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Fusion and breakup of weakly bound nuclei

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Abstract. In this paper the phenomenon of heavy ion fusion at low energies is discussed, with special emphasis given to the fusion of loosely bound stable and unstable projectiles. A review of the experimental methods and techniques used to measure the fusion and the breakup cross section is also presented, and the experimental challenges encountered in the measurement of the fusion cross section of these systems are pointed out. The theoretical description of the fusion of these loosely bound nuclei is reviewed.

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1. Introduction

Over the last two decades nuclear physics acquired new tools which allowed the experimental investigation of very loosely bound radioactive (rare) isotopes (both neutron- and proton-rich). Notorious among these nuclei are those that exhibit the halo feature: as more neutrons are added or removed, the nucleus becomes favorable to an equilibrium configuration containing a rather inert core plus one or two extra neutrons (protons), very loosely bound and circulating around the core in an orbit whose radius far exceeds that of the core. This halo structure has been confirmed in several cases. Systems such as ^{11}Li, ^{6}He and ^{14}Be are considered as two-neutron Borromean halo nuclei; none of the individual neutron forms a bound state with the core, let alone the two neutron subsystem. The binding of the three-body system

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happens just like the Borromean rings.

The nuclei ^{11}Be and ^{19}C are one-neutron halo, while ^{8}B is a one-proton halo. An important feature of these exotic nuclei is their dipole response. They exhibit the so-called soft dipole resonance, a threshold phenomenon reminiscent of the Feshbach resonance widely used in manipulating gases of cold atoms. Another important feature is the low threshold of breakup reactions owing to the small binding energy of the excess neutrons or protons. In recent years the effects of these features on the fusion of these nuclei with heavy targets has received considerable attention from theorists and experimentalists. In [1], [2] and [3] it was suggested that the excitation of the soft mode would increase the fusion cross section at sub-barrier energies. It was later realized [4] that the excitation of the soft mode is necessarily accompanied by the breakup of the projectile, which ends up erasing the enhancement and may replace it by a reduction of the fusion compared to the prediction of the barrier penetration model (BPM). Conflicting conclusions concerning the effect of breakup on the fusion of exotic nuclei ensued [5]. An important feature of collisions of weakly bound nuclei is that the breakup mechanism may give rise to different types of fusion. To illustrate this point, we consider collisions of a weakly bound projectile, which may break up into two or more fragments. The first type of fusion is the *Complete Fusion* (CF), in which the compound nucleus (CN) contains the whole masses of the projectile and the target. If no breakup occurs, and the fusion takes place in a single step, the process is called *Direct Complete Fusion* (DCF). Other fusion reactions may occur when the projectile breaks up as it approaches the target. If all the projectile's fragments are sequentially absorbed by the target, the process is called *Sequential Complete Fusion* (SCF). Since the CN contains all the projectile's and target's nucleons, SCF is a type of CF. Another type of fusion following breakup is the *Incomplete Fusion* (ICF). In this case, at least one charged fragment is absorbed by the target while part of the projetile's mass moves away from the interaction region. The sum off all fusion processes is called *Total Fusion* (TF) and the corresponding cross section is

$$\sigma_{TF} = \sigma_{CF} \; + \; \sigma_{ICF} \, . \tag{1}$$

It may also happen that the projectile breaks up but none of its fragments fuses with the target. In this case, the reaction is called *Non-Capture Breakup*[1] (NCBU). The corresponding cross section would contain all possible target excitations.

Several experiments were performed to assess the situation. In particular, fusion measurements of easily breakable stable nuclei such as ^{6}Li, ^{7}Li and ^{9}Be with heavy targets were reported and the above mentioned reduction in the fusion cross section was confirmed [6–8]. The fusion of halo nuclei was also measured by different groups. Very recently, it was found that in the reaction of ^{6}He with ^{238}U at near and sub-barrier energies, the complete fusion was comparable to that of ^{4}He. At sub-barrier energies, the two-neutron transfer cross section was found to be much larger than

[1] Non-capture breakup is frequently called *Elastic Breakup*. We do not use this term to avoid confusion with the exclusive breakup process in which the target is left in its ground state.

the CF [9]. For the ^{6}He + ^{208}Bi system, it was also observed that the 2n-transfer is the process with largest cross section at sub-barrier energies [10, 11]. Fusion cross sections of ^{11}Be projectiles were also measured [12, 13]. Several measurements of fusion cross sections in collisions of stable weakly bound nuclei with light targets have been performed [14–19]. Recently, measurements of fusion cross sections in collisions of ^{6}He with light targets have been reported [20, 21].

