Proton-induced ^{3}He breakup at 156 MeV

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(Received 10 March 1975)

The ^{3}He breakup induced by a 156 MeV proton beam was studied using a liquid target and the adequate kinematic conditions for p-p, p-n, and p-d quasifree scattering or three nucleon final state interactions. The $(p, 2p)$ and (p, pn) differential cross section spectra ($d^3\sigma$) are similar to each other for recoil energy less than 10 MeV and coincide to those calculated with the plane-wave impulse approximation. The $d^3\sigma$ spectrum of the (p,pd) reaction shows a peak at the minimum p-d relative energy indicating their final state interaction.

[NUCLEAR REACTIONS $(d^3\sigma/d\Omega_1 d\Omega_2 dE_1)_{\rm exp,PWIA}$ for ^{3}He(p,dp), $(p,2p)$, and (p,pn) at 156 MeV. Studies of p-p, p-n, and p-d quasifree interactions. The p-d final state interaction observed.]

Recently, several experiments on deuteron breakup induced by protons were performed at Orsay with the 156 MeV proton beam in order to obtain information on the nucleon-nucleon interaction in a three nucleon system. The simultaneous measurement of the $(p, 2p)$ and (p,pn) cross sections allowed a direct comparison between p-p and p-n data in the quasifree scattering (QFS) and in the final state interaction (FSI) kinematic regions.[1] The differential cross section spectra obtained in this study were compared with some theoretical calculations carried out within the framework of approximate solutions of the Faddeev equations.[2] We desired to extend such studies to the four nucleon system by means of proton-induced ^{3}He breakup. Recently, ^{3}He$(p, 2p)d$ and $\tilde{d}$ (the singlet S virtual state of a deuteron) and ^{3}He$(p,pd)p$ reactions at 156 MeV have been studied at Orsay[3] for small recoil momentum of the spectator particle ($k_r \leq 0.65$ fm^{-1}) and it seems interesting to study them over a larger interval.

The search for three nucleon excited or virtual states is an exciting field and has been the subject of intensive experimental and theoretical investigations.[4] We have attempted to detect an excited state near the breakup threshold of ^{3}He arising from FSI between three nucleons, using the kinematic conditions which correspond to the three nucleon relative energy near zero; for example $\theta_1 = 40°$, $\theta_2 = -70°$, and $E_p \sim 18$ MeV for p-$2p$ and p-pn, and $E_d \sim 40$ MeV for d-p FSI.

A 156 MeV proton beam and a liquid flat ^{3}He target of 4.5 mm thickness were used. The two emerging particles were detected in coincidence on opposite sides of the beam direction in coplanar geometry. The detection system and the electronic system were almost identical to that described in Ref. 1. The cross sections in ^{3}He breakup are generally smaller than those in deuteron breakup and several reactions are induced. Therefore, we have measured more experimental parameters to overcome these difficulties.

The first counter telescope consisted of a ring-type thin plastic scintillation counter coupled in anticoincidence to eliminate scattering from the collimator, a transmission-type Si surface-barrier detector of 350 μm thickness as a ΔE detector, and a NaI crystal (diam = 5.1 cm, l = 7.6 cm) as a E detector. This telescope was used for the detection of charged particles scattered at the angle θ_1. The second counter telescope consisted of a plastic scintillation counter S_2 (diam = 180 mm, thickness = 2 mm) and a liquid NE213 scintillation counter (diam = 175 mm, length = 254 mm, volume = 6 l). This second telescope detected either neutrons or charged particles scattered at the angle θ_2, depending on whether the counters S_2 and NE213 were coupled in anticoincidence or in coincidence, respectively. Using these experimental devices, five physical parameters were determined for each event; namely, the energy of the first particle E_1, its energy loss ΔE_1, the energy of the correlated second particle E_2, a charge identifying signal for the particle which entered into the second telescope, and the time of flight difference between the first and the second particle T_{12}. These parameters were recorded on line using a Hewlett Packard 2300 computer system. The recorded events were then classified using a UNIVAC 1110 computer system. Charged particles detected with the first telescope were identified using two-dimensional E_1-ΔE_1 spectra and those detected with the se-

