[13]To simplify the notation, Eqs. (3) and (6) have been written down for the case of $s$-$p$-shell nuclei only; for, in this case, the sum $\sum_{\nu\mu\lambda}$ reduces to $\sum_{\nu\mu}$.

[14]It should be emphasized that there are no *a priori* reasons to introduce a Pauli operator into the JCF, since in the Jastrow wave function the Pauli principle is already satisfied by the Slater determinant.

[15]In Ref. 6(a), on the contrary, it is stated that "... for computing binding energies and rms radii a more careful analysis of the self-consistency conditions is a prerequisite."

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# Search for a State in $^3$He via the $p + D \rightarrow p + d^*$ Reaction†

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Excitation functions for the $^2$H($p$, $pp$)$n$ reaction have been measured at pairs of proton angles chosen so that the $p$-$n$ system with zero relative energy was at 30 and 90° in the c.m. system. The differential cross sections $d\sigma/d\Omega_1 d\Omega_2$ corresponding to the production of a $p$-$n$ system with relative $p$-$n$ energy below 100 keV are presented. The excitation functions cover the incident proton energy range of 7 to 14.5 MeV in 0.5-MeV steps. The energy dependence of the primary interaction has been extracted by using final-stage modifications of the Watson type. No evidence was found for structure in either the excitation function for the differential cross section or in the excitation function for the primary interaction factor.

There has been considerable work done looking for evidence of excited states in the three-nucleon system; in particular some recent experiments[1,2] have reported measurements of the excitation function for the reaction $p + D \rightarrow d^* + p$ (where $d^*$ is a $p$-$n$ system with small relative energy). Niiler *et al.*[1] have reported a bump in this excitation function at about 10.5-MeV incident proton energy, corresponding to a possible resonance at 12.5-MeV excitation in $^3$He. The two protons in the final state were detected with counter angles chosen so that the $d^*$ had a laboratory angle of 30° at each incident energy. On the other hand, van der Weerd *et al.*[2] saw considerably less structure in an experiment in which they detected the proton and neutron from the $d^*$ at 25° in the lab for each energy, and in addition measured $d^*$ angular distribution at seven energies. We have measured the excitation function for this reaction from 7- to 14.5-MeV incident proton energy at two angles. Since we are looking for possible resonances in the $^3$He system, these angles were not fixed laboratory angles, but were varied with energy to correspond to fixed c.m. angles of 30 and 90° for the outgoing $p$-$n$ system with zero relative energy. For comparison, the corresponding c.m. angle for the experiment of Ref. 1 varies from 65.6 to 69.2°, and the c.m. angle for the experiment of Ref. 2 varies from 53.3 to 60.9° over the energy range of the excitation functions.

Since the final state consists of three particles, it is necessary to detect two of them to determine all the kinematical variables. In this experiment both protons were detected, at angles chosen to include the case of zero relative energy between the neutron and one of the protons. The kinematical relationships in the final state can be understood readily by considering the c.m. system for the proton and neutron that comprise the $d^*$. If we consider the $d^*$'s with zero to a few hundred keV excitation energy to be leaving the reaction at an angle $\theta_{d^*}$, then the recoil proton angle $\theta_2$ is fairly well defined. (For any particular excitation of the $d^*$, $\theta_2$ is defined exactly; it changes slowly over a range of a few hundred keV $d^*$ excitation when the incident proton energy is several MeV.) If the scattered proton is detected at $\theta_2$ and a second counter is placed at $\theta_{d^*}$, it will simultaneously detect the proton coming from the decay of the zero-excitation $d^*$. The kinematic loci for the proton energies $E_1$ and $E_2$ are shown in Fig. 1, together with the $d^*$ excitation energy. $E_1$ is the energy of the proton from the $d^*$; $E_2$ is the energy of the other proton.

In the present experiment a deuterated polyethylene target of approximately 1 mg/cm$^2$ was bombarded with protons from the University of Washington Van de Graaff accelerator. The outgoing protons were detected in two silicon detectors. The counter angles, as mentioned previously,

