One- and Two-Neutron Transfer Reactions in ^{11}Be+^{208}Pb and Mechanism of Lowering Fusion Barrier

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We study one- and two-neutron transfer reactions in $^{11}Be+^{208}Pb$ by using the quantum molecular dynamics model. We find that lowering about 1−2 MeV of the potential barrier of ^{208}Pb for fusion is gained when two neutrons separated from ^{11}Be enter into ^{208}Pb. Whereas no significant change of potential barrier is found when only the halo neutron separated from ^{11}Be enters into ^{208}Pb. The dynamical interplay between suppression and enhancement effects on the fusion probability in reaction $^{11}Be+^{208}Pb$ stemming from the easy separation of halo neutron and the long extending of neutron distribution is discussed.

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Recently, the research for fusion induced by unstable nucleus ^{11}Be at near and above coulomb barrier has attracted considerable attention[1−3]. Some extensive theoretical and experimental works have been done in fusion reaction caused by these halo nucleus. However, the results are very different. Some concluded that the extended neutron matter distribution led to strong interaction with target and resulted in an enhancement of fusion cross section,[4] while the others obtained the contrary results, i.e. the small separation energy of a weakly bound nuclear system made the system breaking up more easily and so the fusion cross section was suppressed.[5−7,3] The contradictory results imply that there may exist a complicated dynamical interplay between these two effects. In this letter, we make a dynamical study on the one- and two-neutron transfer reactions in order to clarify how the enhancement and suppression effect plays a role dynamically. The quantum molecular dynamics (QMD) model as a microscopic dynamical one has been applied to the intermediate energy heavy ion reactions rather successfully.[8] This model was also applied for studying the low energy reactions including the fusion process and transfer reactions successfully.[9] In order to apply QMD model to a neutron-rich system, a suitable initialization and the isospin dependence of both the mean field and the cross section of two body scattering should be carefully taken into account. Then we will present the results of dynamical study on the one- and two-neutron transfer reactions in ^{11}Be + ^{208}Pb through breakup of ^{11}Be into 1n+^{10}Be and 2n+ ^{9}Be. The study of the time evolution of the potential barrier can provide us with a deep insight into the mechanism of the enhancement or suppression of the fusion process. Therefore, we pay a great deal of attention to the investigation of the dynamical effects on the potential barrier for the different incident energies and impact parameters. Finally, a brief summary will be given.

In our QMD calculations, the effective nucleon-nucleon interaction is taken as the same form as Ref. 10. Concerning the collision part, we notice that the experimental data show that the two-body scattering cross section for neutron-proton is about three times larger than that of neutron(proton)-neutron(proton) at the low energy case.[11] One can expect this isospin dependent effect may have an important influence on the reactions induced by the neutron-rich projectile, and therefore we have made modification for the collision part of QMD model by introducing the isospin dependence of the two-body scattering cross section.

In the present work, the initial ^{208}Pb nuclei are prepared with the same procedures given in Ref. 10. For ^{11}Be, it is well known that it has one neutron halo and its neutron density distribution extends to a long radius. Therefore, the space distribution of nucleons in ^{11}Be is sampled at present according to the particle distribution of the Hartree-Fork theory given in Ref. 12. The special feature of the density distribution of ^{11}Be is that the neutron distribution has a longer tail than that of protons. Thus the Fermi momentum based on the local density approximation is very different for neutron and proton because of their different density distribution. The momentum distribution is then sampled by the neutron and proton local Fermi momentum, respectively.

Furthermore, for ^{11}Be, except for those requirements adopted in the selection of ^{208}Pb, it is also required that the initial ^{11}Be nuclei should have a correct one-neutron halo structure. Namely, not only their static properties of ground state such as the binding energy and the root mean square radius can be reproduced well, but also each of them possesses certain probability that one of the neutrons has large trajectory radius. To do this we let the pre-selected ^{11}Be nuclei self-evolve until 800 fm/c and then make fur-

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ther selection for the correct halo structure. From the 30000 pre-prepared ^{11}Be system, we elaborately select 10 ^{11}Be nuclei. We have checked the neutron and proton density distribution of these selected ^{11}Be nuclei, and find that the HF results can be reproduced well. As an example, in Fig. 1 we show the trajectories of all nucleons in one ^{11}Be during the period of 800 fm/c, and the halo structure can be seen clearly in the figure. We will find the halo structure affects the fusion and breakup process greatly.

