Density effect of the neutron halo nucleus induced reactions in intermediate energy heavy ion collisions*

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Abstract Using an isospin-dependent quantum molecular dynamics (IQMD) model, we study the ^{15}C induced reactions from 30—120 MeV/nucleon systematically. Here the valence neutron of ^{15}C is assigned at both $1d5/2$ and $2s1/2$ states respectively in order to study the density effect of reaction mechanism. It is believed that the existent neutron halo structure at the $2s1/2$ state of ^{15}C will affect the light particle emission evidently. In our calculation, the different density distributions of ^{15}C at two states are calculated by relativistic mean field (RMF) model and introduced in the initiation of IQMD model, respectively. It is found that some observables such as emission fragmentation multiplicity, emission neutron/proton ratio and emission neutrons' kinetic energy spectrum are sensitive to the initial density distribution.

Key words neutron halo nucleus, valence neutron, density effect, IQMD, RMF

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1 Introduction

The investigations of the halo structure and the reaction dynamics induced by halo nuclei have made great progress experimentally and theoretically[1—9] over the last few years. The wave function of the valence nucleon in halo nucleus is expected to extend far beyond the standard nuclear size, which results in small separation energy and narrow momentum distribution. How the loosely bound structure affects the reaction dynamics has been studied by Liu Jian-Ye et al.[9]. They studied the fragmentation multiplicity and momentum dissipation by comparing reactions induced by halo nucleus and the same mass stable nucleus within IQMD framework. It is found that the neutron halo structure increases the fragmentation multiplicity and weakens the momentum dissipation in the lower beam energy region.

Whether the effects discovered above exist if we only consider the density effect of the halo nucleus by deducting the isospin. Using IQMD model, we carry out the calculation by comparing the reactions induced by the ^{15}C project on ^{12}C target with the ^{15}C's valence neutron in $1d5/2$ state and $2s1/2$ state, respectively. It is indicated that there exists one-neutron halo structure in ^{15}C with the last neutron in $2s1/2$ state[7]. Here the density distribution of both states of ^{15}C are calculated by RMF model. The results show that the density distribution of the valence neutron plays important role in the light particle emission in intermediate energy heavy ion collisions.

2 IQMD model

The QMD model is a many-body theory that can describe heavy ion collisions from intermediate energy to 2 GeV/nucleon[10]. It includes several important factors: initialization of the projectile and the

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target, nucleon propagation in the effective potential, NN collisions in a nuclear medium, the Pauli blocking effect, and the numerical test. A general review about QMD model can be found in Ref. [11].

The IQMD model is based on the QMD model which affiliates the isospin factors in mean field, two-body NN collisions and Pauli blocking[12—16]. In addition, the sampling of phase space of neutrons and protons in the initialization should be treated separately because of the large difference between neutron and proton density distributions for nuclei far from the β-stability line. In our study, in order to incorporate nuclear structure effect into the microscopic transport process, we sample the initialized nuclei from the density calculated by RMF model.

In the IQMD model, each nucleon is represented by a Gaussian wave packet with a width $\sqrt{L}$ (here $L = 2.16\ \mathrm{fm}^2$) centered around the mean position $\boldsymbol{r}_\mathrm{i}(t)$ and the mean momentum $\boldsymbol{p}_\mathrm{i}(t)$,

$$\psi_i(\boldsymbol{r},t) = \frac{1}{(2\pi L)^{\frac{3}{4}}} \exp\left[-\frac{(\boldsymbol{r}-\boldsymbol{r}_\mathrm{i}(t))^2}{4L}\right] \exp\left[-\frac{\mathrm{i}\boldsymbol{r}\cdot\boldsymbol{p}_\mathrm{i}(t)}{\hbar}\right]. \tag{1}$$

