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Elastic and inelastic breakup of the ^{3}He particle

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Within the framework of the post form distorted-wave Born-approximation theory of breakup reactions, we study the elastic and inelastic breakup of the ^{3}He particle. With the standard set of parameters for the optical model potential we are able to understand coincidence and inclusive data for this process, which were recently measured by Matsuoka *et al.* at the incident ^{3}He energy of 90.0 MeV. The elastic breakup accounts only for about 20% of the total inclusive (^{3}He,d) yield. With our theory we are able to understand quantitatively the breakup process, a dominant peripheral reaction mechanism.

[NUCLEAR REACTIONS $A(^3\text{He},d)$ breakup at $E_{^3\text{He}} = 90.0$ MeV, $A = {}^{51}$V, ^{90}Zr; calculated elastic and inelastic breakup cross sections; post form DWBA theory of breakup.]

I. INTRODUCTION

The breakup reaction is a dominant reaction mechanism for grazing nucleus-nucleus collisions.[1] It has been intensively studied in inclusive particle spectra from light [2] and heavy ion[3] induced reactions. In inclusive experiments, information about the complete final state is lost. Sometimes this may simplify the theoretical description of such processes if one can use unitarity to sum over the information which is lost in inclusive types of measurements.[4] Yet, for a more detailed and complete study of the breakup channels, it is necessary to analyze coincidence measurements. With the help of such experiments it becomes possible to distinguish more clearly between various theoretical models for breakup reactions. Such experiments have been done for deuteron,[5] alpha,[6] and heavy ion[3] induced reactions.

A rather complete coincidence study of the ^{3}He breakup has very recently been published by Matsuoka *et al.*[7] Rather similar experiments with somewhat lower ^{3}He incident energies have recently done in Groningen.[8] Since the theory for the breakup reaction, formulated in the post form of the distorted-wave Born approximation (DWBA) (Refs. 6, 9, 10) is in quite good agreement with the experimental d and α breakup coincidence data, it seems interesting to apply this theory to these rather extensive measurements.[7] This is especially favorable for the following reasons: The incident energy $E_{^3\text{He}} = 90$ MeV is rather high compared to the binding energy of ^{3}He; thus the breakup is an important reaction mode. The experimental data are very systematic, measurements have been made for many combinations of the deuteron and proton angles for a number of target nuclei. The ^{3}He particle is the "next complicated" particle with respect to the deuteron. Thus such a study can be a step towards heavy ion breakup reactions with its many different breakup channels. Yet, one "complication" of heavy ion breakup reactions is missing, there are no excited states (resonances) (above the particle breakup threshold) of the ^{3}He system. Thus, the competing mechanism, whereby the projectile is excited in the field of the target nucleus to some excited (resonant) state, which decays subsequently, is not present here.

Thus we apply, quite similarly to the (α, tp) breakup reaction[6] our breakup theory to the (^{3}He, dp) process. In that work it was found that the coincidence data are more sensitive to the optical model parameters than the inclusive data. This can be understood because the averaging in the inclusive cross sections leads to the insensitivity of the theoretical result on the phases of certain matrix elements. Since optical model studies for ^{3}He, d, and p are rather systematically developed, the input into our theoretical calculations is rather well determined. Furthermore, it has been our claim[2,4,11] that inclusive spectra are not dominated by the elastic but by the inelastic breakup we can see again whether this is true for the ^{3}He breakup reaction, because in our formulation of the inclusive breakup reaction[4,11] we can analyze inclusive as well as coincidence experiments simultaneously with the same set of input parameters.

After a brief summary of our theoretical formulation we present in Sec. II the numerical calculations and results. Our conclusions are given in Sec. III

II. THEORETICAL FORMULATION, NUMERICAL RESULTS, AND COMPARISON WITH EXPERIMENTS

A. A brief description of our theoretical framework

For the theoretical study of the (^{3}He,dp) coincidence spectra we use the formulation give in Refs. 9 and 10. There the post form of the DWBA was applied to (d,pn) processes below and above the Coulomb barrier. This formalism can be carried over to the case of three charged particles in the final state.[6] We rely here, as we did also in the case of deuteron breakup, on the zero range expression, which is a good approximation[12] for light ion reactions, and take into account finite range effects by means of the local energy approximation (LEA). This is much easier than a full finite range calculation.

