Radiative capture of polarized neutrons by polarized protons at $T_n = 183$ MeV

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In order to provide a quantitative test of theoretical calculations incorporating meson-exchange currents and intermediate $\Delta$ resonances, we measure the normal-component spin correlation coefficient $C_{NN}$, the differential cross section $d\sigma/d\Omega$, and the neutron and proton analyzing powers $A_n$ and $A_p$, each as a function of angle, for $n\vec{p} \rightarrow d\gamma$ at $T_n = 183$ MeV. Our $n\vec{p} \rightarrow d\gamma$ results, combined with the previous cross section and photon asymmetry data collected in the past decade, place quite strong constraints on model calculations. Our data are in excellent agreement with theoretical predictions by Jaus and Woolcock that incorporate meson-exchange and isobar current effects and relativistic corrections, signifying great recent progress in our understanding of these effects in the nucleon-nucleon system.

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I. INTRODUCTION

Radiative capture of neutrons by protons, or its time-reversed reaction, deuteron photodisintegration, is one of the simplest, yet most fundamental nuclear processes. The primary interaction is electromagnetic, and is thus well understood; the leading effects of the strong interaction, occurring between two nucleons, are also well characterized. Thus, observables for this reaction, if measured with sufficient precision, can provide a sensitive probe to "corrections" associated, for example, with the role of subnucleonic degrees of freedom and with relativistic effects.

If the momentum transfer ($q$) in the reaction is not too high, one would hope that the role of subnucleonic degrees of freedom could be efficiently described in terms of the contributions of meson-exchange currents (MEC's) and isobar currents (IC's) to the reaction amplitude. The effects of meson exchange between nucleons in diagrams in which the photon couples directly to the nucleons are already implicitly included via Siegert's theorem[1] in any calculation employing a realistic nucleon-nucleon ($NN$) potential. However, the explicit coupling of the photon to exchanged mesons and intermediate-state $\Delta$'s is not so included. The electric dipole coupling of the photon to the nucleons is known to dominate the reaction at low momentum transfer; however, for $q \approx 1$ fm$^{-1}$ the explicit MEC and IC contributions begin to introduce appreciable magnetic (mainly $M1$) transition amplitudes [2]. The different sensitivities of the magnetic and electric transitions to the spin state of the nucleons suggest that a full investigation of the role of MEC and IC contributions requires polarization as well as cross section measurements at sufficiently high $q$.

In recent years, there have been several polarization observable measurements for deuteron photodisintegration and $np$ radiative capture at intermediate energies [3–5]. While the results generally agree well with theoretical calculations that incorporate MEC's and IC's [2,6–8], the quantities measured were not always very sensitive to the role of subnucleonic degrees of freedom (for example, see [3]).

The goal of the present work was to measure a polarization observable with particularly strong sensitivity to MEC and IC contributions to deuteron photodisintegration, in order to test quantitatively the validity of calculations of these effects. The effects are manifested primarily via magnetic ($M1$) transition amplitudes, which couple spin singlet $np$ states to the bound $^1S$ and $^3D$ states of the deuteron. In contrast, the dominant electric dipole transition couples spin triplet $np$ states to the deuteron. The magnetic transitions are thus most directly distinguished by observables which are sensitive to the relative orientations of the $n$ and $p$ spins, i.e., to the so-called spin correlation coefficients $C_{ij}$ in $n\vec{p} \rightarrow d\gamma$. Measurements of $np$ radiative capture have never previously been made utilizing both polarized beams and polarized targets. In the present experiment we have utilized neutron beam and proton target polarizations normal ($N$) to the $n\vec{p} \rightarrow d\gamma$ reaction plane, and have thus measured the normal-component spin correlation coefficient, defined as the relative difference in cross sections for $n$ and $p$ spins parallel vs antiparallel:

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where \( d\sigma/d\Omega_{11} \) and \( N_{11} \) are the \( np \rightarrow d\gamma \) differential cross section and normalized yield, respectively, for neutron spin up, proton spin down, at a given \( \gamma \) angle. The other terms are similarly defined. \( P_n \) and \( P_p \) are beam and target polarizations, respectively.

