Dissociation of deuteron, $^6$He and $^{11}$Be from Coulomb dissociation reaction cross-section

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Abstract. The fragmentation of deuteron, $^6$He and $^{11}$Be have been studied during interaction with the $^{208}$Pb nucleus at various projectile energies. The Coulomb dissociation cross-sections and the momentum distribution of the break-up fragments have been analysed within the framework of the direct fragmentation model. The post-acceleration effect of deuteron during break-up and the halo structures of both the $^6$He and $^{11}$Be have been investigated.

Keywords. Diffraction dissociation; Coulomb effect; post-acceleration phenomenon; momentum distribution; bremsstrahlung integral; halo structure.

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1. Introduction

In recent years an exhaustive study of neutron-rich drip line nuclei has been done by virtue of the availability of the radioactive ion beams [1,2]. In the present research scheme, we have studied the process of dissociation of the neutron-rich halo nuclei through Coulomb and nuclear effects and have tried to understand the characteristic features of the reaction cross-section and the energy distribution of the outgoing charged fragment after dissociation. Also we have thoroughly studied the comparative importance of the two contributions (e.g., Coulomb and nuclear) during dissociation of the projectiles of variable energies.

The model has been applied previously on a few halo nuclei [2,3]. The post-acceleration effect is a new interesting feature in case of the deuteron [4] when it breaks under the strong Coulomb field of the $^{208}$Pb target, and the dissociation process has recently been studied by semi-classical coupled channel approach [4].

The present method, by using several applications [5–10], is mainly based on DWBA method, where the knowledge of the ground state wave function of the projectile is necessary and $E1$ strength distribution is completely inconsequential in this framework. The role of the Coulomb break-up reaction process has also been
Figure 1. The proton energy distribution at 100, 120 and 200 MeV beam energies due to Coulomb break-up reaction process for $0^+$ emission. The $x$-axis represents the ejected proton energy in MeV and $y$-axis shows the energy distribution $\frac{d^2\sigma}{d\Omega \, dE_p}$ in mb/str·MeV. The curves I, II and III indicate projectile energies for 100, 120 and 200 MeV respectively.

observed in the case of $^{11}\text{Li}$ [10–12] where the concept of electric-dipole response has been taken into consideration.

Apart from $^d\text{He}$, extensive experimental informations rest on the halo structure of $^{11}\text{Be}$ [13]. Both the two lowest excited states are bound and the nucleus exhibits halo structure because rms radius of the nucleus is larger than rms radius of the core nucleus $^{10}\text{Be}$ [1]. The spatially extended ground and first excited states also exhibit the halo nature [14]. The halo structure is also confirmed from the value of large anomalous dissociation cross-section of the nucleus and from the extension of the density of the nuclear matter distribution [15]. The photoabsorption cross-section also provides useful information on $^{11}\text{Be}$ nucleus and its halo structure [15,16] where E1 transition probability to ground state dominates. The photoabsorption cross-section, located near threshold energy, shows a narrow peak, and it is related to soft oscillation mode of $^{11}\text{Be}$ [17]. Recently, giant dipole strength distribution of this nucleus has been studied [18] through Coulomb excitation mechanism on Pb target. A strong peak in dipole strength distribution at low excitation energy has been detected.

The detailed background of the model has been discussed in [2]. We summarize it in the next section.
Coulomb dissociation cross-section

Figure 2. The nuclear and Coulomb break-up reaction cross-sections as a function of deuteron beam energy. The dashed line parallel to x-axis denotes nuclear effect and continuous curve shows the effect from the Coulomb contribution. The x- and y-axes represent energy in MeV and total reaction cross-section in mbarn respectively.