From the theory side, a detailed Continuum Discretized Coupled Channels (CDCC) calculation was reported for the fusion of ^{11}Be with ^{208}Pb [22]. It was difficult to draw definitive conclusions concerning the complete fusion cross-section as this method cannot evaluate the contribution from the sequential process. The calculation of the incomplete fusion within the CDCC, needed to obtain the complete fusion, is still being investigated [23]. In another paper [24] a more restricted CDCC, with no continuum channel-channel coupling, gave enhanced total fusion at sub-barrier energies and a reduced one at above-barrier energies.

The status of the fusion of weakly bound stable and unstable nuclei is therefore that of an ongoing extensive effort both in theory and experiment. Recent reviews on these subjects can be found in refs. [25, 26]. It is our aim here to give a summary of the work of ref. [25]

2. Fusion and breakup of weakly bound nuclei

The fusion of weakly bound nuclei differs in a fundamental way from that of tightly bound ones in so far as the influence of the breakup channel is concerned. Whereas this channel does play an important role in reducing the fusion cross section of the latter well above the Coulomb barrier, the effect in the former is felt in the vicinity of the Coulomb barrier, owing to the small Q-value involved. As discussed in the previous section, breakup is followed by SCF, ICF or NCBU. In this way, DCF, SCF, ICF or NCBU are competing processes. Since SCF is a process of higher order it is unlikely to have a large cross section. From the experimental point of view, it is very difficult to distinguish CF from ICF. It has only been possible for some particular projectile-target combinations. For this reason, operational definitions of CF and ICF are usually adopted: CF is defined as the process in which the total projectile charge fuses with the target while ICF occurs when some charged fragment survives the fusion process. The different processes that can take place in a collision of a weakly bound projectile are depicted in figure 1, in a varying degree of complexity. Is this example, the projectile may breakup into two fragments. The CF cross section, σ_{CF}, is the sum of its DCF and SCF contributions,

$$\sigma_{CF} = \sigma_{DCF} + \sigma_{SCF}. \tag{2}$$

If both fragments represented in figure 1 are charged, the ICF cross section is given by the sum

$$\sigma_{ICF} = \sigma_{ICF1} + \sigma_{ICF2}. \tag{3}$$

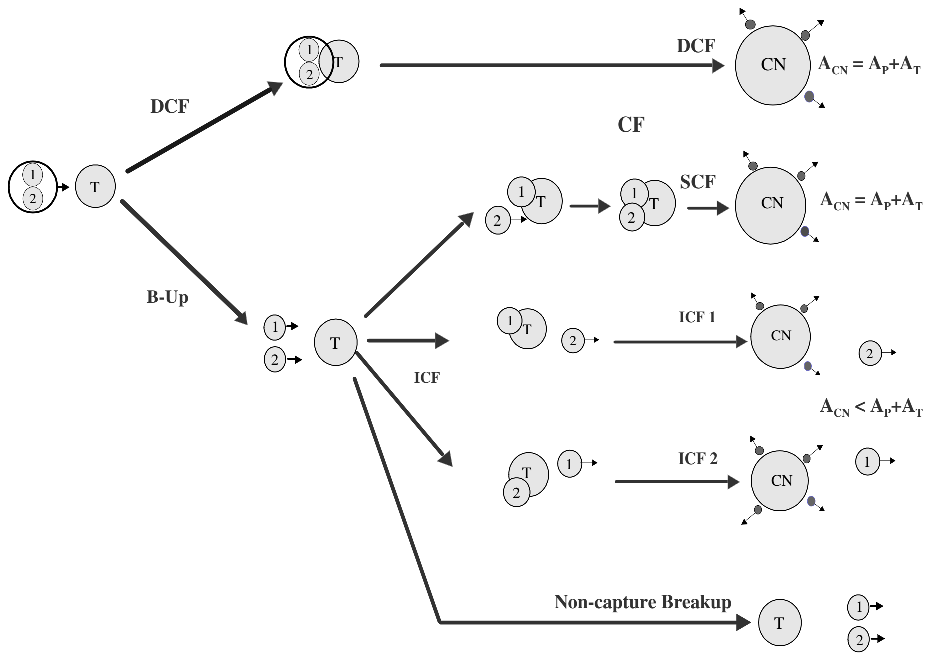

Fig. 1. Schematic representation of the fusion and breakup processes that can take place in the collision of a weakly bound projectile. For simplicity we assume that the breakup produces two fragments. The generalization of this situation is straightforward.

