PHYSICAL REVIEW C VOLUME 35, NUMBER 1 JANUARY 1987

Proton radiative capture by deuterium between 100 and 200 MeV

M. A. Pickar,* H. J. Karwowski,† J. D. Brown,‡ J. R. Hall,§ M. Hugi,§ R. E. Pollock,
V. R. Cupps, M. Fatyga, and A. D. Bacher
Indiana University Cyclotron Facility, Bloomington, Indiana 47405
(Received 2 September 1986)

Differential cross sections, $(d\sigma/d\Omega)(\theta)$, and analyzing powers, $A_y(\theta)$, have been measured for the reaction ^{2}H$(\vec{p},\gamma)^3$He at laboratory energies of 99.1, 150.3, and 200.7 MeV. The cross sections obtained are found to be in very good agreement with those of other authors. Both the size and shape of the angular distributions for the cross sections are found to be well accounted for by a simple "quasideuteron" model. Further support for this model is provided by the measured analyzing powers. Both the shape and size of the angular distributions for A_y are found to be very similar to those predicted for n$(\vec{p},\gamma)$d at the same $E_\gamma^{\text{c.m.}}$.

I. INTRODUCTION

Radiative capture and its inverse, photodisintegration, is of interest as a mechanism that at medium to high energies provides a means of investigating processes involving a large momentum transfer to a nucleus. Theoretical studies[1–4] of the two-nucleon system (np$\leftrightarrow$dγ) have indicated that meson exchange currents make an important contribution at energies as low as 10 MeV, and dominate the reaction at the threshold for pion production (135 MeV). It has been demonstrated,[1] however, that in this medium energy region the effects of meson exchange contributions can be adequately accounted for through the use of Siegert's theorem in a more conventional type of calculation, as done by Partovi.[5]

Our understanding of the role played by meson exchange currents in heavier nuclei is not as satisfactory. The dipole sum rule provides evidence that meson exchange contributions become even greater for heavier nuclei[2] than they are in the two-nucleon system. A possible bridge from the two-nucleon process to that in the multinucleon system is through the use of the three-nucleon system. This system serves as an important laboratory for investigating reaction mechanisms in nuclear physics. Because the initial and final state wave functions can be unambiguously determined via the Faddeev equations, the uncertainties arising from nuclear structure are minimized. As the simplest multinucleon system it provides a crucial link between our understanding of a specific mechanism in the two-nucleon system and that mechanism in a many-nucleon system.

Calculations of the differential cross section for pd$\rightarrow$^{3}Heγ using only the Born nucleonic terms and neglecting meson exchange contributions have been unsuccessful in accounting for the data at $E_\gamma = 100$ MeV.[6,7] A less exact calculation incorporating a "quasideuteron" term,[8] however, was successful in reproducing both the shape and size of the observed differential cross sections at medium energies. The success of this approach has been attributed to the fact that the quasideuteron term effectively incorporates much of the contribution made by meson exchange currents.[2] Indeed, it is suggested that the greater the contribution made by meson exchange currents the more important the role of the quasideuteron mechanism.

Although it has been demonstrated by Arenhövel[1] that meson exchange currents make a very important contribution to the analyzing power A_y in the two-nucleon system, there had been until recently very little work involving this spin observable for the three-nucleon system at medium energies. One set of measurements has been made starting at the threshold energy for pion production by Cameron *et al.*, with an accompanying microscopic calculation by Laget.[9] In this paper we present the results of a set of measurements taken in that medium energy region ($E_\gamma^{\text{c.m.}} = 70$—$133$ MeV) in which the contribution made by meson exchange currents is sufficiently large and the contribution by isobars sufficiently small that the data ought to be interpretable in the spirit of a simple quasideuteron model. It is hoped that the presentation of these results might encourage a rigorous test by exact, microscopic calculations.

II. EXPERIMENTAL METHOD

The experiment was performed at the Indiana University Cyclotron Facility (IUCF). The measurements were made using a polarized proton beam incident on a deuterated polyethylene (CD_2) target at $T_p = 99.1$, 150.3, and 200.7 MeV, corresponding to $E_\gamma^{\text{c.m.}} = 69.9$, 102.1, and 133.1 MeV, respectively.

To ensure unique identification of reaction products, in this experiment a coincidence was required between the recoiling ^{3}He and the radiated gamma ray. The kinematics for the process are illustrated in Fig. 1. One observes that in the laboratory the recoiling ^{3}He are confined to small angles, $\theta < 14°$, and have energies ranging from 23 to 98 MeV. The kinematic conversion to the center-of-mass (c.m.) of the gamma ray coordinates, θ_γ and E_γ, has a comparatively small effect.