2. Dissociation of weakly bound projectile nucleus

The role of interplay between the nuclear and Coulomb interactions in the reaction mechanism can be written as [2]

\[ a(b + c) + A_T \rightarrow b + (c + A_T), \]

(1)

where we have assumed that the projectile \( a \) consists of \( b \) and \( c \). \( A_T \) is the target nucleus. For the break-up of deuteron, \(^6\)He and \(^{11}\)Be, \( b = \) proton, \(^4\)He and \(^{10}\)Be and \( c = \) neutron, two neutron and neutron respectively. The total cross-section on dissociation (\( \sigma_{-xn} \), with \( x = 1 \) or 2) for the reaction (1) can be written as

\[ \sigma_{-xn} = \sigma_{-xn}^N + \sigma_{-xn}^C + \sigma_{-xn}^{CN}, \]

(2)

where \( \sigma_{-xn}^C \) is the electromagnetic (Coulomb) dissociation cross-section and \( \sigma_{-xn}^N \) is the nuclear-breakup cross-section. The Coulomb–nuclear interference contribution is denoted by \( \sigma_{-xn}^{CN} \). The nuclear break-up term is the sum of two parts, i.e.,

\[ \sigma_{-xn}^N = \sigma_{-xn}^{ND} + \sigma_{-xn}^{NS}. \]

(3)
Table 1. For deuteron, the maximum value of the total reaction cross-section has been mentioned as we have quoted the result from Tanihata et al [1]. For $^6$He the experimental references, see §3.

<table>
<thead>
<tr>
<th>Target</th>
<th>Beam and energy</th>
<th>$\sigma$ (Theo.)</th>
<th>$\sigma$ (Exp.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{208}$Pb</td>
<td>$d$</td>
<td>400</td>
<td>1480</td>
</tr>
</tbody>
</table>

The differential cross-section for the diffraction dissociation is

$$
\frac{d^3\sigma_D}{d\Omega_b d\Omega_c dE_b} = \frac{\mu}{(2\pi)^3 \hbar^2} \frac{k_b k_c}{k_a} |f_D(q \cdot Q)|^2.
$$

(4)

3. Results and discussion

The input values of the radius parameter $r_0$ and the diffuseness parameter $\Delta$ have been taken as 1.2 fm and 0.5 fm respectively [3]. The separation energy of neutron from deuteron is 2.225 MeV. The Coulomb energy distribution of the proton beam from deuteron break-up has been plotted against proton energy in figure 1. The graph exhibits the effect of the proton energy dependence of $\sigma_{-n}$ for $d + ^{208}$Pb $\rightarrow$ n + X reaction. The figures have been drawn for the incident deuteron beam energies at 100, 120 and 200 MeV respectively. Figure 2 depicts the contribution of the total reaction cross-section from the Coulomb and nuclear effects. The dotted line parallel to $x$-axis corresponds to the nuclear effect and the continuous line indicates the results from the Coulomb contribution. Here we also see the effect of Coulomb interaction that decreases initially. The nuclear break-up cross-section remains constant and is independent of projectile energy (figure 2) [16]. The estimation of the reaction cross-section by Tanihata et al [1] has been compared with our theoretical estimate for the total dissociation reaction cross-section and has been depicted in table 1. A comparatively much bigger value of the same by Tanihata et al can be accounted for the overestimation of the reaction cross-section from geometrical consideration. In particular, at present no experimental results on the dissociation cross-section of deuteron are available in literature. So for the fidelity of our calculated results, we have depicted results of Tanihata et al [1] in table 1.

From the present research, we observe that nuclear effect practically remains constant over a wide energy range of the incident projectile. But we see marked variation of Coulomb energy dissociation reaction cross-section. Thus the effect of Coulomb dissociation at higher beam energy and its dominance over nuclear dissociation mechanism increases gradually. The break-up of $d$, having large separation energy, shows the post-acceleration effect of the proton fragment in the final reaction channel (figure 2). This accelerating phenomenon is solely due to Coulomb effect and thereby exhibiting its strong effect through direct fragmentation model as Coulomb dissociation cross-section sharply rises at half of incident beam energy.

In our present findings on $d$ dissociation, figures 1 and 2 demonstrate clearly the post-acceleration effect.
Finally, in order to exhibit the post-acceleration effect we have also calculated the momentum distribution of the outgoing proton at 100 MeV. The Gaussian peak in forward direction verifies this physical picture and it has also been detected by Canto et al [4]. This is also one of the main outcomes of the present model as the accelerated particle takes away the burden of the momentum and enhances the process of the break-up.

References