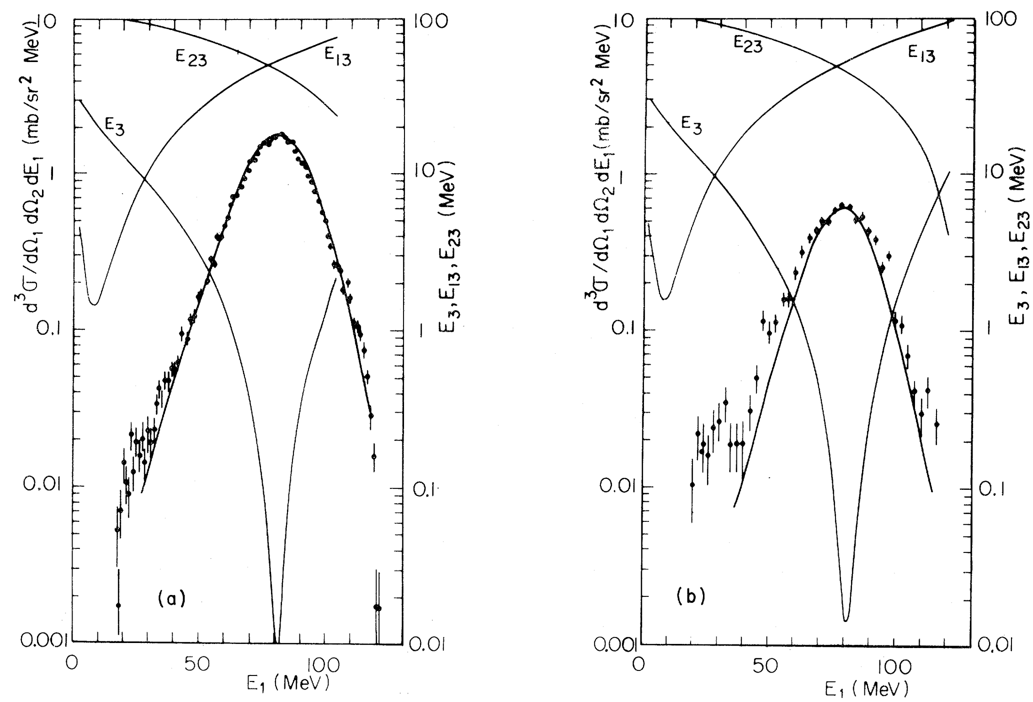

FIG. 1. (a) The $d^3\sigma/d\Omega_1 d\Omega_2 dE_1$ spectrum for ^{3}He$(p,2p)d$ and $\bar{d}$ at $\theta_{p1}=40°$ and $\theta_{p2}=-44°$. (b) The same spectrum for ^{3}He$(p,pn)2p$. The experimental points are indicated with statistical error bars. The solid curve E_3 indicates the kinematic energy (in laboratory system) of the recoil deuteron or the two nucleon system, and E_{13}, E_{23} indicate the relative energies between the proton detected in the first detector (or the second nucleon detected by the second detector) and the spectator deuteron or a two nucleon system. The solid curve without a label represents the $d^3\sigma$ calculated with PWIA.

cond telescope were identified using E_2-T_{12} spectra; neutrons detected with the second telescope were identified by T_{12}.

Figures 1(a) and 1(b) show the typical E_1-E_2 energy sharing spectra projected on E_1 ($d^3\sigma/d\Omega_1 d\Omega_2 dE_1$) for the ^{3}He$(p,2p)d$ and $\bar{d}$ (a scattering state, ^1S of p-n) reactions, and that for the ^{3}He$(p,pn)\,2p$ reaction at $\theta_{p1}=40°$ and θ_{p2} (or θ_n) $=-44°$. The solid curve labeled E_3 corresponds to a plot of the kinematic energy (in the laboratory system) of the recoil deuteron or the two-nucleon center of mass whose relative energy is about 0.4 MeV. The curve labeled E_{13} (or E_{23}) corresponds to a plot of the relative energy (in the center of mass system) between the particle detected by the first (or the second) telescope and the recoil particle (deuteron or two-nucleon center of mass).

The cross section spectrum for the ^{3}He$(p,pn)2p$ reaction was obtained for the first time in this energy region. It is interesting to compare the cross section for the ^{3}He$(p,pn)2p$ reaction with the cross sections for the ^{3}He$(p,2p)d$ and $\bar{d}$ reactions at the QFS peaks. These shapes are almost coincident with each other for a kinematic energy of the spectator particle less than 10 MeV.

