Constraints on symmetry energy and n/p effective mass splitting with improved quantum molecular dynamics model Postprint

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Abstract

A new version of improved quantum molecular dynamics model that includes standard Skyrme interactions has been developed. Based on the new code, four commonly used parameter sets, SLy4, SkI2, SkM* and Gs are adopted in the improved quantum molecular dynamics model and the isospin sensitive observables, namely isospin transport ratios, single and double ratios of the yields of neutrons and protons are investigated. The isospin transport ratios are strongly sensitive to the slope of symmetry energy, and are not very sensitive to the nucleon effective mass splitting. On the other hand, the high energy neutrons and protons yields ratios from reactions at different incident energies provide a good observable to the momentum dependence of nucleon effective mass splitting. By comparing our calculations with the data, we find that the constrained L value (the slope of density dependence of symmetry energy) is about ~46 MeV when the Skyrme type interaction is considered in transport models, and the isospin diffusion data prefer to mn$>mp$, but it is not a strong constraint with deep 2 minimum.

Full Text

Constraints on Symmetry Energy and Neutron-Proton Effective Mass Splitting with Improved Quantum Molecular Dynamics Model

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Abstract

A new version of the improved quantum molecular dynamics model that includes standard Skyrme interactions has been developed. Based on this code, four commonly used parameter sets—SLy4, SkI2, SkM*, and Gs—are adopted, and isospin-sensitive observables, namely isospin transport ratios and single and double ratios of neutron and proton yields, are investigated. The isospin transport ratios are strongly sensitive to the slope of symmetry energy and only weakly sensitive to nucleon effective mass splitting. Conversely, high-energy neutron and proton yield ratios from reactions at different incident energies provide a good observable for the momentum dependence of nucleon effective mass splitting. By comparing calculations with experimental data, we find that the constrained L value (the slope of density dependence of symmetry energy) is approximately 46 MeV when Skyrme-type interactions are considered in transport models, and the isospin diffusion data prefer m_n* > m_p*, though this is not a strong constraint with a deep χ^2 minimum.

Key words Symmetry energy, Nucleon effective mass splitting, Heavy ion collisions, ImQMD

Introduction

Constraints from heavy ion collisions are obtained by comparing isospin-sensitive observable data with predictions from transport models that include the density dependence of symmetry energy as an input variable. Tighter constraints can be obtained by improving theoretical models to incorporate missing physics.

Knowledge of the symmetry energy—defined as the difference in binding energy between pure neutron matter and symmetric nuclear matter—is important for understanding nuclear structure, nuclear reactions, and astrophysical phenomena. Recent observables used to constrain symmetry energy range from isospin diffusions in heavy ion collisions (HIC) [1-14] to nuclear properties such as neutron skin, Pygmy Dipole Resonance, masses of Isobaric Analog States, and nuclear masses in the Finite Range Droplet Model [15-24].

While a general consensus has emerged regarding the symmetry energy S_0 at saturation density and its slope parameter L, significant uncertainties remain and require further constraints.

In addition to dependence on nuclear density, the symmetry potential also depends on nucleon momentum in the system. Such dependence leads to splitting of the nucleon effective mass, especially in high-density regions. An important question concerns whether the effective mass for neutrons (m*_n) is higher than, *equal to, or lower than that for protons (m)*, and how this effective mass splitting changes with nucleon momentum. Our lack of reliable knowledge about neutron-proton effective mass splitting has hindered accurate extraction of S( ) from nuclear reactions using transport models, because the compressed nuclear system is excited by violent nucleon-nucleon collisions and contributions from the momentum dependence of the symmetry potential cannot be entirely described with local density approximation [1,25,26]. Efforts to constrain nucleon effective mass splitting by analyzing nuclear optical potential data [1,27] have ruled out the case $m_n^* < m_p^*$ around normal density and Fermi momentum. Furthermore, it is important to provide constraints on the momentum dependence of effective mass splitting from heavy ion collision data. In this paper, we investigate such dependence in a transport model by selecting different Skyrme effective nucleon-nucleon interactions.

