STUDY OF SUB-BARRIER AND NEAR- BARRIER FUSION OF HALO NUCLEI

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Coupled channel calculations were performed to investigate the near-barrier and sub-barrier fusion cross section of light unstable nuclei and their associate stable isotopes. A microscopic optical potential was used to generate the entrance channel potential. A rather satisfactory description of the experimental data was obtained under the condition that the optical potential is reduced for the weakly bound systems. The analysis points out some complementary measurements which are necessary to obtain a better understanding of the sub-barrier fusion process involving light weakly bound systems.

1 Introduction

Several experimental and theoretical studies concerning the fusion of two asymmetric nuclei under and near the coulomb barrier were performed in the past[1]. Most of the times the results were interpreted adequately well under the context of coupled channel calculations [2]. With the advent of radioactive beam facilities, the interest on such studies was renewed, aiming to reveal the structure and behaviour of halo nuclei [3]. Such nuclei present specific features like an extended neutron tail, low-lying dipole modes and very low energy thresholds for breakup. Fusion, as other reaction processes should be appreciably affected by such features. In this letter we attempt to describe into the same framework, near-barrier and sub-barrier fusion for both stable and halo nuclei.

The first measurements with halo nuclei were visualized through the systems ^{11}Be+^{209}Bi [4], ^{6}He+^{209}Bi [5] and ^{6}He+^{238}U [6].

The data are presented in Fig.1 together with the data of the associated stable isotopes ^{9}Be+^{209}Bi [4], ^{4}He+^{209}Bi [7] and ^{4}He+^{238}U [6,8]. Cross sections are presented as a function of the energy divided by the coulomb barrier, V_b. In the present case V_b's were extracted via the relations of Christensen and Winther and are shown in Table 1.

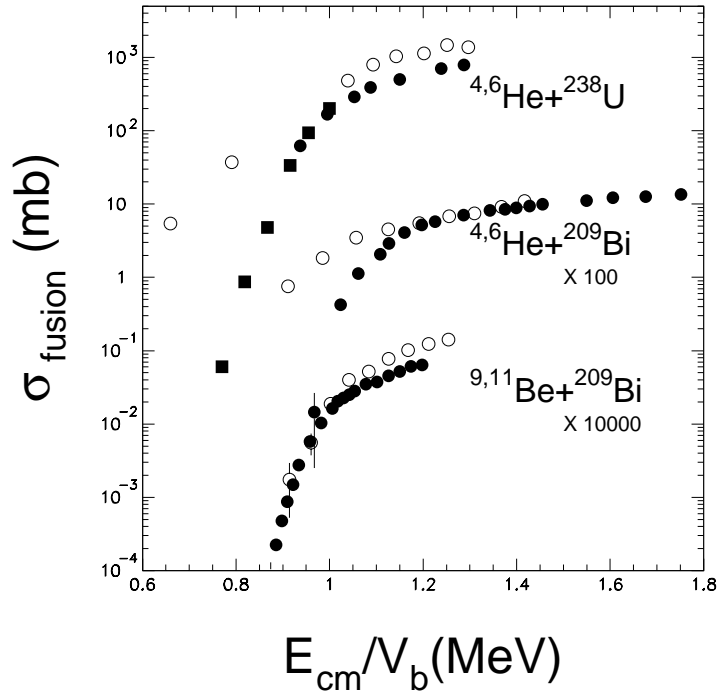The presentation of all the data in Fig.1 facilitates the extraction of the

Figure 1: Fusion measurements for the halo systems and their associated stable isotopes

following conclusions. For energies higher than the coulomb barrier the cross sections for the fusion of ^{9,11}Be and ^{4,6}He on ^{209}Bi and ^{238}U targets present the same behaviour. That is the cross sections with halo projectiles are enhanced over the cross sections with the stable ones. On the other hand, no apparent enhancement is seen for the fusion of the ^{6}He over that of ^{4}He on ^{209}Bi targets. For lower energies than the coulomb barrier, the fusion cross section for the halo nucleus ^{6}He on ^{238}U and ^{209}Bi targets is enhanced over that of ^{4}He, no such enhancement is observed for the fusion of the ^{11}Be on ^{209}Bi over that of ^{9}Be .

Into this paper we will perform a consistent analysis of all the above sys-

Table 1: Coulomb heights according to A. Christensen and Winther B. The BDM3Y1 potential and C. The BDM3Y1 potential reduced by 40%.

	V_b(MeV)		
system	A	B	C
^{4}He+^{238}U	22.61	22.48±0.2	
^{4}He+^{209}Bi	20.90	21.34±0.2	
^{9}Be+^{209}Bi	39.95	38.44±0.2	39.92±0.2
^{6}He+^{238}U	22.14	19.51±0.2	20.37±0.2
^{6}He+^{209}Bi	20.47	18.18±0.2	19.10 ±0.2
^{11}Be+^{209}Bi	39.46	35.68±0.2	37.40±0.2

tems and we will try to unreveal new aspects in physics that may emerge from these measurements.

