PHYSICAL REVIEW C VOLUME 44, NUMBER 2 AUGUST 1991

Projectile breakup by nuclear and Coulomb fields and application to astrophysically relevant radiative-capture processes

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(Received 26 December 1990)

The interplay of nuclear and Coulomb contributions to breakup processes is studied theoretically. This is especially relevant for the extraction of astrophysical S factors for radiative-capture reactions. We study explicitly the breakup of ^{6}Li and ^{7}Li projectiles. Results of our calculations are in good agreement with recent experimental data. The different behavior of the nuclear and Coulomb amplitudes as a function of angle and energy helps to separate them from each other. This is vital for reliable extraction of astrophysical S factors of radiative-capture processes from breakup experiments.

The Coulomb dissociation method for studying astrophysically relevant radiative-capture processes was proposed in Ref. [1]. It rests on the assumption that the nuclei do not interact strongly with each other. In this case the breakup reaction $a+Z \rightarrow (b+x)+Z$ proceeds entirely via the electromagnetic interaction. By further assumption that the electromagnetic excitation process is of first order, one can relate [1] directly the measured cross section for this reaction to that of the radiative capture cross $b+x \rightarrow a+\gamma$. Therefore, astrophysical S factors for the radiative-capture processes can be determined from the study of breakup reactions under these conditions. This procedure is essentially the same as the extraction of electromagnetic matrix elements (between nuclear bound states) in Coulomb excitation [2].

However, for breakup reactions induced by projectiles with beam energies (E_{beam}) above the Coulomb barrier, the strong interaction processes can interfere with the Coulomb excitation mechanism. This happens even at very forward angles, where predominantly large impact parameters contribute. Therefore, one has to pin down the kinematic conditions under which nuclear contributions do not substantially alter the predictions of a pure Coulomb dissociation process (or at least they can be taken into account in a reliable way). This is necessary for an accurate extraction of astrophysical S factors from the breakup data.

The purpose of the present Brief Report is to give a direct reaction calculation of the nuclear and Coulomb breakup and investigate their roles in different kinematical situations. The amplitude for the Coulomb breakup can be calculated essentially free of uncertainties (the electromagnetic matrix elements being the only external input). However, in the calculation of the nuclear breakup amplitude, the optical potentials in the outgoing and incoming channels are required. The parameters of these potentials inevitably involve uncertainties. Nevertheless, such kind of direct reactions have been extensively studied for several decades [3], and the parameters of the potentials are known to a large extent by recourse to other sources such as elastic scattering. Therefore, the nuclear breakup amplitudes can also be calculated with little uncertainty.

The quantal treatment of the Coulomb and nuclear excitations is well known [2,3]. The expression for the differential cross section corresponding to a transition of multipolarity L is represented as

$$\frac{d\sigma}{d\Omega} \propto \sum_{L=-M}^{L=+M} |T_M^L|^2 , \tag{1}$$

with

$$T_M^L \propto \int_0^\infty dr\, R_{L_i}(k_i r)(F_C^L + F_N^L) R_{L_f}(k_f r) , \tag{2}$$

where indices i and f refer to the incoming and outgoing channels, respectively. F_C^L and F_N^L denote the form factors for the Coulomb and nuclear excitations, respectively. For F_C^L we take the following form:

$$F_C^L(r) = \begin{cases} \beta_L^C b / r^{L+1}, & r \geq R_C, \quad (3) \\ \beta_L^C c r^L, & r \leq R_C , \quad (4) \end{cases}$$

where β_L^C is the "Coulomb deformation parameter." This is related to the $B(EL)$ value of the transition by

$$\beta_L^C = \left[\frac{4\pi}{3 Z_T R_C^L} \right] \left[\frac{B(EL)\uparrow}{e^2} \right]^{1/2} . \tag{5}$$

In this equation, $b = [3 Z_p Z_T e^2)/(2L+1)] R_C^L$ and $c = (b / R_C^{2L+1})$. R_C is given by $1.2 A_T^{1/3}$ fm with Z_p, Z_T, and A_T being the charge of the projectile and charge and mass of the target nucleus, respectively. For the nuclear form factor F_N^L, we take the usual collective model expression with the value of the "nuclear deformation parameter" β_L^N being the same as β_L^C.

