# Importance of the breakup mechanism for composite particle scattering

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We calculate in our formulation of the elastic and inelastic breakup process in nucleus-nucleus collisions the corresponding flux removed from the elastic channel. It is the dominant reaction mode for surface partial waves. Strongly reminiscent of the Serber model, the absorption can be characterized by "geometrical" quantities (radius of the projectile and target nucleus) and a "strength parameter" which becomes constant for energies much larger than the binding energy of the projectile.

[NUCLEAR REACTIONS $A(d,p)$ breakup at $E_d$=25.5, 80 MeV, $A$=27, 62, 93, 181, 197; $A(\alpha,{}^3\text{He})$ breakup at $E_\alpha$=100, 140, 172.5 MeV, $A$=58, 62, 90; calculated breakup probabilities, total cross sections, deduced gross properties.]

It has long been suspected that in deuteron nucleus collisions the breakup process has a strong influence on other channels. Whereas recent investigations[1,2,3] have emphasized the study of the feedback of the breakup channel on the elastic channel, the real breakup has been calculated theoretically[4,5,6] and compared to very complete experiments recently.[5,6] Of course, the breakup mode will also have an influence on stripping channels as shown in detailed investigations by Johnson and Soper.[7] Since the distorted-wave Born approximation (DWBA) theory for elastic and inelastic breakup is in rather good agreement with experiment,[6] we feel that it is now possible to take this approach as a starting point for the investigation of the effect of breakup on other reaction channels. It is the purpose of this paper to determine the influence of the breakup process on the absorption in the elastic channel. The breakup mode is not only important for the weakly bound deuteron but also, at sufficiently high incident energies, for all other composite particles. As an example, we study the $\alpha$-particle breakup process on medium mass nuclei at $E_\alpha$ = 100–172 MeV.[8,9] It turns out in our calculations that the absorption due to breakup is very important in the surface region. Similar to the Serber model,[10] where the breakup cross section is determined by geometrical quantities (the radii of projectile and target nucleus), we find simple scaling properties for the breakup probability.

We consider a projectile $a$ to be composed of $b+n$ (e.g., $a=d$, $b=p$; for more complex particles, of course, different modes of fragmentation exist). The inclusive $A(a,b)$ spectrum consists of the elastic and inelastic modes[6] (depending on whether the target nucleus $A$ stays in the ground state or not during the reaction). It is calculated following the procedure described in Ref. 6. In this first order theory, only the coupling of the elastic channel to the breakup channel is considered, whereas the coupling of the breakup channel back to the elastic channel or to other channels is neglected.

Even without introducing such a coupling we can determine an influence of the breakup process on the elastic scattering. We consider the transmission coefficient $T_{l_a}$, which determines the total reaction cross section of $a+A$ scattering, as given by

$$T_{l_a}=1-|S_{l_a l_a}|^2=\sum_{c\neq l_a}|S_{l_{ac}}|^2 . \quad (1)$$

Here $l_a$ denotes the elastic channel. For simplicity of notation we take $a$ and $A$ to be spinless; hence $l_a$ corresponds to the total spin, and $c$ describes any other channel with total angular momentum $l_a$. Because of the unitarity of the $S$-matrix, we can express the transmission coefficient $T_{l_a}$ as a sum (or integral for continuous channels) over all reaction channels. This allows us to study the effect of the breakup channel on $T_{l_a}$ in an explicit way, even in a first order theory.

We define the "probability of break-up" $T_{l_a}^{\text{b-up}(a,b)}$ by

$$\sigma_{\text{total}}^{\text{breakup}(a,b)}=\frac{\pi}{q_a^2}\sum_{l_a}(2l_a+1)T_{l_a}^{\text{b-up}(a,b)}$$
$$=\iint dE_b d\Omega_b \frac{d^2\sigma(a,b)}{d\Omega_b dE_b} , \quad (2)$$

where $d^2\sigma(a,b)/d\Omega_b dE_b$ denotes the inclusive double differential cross section; it is calculated as described in Refs. 6 and 9. The integration over $\Omega_b$ can be done analytically and the energy integration is performed numerically. Enough partial waves are used to ensure convergence, and we go substantially beyond the grazing partial waves, in order to make sure that the long-range Coulomb effects are also taken into account.

