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Coulomb- and nuclear-induced break-up of halo nuclei at bombarding energies around the Coulomb barrier

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Abstract

We investigate the relative importance of the Coulomb and nuclear fields to induce the break-up of neutron-rich nuclei such as ^{11}Li at energies close to the Coulomb barrier. We assume that the mechanism that leads to the separation is the excitation of a low-lying dipole mode in which the weakly-bound neutron halo performs a collective oscillation against the residual nuclear core. To this end we exploit semiclassical prescriptions that are adequate to calculate not only the average break-up probabilities but also to estimate the size of fluctuations about the quantal expectation values. Possible outcomes are explored as a function of both bombarding energy and impact parameter. Consequences of the couplings for elastic scattering and fusion processes are also discussed.

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1. Introduction

In the study of nuclei far from the stability line special attention has been devoted to extremely neutron-rich systems such as ^{11}Li. In this specific case the very small binding energy of the last two neutrons causes their density distribution to extend considerably far from the ^{9}Li core, in a sort of diluted nuclear halo. This peculiar situation is reflected in the characteristic response of the system to external electromagnetic and nuclear probes. In fact, break-up processes induced by the collision of ^{11}Li nuclei with different targets have put in evidence the presence of unusual concentrations of strength at low excitation energies [1,2]. Whether this observation can be associated with the existence of a soft-

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dipole mode in which the weakly-bound neutron halo performs collective oscillations against the residual nuclear core is still under debate.

In the implementation of reaction formalisms a microscopic or macroscopic description of the two-neutron system is needed. Different models have been contemplated for this purpose; they range from those incorporating a strong correlation between the particles (cluster model) to those based on an independent-particle picture [3,4]. The role of Coulomb dissociation in connection with these plausible scenarios was investigated in a variety of circumstances. Studies have, however, concentrated in the high-energy regime at which experimental data are available and where the simple straight-line dynamics allows for closed analytical expressions of the Coulomb excitation probabilities [5,6]. At these energies and for large impact parameters the dipole component of the Coulomb field is the dominant coupling that induces the electromagnetic dissociation of the ^{11}Li projectiles. Far more controversial is, on the other hand, the contribution to the break-up process arising from the nuclear interactions. This is specially sensitive to the single-particle and collective aspects introduced by the chosen description of the di-neutron system and of the reaction mechanism.

In addition to the study of break-up events induced by currently available ^{11}Li beams a radically different regime of bombarding energies and processes is under consideration; one for which a better understanding of the prevailing mechanisms becomes more crucial. We refer to central collisions near the barrier, i.e. initial conditions that are likely to involve a substantial probability for fusion. The effect of the Coulomb field in the excitation process has recently been studied in terms of polarization potentials in Refs. [19,20].

It has been known for a long time that fusion cross sections reflect the gradual increase of the nuclear radii for the heaviest isotopes of a given element by a systematic reduction of the effective barrier height. This per se is an important consideration in favor of neutron-rich beams, since the same level of cross section for the formation of a given element can be obtained at a lower bombarding energy (and, therefore, at the low excitation energies that prevent re-separation). A neutron excess in the projectile is also convenient as it helps to form compound systems that are closer to the stability valley.

If neutron-rich nuclei—and, specifically, systems with weakly-bound neutron halos—do exhibit a soft-dipole mode there should be additional dynamical consequences affecting the fusion process. The mechanism by which such an internal degree of freedom may further contribute to enhance the fusion probability at subbarrier energies was discussed in Refs. [7,8]. Basically, the polarization of the projectile induced by the Coulomb field brings the neutron halo closer to the target; the larger overlap of the nuclear densities and the resulting attractive forces can then drive the systems into fusion confronting a substantially lower resistance.

A characteristic of low-lying collective vibrations is that the associated restoring forces are relatively small. Naturally, then, the *same* polarization mechanism that favors the process of nuclear fusion in the way outlined above has the potential to induce separations of the halo from the ^{9}Li core that stretch beyond the point that can be sustained by the weak residual forces that hold them together. The relevance of this break-up process of ^{11}Li at the bombarding conditions that may lead to fusion has been a matter of recent controversy [9-11]. To address the many questions associated with this issue one aspect of the problem that should be quantitatively examined is the actual role played by the nuclear couplings. Some calculations have been made to estimate the nature of these effects, for instance in Ref. [12]. In that work, however, the competition of nuclear effects with Coulomb break-up was analyzed for the high-energy regime and the results therefore do not directly apply to the fusion studies in the near-barrier domain we consider here.