The sensitivity of \( C_{NN} \) to magnetic transitions can be understood qualitatively. For the \( S=1 \) (triplet) \( np \) states coupled to the deuteron by electric transitions, the \( n \) and \( p \) spins are predominantly parallel, and hence \( C_{NN} \rightarrow 0 \). For example, consider the angular momentum coupling constraints for the \( ^3P_2 \) states that couple to the \( ^3S_1 \) deuteron ground state. Noting that the orbital angular momentum projection normal to the plane is restricted to \( \pm 1 \) for the \( L=1 \) parts of the incident plane wave, \( ^3P_2 \) gives \( C_{NN} = 2S \), \( ^3P_1 \) gives \( C_{NN} = 0 \), and \( ^3P_0 \) gives \( C_{NN} = 1 \). In contrast, all singlet \( np \) states, such as \( ^1S_0 \) and \( ^1D_2 \), which are coupled to the deuteron by \( M=1 \) transitions, give a value of \( C_{NN} = -1 \). Therefore, we may expect this observable to become more negative with increasing bombarding energy as MEC and IC terms begin to contribute significantly. Even small additional currents can have a significant effect on the spin correlation coefficients. The substantial sensitivity of \( C_{NN} \) to MEC and IC effects has been confirmed theoretically in recent calculations by Jaus and Woolcock [6] and Schmitt and Arenhövel [2]. The calculations will be discussed later in this paper.

We chose to measure \( C_{NN} \) for \( np \) radiative capture at a bombarding energy \( T_n = 183 \) MeV (corresponding to \( E_\gamma = 95 \) MeV for deuteron photodisintegration) for several reasons. This energy is high enough that MEC and IC effects are expected to be significant, yet low enough that the inclusion of only a small number of relatively light mesons and only the \( \Delta(1232) \) baryon resonance should be a good approximation in the theoretical calculations. Another consideration that influenced the choice of bombarding energy was the desire to minimize background that might arise from \( n^2 \) production on protons bound inside contaminant nuclei in the polarized proton target. It is also useful to note that the measurement of \( C_{NN} \) requires that the neutron beam and proton target be simultaneously polarized. By reversing the beam and target spins independently, we were able to extract, at the same time as \( C_{NN} \), the neutron and proton analyzing powers \( A_n \) and \( A_p \) (each defined as the relative difference in cross sections for the corresponding nucleon spin up vs down):

\[
A_n(\theta) = \frac{1}{P_n} \frac{N_{11} - N_{11} + N_{11} - N_{11}}{N_{11} + N_{11} + N_{11} + N_{11}},
\]

\[
A_p(\theta) = \frac{1}{P_p} \frac{N_{11} - N_{11} - N_{11} + N_{11}}{N_{11} + N_{11} + N_{11} + N_{11}}.
\]

Although the analyzing powers are not predicted to be particularly sensitive to MEC and IC effects, they help to constrain ambiguities that may arise in other aspects of the calculations. We designed the experiment to measure \( C_{NN} \) at a number of angles to an accuracy of \( \pm 0.05 \), i.e., with sufficient precision to distinguish among various levels of inclusion of MEC, IC and relativistic effects in the theoretical calculations.

The spin observable results of this experiment have been published previously [9]. The present paper presents a more detailed description of the experimental techniques and the assessment of systematic errors for the spin observable results. In particular, these results have been renormalized, in comparison with Ref. [9], in light of an improved calibration [10] of the neutron beam polarization. In addition, we report here the absolute differential cross sections for \( np \rightarrow d\gamma \), as determined in our experiment.

II. EXPERIMENTAL APPARATUS AND DATA ACQUISITION

A. Experimental overview

The experiment was carried out in the polarized neutron facility (PFN) at the Indiana University Cyclotron Facility. The data acquisition was completed through three production runs, for a total of roughly 1000 hours of beam time.