The apparatus used to perform these measurements is illustrated in Fig. 2. To minimize the multiple scattering and energy loss of the recoiling ^{3}He, a special target

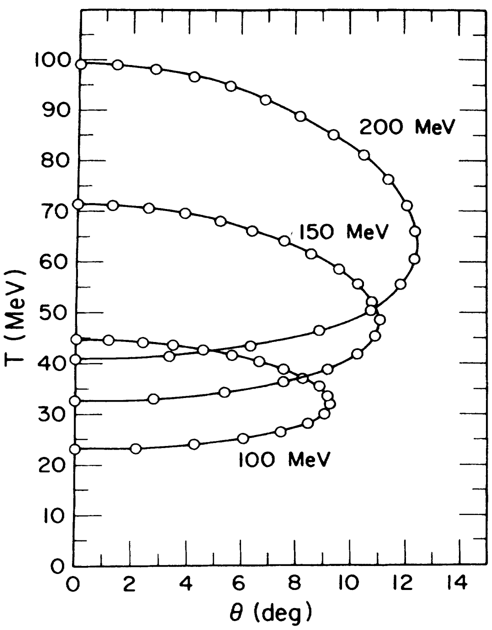

FIG. 1. The laboratory kinematics for the recoiling ^{3}He in ^{2}H(p,γ)^{3}He at bombarding energies of 200, 150, and 100 MeV (from top to bottom). The open circles (○) on each locus correspond to the associated γ in 10° steps, starting at 0° (the lowest point) and going up to 180° (the highest point).

chamber was constructed. This provided a path in vacuo for most of the 1.0 m flight path of the recoils. The recoils exited through a thin (50 μm) Kapton window and were detected in the charged particle hodoscope. Slightly thicker (130 μm) Kapton windows were provided on the sides for the exiting γ rays and fast charged particles. The chamber included an eight position target ladder assembly holding the following: two production CD_2 targets (11.0 and 17.1 mg/cm^2); one reference CD_2 target (30.5 mg/cm^2), used only to check the deuterium content of the production targets throughout the experiment; two CH_2 targets (22.1 and 46.3 mg/cm^2), used to examine carbon background; an empty frame, used in reducing beam halo; and a thin plastic scintillator, with a hole and fiducial marks, used to inspect the position and shape of the beam spot. The positioning scintillator was viewed

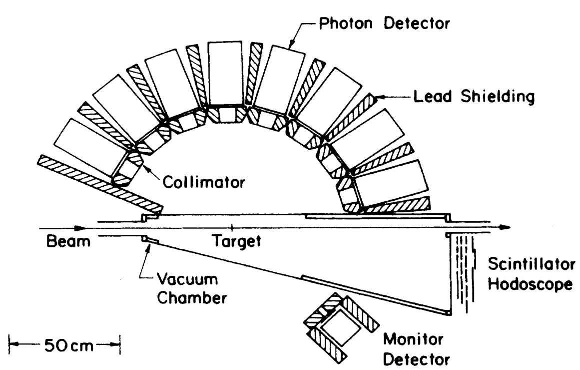

FIG. 2. Schematic of the apparatus used in the measurement.

through a Plexiglas plug in the bottom of the target rod assembly.

The particles exiting the rear window of the target chamber were detected in a four plane array of plastic scintillators: the $E1$ plane, consisting of four elements, each 0.38 mm thick; the $E2$ plane, consisting of five elements, each 1.59 mm thick; the $E3$ plane, consisting of six elements, each 3.18 mm thick; and the veto plane, consisting of three elements, each 3.18 mm thick. The elements of a plane were positioned half-overlapping those of the preceding plane where possible. We were thereby able to obtain a spatial resolution of 3.5 cm (2.0°) for most recoils. An absorber was positioned between the $E3$ and veto planes at those higher energies for which ^{3}He recoils could exit the $E3$ plane with sufficient energy to trigger the veto plane. The scintillator array provided ΔE-E signals sufficient for identification of highly ionizing particles over the range of ^{3}He energies of interest. The elements were sufficiently small and thin, and run at sufficiently low photomultiplier gain, that the very high rate arising from small angle elastic scattering could be tolerated for beam currents of up to 50 nA.

The high energy photons emitted in this (p,γ) reaction had energies ranging from 60 to 160 MeV and were detected in an array of eight lead glass Čerenkov detectors. Each detector consisted of a block of Schott F2 glass, $15\times15\times30$ cm^3, coupled to an Amperex XP2041 photomultiplier tube via a flange filled with a low viscosity silicone oil.[10] Commercial photomultiplier bases (ORTEC 269) were used with all photomultipliers. Each detector was provided with a lead collimator 7.62 cm thick subtending a geometric solid angle of 20.8 msr. The detectors and collimators were so positioned that the trajectory of any photon passing through the collimator intersected the back face of the lead glass block, and was never closer than 1.0 cm to the boundary of that face. The inner faces of the collimator were angled so that gammas either passed through with no obstruction, or were required to penetrate the full 7.62 cm of lead. Lead shielding was placed between the detectors to reduce cross talk to negligible levels. A plastic Čerenkov detector 1.25 cm thick was placed between each collimator and its lead glass detector.

