PRAMANA — journal of physics
© Indian Academy of Sciences
Vol. 61, No. 3
September 2003
pp. 529–538

Fusion of light exotic nuclei at near-barrier energies: Effect of inelastic excitation

P BANERJEE*, K KRISHAN, S BHATTACHARYA and C BHATTACHARYA
Variable Energy Cyclotron Centre, 1/AF Bidhan Nagar, Kolkata 700 064, India
*Present address: Department of Physics, Jhargram Raj College, West Bengal 721 507, India
Email: kewal@veccal.ernet.in

MS received 18 April 2002; revised 27 February 2003; accepted 1 April 2003

Abstract. The effect of inelastic excitation of exotic light projectiles (proton- as well as neutron-rich) ^{17}F and ^{11}Be on fusion with heavy target has been studied at near-barrier energies. The calculations have been performed in the coupled channels approach where, in addition to the normal coupling of the ground state of the projectile to the continuum, inelastic excitation of the projectile to the bound excited state and its coupling to the continuum have also been taken into consideration. The inclusion of these additional couplings has been found to have significant effect on the fusion excitation function of neutron-rich ^{11}Be on ^{208}Pb whereas the effect has been observed to be nominal for the case of proton-rich ^{17}F on the same target. The pronounced effect of the channel coupling on the fusion process in the case of ^{11}Be is attributed to its well-developed halo structure.

Keywords. Fusion cross-sections; coupled channel; proton- and neutron-rich nuclei; ^{17}F; ^{11}Be; inelastic excitations; sub-barrier fusion.

PACS Nos 25.60.Dz; 25.60.Pj; 25.70.Jj

1. Introduction

One of the interesting aspects of the study of nuclear reactions involving radioactive beams is the possibility of using radioactive projectiles to synthesize new, exotic heavy nuclei [1]. In particular, nuclei located near the neutron or proton drip lines, for which the valence particles are very loosely bound, give rise to interesting new phenomena, e.g., formation of halo structures [2]. The low binding energies of the valence nucleons result in large sizes and thus, in increased probabilities for specific reaction channels such as nucleon transfer and fusion. The synthesis of heavier nuclei could thus be achieved through fusion reactions induced by these exotic nuclei.

Due to the increasing availability of radioactive ion beams, many questions concerning the effects of breakup processes on sub-barrier fusion of drip-line nuclei have been raised recently, both from the experimental [3–9] and theoretical [10–13] points of view. From studies of fusion of stable nuclei where breakup process is not so important, it is known that any coupling of the relative motion of the colliding nuclei to nuclear intrinsic excitations causes large enhancements of the fusion cross-sections at sub-barrier energies over the predictions of a simple barrier penetration model. It is expected that the same thing happens for coupling to the breakup channel as well, especially for the weakly bound exotic nuclei lying close to or on the neutron/proton drip lines, for which the probability of dissociation prior to or at the point of contact is quite high. Therefore, for these nuclei, the cross-sections for inclusive processes, i.e., the sum of complete and incomplete fusion cross-sections should be enhanced when couplings to the breakup channels are considered. Considered from another point of view, the presence of halo structure means a root mean square (rms) matter radius larger than the usual value deduced from the $r_0A^{1/3}$ systematics. As a consequence, the sub-barrier fusion cross-section should be enhanced since the Coulomb barrier is lowered. On the other hand, one could also argue intuitively that increased breakup probabilities for these nuclei remove a significant part of the flux and thus cross-sections for complete fusion would be hindered.