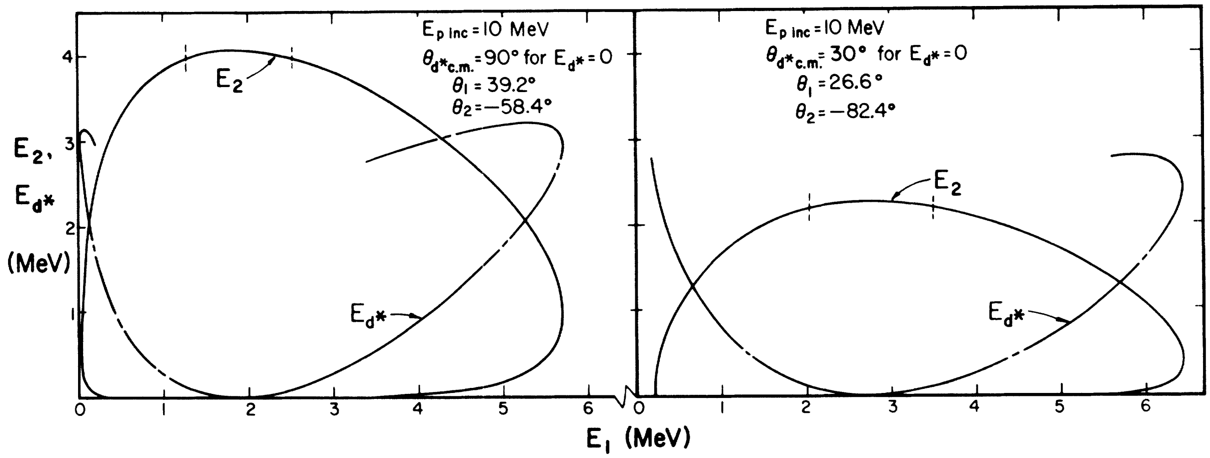


FIG. 1. Kinematics for $p$-$d$ breakup at proton angles chosen to include $d^*$'s in the final state. The subscripts 1 and 2 refer to the proton coming from the $d^*$ and the other proton in the final state, respectively. The vertical marks on the $E_1$-$E_2$ curve indicate the points corresponding to $d^*$ excitations for 100 keV.

were set corresponding to outgoing $d^*$ c.m. angles of 30 and 90°. Timing signals from the zero crossings of bipolar proton-energy pulses started or stopped a time-to-amplitude converter (TAC). The two energy signals and the TAC signal were digitized and stored by the SDS 930 computer. Using the computer, we were able to vary the acceptable TAC values corresponding to prompt coincidences to suit the appropriate energy region. Thus we were able to obtain time resolutions of

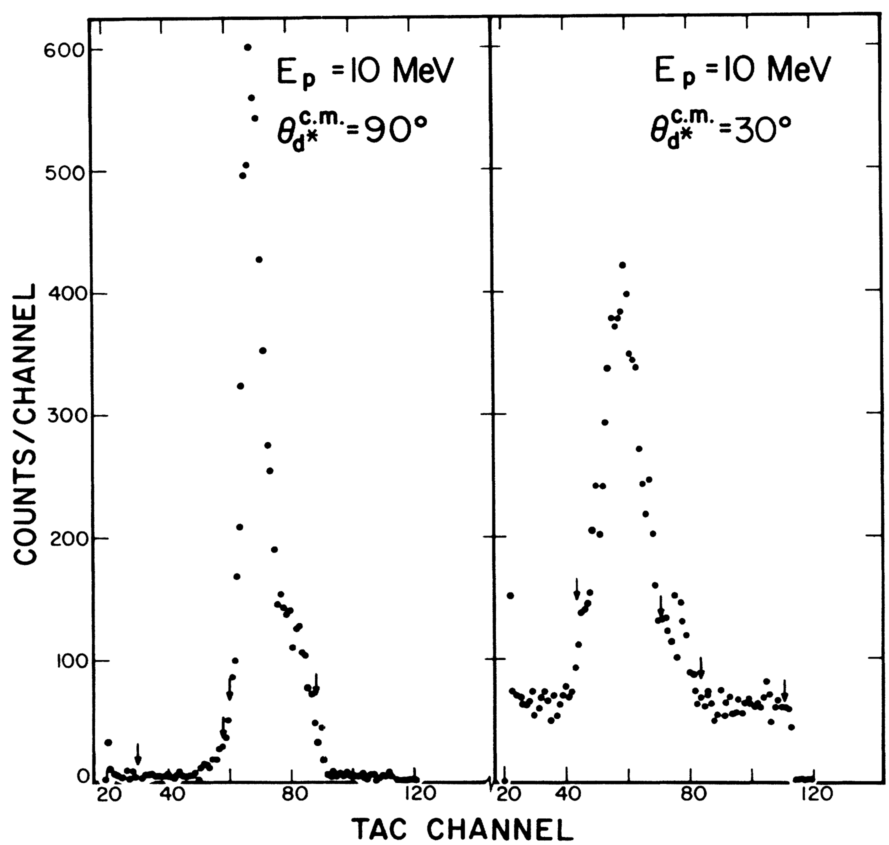


FIG. 2. Time spectra from the two sets of proton angles corresponding to c.m. $d^*$ angles of 90 and 30° (approx. 0.8 nsec/channel). The small arrows indicate the acceptance intervals used to determine prompt and accidental coincidences.