Because of the small cross sections for the reaction of interest in this study, a light-emitting-diode (LED) pulser system was needed to simulate events of interest and thereby facilitate the testing of the apparatus. We used two different systems: a "slow" system that gave a large amplitude light pulse,[11] and a "fast" system[12] that gave less light but better simulated the pulse shape of the Čerenkov detectors. The use of these two systems made it possible to set up the apparatus with only a minimum of beam time. The same LED system was also used to monitor dead time during the experiment.

A particle telescope consisting of a plastic scintillator (3.2 mm NE102) and a NaI crystal (diam 12.7 cm$\times$12.7 cm thick) was set up at 45° to monitor the deuterium content of the production targets. At frequent intervals the beam current was lowered to $\sim$1 nA and the yield for pd elastic scattering was measured for the production targets and compared to that from the reference target. The latter was never exposed to a full intensity beam. The shape of the carbon background was determined by using a CH_2 target. The measurements permitted a cross calibration of the relative deuterium content of the targets to better than 4%. During the course of the experiment neither production target was found to experience a more than 5% loss in deuterium content.

The deuterium targets were made from deuterated polyethylene foils, whose atomic composition was 98 ± 1 % CD_2 and 2 ± 1 % CH_2. The initial thickness of all targets, CD_2 and CH_2, was determined by measurements of mass and area. The uniformity of each target was examined by performing these measurements on many small samples of the material used for that target. This work provided a determination of the initial absolute thickness of each target to 5%. The outcome of the first cross calibration measurement of deuterium content was consistent with that result.

Beam polarization was measured frequently using $p\alpha$ elastic scattering after the injecter stage cyclotron.[13] Although there has been some recent evidence for depolarization between this point and the experimental target station,[14] the effect is estimated to be less than 3%.[13,14] This and the uncertainty in our measurements yielded an uncertainty of 5% in the absolute beam polarization at the experimental target. The beam polarization was typically 78%.

Data were recorded event-by-event on magnetic tape using the data acquisition program RAQUEL.[15] Information recorded included: hodoscope elements fired, photon detectors fired, pulse height in each of the hodoscope planes, pulse height in each of the photon detectors, rf time-of-flight (TOF) for each of the hodoscope planes, and rf TOF for each of the photon detectors. The proton beam polarization was flipped once every 100 s, and the contents of numerous scalers used to monitor beam current, dead time, and various event rates were recorded at each spin reversal.

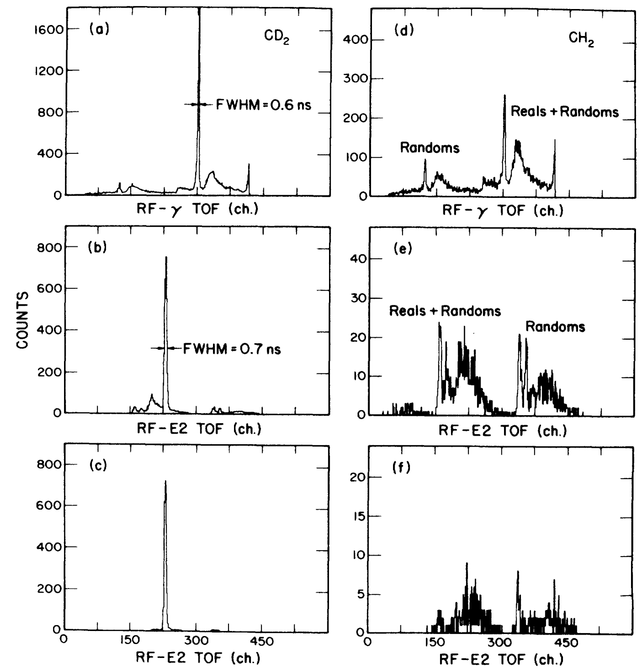

FIG. 3. Representative spectra obtained in the 150 MeV bombardment of a CD_2 target (left) and a CH_2 target (right). The product of integrated charge and total target thickness for the CD_2 target is 1.50 times that for the CH_2 target. In (a) and (d) are shown the rf-γ TOF spectra obtained with no cuts other than those of the hardware. In (b) and (e) are shown the rf-particle TOF spectra for the $E2$ plane of the hodoscope gated by a cut on the prompt γ TOF peak. Finally, shown in (c) and (f) are the rf-particle TOF spectra gated by both a cut on the prompt γ TOF peak and a cut on particle pulse height, requiring the recoil to be highly ionizing.

III. DATA REDUCTION AND ANALYSIS

The experimental apparatus described above was found to give a clean identification of the events of interest. The requirement of a prompt coincidence between a heavy, highly ionizing particle and a photon with an energy much higher than that typically encountered in nuclear transitions yielded a background from other processes that was essentially negligible. The lead glass photon detectors and thin plastic scintillators used to detect the recoiling ^{3}He tolerated high singles rates and permitted use of a beam current ($\sim$20 nA) that led to the completion of the measurements at three energies in one week of beam time.