In Fig. 1 we show our results for the reaction $^{93}$Nb$(d,p)$ at the incident deuteron energy of 25.5 MeV. The potential parameters used are the same as described in Ref. 6, where it is shown that our theory is in good agreement with the experimental breakup spectra. Whereas the transmission coefficient (which is calculated with a standard optical model potential) shows a "smooth cutoff" behavior, $T_{l_d}^{\text{b-up}(d,p)}$ shows a distinct peak around grazing partial waves ($l_d \simeq 11$). With increasing projectile energy our calculations show that the localization of the breakup probability in $l$ space becomes much more pronounced because of the smaller wavelength of the incident particle. Thus we have established the peripheral nature of the breakup process. It is worthwhile to compare our results with other approaches. Whereas in Rawitscher's approach there is some surface peaking of the breakup probability,[11] we have close resemblance with Austern *et al.*,[1] as can be seen in Fig. 3 of Ref. 1. (Although these authors consider in a very sophisticated model a different target nucleus and rather simple types of interactions, a qualitative comparison of our results with those of Ref. 1 seems meaningful.) However, we cannot corroborate their "$L=9$ effect" (see Ref. 1); instead, we have a rather smooth dependence of $T_{l_d}^{\text{b-up}(d,p)}$ on $l_d$, which is expected if semiclassical concepts are meaningful. The surface peaking of the breakup probability is also present in the results of Ref. 3. In these calculations, only the elastic breakup is included, and a large part of the absorption, which is due to the inelastic breakup, is thereby missed.

Another interesting feature of Fig. 1 is the fact that for $l_d > 13$, $T_{l_d}^{\text{b-up}(d,p)}$ exceeds the total transmission coefficient. Of course, we must always have $T_{l_d} > T_{l_d}^{\text{b-up}(d,p)}$. This is not a deficiency of our breakup calculations; rather, it shows the inadequacy of the phenomenological deuteron optical model potential used to determine transmission coefficients $T_{l_d}$ for large values of $l_d$. The fitting procedures to obtain such optical model parameters are too restricted in their radius dependence: The Woods-Saxon shape precludes the slow decrease of $T_{l_d}$ for large $l_d$. Thus our calculations provide direct evidence for a large extension of absorption in deuteron nucleus scattering.