The nuclear mean field can be parameterized by

$$U(\rho,\tau_\mathrm{z}) = \alpha\left(\frac{\rho}{\rho_0}\right)+\beta\left(\frac{\rho}{\rho_0}\right)^\gamma+\frac{1}{2}(1-\tau_\mathrm{z})V_\mathrm{c}+ C_\mathrm{sym}\frac{\rho_\mathrm{n}-\rho_\mathrm{p}}{\rho_0}\tau_\mathrm{z}+U^\mathrm{Yuk}, \tag{2}$$

with $\rho_0 = 0.16\ \mathrm{fm}^{-3}$ (the normal nuclear matter density). ρ, ρ_n and ρ_p are the total, neutron and proton densities, respectively. τ_z is zth component of the isospin degree of freedom, which equals 1 or -1 for neutrons or protons, respectively. The coefficients α, β and γ are parameters for nuclear equation of state (EOS). C_sym is the symmetry energy strength due to the difference of neutron and proton. In the present work, we take $\alpha = -356$ MeV, $\beta = 303$ MeV and $\gamma = 7/6$ which corresponds to the so-called soft EOS with an incompressibility of $K = 200$ MeV and $C_\mathrm{sym} = 32$ MeV[11]. V_c is the Coulomb potential and U^Yuk is Yukawa (surface) potential.

The Pauli blocking effect in IQMD is treated separately for the neutron and the proton.

In this paper, the density distributions for initial projectile and target used in the IQMD model are taken from RMF calculation, then we get the initial coordinate of nucleons in nuclei in terms of the Monte Carlo sampling method. The momentum distribution of nucleons is generated by means of the local Fermi gas approximation:

$$P_\mathrm{F}^\mathrm{i}(\boldsymbol{r}) = \hbar[3\pi^2\rho_\mathrm{i}(\boldsymbol{r})]^{\frac{1}{3}}, \qquad (\mathrm{i}=\mathrm{n},\mathrm{p}). \tag{3}$$

The stability of the initialized nucleus is checked by the time evolution according to the evolution of the average binding energies and root-mean-square radius of the system at zero temperature.

In IQMD model, nuclear clusters are constructed by a coalescence model, in which particles with relative momentum smaller than P_0 and relative distance smaller than R_0 are considered to belong one cluster. We adopted the parameter set $P_0 = 300\ \mathrm{MeV}/c$ and $R_0 = 3.5$ fm.

3 Results and discussions

We simulated the reactions of $^{15}C + {}^{12}C$ with two kinds of ^{15}C density distributions at several beam energies E/nucleon = 30 MeV, 60 MeV, 90 MeV, 120 MeV with impact parameter from 0 fm to 8 fm. In this paper, we extract the following physics results at 200 fm/c as freeze-out time.

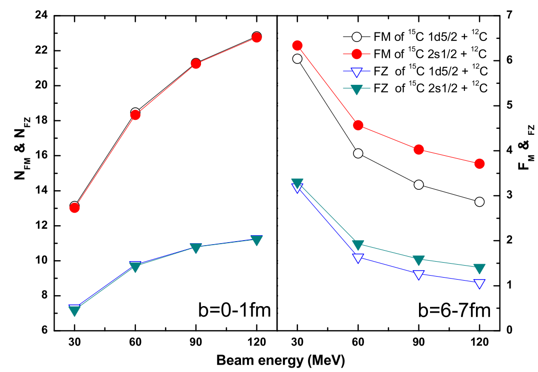

Fig. 1. The N_FM and N_FZ of $^{15}C_{1d5/2} + {}^{12}C$ and $^{15}C_{2s1/2} + {}^{12}C$ at $t = 200$ fm/c for different impact parameters as a function of beam energy.

The fragmentation multiplicities N_FM and N_FZ of $^{15}C_{1d5/2} + {}^{12}C$ and $^{15}C_{2s1/2} + {}^{12}C$ are shown in Fig. 1, in which N_FM is mass multiplicity including all the products with mass number A from 1 to 14, N_FZ is charge multiplicity including all the products with charge number Z from 1 to 5 and $^{15}C_{1d5/2}$ and $^{15}C_{2s1/2}$ represent the initialized ^{15}C projectile with different density distributions distinguished between the valence neutron of ^{15}C in $1d5/2$ state and $2s1/2$ state, respectively. The right panel of Fig. 1 shows that $^{15}C_{2s1/2}$ induced collisions simultaneously increases N_FM and N_FZ in peripheral collisions compared to $^{15}C_{1d5/2}$ induced collisions. The effect of loose neutron halo structure on fragmentation multiplicity is consistent with the conclusions in Ref. [9], which shows the loose neutron halo structure of ^{19}B increases the fragmentation multiplicity compared to that of ^{19}F induced reactions at impact parameter of 1.0 fm. Fig. 1 also show the energy dependence for fragmentation multiplicity of the two colliding system in central collisions and peripheral collisions. In central collisions the fragmentation multiplicity increases with the beam energy while the contrary results are observed in peripheral collisions. It is indicated that the larger fragmentation multiplicity at large impact parameter is due to the more weakly bounded valence neutron of $^{15}C_{2s1/2}$ than $^{15}C_{1d5/2}$.