In Eq. (2), $R_{L_i}(k_i r)$ and $R_{L_f}(k_f r)$ define the wave functions for the relative motion in the incoming and outgoing channels, respectively. These are obtained by solving the Schrödinger equation with appropriate optical potentials which are determined by fitting the elastic-scattering cross sections in respective channels.

Now we use these formulas to study the breakup reactions $^6\mathrm{Li}\rightarrow\alpha+d$ and $^7\mathrm{Li}\rightarrow\alpha+t$ on a $^{208}\mathrm{Pb}$ target, where the experimental data in the relevant energy region have recently become available [4–6]. In particular, we investigate the resonant breakup via 3^+ and $\frac{7}{2}^-$ levels in ^{6}Li and ^{7}Li, respectively. This has the advantage that the corresponding $B(E2)$ values are known from other appropriate experiments (see, e.g., Ref. [7]), and a quantitative comparison with the experimental data is possible. The optical potentials needed in our calculations have been taken from Ref. [8] for ^{6}Li (at $E_{\mathrm{beam}}=156$ MeV) and from Ref. [5] for ^{7}Li (at $E_{\mathrm{beam}}=63$ MeV). We have used the same set of potentials for the incoming and outgoing channels.

In the left part of Fig. 1, we consider the resonant breakup of ^{7}Li on a ^{208}Pb target with $E_{\mathrm{beam}}=63$ MeV. The data [5] correspond to a $\frac{3}{2}^-\rightarrow\frac{7}{2}^-$ excitation with a known $B(E2)$ value of 15.5 $e^2\mathrm{fm}^4$. The solid line shows the results obtained with both nuclear and Coulomb excitations (and their interference) included into the calculations. The long-dashed (short-dashed) line depicts the cross section for pure Coulomb (nuclear) excitation. The Coulomb form factor is determined entirely by the corresponding $B(E2)$ value. As described above, we use Eq. (4) to extend it to the radii smaller than R_C. Anyway, it is worthwhile to note that this interior region contributes very little. It can be seen in this figure that the angular distribution corresponding to the Coulomb form factor is a smooth curve approaching to zero as $\theta\rightarrow 0$. This reflects the semiclassical nature of the process. The adiabaticity condition for the excitation leads to the vanishing of the cross section in the limit of zero angle (which corresponds to impact parameter tending to infinity). On the other hand, the nuclear cross section, although generally smaller than the Coulomb one, tends to a finite value as $\theta\rightarrow 0$. This shows a typical diffraction pattern, which persists in the full (nuclear plus Coulomb) curve as well underlining the relative importance of the nuclear contributions throughout.

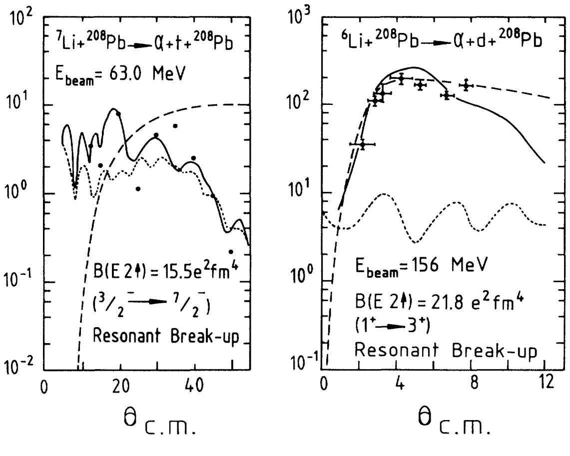

FIG. 1. Angular distributions for $^7\mathrm{Li}+{}^{208}\mathrm{Pb}\rightarrow{}^7\mathrm{Li}^*(\alpha+t)+{}^{208}\mathrm{Pb}$ (left side) and $^6\mathrm{Li}+{}^{208}\mathrm{Pb}\rightarrow{}^6\mathrm{Li}^*(\alpha+d)+{}^{208}\mathrm{Pb}$ (right side) reactions, They proceed via $(\frac{3}{2}^-\rightarrow\frac{7}{2}^-)$ and $(1^+\rightarrow 3^+)$ transitions, respectively. The long-dashed (short-dashed) curve represents the result of pure Coulomb (nuclear) excitation calculation. Their coherent sum is depicted by solid curve. $\theta_{\mathrm{c.m.}}$ represents the center-of-mass angle of outgoing Li*.