The experimental differential cross sections $d^3\sigma/d\Omega_1 d\Omega_2 dE_1$ for the ^{3}He$(p,2p)d$ and $\bar{d}$, and for the ^{3}He$(p,pn)2p$ reactions at their QFS peak have been obtained to be (1.80 ± 0.03) and (0.60 ± 0.03) mb/sr^2 MeV, respectively. The energy resolution in E_2 for the QFS peak neighborhood being ± 2.2 MeV, the ^{3}He$(p,2p)d$ and $(p,2p)\bar{d}$ reactions could not be distinguished. But we can estimate their yield ratio by obtaining the $d^4\sigma/d\Omega_1 d\Omega_2 dE_1 dE_2$ spectrum cutting the E_1-E_2 biparametric spectra with a constant E_2 value and fitting the plane wave impulse approximation (PWIA) spectrum[5] using the $d/\bar{d}$ ratio as a parameter. For instance, the $d^4\sigma$ spectrum obtained for $E_2=68.5$ MeV (the value corresponding to the QFS peak) is presented in Fig. 2. The PWIA spectrum with the $d/\bar{d}$ ratio taken as 3.54 ± 0.5 resulting in $d^3\sigma_d=(1.40\pm 0.4)$ mb/sr^2 MeV and $d^3\sigma_{\bar{d}}=(0.41\pm 0.5)$ mb is presented in a solid line. The energy interval of the n-p system is 15 MeV. The ratio of $d^3\sigma$ divided by $(d\sigma/d\Omega)_{\rm c.m.}$ for these two reactions by using $d^3\sigma_{p,2p}=1.8$ mb/sr^2 MeV, $d^3\sigma_{p,pn}=0.6$ mb/sr^2 MeV and $(d\sigma/d\Omega)^{\rm c.m.}_{p-p}=3.7$ mb/sr, $(d\sigma/d\Omega)^{\rm c.m.}_{p-n}=2.5$ mb/sr, respectively, for $E_2=68.5$ MeV is

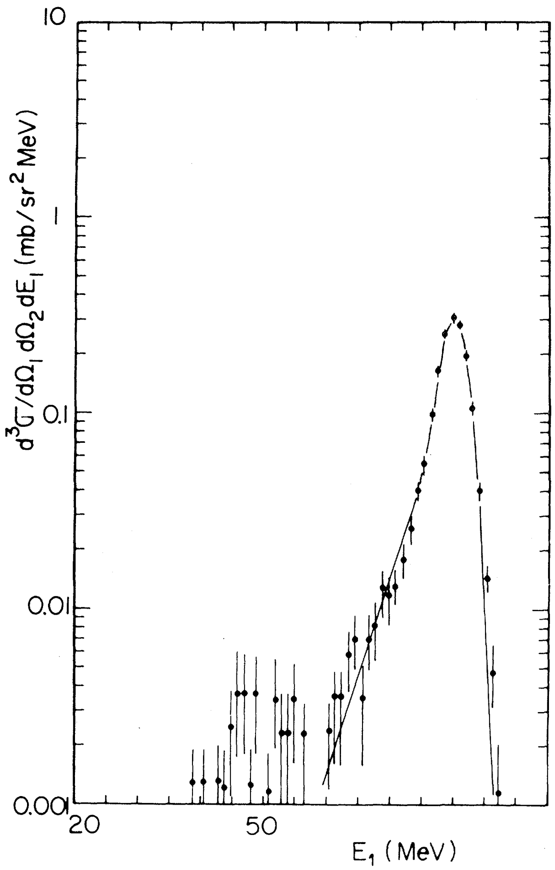

FIG. 2. The $d^4\sigma$ spectrum for $^3He(p,dp)p$ at $\theta_d = 40°$, $\theta_p = -70°$, and $E_2 = 68.5$ MeV. The experimental points are indicated with statistical error bars. The solid curve represents the PWIA calculation using the energy interval of 15 MeV and the $d/\bar{d}$ ratio is 3.50 ± 0.5.