In the post form of the DWBA, the triple differential cross section for the (^{3}He,dp) reaction can be expressed as

$$\frac{d^3\sigma}{d\Omega_d\Omega_p dE_d}=2\pi\,\frac{m_{^3\text{He}A}m_{dA}m_p}{(2\pi\hbar)^6}\,\frac{q_dq_p}{q_{^3\text{He}}}\,|T_{fi}|^2\,, \quad (1)$$

where the T matrix element is given, in partial wave decomposition, as

$$T_{fi}=D_0(4\pi)^2\sum_{l_{^3\text{He}}l_dl_p} i^{l_{^3\text{He}}+l_d+l_p}e^{i(\sigma_{l_{^3\text{He}}}+\sigma_{l_d}+\sigma_{l_p})}(2l_{^3\text{He}}+1)^{1/2}(2l_d+1)^{1/2}(2l_p+1)^{1/2}$$
$$\times\begin{pmatrix} l_{^3\text{He}} & l_d & l_p\\ 0 & 0 & 0\end{pmatrix}\sum_{m_p}\langle l_d-m_pl_pm_p|l_{^3\text{He}}0\rangle\, Y_{l_d-m_p}(\vartheta_p,\varphi_d)\,Y_{l_pm_p}(\vartheta_p,\varphi_p)\times R_{l_{^3\text{He}}l_dl_p}\,. \quad (2)$$

Here the Coulomb phase shifts are denoted by σ_l, the angle of emission of the deuteron and the proton are given by ϑ_d and (ϑ_p,φ_p), respectively. We can choose the azimuthal angle $\varphi_d=0$. The radial matrix elements $R_{l_{^3\text{He}}l_dl_p}$ are given in terms of the radial optical model wave functions $\chi_l(q,r)$ by

$$R_{l_{^3\text{He}}l_dl_p}=\int_0^\infty dR\;\chi_{l_d}\!\left(q_d,\frac{A}{A+1}R\right)\chi_{l_p}(q_p,R)\chi_{l_{^3\text{He}}}(q_{^3\text{He}},R)\cdot\Lambda(R)\cdot P(R)\,, \quad (3)$$

where finite range and nonlocality corrections are included in the standard way (see e.g., Ref. 10) by the factor $\Lambda(R)$ and $P(R)$. In Eq. (2) D_0 denotes the zero range normalization constant. There has been much discussion in literature about its value.[13,14] Recently Werby and Strayer[14] evaluated this constant by using various realistic trinucleon wave functions. We have used the value reported by the above authors using a trinucleon wave function which reproduces the correct asymptotic shapes for $n+d$ and $n+p$ relative motion wave functions (set V, Table 1, of Werby and Strayer[14]). This magnitude of D_0 is also obtained using modern dispersion relation techniques.[15]

Note that in Eq. (2) the sum over the proton partial waves is coherent; this property gets lost for the (^{3}He,d) inclusive cross section. Thus the coincidence cross section is more sensitive to relative phases of matrix elements, as one may expect.

Since we want to discuss in this paper also the inclusive (^{3}He,d) spectra, we present here a short summary of our theory for this inclusive reaction.[4,11] In the inclusive (^{3}He,d) spectrum all processes will contribute where the interaction of the proton with the target nucleus is elastic (any type of reaction). The contribution of the elastic breakup to the inclusive spectrum can be obtained by the integration of expression Eq. (1) over the angle of the unobserved proton. In order to calculate the inelastic breakup, the summation over all channels c that are open for the system p + target has to be performed. This can be done by exploiting the peripheral character of the breakup process and the unitarity of the S matrix.[4,11] The inclusive cross section consists of an incoherent sum of the elastic and inelastic contributions, which can be written in the rather compact final form (for details see Ref. 4 especially)

$$\frac{d^2\sigma}{d\Omega_d dE_d}=\frac{2\pi}{\hbar v}\,\rho(\text{phase})\times\sum_{l_pm_p}\left(|T_{l_pm_p}|^2+\frac{\sigma^{\text{reac}}_{l_p}}{\sigma^{\text{el}}_{l_p}}\,|T_{l_pm_p}-T^0_{l_pm_p}|^2\right). \quad (4)$$