In the right part of Fig. 1, the corresponding results for the resonant breakup of ^{6}Li on a ^{208}Pb target at $E_{\mathrm{beam}}=156$ MeV is shown. The experimental points are taken from Ref. [6]. In this high-energy case, the Coulomb amplitude dominates. For $\theta\leq 4°$, nuclear effects modify the total amplitudes only marginally (except for the region very close to $\theta=0$). Thus higher energies (accompanied, of course, by more forward angles) should be a more favorable region for the extraction of S factors of the astrophysically interesting radiative-capture reactions. Furthermore, the "Coulomb final-state effects" (some times also called as post-acceleration effects [9,10] are less severe at higher energies (see also Ref. [11] for a recent review, which includes the experimental aspects as well).

The origin of the different angular distribution patterns for the nuclear and Coulomb amplitudes can be traced back to the different behavior of the radial matrix elements corresponding to these processes in the orbital angular momentum (L) space. This is shown in Fig. 2, where we have plotted them as a function of the incident channel orbital angular momentum for the ^{6}Li breakup. For illustration purposes we select the case $L_i=L_f$ and $M=1$ (all other combinations of these quantum numbers have the same typical behavior). The nuclear part (short-dashed line) shows the expected narrow peak around the grazing partial wave L_{gr}. On the other hand, the long-range quadrupole Coulomb interaction leads to radial matrix elements which extend very far out. The (coherent) sum of the nuclear and Coulomb contributions are shown by solid curve. Because of absorption effects in the distorted waves, the Coulomb contribution (long-dashed line) becomes very small for partial waves $L\leq L_{\mathrm{gr}}$. This substantiates our earlier remark that the Coulomb form factor for the region $r\leq R_C$ contributes negligibly to the corresponding amplitude. Because of this contrasting L-space behavior of the their respective radial matrix elements, nuclear and Coulomb breakup amplitudes show different angular distributions, diffractive type for the former and smooth for the latter. We further remark that because of their smooth behavior, the Coulomb amplitudes are quite amenable to the semiclassical methods (such as performing the L-space summation by saddle-point method). This will prove to

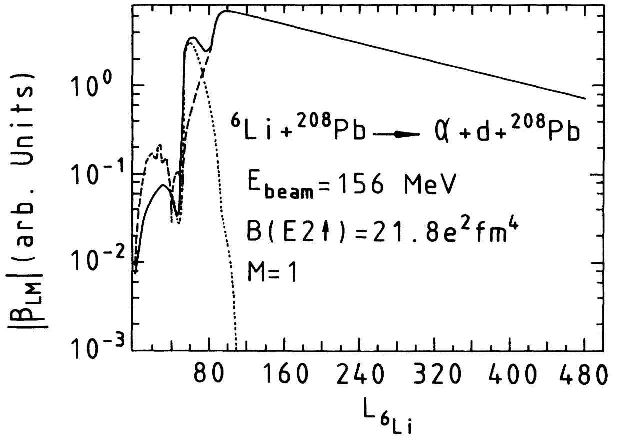

FIG. 2. Modulus of the radial matrix elements (β_{LM}) as a function of the entrance channel orbital angular momentum ($L_{^6\mathrm{Li}}$) for the reaction $^6\mathrm{Li}+^{208}\mathrm{Pb}\to\alpha+d+^{208}\mathrm{Pb}$. Various curves have the same meaning as in Fig. 1.