Figure 2 shows the n/p ratio of the two colliding systems at different beam energies. The n/p ratio of $^{15}C_{2s1/2}$ + ^{12}C reactions is larger than the corresponding results of $^{15}C_{1d5/2}$ + ^{12}C at different calculated beam energies in peripheral collisions and the density effect of n/p ratio seems to disappear in central collision. Thus n/p ratio is sensitive to the neutron halo structure of ^{15}C in peripheral collisions.

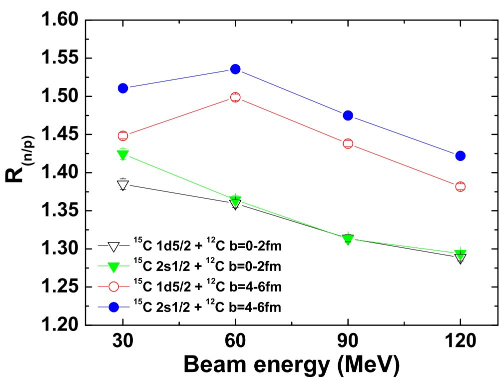

Fig. 2. The $R_{\rm n/p}$ of $^{15}C_{1d5/2}$ + ^{12}C and $^{15}C_{2s1/2}$ + ^{12}C at t = 200 fm/c for different impact parameters as a function of beam energy.

We also extract the two colliding systems' kinetic energy spectrum ratio of emission neutrons. Fig. 3 shows kinetic energy spectrum ratio of emission neutrons at several beam energies with different impact parameters. It is interesting to note that the neutrons emit more for $^{15}C_{2s1/2}$ + ^{12}C reactions than $^{15}C_{1d5/2}$ + ^{12}C reactions at large impact parameter in range of selected kinetic energies.

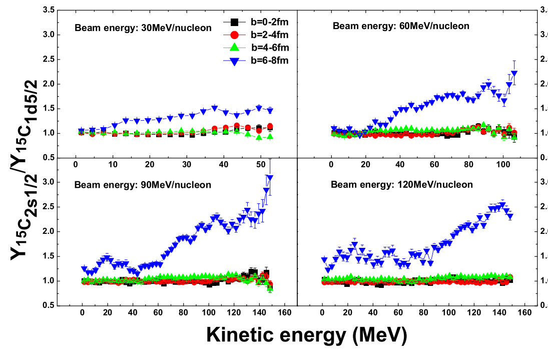

Fig. 3. The emission neutrons' kinetic spectrum ratio of $^{15}C_{1d5/2}$ + ^{12}C and $^{15}C_{2s1/2}$ + ^{12}C at t = 200 fm/c for different impact parameters as a function of kinetic energy.

4 Summary

We applied IQMD model to investigate the bulk property and neutrons, protons emission of different initialized ^{15}C projectiles on ^{12}C target reactions at different beam energies. It is found that $^{15}C_{2s1/2}$ induced reactions on ^{12}C gives rise to larger fragmentation multiplicity, n/p ratio than the case of $^{15}C_{1d5/2}$ in peripheral collisions. The kinetic spectrum ratio also shows the extended valence neutron's density distribution of $^{15}C_{2s1/2}$ lead to more neutron emission in peripheral collisions at different beam energies. Therefore, we can conclude that the fragmentation multiplicity, n/p ratio and neutron kinetic spectrum in peripheral collisions are sensitive observables of valence neutron's density distribution in intermediate energy heavy ion collisions.

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