The purpose of this contribution is to investigate the interplay of fusion, break-up and elastic scattering processes in reactions involving halo nuclei. To this end we exploit semiclassical techniques that have proven to be quite accurate and reliable in the study of reaction phenomena at energies close to the Coulomb barrier. It will here be assumed that the aforementioned processes are indeed conditioned by the excitation of a low-lying dipole mode involving the weakly-bound neutron halo and the residual nuclear core.

The organization of the paper is as follows. In the next section we construct basic ingredients of the formalism, namely the diagonal and off-diagonal elements of the coupling between relative motion and intrinsic states. In Section 3 we introduce the actual dynamical model and the prescriptions that are used to estimate quantitatively the probabilities for the various processes. Calculations for the reaction ^{11}Li+^{208}Pb illustrate in Section 4 the results of the scheme. A brief summary and conclusions close the presentation.

2. Effective interactions and form factors

We begin by identifying the interactions between the two reaction partners and the relevant internal degrees of freedom excited in the collision. As is well known, effective ion-ion interactions incorporate the dynamic response of the reacting nuclei in a rather complicated way. The zeroth-order static potential can, however, be directly obtained from the equilibrium nuclear densities of the colliding systems. For excitation of collective modes this diagonal term of the interaction is specially useful, since it also provides a key to constructing off-diagonal elements of the coupling matrix [13].

To calculate the static ion-ion potential the proton and neutron densities of both reaction partners are needed. We performed density calculations for ^{208}Pb in the mean-field approximation, solving the Hartree-Fock equations with a Skyrme III interaction. In the case of ^{11}Li we used the Hartree-Fock procedure only to evaluate the proton and neutron densities associated with the ^{9}Li core. For the density of the valence neutrons we adopted the same parametrization as in Ref. [7], namely

$$\rho_h(r) = \frac{\kappa}{\pi}\frac{\exp(-2\kappa r)}{r^2}, \tag{1}$$

where the exponential slope parameter κ is related to the separation energy, $\epsilon = 0.3$ MeV. This expression is consistent with the exponential decay of the di-neutron wave function

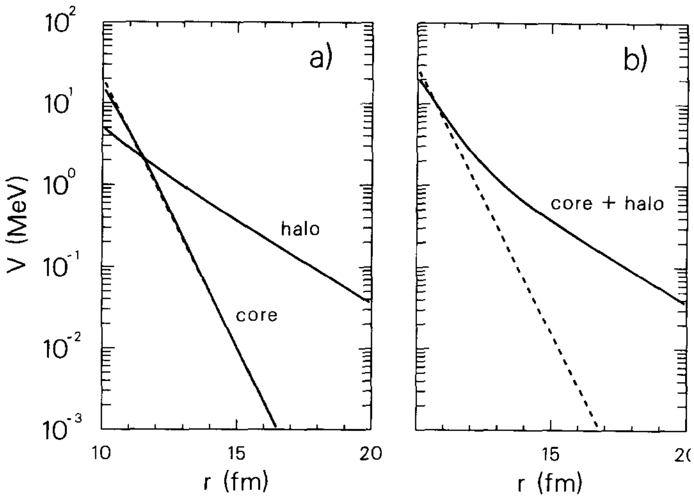

Fig. 1. (a) Components of the folded nuclear potential for the system ^{11}Li+^{208}Pb, arising from the core and halo densities in ^{11}Li. The dashed line represents the ^{9}Li+^{208}Pb potential obtained according to the Akyüz-Winther parametrization. For details on densities and nucleon-nucleon interaction, see text. (b) Total folded potential (solid line) for the system ^{11}Li+^{208}Pb, in comparison with the corresponding potential obtained according to the Akyüz-Winther parametrization.

in the force-free region [3]. Its behaviour near the origin, however, tends to lower the density values in the tail by about 20% when compared with other parametrizations [14,15].

