Reduction methodology for reaction cross sections induced by weakly bound nuclei

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Introduction

The interest in nuclear reactions with weakly bound nuclei has increased considerably along the last decade [1]. Several experiments with stable and unstable projectiles have been performed and a variety of theoretical approaches have been developed. In particular, fusion and breakup reactions induced by such projectiles have been the object of several studies. Owing to the weak binding of the projectile, the breakup cross section may be quite large and coupling with the breakup channel can strongly affect the fusion cross section at near-barrier energies. This influence stems from two effects, one of a static and the other of a dynamic nature, which are, however, not easy to be disentangled. The static effect results from the more diffuse density of the weakly bound nuclei, as compared with a strongly bound one. The contribution from weakly bound nucleons to the nuclear density extends further out and this gives rise to a lower and thicker potential barrier. There is general understanding that this static effect enhances the fusion cross section at near barrier energies. On the other hand, there is the dynamic effect corresponding to the coupling with the breakup channel. It is well known that the coupling with a finite number of bound channels enhances the sub-barrier fusion cross section. However, the effect of coupling to channels in the continuum (breakup) is controversial. In first place, one should have in mind that there are different fusion processes in collisions of weakly bound projectiles. One of such processes is the complete fusion, which takes place when the whole mass of the projectile fuses with the target. There may be fusion following breakup. In this case, the compound nucleus may contain the whole mass of the projectile (through sequential fusion of the fragments), or some fragment can escape the interaction region. The former corresponds also to complete fusion (sequential complete fusion) while the latter is known as incomplete fusion. So far, only a few experiments with some special projectile-target combinations can distinguish between these two processes. From the theoretical point of view, these two processes can be distinguished in some simpler models but not in more realistic calculations.

Some experiments with weakly bound projectiles on heavy targets find that the complete fusion cross section at energies slightly above the barrier is hindered as compared with the results for tightly bound isotopes [2]. The reduction is found to be from 10 to 30%. On the other hand, the results for beams of the two isotopes on lighter targets are rather similar. On the other hand, different experiments with unstable beams on various targets lead to different conclusions. Owing the very low intensity of radioactive beams, these experiments are very hard to perform.

From the theoretical point of view, the situation is not very different. To assess the influence of the breakup channel on the fusion cross section it would be necessary to perform coupled-channel calculation including the continuum and this is a complicated task. For this reason the majority of the theoretical model available are qualitative and do not allow a reliable determination of the fusion cross section.

In order to perform a systematic study of fusion with different weakly bound projectile with several targets, it is necessary to compare cross sections for different systems. For this purpose, it is necessary to suppress trivial differences, arising from the size and charges of the systems. This can be done in different ways. The most frequent one is to normalize the collision energy with respect to the barrier height and to divide the cross section by its geometrical value. That is, to plot $\sigma_R/\pi R_B^2$ against $E_{c.m.}$-V_B, where R_B and V_B are respectively the s-wave barrier radius and height. However, when weakly bound projectile nuclei are involved, care should be taken in order to preserve the static effects arising from the low breakup energy of the projectile. In this way, the barrier parameters should depend on the masses and charges of the collision partners but not on specific features of the projectile density. This plot is $\sigma_R/(A_p^{1/3}+A_t^{1/3})^2$ versus $E_{c.m.}\,(A_p^{1/3}+A_t^{1/3})\,/Z_p\,Z_t$. This prescription was applied to a variety of systems, comparing fusion and total reaction cross sections for different systems, and interesting correlations with the breakup threshold were found [3,4], such as the smaller this value, the larger the total reaction cross section.

In the present work, a third methodology allows one to distinguish static and dynamic effects on the fusion cross section and also disentangle dynamic effects arising from couplings to inelastic and breakup channels. The first step is to use the reaction function F(x) dependent on the dimensionless variable, $(E - V_B)/\hbar\omega$, described in detail elsewhere [5]

Our systematic study of reaction functions over different mass ranges leads to the general conclusion that reactions function for the weakly bound nuclei is consistently larger than those for stable systems.

References

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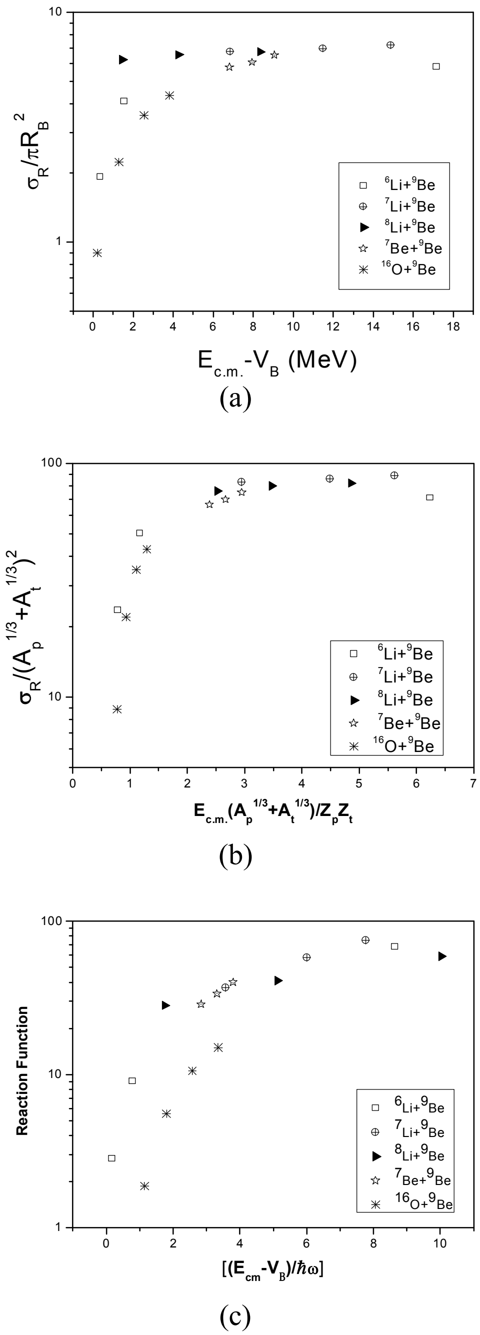

Fig.1. Comparison of total reaction cross section for weakly bound and strongly bound isotopes. In (a), (b) & (c) the data are reduced according to different prescribed format. For details see in text.