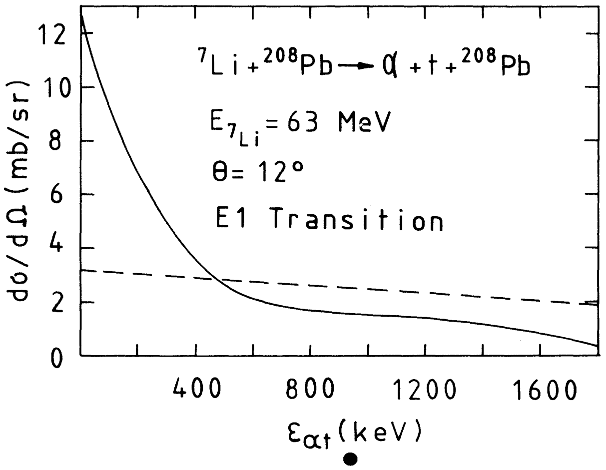

FIG. 3. Differential cross section for the $^7\mathrm{Li}+^{208}\mathrm{Pb}\to\alpha+t+^{208}\mathrm{Pb}$ reaction as a function of the α-t relative energy $\epsilon_{\alpha t}$. Solid curve shows the results of full Coulomb excitation calculations, while dashed lines represents the same for pure Coulomb excitation.

be quite handy for future calculations involving far higher energies and more massive particles (experiments for such cases are already being performed at RIKEN and GANIL [12]). For the reactions investigated in this Brief Report, calculations have been done by exact quantum-mechanical methods (which have to be used for the nuclear part any way).

Recently Utsunomiya *et al.* [13] have raised an interesting possibility which simplifies the analysis of their very beautiful data on ^{7}Li breakup. From a distorted-wave Born approximation (DWBA) calculation, they suggest that there is a parallelism between the nuclear and Coulomb excitation cross sections as a function of the excitation energy [or the α-t relative energy ($\epsilon_{\alpha t}$)] for their experimental conditions. We have tried to investigate this point in our first-order DWBA model. Assuming an energy independent $B(E1)$ value (and hence a constant value for β_L^c and β_L^N), we show in Fig. 3 the corresponding nuclear and Coulomb excitation cross sections (for the sake of simplicity, we have left out the interference term). We note that whereas the cross section for the nuclear excitation (dashed line) is only weakly dependent on the excitation energy (corresponding to $\epsilon_{\alpha t}$ values between 0 and 2 MeV), that for the Coulomb excitation (solid line) shows the expected decrease with increasing energy. As can be seen in this figure, we fail to corroborate the existence of parallelism between nuclear and Coulomb cross sections, particularly for energies below 200 keV, which is relevant for nuclear astrophysics.

In conclusion, we want to say that the direct reaction model including Coulomb as well as nuclear contributions is very well suited for the study of breakup reactions at moderately high energies. As a test case, we performed calculations for the breakup of ^{6}Li and ^{7}Li projectiles on the ^{208}Pb target at the beam energies of 156 and 63 MeV, respectively. Using standard optical model parameters (which are determined by the elastic-scattering studies) and well-known $B(EL)$ values, a very satisfactory agreement with the experimental data is obtained. The different angular distributions of the nuclear and Coulomb contributions are the direct consequence of the different behavior of the corresponding amplitudes in the L space: Nuclear amplitudes are well localized in this space, while very high values of L contribute to the Coulomb amplitude. Because of this, the corresponding angular distributions are characteristically different for nuclear and Coulomb excitations. Therefore, one can be confident that by careful analysis of a range of experimental data the Coulomb breakup part, and hence the astrophysically relevant cross sections, can be determined almost in a model-independent way.

Our calculations suggest that higher beam energies and forward angles provide a more favorable regime for the extraction of S factors of the radiative-capture processes from measurements of the breakup cross sections. In this regime the nuclear contributions only marginally affect the total amplitudes. We further remark that we fail to observe the parallelism between nuclear and Coulomb excitation cross sections for the breakup of ^{7}Li at low beam energies, for excitation energies of astrophysical interest. It may be necessary to further check this point by using more proper nuclear form factors and also to calculate the coincidence cross sections for outgoing fragments. Such studies are in progress.

One of us (R.S.) would like to thank Prof. U. Mosel for his very kind hospitality at the University of Giessen. Useful discussions with Prof. H. Rebel are also gratefully acknowledged. This work was supported by BMFT and GSI Darmstadt.

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