Following this prescription, the ion-ion potential obtained by double-folding an effective nucleon-nucleon interaction with the total densities of the two reaction partners is divided into the separate contributions $V_c(r_c)$ and $V_h(r_h)$ associated with the interaction of ^{208}Pb with the core and halo densities of ^{11}Li. The two components are shown in Fig. 1a. Both the isoscalar and isovector terms in the nucleon-nucleon interaction were included; the M3Y potential was used for the isoscalar part and the effective interaction of Love for the isovector term [16]. The prolonged tail of the halo density is directly reflected in the long range of the corresponding contribution to the ion-ion potential. To appreciate the unusual consequences of the valence halo, we also show in Fig. 1a the potential for the ^{9}Li+^{208}Pb system obtained with the standard parametrization of Akyüz-Winther [17]. The results are found to hold extremely close to the actual microscopic double-folding calculation, in spite of the rather large $N/Z = 2$ ratio in ^{9}Li. The two contributions are summed and again compared with the parameterized potential for ^{11}Li+^{208}Pb in Fig. 1b. One notes here that the limited dependence on $(N - Z)$ embedded in the analytic formula slightly scales the strong interaction radius but cannot account for the pronounced tail of the potential generated by the halo.

The total ion-ion potential, i.e. including the Coulomb contribution, is shown in Fig. 2 for the ^{11}Li+^{208}Pb and ^{9}Li+^{208}Pb cases. One expects that the long nuclear tail arising from the halo should be completely masked when added to the much larger Coulomb interaction. The total potential is indeed dominated by the electric component at very

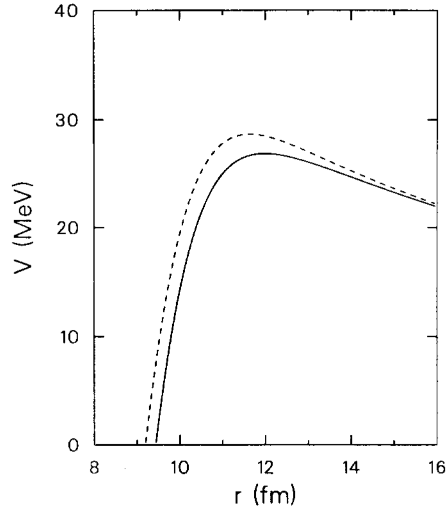

Fig. 2. Total potentials (Coulomb plus folded nuclear) for the systems $^{11}Li+^{208}Pb$ (solid line) and $^{9}Li+^{208}Pb$ (dashed line).

large distances, yielding practically identical functions in both cases. The presence of the halo, however, does have a noticeable effect at closer distances. In fact, only a half of the lowering of the Coulomb barrier by about 2 MeV can be attributed to the systematic increase of the nuclear radius as would be obtained, for instance, with a consistent use of the Akyüz-Winther parametrization for the family of lithium isotopes.

The strength of the three components of the ion-ion potential (Coulomb ion-core, nuclear ion-halo, nuclear ion-core) determines the relative magnitude of the coupling interactions. As was anticipated, the intrinsic degree of freedom of ^{11}Li considered here is associated with the displacement of the neutron halo with respect to the ^{9}Li core. In leading order, the radial dependence of the driving forces for the excitation of this collective mode are proportional to the derivatives of the corresponding potential terms. These form factors are displayed in Fig. 3. (Note that in order to compare the absolute values of the couplings, the curves in the figure incorporate some simple scaling factors g_c, g_h, involving the ratio of masses between the halo and the core; they are given in Section 3). The Coulomb form factor (negative) is dominant at large distances. Among the nuclear contributions, the term associated with the halo (also negative) extends much further out than the one arising from the core (positive). While the Coulomb and the nuclear driving forces generated by the core have the familiar opposite signs the nuclear contribution arising from the halo has the same sign as the Coulomb term [7]. As a consequence, the nuclear and Coulomb effects at large distances add up constructively, a rather unusual feature that will be apparent in the results of the calculation.

It is also important to note that the magnitudes of the Coulomb and nuclear form factors are comparable around the barrier radius. It will be shown in Section 4 that this leads to a considerable contribution of the Coulomb coupling to the break-up process at bombarding energies close to the barrier (cf. Fig. 5).