Representative spectra as obtained at various points in the analysis are presented in Fig. 3. The spectra shown are the result of a coincidence between the photon detector at 54° with the hodoscope planes $E1$ and $E2$, for an incident proton beam energy of 150 MeV. The detected photon had an energy of 112 MeV, and its detector had a hardware threshold of 23 MeV. The ^{3}He recoils had a kinetic energy of 43 MeV, and deposited about 6 MeV and 37 MeV in the $E1$ and $E2$ detectors, respectively. Hardware thresholds for the $E1$ and $E2$ detectors were set at 0.3 of the ^{3}He pulse height in each detector. The resulting spectra for a CD_2 target ($\rho t = 17.1$ mg/cm^2, $Q = 132$ μC) are presented on the left, and those for a CH_2 target ($\rho t = 22.1$ mg/cm^2, $Q = 68$ μC) on the right.

The rf-γ TOF spectra obtained with no conditions other than those given by the hardware are seen in Fig. 3(a) (CD_2) and Fig. 3(d) (CH_2). In both cases one finds a clean and narrow line (FWHM=0.6 ns) originating from prompt γ's emitted by the target. The broad bump immediately to the right of the γ line arises from particles (principally protons and neutrons) coming from the target which interact with the lead glass to form photons, via nuclear deexcitation and bremsstrahlung, of sufficient energy to exceed the discriminator threshold of the photon detector. The good time resolution of these photon detectors and of the IUCF proton beam permitted a clean separation between γ's and particles.

In this first pair of figures is also seen a group of purely random events separated from the group of real plus random events by the time between beam bursts (31.8 ns). One notes that not only is the yield from the CH_2 target much less than that of the CD_2 target, but that the ratio of real events to random events is also much smaller.

Upon applying a narrow gate on that region of rf-γ TOF containing real γ's, one obtains the spectra for rf-$E2$ TOF illustrated in Figs. 3(b) and (e). For the CD_2 target we find a clean and narrow peak (FWHM=0.7 ns) originating from the recoiling ^{3}He in the ^{2}H(p,γ)^{3}He reaction. The peak sits on a smooth background arising from p and d emitted in radiative breakup processes (pd→pdγ and pd→ppnγ). At this stage of the analysis the random events are seen to make only a small contribution to the background in the vicinity of the peak. In contrast, we find for the CH_2 target that more than half of the events in the region containing real events are random.

When we apply a cut on particle pulse height in $E1$ and $E2$, requiring the recoil to be a highly ionizing particle, we eliminate most of the background and obtain the spectra in Figs. 3(c) and (f). For the CD_2 target the background is nearly entirely random, and very small. Almost no real events are observed for the CH_2 target. The background, which was found to vary slowly with angle, is further reduced by a cut on the hodoscope bin, which is equivalent to restricting the exit particle angle. The resulting background for the CD_2 target was essentially flat in rf-$E2$ TOF, and never exceeded 5% under the peak for any combination of γ detector and hodoscope.

The negligible background arising from the carbon and hydrogen in the CD_2 and CH_2 targets is illustrated most graphically in the γ pulse height spectra obtained upon application of all conditions [Fig. 4(a) and (b)]. The 112 MeV photons detected from the CD_2 target give rise to a broad peak (FWHM=40 MeV) that is well above the discriminator level [Fig. 4(a)]. Also visible is a low energy tail. From Fig. 4(b) it is clearly evident that only a very small part of this tail can be attributed to background from carbon or hydrogen. A more detailed study revealed that only a very small part of this tail can be attributed to any kind of background. In other words, most of the tail comes from real events.

A similar spectrum was observed in a measurement of ^{2}H(p,γ)^{3}He made by Didelez *et al.*[7] at $T_p=156$ MeV. They concluded that the tail arose from the flux of showers initiated by photons in the collimator escaping into the photon detector. After calculating the response of our detectors, including the effect of the collimator, using Monte Carlo techniques, we reached the same conclusion. Almost all the counts in the tail arise from photons interacting in the inner edges of the collimator to form showers of electrons and photons that partially escape into the photon detector. To reduce the uncertainty related to this effect we imposed a cut on γ pulse height at half the peak height in our final analysis. Our calculations indicate that such a procedure yields an effective solid angle only about 5% larger than the geometric solid angle. These calculations and our knowledge of the geometry lead to an uncertainty in the absolute effective solid angle for the photon detectors of 3%.