Here v is the relative velocity in the initial state, ρ(phase) the phase space factor, and $\sigma^{\text{el}}_{l_p}$ and $\sigma^{\text{reac}}_{l_p}$ the total proton target elastic and reaction cross sections in the l_p th partial wave, respectively. The matrix elements $T_{l_pm_p}$ which describe the elastic breakup (integrated over proton angles) are given by

$$T_{l_p m_p} = D_0 \int \chi_d^{(-)*}\left(\frac{A}{A+1}\vec{R}\right)\chi_{l_p}(R) Y_{l_p m_p}(\hat{R}) \times \chi_{^3\mathrm{He}}^{(+)}(\vec{R})\Lambda(R)P(R)d^3R \; . \tag{5}$$

Here $\chi_{^3\mathrm{He}}^{(+)}$ and $\chi_d^{(-)}$ denote the (three-dimensional) distorted waves of the incoming and outgoing ^{3}He and d respectively. The radial proton wave function is denoted by $\chi_{l_p}(R)$, as in Eq. (3). The quantity $T^0_{l_p m_p}$ is a corresponding matrix element with $\chi_{l_p}(R)$ replaced by the regular Coulomb wave function $F_{l_p}(q_p R)/q_p R$.

B. Results of numerical calculations and comparison with experiments

As it is discussed in Ref. 6, the triple differential cross section turned out to be rather sensitive to the optical potential parameters used in the various channels. These potential parameters together with the zero range constant D_0 are the only input of our theoretical calculations. To minimize the uncertainty of our results we have tried to use standard sets of potential parameters for all three optical model interactions (^{3}He, d, and p). In the case of the ^{90}Zr target nucleus, we use for the ^{3}He target interaction the potential given by Hyakutake *et al.*[16] For the deuteron channel, the potentials given by Duhamel *et al.*[17] are used. For the ^{51}V target, we take the potentials given by Hyakutake *et al.*[16] for a ^{58}Ni target at the incident energy of $E_{^3\mathrm{He}} = 89.3$ MeV. However, we reduce the strength and the diffuseness of the imaginary part by 1.8 MeV and 0.04 fm respectively, in order to take into account the A dependence, as discussed by Goldberg *et al.*[18] All other parameters were left unchanged as they have a very weak A dependence according to these authors . For the deuteron channel we use the potential given by Hinterberger *et al.*[19] For both nuclei, the standard Becchetti-Greenlees potentials[20] have been used for the proton target interaction. In our calculations, the deuteron potential parameters used correspond to the peak energy ($\sim\frac{2}{3}E_{^3\mathrm{He}}$), and they were kept fixed for all other deuteron energies. Noncentral components of the various potentials were neglected; we do not expect significant effects of those on the "unpolarized" cross sections; their inclusion, although rather straightforward, would strongly increase the computing time.

The numerical results of our theoretical calculations are shown in Figs. 1–4, where a comparison is made with the coincidence[7] and inclusive[21] experimental results of Matsuoka *et al.* The incident ^{3}He energy will always be $E_{^3\mathrm{He}} = 90$ MeV.

In Fig. 1 we show the elastic breakup reaction ^{90}Zr(^{3}He,dp)^{90}Zr for $\theta_d = 15°$ and $\theta_p = -20°$. As