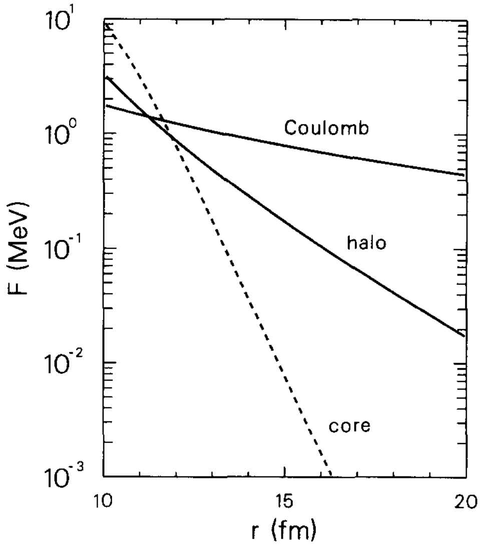

Fig. 3. First-order coupling potentials for the excitation of the soft-dipole mode in ^{11}Li, in the reaction ^{11}Li+^{208}Pb. The three components (Coulomb ion-core, nuclear ion-core, nuclear ion-halo) are separately displayed. Dashed lines have to be taken with negative sign, solid lines with positive sign.

3. Dynamical model

In what follows we implement a simple semiclassical model where aspects of the problem concerning elastic scattering, break-up and fusion events as a function of bombarding energy and impact parameter can be explored quantitatively. We have in mind a collision between ^{11}Li and ^{208}Pb but state the problem in a general notation since the formalism can easily be applied to other situations. In fact, a quite similar scheme was used in Ref. [8] for reactions involving heavy ions.

We consider a collision between a projectile P and a target T with charge and mass numbers Z_P, A_P and Z_T, A_T, respectively. The motion of these systems is described by the relative coordinate between their centers of mass, $\boldsymbol{r}$, and its conjugate momentum, $\boldsymbol{p}$. We assume that N_c of the neutrons in the projectile are tightly bound to the protons to form a core, while the rest, $N_h = (N_P - N_c)$ (i.e. the "halo"), can perform collective oscillations against them. The variable characterizing this intrinsic motion in the projectile is the separation of the center of mass of the surplus neutrons with respect to the core. This distance we express on units of the projectile radius R_P and thus introduce the dimensionless amplitude $\boldsymbol{\alpha}$ and its conjugate momentum $\boldsymbol{\Pi}$. The motion takes place in a plane perpendicular to the initial orientation of the angular momentum. Selecting that to be the z-axis the coordinates of relative and intrinsic motion are determined by two components in the xy-reaction plane. We adopt polar coordinates for the former,

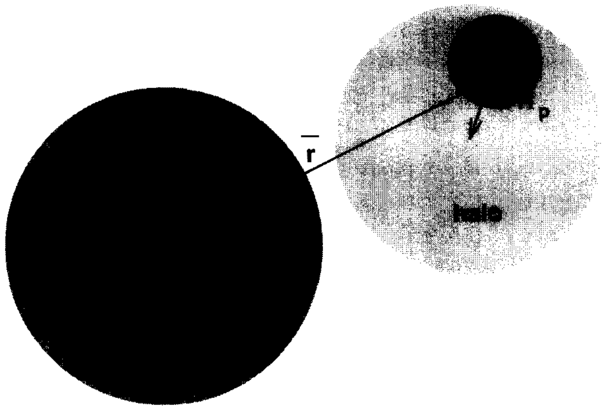

Fig. 4. Schematic picture of the coordinates involved in the reaction.

$\boldsymbol{r} = (r, \phi)$ and Cartesian amplitudes for the intrinsic variable, $\boldsymbol{\alpha} = (\alpha_x, \alpha_y)$ [1]. This situation is illustrated in Fig. 4.

For relatively small displacements the intrinsic motion is harmonic and the evolution of the system can be described by the Hamiltonian

$$H(\boldsymbol{r}, \boldsymbol{p}, \boldsymbol{\alpha}, \boldsymbol{\Pi}) = \frac{p_r^2}{2m} + \frac{p_\phi^2}{2mr^2} + \frac{\Pi_x^2 + \Pi_y^2}{2D} + \frac{C}{2}(\alpha_x^2 + \alpha_y^2) + V_{\text{coup}}(\boldsymbol{r}, \boldsymbol{\alpha}) , \tag{2}$$

where m is the reduced mass and C and D the restoring force and mass parameters of the collective vibration. These last two quantities were related to the energy $\hbar\omega$ and deformation parameter β of the mode by $C = 3\hbar\omega/(2\beta^2)$ and $D = 3\hbar/(2\omega\beta^2)$. There is consensus that the energy of the low-lying collective mode lies about 1 MeV. Estimates for β are less firm and subject to some ambiguity. In our calculations involving ^{11}Li we have settled for a value of $\hbar\omega$ = 1 MeV, and explored values of the deformation parameter around $\beta \approx 0.4$.