After all our cuts we obtain a set of yields from which we calculate a preliminary set of $d\sigma/d\Omega$ and A_y. With these we compute the correction for the finite acceptance of the photon detectors and apply it to the data to obtain

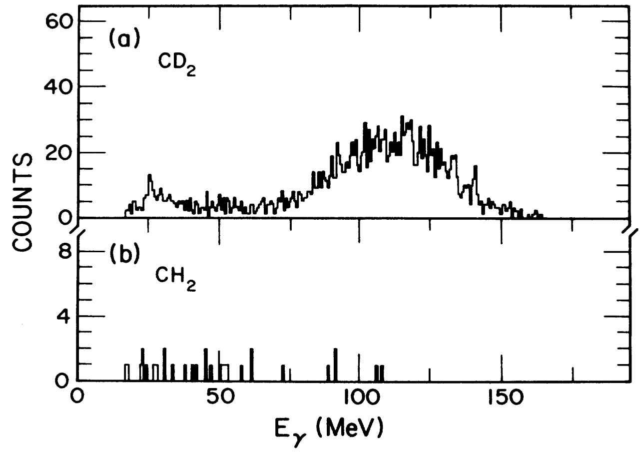

FIG. 4. Representative γ pulse height spectra obtained in the 150 MeV bombardment of a CD_2 target (a) and a CH_2 target (b). Both spectra have been subject to identical cuts on γ TOF, particle TOF, and particle pulse height.

the final results. In all cases this correction was less than the statistical uncertainty.

IV. RESULTS

The cross sections, $d\sigma/d\Omega(\theta)$, and analyzing powers, $A_y(\theta)$, resulting from the final analysis are listed in Table I. The uncertainties quoted for A_y do not include a 5% uncertainty in the absolute polarization of the beam. The uncertainties quoted for $d\sigma/d\Omega$ do not include an uncertainty of 8% in absolute normalization arising from uncertainties in target thickness (6%), charge integration of the Faraday cup (2%), scintillator efficiency (3%), lead glass efficiency (2%), and total solid angle (4%).

V. DISCUSSION

The cross sections resulting from this measurement are illustrated in Fig. 5. Our results are shown compared to those of O'Fallon *et al.*,[16] Didelez *et al.*,[7] and Cameron *et al.*[9] We find very good agreement at all three energies. The agreement with the data of O'Fallon *et al.*, taken in the time reversed channel $\gamma\,^3$He→pd and related to this work by detailed balance, provides no evidence for a violation of time reversal invariance larger than 15%.

The solid curves in Fig. 5 are predicted cross sections for pd→^{3}Heγ calculated using the reaction amplitude given by Prats.[8] The amplitude obtained by Prats incorporates the contributions made by both the proton and deuteron pole diagrams with that given by the triangle diagram associated with the "quasideuteron" reaction mechanism (Fig. 6). The result obtained when the triangle term is neglected is illustrated by the dashed curves in Fig. 5. These results obtained using only the nucleonic Born, or pole, terms are similar in both size and shape to those obtained by Craver, Kim, and Tubis,[6] who performed more

TABLE I. Differential cross sections and analyzing powers in the center-of-mass frame for the ^{2}H($\vec{p}$,γ)^{3}He reaction at nominal laboratory energies of 100, 150, and 200 MeV. The errors quoted do not include uncertainties in the absolute normalization, which amount to 8% for the cross sections and 5% for the analyzing powers.

Photon detector	θ_γ (c.m.) (deg)	$d\sigma/d\Omega$ (c.m.) (nb/sr)	A_y (c.m.)
		T_p(lab) = 99.1 MeV E_γ(c.m.) = 69.9 MeV	
1	19.3	167.6±8.4	+0.082±0.011
2	40.4	267.2±13.4	+0.096±0.008
3	61.4	279.0±13.9	+0.051±0.007
4	81.4	200.3±10.0	−0.010±0.010
5	100.5	152.2±7.6	−0.099±0.012
6	118.7	114.1±5.7	−0.177±0.014
7	136.0	73.9±3.7	−0.243±0.019
8	152.8	59.4±3.0	−0.271±0.021
		T_p(lab) = 150.3 MeV E_γ(c.m.) = 102.1 MeV	
1	19.9	132.9±6.6	+0.069±0.015
2	41.8	183.0±9.2	+0.090±0.011
3	63.2	185.0±20.0	+0.049±0.012
4	83.4	100.0±7.0	−0.071±0.016
5	102.5	82.5±4.1	−0.155±0.016
6	120.4	63.2±3.2	−0.251±0.019
7	137.4	45.6±2.3	−0.351±0.023
8	153.7	33.3±1.7	−0.328±0.028
		T_p(lab) = 200.7 MeV E_γ(c.m.) = 133.1 MeV	
1	20.5	110.4±5.5	+0.112±0.010
2	42.9	130.0±26.0	+0.120±0.016
3	64.7	114.6±10.6	+0.026±0.015
4	85.1	84.1±4.2	+0.024±0.015
5	104.1	50.3±2.5	−0.110±0.020
6	121.8	38.6±1.9	−0.204±0.024
7	138.5	26.1±1.3	−0.213±0.030
8	154.5	17.6±0.9	−0.340±0.039

exact calculations with better wave functions but included only those terms. Laget, who has made microscopic calculations at intermediate energies, also obtains cross sections in agreement with the others for the case where only the nucleonic Born terms are included.[9] In other words, evaluation of these Born terms using improved wave functions does not lead to significantly different results—the Born terms make only a small contribution to the cross section at medium energies. Fearing has made calculations of the cross section at intermediate energies using a quasideuteron approach, but neglects the Born terms.[17,9] He obtains results in good agreement with the data at all but the most forward angles, where the Born terms might be expected to have a discernible influence.