Since the halo effects have first been detected in the two-neutron halo nucleus ^{11}Li, most of the early investigations dealt with nuclei involving weakly bound neutrons. This has been the trend as well in so far as fusion reactions are concerned. Very recently, fusion at near-barrier energies has been investigated theoretically for the neutron halo nuclei ^{11}Be and ^{6}He on Pb target. Coupled channel calculations have been performed by discretizing in energy the particle continuum states [13]. The calculations show that the coupling to the breakup channels has two effects: the loss of flux to the breakup channels and the dynamical modification of fusion potential. Their net effects differ depending on the energy region. At energies above the Coulomb barrier, the former effect dominates over the latter and cross-sections for complete fusion are hindered compared to the no-coupling case. On the other hand, at sub-barrier energies the latter effect is much larger than the former and complete fusion cross-sections are enhanced consequently. This is unlike the outcome of the theoretical formulation by Hussein *et al*, according to which the breakup process always hinders complete fusion cross-sections [10].

Recently, a complete fusion excitation function has been measured for the loosely bound nucleus ^{9}Be on a Pb target at near-barrier energies [7]. The measurements show that cross-sections for complete fusion are considerably smaller at above-barrier energies compared with a theoretical calculation that reproduces the total fusion cross-sections. Also, the fusion cross-sections for the ^{4,6}He + ^{238}U systems measured by the SACLAY group seem to indicate that the breakup effects enhance fusion cross-sections at sub-barrier energies [8]. However, these data are for total fusion and not for complete fusion. Very recent data for the loosely bound ^{7}Li nucleus on a ^{165}Ho target show enhancement of the complete fusion cross-sections below the Coulomb barrier and reduction above the barrier [9].

Fusion induced by light proton-rich systems has received attention only recently [4], but not to a good extent. Unlike the neutron-rich systems the valence proton in the loosely bound proton-rich exotic nuclei has to tunnel through the barrier resulting from the Coulomb repulsion due to the charged core, which hinders the formation of proton halo. In fusion reaction, this might not lead to a significant lowering of the Coulomb barrier when such nuclei interact with a target. Thus the observations made in connection with fusion of neutron-rich nuclei at energies around the Coulomb barrier may not be the same for them. The breakup probabilities of the exotic nuclei depend significantly on the separation energy of the valence nucleon as well as its orbital angular momentum configuration [14]. Any non-zero angular momentum with respect to the core will lead to a centrifugal barrier, which will restrict the extent of the wave function in the coordinate space. The increase of the separation energy of the valence nucleon further decreases the spread of the wave function and thereby the cross-sections of the breakup processes in which the valence particle is removed from the nucleus also decrease [14]. If the exotic nucleus has some bound excited state(s), a part of the flux will go to its inelastic transition(s) from the ground state to the excited state(s). Transition from the ground state into the continuum via the excited state(s) would be possible. All these could also affect its fusion with a target nucleus.

We find it interesting to investigate the roles of all these aspects that could affect the fusion of an unstable, exotic nucleus with a stable, normal target. In the present work, we first report calculations on fusion reactions induced by the proton drip line exotic nucleus ^{17}F and examine the effects of its inelastic excitation on the fusion cross-sections. To compare and contrast the situation with a light neutron-rich exotic nucleus, we also perform calculations for the one-neutron halo nucleus ^{11}Be. The paper is organised as follows. Theoretical formalism is described in brief in §2. Section 3 contains the results and discussion and finally the concluding remarks are given in §4.

2. Formalism

The coupled channel formalism used in the present paper has been described in detail in refs [13,15] (and the references therein). A brief outline of the formalism is given below. The coupled channel equations for the projectile (P)–target (T) system (with reduced mass μ) in the isocentrifugal approximation [16] are given by [15]

$$\left[-\frac{\hbar^2}{2\mu}\frac{\mathrm{d}^2}{\mathrm{d}r^2}+\frac{l(l+1)\hbar^2}{2\mu r^2}+V_{\mathrm{N}}^{(0)}(r)+\frac{Z_{\mathrm{P}}Z_{\mathrm{T}}e^2}{r}+\varepsilon_n-E\right]\psi_n(r) = -\sum_m V_{nm}(r)\psi_m(r). \tag{1}$$