The coupling V_{coup} between the intrinsic and relative motion variables arises from the Coulomb and nuclear interactions between projectile and target. Following the preceding discussion we write this as

$$V_{\text{coup}} = \frac{Z_P Z_T e^2}{|\boldsymbol{r} - g_c \boldsymbol{\alpha} R_P|} + V_c(|\boldsymbol{r} - g_c \boldsymbol{\alpha} R_P|) + V_h(|\boldsymbol{r} + g_h \boldsymbol{\alpha} R_P|) , \tag{3}$$

where the quantities proportional to the variable α—involving the mass factors $g_h = A_c/A_P$, $g_c = A_h/A_P$—take into account the shift in position of the center of charge and the modification in the separation distance between the nuclear densities generated by

[1] The components α_x, α_y are directly related to the real and imaginary parts of the dipole amplitudes $\alpha_{\lambda=1,\pm1}$ that displace the center of mass of a system whose radius is given in terms of the familiar expansion in spherical harmonics. A fully consistent treatment requires the z-component of the variable α as well. This would introduce fluctuations between the initial and final orientations of the angular momentum as the trajectories are not strictly contained in a plane. The effect is however small and will be ignored here.

the intrinsic motion. (The factors g_h, g_c are, respectively, 9/11 and 2/11 for our ^{11}Li case, implying that most of the displacement is actually made by the light-mass halo.)

To take into account quantal effects associated with the excitation of the harmonic degrees of freedom we sample for each impact parameter the time evolution of the system for an ensemble of initial conditions in the $\alpha\Pi$-planes that is consistent with the ground-state distributions of coordinates and momenta of the dipole mode. These are given by the conditions $\Pi_x^2(0)/D + C\alpha_x^2(0) = \hbar\omega$ and $\Pi_y^2(0)/D + C\alpha_y^2(0) = \hbar\omega$. Details and illustrations of this procedure can be found in Ref. [18].

We have solved the classical equations of motion derived from (2) for the reaction ^{11}Li+^{208}Pb in a range of energies around the Coulomb barrier, $V_B \sim 26$ MeV. A few distinct types of outcomes are noted and described below.

There are situations where the integration of a given trajectory involves a very low excitation energy. In this case the reaction remains binary throughout and the survival of ^{11}Li in a scattering state is preserved. If, on the other hand, the excitation exceeds a threshold level (taken to be equal to the cohesive energy holding the two neutrons and the ^{9}Li core together) the collision is assumed to trigger projectile dissociation. It is the accumulated statistical weight associated with those initial conditions that builds up the total break-up probability for a given impact parameter. Finally, a third possibility arises when the reaction partners come close to the strong interaction radius. This happens whenever the choice of initial bombarding energy and impact parameter—combined with the dynamical evolution—enables the projectile to overcome the effective repulsive barrier. Overlaps of the nuclear densities well inside the barrier become large and fusion sets in. In calculations for the reaction ^{11}Li+^{208}Pb a fusion radius $r_f \approx 9$ fm was used (cf. Fig. 2). When these conditions are met it no longer matters whether the kinetic energy in the intrinsic motion could eventually cause a break-up since both the projectile core and its excess neutrons find themselves trapped in the target field.

4. Results

To gain some insight into these competing processes we start by considering the simple case of head-on collisions. Fig. 5 shows the variation with bombarding energy of the break-up and fusion probabilities for two values of the deformation parameter β. The results are compared with those obtained when only the Coulomb or nuclear components of the coupling are included. As the energy is increased in the subbarrier region the probabilities for break-up increase regularly, as expected from the fact that the systems get closer to each other and explore larger couplings (cf. Fig. 3). Although the form factor associated with the halo extends much farther than usual, break-up via the nuclear field acting alone would only become effective at the Coulomb barrier. Its presence is however noticeable at lower energies when combined with the Coulomb field. Both contributions add up constructively (cf. the sign of the different terms in Fig. 3) and the polarization induced by the Coulomb term allows the nuclear coupling to act at shorter separation distances. At higher bombarding energies the ^{11}Li can overcome