The success of the approximation used by Prats in calculating the cross section is clearly evident in Fig. 5. Both the shape and size of the calculated cross sections are in remarkable agreement with the data at all three energies. Further, the calculation indicates that the contribution made by the quasideuteron mechanism dominates the reaction at all but the most forward angles.

The importance of the triangle term can be attributed to two principal effects. The first of these is due to the large momentum transfer made to the residual nucleus in this reaction. At 100 MeV a minimum of 219 MeV/c is transferred at 0°, and a maximum of 543 MeV/c is transferred at 200 MeV at 180°. It is to be expected that a process that distributes the momentum transfer among three nucleons will make a larger contribution to the cross section than a process that forces the momentum transfer into one nucleon, once the momentum transfer becomes large. The calculation clearly demonstrates that at back angles the Born terms make only a very small contribution to the cross section.

Another effect leading to the dominance of the quasideuteron term is the increased importance of meson exchange currents (MEC) at medium energies. Theoretical studies of the two-nucleon process (np$\leftrightarrow$dγ)[1–4] have

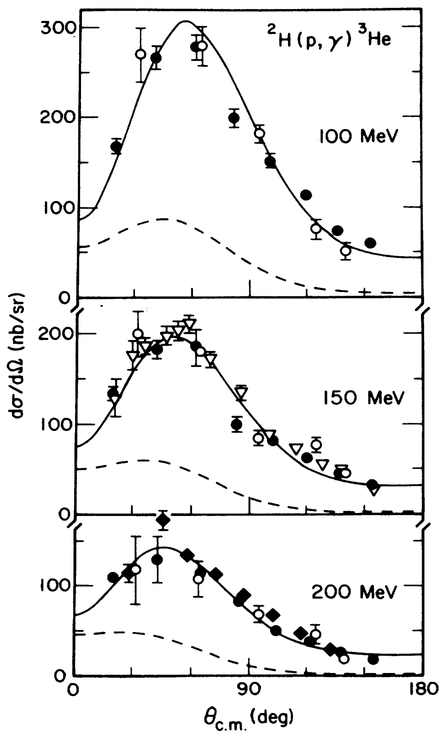

FIG. 5. Cross sections for $^2H(p,\gamma)^3He$ at bombarding energies of 100, 150, and 200 MeV (top to bottom), corresponding to $E_\gamma^{c.m.}=70$, 102, and 133 MeV. The results of the present work are plotted as solid circles (●), while those of other authors are represented by open circles (○) (Ref. 16), open triangles (▽) (Ref. 7), and closed diamonds (♦) (Ref. 9). Unless shown, the relative uncertainty for a given data set is smaller than the size of the plotting symbol. The solid curves are results calculated using the amplitude given by Prats (Ref. 8). The dashed curves are the results obtained using that amplitude when one neglects the contribution of the "quasideuteron" term.

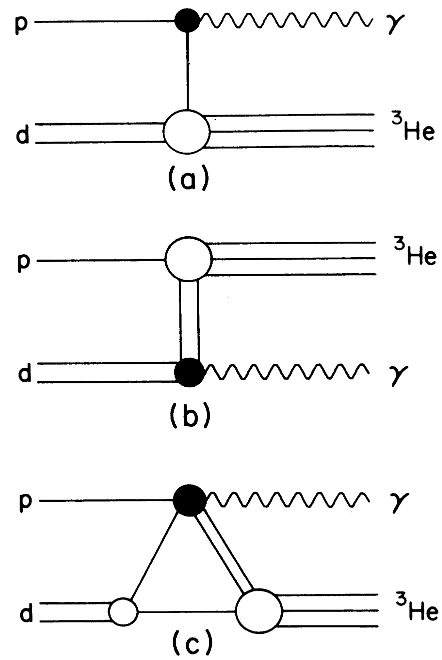

FIG. 6. Diagrams included in the amplitude calculated by Prats (Ref. 8). The nucleon Born, or pole, terms are represented by (a) and (b), and the triangle, or "quasideuteron," term is represented by (c).

demonstrated that MEC dominate the reaction by the time one reaches the threshold for pion production (135 MeV). One expects such processes to become even more important for heavier nuclei.[2] The success of the quasideuteron approach in heavier nuclei has been attributed in part to the fact that it effectively incorporates much of the contribution made by meson exchange currents.[2] It also has been shown that at medium energies the principal effects of MEC can be incorporated into the two-nucleon input ($np\leftrightarrow d\gamma$) for the quasideuteron model through the use of Siegert's theorem.[1]

The success of the quasideuteron model in accounting for the cross section in $pd\leftrightarrow {}^3He\gamma$ should lead one to expect some degree of success in accounting for the spin dependent observable A_y. There is, unfortunately, no calculation of this quantity made in the context of this model. In all calculations to date the fundamental two-nucleon input to the model has been approximated as spin-independent, although we know this to be of questionable validity. Recent theoretical studies[1,3–5] indicate reasonably large values for A_y in $np\leftrightarrow d\gamma$ at medium energies. These studies are in good agreement with each other and with the available data.[18]

