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DEUTERON BREAKUP MECHANISM IN THE INTERMEDIATE-ENERGY REGION*

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Abstract: In an earlier investigation, we have explored[1] the possibility of explaining the deuteron breakup mechanism in terms of the Udagawa and Tannura (UT) formalism of the breakup-fusion process. The experimental doubly differential data were very well reproduced for the test cases studies. However, the application of UT formalixm in the spirit of DWBA involves the use of optical-model parameters for different nuclei and at different energies. The optical model parameters are not always unique. In the present study we investigate the deuteron breakup mechanism in terms of the semiclassical models of Serber[2] (for the nuclear interaction part) and Dancoff[3] (for the electromagnetic dissociation). In the case of Serber model the modification due to the finite range of the deuteron and the Glauber[4] correction for the diffractive disassociation are considered. The modified deuteron breakup cross section either for the (d,p) or the (d,n) process is proportional to the product of the target radius and the deuteron radius ($R_{target} \cdot R_{deuteron}$). The predicted proton/neutron spectrum is centered around 1/2 E_d and forward peaked. The Coulomb dissociation of deuteron is attributed to the deuteron dipole excitation in the presence of the nuclear Coulomb field. The neutron/proton spectrum, resulting from the Coulomb breakup of the deuteron, is highly forward peaked and also centered around 1/2 E_d. The systematics of the deuteron breakup neutron/proton spectra are investigated for medium to heavy target nuclei at 50-200 MeV deuteron energies.

Deuteron-Target Interaction

Low deuteron binding energy of deuteron makes it a very interesting projectile to study the projectile breakup mechanism. Depending upon the impact parameter of the intermediate-energy incident deuteron with respect to the target nucleus, three types of interactions take place: (1) A high energy proton (neutron) may be produced by a direct collission between one of the particles of deuteron and a particle of the target nucleus, when the impact parameter is smaller than the nuclear size. (2) If the deuteron merely grazes the nucleus the neutron (proton) may be stripped and proton (neutron) continues forward with almost the velocity of the incident deuteron. In addition to the stripping process, diffraction dissociation of the deuteron resulting in the breakup of the deuteron takes place with proton and neutron flying away from the nucleus. (3) If the impact parameter is 2-3 times the nuclear radius, Coulomb dissociating of the deuteron takes place as it passes the nucleus. In addition, precompound and compound nuclear processes cannot be ignored completely even at the intermediate energy range. In this short paper we address the energy and angular distribution of proton due to the second and the third type of deuteron interactions with the nucleus.

Semi-classical Treatment of Deuteron Breakup

Based on semiclassical arguments Serber[2] derived the following expression for the total breakup (stripping) cross section:

$$\sigma_{SB} = \frac{\pi R}{2}\int_0^\infty r \,|\Psi_d(r)|^2\, d\vec{r}; \quad d\vec{r} = 4\pi r^2 dr$$

$$= \frac{\pi}{2} R\, R_d$$

where R_d is the average separation of p and n in the deuteron. R_d may be taken to be the size of deuteron. If Ψ_d is taken to be the zero range deuteron ground state

$$\Psi_d = \sqrt{\frac{\alpha}{2\pi}}\,\frac{e^{-\alpha r}}{r} \qquad \alpha = \sqrt{M_d E_B}\,/\hbar$$

then $R_d \sim 2.1$ fermis. Finite range correction to σ_{sb} gives a factor of $(1+\alpha\, r_t) \sim 1.3$, where r_t the triplet range. Furthermore, Glauber[4] pointed out that diffraction dissociation of

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deuteron off the nuclear edge gives rise to an additional correction to σ_{sb}, which is about $0.59\sigma_{sb}$. Hence the modified Serber breakup cross section

$$\sigma_{sB} = \sigma_{sB}\ (1+0.59)\ 1.3$$

$$\sim 2\sigma_{sB}$$

$$\sigma_{sB}^{M} = \pi\ R\ R_d$$

In this work the application of Serber's deuteron breakup theory[2] is restricted to the case when the target nuclear radius is much greater than the size of deuteron. i.e., the nucleus behaves like an opaque object for the incident deuterons. Serber has shown that the energy distribution of protons (or neutrons) is centered around 1/2 the deuteron energy E_d with a half-width ~ twice the product of deuteron binding energy E_B and E_d;ΔE=1.5 E_B E_d MeV. And the angular distribution of protons is highly forward peaked.