In writing the above equation, the angular momentum of the relative motion in each channel has been replaced by the total angular momentum l [16]. In eq. (1), $V_{\mathrm{N}}^{(0)}$ is the nuclear potential in the entrance channel and ε_n is the excitation energy of the nth channel. Here we assume that $n=0$ labels the ground state of the projectile nucleus and all other ns refer to bound excited states or particle continuum states of the projectile. V_{nm} are the coupling form factors computed on the microscopic basis. They are obtained by folding the external nuclear and Coulomb fields with the proper single-particle transition densities, in which the last weakly bound nucleon is promoted from the ground state to excited states below the breakup threshold or in the continuum. More explicitly, the coupling form factor for the promotion of the single valence particle from the bound state $(n_1 l_1 j_1 m_1)$ to the continuum state $(l_2 j_2 m_2)$ with continuum energy E_{c} is given by

$$V_{nm}(r) = \sum_{m_{\mathrm{c}}}\langle j_1 m_1 j_{\mathrm{c}} m_{\mathrm{c}} \mid J_{\mathrm{i}} M_{\mathrm{i}}\rangle\langle j_2 m_2 j_{\mathrm{c}} m_{\mathrm{c}} \mid J_{\mathrm{f}} M_{\mathrm{f}}\rangle \times f_{n_1 l_1 j_1 m_1 \to l_2 j_2 m_2}(r), \tag{2}$$

where $J_{\mathrm{i(f)}}, M_{\mathrm{i(f)}}$ are the total spin of the projectile and its projection quantum number in the initial (final) state. j_{c} is the spin of the core and m_{c} is its projection. We have assumed a core + single particle structure for the projectile. The single-particle form factor f in eq. (2), which describes transitions from ground state to excited bound states or to continuum is given in detail in refs [13,15].

The coupled channel eq. (1) is solved by imposing the incoming wave boundary condition (IWBC) [17], where there are only incoming waves at $r_{\min}$ which is taken to be the minimum position of the Coulomb pocket inside the barrier. This type of boundary condition is valid for heavy-ion reactions, for which there is a strong absorption inside the Coulomb barrier. The boundary conditions are expressed as

$$\psi_n(r) \to T_n \exp\left(-i\int_{r_{\min}}^{r} k_n(r')\mathrm{d}r'\right), \quad r \le r_{\min}, \tag{3}$$

$$\to H_l^{(-)}(k_n r)\delta_{n,0} + R_n H_l^{(+)}(k_n r), \;\; r > r_{\max}, \tag{4}$$

where

$$k_n(r) = \sqrt{\frac{2\mu}{\hbar^2}\left(E - \varepsilon_n - \frac{l(l+1)\hbar^2}{2\mu r^2} - V_{\mathrm{N}}^{(0)}(r) - \frac{Z_{\mathrm{P}}Z_{\mathrm{T}}e^2}{r}\right)} \tag{5}$$

is the local wave number for the nth channel and k_n, in eq. (4), is equal to $\sqrt{2\mu(E-\varepsilon_n)/\hbar^2}$. $H_l^{(-)}$ and $H_l^{(+)}$ are the incoming and outgoing Coulomb functions, respectively. $r_{\max}$ is taken to be the distance beyond which both the nuclear potential and the Coulomb coupling are sufficiently small.

The fusion probability is defined as the ratio between the flux inside the Coulomb barrier and the incident flux. For the boundary conditions given by eqs (3) and (4), it becomes

$$P_n = \frac{k_n(r_{\min})}{k_0}|T_n|^2 \tag{6}$$

for the nth channel. Complete fusion is a process where all the nucleons of the projectile are captured by the target nucleus. We thus define cross-section of the complete fusion using the flux for the non-continuum channel (i.e. $n = 0$) as [15]

$$\sigma_{\mathrm{CF}} = \frac{\pi}{k_0^2}\sum_l (2l+1)P_0 = \frac{\pi}{k_0^2}\sum_l (2l+1)\frac{k_0(r_{\min})}{k_0}|T_0|^2. \tag{7}$$