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2 New Version of ImQMD

The Quantum Molecular Dynamics Model (QMD) represents individual nucleons as Gaussian wave packets that move according to the Ehrenfest theorem; i.e., Hamilton' s equations [8]. At the China Institute of Atomic Energy (CIAE), we developed and successfully applied a new QMD code, labeled ImQMD, which includes mean-field potentials calculated using a Skyrme energy density functional with options for different forms of the density dependence of the symmetry potential, to study heavy ion reactions ranging from Coulomb barrier energies to 400 MeV per nucleon [28]. With these modifications, ImQMD has successfully described the multiplicity of reaction products, collective flows, and stopping powers in intermediate-energy Heavy Ion Collisions (HICs), but this version lacked consideration of nucleon effective mass splitting.

We improve the mean-field part of the Improved Quantum Molecular Dynamics (ImQMD05) code by including the isospin-dependent Skyrme-like momentum-dependent interaction. The nucleon phase space distribution function is given by standard QMD formulations. The coefficients C_0 and D_0 can be determined through standard relationships.

In the new version of the ImQMD code (ImQMD-Sky), the potential energy U is:

$U = U_{loc} + U_{md} + U_{Coul}$

The nuclear contributions are represented in integral form. The energy density u_{loc} is:

$u_{loc} = [A(/ _0) + B(/ _0)^\alpha + g_{sur}( )^2 + g_{sur},iso((-))^2] + (1/2)sym( )\delta^2 + (1/2)B_{sym}( )\delta^2$

Here, δ is the isospin asymmetry, $\delta = (-)/(+)$, where and are neutron and proton densities, respectively. The coefficients α, β, g_{sur}, g_{sur},iso, A_{sym} and B_{sym} can be obtained from the standard Skyrme interaction parameters as in previous work [28]. U_{Coul} is the Coulomb energy. The mean fields acting on these wave packets are derived from the potential energy.

These calculations use isospin-dependent in-medium nucleon-nucleon scattering cross sections in the collision term and Pauli blocking effects as described in Ref. [28]. With this new version of the Improved Quantum Molecular Dynamics code, we can directly use interaction parameters that have been widely applied in nuclear structure studies in heavy ion collisions and provide constraints on the density dependence of symmetry energy and neutron-proton effective mass splitting.

Based on the Skyrme interaction, one can obtain the density dependence of symmetry energy, neutron and proton effective masses, and the symmetry potential for cold nuclear matter at the mean-field level. Eq. (9) gives the density dependence of symmetry energy for cold nuclear matter. The first term comes from the kinetic energy contribution, while the second and third terms arise from two-body and three-body terms in Skyrme interactions. The last term in Eq. (9) originates from the momentum-dependent interaction term in the Skyrme interaction, and C_{sym} is determined as in Ref. [28]. Eq. (10) defines the effective mass, where _τ is the neutron or proton density for τ = n, p. Eq. (11) represents the symmetry potential, also known as the Lane potential, which gives the strength of the symmetry potential in asymmetric nuclear matter.

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3 Results and Discussion

In the following studies, we choose four Skyrme interaction parameter sets—SLy4, SkI2, SkM*, and Gs—which have similar effective mass and incompressibility (i.e., m* 0.7 ± 0.1, K_0 = 230 ± 20 MeV) and have been widely used in studies of nuclear structure and neutron stars. SLy4 and SkI2 were fitted to properties of neutron matter, neutron stars, and ground-state variables of neutron-rich heavy nuclei, with neutron effective mass less than proton effective mass (m_n* < m_p*). We select these two interactions because the slopes of symmetry energy L are very different: L is 46 MeV for SLy4 and 104 MeV for SkI2. SkM** and Gs were fitted to binding energies of finite nuclei and actinide fission barriers, with neutron effective mass greater than proton effective mass (m_n* > m_p*). L for SkM** is 46 MeV, and 93 MeV for Gs. By analyzing results from calculations using SLy4, SkI2, SkM*, and Gs and comparing them to data, we hope to understand the sensitivities of the density dependence of symmetry energy and neutron-proton effective mass splitting simultaneously and obtain their constraints. In this paper, we focus our discussion on the ^{112},^{124}Sn+^{112},^{124}Sn reactions at 50A MeV, which have been measured by the MSU/NSCL group.