We should emphasize that if one of the fragments is uncharged, its capture does not correspond to ICF. It would be only a mass transfer, such as seen in the ^{6}He + ^{238}U system [9], where the two neutrons in the halo are transfered to the target.

The difficulty in measuring CF and ICF renders the study of the fusion of weakly bound nuclei quite challenging. Further, this difficulty is shared by theory as well. In order to account for both CF and ICF one needs to develop a three-body reaction theory with absorption. Not having such a theory currently available one resorts to approximate schemes. The breakup channel is described by the Continuum Discretized Coupled Channel (CDCC) method. The continuum that describes the breakup channel is discretized into bins [27, 28]. Since the resulting many coupled-channels still represent a binary system [22], this method cannot evaluate the contribution from the sequential process to the CF cross section and their estimates of the ICF cross sections may be inaccurate. Other approaches rely on the use of formulae developed for inclusive breakup to calculate the ICF cross section [29, 30]. Extending such description to the calculation of CF requires the introduction of genuine three-body optical potential [31], a rather alien concept to conventional reaction theory.

As already mentioned, the initial theoretical studies of sub-barrier fusion with these nuclei gave conflicting predictions. Some authors found that the coupling to the breakup channel reduced the cross section [4, 32–34], while others encountered an enhancement [5]. As most of these calculations were schematic, involving either semiclassical assumptions or gross approximations in the treatment of the continuum, more detailed coupled-channel calculations were clearly needed to shed light on this discussion.

A theory for the reactions of weakly bound nuclei should take into account two aspects. The first is the longer tail of the optical potential, arising from the weakly bound nucleons. The second is the strong coupling between the elastic channel and the continuum states representing the breakup channel. These features have strong influence on all reaction channels but they are particularly important for the fusion cross section.

In collisions of weakly bound projectiles with strongly bound targets it is safe to assume that the target remains intact. Its contribution to the breakup process is through the Coulomb and nuclear forces that disrupt the projectile nucleus. Let us then consider the breakup of the projectile P into two fragments F_1 and F_2.

The CDCC calculations describing the breakup of a projectile P are performed replacing the continuum by a finite number of configurations of the $P = F_1 + F_2$ system [35]. The energies of these internal excitations are assumed to extend to some maximum energy, characterized by the relative wave number q_{max}. The inclusion of continuum-continuum couplings in calculations of fusion cross sections is fundamentally important. If they are neglected, the CDCC calculations predict strong enhancements of the TF and CF cross sections at energies around and below the Coulomb barrier. The inclusion of continuum-continuum couplings changes completely this picture: the CF cross section is suppressed in the barrier region and the enhancement only appears at much lower energies. In addition to continuum-continuum couplings, it is also necessary to include a wide range of continuum states to get convergence in the CDCC calculations. The space and the couplings of a typical CDCC calculation are illustrated in figure 2. The figure represents in a schematic way, bound and discretized states of ^{11}Be, together with their couplings. The solid arrows correspond to couplings between bound and continuum states, while the dashed arrows represent continuum-contiuum couplings. Since each continuum state is coupled to many other continuum states, it is unlikely that its population returns to a bound state. In this way, continuum-continuum couplings contribute to the irreversible nature of the breakup channel, found in realistic CDCC calculations.