A schematic illustration of the experimental setup used for production running is shown in Fig. 1. The experiment used a polarized neutron beam and a polarized proton target (PPT). A "dummy" target, which simulated the nonhydrogenic components of the in-beam materials of the PPT, was used to measure background, including quasi-free \( A(n,d\gamma) \) reactions initiated on protons bound in contaminant nuclei in the PPT. In order to suppress background, the outgoing deuterons and photons were measured in coincidence. The deuterons were detected near \( 0^\circ \) by \( \Delta E \) and \( E \) plastic scintillators and by four multwire proportional chambers (MWPC's; labeled \( X_1, Y_1, X_2, \) and \( Y_2 \) in Fig. 1). A veto scintillator \( V \), placed behind the \( E \) detector, was used to identify and veto high-energy protons produced by the neutron beam. The coincident \( \gamma \)'s were detected by an array of 160 Pb-glass Čerenkov counters, spanning laboratory angles from \( 34^\circ \) to \( 109^\circ \) to the left of the beam and from \( 79^\circ \) to \( 124^\circ \) to the right. The left-right asymmetric arrangement of Čerenkov counters was chosen to cover the entire angle range of interest, while avoiding photon attenuation through thick metal posts that constituted part of the superconducting magnet assembly inside the PPT Dewar.) The relative neutron flux was monitored for each beam-target spin state independently by two pairs of in-beam scintillators, only one of which—\( S_0 \) and \( S_1 \)—is shown in Fig. 1. The beam and target polarizations were monitored continuously by detecting \( np \) elastic scattering coincidences from the PPT, with proton detectors on the beam left and neutron detectors on the right. The performance of all the detectors is described in more detail in ensuing sections.

B. Beam and targets

Details of the PNF, the PPT, and the dummy target have already been discussed in Refs. [11,12]. Here we briefly
FIG. 1. Scale rendering of the detector setup. Each stack of Pb-glass detectors is labeled by its central laboratory polar angle. The polarized target is indicated schematically and labeled by PPT. Details are discussed in the text.

summarize their properties relevant to the present experiment. The neutron beam was produced via the $^3$H($p$,n)2p reaction at $\theta_{ab}=10^\circ$, initiated by 200 MeV polarized protons on a 20 cm thick liquid deuterium target. Neutrons selected for study (by their time of flight) had a mean kinetic energy of 183 MeV, with an energy spread of 15 MeV full width at half maximum (FWHM). The vertical polarization of the neutron beam was typically 0.50–0.65, and its direction was reversed every 15 s. The primary proton beam was pulsed, with a time separation of 57 ns between consecutive pulses. The average primary beam current was 224 nA, giving about $4\times10^6$ neutrons/s in a beam spot 5 cm wide by 7 cm high at the target position.

The PPT, of "spin-refrigerator" type [13], contained 1.0 g/cm$^2$ of the target material yttrium ethyl sulfate [Y(C$_2$H$_5$SO$_4$)$_3$•H$_2$O, or YES], doped with Yb. It was polarized twice per day by rotating the target crystals at about 40 Hz in the presence of a 1.2 T polarizing field at a temperature $\approx 0.5$ K [12]. During data acquisition, the target was held stationary in a reduced magnetic field (0.059 T). The target could be set in either one of two modes: normal (NRM) mode, in which the holding field direction is kept parallel to that of the proton polarization, or adiabatic fast passage (AFP) mode, in which case they are antiparallel [11].

The relaxation time of the polarization at the holding field strength used was typically 80–150 h, and the time-averaged polarization during running periods was about 0.40.

In comparison with its use in Ref. [11], the PPT was placed further downstream of the neutron production target (4.7 m instead of 4.3 m), and the PPT Dewar was rotated by $\approx 45^\circ$ so that the copper and stainless steel posts of the PPT magnet assembly would not block photons emitted toward the Pb-glass detectors. The neutron beam collimator was modified, in accordance with the change in target position, in order to keep the neutron beam size at the target position the same as that of the YES crystals.

In addition to the PPT and the dummy target, a few auxiliary targets were also used in this experiment for calibration and setup purposes. These included a 0.452 g/cm$^2$ CH$_2$ target, of transverse area much larger than that of the beam spot. Because this target contained relatively more hydrogen and fewer contaminant nuclei than the PPT, it was used to calibrate the gain of the np polarimeter neutron detectors (see Sec. II C), and the absolute neutron flux, by detecting the forward-going high-energy protons from np elastic scattering events induced in the target (see Sec. III D). To measure background caused by the contaminant carbon nuclei in the CH$_2$ target and by other materials along the beam path (e.g., the $\Delta E$ scintillator), data were taken with a 0.432 g/cm$^2$ carbon target and also without any target.