[Figure 1: see original paper] shows the density dependence of symmetry energy (left panel) and the energy dependence of the Lane potential (right panel) for cold nuclear matter. At subsaturation density, the strengths of symmetry energy obtained with SLy4 (top solid lines) and SkM* (bottom solid line) are stronger than those obtained with SkI2 (top dashed lines) and Gs (bottom dashed lines). The separation of the two groups of lines (solid and dashed) is strongly correlated with the L values. Smaller L values yield higher symmetry energy at subsaturation densities, while the opposite is true in the suprasaturation density region. The right panels of Fig. 1 show the Lane potentials for the four interactions at 0.5 $_0$ (top panel) and at $_0$ (bottom panel) as a function of nucleon kinetic energy. The energy dependence of the symmetry potential for SLy4 and SkI2 is positive and increases with nucleon energy. However, those for SkM* and Gs decrease with kinetic energy and become negative above 200 MeV. When m__n* < m__p*, as in the case of SLy4 and SkI2, neutrons experience stronger repulsion than protons, and this effect increases with kinetic energy. The opposite is true for SkM* and Gs where m__n* > m__p*; protons experience stronger repulsion as kinetic energy increases.

The symmetry potential (Lane potential) also provides an accurate estimate for the difference in force between neutrons and protons in asymmetric nuclear matter and directly influences the n/p ratios of emitted nucleons. The larger the Lane potential, the larger the n/p ratio. At high energy, one can expect that the n/p ratios with m__n* < m__p* will be greater than those for m__n* > m__p* because the Lane potential for the former cases is larger than for the latter. Furthermore, we observe a crossing of the two symmetry potentials for SLy4 and SkM* at approximately 70 MeV for $= {}_0$ and at 30 MeV for $= 0.5{}_0$. Below the crossing energy, the Lane potential for m__n* < m__p* is larger than that for m__n* > m__p*, so we can expect that the n/p ratios with m__n* < m__p* will be less than those for m__n* > m__p* if their differences in the Lane potential are large enough.

Before analyzing isospin-sensitive observables, we first check the calculated results for charge distribution for ^{124}Sn+^{124}Sn with ImQMD-Sky.

[Figure 2: see original paper] shows the charge distributions for ^{124}Sn+^{124}Sn at E_{beam} = 50A MeV obtained with the four Skyrme parameter sets: SLy4, SkI2, SkM*, and Gs. It is clear that the charge distribution, which is considered an isoscalar observable, is weakly sensitive to the slope of symmetry energy and nucleon effective mass splitting among the selected parameters.

In previous studies [3,6,8,9,11], the density dependence of symmetry energy has been probed using peripheral collisions to measure isospin diffusion and isospin transport ratios as a function of rapidity. Moreover, although there are data from n/p yield ratios and flow, the constraints on symmetry energy from heavy ion collisions rely heavily on isospin diffusion data.

In this paper, we simulated collisions of ^{124}Sn+^{124}Sn, ^{124}Sn+^{112}Sn, ^{112}Sn+^{124}Sn, and ^{112}Sn+^{112}Sn reactions at a beam energy of 50 MeV per nucleon using the ImQMD-Sky code. 64,000 events were obtained for each reaction at b = 6 fm. In the left panel of Fig. 3, we plot the isospin diffusion transport ratios obtained with SLy4, SkI2, SkM*, and Gs interactions. As in previous studies [6,8], we analyze the amount of isospin diffusion by constructing a tracer from the isospin asymmetry of the emitting source, which includes all emitted nucleons (N) and fragments with v_{cm}/v_{beam} > 0.5. The shaded regions represent the isospin diffusion data obtained by constructing the isospin transport ratios with isoscaling parameter $X = \alpha$. Faster equilibration occurs for smaller L values, which correspond to stronger symmetry potentials at subsaturation density. Our results show that the R_i values for SLy4 (solid circles) and SkM* (solid squares), both with L = 46 MeV, are smaller than those for SkI2 (open circles, L = 104 MeV) and Gs (open squares, L = 93 MeV) with similar effective mass splitting. The overall effect of mass splitting on isospin diffusion is small. When m_n* < m_p*, the isospin diffusion process is accelerated at subsaturation densities due to the stronger Lane potential. R_i values increase in the order R_i(SLy4: L = 46 MeV, m_n* < m_p*) < R_i(SkM*: L = 46 MeV, m_n* > m_p*) < R_i(Gs: L = 93 MeV, m_n* > m_p*) < R_i(SkI2: L = 104 MeV, m_n* < m_p*). By comparing to the data, we find that the R_i obtained with both SLy4 and SkM* (L = 46 MeV) fall within the experimental uncertainties among the interactions we adopted. The data prefer softer symmetry potentials with lower L values.

