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Isospin Effect in Intermediate Energy Heavy Ion Collisions *

LI Zhu-Xia[1,2,3;1)] ZHANG Ying-Xun[1] LI Qing-Feng[2] ZHAO Kai[1] WU Xi-Zhen[1,3]

1(China Institute of Atomic Energy, Beijing 102413, China)

2(Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100080, China)

3(Center of Theoretical Nuclear Physics, National Laboratory of Heavy Ion Accelerator of Lanzhou, Lanzhou 730000, China)

Abstract The isospin effect in central and peripheral heavy-ion collisions at intermediate energies is studied by means of improved quantum molecular dynamics and isospin dependent quantum molecular model. It is shown that the influence of the density dependence of the symmetry potential on the average N/Z ratio of the products in central and peripheral reactions exhibits different character due to the different mechanism of particle emission. We find that the average N/Z ratio of emitted nucleons in neutron-rich heavy ion collisions is sensitive to the symmetry potential for both central and peripheral cases. Furthermore, for peripheral neutron-rich heavy ion collisions, the N/Z ratio of intermediate mass fragments is also sensitive to the density dependence of the symmetry potential, which provides us with a useful probe to the symmetry potential.

Key words isospin effect, heavy ion reaction, quantum molecular dynamical model

1 Introduction

Nowadays, the nuclear equation of state (EOS) for asymmetric nuclear systems has attracted considerable attention. The empirical parabolic law for energy per nucleon reads

$$e(\rho,\delta) = e_0(\rho,0) + e_{sym}(\rho)\delta^2 + O(\delta^4), \qquad (1)$$

where $\delta = (\rho_n - \rho_p)/\rho$; 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. Fig.1 shows the e_{sym} calculated with 18 Skyrme interaction parameters by Brown[1]. From the figure one sees an extreme variation for the density dependence of the symmetry energy. The sign of the symmetry potential at $\rho \geqslant 3\rho_0$ is very uncertain and the increasing slope at low density is very different. Even at the normal density the values of e_{sym} (symmetry energy coefficient) are different for different interactions. The theoretical predicted value of the symmetry energy coefficient is about 27—38MeV by non-relativistic Hartree-Fock approach[2] and 35—40MeV by relativistic mean field approach[3,4,5]. The range of e_{sym} is reduced in Brueckner-Hartree-Fock theory (BHF)[6] and extended BHF theory[7] calculations. The knowledge of the symmetry energy term is essential in astrophysics. Therefore, to reduce the uncertainties in the symmetry energy term becomes one of the

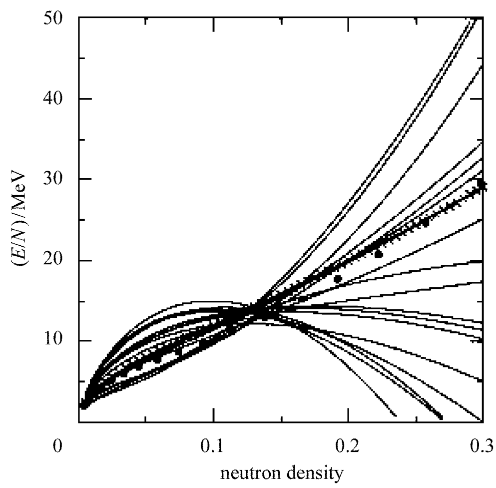

Fig.1. e_{sym} calculated with 18 Skyrme interaction parameters by Brown[1].

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1) E-mail: lizwux@iris.ciae.ac.cn

goal in nuclear physics at present. The facilities of rare isotopes beams provide opportunities to study the density dependence of the asymmetry term of nuclear equation of state in laboratories. One of the important means to extract the information of the asymmetry term in EOS is to study the isospin effect in intermediate energy heavy ion collisions (for example, Refs.[8—11]). In this talk, the isospin distribution for the products in central and peripheral heavy ion collisions at intermediate energies will be shown and the observables sensitive to the symmetry potential will be investigated. The calculations are performed by means of the isospin dependent quantum molecular dynamics (IQMD) and the improved quantum molecular dynamics (ImQMD) model. In Sec.II I will give a brief introduction on the model. The results for isospin distribution in multifragmentation precess in central collisions are given in Sec.III. In Sec.IV the results for peripheral collisions at Fermi energies will be given. Finally a summary will be given in section V.