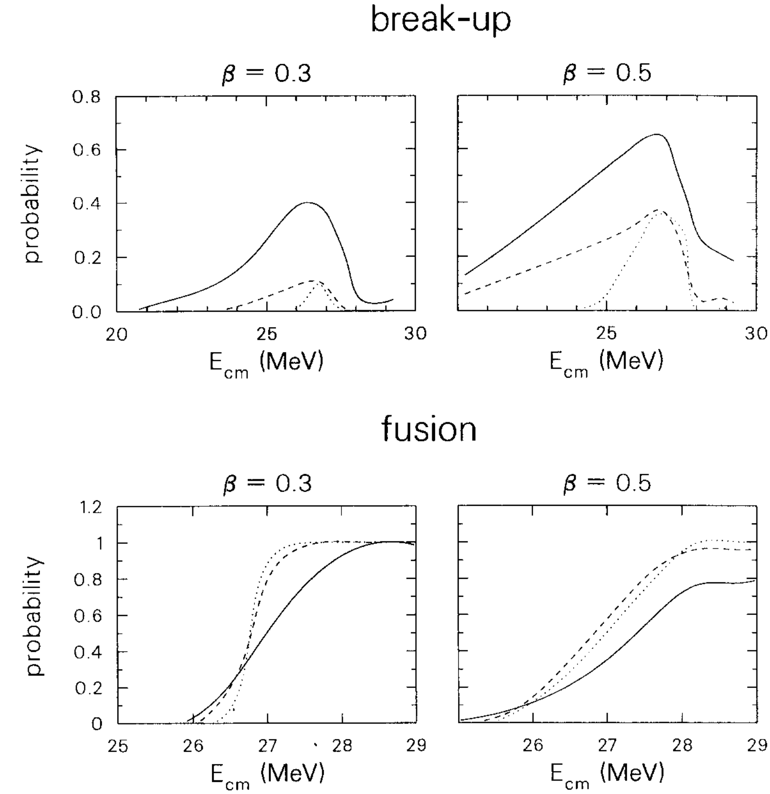

Fig. 5. Break-up and fusion probabilities in the reaction $^{11}Li+^{208}Pb$ as a function of the bombarding energy E_{cm} for a head-on collision. The two columns refer to different values of the dipole deformation parameter β. The dashed and dotted lines give the probabilities when only the Coulomb or the nuclear coupling are included, while the solid lines refer to the case when both are active.

the Coulomb barrier and reach the "fusion" point before the energy transferred into the dipole mode has led to an irreversible separation of the two fragments. Thus the fusion becomes predominant and break-up probabilities rapidly decrease.

In Fig. 6 the partial cross section $d\sigma/db = 2\pi bP(b)$ is shown as a function of the impact parameter b for different values of the bombarding energy E_{cm}. Both the Coulomb and the nuclear components of the coupling are included, with a value of the deformation parameter $\beta = 0.5$. The solid, dashed and dot-dashed curves refer respectively to the fusion, break-up and quasielastic events. As expected, fusion is favored in central collisions at energies above the barrier. Break-up processes are mostly associated with peripheral collisions but get also significant contributions from large impact parameters due to the long range of the Coulomb interaction. Note that a small dissociation probability remains in competition with fusion even at the low impact-parameter range.

We display in Fig. 7 the elastic deflection functions associated with the potential scattering of ^{11}Li by ^{208}Pb (i.e. core+valence components in the absence of coupling)