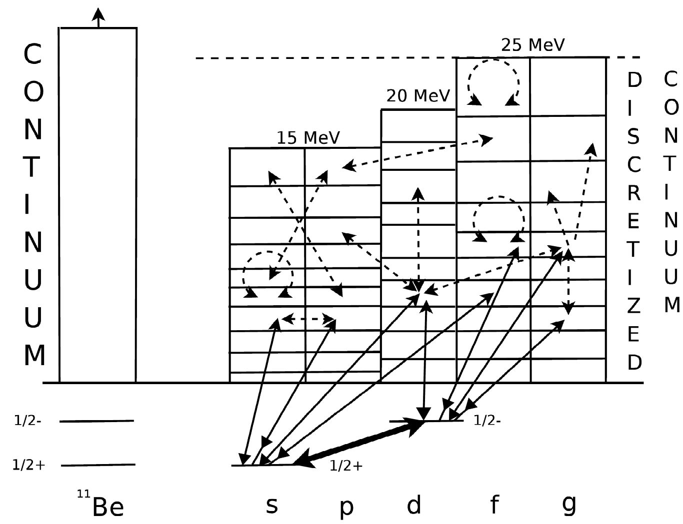

Fig. 2. Schematic representation of bound and continuum states and their couplings in a CDCC calculation for ^{11}Be. Further details are given in the text.

3. Discussion and conclusions

The experimental techniques to measure fusion cross sections include the direct detection of fusion-evaporation residues, fission fragments, and also the direct detection of alpha particles and γ and X-rays emitted by the residues. The identification of the particles is performed by $E - \Delta E$ telescopes, time-of-flight devices, and coincidence measurements. Typical detection devices for reactions involving radioactive nuclei require a much higher efficiency than those for stable nuclei. Coincidence measurements between the breakup fragments and between those and gamma rays have allowed the measurement and identification of breakup, transfer and ICF processes.

The theoretical treatment of the fusion and breakup processes of weakly bound nuclei is very complex. It should include several reaction mechanisms such as the usual complete fusion and direct transfer processes and the breakup itself. This last process can be followed by the capture of one or more of the projectile fragments by the target nucleus. Some still open questions in this area are: How does the breakup channel affect the CF or TF processes at energies below and above the barrier, according to target mass? How important are the relative contributions from the nuclear and Coulomb breakup couplings for such systems? Thus far, no theory can fully account for the whole complexity of the breakup process and the following interactions between the fragments and the target.

Weakly bound nuclei, specially radioactive halo nuclei, are associated with a long tail of the optical potential and are subject to strong coupling between the elastic channel and the continuum states. Presently the CDCC are the most reliable calculations for reactions involving those nuclei, although more schematic models related to dynamic polarization potentials and semiclassical CC calculations have been useful for such studies.

At present there is a large amount of experimental data on the fusion cross section of stable weakly bound projectiles, mostly at energies close and above the Coulomb barrier, mainly for heavy targets. However, most of these data corresponds to TF cross sections. Few experiments have been reported concerning the fusion of radioactive weakly bound projectiles, either neutron- or proton-rich. Recently efforts have been made to perform exclusive measurements of the breakup itself. Experiments on elastic scattering of weakly bound nuclei allow the study of the threshold anomaly phenomenon and the derivation of reaction cross sections.

The main conclusions from the available experimental data are (for details see ref.[25]:

1. For stable, weakly bound projectiles and heavy targets, there is a CF suppression at energies above the barrier, which can be of the order of 30% of the CF-cross section that would be expected if no breakup occurred. This suppression is attributed to the ICF process. The TF-cross section does not seem to be affected by the breakup channel.

2. For these systems, at energies below the Coulomb barrier, no significant effect (neither enhancement nor suppression) has been observed. Due to the uncertainties in the theoretical calculations employed to compare with the data, no strong conclusion can be drawn.

3. For stable weakly bound projectiles and light and medium mass targets, the possible CF suppression is not clearly observed, since ICF is not as significant as for heavy targets. Most of the fusion cross sections measured for such systems correspond to TF, which, even for heavy targets, is not much affected by the breakup channel.

4. The non-capture breakup occurs at energies both above and below the barrier. For $E > V_B$ it is found that the non-capture breakup plus transfer cross section is smaller than total cross section for fusion. At sub-barrier energies, however, there are experimental evidences that the opposite situation occurs.

5. The usual threshold anomaly in the elastic scattering, present in the scattering of tightly bound projectiles, was not observed in the scattering of ^{6}Li and there are contradictory evidences on its existence in the scattering of ^{7}Li and ^{9}Be. The vanishing of the TA is attributed to a repulsive polarization potential which arises from the breakup process.

