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Higher-order electromagnetic interaction in the dissociation of fast particles

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Abstract: We study the effects of higher-order electromagnetic interactions in the dissociation of fast particles, especially ^{11}Li. First, we use a classical approach, where a "breakup radius" is introduced. This is contrasted to a quantal approach, where higher-order effects are summed up using the sudden approximation.

1. Introduction

Peripheral nuclear reactions have been of great interest. If first-order electromagnetic interaction is responsible for the reaction, one can directly relate the cross section for dissociation to the corresponding photodisintegration process [see e.g. refs. [1,2])]. In this way, one can study giant resonances of stable and unstable nuclei, by using the equivalent photon method. Of course, the presence of higher-order electromagnetic interaction will change this simple picture. These higher-order effects can be considered as useful, e.g. one can try to populate new nuclear states, like multiphonon giant resonances [3]). On the other hand, the presence of higher-order effects can cause a complication, when one wants to apply a first-order analysis and extract electromagnetic matrix elements for transitions from the ground state. This is of relevance e.g. for the determination of electromagnetic strength distribution in ^{11}Li or for the application of electromagnetic dissociation to radiative-capture processes relevant for nuclear astrophysics [2]). This effect (sometimes also called "post acceleration" or "Coulomb final-state interaction") could be especially troublesome in the transition to continuum states. The relative energy between the fragments could be distorted by this long-range final-state interaction. On the other hand, the transient Coulomb field might be used as a clock to study the time dependence of excited states.

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Since higher-order effects can involve the whole spectrum of intermediate states, they are not so easily studied in general. A tremendous simplification occurs for cases where the collision time $\tau_{\rm coll}$ is much smaller than the typical nuclear excitation times $\tau_{\rm nucl} \simeq \hbar/(E_n - E_0)$, where $E_n - E_0$ are typical excitation energies, i.e. we can apply the sudden approximation, or Glauber theory. In sect. 2, we study the effects of post acceleration in a rather classical model. This can be useful for order of magnitude estimates. In sect. 3, the sudden approximation is used to calculate the effects of higher-order electromagnetic interactions. Our conclusions are given in sect. 4.

2. Coulomb break-up of cluster projectiles. Classical considerations

Let us consider the Coulomb break-up of a projectile a in a collision with a target A. Assuming that the projectile is formed by fragments b and x, this process can be represented as

$$\mathrm{a}+\mathrm{A}\rightarrow \mathrm{b}+\mathrm{x}+\mathrm{A}\,. \tag{2.1}$$

In the break-up of ^{11}Li, b = ^{9}Li and x = n + n. The Coulomb excitation probability per unit energy for the process (2.1) in a collision with impact parameter b is given by [1]) (we consider here only the leading multipolarities)

$$\frac{\mathrm{d}P}{\mathrm{d}E_{\mathrm{x}}}=\frac{N_{\mathrm{E1}}(E_{\mathrm{x}},b)}{E_{\mathrm{x}}}\,\sigma_\gamma^{\mathrm{E1}}(E_{\mathrm{x}})+\frac{N_{\mathrm{E2}}(E_{\mathrm{x}},b)}{E_{\mathrm{x}}}\,\sigma_\gamma^{\mathrm{E2}}(E_{\mathrm{x}})\,, \tag{2.2}$$

where $N_{\mathrm{E}\lambda}(E_{\mathrm{x}},b)$ are the number of virtual photons [1]) with energy E_{x} for a collision, with impact parameter b, and $\sigma_\gamma^{\mathrm{E}\lambda}$ are the cross sections for the excitation induced by real photons. The functions $N_{\mathrm{E}\lambda}(E_{\mathrm{x}},b)$ are given analytically for high-energy collisions. At intermediate-energy (some tens of MeV/nucleon) collisions the same expressions can be used by inclusion of a recoil correction [4]), with a 5-20% accuracy.

In terms of the reduced matrix elements $B(\mathrm{E1})$ and $B(\mathrm{E2})$, the photo-dissociation-cross sections are given by

$$\sigma_\gamma^{\mathrm{E1}}(E_{\mathrm{x}})=\frac{16\pi^3}{9}\left(\frac{E_{\mathrm{x}}}{\hbar c}\right)\frac{\mathrm{d}B(\mathrm{E1};\,E_{\mathrm{x}})}{\mathrm{d}E_{\mathrm{x}}}\,,$$

$$\sigma_\gamma^{\mathrm{E2}}(E_{\mathrm{x}})=\frac{12\pi^3}{225}\left(\frac{E_{\mathrm{x}}}{\hbar c}\right)^3\frac{\mathrm{d}B(\mathrm{E2};\,E_{\mathrm{x}})}{\mathrm{d}E_{\mathrm{x}}}\,. \tag{2.3}$$