2 Brief introduction on the model

The isospin dependent quantum molecular dynamic model and its improved version, the improved quantum molecular dynamic model[12,13] are adopted in our studies. Here we mainly introduce the ImQMD model. In the ImQMD model, the one-body phase space distribution function for N-distinguishable particles is given by:

$$f(\boldsymbol{r},\boldsymbol{p}) = \sum_i \frac{1}{(\pi\hbar)^3}\exp\left[-\frac{(\boldsymbol{r}-\boldsymbol{r}_i)^2}{2\sigma_r^2}-\frac{2\sigma_r^2}{\hbar^2}(\boldsymbol{p}-\boldsymbol{p}_i)^2\right]. \tag{2}$$

For identical fermions, the effects of the Pauli principle has to be considered. In the ImQMD model, the approximate treatment of anti-symmetrization is adopted by means of the phase space occupation constraint method[12—14] but in the IQMD model it is not included. The propagation of nucleons under the self-consistently generated mean field is governed by Hamiltonian equations of motion:

$$\dot{\boldsymbol{r}}_i = \frac{\partial H}{\partial \boldsymbol{p}_i}, \dot{\boldsymbol{p}}_i = -\frac{\partial H}{\partial \boldsymbol{r}_i}. \tag{3}$$

The Hamiltonian H consists of the kinetic energy and the effective interaction potential energy:

$$H = T + U, \tag{4}$$

$$T = \sum_i \frac{\boldsymbol{p}_i^2}{2m}. \tag{5}$$

The effective interaction potential energy includes the nuclear local interaction potential energy and the Coulomb interaction potential energy:

$$U = U_{\rm loc} + U_{\rm Coul}. \tag{6}$$

And

$$U_{\rm loc} = \int V_{\rm loc}(\rho(\boldsymbol{r}))\mathrm{d}\boldsymbol{r}, \tag{7}$$

where $V_{\rm loc}(\boldsymbol{r})$ is potential energy density.

The potential energy density functional $V_{\rm loc}(\rho(\boldsymbol{r}))$ in the ImQMD model reads

$$V_{\rm loc} = \frac{\alpha}{2}\frac{\rho^2}{\rho_0} + \frac{\beta}{\gamma+1}\frac{\rho^{\gamma+1}}{\rho_0^{\gamma}} + \frac{g_{\rm sur}}{2\rho_0}(\nabla\rho)^2 + \frac{C_{\rm s}}{2\rho_0}(\rho^2 - \kappa_{\rm s}(\nabla\rho)^2)\delta^2. \tag{8}$$

The fourth term in (8) is the symmetry energy term in which both the bulk and the surface symmetry energy are included. The Coulomb energy can be written as the sum of the direct and the exchange contribution, i.e.

$$U_{\rm Coul} = \frac{1}{2}\int \rho_{\rm p}(\boldsymbol{r})\frac{e^2}{|\boldsymbol{r}-\boldsymbol{r}'|}\rho_{\rm p}(\boldsymbol{r}')\mathrm{d}\boldsymbol{r}\mathrm{d}\boldsymbol{r}' - e^2\frac{3}{4}\left(\frac{3}{\pi}\right)^{1/3}\int \rho_{\rm p}^{4/3}\mathrm{d}\boldsymbol{R}. \tag{9}$$

In the collision term, isospin dependent nucleon-nucleon scattering cross sections are used[15] and the Pauli blocking effect is treated as the same as in Ref.[16]. For energies at about hundreds AMeV cases the IQMD model is suitable which is simpler than the ImQMD model. The details of IQMD can be found in Ref.[16]. In the following, the calculation results for reactions at energies $E \geqslant 50$ AMeV are obtained with the IQMD model and those at $E = 25$ AMeV are with the ImQMD model.

