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Effect of Coulomb dipole polarizability of halo nuclei on their near-barrier fusion with heavy targets

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We show that the very strong Coulomb dipole polarizability and breakup of ^{11}Li reduces significantly its near-barrier fusion cross section with a heavy target nucleus. We suggest that the measurement of σ_F concomitantly with that of the elastic scattering would allow an unambiguous extraction of the dipole polarizability of halo nuclei.

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Recently, an upsurge of interest in the sub-barrier fusion of radioactive nuclei has arisen [1–4]. One reason for this is the quest for an understanding of the dynamics of tunneling, accompanied by competition of enhancement and hindrance coupled channel effects. The enhancement arises from the strong coupling to the so-called soft giant dipole mode (SGM) of excitation. The hindrance comes about because of the equally strong coupling to the breakup channels. This rather peculiar phenomenon is characteristic of halo nuclei with very low Q values.

In this paper we point out that the Coulomb dipole polarizability and breakup of ^{11}Li colliding with a heavy nucleus like ^{208}Pb is so strong that it basically erases all the enhancement alluded to above. We have recently found [5] that the elastic scattering cross section of the above system at low energies is also strongly damped. These facts allow us to suggest that the measurements of both σ_F and σ_{el} would furnish invaluable and unambiguous measures of the dipole polarizability. This could resolve several questions recently raised from studies of breakup reactions and reacceleration [6].

In our previous work [1] we used time-independent coupled channels theory to obtain the fusion cross section. Here, we discuss a time-dependent semiclassical theory of coupled channels, which shows the channel-coupling effect on σ_F in a transparent form.

We consider a set of coupled channels labeled by n, calling the corresponding time-dependent probability amplitude and the excitation energy, $a_n(t)$ and E_n, respectively. The system Hamiltonian contains complex optical potentials $V_{\rm opt}^{(n)}(r)$, which are diagonal in channel-space, and the channel-coupling interaction $\mathscr{V}$. The imaginary parts of the optical potentials account for the loss of flux going into other channels not considered explicitly. One can easily derive the set of coupled equations,

$$i\hbar \dot{a}_n=\sum_m [\delta_{n,m}V_{\rm opt}^{(n)}+\langle n|\mathscr{V}|m\rangle]e^{(i/\hbar)(E_n-E_m)t}a_m, \qquad (1)$$

where the intrinsic states of the system are represented by the vectors $|n\rangle$.

Using the complex conjugate version of Eq. (1), and defining the time-dependent total fusion probability by $P_F(t)$ (from this point we are assuming that the absorbed flux goes into the fusion channel),

$$P_F(t)=1-\sum_n |a_n(t)|^2, \qquad (2)$$

we obtain the equation

$$\frac{dP_F}{dt}=-\sum_n (a_n^*\dot{a}_n+a_n\dot{a}_n^*), \qquad (3)$$

where a_n^* satisfies the complex conjugate version of Eq. (1). After simple algebra, Eq. (3) can be reduced to the desired form

$$\frac{dP_F}{dt}=-\frac{2}{\hbar}\sum_{n,m} {\rm Im}\{\delta_{n,m}V_{\rm opt}^{(n)}+\langle n|\mathscr{V}|m\rangle\}e^{(i/\hbar)(E_n-E_m)t}a_m a_n^*. \qquad (4)$$

Equation (4) leads to a time-dependent version of the formula for the fusion cross section employed earlier [1],

$$\sigma_F=-\frac{k}{E}\sum_{i,j} \langle \psi_i^{(+)}|{\rm Im}\{H\}|\psi_j^{(+)}\rangle, \qquad (5)$$

where H is the full Hamiltonian of the system and $\psi_i^{(+)}$ is the exact wave function in channel i.

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In most applications, the channel-coupling interaction is taken to be real. Accordingly, Eq. (4) takes the simple form

$$\frac{dP_F(r_l(t))}{dt} = -\frac{2}{\hbar}\sum_n \operatorname{Im}\{V_{\rm opt}^{(n)}[r_l(t)]\}P_n[r_l(t)]. \qquad (6)$$

Above, we have made explicit the angular momentum and time dependences, which appear through the classical trajectory $r_l(t)$. We should stress here that, though not apparent, $P_F(r_l(t))$ of Eq. (6) depends strongly on the Q value involved in the nonelastic transitions since $P_n(t)=|a_n(t)|^2$ contains this dependence. A semiclassical theory of P_F which does not employ explicit absorption is given Ref. [7]