In the cluster model [5]) one gets

$$\frac{\mathrm{d}B(\mathrm{E1};\,E_{\mathrm{x}})}{\mathrm{d}E_{\mathrm{x}}}=\frac{3\hbar^2e^2}{\pi^2\mu}\left(\frac{Z_{\mathrm{b}}A_{\mathrm{x}}-Z_{\mathrm{x}}A_{\mathrm{b}}}{A_{\mathrm{a}}}\right)^2\frac{\sqrt{S_{2\mathrm{n}}}(E_{\mathrm{x}}-S_{2\mathrm{n}})^{3/2}}{E_{\mathrm{x}}^4}\,,$$

$$\frac{\mathrm{d}B(\mathrm{E2};\,E_{\mathrm{x}})}{\mathrm{d}E_{\mathrm{x}}}=\frac{40\hbar^4e^2}{\pi^2\mu^2}\left(\frac{Z_{\mathrm{b}}A_{\mathrm{x}}^2+Z_{\mathrm{x}}A_{\mathrm{b}}^2}{A_{\mathrm{a}}^2}\right)^2\frac{\sqrt{S_{2\mathrm{n}}}(E_{\mathrm{x}}-S_{2\mathrm{n}})^{5/2}}{E_{\mathrm{x}}^6}\,, \tag{2.4}$$

where $\mu = 2\times 9m_N/11$ is the reduced mass of the ^{9}Li+2n system, (Z_b, A_b) is the charge and mass number of ^{9}Li, i.e. $Z_b = 3$, $A_b = 8$ and (Z_x, A_x) is the same for the two-neutron system, i.e. $Z_x = 0$ and $A_x = 2$.

In fig. 1 we plot the photo-disintegration cross section for ^{11}Li based on the formulas above. We observe that its value for the E1 multipolarity is larger than for the E2 case (by a factor 10^5). Also, while the σ^{E1} cross section peaks strongly at low values of E_x, σ^{E2} is more sensitive to larger values of E_x. This fact arises from the extra factor $E_x - S_{2n}$ which appears in eq. (2.4) for $dB(E2; E_x)/dE_x$.

It has been argued [6]) that the contributions from E2 multipolarity could be important for the break-up of ^{11}Li projectiles in intermediate-energy collisions. The reason is that although the E2 photo-dissociation cross section is small, the virtual-photon numbers for the E2 multipolarity are larger than that for the E1 multipolarity in intermediate-energy collisions [1]). The folding of the two factors could then yield a reasonable contribution for the dissociation cross sections. We have checked this hypothesis by integrating eq. (2.2) over impact parameters and we obtained that for collisions at 30 MeV/nucleon the E2 cross section is less than the E1 by a factor 300. This can be seen in fig. 2 where the differential cross sections for the two multipolarities are shown for the collision ^{11}Li + Pb at 30 MeV/nucleon. However, this does not rule out the hypothesis that E2 excitations could play a role in the dissociation of ^{11}Li projectiles. The excitation of electric quadrupole modes in the ^{9}Li core could be an important mechanism for the absorption of virtual photons

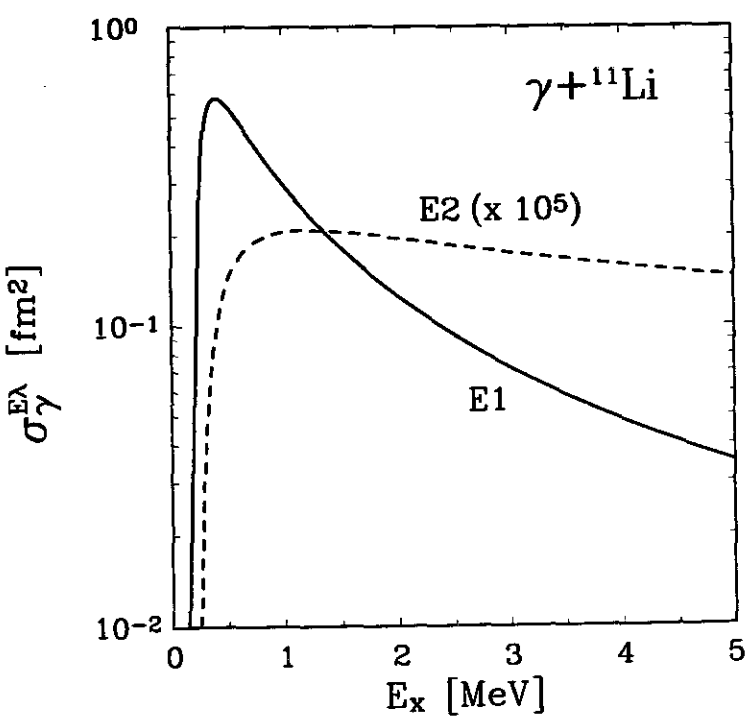

Fig. 1. Photo-dissociation cross section of ^{11}Li, as a function of the energy of the photon. Solid (dashed) line corresponds to the electric dipole (quadrupole) contribution.