In order to study the effect of the density dependence of the symmetry potential on heavy ion collisions by means of the transport theory we verify the form of the density dependence of the symmetry potential energy. For simplicity, a form of

$$v_{\rm sym}(\rho) = \frac{C_{\rm s}}{2}u^{\gamma}\rho\delta^2 \tag{10}$$

is taken to replace the linear form in Eq.(8). Where $u = \rho/\rho_0$ and $\gamma = 0.5$ refer to the soft symmetry potential (soft-sym) case, $\gamma = 1.0$ refer to the stiff symmetry potential (stiff-sym) case and $\gamma = 2.0$ refer to super-stiff-symmetry potential. The corresponding symmetry energy coefficient is

$$a_{\rm sym} = \frac{3}{5}(2^{2/3}-1)\varepsilon_{\rm F}^0 + \frac{C_{\rm s}}{2} \simeq \frac{\varepsilon_{\rm F}^0}{3} + \frac{C_{\rm s}}{2}. \tag{11}$$

Here $\varepsilon_{\rm F}^0$ is the Fermi energy of the symmetric system at $\rho = \rho_0$ and taken to be 38MeV. The neutron/proton chemical potential reads

$$\mu_{n/p} \equiv \frac{\partial \varepsilon(u,\delta)}{\partial \rho_{n/p}} = \alpha u + \beta u^{\sigma} + \varepsilon_F^0 u^{2/3} + \left[\frac{C_s}{2}(\gamma - 1)u^{\gamma} - \frac{1}{9}\varepsilon_F^0 u^{2/3}\right]\delta^2 \pm [C_s u^{\gamma} + \frac{2}{3}\varepsilon_F^0 u^{2/3}]\delta. \quad (12)$$

The difference between neutron and proton chemical potential is

$$\mu_n - \mu_p = 4 e_{sym} \rho\delta. \quad (13)$$

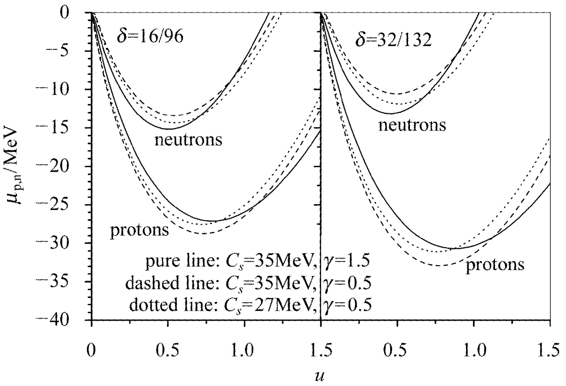

Fig.2. μ_n and μ_p as a function of density for $\delta = 16/96$ and 32/132 with $C_s = 35$MeV, $\gamma = 0.5$, 1.5, and $C_s = 27$MeV, $\gamma = 0.5$ cases, respectively.

This expression indicates that the difference between μ_n and μ_p depends on both isospin asymmetry and the density. Fig.2 shows μ_n and μ_p versus density with $C_s = 35$MeV, $\gamma = 0.5$, 1.5, and $C_s = 27$MeV, $\gamma = 0.5$ case for $^{96}Zr + ^{96}Zr$ ($\delta = 16/96$), and $^{132}Sn + ^{132}Sn$ ($\delta = 32/132$), respectively. One can see from Fig.2 that the larger the C_s is, the larger the difference between μ_n and μ_p is and accordingly the more easily neutrons are emitted than protons. Concerning the effect of the density dependence of symmetry potential, the difference between μ_n and μ_p for stiff-sym (super-stiff-sym) is larger than that for soft-sym case for $\rho > \rho_0$, and the opposite for $\rho < \rho_0$. Thus we can expect that the dynamical effect of the density dependence of the symmetry potential can be very different for the process corresponding to the densities higher than the normal density and lower than the normal density.

3 The isospin effect in central heavy ion collisions at intermediate energies

One of the most important decay mode of hot nuclear systems produced in heavy ion collisions is the multifragmentation process. It has attracted a lot of interests. The nuclear

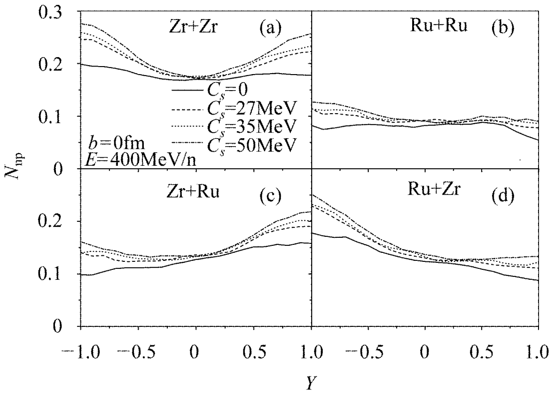

Fig.3. The rapidity distribution of differential neutron-proton counting for a) $^{96}Zr + ^{96}Zr$, b) $^{96}Ru + ^{96}Ru$, c) $^{96}Zr + ^{96}Ru$, and d) $^{96}Ru + ^{96}Zr$ at beam energy 400AMeV $b = 0$fm, calculated with different C_s, respectively.