The flux for the particle continuum channel ($n \neq 0$) is associated with incomplete fusion, whose cross-section is given as

$$\sigma_{\mathrm{ICF}} = \frac{\pi}{k_0^2}\sum_l (2l+1)\sum_{n\neq 0} P_n = \frac{\pi}{k_0^2}\sum_l (2l+1)\sum_{n\neq 0}\frac{k_n(r_{\min})}{k_0}|T_n|^2. \tag{8}$$

Equations (7) and (8) are correct when there is only one bound state below the breakup threshold. If there are more bound excited states below the threshold other than the ground state, the summations in these equations are to be carried out accordingly.

It may be mentioned here that the complete fusion cross-section calculated using eq. (7) is the lower limit of the physical complete fusion cross-section, as the present calculation does not take into account the capture of all projectile fragments (e.g. ^{16}O + p) from the breakup channel. Such events (capture of both the projectile fragments) would also contribute to the complete fusion, but the present model cannot differentiate them from the rest of the events (capture of only one projectile fragment). Furthermore, in the break-up of some halo nuclei (e.g. $^{8}B \longrightarrow {}^{7}Be + p$) [15], the projectile core (^{7}Be) itself is weakly bound and may break up further. The present calculation for the incomplete fusion cross-section (eq. (8)) does not take into account such core break-up. However, inclusion of this type of events in the calculation will only cause a redistribution of the flux for the particle continuum channels keeping σ_{ICF} unchanged.

3. Results and discussion

In the present calculations, the target is assumed to be inert in all cases, i.e., possible excitations of the target are neglected. Both Coulomb and nuclear effects are included in the calculations. In recent measurements with the proton drip line, exotic nucleus ^{17}F in fusion–fission reaction on ^{208}Pb at energies around the Coulomb barrier, no enhancement of the fusion cross-section is observed [4]. In figure 1, we show our calculations on the fusion cross-section for $^{17}F + {}^{208}Pb$ at near-barrier energies along with the data [4]. We have done two sets of calculations. In the first set of calculation (left half of figure 1), we consider only the transition from the ground state of ^{17}F (600 keV below the breakup threshold) into the continuum. In the second set (right half of figure 1), the bound first excited state situated 495 keV above the ground state is also included in the calculation. This

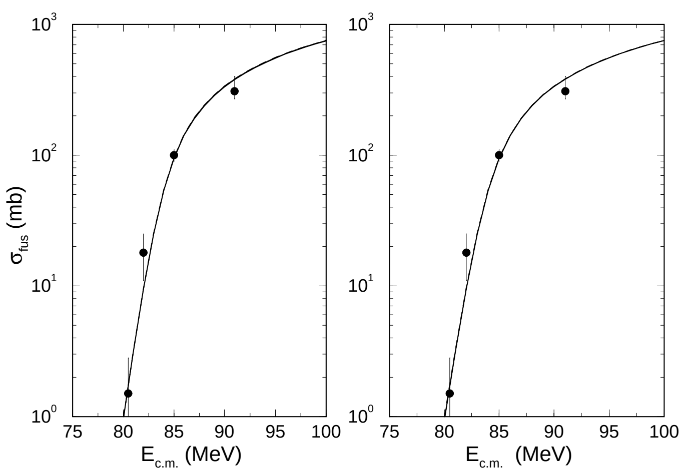

Figure 1. Fusion cross-sections in the $^{17}F + Pb$ reaction at energies around the Coulomb barrier on a semi-log scale. The thick solid line gives the complete fusion cross-sections. The total (complete + incomplete) fusion cross-sections and the fusion cross-sections with zero coupling fall on the same solid thick line. The small differences among the three calculated cross-sections are, however, visible in figure 2. The left part of the figure shows the cross-sections when only the couplings from the ground state of ^{17}F to the continuum are considered. The right part shows the results when the first excited state of ^{17}F has also been included in the calculation (see text). The data giving total fusion cross-sections have been taken from [4].