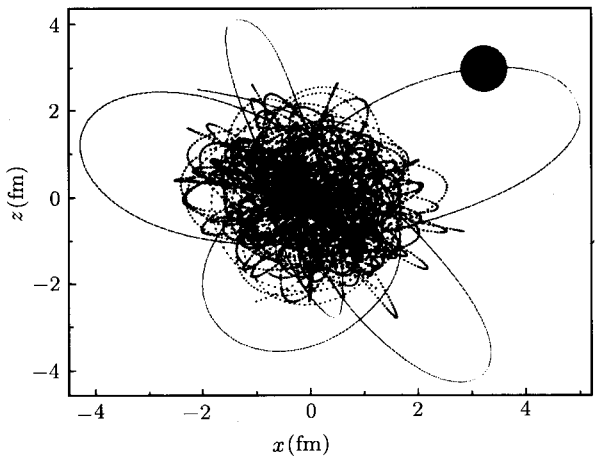

Fig. 1. Trajectories of all the nucleons of ^{11}Be during the period of 800 fm/c. The curve with big solid-circle denotes the trajectory of the halo neutron.

By rotating these prepared ^{11}Be and ^{208}Pb around their center of mass by an Euler angle chosen randomly, we create 100 bombarding events for each reaction energy E and impact parameter b. Through counting the number of the one-neutron and two-neutron transfer events, we obtain the probability of one-neutron and two-neutron transfer reaction $g_{\rm one}(E,b)$ and $g_{\rm two}(E,b)$ for each E and b, respectively. Then the cross section is calculated by using the expression

$$\sigma_i = 2\pi \int_0^{b_{\max}} b g_i(E,b) \mathrm{d}\, b = 2\pi \sum b g_i(E,b) \Delta b, \quad (1)$$

where the subscript i means one- or two-neutron transfer. The distance from projectile to target at initial time is taken to be $l \geq 20$ fm.

We study the time evolution of the potential of ^{208}Pb during the process that ^{11}Be breaks up into two neutrons plus ^{9}Be or one neutron plus ^{10}Be, then two or one neutrons are captured by the target and the rest of ^{11}Be still flies further.

In the QMD model, the mean potential produced by target reads

$$V(\boldsymbol{r}) = \int \rho_{\rm targ}(\boldsymbol{r}') V(\boldsymbol{r} - \boldsymbol{r}') \mathrm{d}\, \boldsymbol{r}'. \quad (2)$$

It is the summation of the contributions from the Skyrme interaction, symmetry energy, Yukawa and Coulomb interaction.

In the three-dimensional Fig. 2, we show the time and radius evolution of the potential of ^{208}Pb for the process that two neutrons are captured and ^{9}Be, the rest of ^{11}Be still flies further. From Fig. 2 one can find that at the initial time the static potential barrier height of ^{208}Pb is about 10 MeV and its radius $r_{\rm b}$ is about 11.2 fm, and after two neutrons of ^{11}Be entering into ^{208}Pb the barrier is lowered about 1−2 MeV. It is different that only one neutron is captured by ^{208}Pb as Fig. 3 shows. In this case, one can find that there is no significant lowering of the barrier height of ^{208}Pb. From the above investigation of the potential barrier change of ^{208}Pb for both after one- and two-neutron entering into ^{208}Pb, we may conclude that two neutron capture (or one neutron capture is followed by another neutron capture) is necessary for gaining significant effect for lowering the barrier. This result has an important dynamical influence on the fusion probability and will be discussed further.

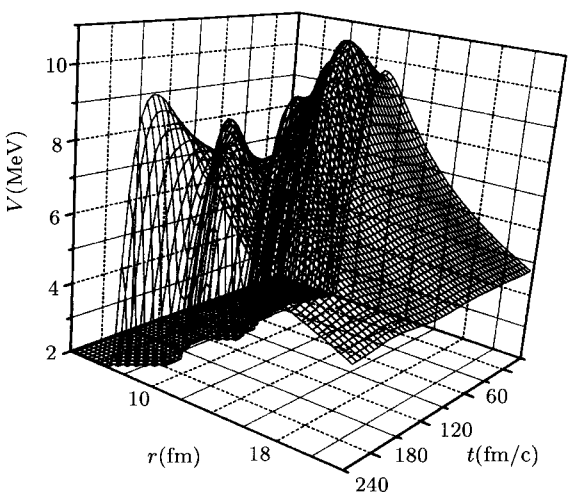

Fig. 2. Time and radius evolution of the potential of ^{208}Pb for the two-neutron transfer reaction in ^{11}Be+^{208}Pb at E=10 MeV/u, b=10 fm.

