SUB-BARRIER FUSION WITH EXOTIC NUCLEI

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Interest in the mechanism of near- and sub-barrier fusion has been renewed, with the advent of radioactive beam facilities, due to the specific properties of unbound and weakly bound beams, such as extended neutron densities, low-lying continuum, and very low energy break-up thresholds. It is expected that these properties will appreciably affect fusion, as well as other reaction channels like breakup. We discuss the role played by these properties in barrier and sub-barrier fusion of weakly bound and unstable nuclei. The data are compared to calculations performed within the coupled channels and continuum discretized coupled channels schemes.

Introduction

With the advent of radioactive beam facilities, interest in near- and sub-barrier fusion studies has been renewed due to their specific features, such as extended neutron densities, low-lying continuum, and very low energy break-up thresholds. The first measurements of near- and sub-barrier fusion with halo nuclei were performed for the $^{11}Be+^{209}Bi$, $^{6}He+^{209}Bi$ and $^{6}He+^{238}U$ systems and for the corresponding stable projectiles $^{9}Be+^{209}Bi$, $^{4}He+^{209}Bi$ and $^{4}He+^{238}U$. A first analysis of these results, in the coupled-channels framework, was presented in [1] and [2]. In the first part of this contribution, we briefly describe the salient futures of this analysis and in the second part we present new calculations for $^{6}He+^{238}U$ near- and sub-barrier fusion. The latter calculations were performed within the continuum discretized coupled channels scheme.

Near- and sub-barrier fusion with exotic nuclei

Most of the results concerning the fusion of two nuclei at bombarding energies below and near the Coulomb barrier were adequately interpreted within the framework of coupled channels (CC) calculations. This kind of calculation with phenomenological nucleus-nucleus potentials can successfully reproduce a vast amount of data [3]. The CC calculations presented here were performed with the ECIS code [4]. The structure of the colliding nuclei is explicitly taken into account via folding models, for the entrance channel potential. This potential is traditionally inferred from elastic scattering data at energies well above the Coulomb barrier. The overall success of realistic folding models for the description of elastic scattering data of stable and well bound nuclei without any renormalization of the real potential for energies well above the Coulomb barrier indicates that the real dynamic polarization potential (DPP) is weak. This is not the case for the scattering of stable but weakly bound nuclei, such as ^{9}Be. For these nuclei, break-up effects generate a real polarization potential of opposite sign to the real potential provided by the folding model, see [5] and the discussion therein.

Coupled channels calculations were performed for the data presented in Fig. 1. The real part of the entrance channel potential was calculated within the double folding model using the BDM3Y1 interaction. This interaction was found to describe elastic scattering data for both stable and weakly bound nuclei [1,2] rather well, provided the normalization factor for the weakly bound nuclei was substantially less than 1.0. The experimental results for ^{4}He projectiles may be well reproduced within this model without any reduction of the potential. For the ^{9}Be+^{209}Bi, system, calculations have been performed for an un-renormalized (solid line) and for a reduced potential (dashed line). The 40% reduction of the potential adopted according to the elastic scattering data is adequate to describe the sub- and near-barrier fusion data.

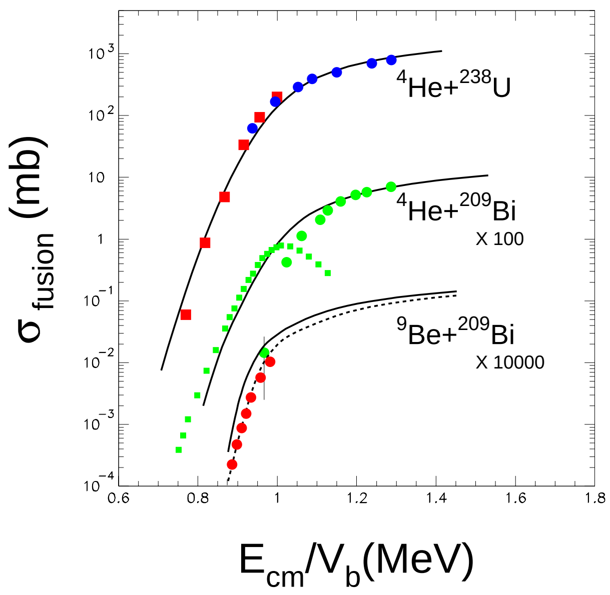

Figure 1. Fusion cross section measurements for stable nuclei compared with CC calculations with an un-renormalized folded optical potential (solid line) [1,2]. For the ^{4}He+^{209}Bi system the circles denote the sum of the 2n, 3n, 4n evaporation channels, while the squares denote the 1n evaporation channel. The dashed line corresponds to a calculation with a reduction of the optical potential by 40%.

Calculations for the halo projectile systems ^{6}He and ^{11}Be are compared with the experimental data in Fig. 2. Good agreement is obtained between data and calculations for the $^{6}He+^{238}U$ and $^{6}He+^{209}Bi$ systems with a 60% reduction of the potential at and above the Coulomb barrier.