about 20 nsec. This resolving time was adequate to eliminate most accidental-coincidence background. Figure 2 shows typical time spectra taken from the $E_1$-$E_2$ region corresponding to the $d^*$.

Typical energy spectra appear in Fig. 3. We have projected the appropriate region of the two-dimensional energy spectra onto the $E_1$ axis. The effect of the $p$-$n$ final-state-interaction enhancement is apparent in the peak. The peak center corresponds to zero $d^*$ excitation energy, and the arrows indicate values of $E_1$ corresponding to $d^*$ excitations of 100 keV. By summing the counts between the arrows and comparing with the number of counts for $p$-$d$ elastic scattering, we obtained cross sections $d\sigma/d\Omega_1 d\Omega_2$ corresponding to production of $p$-$n$ systems with excitation between zero and 100 keV. There are other final states in this region besides the $d^*$. In particular, there are contributions from the triplet $p$-$n$ system, from final-state interactions involving the "other" proton, and from "three-body phase-space breakup." These contributions are discussed in Ref. 1 and are shown to be small (a few percent) for $d^*$ excitation below a few hundred keV. Figure 4 shows $d\sigma/d\Omega_1 d\Omega_2$ plotted versus incident energy for the angles corresponding to the $d^*$ at 30° and corresponding to the $d^*$ at 90° in the c.m. system. There is no structure, and the excitation functions are both rising slowly. The uncertainties are generally about 5%, although in some cases they are higher, resulting primarily from uncertainties in the determination of the $E_1$ channel corresponding to the 100-keV $d^*$ excitation and from uncertainties in the dead-time determination. In addition, there is an over-all uncertainty of about 10% due to the determination of the $p$-$d$ elastic cross section which was used for normalization. This cross section was obtained by interpolation using existing data.[3]

Since resonances show up more clearly in the energy dependence of matrix elements than in cross sections, we have extracted the energy dependence of the part of the interaction involving the $^3$He intermediate state. This extraction was done by removing the effects of the final-state interaction and phase space on the cross section. We have

