

# Heavy ion stripping reactions at intermediate energies

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## Abstract

The concept of the critical distance between clusters forming the projectile is taken into account in the theory of direct nuclear reactions, in addition to the assumption of nuclear surface diffuseness. This approach describes well both the energy and angular distributions of light and heavy projectile fragments.

## 1. Introduction

The study of the nucleus-nucleus collisions is an important source of information about the mechanism of various nuclear reactions as well as a source of information about the nuclear structure. Projectile dissociations and stripping reactions are projectile breakup processes of great interest in this direction.

The simple theory of deuteron stripping at intermediate energies was first developed by Serber<sup>1</sup> who proposed two models, the opaque and transparent models, to account for deuteron stripping reactions. Serber applied the two models to the deuteron stripping at 190 MeV. The calculations showed that approximately there is no difference between the two models.

In 1957 Akhiezer and Sitenko<sup>2</sup> developed a deuteron stripping reaction theory based on the deuteron-nucleus diffraction interaction theory<sup>3</sup>. The cross section of the deuteron stripping reaction by an absorbing nucleus with sharp boundary coincides with that calculated by Serber's opaque model. Different aspects of the deuteron stripping theory were further studied by several authors<sup>4-6</sup>.

In 1982 Matsuse et al.<sup>7</sup> introduced a new concept of a critical distance,  $R_c$ , when two colliding nuclei come close to form a compound nucleus during fusion reaction.

Utsunomyia<sup>8</sup> extended the opaque version of Serber model to the case of heavy ion stripping reactions, by incorporating the critical distance between constituent clusters in the projectile. Utsunomyia's model was applied to the experimental data of 280 MeV ( $N^{14}$  on  $Ho^{165}$ ), 218-315 MeV ( $O^{16}$  on  $Pb^{208}$ ) and 7.5-20 MeV/n ( $Ne^{22}$  on  $Au^{197}$ ). Although Utsunomyia's angular and energy distributions of the particles released in the nucleon-transfer reactions are in agreement with the experiment, however, Utsunomyia did not take account of the nuclear surface diffuseness in his calculations.

Later, Berezhnoy and Korda<sup>9</sup> calculated the integral and differential cross sections of the deuteron-stripping reaction taking into account the nuclear surface diffuseness on the basis of diffraction theory. It was shown that the integral cross section of the inclusive stripping reaction has two terms. One coincides with the Serber opaque model cross section, while the other is due to the finite value of the nuclear surface diffuseness. Good agreement was obtained with 650 MeV deuteron experimental data.

In this work, we slightly modify Utsunomyia's calculations by taking into account the nuclear surface diffuseness. Energy and angular distributions of stripping fragments resulting from heavy ion collisions are calculated.

## 2. Energy and Angular Spectra of Stripping Fragments

In this calculations we use the same approach as that used in<sup>8</sup> taking into account the surface diffuseness effect<sup>9</sup>. The differential cross section  $d\sigma_s$  contains two terms:

In fig (1) ,we present the energy spectra of  $C^{12}$  emitted at  $14^\circ$  from collision of  $N^{14}$  on  $Ho^{165}$  at 280 MeV. Fig (1a) shows the results of calculations of Utsunomyia's model<sup>8</sup> .A dependence of the calculation on the values of  $R_c$  is shown . It should be noticed that the larger the value of  $R_c$  the narrower the width of the spectrum . While in fig.(1b) we display the results of our calculations using eq.(2) .The surface diffuseness term in eq.(2) ,improves the agreement with the data certainly at the lower energy part of the spectrum. Our present approach is further applied to the energy spectra of  $N^{15}$  and  $C^{12}$  from the collisions of  $O^{16}$  on  $Pb^{208}$  at 218 MeV , in fig.(2) , with  $R_c=2.7$  fm .

Figs (3) shows our calculations of the angular distribution ,eq(4) , as applied to various projectiles  $Li^6$  ,  $Li^7$  , and  $Ne^{22}$  . The data are taken from<sup>11,12,13</sup> respectively . These figures reflect clearly the good coincidence with the experimental data .