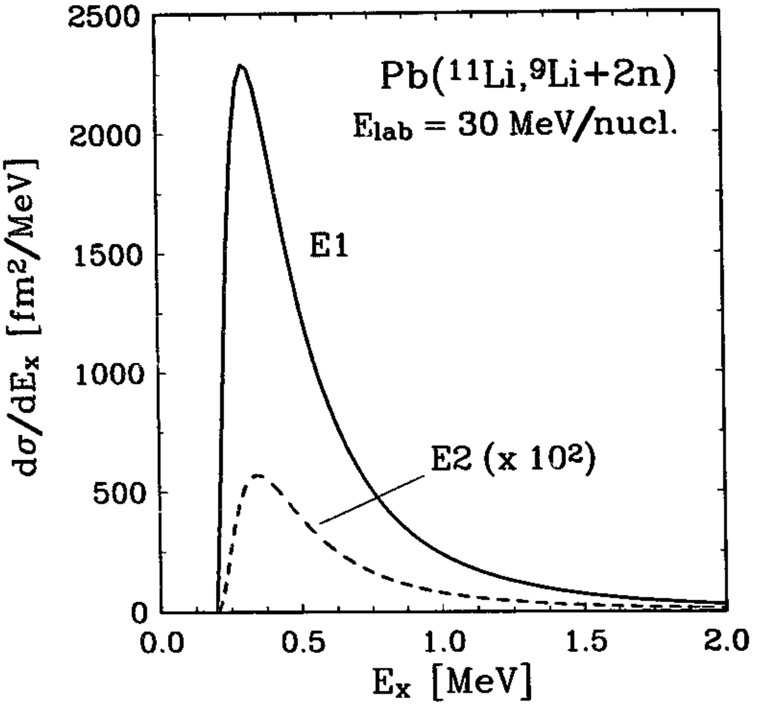

Fig. 2. Coulomb-dissociation cross section of ^{11}Li projectiles incident on lead targets at 30 MeV/nucleon, as a function of the energy transferred to the ^{11}Li.

with sequential fragmentation of ^{11}Li. This needs an extra study which is beyond the present approach.

An important quantity, to be used later, is the average energy transfer to the projectile defined as

$$\langle E_x\rangle = \int_{S_{2n}}^{\infty} dE_x\, E_x \frac{dP}{dE_x} \Big/ \int_{S_{2n}}^{\infty} dE_x \frac{dP}{dE_x}, \tag{2.5}$$

where

$$\frac{dP}{dE_x} = \frac{N_{E1}}{E_x}\sigma_\gamma$$

(we neglect the E2 contribution). The average kinetic energy of relative motion between the fragments after the break-up is then given by $\langle T\rangle = \langle E_x\rangle - S_{2n}$.

In fig. 3 we show the value of $\langle E_x\rangle$ as a function of the bombarding energy per nucleon. We observe that this result is in good agreement with the calculations of Esbensen and Bertsch [7]) using a more elaborate model for the response function of ^{11}Li. This is remarkable in view of the simplicity of the cluster model. Also, a high-energy limit ($\gamma = (1 - v^2/c^2)^{-1/2} \to \infty$) is readily workable from eq. (2.5), using eq. (2.3), and the high-energy limit of the virtual-photon numbers (basically, that

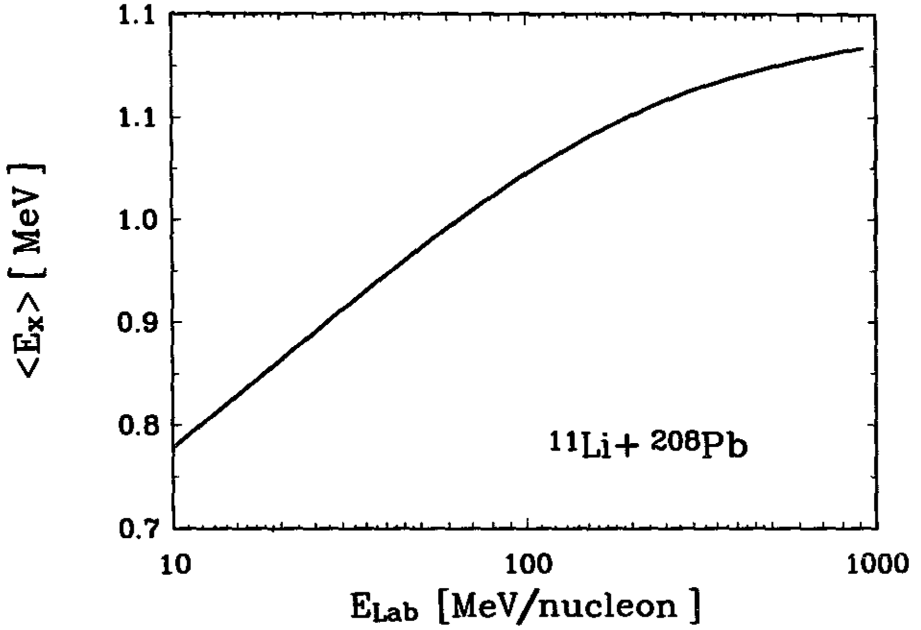

Fig. 3. Average energy transferred to ^{11}Li projectiles incident on lead targets, as a function of the lab energy per nucleon.

$x^2K_1^2(x) \approx 1$ for $x \ll 1$, where K_1 is the modified Bessel function). One obtains

$$\langle E_x \rangle \simeq \int_{S_{2n}}^{\infty} \mathrm{d}E_x \frac{(E_x - S_{2n})^{3/2}}{E_x^3} \Big/ \int_{S_{2n}}^{\infty} \mathrm{d}E_x \frac{(E_x - S_{2n})^{3/2}}{E_x^4}$$
$$= 6S_{2n} \simeq 1.5\ \mathrm{MeV}. \qquad (2.6)$$

Let us consider the break-up of ^{11}Li projectiles as displayed in fig. 4. For simplicity we consider the center-of-mass motion of the incident particles and the fragments to move along a straight line. This is nearly the truth for the bombarding energy considered. Neglecting the recoil of the target, at the break-up point we have the