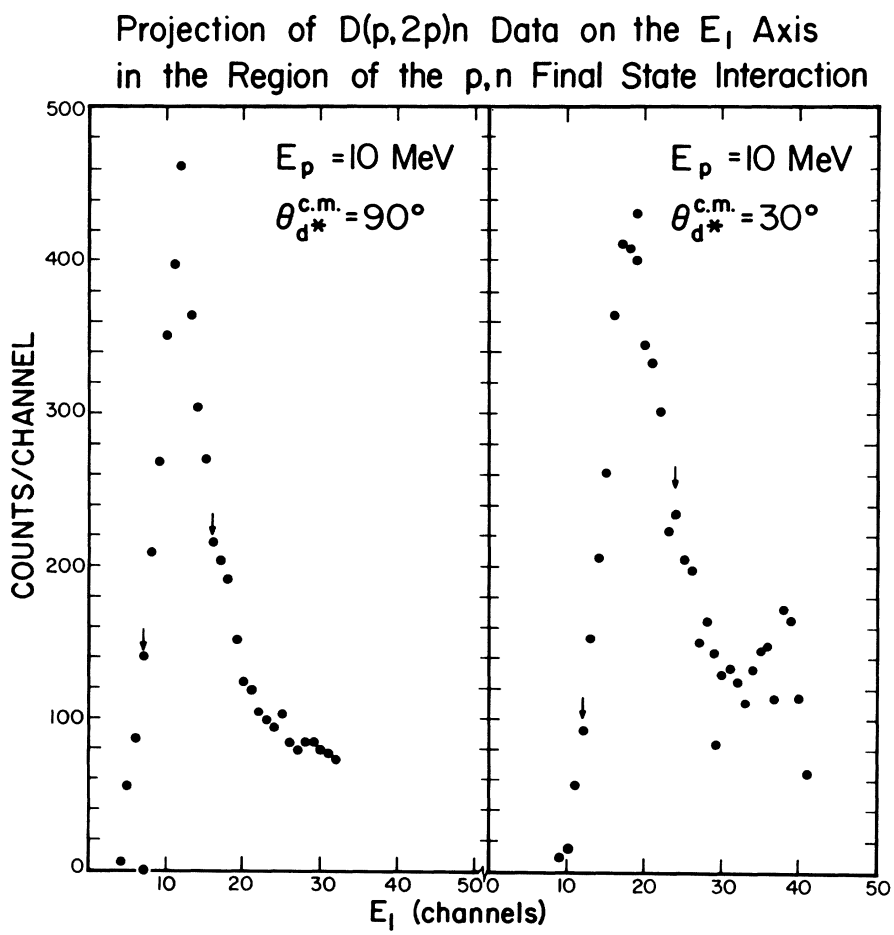


FIG. 3. $E_1$ spectra for the two sets of proton angles. The small arrows indicate excitation of 100 keV in the $d^*$ system.

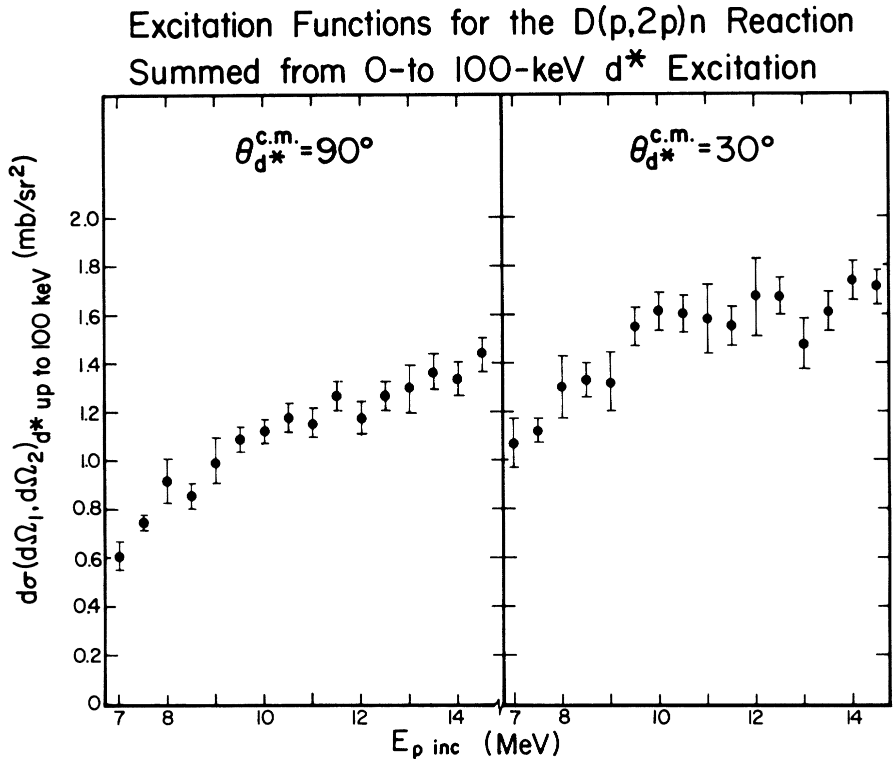


FIG. 4. Excitation functions for c.m. cross sections $d\sigma/d\Omega_1 d\Omega_2$ corresponding to $d^*$'s of excitation up to 100 keV. The resonance reported by Niiler *et al.* (Ref. 1) would lie at 10.25 MeV with a width of 1–2 MeV.