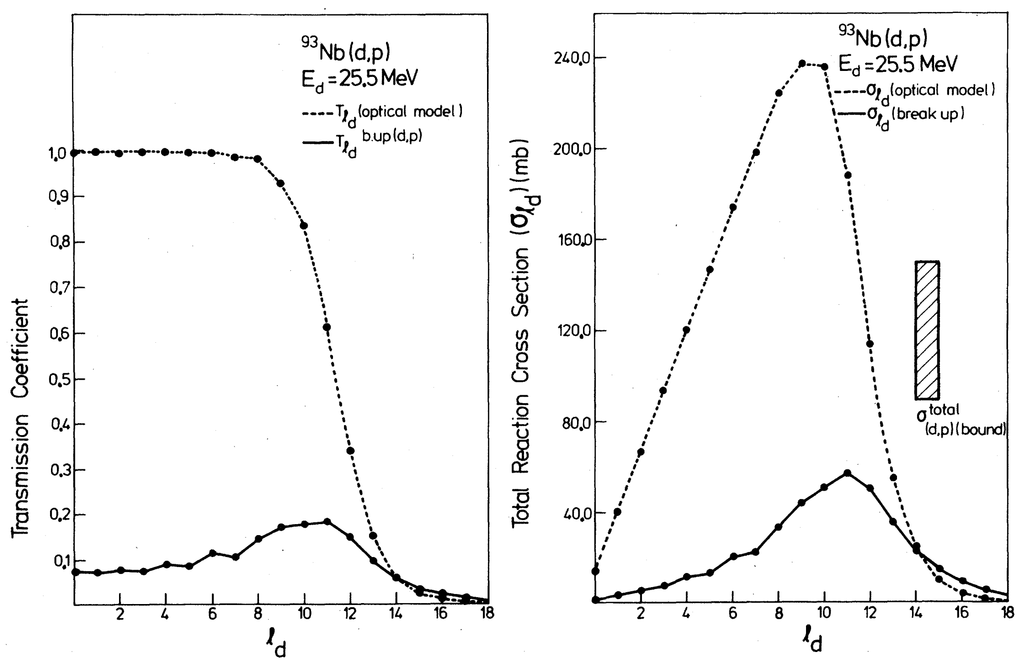


FIG. 1. On the left-hand side, the transmission coefficient as calculated from a standard optical model potential and the $(d,p)$ breakup probability are shown for the deuteron induced reaction on $^{93}$Nb at $E_d = 25.5$ MeV. On the right-hand side, the corresponding total breakup and reaction cross sections are shown. For the sake of comparison we show in the shaded area the magnitude of the experimental total cross section for $(d,p)$ stripping to bound states, as taken from Ref. 6.

In model calculations,[12] where we have switched off the nuclear part of the projectile target interaction, we could explicitly see that this long range deuteron absorption is entirely due to the Coulomb breakup. In Fig. 1 we also show the experimentally observed total cross section for $(d,p)$ stripping to bound states $(E_n<0)$. It is only a minor fraction of the direct $(d,p)$ processes.

As another example, we calculate the breakup probability $T_{l_\alpha}^{\text{b-up}(\alpha,{}^3\text{He})}$. For simplicity we consider here only the $(\alpha,{}^3\text{He})$ breakup process; a similar effect is expected for $(\alpha,t)$ breakup. (In addition, there will be other fragmentation modes like $\alpha\to d+d$, etc.) In Fig. 2 we show the impact parameter dependence of the total $(\alpha,{}^3\text{He})$ breakup cross section defined by

$$\sigma_{\text{total}}^{\text{break-up}(\alpha,{}^3\text{He})}=\frac{\pi}{q_\alpha{}^2}\sum_{l_\alpha}(2l_\alpha+1)T_{l_\alpha}^{\text{b-up}(\alpha,{}^3\text{He})} \simeq 2\pi\int db\, b\,T_{l_\alpha}^{\text{b-up}(\alpha,{}^3\text{He})}, \quad (3)$$

where $b=(l_\alpha+\frac{1}{2})/q_\alpha$ is the impact parameter. The optical model parameters used are taken from Ref. 9. Even more strongly than in the $(d,p)$ case, we note in Fig. 2 the localization of the breakup probability at peripheral impact parameters. We can see that for increasing $\alpha$-particle energy the shape of the breakup probability curve remains unchanged; only its magnitude increases, with some kind of "saturation." This shows the geometrical nature of the breakup process. Thus it is established that the breakup is an important absorption effect in the surface region for $\alpha$-induced reactions (at least for $\alpha$-particle energies much larger than the breakup threshold). Therefore all kinds of theories which disregard the possibility of the breakup of the $\alpha$ particle must lead to quite appreciable deviations of the theoretical transmission coefficients as compared to the experimental ones. Since the grazing angular momenta determine the angular distributions, the possibility of breakup has to be included in all optical model theories for composite particles. This holds especially for the $\alpha$-nucleus optical potentials calculated in Ref. 13, where absorption is assumed to be only due to the excitation of target states treating the $\alpha$ particle as an elementary particle.