We also compare the calculation results to R_i as a function of scaled rapidity for SLy4, SkI2, SkM*, and Gs interactions, as shown in the right panel of Fig. 3. The star symbols in the right panel are experimental data obtained in Ref. [13] for peripheral collisions. This ratio was generated using the isospin tracer X = ln[Y(^{7}Li)/Y(^{7}Be)], where Y(^{7}Li)/Y(^{7}Be) is the yield ratio of the mirror nuclei ^{7}Li and ^{7}Be [13]. For comparison, ImQMD-Sky calculations of R_i(X = δ_N,frag) are plotted as lines for b = 6 fm. The interactions with smaller L values, SLy4 and SkM* (solid lines), agree better with the data, especially in the high rapidity region.

However, ^{2} analysis suggests that the data fit the results from SkM* better.

Rizzo [26] has shown that the neutron/proton yield ratio, Y(n)/Y(p), as a function of p from central collisions is a robust observable for studying nucleon effective mass splitting. In Fig. 4, we plot the R(n/p) = Y(n)/Y(p) ratio for ^{112}Sn+^{112}Sn (left panel) and ^{124}Sn+^{124}Sn (middle panel) at b = 2 fm with angular gate 70° < _c.m. < 110°. The lines connecting the solid and open circles correspond to the m_n* < m_p* case, and the lines connecting the squares correspond to the m_n* > m_p* case. As expected, the Y(n)/Y(p) ratios are larger for the neutron-rich system ^{124}Sn+^{124}Sn in the middle panel. Consistent with Refs. [26,27], the differences in the Y(n)/Y(p) ratios between the m_n* < m_p* (circles) and m_n* > m_p* (squares) cases increase with nucleon kinetic energy. In this high-energy region, the single ratios (left and middle panels) are more sensitive to effective mass splitting than the isospin diffusion observables. This is because contributions from the momentum-dependent part of the symmetry potential play increasingly important roles in the Y(n)/Y(p) ratios as the relative momentum of nucleons increases. As shown in the right panel of Fig.

1, the Lane potentials at high kinetic energy become larger for m__n* < m__p* and cause enhanced neutron emissions. Thus, information about the momentum dependence of nucleon effective mass splitting is contained in the energy spectra of pre-equilibrium transverse emission of nucleons at the early stage of reactions.

The calculations with SLy4 interactions agree with the double ratio data [4], DR(n/p) = (Y__A(n)/Y__A(p))/(Y__B(n)/Y__B(p)), where A = ^{124}Sn+^{124}Sn and B = ^{112}Sn+^{112}Sn, from Ref. [4], which have very large uncertainties, especially for ratios of high-energy nucleons. Thus, exact constraints on effective mass splitting require re-measurements of the data with high quality. Since the effect of mass splitting should be larger at higher densities, most likely one needs data on the DR(n/p) ratios at different incident energies, which should provide the momentum dependence of n/p effective mass splitting through improved comparisons with transport model calculations, yielding more stringent constraints on collisions.

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4 Conclusion

In summary, we have used a new version of the improved quantum molecular dynamics code that can accommodate Skyrme interaction parameters to study isospin-sensitive observables such as isospin diffusion, isospin transport ratios as a function of rapidity, and single and double neutron-proton yield ratios.

We find that the neutron-proton effective mass splitting plays an important role in the n/p ratios of transversely emitted nucleons at high kinetic energy. The mass splitting affects isospin diffusion, but the effects are not strong. Our results show that the constrained L value is approximately 46 MeV. The isospin diffusion data prefer m__n* > m__p*, but this is not a strong constraint with a deep ^{2} minimum. We also show that the single and double n/p ratios from high-energy nucleons are more sensitive to mass splitting effects. The results suggest that effective nucleon masses should be further studied at different incident energies.

Finally, new neutron and proton spectral data with much smaller uncertainties than previous data at different beam energies may allow determination of the sign and momentum dependence of the mass splitting.

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Note: Figure translations are in progress. See original paper for figures.