As a first approximation, it is reasonable to assume that the spin dependence of the triangle term is similar to that of the two-nucleon input. In other words, we might expect the analyzing power for $\vec{p}d\rightarrow {}^3He\gamma$ to be similar to that for $\vec{p}n\rightarrow d\gamma$ at the same $E_\gamma^{c.m.}$, assuming the dominance of the quasideuteron reaction mechanism. What we in fact discover is that the data for $\vec{p}d\rightarrow {}^3He\gamma$ are *remarkably* similar to the predictions for $\vec{p}n\rightarrow d\gamma$. The solid curves in Fig. 7 are Partovi's predictions for A_y in $\vec{p}n\rightarrow d\gamma$ (Ref. 5) at the same $E_\gamma^{c.m.}$ as the indicated data for $\vec{p}d\rightarrow {}^3He\gamma$. These predictions are not significantly different from other calculations of A_y for $np\rightarrow d\gamma$ at medium energy,[1,3,4] in which MEC are included explicitly rather than implicitly through the use of Siegert's theorem, as done by Partovi.

We have seen that the cross section for $pd\rightarrow {}^3He\gamma$ is dominated at all but the most forward angles by the quasideuteron term. Assuming that the spin dependence of the other terms is no larger than that of the triangle term, we may then conclude that they will have only a small effect on the overall spin dependence. Laget has made a calculation of A_y at $T_p=200$ MeV.[9] He finds that if he neglects nucleon rescattering terms equivalent to the triangle term, retaining only the Born nucleonic terms, one obtains values of A_y that are essentially zero at all angles. The inclusion of these rescattering terms yields results qualitatively similar to the data. His work thus provides further support for concluding that the analyzing

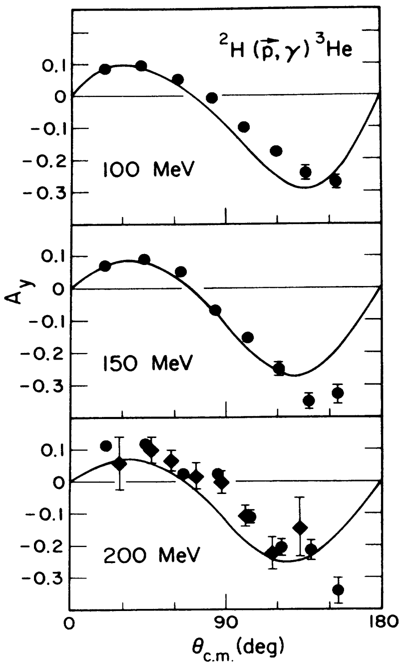

FIG. 7. Analyzing powers for ^{2}H($\vec{p}$,γ)^{3}He at bombarding energies of 100, 150, and 200 MeV (top to bottom). The results of the present work are plotted as solid circles (●), while those of Cameron *et al.* (Ref. 9), are plotted as closed diamonds (♦). Unless shown, the relative uncertainty for a given data set is smaller than the size of the plotting symbol. The solid curves are predictions of Partovi (Ref. 5) for n($\vec{p}$,γ)d at the same $E_\gamma^{c.m.}$.

power is indeed dominated by the quasideuteron term at medium energies.

The present experiment appears to indicate that the spin dependence of the quasideuteron term, as reflected by the analyzing power A_y, is very similar to that of the two-nucleon input, $\vec{p}n \rightarrow d\gamma$. It in fact looks as if the connection between the analyzing powers for $\vec{p}d \rightarrow {}^3He\gamma$ and $\vec{p}n \rightarrow d\gamma$ may be both simpler and more direct than that between their cross sections. A rigorous confirmation of this conjecture requires a comprehensive theoretical study. It is to be hoped that our work might stimulate an extension of future theoretical studies to include the spin dependent observables.

VI. CONCLUSION

We have measured differential cross sections, $(d\sigma/d\Omega)(\theta)$, and analyzing powers, $A_y(\theta)$, for the reaction $pd \rightarrow {}^3He\gamma$ in the medium energy region ($70 < E_\gamma^{c.m.} < 135$ MeV). The cross sections obtained are in very good agreement with the results of other experiments. We find no evidence for a violation of time reversal invariance greater than 15%. The analyzing powers are found to be quite large and to exhibit a shape that varies little in this energy range.

It has been further demonstrated that both the cross section and the analyzing power can be accounted for in the context of a model incorporating a quasideuteron reaction mechanism. We note that the analyzing power for $\vec{p}d \rightarrow {}^3He\gamma$ is nearly identical to predictions for $\vec{p}n \rightarrow d\gamma$. The importance of the quasideuteron mechanism is due to the increased probability to share high momentum transfer among three nucleons and to the increased dominance of meson exchange contributions at these energies. In the special case of $pd \rightarrow {}^3He\gamma$, this mechanism may be enhanced because the final state nucleus has a large deuteronlike component.[19] Thus it should perhaps come as no surprise that this particular reaction mechanism plays a very important role. However, it is rather remarkable to find that the analyzing power appears to be almost completely determined by the spin dependence of the two-nucleon interaction, $\vec{p}n \rightarrow d\gamma$.