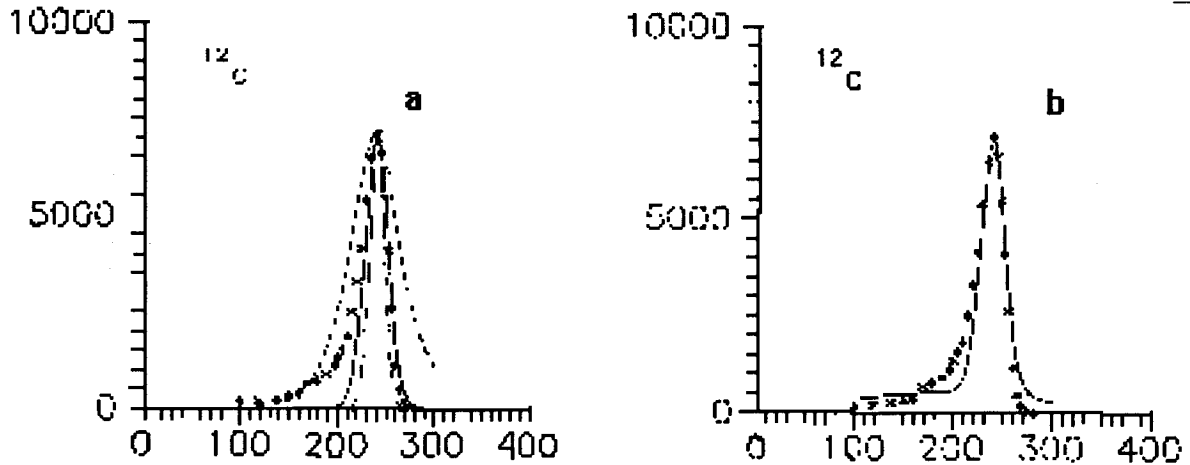


Fig. 1 Energy spectra of  $^{12}C$  emitted at  $14^\circ$  from the collision of  $^{14}N$  on  $^{165}Ho$  at 280 MeV: (a) A comparison with Utsunomyia' calculations (solid curve) with  $R_c = 2.61$  fm , short-dashed curve stands for  $R_c = 0$  while long dashed curve for  $R_c = 10$  fm. (b) Results of our calculations, eq. (2), with  $R_c = 3.55$  fm

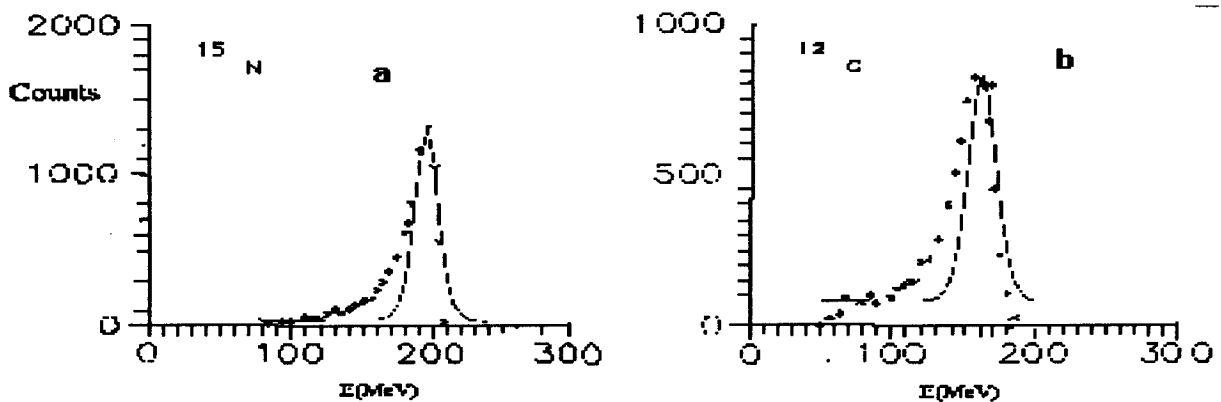


Fig. 2 Energy spectra of  $^{15}N$  and  $^{12}C$  from the collision of  $^{16}O+^{208}Pb$  at 218 MeV. Data are taken from [10].

$$(d\sigma_s) = (d\sigma_s)_U + (d\sigma_s)_d \quad (1)$$

$(d\sigma_s)_U$  is the stripping reaction cross section as given by Utsunomiya, and  $(d\sigma_s)_d$  is that due to surface diffuseness and is calculated by:

$$(d\sigma_s)_d = d\left(\frac{\partial}{\partial d} d\sigma_s\right)_{d=0}$$

where  $d$  is the diffuseness parameter.

Therefore the double differential cross section of the stripping fragment  $b$ , due to eq.(1), is:

$$\frac{d^2\sigma}{d\Omega_b dE_b} = C \left[ \frac{A_b P_b}{(\alpha\hbar)^2 + P_b^2 + P_0^2 - 2P_b P_0 \cos\theta} \int_0^{2\pi} \frac{\text{Exp}\left[-2\left(\frac{R_c}{\hbar}\right)(\alpha^2\hbar^2 + P_{II}^2 + P_{\perp}^2 \sin^2 x)^{1/2}\right]}{(\alpha^2\hbar^2 + P_{II}^2 + P_{\perp}^2 \sin^2 x)^{3/2}} dx + \frac{10Rd\alpha\hbar^2}{3\pi} \frac{P_0^2}{[(\alpha\hbar)^2 + P_b^2]^2} \right] \quad [2]$$