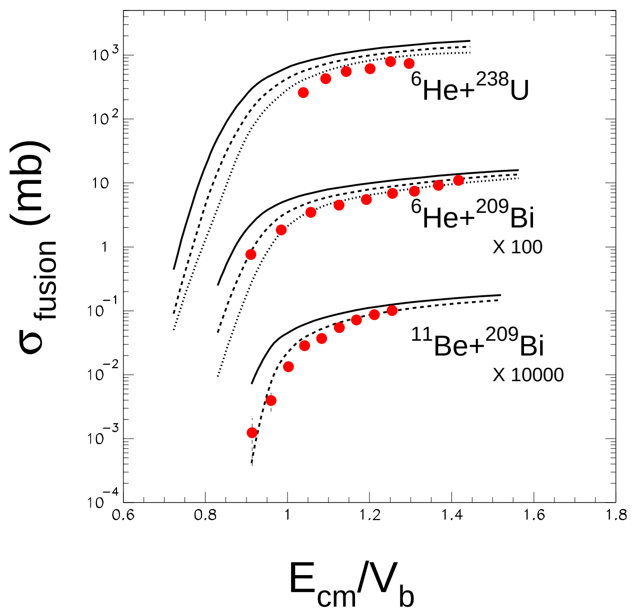

Figure 2. Fusion cross section measurements for unstable nuclei compared with CC calculations with un-renormalized (solid lines) and reduced by 40% (dashed lines) double-folding model potentials. The dotted lines correspond to calculations with a reduction of the double-folding potential by 60%. The data for the $^{6}He+^{238}U$, $^{6}He+^{209}Bi$ and $^{11}Be+^{209}Bi$ systems were obtained from [6], [7] and [8], respectively.

The new $^{11}Be+^{209}Bi$ data are in good agreement with calculations with a potential reduction of the order of 40%. We would like to add here a comment concerning our first theoretical analysis on this subject [1]. The experimental data discussed in this paper [1] for both the $^{6}He+^{238}U$ and $^{11}Be+^{209}Bi$ systems were overestimated, by a factor of the order of 50% for $^{6}He+^{238}U$ [6] and by a factor of 1/sqrt(2) for $^{11}Be+^{209}Bi$ [8]. This led to an agreement between the experimental data and the theoretical predictions that was not as spectacular as it appears today in figure 2. Therefore, the discussion and calculations in this earlier paper [1] should be considered today as predictions. However, there is one point concerning this analysis we would like to discuss further: *Do continuum discretized coupled channel calculations support the ideas presented in this first section?*

Calculations in the CDCC scheme.

The method of continuum discretized coupled channels (CDCC) offers one of the most complete approximations to the three body problem (three body Schrödinger equation) involving a two-body projectile (d, ^{6}Li, ^{7}Li ^{8}B, ^{11}Be, ^{17}F and ^{19}C) impinging on a target. It has been shown that CDDC is the first-order approximation to the distorted Faddeev equations [9]. In CDCC the states of a projectile described by two fragments are classified by the linear and angular momentum of these two fragments. In practice, the resulting coupled equations are impossible to solve because of the infinite number of coupled break-up channels. However, the problem may be solved by discretization of the linear momentum of the two fragments, that is discretization of the linear continuum. It is therefore obvious that truncation and discretization are two key issues for solving CDDC. Many methods for discretization have been proposed and there is hope that within one of them, the pseudo-state discretization, it will be possible to solve problems involving three body projectiles, but this discussion goes beyond the scope of the present contribution. With increasing computing power, the CDDC method became popular and is currently applied in reactions involving exotic nuclei. For a recent paper concerning up-to-date calculations for (d,p) transfer see [10].

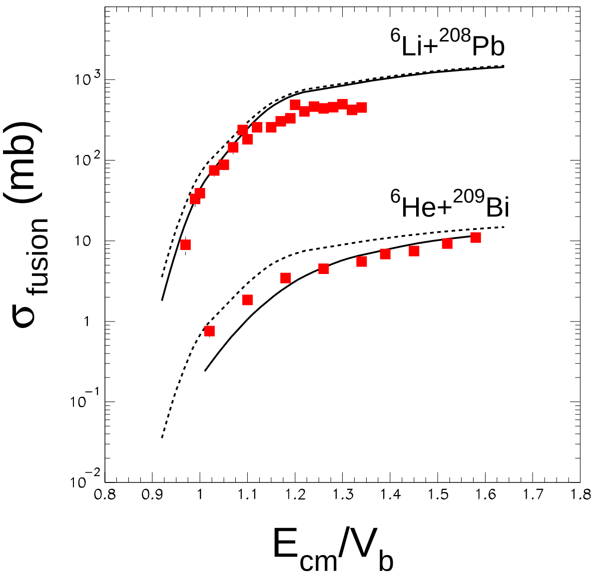

Figure 3. Fusion cross sections for ^{6}Li + ^{208}Pb and ^{6}He + ^{209}Bi calculated using the CDCC/BPM combination compared to the data. The dotted curves are the no coupling predictions.