6. Concerning the fusion of radioactive beams, there is no evidence of a significant effect at energies above the barrier, as compared with the fusion of stable isotopes. At sub-barrier energies there are contradictory results. While for ^{6}He + ^{238}U and ^{17}F + ^{208}Pb there is no enhancement when compared with the stable isotope (actually some suppression can be observed) a large enhancement was observed for the ^{6}He + ^{209}Bi system. On the basis of the available data, one can identify no systematic difference between the radiactive beam-induced fusion and the fusion induced by the corresponding stable isotopes.

7. For the radioactive beams, the behavior of the non-capture breakup is qualitatively similar to that of stable weakly bound nuclei: at sub-barrier energies is much larger than the fusion cross section, and it is smaller than the fusion cross section at energies above the barrier. The reaction cross section is significantly increased when compared with that induced by tightly bound projectiles both for heavy and light targets.

It is a still open question the importance of direct transfer processes in reactions induced by weakly bound projectiles and its differentiation from the ICF process. There is a strong need for more exclusive experiments concerning breakup, transfer and ICF processes in order to clarify this point.

In so far as the usual analysis of possible fusion suppression or enhancement, one should be aware that the conclusions may vary drastically depending on the optical potential employed, the CC calculations, and the way that one compares different systems. "Realistic" nuclear potentials are usually employed, for which the range of acceptable parameters may be questioned and which may lead to contradictory conclusions. The use of potentials that fit elastic scattering angular distributions may also be not a reliable procedure. A strong constraint for the potential paramenters that may be used is the experimental derivation of fusion barrier distributions, which should be matched by the potential. Recently the use of a reliable double-folding potential (São Paulo potential) has been proposed for systems that have not derived barrier distributions.

On the theoretical side, as already mentioned, CDCC calculations are presently the most reliable. For heavy targets, they predict a suppression of the CF cross section above and near the Coulomb barrier, whereas an enhancement is also predicted, although at lower energies, much below the barrier. Therefore, the breakup coupling has a distinctly different role on the fusion when compared to coupling to inelastic channels, in the sense that the latter gives rise to enhancement of the fusion cross section around and below the Coulomb barrier while the former does not. Thus, the breakup coupling tends to be irreversible and, accordingly incoherent, while that of inelastic or transfer channel is reversible and coherent. The available data on the complete fusion of nuclei such as ^{6}Li, ^{7}Li, ^{9}Be on heavy targets seem to support the general conclusion that breakup coupling leads to suppression, except at very low energies. At these energies, this coupling becomes virtual and gives rise to an adiabatic attractive correction to the Coulomb barrier, which leads to enhancement of the tunneling probability compared to the one-dimensional barrier penetration model (no coupling) limit. When the continuum space is large enough and continuum-continuum couplings are included in a CDCC calculation, the process acquires statistical character, which leads to the above mentioned irreversibility. It is evident that the full description of fusion and breakup requires a three-body theory (considering only two projectile fragments). The CDCC cannot deal with this situation, especially the calculation of the individual incomplete fusion of each fragments and the sequential fusion (breakup fusion). The CDCC can supply the total incomplete fusion (fusion from the continuum). Thus the complete fusion of CDCC (fusion from the bound states) misses the sequential complete fusion. The total fusion suffers from the same shortcoming. Classical three-body theories, such as the Classical Trajectory Monte-Carlo model can handle this situation but there is no tunneling. Quantal three-body models require powerful computer resources. Simple spectator-inspired models supported to an extent by the irreversible nature of the continuum can supply upper limits to ICF and SCF.

Concerning the elastic scattering of weakly bound nuclei, measurement for neutron rich nuclei near the Coulomb barrier have shown great reduction when compared to similar mass tightly bound nuclei scattering. This stems from the long range absorption due to the coupling to the breakup channel. Both CDCC calculations and those based on the explicit use of the dynamic breakup polarization potential account nicely for the available data on ^{6}He + ^{208}Pb at near barrier energies. There is evidence that the breakup polarization potential has a repulsive real part, which gives credence to a slight increase of the effective barrier, leading to the above mentioned hindrance in the tunneling and thus fusion. The decrease in attraction and increase in absorption of the optical potential as the energy is lowered below the barrier, may hint to a different type of threshold anomaly in the scattering of weakly bound nuclei.

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