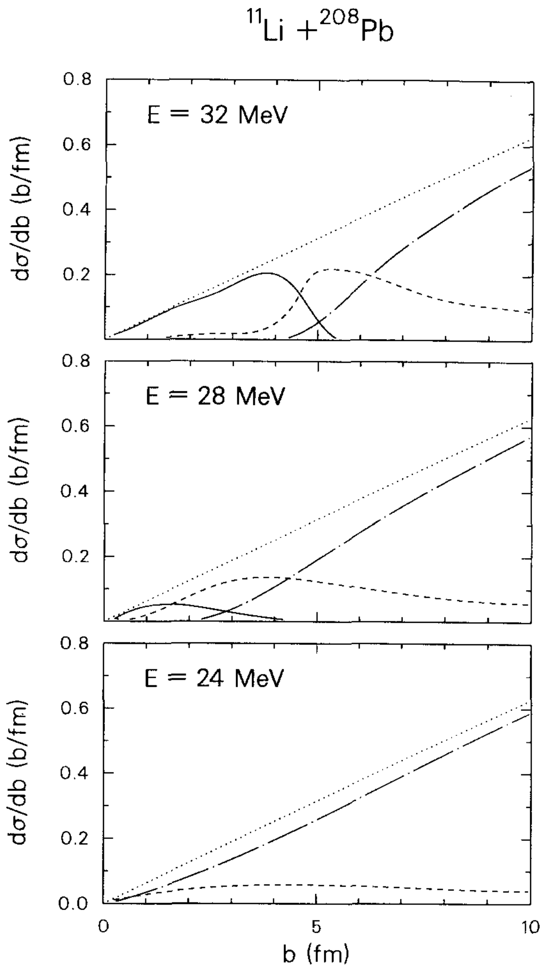

Fig. 6. Partial cross sections $d\sigma/db$ as a function of the impact parameter b for different values of the bombarding energy E_{cm}. Solid, dashed and dash-dotted lines give the fusion, the break-up and the quasi-elastic cross sections, respectively. For reference, the geometrical cross section is also shown as a dotted line.

for the three bombarding energies used in the previous illustration. When the coupling to the intrinsic dipole mode is turned on, deflection functions below the barrier are affected slightly and remain Coulomb-like in nature. Above the barrier, on the other hand, only the larger impact parameters still contribute a major fraction of their statistical weights to quasielastic scattering events. As one moves into more central collisions, a growing number of trajectories generated by the ensemble of initial conditions are removed from the outgoing ^{11}Li channel by either fusion or projectile dissociation. Within the subset of events that survive, dynamical effects introduced by the coupling yield different final scattering angles. The extent of the spread in angles can be inferred from the points with bars in Fig. 7, that give the centroid and dispersion of these distributions at selected values of the impact parameter. This information is shown only for the case of

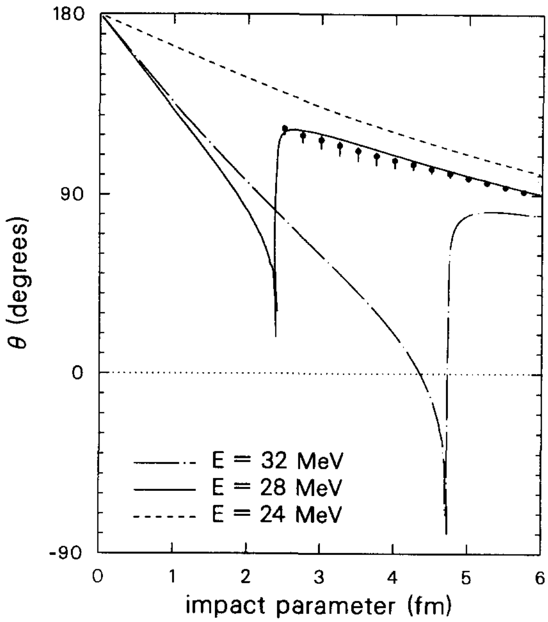

Fig. 7. Elastic deflection function for the potential scattering of ^{11}Li on ^{208}Pb in the absence of coupling to the intrinsic modes. The curves correspond to E_{cm} = 24 MeV (dashed), E_{cm} = 28 MeV (full) and E_{cm} = 32 MeV (dash-dotted). For the coupled situation (only displayed for E_{cm} = 24 MeV) the dots give the average value of the distribution of scattering angles that results from the ensemble of trajectories for selected impact parameters. The "error" bars on the points indicate the standard deviation of the distribution.

E_{cm} = 28 MeV, about 2 MeV above the barrier. One should keep in mind that towards the fusion regime the statistics used to construct the average scattering angle and its standard deviation gets poorer because of competition with the other processes, an aspect that is not readily apparent in the figure.

Finally, total break-up and fusion cross sections are shown in Fig. 8 as a function of the incident energy. Although they are not included in the plot, results of the integration over b for the nuclear and Coulomb couplings acting alone follow a behaviour quite similar to the case of head-on collisions displayed in Fig. 5. At energies close to the barrier the Coulomb field by itself would generate break-up cross sections comparable to the ones shown in the figure. Absolute values are consistent in order of magnitude with what is known experimentally at the higher-energy regime. We note, however, that collective effects should become less relevant as the collision time gets to be much shorter than the characteristic period of the mode $\approx 1\hbar$ MeV^{-1}.

