as $\rho^{8/3}$ and $\rho^{8/3}\delta^2$ term in Eq. (2) in Ref. [45]), where $\tau = \tau_n + \tau_p$, $\tau_q = \frac{3}{5}k_{q,F}^2\rho_q$. $A_0 = 1/8[t_1(2+x_1) + t_2(2+x_2)]$, $B_0 = 1/8[t_2(2x_2+1) - t_1(2x_1+1)]$. The local part of energy density is defined as:

$$\begin{aligned} u_\rho &= \frac{\alpha}{2}\frac{\rho^2}{\rho_0} + \frac{\beta}{\eta+1}\frac{\rho^{\eta+1}}{\rho_0^\eta} + \frac{g_{sur}}{2\rho_0}(\nabla\rho)^2 \\ &\quad + \frac{g_{sur,iso}}{\rho_0}\big[\nabla(\rho_n - \rho_p)\big]^2 \\ &\quad + A_{sym}\rho^2\delta^2 + B_{sym}\rho^{\eta+1}\delta^2 \end{aligned} \tag{5}$$

here, $\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p)$ is the isospin asymmetry, ρ_n and ρ_p are the neutron and proton densities, respectively. The coefficients of α, β, g_{sur}, $g_{sur,iso}$, A_{sym} and B_{sym} can be obtained by the standard Skyrme interaction parameters as in previous work [45]. These calculations use isospin-dependent in-medium nucleon–nucleon scattering cross sections in the collision term and Pauli blocking effects as described in [45]. This new version of Quantum Molecular Dynamics code (ImQMD-Sky) retains the many-body correlations incorporated in the original QMD approaches [42,46].

In the following studies, we choose four Skyrme interaction parameter sets, SLy4, SkI2, SkM* and Gs [47–50] which have similar incompressibility (K_0), symmetry energy coefficient (S_0) and isoscalar effective mass (m^*), i.e., $K_0 = 230 \pm 20$ MeV, $S_0 = 32 \pm 2$ MeV and $m^*/m = 0.7 \pm 0.1$. The SLy4 and SkI2 [47,48] have similar nucleon effective mass splitting, with $m_n^* < m_p^*$, but very different slopes of symmetry energy L values, 46 MeV for SLy4, and 104 MeV for SkI2. The other two Skyrme interaction parameter sets with $m_n^* > m_p^*$ also have different L values, 46 MeV for SkM* [49], and 93 MeV for Gs [50]. The saturation properties of nuclear matter for these four Skyrme interactions are listed in Table 1. By analyzing the results from calculations that use these interactions, we hope to disentangle the sensitivities of the isospin observables on the density dependence of symmetry energy and neutron proton effective mass splitting.

The left panel of Fig. 1 shows the density dependence of symmetry energy for cold nuclear matter, $S(\rho) = \frac{1}{3}\frac{\hbar^2}{2m}\rho_0^{2/3}(\frac{3\pi^2}{2}\frac{\rho}{\rho_0})^{2/3} + A_{sym}\rho + B_{sym}\rho^\eta + C_{sym}\rho^{5/3}$. The last term in $S(\rho)$ is derived from the u_{md} in Eq. (2), and $C_{sym} = -\frac{1}{24}(\frac{3\pi^2}{2})^{2/3}\Theta_{sym}$, $\Theta_{sym} = 3t_1x_1 - t_2(4+5x_2)$. Smaller L values yield higher symmetry energy at subsaturation densities while the opposite is true at the suprasaturation density regions. The right panels of Fig. 1 show the Lane potentials $U_{sym} = \frac{U_n - U_p}{2\delta} = 2A_{sym}\rho + 2B_{sym}\rho^\eta + 2D_0 m\rho E_k$ for cold nuclear matter at $0.5\rho_0$ (top panel) and at ρ_0 (bottom panel) as a function of nucleon kinetic energy. The Lane potential gives an accurate estimate for the difference of the force between neutron and proton experienced in asymmetric nuclear matter, and directly influences the neutron proton yield ratios, $Y(n)/Y(p)$. The