The effect of proton halo on fusion reactions

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Abstract. In a recent brief report [Kumar et al., Phys. Rev. C 89, 027601 (2014)] we proposed a method to include the effect of a large break up in fusion reactions with neutron and proton halo nuclei. A stronger enhancement on the total fusion cross section was found for the proton case. However, neither complete nor incomplete fusion was studied and only one target was considered. Here, we revisit the problem in order to address the importance of complete and incomplete fusion. The sensitivity of the cross section to the target is also explored.

1. Introduction

Fusion reactions at energies below the barrier is one of the most useful tools to explore the structure of nuclei, since their variation with the energy is known to be driven by the internal degrees of freedom of the two counterparts [1, 2]. This fact has been largely explored for fusion of heavy-ions, where it is possible to identify the coupled channels driving the behaviour of the cross sections, normally corresponding to rotor or vibrator schemes. These channels have well determined potentials and have been largely studied in comparison with light ions or more generally with weakly bound nuclei.

In the case of fusion with light ions, the large probability of break up imposes the treatment of strongly coupled continuum channels with the consequent inclusion of at least three-body kinematics. This complexity makes almost impossible to single out specific issues from a full continuum calculation, being one of the reasons why there is no general agreement on the effect of the break up and the presence of a charged proton halo on the fusion cross section.

In order to face this problem, we proposed recently a very simplified model consisting of two channels with a schematic description of the break up of the projectile [3]. Within this simple model, a large enhancement of the sub-barrier fusion cross section was found for the case of $^8$B on $^{58}$Ni. This reactions was chosen after the experiment by E. F. Aguilera and collaborators [4]. However, this cross section included complete fusion and the fusion of $^7$Be, i.e. the fusion of the core of the projectile after losing a proton. The particular role of each channel was not explored. Also the sensitivity of the enhancement found to different targets was not considered even though there is an experiment with $^8$B on $^{28}$Si by A. Pakou and collaborators [5].

In the present contribution, we continue developing this model to address the role of complete and incomplete fusion following the prescription of [6], as well as the effect of the specific target.

2. Reaction framework

We will consider two different halo projectiles representative of the neutron halo case, $^{11}$Be, and the proton halo case, $^8$B. Together with the complete fusion of these two projectiles with the
functions $\chi$ of the internal state of the projectile $\phi_\beta$ and the radial wave functions $\chi_\beta$ that accounts for the relative motion between projectile and target:

$$\Psi^+ = \sum_\beta \frac{\chi_\beta(R)}{R} \phi_\beta.$$  \hspace{1cm} (1)

This leads to a set of coupled equations for $\chi_\beta$. In our model case, we will only consider two channels, the incoming channel and one channel representative of the break-up and later fusion without the ejected particle:

$$\frac{d^2 \chi_1}{dR^2} + \frac{2\mu_1}{\hbar^2} [E_1 - V_1] \chi_1 = \frac{2\mu_1}{\hbar^2} V_{\text{coup}} \chi_2,$$

$$\frac{d^2 \chi_2}{dR^2} + \frac{2\mu_2}{\hbar^2} [E_2 - V_2] \chi_2 = \frac{2\mu_2}{\hbar^2} V_{\text{coup}} \chi_1,$$  \hspace{1cm} (2)

where, in our case, $E_1 = E$, the incoming energy, and $E_2 = E_{\text{bu}}$, the energy in the break-up channel.

This energy $E_{\text{bu}}$ can be estimated by subtracting the energy needed for break up and the average excitation energy, $\langle E^* \rangle$, in the core-nucleon relative motion, and then sharing the energy between them according to a distant break up scenario. In this way, we consider $E_{\text{bu}} = (E - S_{1N} - \langle E^* \rangle) \cdot \frac{A-1}{A-1}$. $S_{1N}$ is the one neutron or one proton separation energy: $S_{1p} = 0.136$ MeV for $^8\text{B}$ and $S_{1n} = 0.504$ MeV for $^{11}\text{Be}$. In order to estimate $\langle E^* \rangle$ we take the peak energy for the dipole electromagnetic transition probabilities, $\langle E^* \rangle = 0.5$ MeV for $^8\text{B}$ and $\langle E^* \rangle = 0.4$ MeV for $^{11}\text{Be}$.