2 The analysis

It is known that, in general, coupled channel calculations can reproduce qualitatively and several times quantitatively the fusion results. For the stable nuclei the main ingredients of the calculations, performed with the code ECIS[9] are the entrance channel potential and the structure of the colliding nuclei. The real potential is calculated within the double folding model [11] by using the BDM3Y1 interaction [22]. This interaction was found to describe rather well elastic scattering for both stable and unstable nuclei [10,23]. The imaginary potential simulated the incoming wave boundary condition. The densities involved in the real double folded potential for the stable isotopes were obtained from electron scattering data by adopting standard procedures [11]. For the radioactive nuclei shell model densities [12], and HF densities [13] were used for ^{6}He and ^{11}Be correspondingly.

The calculation for the system ^{4}He+^{238}U has been performed within the rotational model. Couplings to the first excited states of ^{238}U were considered with deformations extracted from B(E2)'s reported previously [14]. In addition to our previous calculation [6] we have used now not only multipolarities with λ=2 but also with λ=4. The calculation for the system ^{4}He+^{209}Bi includes coupling to the two excited levels of ^{209}Bi, E=0.896 MeV(λ=2) and E=1.608 MeV (λ=3) with deformations reported in the compilation [16]. Finally for the system ^{9}Be+^{209}Bi, we have taken into account the excited state of ^{9}Be, E=2.430 MeV (λ=2). The B(E2) for the transition to this state, was obtained
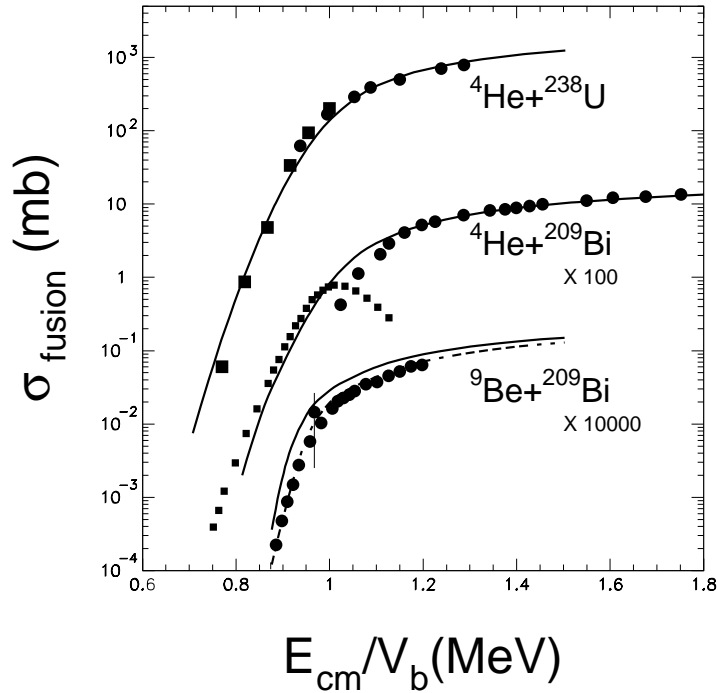
Figure 2: Fusion cross section for stable nuclei.

recently by Rudchik et al. [17].

The coulomb barriers and radii of the potentials are shown in Table 1. It is obvious that potential heights of systems with radioactive nuclei present a reduction of ~ 3 MeV relatively to the heights of systems with their associated stable isotopes. This is a well known effect, and a quantitative understanding has been achieved in terms of the halo structure [18]. The consequence of a reduced height is the enhancement of the sub-barrier fusion cross sections, sometimes by several orders of magnitude. The results of the calculation for the stable projectiles are shown in Fig.2 together with the same data which are presented in Fig.1. The fits are adequately good, for both the ^{4}He+^{238}U and

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^{4}He+^{209}Bi systems. We point out the additional data indicated in Fig.2 with squares, obtained previously[19] . These data concern the 1n evaporation channel of the reaction, ^{209}Bi(α,n)^{212}At. The addition of these points make the fit excellent. On the other hand, the calculations for the system ^{9}Be +^{209}Bi, overestimate highly the results. The same effect was reported before for the system ^{9}Bi+^{209}Pb[20]and it can be well assigned to the coupling to the continuum. The nucleus ^{9}Be presents a very low threshold to one neutron emission (S_n=1.67 MeV). Elastic scattering of such nuclei with a weak binding energy, has been described by Satchler and Love[11], into a microscopic description with a reduced potential than the one describing elastic scattering of stable nuclei. The effect was studied also by Sakuragi et al. [21] into a context of discretized coupled channel calculations and was attributed to the coupling to the continuum due to their weak binding energy. Moreover into a recent study by Trache et al. [23] for elastic scattering of light elements including ^{9}Be, it was found that the description of ^{9}Be can be successfully done via a potential reduced by a factor of $\sim$40%. It has to be pointed out here that Trache et al. [23] have been using the microscopic potential BDM3Y1, which is used in the present work. Into this context, it is clear to us that two types of calculations can anticipate the reduction of the potential height and describe sub-barrier and near-barrier fusion. The first is the method of discretized coupled channel calculations[21, 24] which is probably the most accurate method but which depends on several parameters not known for each system. The second one involves a reduced real potential, which is a local representation (not exact) of the discretized coupled channel calculation. It is obvious that the effect of the coupling to the continuum may not be represented by a simple reduction of the entrance channel potential but may also affect its shape[27].