multifragmentation is supposed to be associate with the liquid-gas phase transition and happens at densities much lower than the normal nuclear density. Theoretical studies have shown that properties of liquid-gas phase transition of asymmetric nuclear system strongly depend on the asymmetry term of EOS. One of the isospin dynamical effects in the liquid-gas phase transition is the isospin distillation effect, which leads to the N/Z ratio of the gas part much higher than the liquid part for neutron-rich systems. Therefore, the isospin distribution of the products in nuclear multifragmentation carries information of the isospin dependence part of EOS. Let us first test the influence of the strength of the symmetry potential C_s on the isospin distribution. Fig.3 shows the rapidity distribution of differential neutron-proton counting for a) $^{96}Zr + ^{96}Zr$, b) $^{96}Ru + ^{96}Ru$, c) $^{96}Zr + ^{96}Ru$, and d) $^{96}Ru + ^{96}Zr$ at beam energy 400AMeV with $C_s = 0$, 27, 35, 50MeV, respectively. The normalized differential neutron-proton counting is defined as:

$$N_{np} = \frac{\langle n \rangle - \langle p \rangle}{\langle n \rangle + \langle p \rangle}. \quad (14)$$

Where $\langle n \rangle$ and $\langle p \rangle$ is the average number of emitted neutrons and protons in an event, respectively. From the figure one can see that the dependence of N_{np} on C_s is very pronounced at the projectile and target rapidity region. The general tendency is that N_{np} increases with C_s. When the isospin dependent part of nuclear potential is switched off ($C_s = 0$), the rapidity distribution of N_{np} becomes flat for symmetric reactions Zr + Zr and Ru + Ru while for asymmetric reactions Zr + Ru and Ru + Zr, it becomes an inclined line from Zr side to Ru side, which indicates the non-equilibrium effect in reactions. The comparison of a) $^{96}Zr + ^{96}Zr$ and b) $^{96}Ru + ^{96}Ru$ indicates that the sensitivity to C_s increases as the system becomes more neutron rich. The relation between N_{np} and the average N/Z ratio of emitted nucleons is $N/Z = \frac{1 + N_{np}}{1 - N_{np}}$. Thus, from Fig.3 we can further draw that the N/Z ratio of emitted nucleons in neutron-rich reaction of $^{96}Zr + ^{96}Zr$ is very sensitive to the C_s. The larger the C_s is, the stronger the effect is. It implies that the diffusion of neutrons increases faster than that of protons as C_s increases.

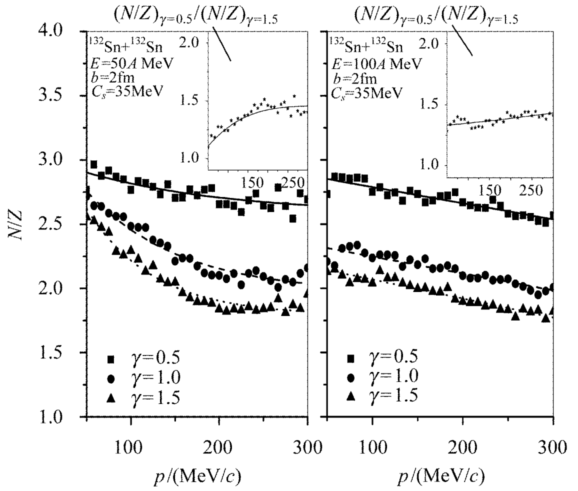

Fig.4. The N/Z ratio of emitted nucleons versus momentum for reaction of $^{132}Sn + ^{132}Sn$ a) at $50A$ MeV and b) at $100A$ MeV calculated with soft-sym, stiff-sym and super-stiff-sym, respectively. The different line types are drawn only for guiding the eyes. The ratio of the results calculated with $\gamma = 0.5$ and 1.5 is shown in their right-top plots, respectively.