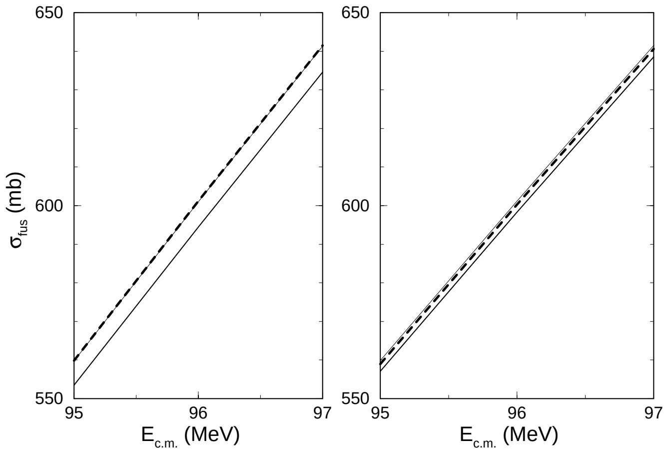

Figure 2. Fusion cross-sections in the ^{17}F + Pb reaction at energies above the Coulomb barrier on a linear scale. The thin solid line gives the cross-sections with zero couplings. The thick solid line and the dashed line give the complete and the total (complete + incomplete) fusion cross-sections respectively. The left part of the figure shows the cross-sections when only the couplings from the ground state of ^{17}F to the continuum are considered. The right part shows the results when the first excited state of ^{17}F has also been included in the calculation.

means that we have considered ground state ($0d_{5/2}$) to first excited state ($1s_{1/2}$) coupling (through quadrupole transition) and also couplings from the first excited state to the continuum. In both the cases, the continuum up to 2 MeV has been considered and it has been found that the results converge. The continuum has been discretized into 10 bins with a bin size of 200 keV. The continuum states have been taken to be situated at the middle of each bin. We consider transitions of multipolarity 1 and 2 for transitions into the continuum, with s-, p-, d- and f-waves in the continuum, for the appropriate transitions. The nuclear part of the valence proton–target interaction, causing the inelastic transition/breakup of ^{17}F, has been taken to be the same as the neutron–target interaction in ref. [13]. The nuclear part of the ion–ion interaction potential has been taken to be equal to that of the neighbouring nucleus ^{16}O on ^{208}Pb at 88 MeV laboratory energy [18]. As far as the structure of ^{17}F is concerned, we assume a single particle potential model in which the valence proton moves in a Coulomb and Woods–Saxon potential relative to ^{16}O core. The parameters of the Woods–Saxon potential (V_0, r_0 and a_0) have been optimised to reproduce the separation energies and the rms sizes of the single particle states [4]. The values of these parameters are $V_0 = 57.03$ MeV, $r_0 = 1.25$ fm and $a_0 = 0.5$ fm. Another optimised set of parameters of the Woods–Saxon potential [19] have been found not to affect the fusion cross-sections.

There is good overall agreement of our calculations with the data. But compared to the no-coupling case, we do not observe any noticeable change of the fusion cross-sections when the channel coupling effects are considered (see left and right parts of figure 1). However, with inclusion of the $1s_{1/2}$ state in the calculation, we see a small increase in the complete fusion cross-sections at above-barrier energies (see left and right parts of figure 2). We have done calculations for lighter targets also (not shown here) and found that the channel coupling effects are even smaller.