C. Detectors

1. Photon detectors

The 160 Pb-glass Čerenkov counters used in the experiment were blocks of Schott F2 glass, measuring 4.2×6.4 cm$^2$ on the front face, 6.4×6.4 cm$^2$ on the back face, and 50 cm in length. This length corresponds to about 10 r.l. for the photon energies of interest. Each block was attached to an EMI 9839B photomultiplier tube that contained 12 dynodes. A test using the tagged photon facility at the University of Illinois [14] showed that the energy resolution of an individual detector for photons (energy 70 MeV) incident near the center of its front face was typically 34%. The test also determined the equivalent photon energy for the cosmic ray peak seen by each detector, which allowed us in the subsequent experiment to calibrate photon energies by detecting cosmic rays interspersed with the reaction product photons. The output of each Pb-glass counter was fed through an individual constant-fraction discriminator (CFD), with a threshold set at $E_\gamma \approx 18$ MeV. As can be seen in Fig. 1, these detectors were arranged into eight stacks, each of which was four blocks wide by five blocks high. The front face of each stack subtended a geometric solid angle of 0.127 sr. For a $d\gamma$ event, the Pb-glass detector with the largest recorded pulse height was chosen to determine the photon's angular information, but the pulse height in the neighboring cells (in the same stack) was added to the largest pulse height to determine the photon energy. The overall efficiency for each stack to detect $d\gamma$ photons was typically 89% (see Sec. III D 3).

The analog signals and CFD timing signals from the 160 Pb-glass detectors were multiplexed into 32 channels, each of which contained inputs from 5 nonneighboring Pb-glass counters. The counters that actually fired for a given event were determined from the pattern of latches set by the CFD outputs for each counter. The analog signals were fed to analog-to-digital converters (ADC's) with ac-coupled inputs to filter out low-frequency noise.

The relative gains and timing of all the Pb-glass counters were monitored continuously throughout the experiment by acquiring cosmic ray events interspersed with np→dγ events. Since only small gain shifts were observed, the gain matching (by high voltage adjustment) was performed once at the beginning of each production running period and then once per day during the run. The time resolution of each Pb-glass detector, measured using cosmic rays, was better than 1.0 ns.

The Pb-glass detectors were quite insensitive to most of the hadrons (p, d, n, π$^\pm$) produced in the beam-target inter-

RADIATIVE CAPTURE OF POLARIZED NEUTRONS BY...
actions, as these particles were too slow to generate Čerenkov light and had a very small probability to generate secondary photons above 18 MeV in nuclear reactions. Thus, despite the presence of a high neutron flux, each individual Pb-glass detector fired at a singles rate of only \(\sim 200\) Hz.

2. In-beam deuteron detectors

The \(\Delta E\) and \(E\) scintillators were 0.32 and 7.0 cm thick, respectively. The dimensions of the \(\Delta E\) and \(E\) scintillators, centered about \(0^\circ\), were chosen so that all deuterons from the \(np\rightarrow d\gamma\) reaction (falling within a cone of laboratory half-angle 9°) could be detected by both detectors and would all be stopped in the \(E\) scintillator. The veto (\(V\)) scintillator had the same transverse dimensions as the \(E\) detector, but was only 0.64 cm thick. The \(E\) and \(V\) scintillators were each viewed by four photomultipliers (two on the left and two on the right end of the \(E\) scintillator and four on the top of the \(V\) scintillator), whose gains were matched during the experiment by recording the pulse heights produced, as a function of impact position, by forward-angle high-energy protons originating from \(np\) elastic scattering in the target. The summed pulse height from the four phototubes was found in each case to be quite uniform (variation \(\leq 10\%\)) over the entire active area of the scintillator.