Integrating Eq. (6) over all times gives us the inclusive fusion transmission coefficient (function of both energy and angular momentum). The fusion cross section is then given by

$$\sigma_F = \frac{\pi}{k^2}\sum_{l=0}^{\infty}(2l+1)P_F[r_l(t\rightarrow\infty)]. \qquad (7)$$

We now turn to the problem of the fusion of ^{11}Li+^{208}Pb at near-barrier energies. We take the following coupled channels into consideration; the elastic channel, the inelastic channel, where ^{11}Li is excited into the soft dipole mode, and the breakup channel consisting of ^{9}Li$+2n$. Since there is a continuum of states in the breakup channel, the probability that the system finds its way back to the fusion channel (^{9}Li fuses and, as a next step, the two neutron fuse with ^{208}Pb) is vanishingly small. It is clear therefore, that there is no complete fusion in the breakup channel. There is certainly an imaginary part in the optical potential acting on the breakup channel, corresponding to *incomplete* fusion. Namely, the fusion of ^{9}Li with the heavy target. However, it is not included in Eq. (6), since the probability P_F takes into account only events that lead to the complete fusion of ^{11}Li with ^{208}Pb.

It is clear from the above that ^{11}Li+^{208}Pb inclusive fusion can be described by the equation

$$\frac{dP_F(r_l(t))}{dt} = -\frac{2}{\hbar}[\operatorname{Im}\{V_{\rm opt}^{(1)}(r_l(t))\}P_1(r_l(t)) + \operatorname{Im}\{V_{\rm opt}^{(2)}(r_l(t))\}P_2(r_l(t))], \qquad (8)$$

where 1 and 2 refer to the elastic and inelastic channels, respectively. $P_1(r_l(t))$ and $P_2(r_l(t))$ are obtained from solving three coupled equations, for the elastic, inelastic and breakup amplitudes. Therefore, the effect of breakup coupling on fusion is through the way it affects P_1 and P_2, which can be represented by depletion factors. A simple approximation is to take $P_1 \approx P_2 \approx P_s$, where P_s is the elastic survival probability, given by [8],

$$P_s(\ell) = \exp\left[\frac{1}{\hbar}\int_{-\infty}^{+\infty}\operatorname{Im}\{V_{\rm DPP}(r_l(t))\}dt\right]. \qquad (9)$$

Above, $V_{\rm DPP}$ is the dynamic polarization potential (DPP), arising from the coupling of the elastic channel to the breakup one.

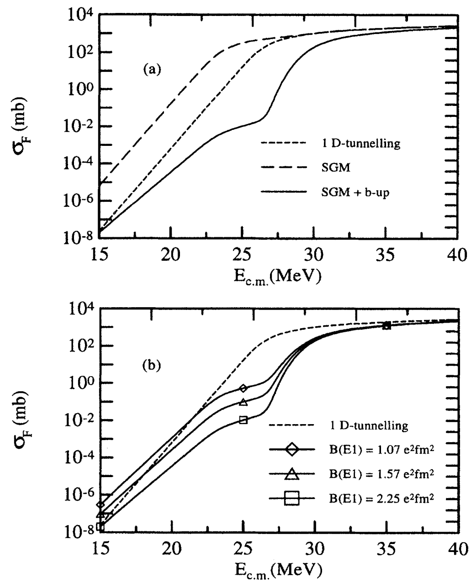

FIG. 1. (a) Fusion cross section for ^{11}Li+^{208}Pb obtained in the absence of coupling, i.e., through a one-dimensional calculation (short-dashed curve), when the coupling to the soft dipole mode is included (long-dashed curve), and when the breakup channel coupling is also included (solid curve). (b) Results of our calculations for other values of $B(E1)\uparrow$. See text for further details.

In our previous work [1] we considered only the nuclear breakup contribution to $V_{\rm DPP}$. Quite recently [5] we have calculated the Coulomb contribution and found it to be by far the dominant one. Using the result of Ref. [5] and following the procedure of Ref. [1], we find for the Coulomb part of the survival probability the simple analytical form,

$$P_s^C = \exp\left[-\frac{16\pi\mu E B_{cl}(E_1)\uparrow |S_l^{(1)}|}{9\hbar^2 Z_P^2 e^2(1+l^2/\eta^2)}\right], \qquad (10)$$

where $B_{\rm cl}(E_1)\uparrow = 2.25$ fm^2 e^2 is the cluster $B(E_1)\uparrow$ value of the soft mode, Z_P is the ^{11}Li atomic number, $k=\sqrt{2\mu E}/\hbar$ is the relative wave number, $S_l^{(1)}$ is the S matrix in the breakup channel as defined in Ref. [1] and η is the Sommerfeld parameter.

