Postacceleration in the elastic breakup of the deuteron

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A semiclassical coupled-channels calculation of the elastic breakup of the deuteron is performed in order to demonstrate that strong postacceleration effects are expected to be observable in the longitudinal velocity spectrum of the outgoing proton. The relevance of this phenomenon in elucidating possibly similar effects in the breakup of light halolike radioactive nuclei is stressed. [S0556-2813(97)50102-6]

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Recently, it has been suggested that the measurement of postacceleration in the breakup of halo nuclei enables one to determine the stage of the collision in which the dissociation dominantly occurs [1–9]. This may shed light on the nature of the dissociation, since a short time scale indicates a few-step mechanism while a long time scale suggests a resonant process. In the latter case, the dissociation would occur through the excitation of a low-lying soft dipole mode (SDM). This issue has been addressed by different authors in recent publications [10,11]. Coulomb acceleration after the breakup (postacceleration) manifests itself through a forward enhancement of the longitudinal velocity distribution in the projectile rest frame. The magnitude of this forward enhancement is critically dependent on the charge to mass ratios of the fragments. In most of the studied cases, one of the fragments carries the entire projectile charge and, therefore, the Coulomb acceleration is fully imparted to this fragment. If, furthermore, most of the projectile mass is concentrated in this fragment, the postacceleration is mainly felt by the projectile center of mass and, accordingly, the forward enhancement in the relative velocity between the fragments is reduced. This should be the case of the breakup of ^{11}Li and more so of ^{11}Be, considered in recent calculations [4,7].

Due to its small dissociation energy and to the dominant S nature of its ground state, the deuteron can be considered as the simplest example of an ''exotic'' nucleus [10]. In this case, the mass of the charged fragment is 50% of the total projectile mass while in the dissociation of ^{11}Li or ^{11}Be the fraction is over 80%. Thus the longitudinal velocity distribution of the proton in the deuteron frame should be much more forward enhanced than its counterpart in the case of ^{11}Li or ^{11}Be. A first indication of this effect was found in the triple differential cross sections measured by Okamura *et al.* [12], in their study of deuteron dissociation on several targets. Therefore, it would be interesting to measure this distribution. In the present work, we calculate the longitudinal velocity distribution of the proton in the deuteron frame as well as the total dissociation cross section. The relevance of the latter quantity relates to the feasibility of an experiment along these lines. Although the dissociation energy of the deuteron is considerably larger than that for ^{11}Li or ^{11}Be, which leads to an expected reduction of the dissociation cross section, we find that this cross section is still of such a magnitude as to allow for easy measurement.

We describe the elastic Coulomb breakup of the deuteron using the semiclassical coupled-channels model of Refs. [4,13]. For the internal wave function of the deuteron, we take

$$\phi_0(r)=\left(\frac{\eta}{2\pi}\right)^{1/2}\frac{e^{-\eta r}}{r}. \tag{1}$$

Above, r is the p-n distance inside the deuteron and $\eta=\sqrt{2\mu B}/\hbar$, where μ is the reduced mass of the n-p system and B the deuteron binding energy. In order to obtain a finite set of coupled-channel equations, we resort to the discretization-of-the-continuum method described in Refs. [13,14]. The resulting set of equations for the amplitudes $a_\alpha(b,t)$, which determine the probability of finding at time t the n-p system in state α for a collision with impact parameter b, is

$$i\hbar\dot{a}_\alpha(b,t)=\sum \langle\phi_\alpha|V|\phi_\beta\rangle e^{i(E_\alpha-E_\beta)t/\hbar}a_\beta(b,t), \tag{2}$$

where V is the coupling potential, which we approximate by its Coulomb dipole part, and ϕ_α stands for the bound state of the deuteron and continuum states of the p-n system. The continuum states were taken to be plane waves. Thus we neglect the final state interaction between the fragments (the proton and the neutron). Such effects were shown to be small [4]. Solving the above equation, we find the asymptotic values ($t\to\infty$) of the ground state (a_0) and the continuum ($a_{\alpha\neq 0}$) amplitudes. Summing over impact parameter, one obtains energy spectra and longitudinal velocity distributions as discussed in detail in Ref. [4].

The excitation energy spectra in the dissociation of deuteron projectiles incident on ^{208}Pb targets are given in Fig. 1 for three collision energies. We notice that the spectra are similar in the three cases. At the lower energies 25 MeV/nucleon and 75 MeV/nucleon, the distributions are

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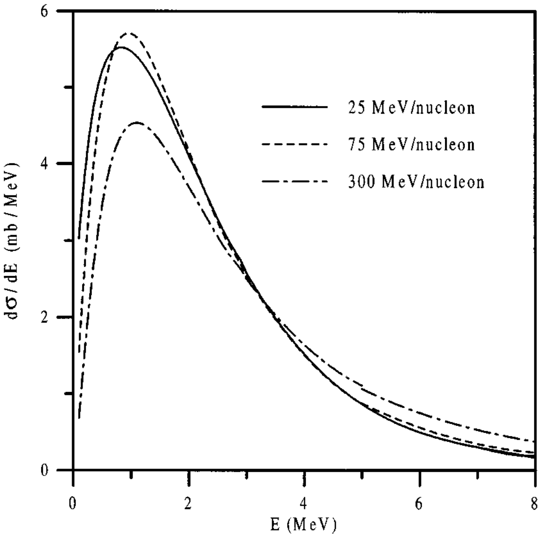

FIG. 1. Energy spectra for the dissociation of deuteron projectiles incident on a ^{208}Pb target, at the collision energies 25, 75, and 300 MeV/nucleon.