Four in-beam multiwire proportional chambers were used for angle measurements and ray-tracing forward-going charged particle tracks back to the target location. The wire spacings of the \(X1, Y1, X2,\) and \(Y2\) chambers were 1.95, 2.54, 4.36, and 5.45 mm, respectively. The active areas accepted all deuterons of interest. When the wire chambers were plateaud for the deuterons of interest, they were able to withstand the full neutron beam intensity with acceptable (<5 \(\mu\)A) leakage currents. The deuteron detection efficiency for each individual wire chamber was nearly 100%. The overall probability for a \(d\gamma\) deuteron to yield at least one hit in each of the four wire chambers was 97.8%, averaged over all of the PPT runs. The overall efficiency for detecting forward-going protons from \(np\) elastic scattering events was somewhat lower (93.6%).

3. Flux monitor detectors

There were two monitors used for measuring the relative neutron flux for each beam-target spin combination. Each flux monitor consisted of a pair of in-beam plastic scintillator paddles of transverse dimensions larger than the beam: a thinner one placed upstream to veto charged particles and a thicker one downstream to detect neutrons (via nuclear reactions within the paddle). Flux monitor 1 was placed immediately downstream of the exit of the neutron collimator, while flux monitor 2 was placed behind the \(V\) detector. Relative measurements between the two monitors agreed typically to within \(\pm 0.1\%\).

4. \(np\) polarimeter detectors

The \(np\) polarimeter was used to monitor the neutron beam and proton target polarizations, by measuring \(np\) elastic scattering induced in the PPT. The polarimeter consisted of an array of 16 liquid scintillator neutron detectors \(N^P\), to the right of the beam, and a \(\Delta E^P-E^P\) plastic scintillator telescope to detect the coincident protons on the left (see Fig. 1). A thin plastic scintillator \(V^P\) was placed in front of the neutron detectors to veto charged ejectiles.

Each of the 16 neutron detectors [11] was 8 cm wide by 10 cm high at its front face, 40 cm deep, and 10 cm wide by 12.5 cm high at the rear. The 16 detectors formed three columns (6 detectors each in columns 0 and 1, and 4 in column 2) centered, at midplane, about laboratory polar angles of 33.3°, 36.4°, and 39.5°, respectively. The planar front face of the detector array was placed 1.46 m from the target. The neutron detectors were gain matched by detecting \(pp\) coincidences induced by a secondary proton beam (obtained by turning off a sweeping magnet in the PNP) on the \(\text{CH}_2\) target placed at the usual PPT position. In this matching procedure, the phototube high voltages were adjusted to yield proton pulse heights that varied with the angle of the liquid scintillator cell in the manner expected from \(pp\) elastic scattering kinematics.

The \(\Delta E^P\) and \(E^P\) detectors were centered at a laboratory angle of 51.0°. The transverse dimensions of both these scintillators were large enough to detect almost all (\(\simeq 98.5\%\)) free-scattering protons in coincidence with the neutrons detected in \(N^P\), even after allowing for multiple scattering of the protons and their deflection in the magnetic holding field of the PPT.

D. Event types

The detectors described above allowed us to record the following types of events simultaneously. 

1. \(np\rightarrow d\gamma\) candidate events: events in which \(\Delta E, E\), at least three of the four wire chambers, and at least one Pb-glass Čerenkov counter fired in coincidence, while the veto detector (\(V\)) and the upstream scintillator \(S_0\) did not fire.

\(S_0\) was used to reject events initiated by charged particles. By requiring only three wire chambers to fire, we were able to keep track of the efficiency of each chamber on line. During the final production period, we removed the wire chamber requirement entirely from the hardware trigger for both \(d\gamma\) and "proton" (see below) events, for diagnostic purposes. However, we still recorded wire chamber hit patterns for each event.

2. "Proton" events: prescaled (by a factor of 400) events in which \(\Delta E, E\), at least three of the four wire chambers, and \(V\) fired in coincidence, while \(S_0\) did not fire.

The "proton" events were used not only to monitor the gains of the in-beam scintillator phototubes, but also to calibrate the absolute neutron flux using the known \(np\) elastic backscattering cross sections (see Sec. III D).

