FEATURES OF NUCLEAR REACTIONS INDUCED BY DRIPLINE LIGHT NUCLEI AT NEAR-BARRIER ENERGIES *

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The mechanisms of nuclear reactions with light loosely bound projectiles (such as ^{11}Be, ^{8}B, ^{11}Li *etc.*) at the near-barrier incident energy (up to 10 MeV/nucleon) were studied. The peculiarities of low energy nuclear dynamics of proton-rich ions were described in comparison with the neutron-rich and ordinary nuclei.

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1. Introduction

A significant progress in the investigations of dripline nuclei, a great number of experimental data [1,2] and achievements in theoretical approaches (especially in three-body states description [3]) have not led up to now to exhaustive and final understanding of the structure of light nuclei far from the stability line and the mechanisms of nuclear reactions induced by such ions. Whereas a neutron halo is affirmed with confidence to exist [1] an active study of proton-rich nuclei [4-7] has not given a clear and unambiguous answer for the question about an existence of proton halo and about its properties. In our opinion an observation of supposed proton halo is too difficult mostly due to dynamics of collision of proton-rich projectile with the target (the Coulomb proton-target interaction would distort the tentative proton halo in the entrance channel as well as the Coulomb forces in the exit channel would influence the proton dynamics). Therefore it is very important to distinguish the role of reaction dynamics (proton — target and proton — projectile core interactions), the role of naturally small binding energy and of concrete behaviour of loosely bound proton wave function, especially the

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manifestation of its large spatial extension. Having this in mind, we consider two type of targets to be appropriate for the study of reactions induced by proton-rich ions and for the search of the proton halo: very heavy targets (to analyse the "largest" contribution of interaction dynamics) and very light targets (the neutron target would be the best because of the absence of the Coulomb distortion of the supposed proton halo).

Low energy nuclear reactions seem to be very fruitful to clarify many features of weakly bound system dynamics. At such energy the motion of a loosely bound proton influences strongly the reactions dynamics in many channels, the explicit study of which could give more information, than cumulative fragment momentum distributions in higher energy reactions. Already at low energy the supposed long tail of the loosely bound nucleon wave function would appear without "admixture" of its internal part. The study of low energy processes could be useful for the spectroscopy of short-lived nuclei. Sub-barrier energy cosmological reactions of nucleosynthesis also demonstrate the important role of dripline nuclei (in particular, ^{8}B).

An appearance of a classical regularities even in low energy nuclear dynamics and the difficulties of a sufficiently complete quantum description justify the interest in the application of classical and semiclassical approaches.

In this work the model of "few-body molecular dynamics" (FMD) [8-10] was developed for comparative analysis of nuclear reactions induced by proton-rich ^{8}B (proton separation energy $\sim$ 137 keV), neutron-rich ^{11}Be (neutron separation energy $\sim$ 500 keV) and ordinary ^{10}B (proton separation energy $\sim$ 6.586 MeV) projectiles at low incident energies ($E/A \leq 10$ MeV/nucleon). Within the framework of FMD ^{11}Be, ^{8}B are supposed to have a cluster structure, in other words they consist of the core and the loosely bound nucleon (^{11}Be=^{10}Be+n, ^{8}B=^{7}Be+p respectively). Indeed, the neutron-rich projectile core structure was shown [11] to be very weakly influenced by external loosely bound neutron.

2. The differences of reaction dynamics with participation of proton-rich and neutron-rich nuclei

The main features of angular and energy distributions of nucleons and heavy charged cores in a projectile break-up channel were analysed. At near-barrier energy neutron and core energy spectra in the ^{11}Be+^{48}Ti reaction have maxima at the energy smaller than the energy of the beam, with increasing of the beam energy these maxima shift to larger energy.

At very low energy ($E/A \leq 2$ MeV/nucleon) the ^{10}Be angular distribution has one maximum at the angles near the Coulomb rainbow angle. With increasing of beam energy ($E/A \sim 3$ MeV/nucleon) at the smaller angles the second "nuclear" maximum arises. At larger energy two maxima shift one towards the other, combine and the angular distribution becomes less expressive (as the neutron angular distribution which has a peak at forward angles at the energy > 3 MeV/nucleon).

We must note that in low energy nuclear reactions induced by proton-rich nuclei the nuclear dissociation plays considerable role (in contrast to neutron-rich ions, their break-up is determined mostly by the Coulomb mechanism). For example, calculations without taking into account the core-target and proton-target nuclear interactions lead to the decrease of the $^{8}\mathrm{B}+^{12}\mathrm{C}\rightarrow^{7}\mathrm{Be}+p+^{12}\mathrm{C}$ reaction cross section more than twice. So it is very important to take into account "interference" of nuclear and Coulomb forces to describe the reactions with neutron-deficient projectiles.