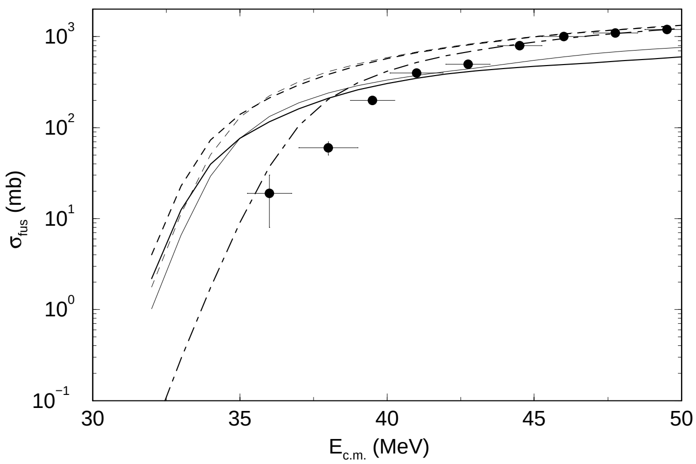

Figure 3. Fusion cross-sections in the ^{11}Be + Pb reaction at energies around the Coulomb barrier. The dash-dotted line gives the cross-sections with zero couplings. The thin solid line and the thin dashed line give the complete and the total fusion cross-sections respectively when only the couplings from the ground state of ^{11}Be to the continuum are considered. The thick solid line and the thick dashed line show the complete and the total fusion cross-sections respectively when the first excited state of ^{11}Be has also been included in the calculation (see text). The data, taken from [5], show the total fusion cross-sections on a Bi target.

However, the observations are much different when fusion cross-sections have been computed for the one-neutron halo nucleus on a Pb target. In this case, our calculations are different from those reported in ref. [13] as mentioned below. (i) We take into account the proper rms size, 2.91 fm [20], of the ^{11}Be nucleus in its ground state. In ref. [13], this was obtained from $r_0 A^{1/3}$, with $r_0 = 1.1$ fm. This gives a rms size of 2.45 fm, which underestimates the actual size by almost 20%. (ii) The first excited state of ^{11}Be, situated at 320 keV with respect to the ground state, has also been included in the present calculation, which was not considered in ref. [13]. (iii) Unlike ref. [13], where the continuum up to 2 MeV has been considered, we consider the continuum up to 8 MeV, thereby ensuring convergence of the results. However, the continuum discretization scheme is the same as that for ^{17}F. (iv) Continuum–continuum couplings have also been considered in the present calculations. (v) We consider dipole transitions only, as we have found contributions from higher multipoles beyond this to be insignificant. But unlike the treatment of ref. [13], in which only $p_{3/2}$ waves in the continuum are considered, we consider s-, p- and d-waves in the continuum. The couplings, corresponding to dipole transitions, have been taken appropriately. It should be mentioned that in ref. [21] it was shown that only first-order dipole transitions in the low energy continuum could explain the experimental data and there was no necessity in considering the effect of continuum–continuum coupling. But this was a Coulomb dissociation measurement at an energy of 72 MeV/A which is much higher than the energies considered here. But even in our present calculations at the near-barrier energies, we have observed that the effects of higher multipole couplings and continuum–continuum couplings on the fusion cross-sections are minimal.

We display the results in figure 3 along with the data on total (i.e. complete plus incomplete) fusion cross-section on a ^{209}Bi target [5], the neighbouring nucleus of ^{208}Pb, since the data on a Pb target is not available for ^{11}Be induced fusion. When only couplings from the ground state to the continuum are considered, we see significant enhancement of the sub-barrier complete and total fusion cross-sections, and suppression of complete fusion cross-sections at energies above the barrier. Above the Coulomb barrier, the total fusion cross-sections gradually become identical with the cross-sections obtained in the no-coupling limit. With inclusion of the first excited state of ^{11}Be in the calculation the total fusion cross-sections remain almost the same at energies above the barrier. But both the complete and the total fusion cross-sections become larger below the barrier, by almost a factor of two at smaller energies. However, there is significant decrease ($\sim$21%) of the complete fusion cross-sections at above-barrier energies when additional couplings with the first excited state are considered (see the two solid lines). Since complete fusion occurs when ^{11}Be is absorbed by the target in its ground state as well as in the bound excited state, this indicates that a considerable amount of flux goes into inelastic excitation of ^{11}Be to its first excited state. This is in agreement with the fact that this transition is known to be one of the strongest dipole transitions, with a $B(E1)$ value equal to 0.36 ± 0.03 W.u. [22].