3. Cosmic ray events: events in which at least one Čerenkov counter and at least one of five plastic scintillator trigger paddles placed on top of the Pb-glass stacks fired in coincidence, while \(E\) did not fire.

For each cosmic ray event, we recorded the pulse height and timing information for all of the Pb-glass detectors, in order to monitor their gains and timing continuously throughout the experiment. In addition, for these events we also recorded the pulse heights for all in-beam and \(np\) polarimeter scintillators (even though these detectors had not fired in principle), in order to keep track of their 60 Hz noise patterns. The phase of each event arrival within a 60 Hz cycle was monitored for all event streams via the amplitude
of a "sawtooth" wave generated in synchronization with the ac power. The event loci in the spectra of sawtooth wave vs noise amplitude for the in-beam and polarimeter scintillators provided high statistics templates that allowed us to subtract the noise or pedestal contribution event by event from the ADC outputs recorded for those detectors for other types of events.

(4) Flux monitor events: prescaled (by a factor of 1000) events in which the rear paddle of the flux monitor scintillator pair fired, while the front paddle did not. The time between the rear paddle signal and the cyclotron rf signal was recorded for each event, in order to monitor the neutron beam energy spectrum.

(5) np polarimeter events: events in which the proton telescope elements $\Delta E^P$ and $E^P$ fired in coincidence with at least one of the 16 neutron detector cells $N^P$, while $S_0$ and $\gamma^P$ did not fire.

### E. Data acquisition

The analog, logic, and timing signals from the detectors described above were digitized by CAMAC modules and then read into a microVAX III computer via an MBD-11 branch controller. The data were also recorded on magnetic tape for subsequent off-line analysis. The software package XSYS [15] was used for both data acquisition and off-line analysis.

The $\bar{n}p \rightarrow d\gamma$ data acquisition was divided into "cycles." A typical cycle lasted roughly 24 h and included the following: 2–3 h of PPT repolarization, followed by roughly 7 h of data acquisition with the PPT in either NRM or AFP mode; another 2–3 h of target repolarization, followed by roughly 7 h of data acquisition with the PPT mode switched (from NRM to AFP or vice versa); finally, 4–5 h of data acquired with the dummy target. In all, 26 such cycles of data were taken. These included 12 cycles from the first production run, during which the PPT was always kept in NRM mode, due to a hardware problem with the nuclear magnetic resonance coil needed to effect the AFP transition.

During each cycle, the PPT holding field was adiabatically reversed every 15 min (a process that took ~40 s) to flip the spin orientation of the polarized protons. Special care was taken to correct for any detector gain shifts caused by this field reversal. Inside the target wall (radius 15 cm), the holding field was approximately 0.059 T. Outside the target wall, the field decreased rapidly with distance, to a typical level of a few $\times 10^{-4}$ T to $10^{-5}$ T near the photomultiplier tubes of the various scintillators. Although all photomultiplier tubes used in this experiment were magnetically shielded, the change in residual magnetic field caused by the target field reversal nonetheless produced appreciable gain shifts in the tubes attached to the Pb-glass detectors and to the neutron detectors used for the polarimeter. The cosmic ray events allowed us to track continuously and to correct for the gain shifts of the Pb-glass detectors, which ranged from 5% to 20%. The gain changes in the neutron detectors were measured in a separate run, utilizing the secondary proton beam. For these measurements, we observed $pp$ elastic scattering coincidences induced on the flux monitor veto scintillator $S_0$ (see Fig. 1), with the forward-going protons traveling to the neutron detectors along paths that did not traverse the PPT Dewar, and thus undergoing negligible deflection from the holding field. By reversing the PPT field in the usual way, we observed neutron detector gain shifts of 1–2%, which were later corrected using software gains and thresholds.

The magnetic holding field also deflected the paths of charged particles as they exited the PPT; for the $\bar{n}p \rightarrow d\gamma$ deuterons of interest, this effect is small (<0.5°) and easily calculable. In addition to correcting for the effects of the target field on an event-by-event basis in the data replay, we used the comparison of the results obtained in NRM (target polarization parallel to the holding field) and AFP (antiparallel) modes to study and cancel any residual field-dependent systematic errors (see Sec. V).