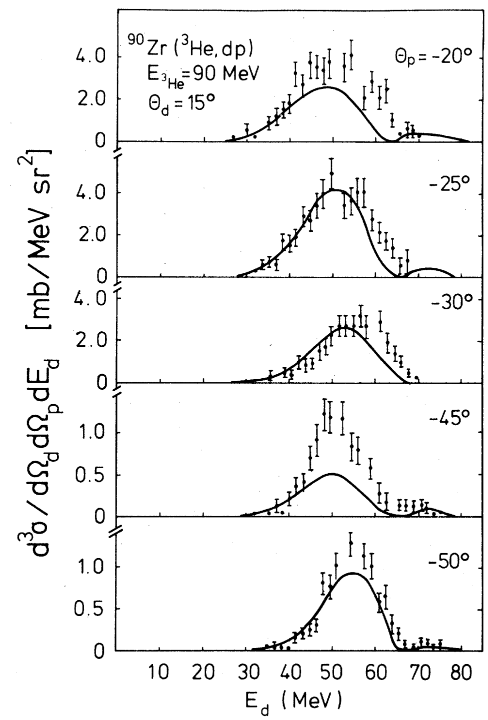

FIG. 1. Deuteron energy spectrum for the ^{90}Zr(^{3}He,dp)^{90}Zr ground state coincidence cross section. Experimental results (Ref. 7) are shown for various proton angles θ_p. The deuteron angle $\theta_d = 15°$ is kept fixed, the geometry is coplanar, the minus sign indicates scattering on opposite side of the beams. The theoretical calculations are given by the continuous line.

one can see, the position of the peak as well as the absolute magnitude of the cross section can be well reproduced.

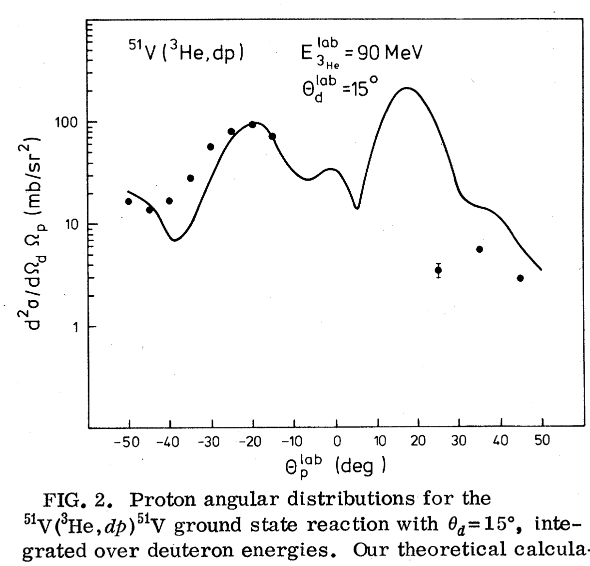

FIG. 2. Proton angular distributions for the ^{51}V(^{3}He,dp)^{51}V ground state reaction with $\theta_d = 15°$, integrated over deuteron energies. Our theoretical calculations (continuous line) are compared to the experimental results of Ref. 7.

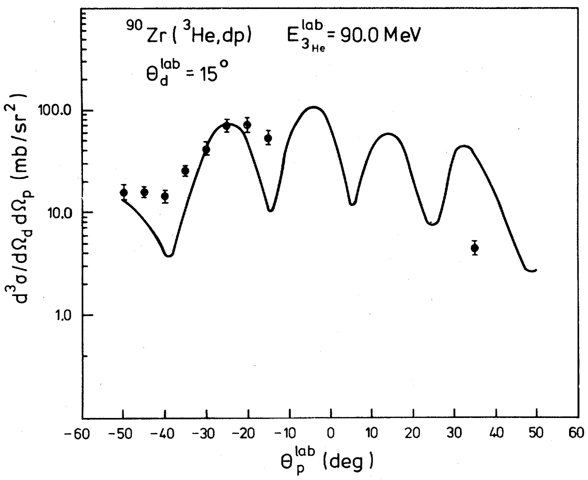

FIG. 3. Same as in Fig. 2 with ^{90}Zr as a target.

In Figs. 2 and 3 we show "proton angular distributions" for energy integrated elastic breakup spectra with fixed deuteron angle $\theta_d = 15°$ for ^{51}V and ^{90}Zr as a target, respectively. A pronounced diffraction structure can be seen in these proton angular distributions. Again, theory and experiment are in satisfactory agreement.