In figure 3, the agreement of the total fusion cross-sections with the data is good at above-barrier energies. However, there are large error bars in the data, both in the horizontal and vertical directions, at sub-barrier energies. At low energies, there are only a few data points. Further high-precision measurements, especially on complete fusion cross-sections are suggested. We expect that it would reveal the importance of including the first excited state of ^{11}Be in the calculation.

Recently, a coupled channel calculation for the fusion cross-section of ^{11}Be on ^{208}Pb has been reported in the literature [23]. In that calculation, the fusion cross-sections above the barrier were found to be underestimated (by $\approx$41%), whereas for the energies below the barrier the calculated values appeared to be in fair agreement with the data. Contrary to the above, the present calculations reproduce the data quite well above the barrier energies but overestimate the data at below-barrier energies, where the data has large uncertainities (as discussed earlier). Though the present calculations and those of ref. [23] are similar in nature yet there are three major differences: (i) The present calculations take into account up to dipole transitions, whereas in ref. [23] higher multipoles have also been considered. It should be mentioned that we have seen in our calculations that contributions of higher multipoles are minimal. (ii) In ref. [23] an absorptive potential inside the barrier has been introduced for calculating complete fusion cross-sections. On the other hand, the present calculations use incoming wave boundary condition to calculate the complete fusion cross-section. Thus the two calculations are formally different. (iii) Thirdly and most importantly, unlike ref. [23] where inclusion of continuum–continuum couplings have been found to significantly reduce the fusion cross-sections below the barrier, we are unable to see this effect in the present calculations.

The difference in features of the fusion cross-sections in reactions induced by ^{17}F and ^{11}Be could be attributed to different structures of these two nuclei. The dominant ground state configuration of ^{11}Be is $^{10}\mathrm{Be}(0^+)\otimes\nu(1\mathrm{s}_{1/2})$, whereas for ^{17}F it is $^{16}\mathrm{O}(0^+)\otimes\pi(0\mathrm{d}_{5/2})$. The valence proton in ^{17}F feels the Coulomb barrier and the $\ell=2$ centrifugal barrier unlike the valence neutron in ^{11}Be which interacts only via nuclear potential with the ^{10}Be core and does not experience any centrifugal barrier. Therefore, although the one-nucleon separation energies are almost the same (0.504 MeV in ^{11}Be and 0.6 MeV in ^{17}F), breakup through one-nucleon removal is much more favoured in the case of ^{11}Be as compared to ^{17}F. We expect that breakup of ^{17}F will have little bearing on its fusion cross-section at near-barrier energies. This is also true so far as its inelastic transition to the first excited state is concerned. Dynamical calculations in ref. [4] also show that the excitation/breakup probabilities of ^{17}F are small enough to affect the fusion process significantly. On the other hand, the cross-sections are very large for excitation/dissociation of ^{11}Be on a heavy target [21]. Due to the large size, there is more chance of lowering of the fusion barrier in the case of ^{11}Be. In fact, the ^{11}Be rms radius is 2.91 fm, $\sim$20% larger than that obtained from the systematics, and consequently the Coulomb barrier is about 1.6 MeV lower. However, ^{17}F is a usual nucleus in this sense with an almost normal size of 3.04 fm [19].