In order to calculate the doubly differential cross section the Serber breakup model may be extended[5] by making use of a more appropriate Hulthen wave function for the deuteron. The details will be published in a separate paper.[6] The double-differential cross sections based on the Extended Serber model may be normalized properly to integral breakup cross section $\sigma^{M}_{sB} = \pi R\ R_d$.

Coulomb Dissociation of Deuteron

The Coulomb interaction between the incident deuteron and the nuclear Coulomb field gives rise to Coulomb excitation of the deuteron to the continuum; the dipole excitation process being the dominant one. The dipole excitation of deuteron in flight results in the breakup of the deuteron in its constituents, neutron and proton. Dancoff[5] has shown that the proton (neutron) angular distribution is highly forward peaked and the energy distribution is centered around 1/2 E_d. The Coulomb breakup cross section $\sigma_{CB} \sim Z^2 e^4$ and increases with Z of the target. The finite range correction was also applicable to σ_{CB}.

Doubly differential cross sections for the Coulomb dissociation of deuteron were calculated following the methods of Dancoff. Currently the Coulomb breakup of light to heavy ions is considerable interest[7] due to the proposed construction of RHIC project at BNL. Details of the calculational approach will be presented in a forthcoming paper.[6] Estimates of (d,p) integral cross-sections, energy and angular spectra were made for 56, 80 and 200 MeV deuteron incident on target masses ranging from 16-200. Doubly differential cross sections were calculated for Au at 80 MeV and ^{58}Ni at 56 MeV. Due to lack of space systematics of the (d,p) energy and angular spectra are presented. In addition, total breakup (or non-equilibrium) cross sections are compared with the corresponding experimental data at 56 and 80 MeV deuteron energies for an extensive range of nuclear masses. Whenever the Serber breakup cross section is referred to, the modified σ_{SB}^{M} cross section is implied. Similarly the Coulomb breakup cross section σ_{CB} was corrected for finite range effects. Even though the calculated results are presented for the outgoing protons, similar results are expected for the outgoing neutrons.

Figure 1 presents proton energy spectra calculated at E_d = 56, 80 and 200 MeV based on the Serber deuteron breakup model for Au target. The peak height of the proton spectrum decreases as the deuteron energy is increased. At 200 MeV deuteron energy the relative magnitudes of the Serber breakup cross section $\sigma_{SB}^{M}(E_p)$ and Coulomb breakup cross section $\sigma_{CB}(E_p)$ is displayed: The Coulomb breakup cross section is much smaller than the Serber breakup cross section. Figure 2 presents the proton angular distribution for Au(d,p) reaction. Both the Serber breakup cross section and the Coulomb dissociation cross section components and their sum are plotted as a function of the proton angle below 25°. The Coulomb breakup cross section falls off rapidly with increasing angle.

The relative magnitudes of the calculated Serber cross sections for different target masses (20-200) is displayed in figure 3 for the case of 80 MeV deuteron energy. The calculated results for two sets of r_o($R_t = r_o A1/3$) and R_d the deuteron radius parameters are shown. The Serber breakup cross section is more than an order of magnitude for most of the target nuclei except for the high Z nuclei. Figure 4a presents a comparison of the experimentally determined[8] cross sections with the combined results of the Serber and Coulomb breakup cross sections at 56MeV deuteron energy. The calculated results are shown for two sets of r_o and R_d values. The experimental data seem to favor the choice of r_o=1.5f and R_d=3.0f for most of the target masses except for the very light mass nuclei. A comparison of the experimentally extracted[9] non-equilibrium component of the proton yield with the combined calculated results of the Serber and Coulomb breakup cross section for the case of E_d=80 MeV for a wide range to target nuclei is shown in Figure 4b. With regard to the experimentally determined non-equilibrium cross section it should be pointed out that the method used by the experimentalists is non-unique and the procedure may be questionable. The calculated results are somewhat lower in magnitude in comparison to the corresponding experimental data, however the general trend of the data as a function of nuclear mass is reproduced.