The density dependence of the symmetry potential is much concerned as the most uncertainty of the symmetry energy is its density dependence. Therefore we further study the effect of the density dependence of the symmetry potential on the multifragmentation. Fig.4(a) and 4(b) show the ratio of emitted neutron numbers and proton numbers versus their momentum for reactions of $^{132}Sn + ^{132}Sn$ at $50A$MeV (Fig.4(a)) and $100A$MeV (Fig.4(b)) calculated with $\gamma = 1/2$, 1, 2 with $C_s = 35$MeV, respectively. The impact parameter $b = 2$ fm is chosen. Different symbols denote calculation results obtained with different γ and the lines are just for guiding the eyes. The case for reactions of $^{132}Sn + ^{132}Sn$ at $E = 50A$MeV has been calculated in Ref.[8]. From Fig.4 one can see that the N/Z ratio of free nucleons with soft-sym case ($\gamma = 1/2$) is much higher than those with the stiff-sym and super-stiff-sym cases, which is in agreement with our expectations. For $E = 50A$MeV case, the influence of the density dependence of the symmetry potential on the N/Z ratio of the energetic nucleons is strongly enhanced and that of low momentum nucleons is diminished. While for $100A$MeV case shown in Fig. 4(b), this effect on low momentum free nucleons and on energetic nucleons is equally strong. It tells us that there is an advantage for taking beam energy at $100A$ MeV to extract the information of the density dependence of the symmetry potential because the number of low momentum nucleons are much larger than those of energetic nucleons with resulting obtaining more accurate the N/Z ratio of low momentum nucleons.

4 The isospin effect in peripheral heavy ion collisions at Fermi energies

Recently, a large enhanced production of neutron rich rare isotopes in peripheral collisions of neutron-rich systems at Fermi energies has been observed[17]. For peripheral reactions, the temperature of system is too low to reach the onset of multifragmentation and therefore the particle emission mechanism should be different from the multifragmentation. One then ask whether the observation of the enhancement of the neutron-rich isotopes in the peripheral heavy ion collisions of neutron-rich systems relate to the density dependence of the symmetry potential? We first study the time evolution of the density distribution in peripheral reactions of $^{124}Sn + ^{86}Kr$ at $E = 25A$MeV. We find there is no obvious compression and expansion for this case, which is very different with the central collision. Thus, we expect that the influence of the density dependence of the symmetry potential on the observables should show different character compared with the central collisions. Fig.5 shows the average N/Z ratios for emitted free nucleons, light charged particles($Z \leqslant 2$), intermediate mass fragments ($2 \leqslant Z \leqslant 10$) and heavy residues ($Z \geqslant 30$) versus impact parameters. The upper panel shows the results for reaction $^{112}Sn + ^{86}Kr$ calculated with stiff-sym (left side) and soft-sym (right side) and the lower panel shows the results for $^{124}Sn + ^{86}Kr$ with stiff-sym (left side in Fig.5) and soft-sym (right side in Fig.5), respectively. One sees that the N/Z ratios for emitted free nucleons and light charged particles are higher than the total system, and the N/Z ratio of the intermediate mass fragments is close to unit for it is energetically more favorable when the system is not strongly excited. Concerning the heavy residues, their average N/Z ratio should be controlled by the N/Z ratio of emitted free nucleons, light charged particles and intermediate mass fragments. The final balance of the ratios of the neutron and proton number of the intermediate mass fragments, the light charged particles emitted and the emitted free nucleons makes the average N/Z ratio of heavy residues weakly depending on the density dependence of the symmetry potential as shown in Fig.5. The interesting thing is that the heavy residues are much neutron rich than that of intermediate mass fragments. Thus, the influence of the different forms of the density dependence of the symmetry energy should be better exhibited in the N/Z ratios of free nucleons light charged particles and intermediate mass fragments for peripheral reactions.

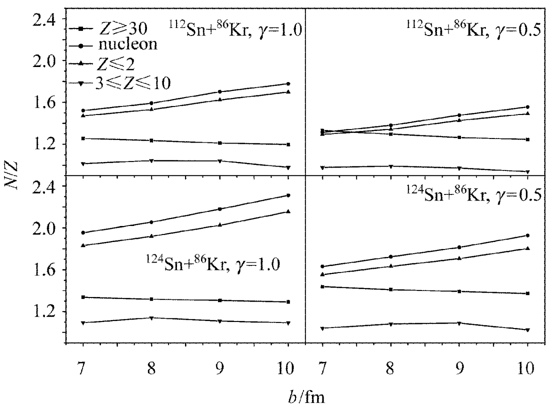

Fig.5. The average N/Z ratio of the free nucleons(circle), $Z\leqslant 2$(up triangle), $3\leqslant Z\leqslant 10$(down triangle) and the heavy residues $Z\geqslant 30$(square) versus impact parameters $b = 7-10$fm. Left column is for $\gamma = 1.0$ and right column is for $\gamma = 0.5$, upper row is for $^{112}Sn + ^{86}Kr$ and lower row for $^{124}Sn + ^{86}Kr$.