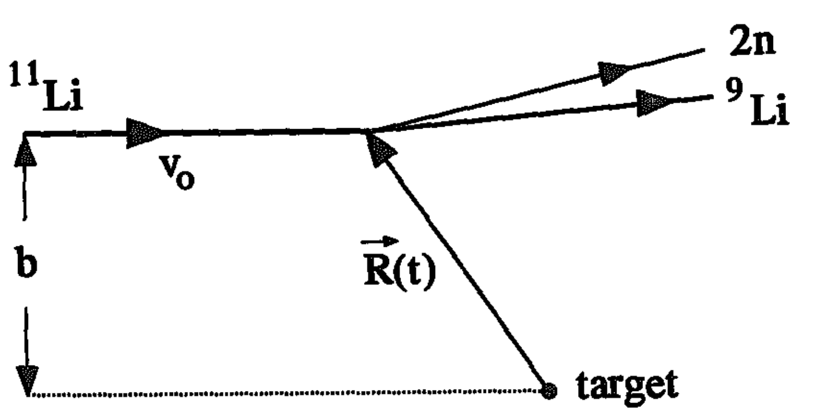

Fig. 4. Schematic representation of the break-up of ^{11}Li projectiles.

following considerations:

$$P_{11} = P_9(t) + P_2(t)\,,$$
$$E_{\rm lab} - V[R(t)] - Q = P_0^2/2m_{11}\,, \qquad (2.7)$$

where Q is the energy transfer to ^{11}Li and $V(R)$ is the Coulomb potential at $R = (b^2 + v_0^2 t^2)^{1/2}$. The time variable is chosen so that $t = 0$ indicates the distance of closest approach (which is b in the approximation considered here).

Let us assume that Q is small compared to the lab energies of ^{9}Li and the two neutrons, 2n, just after the break-up. Then $v_9(t) \simeq v_2(t)$ and one obtains

$$P_{11} \simeq \tfrac{11}{9} P_9^2/2m_9 \simeq \tfrac{11}{2} P_2^2/2m_2\,. \qquad (2.8)$$

This implies

$$E_{\rm lab} - V[R(t)] - Q \simeq \tfrac{11}{9} P_9^2/2m_9\,. \qquad (2.9)$$

This means that the energy of ^{9}Li just after the break-up is

$$E_9(t) = \tfrac{9}{11}[E_{\rm lab} - Q] + \tfrac{2}{11} V[R(t)]\,. \qquad (2.10)$$

Since the potential is conservative, this will be the kinetic energy of ^{11}Li as it reaches the detector. The *extra energy* that the nucleus ^{9}Li will have relatively to its initial share of the projectile energy is then

$$\Delta E_9 = E_9(t) - \tfrac{9}{11} E_{\rm lab} = -\tfrac{9}{11} Q + \tfrac{2}{11} V[R(t)]\,. \qquad (2.11)$$

Repeating the same arguments for calculating the extra-energy for the two neutrons we get

$$\Delta E_2 = -\tfrac{2}{11} Q - \tfrac{2}{11} V[R(t)]\,. \qquad (2.12)$$

In other words ^{9}Li gets post accelerated and acquires an extra energy dictated by eq. (2.11) in a collision for which the break-up occurs at time t, while the ^{9}Li nuclei will be faster than the beam after the break-up, the two neutrons will be slower by conservation of energy. A quite similar effect is well known in the break-up of light ions at lower energies, see e.g. ref. [8]), especially p. 354. This fact really seems to be implicit in the data of recent experiments [9]) of ^{11}Li break-up.

The post-acceleration energy, weighted over time is

$$\langle \Delta E_9 \rangle (b) = \int_{-\infty}^{\infty} \mathrm{d}t\, \Delta E_9(b,t) \frac{\mathrm{d}}{\mathrm{d}t} P(b,t) \Big/ \int_{-\infty}^{\infty} \mathrm{d}t \frac{\mathrm{d}}{\mathrm{d}t} P(b,t)$$
$$= \int_{-\infty}^{\infty} \mathrm{d}t\, \Delta E_9(b,t) \frac{\mathrm{d}}{\mathrm{d}t} \left[\frac{P(b,t)}{P(b,\infty)} \right], \qquad (2.13)$$

where $P(b, t)$ is the break-up probability as a function of the impact parameter, b, and time, t.

The quantity $P(b,t)/P(b,\infty)$ does not depend on the nuclear model for the response function of the projectile, since the excitation probabilities at any time are a product of a kinematical factor (virtual-photon number) and the reduced matrix elements for the electromagnetic excitation [1]). The ratio therefore factors out the matrix elements, which depend on the response function. For a straight-line motion, one gets [10])

$$\frac{P(b,t)}{P(b,\infty)}=\frac{1}{4}\left\{\left[1+\frac{vt/b}{\sqrt{1+v^2t^2/b^2}}\right]^2+\frac{1}{1+v^2t^2/b^2}\right\}, \tag{2.14}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\left[\frac{P(b,t)}{P(b,\infty)}\right]=\frac{v}{2b(1+v^2t^2/b^2)^{3/2}}. \tag{2.15}$$

Inserting this in eq. (2.11) and doing the time integral we find

$$\langle \Delta E_9(b)\rangle=-\tfrac{9}{11}Q+\tfrac{1}{22}\pi(Z_\mathrm{T}Z_\mathrm{a}e^2)/b\,,$$

$$\langle \Delta E_{2\mathrm{n}}(b)\rangle=-\tfrac{2}{11}Q-\tfrac{1}{22}\pi(Z_\mathrm{T}Z_\mathrm{a}e^2)/b\,. \tag{2.16}$$

The energy transfer Q to the excitation of ^{11}Li is practically constant over the relevant impact parameters. We can associate it to the average energy transfer of eq. (2.5) which is approximately $Q\simeq 1$ MeV for bombarding energies in the range 30–100 MeV/nucleon.