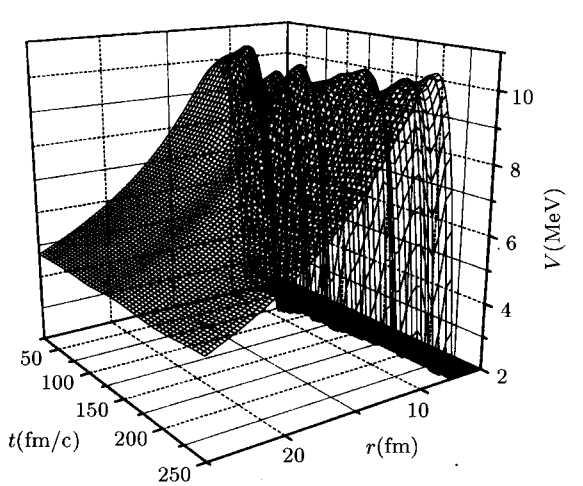

Fig. 3. Time and radius evolution of the potential of ^{208}Pb for the one-neutron transfer reaction in ^{11}Be+^{208}Pb at $E = 10$ MeV/u, $b = 11.4$ fm.

Figure 4 shows the excitation fuctions for the one and two-neutron transfer reaction in the peripherial collisions of ^{11}Be+^{208}Pb. Here the impact parameter ranges from 9 to 18 fm for the one-neutron transfer reaction and 9 to 13 fm for the two-neutron transfer reaction. Because we find that the one- and two-neutron transfer reactions mainly occur at peripheral reaction when E is above the barrier. In Fig. 4, the circles denote the one-neutron transfer and the squares denote the two-neutron transfer. It is shown that the cross section for the one-neutron transfer is more than one order of magnitude larger than that of the two-neutron transfer for the lower incident energy up to 3.5 MeV, and with the increasing energy the cross section for the two-neutron transfer increases and the cross section for the one-neutron transfer decreases slowly and consequently the ratio between them decreases more than one half. The energy dependence of one- and two-neutron transfer cross sections result from the special properties of ^{11}Be. From the calculation in Ref. 13 that the one-neutron separation energy of ^{11}Be is about 0.5 MeV and two neutron separation energy is about 7 MeV, one can expect that the separation of one neutron from ^{11}Be is much easier than that of two neutrons. Nevertheless, this effect resulting from the difference of separation energy should be weaker as the reaction energy increases. In addition, the strong interaction between the halo neutron and the target makes the halo neutron very easy to be captured by the target. All these effects result in the different behavior of the energy dependence of the one- and two-neutron transfer cross sections.

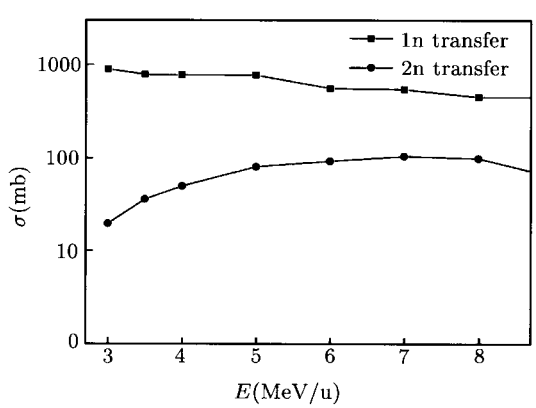

Fig. 4. Excitation functions of the one-neutron and two-neutron transfers in the peripheral collisions of ^{11}Be + ^{208}Pb. The squared line denotes the one-neutron transfer reactions and the circled line denotes the two-neutron transfer reaction. The impact range is given in the text.

In summary, we have studied the one- and two-neutron transfer reactions in ^{11}Be+^{208}Pb by applying QMD model. This is the first time to study the halo nuclei induced reactions by applying this model. We find that, for the reaction ^{11}Be+^{208}Pb, the potential barrier of ^{208}Pb is lowered significantly after two neutrons separated from ^{11}Be entering into ^{208}Pb but without significant change when only one neutron enters into ^{208}Pb. It means that at lease two neutrons separated from ^{11}Be entering into target (or one halo neutron followed by the second neutron entering) is necessary in order to have significant enhancement of fusion probability based on the view of the change of the fusion barrier. The experimental result that there is no significant difference for the measured fusion excitation function of both ^{11}Be and ^{10}Be on ^{208}Pb around the Coulomb barrier[14] seems to support this conclusion. Our results also show an obvious different behavior of the energy dependence of the one- and two-neutron transfer cross sections. When energy is much lower than the barrier, the cross section of two-neutron transfer is much smaller than that of the one neutron transfer reaction, and when the energy increases the cross section of two-neutron transfer increases fast and that of the one neutron transfer reduces. This implies that the effect of the suppression and enhancement on the fusion in reaction ^{11}Be+^{208}Pb is energy dependent, for the one far lower than barrier energy the suppression effect becomes much faver than that of enhancement because of the very low one neutron separation energy, and the situation changes as the energy increases because the effect of the enhancement due to the effect of lowering the fusion barrier may become important following the increase of the probability of two neutrons entering into target. Based on this point of view, the study of the fusion mechanism for ^{11}Be + ^{208}Pb is in progress.

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