The total potential for each channel $V_{1,2}(R)$ is given by the sum of Coulomb and a nuclear proximity potential given by Broglia and Winther [8] parameterization. The coupling potential $V_{\text{coup}}$ is taken as a derivative Woods Saxon form with the same diffuseness of the proximity potential for the incoming channel and the radius corresponding to the position of the maximum of the Coulomb barrier. The strength is set to a 10% of the strength of the same proximity potential.

Finally, in order to obtain fusion cross section from the coupled-channel equations, we solve them under ingoing-wave boundary conditions (IWBC). Within this approximation the solution is matched with the incoming and outcoming Coulomb wavefunctions obtaining the transmission coefficient for each channel, see [3]. The total transmission probability will be:

$$T = \sum_\beta \left| T_{\beta}^2 \right| = |t_1|^2 + \frac{v_2}{v_1}|t_2|^2,$$  \hspace{1cm} (3)

where $v_1$ and $v_2$ are the velocities corresponding to channel 1 and 2.

From here we can compute separate cross section for each channel:

$$\sigma = \sigma_1 + \sigma_2 = \frac{\pi \hbar^2}{2\mu_1 E} \sum_{\ell=0}^{\ell_{\text{max}}} (2\ell + 1)T_1^2(E) + \frac{\pi \hbar^2}{2\mu_1 E} \sum_{\ell=0}^{\ell_{\text{max}}} (2\ell + 1)T_2^2(E),$$  \hspace{1cm} (4)

where:

$$T_1 = |t_1|^2, \quad T_2 = \frac{v_2}{v_1}|t_2|^2,$$  \hspace{1cm} (5)

being evaluated for each angular momentum $\ell$.

It is necessary to stress that the cross section for the second channel $\sigma_2$ implies the fusion of all the charge only for the neutron case. In the proton case, the fusion results from the different channels will have different charge.
3. Results

We first attempt the problem of distinguishing the contributions to the total cross section of the two channels. In Fig. 1, we considered the fusion of $^8$B on $^{58}$Ni, the same case as in Ref. [3]. Black solid line shows a case without break up and the black dashed line, the enhancement found for the proton halo where the total cross section is considered. Here we also display the contribution of the two channels. We see in Fig. 1 the cross section for the fusion of the full $^8$B (red solid line) and the cross section of the break up channel, i.e. $^7$Be on $^{58}$Ni (red dashed line). If we only considered the complete fusion (first channel), we found that the enhancement is only found for really small energies.

On the other hand, we saw that this enhancement can be explained through the definition of an effective $Q$ value arising from the different Coulomb barrier $V_B$ present in each channel:

$$Q_{eff} = (E_{bu} - V_B^2) - (E - V_B^1).$$  \hspace{1cm} (6)

For an incoming energy around the Coulomb barrier $E \approx V_B^1$, this $Q$ value can be approximated for the neutron and the proton case:

$$Q_{eff}^{(n)} \simeq -\frac{1}{A_{proj}}V_B^1,$$

$$Q_{eff}^{(p)} \simeq \left(\frac{1}{Z_{proj}} - \frac{1}{A_{proj}}\right)V_B^1.$$ \hspace{1cm} (8)

Notice that for the neutron halo $Q_{eff}^{(n)}$ is always negative, whereas $Q_{eff}^{(p)}$ is always positive. Moreover, these values are proportional to the Coulomb barrier. Therefore, the enhancement is expected to be smaller for lighter targets.

Having this in mind, in Fig. 2 we show the reduced cross sections for the fusion of $^8$B (red lines) and $^{11}$Be (black lines) on a $^{28}$Si target. Dashed lines represents the case where we include...
the break up and the solid line, those without break up. Here the proton enhancement reaches the neutron cross section only for really low energies. If we compare with the $^{58}$Ni case, see Fig. 3 in Ref. [3], we found a weaker enhancement for this case as expected with the corresponding Coulomb barriers.

4. Conclusions
We have considered here the effect of proton halo in the fusion of the nucleus $^8B$ on different targets, $^{58}$Ni and $^{28}$Si, using a simplified model of the break up of the halo nucleus. For both targets, a certain enhancement of the fusion cross section is found when we include the coupling to the break up. This enhancement is smaller for the $^{28}$Si case, as expected from a simple analysis of the effective Q value proposed. Here we have compared with a neutron halo case by computing the fusion cross section for $^{11}$Be on $^{28}$Si.

This enhancement is obtained when we considered also the fusion following break up. However, with this simple model we can compute separately the contribution to the fusion of each channel. If we focused on the complete fusion, therefore only considering the fusion from the first channel, it is only enhanced with respect to the case without coupling to the break up for extremely low energies.

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