The fusion cross section is then given by

$$\sigma_F = \frac{\pi}{k^2}\sum_{l=0}^{\infty}(2l+1)P_F(r_l(t\rightarrow\infty))\cdot P_s(l), \qquad (11)$$

where

$$P_s(l) = P_s^N(l)\cdot P_s^C(l). \qquad (12)$$

$P_s^C(l)$ is given by Eq. (10) and $P_s^N(l)$ is given in Ref. [1].

The result of our calculation of σ_F using Eq. (11), is shown in Fig. 1(a). The effect of the Coulomb breakup depletion is clearly very important. Similar depletion was found to be inflicted on the elastic scattering [5].

While there is no definite experimental evidence of the transition strength at the moment, the empirical excitation energy of the soft dipole mode is close to that predicted by the single-particle model. The calculation shown is if Fig. 1(a) was carried out with $B(E_1)\uparrow = 2.25$ fm^2 e^2. It is appropriate that we give results for σ_F using other values of $B(E_1)\uparrow$. This we present in Fig 1(b), where $B(E_1)\uparrow$ values of 1.07 fm^2 e^2 and 1.57 fm^2 e^2 are used and the results are compared to those obtained with the above-mentioned cluster model value. The two smaller values correspond to the predictions of a pure single-particle model [$B(E_1)\uparrow = 1.07$ fm^2 e^2] and a correlated single particle model [$B(E_1)\uparrow = 1.57$ fm^2 e^2] [9]. As can be seen in Fig. 1(b), different values of $B(E_1)\uparrow$ result in rather different fusion cross sections. However, the major qualitative effect of the breakup coupling discussed above is evident in all the three curves.

Another commonly used form of presenting coupling effects on σ_F is by plotting $d^2(E\sigma_F)/dE^2$) vs E. This quantity gives direct information on the effective barrier distribution, originated from channel couplings. The results are shown in Fig. 2. We used for the calculation the cluster value $B(E_1)\uparrow = 2.25$ fm^2 e^2. We clearly see the dramatic effect of the coupling to the breakup channel: the enhancement due to the coupling to the soft dipole mode manifests itself in the two-peak distribution of Fig. 2(b). This effect is not as clearly shown in the fusion excitation function, Fig. 1(a). In fact, one notices that the corresponding curve is quite smooth in this logarithmic plot. With Coulomb and nuclear breakup included, one goes back to a one barrier situation, except that the new effective barrier is now shifted to higher energies. In the present case, the shift from no coupling [Fig. 2(a)] to full coupling [Fig. 2(c)] is 3 MeV. Thus, the dipole polarizability of ^{11}Li , in the context of sub-barrier fusion, can be simulated by a 3 MeV upward shift in the Coulomb barrier. This should be easily detected experimentally.

In conclusion, we suggest that a careful measurement of both σ_F and σ_{el} at low energies should supply much needed information about the nature of the soft dipole modes in halo nuclei.

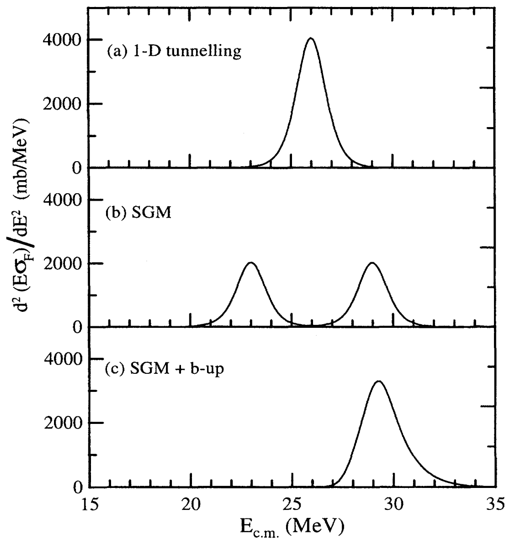

FIG. 2. The function $d^2(E\sigma_F)/dE^2$. In (a) the calculation was performed in the absence of coupling, in (b) only coupling to the soft dipole mode was considered, and in (c) coupling to the breakup channel was also included. See text for further details.

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