Recently, we applied the CDDC method to the calculation of the break-up and fusion of ^{6}Li and ^{6}He interacting with a ^{208}Pb target [11]. Figure 3 shows the calculated fusion cross sections compared to the data for the ^{6}Li + ^{208}Pb [12] and ^{6}He + ^{209}Bi [7] systems. Agreement is satisfactory in both cases. CDCC calculations of sub-barrier fusion for the ^{6}He+^{238}U system are presented in figure 4. They were obtained using a barrier penetration model (BMP) with the real effective potential between the projectile and the target being the sum of the bare potential and the dynamic polarization potential (DPP) derived from the CDCC channel couplings. Indeed, this procedure takes into account a possible energy variation of the DPP, which was not accounted for by the simple procedure used in the first part of this contribution. As may be seen in the figure

4, the overall agreement with the measured fusion cross sections is again rather good.

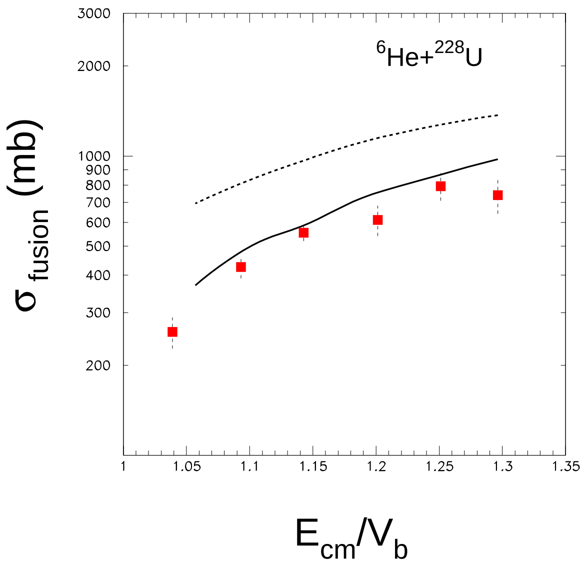

Figure 4. Fusion cross sections for the $^{6}He + ^{238}U$ system calculated using the CDCC/BPM combination compared to the data. The dotted curve is the no coupling prediction.

Conclusions

From this analysis we may draw the conclusion that CC calculations, taking into account in a simplistic way break-up effects via a reduced magnitude real potential, reproduce the gross properties of near and sub-barrier fusion, for weakly bound stable nuclei. The agreement between the calculations and the data is particularly spectacular in the case of the $^{9}Be+^{209}Bi$ system where the reduction of the potential is known from elastic scattering. From the analysis of these pioneering experiments, it is found that a fundamental difference occurs between stable and unstable systems. The dominant channel in the barrier energy region of stable systems is fusion. For unstable and weakly bound nuclei this is not the case. Loss of flux through other channels like break-up takes place, and can be taken into account by the reduction of the entrance channel optical potential, i.e. exactly in the same way as for elastic scattering data. In that respect, descriptions of the weakly bound systems- ^{9}Be+^{209}Bi, ^{9}Be+^{208}Pb and the halo systems- ^{6}He+^{209}Bi, ^{6}He+^{238}U and ^{11}Be+^{209}Bi - were obtained by making use of a reduced potential to account for the break-up processes. This Toy-model description is justified in section 3 by CDCC/BPM calculations. These calculations show indeed the reduction of the total potential, provide a reasonable description of the complete fusion data and predict a suppression of the fusion by break-up at energies close to the Coulomb barrier.

References

1. N. Alamanos, A. Pakou, V. Lapoux, J. L. Sida and M. Trotta, *Phys. Rev.* **C65**, 054606 (2002).
2. N. Alamanos and A. Gillibert, in: J. Al-Khalili, E. Roeckl (Eds.), *The Euroschool Lectures on Physics with Exotic Beams, Vol. I*, Lect. Notes Phys. **651** (Springer, Berlin Heidelberg 2004), p. 295.
3. S. G. Steadman and M. J. Rhoades-Brown, Ann. Rev. Part. Sc. **36** (1986) 649.
4. J. Raynal, *Phys. Rev.* **C23**, 2571 (1981).
5. V. Lapoux et al., *Phys. Rev.* **C66**, 034608 (2002).
6. R. Raabe et al., to be published in Nature.
7. J.J. Kolata et al., *Phys. Rev. Lett.* **81**, 2342 (2000).
8. C. Signorini et al., *Nucl. Phys.* **A735**, 329 (2004)
9. Matsumoto et al., arXiv:nucl-th/0302034
10. N. Keeley, N. Alamanos and V. Lapoux, *Phys. Rev.* **C69**, 064604 (2004).
11. K. Rusek, N. Alamanos, N. Keeley, V. Lapoux and A. Pakou, *Phys. Rev.* **C70**, 014603 (2004).
12. Y.W. Wu, Z.H. Liu, C.J. Lin, H.Q. Zhang , M. Ruan, F. Yang, Z.C. Li, M. Trotta, and K. Hagino, *Phys. Rev.* **C68**, 044605 (2003).