In Fig. 4 we compare the (^{3}He,d) inclusive spectra on ^{90}Zr for $\theta_d = 13°$ and $16°$ with experiment.[21] It can be seen that around the breakup peak region our theoretical calculations are in quite good agreement with the experimental data, as far as shape as well as absolute magnitude are concerned. We note that the inclusive cross section remains finite at the breakup threshold[4,11,21] corresponding to $E_p = 0$ (see also Ref. 22). The elastic breakup vanishes at this threshold; there only the inelastic mode contributes. It can also be seen that the elastic breakup represents only a minor fraction of the total inclusive (^{3}He,d) cross section. In Ref. 7, an experimental upper limit of about 20–50% is given for the ratio of elastic to inclusive contributions for the (^{3}He,d) reaction

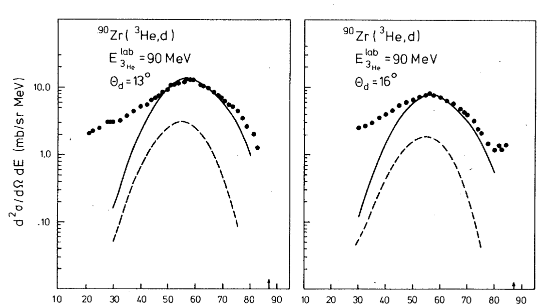

FIG. 4. Comparison of experimental ^{90}Zr(^{3}He,d) inclusive spectra (Ref. 21) with our theoretical calculations (continuous line) for inclusive breakup. The theoretically calculated contribution due to elastic breakup alone is shown separately in the dashed line.

at $\theta_d = 15°$. This limit compares favorably with our theoretical ratio of about 1:5. As already observed in a similar situation,[6] there is a distinct shift in the peak energy of the elastic and inclusive deuteron spectrum.

III. CONCLUSIONS

Let us first comment on other theoretical approaches to the ^{3}He breakup reaction. The authors of Ref. 7 give a theoretical analysis of their data in a plane wave model. By introducing a cutoff in the plane-wave Born approximation (PWBA) integral, nuclear interactions are taken into account in complete analogy to the time-honored Butler stripping theory. Thus, intuitively speaking, the physical model behind the approach of Ref. 7 is the same as ours; however, we take these interactions much more seriously into account by using optical model interactions. Thus we understand why the authors of Ref. 7 can qualitatively explain their data; the need to do more realistic calculations was also pointed out there, This model can be considered[22] as a refinement, in terms of modern direct reaction theory, of the early and successful breakup model of Serber.[23]

Another approach is followed by Udagawa and Tamura.[24] Restricting them selves to the elastic breakup, these authors use the prior interaction form of the DWBA. It was studied before by Rybicki and Austern[25] for deuteron breakup and found to be inadequate. This calculation can be viewed as the inelastic excitation of the projectile into some continuum state which decays subsequently. Such a process has been studied experimentally for heavy ion (^{6}Li, ^{12}C, etc.) induced reactions.[3,26] The deuteron does not posses such resonant states. This can explain the failure of the theoretical approach of Ref. 25 to the deuteron breakup. Since the ^{3}He particle does not show such resonances either, we view the model of Ref. 24 for the ^{3}He breakup with caution. Instead of directly evaluating the prior form DWBA matrix element, as it is done in Ref. 25, the authors of Ref. 24 introduce further approximations in order to evaluate that matrix element. They discuss their validity for strongly absorbing projectiles.

In this paper we have applied our theory of elastic and inelastic breakup processes to the ^{3}He breakup. We obtain good agreement with the experimental data by using a standard set of optical model parameters and a reasonable value for the vertex constant D_0. Quite similar to the case of the α breakup studied in Ref. 6 we obtain agreement for both elastic and inelastic breakup with a consistent set of parameters. We find that the elastic breakup contributes about one fifth to the total inclusive (^{3}He,d) yield, which is in agreement with experimental estimates.

Thus, with our theoretical approach we are able to describe well the coincidence as well as the inclusive cross sections for the ^{3}He breakup reactions, just as for d and α breakup. This definitely gives us an impetus to extend our approach in order to analyze the heavy ion fragmentation, for which a wealth of experimental data has recently become available.[3,27]

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