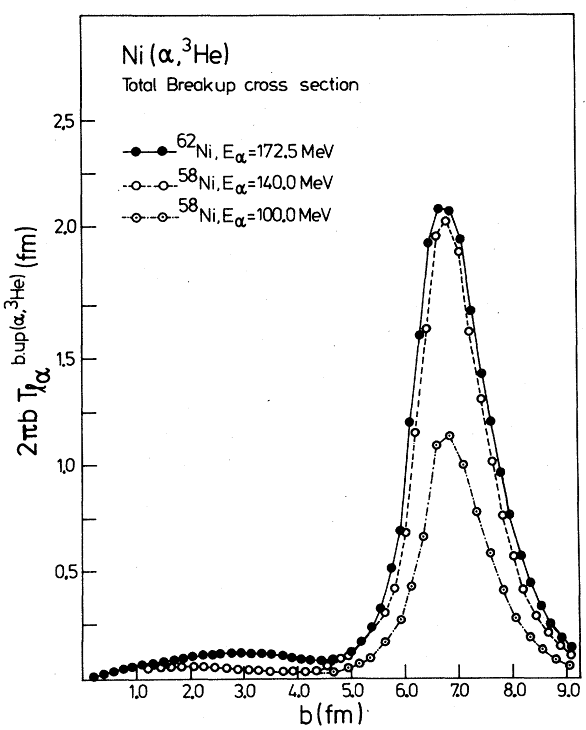


FIG. 2. Impact parameter dependence of the total $(\alpha,{}^3\text{He})$ breakup cross section on Ni targets for various $\alpha$-energies $E_\alpha$.

Finally we try to extract some "gross properties" of the breakup reaction. We introduce a simple parametrization of our numerical results, which shows a remarkable similarity to the Serber picture. We write

$$T_l^{\text{b-up}(a,b)}=\beta(E_a,E_{\text{bind}})e^{-(l-l_0)^2/(\Delta l)^2} =\beta(E_a,E_{\text{bind}})e^{-(b-b_0)^2/(\Delta R)^2}, \quad (4)$$

with $b=l/q_a$, $b_0=l_0/q_a$, $\Delta R=\Delta l/q_a$, and $q_a$ being the wave number of the projectile. $E_a$ and $E_{\text{bind}}$ correspond to the incident and binding energies of the projectile, respectively. The breakup probability has a peak at a partial wave $l_0$ with a width $\Delta l$. The impact parameter $b_0$ and $\Delta R$ are almost independent of the incident energy. The factor $\beta$ describes the strength of the breakup process, which is expected to show a saturation for suffici-

TABLE I. Simple parametrization of the breakup probability, Eq. (4). The numbers are determined by fitting our numerical results to Eq. (4).

| $A$ | $r_0$ | $\Delta R$ | $\beta$ |
|---|---|---|---|
| | $(d,p)$ breakup at $E_d=25.5$ MeV | | |
| 27 | 1.29 | 1.85 | 0.205 |
| 62 | 1.25 | 1.90 | 0.185 |
| 93 | 1.24 | 1.89 | 0.185 |
| 181 | 1.13 | 1.95 | 0.185 |
| | $(d,p)$ breakup at $E_d=80.0$ MeV | | |
| 27 | 1.09 | 1.63 | 0.420 |
| 93 | 1.15 | 1.92 | 0.315 |
| 197 | 1.19 | 1.90 | 0.280 |
| | $(\alpha,{}^3\text{He})$ breakup at $E_\alpha=140$ MeV | | |
| 58 | 1.18 | 1.05 | 0.048 |
| 90 | 1.16 | 1.15 | 0.047 |

ently high incident energies and vanish for small incident energies. We relate $b_0$ to the size of the target and projectile by $b_0=r_0(A^{1/3}+a^{1/3})$. In Table I we show the values of $r_0$ and $\Delta R$ extracted from the cases we have studied in deuteron scattering at $E_d=25.5$ MeV and 80.0 MeV, and $\alpha$ scattering at $E_\alpha=100$, 140, and 172.5 MeV. *These numbers are remarkably independent of A and* $E_a$; this supports the Serber picture. The slight decrease of $r_0$ with $A$ for $E_d=25.5$ MeV deuteron breakup can be explained[12] by destructive nuclear Coulomb interference which becomes more important for increasing $A$. The optical model parameters used in these calculations are of the standard type; extensive details will be given in Ref. 12.

In conclusion, we want to say that we have studied the influence of the breakup channel on the elastic channel. We use our method[6,9,12] to calculate the real breakup, which reproduces the experimental breakup cross sections. Then we use unitarity to determine quantitatively the influence of breakup on the elastic channel. Since $T_l^{\text{b-up}(a,b)}$ is smaller than 1, our first order theory gives reliable results. On the other hand, these breakup probabilities are large enough to be of great importance as a surface absorption mechanism. Finally we give a very simple geometrical interpretation of our numerical results for the breakup process, which confirms some of the concepts of the Serber model.

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