The role of the different interactions (core-nucleon, core-target, and nucleon-target) responsible for reaction mechanism were studied. In particular, proton yield at large angles ($\theta_p \geq 30^o$ for the ^{12}C target) was demonstrated to be caused by projectile-target nuclear interaction (not only nucleon-target as for neutron-rich nuclei [9,10]). The proton angular distribution in the loosely bound nucleus break-up reaction ($^{8}\mathrm{B}+^{12}\mathrm{C}\rightarrow{}^{7}\mathrm{Be}+p+^{12}\mathrm{C}$) was found to have a maximum at smaller angles in contrast to the break-up of a normally bound projectile.

Different fragment-fragment correlations in the loosely bound projectile break-up reactions were also analysed.

Excitation functions for the different reaction channels — complete and incomplete fusion (the capture of the projectile core only), nucleon transfer, projectile break-up — were calculated. At the incident energy $E/A < 3$ MeV/nucleon an inclusive yield of the ^{10}Be (for example, in the $^{11}\mathrm{Be}+^{48}\mathrm{Ti}$ reaction) is significantly larger than the neutron yield [10]. At low energies dissipative deceleration and the Coulomb repulsion of the neutron-rich projectile core lead to shaking-off the loosely bound neutron with subsequent absorption of it by a target, and the break-up cross section is much smaller than the stripping one. At the energies higher than 3 MeV/nucleon neutron transfer probability slowly decreases whereas break-up cross section becomes more and more important. Fusion cross section increases very fast at above-barrier energies but then saturates and slowly goes down.

At the energy $E/A \leq 10$ MeV/nucleon the Coulomb repulsion of the proton-rich projectile does not lead to shaking-off the weakly bound proton and the break-up cross section as well as proton transfer cross section are considerably small (for example, in the $^{8}\mathrm{B}+^{28}\mathrm{Si}$ reaction). The proton inclusive yield turns out to be much larger than the projectile core (*i.e.* the ^{7}Be) inclusive yield. So the incomplete fusion cross section (capture of the ^{7}Be nuclei by the target) was found to be large in comparison with the ordinary (dashed lines in Fig. 1) and neutron-rich nuclei.

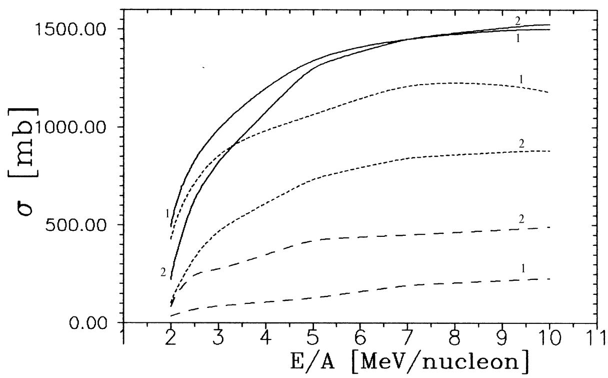

Fig. 1. Total reaction cross sections (solid lines), complete fusion (dotted lines) and incomplete fusion (dashed lines) cross sections for the $^{10}B+^{28}Si$ reaction (in this case they are noted by number 1) in comparison with the same ones for the $^{8}B+^{28}Si$ reaction (they are noted by number 2).

3. The role of loosely bound neutrons and protons in fusion process

It was noted [12] that the total reaction cross section of proton-halo candidate ^{8}B shows significant enhancement at incident energy $\sim$ 40 MeV/nucleon. FMD also predicts at such energy the total cross section of, for example, $^{8}B+^{28}Si$ reaction to exceed the cross section of $^{10}B+^{28}Si$ reaction. However, at near-barrier energy the situation is different. Fig. 1 shows the fusion and the total reaction cross sections of the proton-rich ^{8}B in comparison with ordinary ^{10}B nucleus. We can see the total cross section of the $^{8}B+^{28}Si$ reaction diminishes rapidly with decreasing of incident energy in contrast to the total cross section of the $^{10}B+^{28}Si$ reaction. It is the complete fusion contribution which yields such a reduction. Excess of protons in ^{8}B in comparison with an ordinary nucleus (such as ^{10}B) causes the decreasing of complete fusion cross section. Cluster structure of the proton-rich ion, in other words the presence of loosely bound proton, dynamically increases the height and the extension of the Coulomb barrier in the ^{8}B - target interaction potential reducing the fusion cross section.

The presence of additional neutron degrees of freedom for neutron-rich nuclei leads to features in fusion dynamics. In particular, investigation of the shape of excitation functions in fusion channel during the interaction of light nuclei has demonstrated significant influence of the nuclear structure and the neutron number on the magnitude and on the shape of fusion barriers [13].