In summary the Serber breakup theory may be used to quantitatively describe the deuteron breakup phenomenon. Except for the high Z nuclei the Coulomb breakup cross section is much smaller than the Serber breakup cross section. The Coulomb dissociation cross section is important for heavy target nuclei and at low angular range with respect to the deuteron beam. The simple Serber model theory assumes the energy-independence of the deuteron projectile energy. Extensive experimental data at several deuteron energies would enable one to study the target radius dependence of the Serber breakup cross section. Below 200 MeV deuteron energy the coulomb dissociation cross section is weakly energy dependent.

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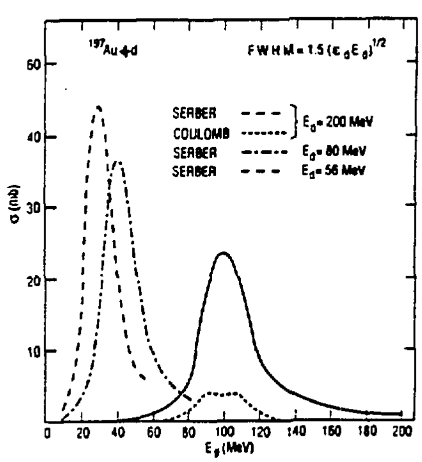

Fig. 1 (d,p) proton energy spectra for Au + d at 56, 80 and 200 MeV deuteron energies. Coulomb Breakup cross section is shown for the 200 MeV case.

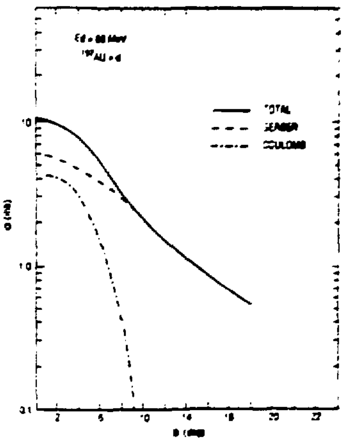

Fig. 2 Low angle Serber and Coulomb Breakup angular distributions for 80 MeV deuterons on Au target.

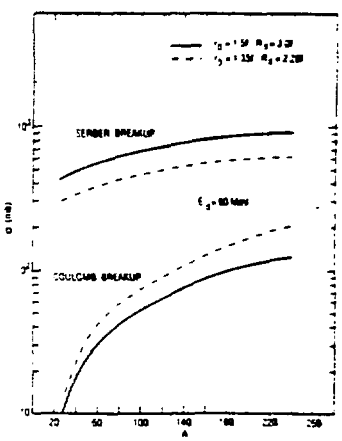

Fig. 3 Integral Serber and Coulomb Breakup cross sections as a function of nuclear mass A for 80 MeV deuteron energy.

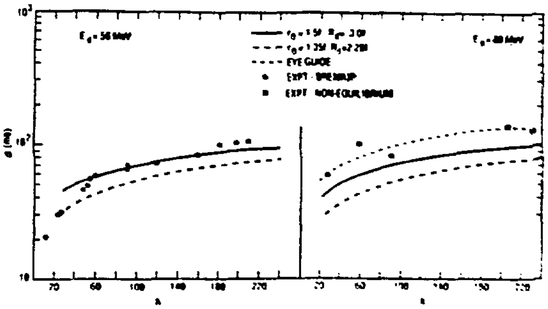

Fig. 4 A comparison of the sum of Serber and Coulomb Breakup cross sections with the experimental non-equilibrium cross section at 56 and 80 MeV deuterons for nuclear mass A=16-200.