In order to get further information about the sizes of potential systematic errors associated with reversal of the PPT holding field, we took three additional cycles of data with the YES target unpolarized, but the holding field on and flipping as usual. In the absence of systematic errors, the target analyzing power asymmetry and the product of target polarization and spin correlation measured in these extra cycles should be exactly zero (see Sec. VA).

### III. DATA ANALYSIS

The primary goal of the data analysis was to identify the $\bar{n}p \rightarrow d\gamma$ events induced on the hydrogen component in the PPT, to subtract any background contributing to this event sample, and to deduce the cross section $\frac{d\sigma}{d\Omega}$ and the normal-component spin observables $A_n$, $A_p$, and $C_{NN}$. The main procedures are discussed below.

#### A. Software corrections to the raw data

Certain corrections had to be applied to the raw data before we could proceed to identify events of interest. These included ac noise and pedestal subtraction from ADC values, software corrections for gain differences among the detectors, time-offset alignment for the time-to-digital converter (TDC) values from the detectors, and corrections for effects of the PPT holding field.

The ac noise and pedestal subtractions for ADC’s from the in-beam and np polarimeter scintillators have been described in Sec. II C. In practice, the ac noise pattern and the ADC pedestal values were updated for every 20,000 cosmic ray events (corresponding to ~30 min intervals). Noise subtraction was not necessary for the Pb-glass counters, for which the ADC inputs were ac coupled.

The detector gains were monitored and were roughly matched online by the techniques described in Sec. II. Software corrections were used to compensate for small remaining gain differences among different phototubes and to take account of the measured gain changes with time and with PPT holding field polarity. Field-dependent gain shifts were appreciable only for the Pb-glass and neutron detectors. The software gain factors were updated for each individual run for the in-beam scintillators, for each data cycle in the case of the Pb-glass counters, and for the three different production running periods in the case of the np polarimeter detectors. An additional software correction compensated for the small measured position dependence observed for the $E$-detector summed pulse height (see Sec. II C 2).
The effect of the PPT holding field on the deuteron motion was also calculated and corrected in software. Since the bend angle was always small (<0.5°), we were able to estimate it with sufficient accuracy using a simplified model that assumed a uniform 0.059 T field within a radius of 15 cm from the target center and zero field outside.

The timing offsets for the 160 Pb-glass detector TDC's were calibrated every two cycles using the online $n\bar{p} \rightarrow d\gamma$ events themselves. After applying a series of software cuts to select these events (see Fig. 2), we observed a narrow peak in the $t_{E\gamma}t_{\Delta E}$ spectrum for each Pb-glass detector, corresponding to the $n\bar{p} \rightarrow d\gamma$ events initiated in the PPT (see Fig. 3). We adjusted the software timing offsets so that the peaks in the $t_{E\gamma}t_{\Delta E}$ spectra were aligned for all 160 counters. This procedure corrected not only for phototube and cable length differences among the photon counters, but also for kinematic differences in the flight time of the coincident deuterons from the target to the $\Delta E$ scintillator.

The signal output time from the single $\Delta E$ phototube, relative to the arrival time of a charged particle at the $\Delta E$ scintillator, varied with the hit position of the particle. This dependence was measured by observing the time difference between the $E$ and $\Delta E$ scintillators for the forward-going proton events from $np$ elastic scattering in the PPT, as a function of hit position as deduced from the wire chamber information. The $E$-scintillator time was taken to be the average value of the arrival times from its four phototubes, resulting in a negligible spatial dependence of the arrival time for the central region of the detector. The small observed position dependence of the $\Delta E$ time signal ($\approx 0.5$ ns within the region of interest for forward-going deuterons) was subsequently corrected in software.

The time spectra for the neutron detectors (with respect to the $E^s$ scintillator) were measured online for $pp$ elastic scattering events in CH$_2$ target runs. We adjusted software timing offsets for each liquid scintillator cell so that all of the $pp$ scattering timing peaks were aligned.