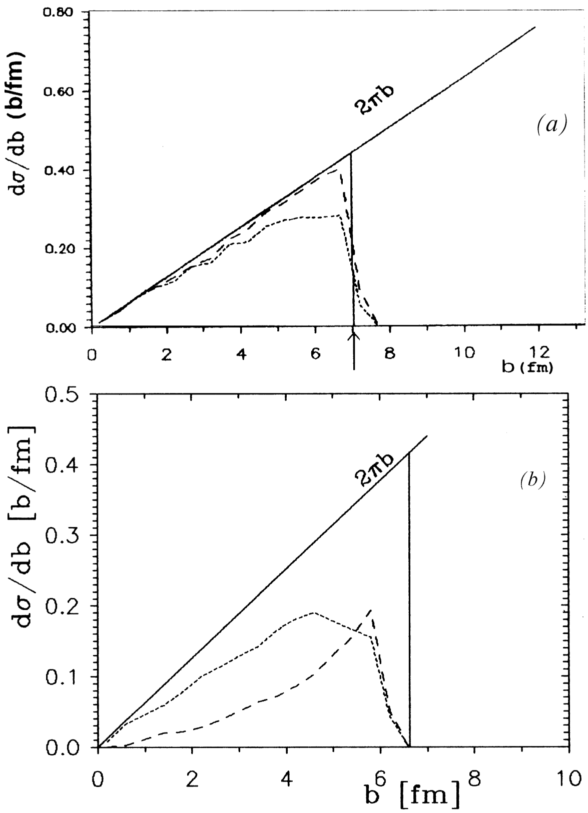

Fig. 2. Contributions of the different impact parameters into the classical fusion cross section (vertical solid line), complete fusion cross section (dotted line) and incomplete fusion cross section in the ^{11}Be+^{48}Ti (a) and in the ^{8}B+^{48}Ti (b) reactions at $E/A = 5$ MeV/nucleon. Dashed line in (a) shows the sum of complete and incomplete fusion cross sections. Dashed line in (b) means only incomplete fusion contribution.

To make clear the role of loosely bound neutron in the fusion analysis of the ^{10}Be nucleus fusion with the ^{48}Ti target was performed within the framework of two-body classical model with friction without taking into account of projectile cluster structure (core+neutron) and within the framework of FMD at $E = 5$ MeV/nucleon. It was shown (Fig. 2a) that the neutron-core weak binding does not lead to the significant change of fusion cross section absolute value (it remains $\sim$ 1550 mb). But the presence of loosely bound neutron induces the features:

(i) the incomplete fusion mechanism (where the neutron does not fuse with the target) contributes considerably into the fusion process;

(ii) an additional neutron degree of freedom causes "washing-out" of the boundary for region of impact parameters which lead to fusion channel (in contrast to the sharp boundary in the two-body model), that means the spin of formed compound nucleus to increase.

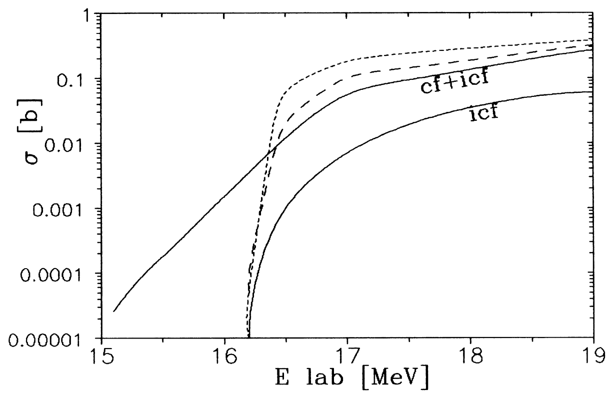

Fig. 3. The complete fusion cross section for the $^{11}Be+^{48}Ti$ reaction depending on the projectile energy obtained by the classical calculations (dotted line), as solution of Langevin equation (dashed line) and by FMD calculations (the mark "icf" corresponds to the contribution of incomplete fusion, *i.e.* capture of only the ^{10}Be, whereas "cf+icf" means the sum of complete and incomplete fusion cross sections).

It is clear (Fig. 2b) that loosely bound proton in neutron-deficient nuclei does not promote the fusion with the target. But one can note the incomplete fusion (capture of ^{7}Be nucleus) to be much larger in comparison with neutron-rich ^{11}Be.

Cluster structure of neutron-rich nuclei was found to give a chance for sub-barrier fusion. Fig. 3 demonstrates the sub-barrier fusion cross section at $E_{\rm lab} < V_{\rm bar} \approx 16.2$ MeV for the $^{11}Be+^{48}Ti$ reaction which is to be connected exactly and only (as provided by FMD calculations) with the relative motion of projectile core (^{10}Be) and the neutron. This motion makes possible the core to have periodically a local energy slightly more than the beam energy (whereas the energy of the projectile center of mass remains the same), so even at sub-barrier energy the core can overcome the Coulomb barrier and fuse with the target attracting the loosely bound neutron.

Note, at last, that in our opinion impulse approximation (IA) could be useful for the description of nuclear reactions induced by weakly bound nuclei. Even at low incident energy ($E_{\rm proj} \leq 10$ MeV) IA is valid ($E_{\rm proj} \gg \varepsilon$, where ε is the nucleon separation energy). However the utilization of IA becomes more difficult due to the presence at least of three charged particles in the proton-rich projectile break-up exit channel (target, proton, projectile core). To avoid this problem the author have proposed [14] an idea of the modification of IA by means of classical and semiclassical approaches.

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