The results eq. (2.16) imply that the post-acceleration energy in a single collision with impact parameter b is energy dependent, as long as we can approximate the trajectory by a straight line. Eq. (2.16) can also be averaged over impact parameters,

$$\overline{\langle \Delta E_9\rangle}=\int_{b_\mathrm{min}}^{\infty}\mathrm{d}^2b\,P(b)\langle\Delta E_9\rangle(b)\bigg/\int_{b_\mathrm{min}}^{\infty}\mathrm{d}^2b\,P(b)\,. \tag{2.17}$$

This quantity is again model independent and is given by

$$\overline{\langle \Delta E_9\rangle}=-\tfrac{9}{11}Q+\frac{\pi}{22}\frac{Z_\mathrm{T}Z_\mathrm{a}e^2}{b_\mathrm{min}}F(X_\mathrm{min})\,,$$

$$\overline{\langle \Delta E_2\rangle}=-\tfrac{2}{11}Q-\frac{\pi}{22}\frac{Z_\mathrm{T}Z_\mathrm{a}e^2}{b_\mathrm{min}}F(X_\mathrm{min})\,, \tag{2.18}$$

where

$$F(X_\mathrm{min})=X_\mathrm{min}\int_{X_\mathrm{min}}^{\infty}\mathrm{d}X\,[K_1^2(X)+K_0^2(X)]\bigg/\int_{X_\mathrm{min}}^{\infty}\mathrm{d}X\,X[K_1^2(X)+K_0^2(X)]\,. \tag{2.19}$$

In the equations above $X_\mathrm{min}=Qb_\mathrm{min}/\hbar v$, where b_min is the minimum impact parameter for pure Coulomb processes. We shall use $b_\mathrm{min}=1.2A_\mathrm{T}^{1/3}+\sqrt{\langle r^2\rangle_{^{11}\mathrm{Li}}}$, where $\sqrt{\langle r^2\rangle_{^{11}\mathrm{Li}}}\simeq 3.2$ fm. $F(X_\mathrm{min})$ is a monotonically increasing function of X_min, attaining values close to 1 for X_min greater than unity.

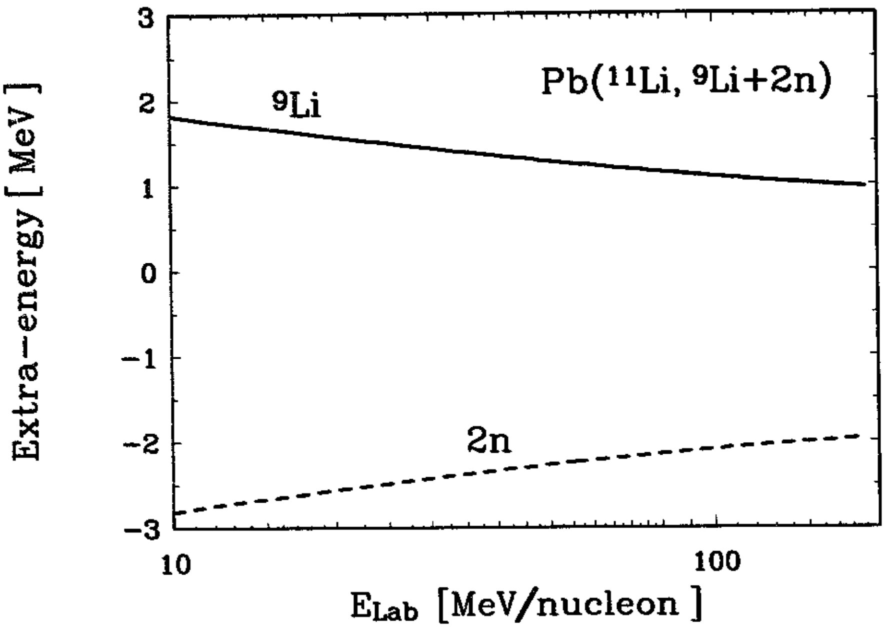

Fig. 5. Post-acceleration energy of ^{9}Li fragments (solid line) and the two neutrons (dashed line) in the reaction ^{11}Li+^{208}Pb as a function of the bombarding energy.

Numerical results for $\overline{\langle \Delta E_{9,2}\rangle}$ are given in fig. 5. We observe that post-acceleration energies are many times larger than the separation energy of ^{11}Li.

3. Higher-order electromagnetic effects in the sudden approximation

In high-energy scattering, higher-order interaction effects are conveniently taken into account using Glauber theory. In a semiclassical approach, the time-dependent coupled equations can be solved conveniently in this limit (sudden approximation). The relation between the quantal and semiclassical methods was discussed recently in ref. [11]). We now retain the concept of a classical motion of the projectile (on a straight-line path), this is a very good approximation for the processes considered here. On the other hand, we now treat the projectile in a completely quantal way, thus avoiding the hard to define concept of a break-up radius, as it was used in the previous section.