This observation indicates that a possible means of examining the relative importance of the quasideuteron term, or rescattering terms, is through a study of the analyzing power. This would also provide an indirect means of investigating contributions made by meson exchange currents. It is known that at low energy careful calculations made including only the Born terms are successful in accounting for measured cross sections.[6] No calculations of A_y have been made at these energies, although measurements show that it is very small.[20,21] It would be of interest to explore the region between 15 and 100 MeV to establish the onset of the need for the inclusion of a quasideuteron term, or nucleon rescattering terms and meson exchange currents.

This study has filled one gap in what is now a very comprehensive body of data for $pd \leftrightarrow {}^3He\gamma$. Data now exist on differential cross sections and analyzing powers at energies extending from threshold to well past the delta resonance. These data can, as they stand, provide qualitative guidelines on the relative roles of different reaction mechanisms in various kinematic regions. However, in order for this reaction to become a laboratory for testing mechanisms for use in heavier nuclei, as is frequently advertised, a considerable amount of theoretical work remains to be done.

This work was supported in part by the U.S. National Science Foundation.

*Present address: Institut für Physik der Universität Basel, CH-4056 Basel, Switzerland.

†Present address: Department of Physics and Astronomy, University of North Carolina, Chapel Hill, NC 27514.

‡Present address: Department of Physics, Princeton University, Princeton, NJ 08544.

§Present address: CERN/EP, CH-1211 Genève 23, Switzerland.

[1]H. Arenhövel, Z. Phys. A **302**, 25 (1981).

[2]M. Gari and H. Hebach, Phys. Rep. **72**, 1 (1981).

[3]J. M. Laget, Nucl. Phys. **A312**, 265 (1978).

[4]H. Arenhövel, Nuovo Cimento **76A**, 256 (1983).

[5]F. Partovi, Ann. Phys. (N.Y.) **27**, 79 (1964).

[6]B. A. Craver, Y. E. Kim, and A. Tubis, Nucl. Phys. **A276**, 237 (1977).

[7]J. P. Didelez, H. Langevin-Joliot, Z. Marić, and V. Radojević, Nucl. Phys. **A143**, 602 (1970).

[8]F. Prats, Phys. Lett. **88B**, 23 (1979).

[9]J. M. Cameron, P. Kitching, W. J. McDonald, J. Pasos, J. Soukup, J. Thekkumthala, H. S. Wilson, R. Abegg, D. A. Hutcheon, C. A. Miller, A. W. Stetz, and I. J. van Heerden, Nucl. Phys. **A424**, 549 (1984).

[10]M. A. Pickar, Ph.D. thesis, Indiana University, 1982; Indiana University Cyclotron Facility Internal Report 82-2, 1982.

[11]M. A. Kovash and S. L. Blatt, Nucl. Instrum. Methods **163**, 113 (1979).

[12]R. Ernwein and Ph. Gorodetzky, Nucl. Instrum. Methods **138**, 57 (1976).

[13]P. Schwandt, H. O. Meyer, W. W. Jacobs, A. D. Bacher, S. E. Vigdor, M. D. Kaitchuck, and T. R. Donoghue, Phys. Rev. C **26**, 55 (1982).

[14]D. A. Low, A. D. Bacher, J. D. Brown, M. S. Cantrell, V. R. Cupps, D. L. Friesel, J. Gering, W. P. Jones, C. Olmer, P. Schwandt, and E. J. Stephenson, Indiana University Cyclotron Facility Scientific and Technical Report 1983, p. 156.

[15]L. C. Welch, IEEE Trans. Nucl. Sci. **NS-28**, 3758 (1981).

[16]N. M. O'Fallon, L. J. Koester, and J. H. Smith, Phys. Rev. C **5**, 1926 (1972).

[17]H. W. Fearing, in Proceedings of the IX International Conference on the Few Body Problem, Eugene, Oregon, 1980 (contributed papers), Vol. 1, p. 39.

[18]J. M. Cameron, C. A. Davis, H. Fielding, P. Kitching, J. Soukup, J. Uegaki, J. Wesick, H. S. Wilson, R. Abegg, D. A. Hutcheon, C. A. Miller, A. W. Stetz, Y. M. Shin, N. Stevenson, and I. J. van Heerden, Phys. Lett. **137B**, 315 (1984).

[19]R. A. Brandenburg, Y. E. Kim, and A. Tubis, Phys. Lett. **49B**, 205 (1974).

[20]D. M. Skopik, H. R. Weller, N. R. Roberson, and S. A. Wender, Phys. Rev. C **19**, 601 (1979).

[21]S. E. King, N. R. Roberson, H. R. Weller, and D. R. Tilley, Phys. Rev. C **30**, 21 (1984).