4. Summary and conclusions

In summary, we have performed coupled channel calculations of fusion cross-sections in reactions induced by the exotic nuclei ^{17}F and ^{11}Be on Pb target. We include couplings to the inelastic and breakup channels of the projectiles. For ^{17}F induced reaction, there is no modification of the fusion cross-sections as compared with the no-coupling case. This is due to the small breakup probabilities of ^{17}F even on a heavy target. The ^{17}F nucleus could exhibit a halo structure in its first excited state which has very low binding energy and that could affect the fusion cross-sections when this state is coupled to the ground state or continuum. However, contrary to expectations, we have not observed any significant effect on fusion cross-sections, which may be a consequence of the suppression of the long tail of the wave function due to the Coulomb barrier. On the other hand, ^{11}Be is an established one-neutron halo nucleus with a well-developed halo structure, and consequently has large probabilities of undergoing dissociation. This is reflected in the large enhancement of the sub-barrier complete and total fusion cross-sections, and suppression of the complete fusion cross-sections at energies above the Coulomb barrier. The suppression becomes less when additional couplings from the only bound excited state of ^{11}Be are taken into consideration. This is due to the strong dipole transition between the ground state and the first excited state of ^{11}Be, which also contributes to the complete fusion cross-section. However, the effects of continuum–continuum couplings on the fusion cross-sections have been found to be minimal in both cases studied here.

Acknowledgements

Fruitful discussions with Andrea Vitturi are gratefully acknowledged.

References

[1] W Loveland, in *Proceedings of the Third International Conference on radioactive nuclear beams* edited by D J Morrissey (Editions Frontières, Gif-sur-Yvette, 1993) pp. 526–536

[2] P G Hansen, A S Jensen and B Jonson, *Ann. Rev. Nucl. Part. Sci.* **45**, 591 (1995) and references therein

[3] J Takahashi *et al*, *Phys. Rev. Lett.* **78**, 30 (1997)

[4] K E Rehm *et al*, *Phys. Rev. Lett.* **81**, 3341 (1998)
[5] C Signiorini *et al* , *Euro. Phys. J.* **A2**, 227 (1998)
[6] J J Kolata *et al*, *Phys. Rev. Lett.* **81**, 4580 (1998)
E F Aguilera *et al*, *Phys. Rev. Lett.* **84**, 5058 (2000)
[7] M Dasgupta *et al*, *Phys. Rev. Lett.* **82**, 1395 (1999)
D J Hinde *et al*, *Phys. Rev. Lett.* **89**, 272701 (2002)
[8] M Trotta *et al*, *Phys. Rev. Lett.* **84**, 2342 (2000)
[9] V Tripathi *et al*, *Phys. Rev. Lett.* **88**, 172701 (2002)
[10] M S Hussein, M P Pato, L F Canto and R Donangelo, *Phys. Rev.* **C46**, 377 (1992)
[11] N Takigawa, M Kuratani and H Sagawa, *Phys. Rev.* **C47**, R2470 (1993)
[12] C H Dasso and A Vitturi, *Phys. Rev.* **C50**, R12 (1994)
[13] K Hagino, A Vitturi, C H Dasso and S M Lenzi, *Phys. Rev.* **C61**, 037602 (2000)
K Hagino and A Vitturi, http://arxiv.org/nucl-th/0009013
[14] R Chatterjee, P Banerjee and R Shyam, *Nucl. Phys.* **A675**, 477 (2000)
[15] P Banerjee, K Krishan, S Bhattacharya and C Bhattacharya, *Int. J. Mod. Phys.* **E11**, 491 (2002)
[16] K Hagino, N Takigawa, A B Balantekin and J R Bennett, *Phys. Rev.* **C52**, 286 (1995)
[17] S Landowne and S C Pierper, *Phys. Rev.* **C29**, 1352 (1984)
[18] F Videbaek *et al*, *Phys. Rev.* **C15**, 954 (1977)
[19] K Krishan, P Banerjee and R Bhattacharya, http://arxiv.org/nucl-th/0109069
[20] P Banerjee, I J Thompson and J A Tostevin, *Phys. Rev.* **C58**, 1042 (1998)
[21] T Nakamura *et al*, *Phys. Lett.* **B331**, 296 (1994)
[22] D J Millener *et al*, *Phys. Rev.* **C28**, 497 (1983)
[23] A Diaz-Torres and I J Thomson, *Phys. Rev.* **C65**, 024606 (2002)