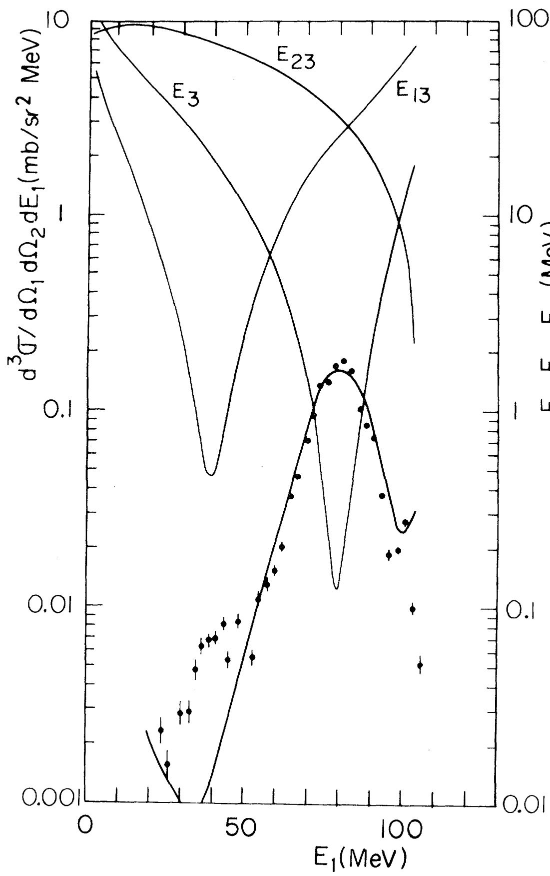

FIG. 3. The $d^3\sigma$ spectrum for $^3He(p,pd)p$ at $\theta_d = 40°$ and $\theta_p = -70°$. The experimental points are indicated with statistical error bars. The solid curves E_{13} and E_{23} correspond, respectively, to the relative energy of the spectator proton and a deuteron entering into the first telescope and that of the proton entering into the second telescope. The E_3 and the PWIA curves are explained in the caption of Fig. 1.

$$\frac{d^3\sigma[^3\mathrm{He}(p,2p)d+\bar{d}]}{(d\sigma/d\Omega)^{\mathrm{c.m.}}_{p-p}} \Big/ \frac{d^3\sigma[^3\mathrm{He}(p,pn)2p]}{(d\sigma/d\Omega)^{\mathrm{c.m.}}_{p-n}} = 2.03 \pm 0.20 . \quad (1)$$

On the other hand, the spin-isospin factor ratio in ^{3}He for these two reactions is obtained as follows:

$$[(p-d)+(p-\bar{d})]_{\mathrm{in}\ ^3\mathrm{He}}/[(n-2p)_{\mathrm{in}\ ^3\mathrm{He}}] = (\tfrac{3}{2}+\tfrac{1}{2})/1 = 2 . \quad (2)$$

In comparing (1) and (2), we find that these two reactions at the QFS peak show great resemblance except for the spin-isospin factor. (The calculated $d^3\sigma$ values with PWIA by using a Hulthén-type wave function for a deuteron, plane-wave functions for $\bar{d}$ and $2p$, and an Irving-Gunn-type wave function for ^{3}He with the normalization factors of 0.70 and 0.76 have been presented in Figs. 1(a) and 1(b).

Figure 3 shows the $d^3\sigma/d\Omega_1 d\Omega_2 dE_1$ spectrum for the $^3He(p, dp)p$ reaction at $\theta_d = 40°$ and $\theta_p = -70°$. This angular pair was chosen in order to observe p-d QFS and possible p-d FSI. The solid curves E_3, E_{13}, and E_{23} have the same meaning as in Fig. 1, except that the first particle is a deuteron and the second and third particles are protons.

In this case, the PWIA calculation curve obtained using Hulthén and Irving-Gunn wave functions for deuteron and ^{3}He, respectively, with the same coefficient of $\alpha_1(0.77)$ for the latter and a little different normalization factor (0.65) explains the experimental spectrum in the region of $k \leq 0.7\ \mathrm{fm}^{-1}$.

One notices that the spectrum for the $^3He(p, dp)$ reaction presents a peak on both sides of the QFS-type peak. The apparent peak on the right-hand side (around $E_1 \sim 101$ MeV and $E_{23} \sim 5$ MeV) arises from a two proton FSI which increases with E_1. The left-hand side peak (around $E_1 \sim 40$ MeV and $E_{13} \sim 0.5$ MeV) is due to the p-d FSI. The three nucleon FSI between p-$\vec{d}$ and p-$2p$ were also studied in ^{3}He$(p, 2p)\vec{d}$ and ^{3}He$(p,pn)2p$ reactions. Unfortunately the statistics are still poor at the present stage.

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