5. Summary and conclusions

We have investigated the relative importance of electric and nuclear dissociation of ^{11}Li in reactions close to the Coulomb barrier, where the break-up process comes in direct interplay with fusion phenomena. Our calculations centered on the reaction

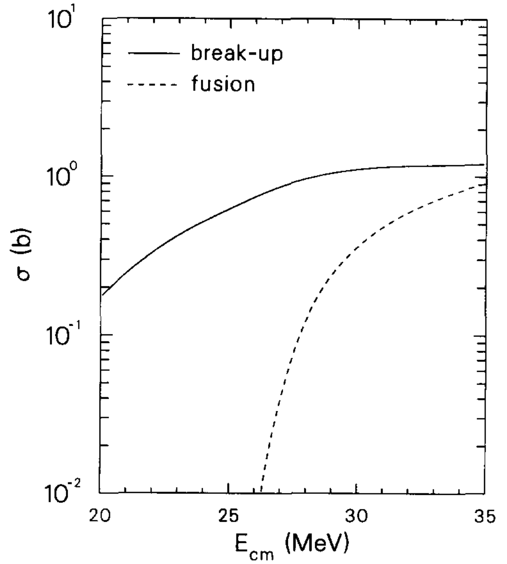

Fig. 8. Total break-up and fusion cross section of $^{11}Li+^{208}Pb$ as a function of the bombarding energy E_{cm}.

$^{11}Li+^{208}Pb$, but the formalism is general enough to accommodate other combinations of projectiles and targets, provided that the former has a neutron excess that forms a weakly-bound halo. We have contemplated displacements of this halo against the projectile core in terms of a low-lying collective vibration of dipole character. Such elementary mode of excitation has a singular role at energies close to the Coulomb barrier as it tends to enhance fusion cross sections while being the vehicle for dissociation of ^{11}Li into $^9Li+2n$. This is illustrated in Fig. 9, where it is shown that at energies below the barrier a larger coupling strength brings not only an increase in the break-up probability (cf. Fig. 5) but larger fusion probabilities as well. We note that similar results were originally found in fully quantal calculations [11]. Effects of the kind discussed in Ref. [11] may appear somewhat surprising although they have been familiar in the subbarrier fusion

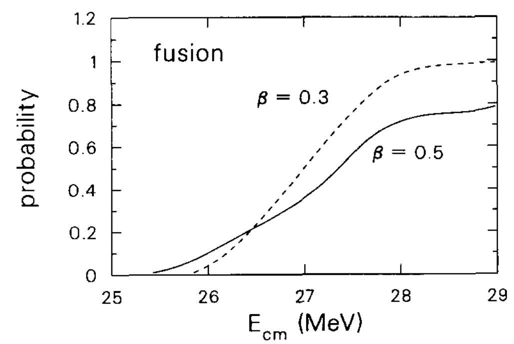

Fig. 9. Fusion probability of $^{11}Li+^{208}Pb$ as a function of bombarding energy for two representative values of the dipole deformation parameter β.

field for over a decade. The reason for this is that ordinary intuition normally associates the presence of reaction channels through which flux can be irreversibly removed with that of an absorptive potential. The tunneling process in the presence of coupling to other reaction channels (whether irreversibly or not) cannot be understood in these terms. In fact, the exponential gain in penetration associated with the lowering of the effective barriers for the additional eigenchannels (which, in simple words, essentially turns classically forbidden transitions into classically allowed ones) can easily outweigh the presumed competition presented by these, as is indeed reflected in the observable, outgoing flux where the intuitive arguments apply. As has been argued elsewhere one can trace problems of interpretation associated with these results to the fact that different parts of the radial couplings are relevant—and act differently—for the transmitted and reflected flux (for a detailed exposition, cf. e.g. Ref. [21]). These characteristics of multidimensional quantal tunneling are often overlooked. It is thus interesting to see how a radically different formalism like the one exploited in this contribution, based on solving Hamilton's equations of motion, can exhibit similar effects to the ones obtained by solving Schrödingers' equation in a complete coupled-channel context. This should actually be expected if one keeps in mind the aforementioned eigenchannel interpretation of the tunneling process which helps visualize a "classical" origin of the largely enhanced transmission factors.

The results of the survey indicate that Coulomb excitation remains an important agent for projectile break-up at energies close to the barrier and even for the most central collisions. Calculations in the literature concerning the fusion regime [9–11] have assumed that nuclear couplings would be predominant and therefore the investigation of these processes may merit further consideration within a more precise, quantal formalism. It could also be interesting to exploit semiclassical approaches similar to the one described here to bridge the gap with the regime of higher bombarding energies ($\approx$ 100 MeV/nucleon) and explore alternative mechanisms of dissociation that may gradually take over.

Acknowledgements

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