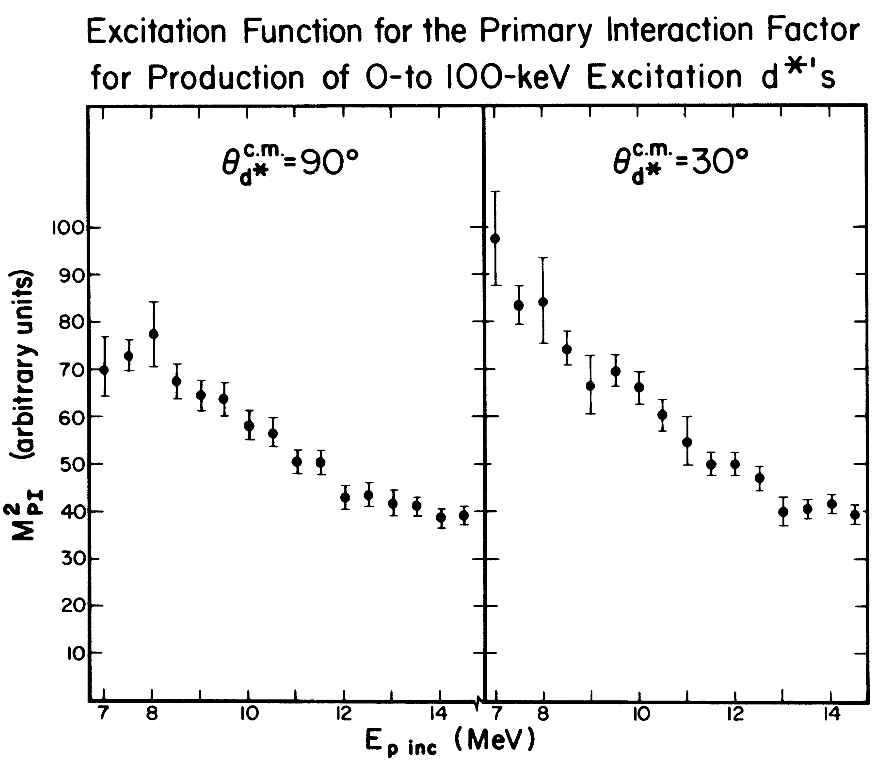


FIG. 5. Excitation functions for the primary interaction factor $M_{\mathrm{PI}}^2$, corresponding to production of $d^*$'s of excitation up to 100 keV. The resonance reported in Ref. 1 would lie at 10.25 MeV with a width of 1–2 MeV.

chosen a small value (100 keV) for the maximum $p$-$n$ excitation for the $d^*$, so the contribution from other breakup mechanisms is small. Thus it is not necessary to attempt to subtract the resulting few percent background. Theoretical extrapolations usually used to determine this background are questionable, and their inclusion should not mask any resonances in the $^3$He intermediate state. The differential cross section near vanishing $d^*$ excitation may be approximated by the product of three terms

$$\frac{d\sigma}{d\Omega_n d\Omega_p dE_p} = M_{\mathrm{PI}}^2 M_{\mathrm{FSI}}^2 \rho .$$

These terms are the primary interaction ($M_{\mathrm{PI}}^2$), the final-state interaction ($M_{\mathrm{FSI}}^2$), and phase space ($\rho$). For fixed c.m. exit angles, the primary interaction depends mainly on the incident energy, while the other two terms depend on the energies of the individual particles in the final state. The expression $M_{\mathrm{FSI}}^2\rho$ was used to calculate the line shape of the spectrum after projection onto the proton-energy axis.

These predictions were averaged over the finite acceptance angles of the detectors and the finite beam-spot size on target using a Monte Carlo sampling of the extended geometry. The efficiency corrections discussed by Niiler *et al.*[1] are implicitly included in this calculation, since we consider only $d^*$'s whose proton is emitted into the solid angle subtended by the detector. The beam spot on target was approximately 0.2 in. in diam and the two proton counters with apertures of 0.50 and 0.63 in., respectively, were placed 5.0 and 7.0 in. from this spot. Although finite-geometry calculations resulted in slight broadening of the peak and slight decrease in the maximum peak height compared to the point-geometry calculations, the overall effect was to reduce the integrated peak yields at each incident energy by approximately the same fraction.

Using standard expressions[4,5] for $M_{\mathrm{FSI}}$ and $\rho$, the product $M_{\mathrm{FSI}}^2\rho$ was calculated for each incident energy. Each value of $M_{\mathrm{FSI}}^2\rho$ was then divided into the corresponding experimental yield in order to extract a value proportional to $M_{\mathrm{PI}}^2$ at each incident energy. The resulting values of $M_{\mathrm{PI}}^2$ are plotted versus incident energy in Fig. 5. While the excitation functions for $d\sigma/d\Omega_1 d\Omega_2$ corresponding to $d^*$'s of 0- to 100-keV excitation increase with energy, the excitation functions for $M_{\mathrm{PI}}^2$ decrease with energy. There is no obvious structure in either excitation function, which we interpret as negative evidence for the existence of resonances in the $^3$He intermediate state. Niiler *et al.*[1] indicate a resonance about 30% higher than the background cross section, while van der Weerd *et al.*[2] do not claim to see a resonance. We would expect any structure more than 5% higher than the background to show up in our data. Since this experiment was carried out at two different fixed c.m. angles, we feel that these results are more significant than the results obtained at a single fixed laboratory angle.

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