Adopting the over simplified point of view that couplings to the continuum affect only the height of the potential and with the experience of the calculation on the case of ^{9}Be we have proceeded with the analysis of the unstable systems. The performed calculations with a standard potential (solid line) and a reduced one by 40% (dashed line) are presented in Fig.3. The calculations involve coupling to the excited states of the targets as before, and the following couplings to excited states of the projectiles. For ^{6}He we considered coupling with the first excited state at 1.87 MeV (λ=2) with deformation extracted from our recent inelastic scattering results ^{6}He(p,p')^{6}He[12, 25]. For ^{11}Be the excited state E=0.320 MeV (λ=1) with a B(E2)=0.116 e^{2}fm^4 was taken into account. We have to keep in mind, that the aim of the present calculations was the achievement of an unified description, in a qualitative basis, for the first sub-barrier and near-barrier fusion data involving halo nuclei. As it is seen from Fig.2 the systems ^{4}He+^{209}Bi and ^{4}He+^{238}U need no reduction of the poten-
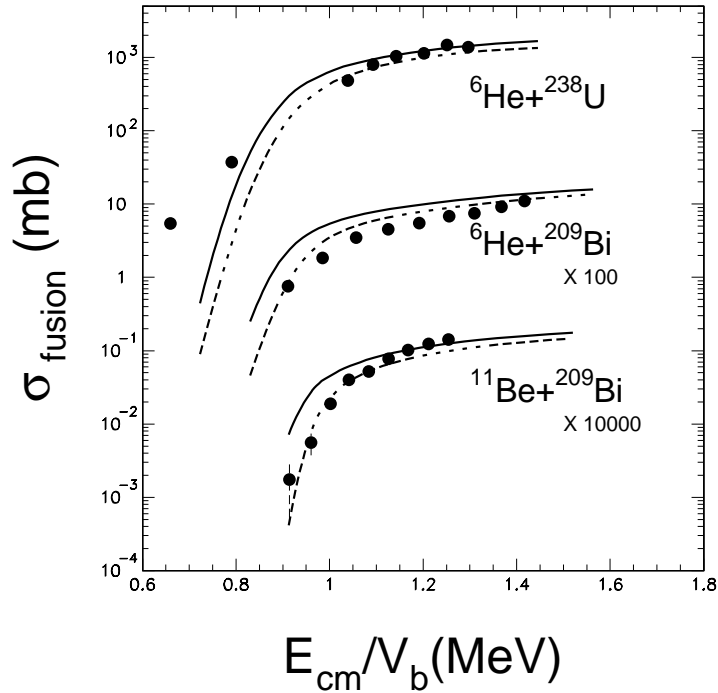
Figure 3: Fusion cross section for unstable nuclei.

tial as it is expected for well bound nuclei. On the contrary, a 40% reduction is necessary to describe the systems ^{9}Be+^{209}Bi, ^{6}He+^{209}Bi and ^{11}Be+^{209}Bi, although for energies well above the coulomb barrier the later system is better described with non reduced potential calculations. The situation is more complex for ^{6}He+^{238}U. Above the coulomb barrier this system is probably better described with calculations with non reduction of the potential, whereas well below the coulomb barrier the calculations fail to reproduce the data. It has to be noticed however that this is the first system for which sub-barrier fusion, for energies well below the coulomb barrier, has been measured. A new experiment is planned to investigate in more details sub-barrier fusion of ^{6}He+^{238}U.

From this discussion we can draw the conclusion that coupled channel calculations reproduce the gross properties of near-barrier fusion involving halo nuclei. The agreement of the calculations with the data is particularly spectacular in the case of ^{9}Be+^{209}Bi and ^{11}Be+^{209}Bi.

3   Conclusions

We have performed coupled channel fusion calculations for several systems with halo and their associated non-halo projectiles. A description of the weakly bound stable system (^{9}Be+^{209}Bi) and the halo systems was qualitatively obtained, by making use of a reduced potential. The reduction of the potential can be understood in terms of breakup processes due to the weak binding energy of the stable nucleus ^{9}Be and the halo nuclei. The reduction of potential was justified before via elastic scattering of weakly bound nuclei and in particular of ^{9}Be on different targets. In this context elastic scattering measurements for halo nuclei are highly requested. These measurements would help to pin down a possible variation of the strength and eventually of the shape of the entrance channel potential.

In general it has to be stressed out that additional measurements including elastic scattering, complete fusion (without contributions due to incomplete fusion) and break-up are necessary to enlight the subject of near-barrier and sub-barrier fusion of halo nuclei.

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