$A_b, P_b$  are the mass number and the momentum of the released particle.  $P_b$  is obtained by coupling of the intrinsic momentum  $\mathbf{P}$  and the momentum  $\mathbf{P}_0$  due to the incident motion of the projectile.  $P_{II}$  and  $P_{\perp}$  are respectively the parallel and transverse components:

$$P_{II} = P_b \cos\theta - P_0 \quad [3]$$

$$P_{\perp} = P_b \sin\theta$$

where  $\theta$  is the laboratory angle.  $C$ , in eq.(2), is a normalization constant and  $\alpha\hbar = (2\mu\epsilon)^{1/2}$ ;  $\mu$  is the reduced mass and  $\epsilon$  is the separation energy.

The angular distribution of the stripping fragment  $b$  is given by:

$$\frac{d\sigma}{d\Omega_b} = C \left\{ \left[ A_b^{3/2} (\epsilon E_a)^{1/2} / A_a^{1/2} \alpha\hbar \cos\theta \right] \int_0^{2\pi} dx \int_{-\infty}^{\infty} dP_{II} (P_{II} + P_0) \frac{\exp\left[-2\left(\frac{R_c}{\hbar}\right)(\alpha^2\hbar^2 + P_{II}^2 + P_{\perp}^2 \sin^2 x)^{1/2}\right]}{(\alpha^2\hbar^2 + P_{II}^2 + P_{\perp}^2 \sin^2 x)^{3/2}} + \frac{5Rd(P_0 / \alpha\hbar)^2}{6(1 + \xi^2)^{3/2}} \right\} \quad [4]$$

Where  $A_a$  and  $E_a$  are the mass number and energy of the incident projectile.  $P_{II}$  is related to  $E_a$  and  $E_b$  (of the emitted fragment) by:

$$P_{II} = \alpha\hbar(E_b - A_b E_a / A_a) / (2A_b \epsilon E_a / A_a)^{1/2}$$

and,

$$\xi = \frac{2P_0}{\alpha\hbar} \sin(\theta/2)$$

as defined in Berezhnoy model<sup>9</sup>.

### 3. Comparison with the experimental data :

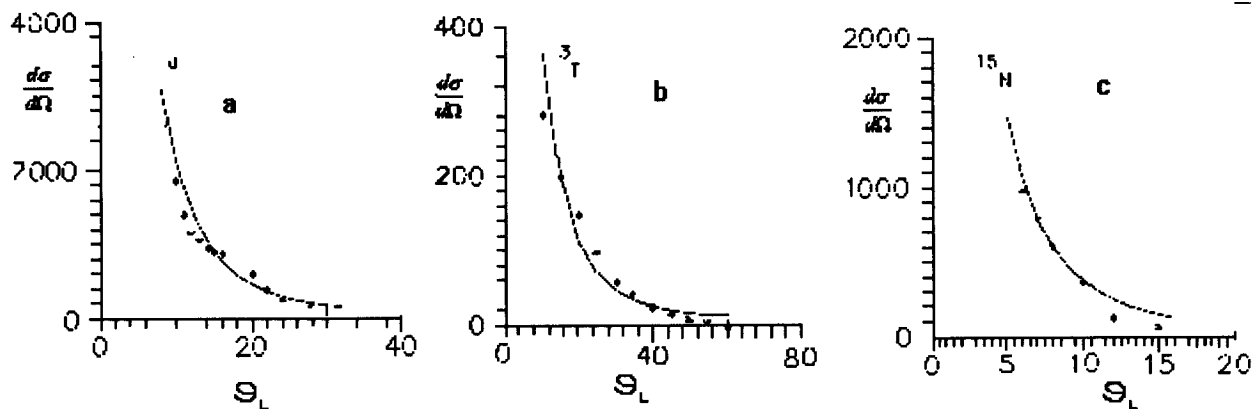


Fig. 3 Angular distribution of (a) deuterons released by 156 MeV  ${}^6\text{Li} + {}^{208}\text{Pb}$ , (b) triton released by 77 MeV  ${}^7\text{Li} + {}^{156}\text{Tb}$ , and (c)  ${}^{15}\text{N}$  resulting from 660 MeV  ${}^{22}\text{Ne} + {}^{93}\text{Nb}$  reactions. Solid curves are the calculations of eq. (4).

#### 4. Conclusion

In this work the concept of the critical distance between clusters forming the projectile is considered in the theory of direct nuclear reactions in addition to the assumption of nuclear surface diffuseness. The present calculations for stripping reactions are shown to be satisfactory in describing both the energy and angular distributions of fragments.

#### 5. References

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