As explained in the previous section, we can use the dipole approximation. First we recall the dipole term of the Coulomb interaction between the projectile and the target [10])

$$V_{\text{dipole}} = \gamma Z Z_{\text{eff}}^{(1)} e^2 \frac{by + vtz}{(b^2+\gamma^2 v^2 t^2)^{3/2}}, \tag{3.1}$$

where $\boldsymbol{r} = (x, y, z)$ is the relative distance between the two clusters $\boldsymbol{b} = (0, b, 0)$, and $\boldsymbol{v} = (0, 0, v)$ are respectively the impact parameter and the velocity of the projectile. Z is the electric charge of the target and Z_{eff} the effective charge of the two clusters.

For the dipole interaction it is given by

$$Z_{\mathrm{eff}}^{(1)} = Z_{\mathrm{x}} \frac{m_{\mathrm{b}}}{m_{\mathrm{a}}} - Z_{\mathrm{b}} \frac{m_{\mathrm{x}}}{m_{\mathrm{a}}} . \tag{3.2}$$

The excitation amplitude in the sudden approximation from the ground state $|0\rangle$ to a (continuum) state $|\boldsymbol{q}\rangle$ is given by

$$a_{0\to q} = \left\langle \boldsymbol{q} \right| \exp\left(\frac{1}{i\hbar}\int_{-\infty}^{\infty} \mathrm{d}t\, V_{\mathrm{dipole}}(t)\right)\left|0\right\rangle = \left\langle \boldsymbol{q}\right| \exp\left(i\frac{\Delta \boldsymbol{p}\cdot \boldsymbol{y}}{\hbar}\right)\left|0\right\rangle , \tag{3.3}$$

where $\Delta p = 2Z_{\mathrm{T}}Z_{\mathrm{eff}}^{(1)}e^2/bv$. This corresponds to the classical momentum transfer in a Coulomb collision, with impact parameter b and velocity v (the monopole term $\Delta^0 p = 2Z_{\mathrm{T}}(Z_{\mathrm{b}}+Z_{\mathrm{x}})e^2/bv$ determines the trajectory of the centre of mass of the projectile, i.e. the relation of the impact prameter b to the c.m. scattering angle θ).

The term containing the z-component vanishes by antisymmetry in eq. (3.1). This is a special property of the sudden approximation, and it will be lost when deviations from the sudden approximation have to be considered. E.g. for the case of 30 MeV/A incident ions, the adiabaticity condition is $\hbar\omega \simeq 50\,\mathrm{MeV}\cdot\mathrm{fm}/b$. Thus the sudden approximation is well applicable to the bulk part of the Coulomb dissociation of ^{11}Li at this energy. A shift of the ^{9}Li fragments to higher velocities in the beam direction (the two neutrons, correspondingly, get slower) was recently observed at MSU [6,9]). This effect does not show up in the present model. It was also absent in model calculations using the post-form DWBA approach [12]). Thus, deviations from the sudden approximation will have to be considered in the future.

Let us now calculate explicitly the transition probability for the case of $^{11}\mathrm{Li} \to {}^{9}\mathrm{Li} + 2\mathrm{n}$. We assume a very simple dineutron cluster model with a zero-range interaction. The ground-state wave function is given by

$$|0\rangle = \sqrt{\frac{\eta}{2\pi}}\frac{\mathrm{e}^{-\eta r}}{r} \tag{3.4}$$

and the continuum wave function is given by a plane wave with relative momentum $\boldsymbol{q}$ plus an S-wave scattering part corresponding to the zero-range potential. We obtain explicitly

$$|\boldsymbol{q}\rangle = \mathrm{e}^{i\boldsymbol{q}\cdot\boldsymbol{r}} - \frac{1}{\eta + iq}\frac{\mathrm{e}^{iqr}}{r} . \tag{3.5}$$

With these model wave functions we calculate the transition amplitude using three different approximations: (i) the first-order time-dependent perturbation theory,

$$a_t^1(q) = \sqrt{32\pi\eta}\,\frac{qC}{q^2+\eta^2}\, X\left[K_1(X)\sin\theta\sin\phi - \frac{1}{\gamma} K_0(X)\cos\theta \right] , \tag{3.6}$$

(ii) in the limit $X \to 0$, which corresponds to the case of vanishing energy loss, we obtain from eq. (3.6)

$$a_s^1(q)=\sqrt{32\pi\eta}\,\frac{qC}{q^2+\eta^2}\sin\theta\sin\phi\,, \tag{3.7}$$

(iii) in all-orders sudden approximation

$$a_s(q)=\sqrt{8\pi\eta}\left\{\frac{1}{q_x^2+(q_y-C)^2+q_z^2+\eta^2}+\frac{1}{2C}\,\frac{1}{q+i\eta}\ln\frac{(q-C)-i\eta}{(q+C)-i\eta}\right\} \tag{3.8}$$

with the following constants: B is the binding energy of the two neutrons; $\eta=\sqrt{2\mu B/\hbar^2}$; $C=\Delta p/\hbar$ are the binding-energy and momentum-transfer corresponding wave numbers; $\hbar\omega=\hbar^2q^2/2\mu_{bx}+B$ is the transition energy and $X=\hbar\omega/\gamma v$ the adiabaticity parameter. For small enough $C=\Delta p/\hbar$ we recover eq. (3.7) from eq. (3.8), as it should be.