Now let us make the comparison between the results calculated with soft-sym (right side) and stiff-sym (left side). It can be seen from the figure that the N/Z ratio of emitted free nucleons calculated with stiff-sym is much higher than that with stiff-sym for both $^{124}Sn + ^{86}Kr$ and $^{112}Sn + ^{86}Kr$, but this effect is much stronger in $^{124}Sn + ^{86}Kr$. Here we see that the tendency of the influence of the density dependence of symmetry potential on the average N/Z ratio shown in the peripheral reactions is similar with the central collisions shown in previous section. While as far as the slope of N/Z ratio of free nucleons respect to impact parameters is concerned, one can see from Fig.5 that the slope of N/Z ratio of free nucleons respect to impact parameters is very different between stiff-sym case and soft-sym case. The slope for stiff-sym case is much larger than that for soft-sym one. This feature is very different from central collisions. The behavior of the average N/Z ratio of light charged particles is similar to that of the emitted free nucleons. Fig.5 also shows that the N/Z ratios of emitted nucleons, light charged particles as well as intermediate mass fragments strongly depend on the isospin asymmetry of the systems if we compare the results for $^{124}Sn + ^{86}Kr$ and $^{112}Sn + ^{86}Kr$. The N/Z ratios of the emitted nucleons and light charged particles for $^{124}Sn + ^{86}Kr$ are much larger than those for $^{112}Sn + ^{86}Kr$ with the same symmetry potential taken. Further, from the impact parameter dependence of the average N/Z ratio of nucleons one can see the neutron skin effect. As shown in the figure that the increasing slope of the N/Z ratio of emitted nucleons as a function of impact parameters for reaction of $^{124}Sn + ^{86}Kr$ is much larger than that of $^{112}Sn + ^{86}Kr$ with both stiff-and soft-symmetry potential. We can attribute this enhancement of the increasing slope for $^{124}Sn + ^{86}Kr$ to the larger neutron skin in ^{124}Sn compared with ^{112}Sn.

5 Summary

In this talk, we first briefly review the present status on the nuclear equation of asymmetry nuclear matter. Then we investigate how the symmetry potential influences the isospin distribution of the products in central and peripheral heavy ion reactions at intermediate energies and seek the sensitive observables to the symmetry potential. Our studies show that the average N/Z ratio of emitted nucleons in neutron-rich heavy ion collisions at intermediate energies is sensitive to both the density dependence and the strength of the symmetry potential. In the central collisions, the particles (fragments) are emitted in multifragmentation process. In this case, The soft-symmetry potential leads to a larger N/Z ratio of emitted nucleons than the stiff-symmetry potential does. While for peripheral collisions, the energy is too low to reach the temperature for the onset of multifragmentation. The influence of the density dependence of symmetry potential on the N/Z ratio of emitted nucleons shows different character from central collisions. Further, we find that the N/Z ratio of heavy residues in neutron-rich peripheral heavy ion reactions at intermediate energies is also sensitive to the density dependence of the symmetry potential and can be used as a useful probe.

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中能重离子碰撞中的同位旋效应*

李祝霞[1,2,3;1)] 张英逊[1] 李庆峰[2] 赵凯[1] 吴锡真[1,3]

1(中国原子能科学研究院 北京 102413)

2(中国科学院理论物理研究所 北京 100080)

3(兰州重离子加速器国家实验室原子核理论中心 兰州 730000)

摘要 利用改进的量子分子动力学模型,研究了中心和擦边重离子反应中的同位旋效应.研究结果表明,在丰中子体系的中心和擦边反应中出射核子的 N/Z 都对对称势敏感,但对称势的密度依赖对中心和擦边反应的影响显示不同的特征.

关键词 同位旋效应 重离子反应 量子分子动力学模型

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1) E-mail: lizwux@iris.ciae.ac.cn