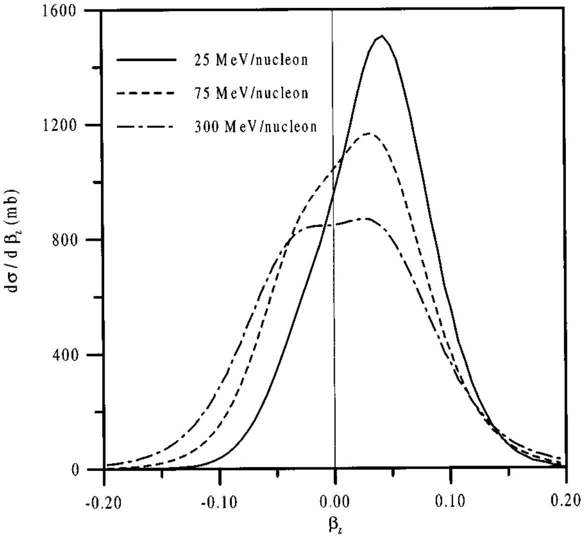

FIG. 2. Longitudinal velocity distribution in deuteron dissociation on a ^{208}Pb target, at the same collision energies as in Fig. 1. The cross sections are plotted against $\beta_z = v_z/c$.

very close. At 300 MeV/nucleon, the maximum is somewhat lower and the high-energy tail falls more slowly. The integrated breakup cross sections are, respectively, 173, 172, and 161 mb. These values are sufficiently large for measurements of the Coulomb breakup process to be relatively simple to perform. The distributions show maxima at energies of approximately 1 MeV and widths at half maximum of $\simeq 3$ MeV. As a result of the larger dissociation energy, the maximum and the width are considerably larger than the corresponding values in the ^{11}Li case.

In Fig. 2, we show the longitudinal velocity distributions for the same collision energies. In the figure, β_z is the ratio of the asymptotic longitudinal component of the n-p relative velocity, v_z, to the speed of light. In contrast to the previous figure, the results strongly depend on the collision energy. At 25 MeV/nucleon there is a very strong forward velocity shift, resulting from postacceleration of the proton, and the distribution presents a pronounced maximum at $\beta_z = 0.044$. It should be mentioned that this result is consistent with the data of Okamura *et al.* [12] on the dissociation of 56 MeV deuteron projectiles on ^{208}Pb. In their triple-differential spectrum for $\theta_p = \theta_n = 0°$, these authors find a sharp maximum at the p-n relative energy $\epsilon \simeq 0.3$ MeV, for forward accelerated protons. This corresponds to the value $\beta_z \simeq 0.036$, which is similar to that predicted in our calculations. At 75 MeV/nucleon, the forward-backward asymmetry is still appreciable and at 300 MeV/nucleon it becomes much weaker. This trend suggests that the forward velocity shift would be still larger at energies below 25 MeV/nucleon. However, our calculation would require corrections to include deviations from the straight line trajectory used in the present work (and in Ref. [4]).

It is important to remark that the measurement of the excitation energy spectra alone is not able to elucidate the dissociation mechanism. For example, the calculation described above clearly implies a direct breakup framework [see, e.g., Eq. (2)]. On the other hand, the energy spectra for the deuteron breakup, shown in Fig. 1, can be accounted for also within an exit doorway framework in terms of a resonant process with strong threshold effects [10]. In this picture the breakup of the deuteron proceeds through a definite exit doorway $|D\rangle$ of unit norm resulting from the action of the relevant transition operator on the deuteron ground state. The transition matrix elements involved in Eq. (2) can then be written as

$$\langle \phi_\alpha | V | \phi_\beta \rangle = \langle \phi_\alpha | V | D \rangle \langle D | \phi_\beta \rangle,$$

where, using standard projection techniques [10,15], the factor $\langle D | \phi_\beta \rangle$ can be written in resonance form as

$$\langle D | \phi_\beta \rangle = \frac{\gamma_D(E_\beta)}{E_\beta - E_D - \Delta_D(E_\beta) - i\Gamma_D(E_\beta)/2}, \qquad (3)$$

where $\Gamma_D(E_\beta) = 2\pi |\gamma_D(E_\beta)|^2$ describes the escape of the exit doorway to the proton-neutron continuum. Strong threshold effects manifest themselves through the energy dependence of the shift $\Delta_D(E_\beta)$ and of the width $\Gamma_D(E_\beta)$. In particular, they cause the line shape to be sensibly different from the usual Breit-Wigner line shape, and consequently lead to a decay law which is also sensibly nonexponential. Similar remarks apply also to the heavier exotic nuclei such as ^{11}Li and ^{11}Be.

The observation of the postacceleration effect will, in any case, set limits to the time scale involved in the breakup process. Independently of the adopted description (''direct'' vs ''exit doorway with strong threshold effects''), experimental data on the deuteron postacceleration effect will be very important in order to assess the adequacy of presently available theoretical descriptions. We feel, moreover, that a careful experimental study of this effect would be extremely useful as a fully quantal calculation, e.g., in terms of three-body coupled equations [14], would be comparatively easy to implement in this case. In particular, the cases of ^{11}Li and ^{11}Be are still hampered by the lack of a fully microscopic description of the structure of the projectiles.

In conclusion, we have estimated the longitudinal velocity distribution of emitted protons in the deuteron elastic breakup reaction with a Pb target using a semiclassical coupled-channels model. The postacceleration is clearly evident at low energies (25 MeV/A) and shows a rather strong dependence with bombarding energy, almost disappearing at 300 MeV/A. For a more complete understanding of this effect, fully quantal coupled-channel calculations as well as detailed measurements are clearly needed.

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