In figs. 6-9 we show the case of ^{11}Li EMD ("electromagnetic dissociation") on ^{208}Pb for the two beam energies, $E/A=30$ MeV/A and 800 MeV/A (the calculations are done in the relativistic framework). Especially for the lower energy, the strong E1 peak is greatly distorted by higher-order effects, also for the high energy, the effect is quite noticeable. This has to be taken into account in an analysis of (future) experiments, where one wishes to extract B(E1) distribution [for a theoretical calculation see e.g. ref. [7]), especially fig. 1]. Especially, an asymmetry is introduced

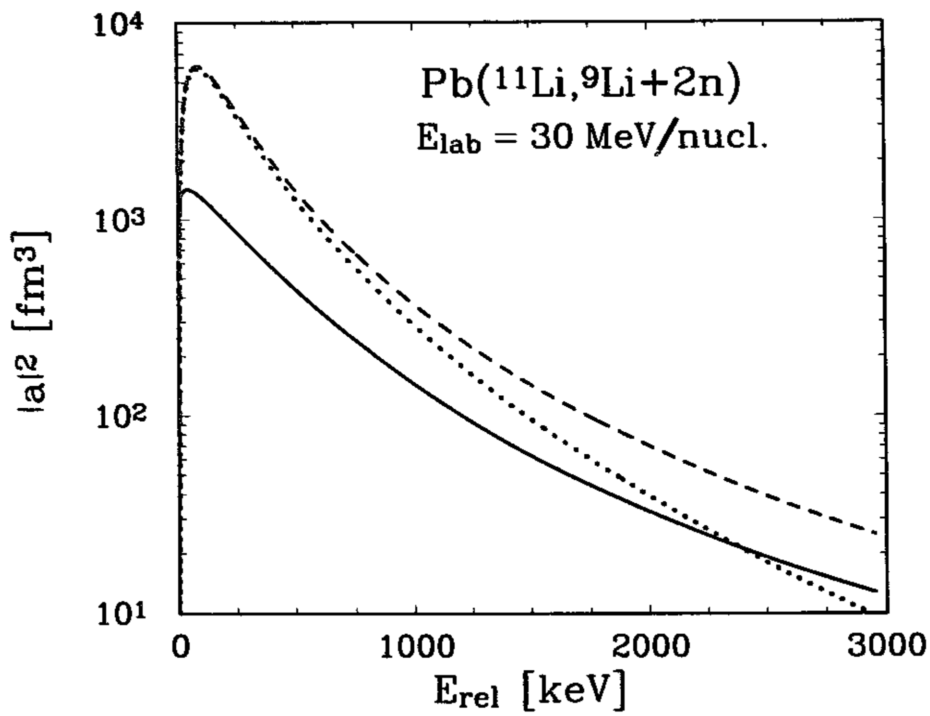

Fig. 6. Squared transition amplitude in $+y$-direction (parallel to $\boldsymbol{b}$) in first-order time-dependent perturbation theory (dotted), first-order sudden approximation (dashed) and all-orders sudden approximation (solid line) for the reaction ^{11}Li + ^{208}Pb → ^{9}Li + 2n + ^{208}Pb at 30 MeV/nucleon lab energy and 15 fm impact parameter, as a function of the relative energy between ^{9}Li and the dineutron.

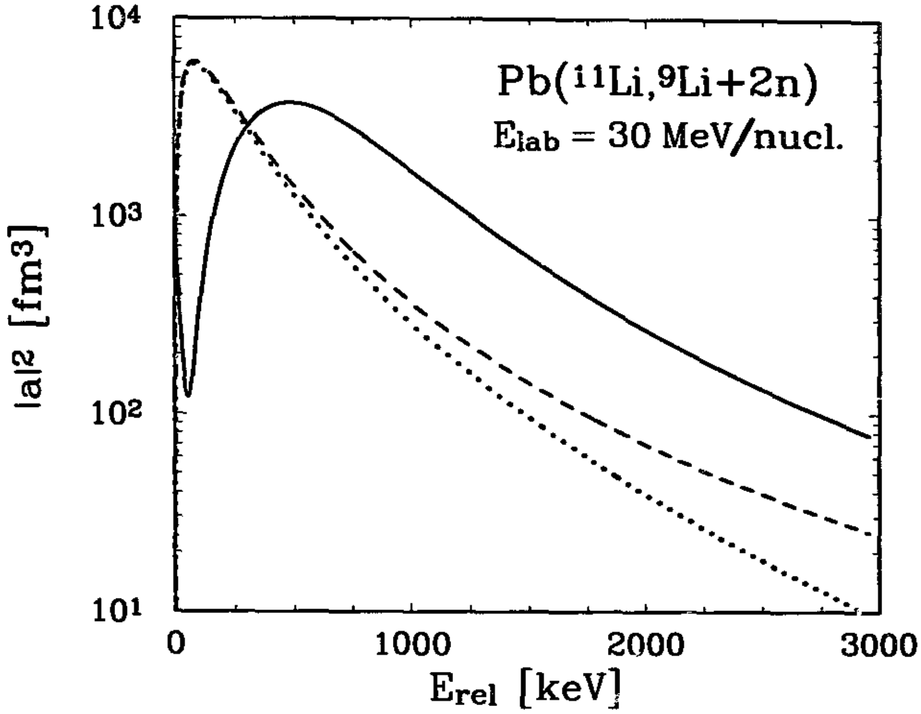

Fig. 7. The same as fig. 6, but with ^{9}Li in $-y$-direction (antiparallel to $\boldsymbol{b}$).

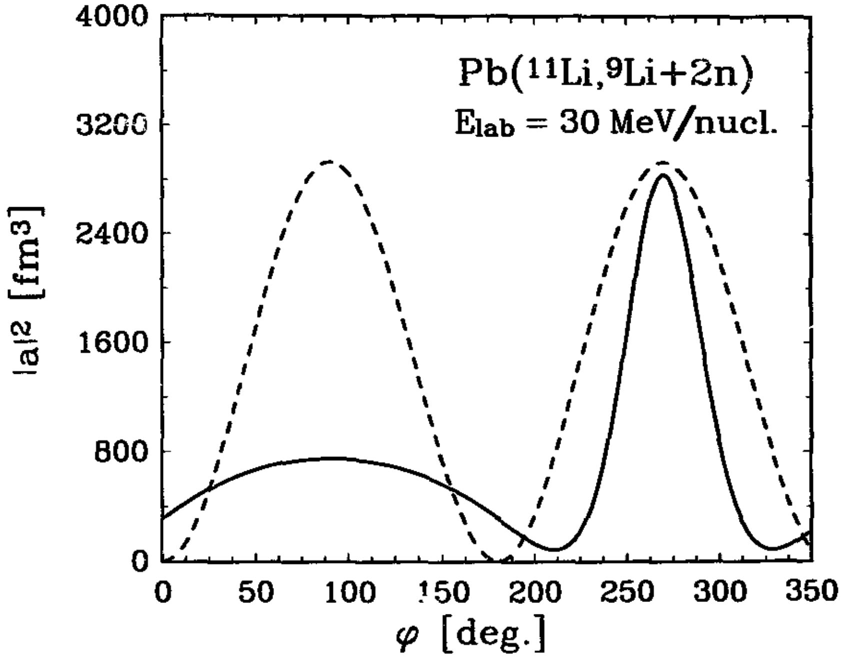

Fig. 8. Dependence of the squared transition amplitude on the polar angle ϕ in the x, y-plane perpendicular to the projectile motion for 300 keV relative energy.

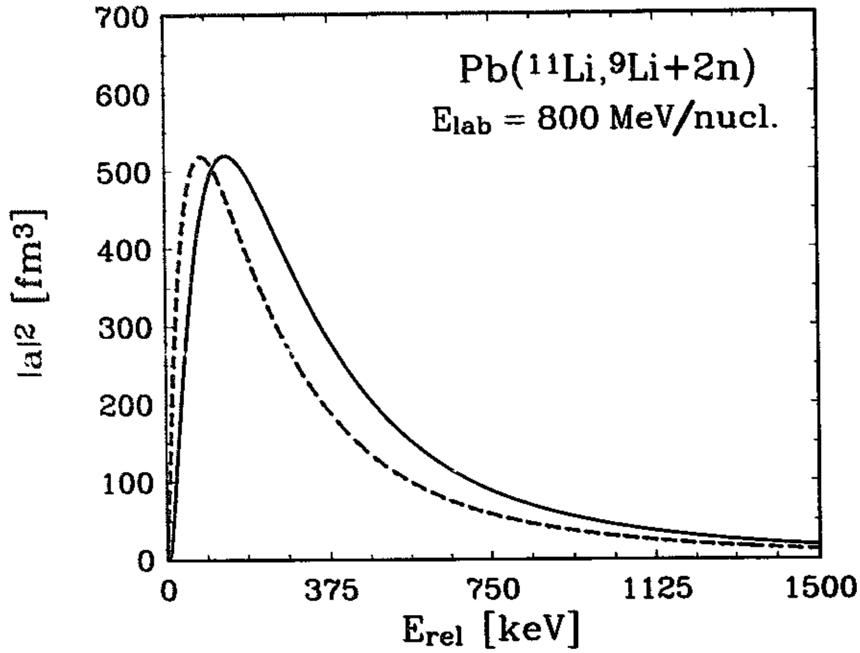

Fig. 9. The same as fig. 7, at 800 MeV/nucleon lab energy.

with respect to the emission in $+y$ and $-y$-directions. However, the symmetry with respect to the x, y-plane is still preserved (this is a characteristic of the sudden approximation, as already noted).

4. Conclusions

Higher-order effects in electromagnetic dissociation can be important. They can spoil the simple relation of EMD cross sections and photodisintegration. It is important to study them carefully. We have presented two limiting cases in this paper, a rather classical calculation, and a quantal one, using a high-energy approximation. Both models are useful in order to assess under which experimental conditions higher-order effects are important.

The quantal calculation was done explicitly for a simple model of ^{11}Li (dineutron cluster model, with zero-range wave functions), where the higher-order effects could be calculated analytically. We continue now our study to treat more difficult situations. Of special interest is the EMD for applications to radiative-capture processes for nuclear astrophysics [2]). In these cases, more elaborate calculations using partial wave expansion are necessary. We mention the reaction $^8\mathrm{B}+{}^{208}\mathrm{Pb}\rightarrow{}^7\mathrm{Be}+\mathrm{p}+{}^{208}\mathrm{Pb}$, which is presently investigated at RIKEN [13]) at $E_{^8\mathrm{B}} = 50$ MeV/A. This is of relevance for the solar-neutrino problem. The sudden approximation as used in this paper, should be well applicable in this case. Finally, we mention the "post-breakup Coulomb acceleration of the ^{9}Li fragment" as it was recently observed [9]) in the longitudinal direction. This is qualitatively understood in our classical model of sect. 2, however this effect is absent in our high-energy quantal model of sect. 3. Thus, deviations from the sudden approximation will have to be considered.

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