**B. $n\bar{p} \rightarrow d\gamma$ data analysis**

1. Identification of $n\bar{p} \rightarrow d\gamma$ events

We identified $n\bar{p} \rightarrow d\gamma$ events via a series of software cuts and conditions, most of which are illustrated in Fig. 2. In order to estimate systematic errors associated with possible spin-dependent removal of events by software cuts, we used two sets of cuts (loose and tight) on all variables except the
$\Delta E$ signal arrival time with respect to the cyclotron rf, which
determines the neutron bombarding energy range accepted.
The physical interpretations of the loose cuts are as follows.

(a) Neutron beam energy: A cut was applied on the neutron
beam time of flight [Fig. 2(a)] TOF = $t_d - t_{d^*} + \Delta t_{d^*}$,
where $t_d$ and $t_{d^*}$ are the times for the rf signal and $\Delta E$
scintillator, respectively, and $\Delta t_{d^*}$ is the calculated flight time
of deuterons from the PPT to the $\Delta E$ scintillator, based on
$np\to d\gamma$ kinematics as a function of lead glass stack number
for the observed coincident photon. This cut selects incident
neutrons approximately in the energy range 170–193 MeV
(mean energy = 183 MeV) [11].

(b) Event origin: Wire chamber hit information was
used to ray-trace outgoing charged particle trajectories back
to the target plane. Cuts were applied on the x and y distrib-
utions of transverse event origin coordinates to eliminate
events that originated outside the target volume [Figs. 2(b)–
2(c)].

(c) Particle identification: Forward-going deuterons
were distinguished from protons by gates on the time of
flight of particles (from $\Delta E$ to E scintillator) vs pulse height
in the E scintillator [Fig. 2(d)] or on $\Delta E$ pulse height vs E
pulse height.

(d) Timing correlation: A cut was placed on $t_f - t_{d^*}$ to
select only those $np\to d\gamma$ events initiated on the PPT [those
in gate 1 in Fig. 2(e)]. The time resolution was sufficient ($\sim1$
ns FWHM) to discriminate cleanly against $np\to d\gamma$ events
initiated on hydrogen in the $\Delta E$ scintillator itself. The
prompt gate was displaced by 57 ns (the separation between
successive beam bursts), yielding gate 2 in Fig. 2(c) to select
an event sample for accidental coincidence subtraction.

(e) Photon energy: The energy of photons from $np\to d\gamma$
events ranged from 70 to 120 MeV over the angle range
covered. A loose software threshold at $\sim22$ MeV was applied
to eliminate accidental coincidences with the abundant
low-energy background $\gamma$'s [Fig. 2(f)].

(f) $\theta_{d^*}$ vs $\theta_{\gamma}$: The observed photon angle was used to
calculate the expected deuteron angle, using two-body ki-
netics. The difference $\Delta \theta$ between this value and the
deuteron angle measured with the wire chambers was restricted
by the loose cut to $\sim\pm4^\circ$ [Fig. 2(g)] for the selected events.

(g) Coplanarity: The d and $\gamma$ should be coplanar with
the neutron beam if they arise from a two-body final state.
In the analysis, the difference in measured azimuthal angles of
the deuteron and the photon, $\phi_{open}$, was restricted by a loose
cut to $180^\circ\pm33^\circ$ [Fig. 2(h)]. This cut, together with that on
$\theta_{d^*}$ eliminated most of the background from quasifree
$A(n,d\gamma)$ reactions induced on contaminant nuclei in the
PPT.

(h) $E_d$ vs $\theta_{\gamma}$: A two-dimensional cut was applied to
select events in which $E_d$ was correlated with $\theta_{\gamma}$, as expected
from two-body kinematics.

Two types of background were subtracted from the event
sample selected by the above cuts. Accidental coincidences
between a charged particle from one beam burst and a pho-
ton from the next (57 ns later) were recorded [those in gate 2
in Fig. 2(e)] and were then subtracted from the prompt
coincidences that satisfied the same cuts on other variables. Any
remaining background was then removed by subtracting the
yields obtained for the dummy target, after application of
identical software gates to those above, subtraction of
dummy-target accidents, and normalization to the same
deadtime-corrected integrated neutron flux as was recorded
for the PPT runs.

The effectiveness and cleanliness of the event selection
can be seen from Figs. 3 and 4. Figures 3(a), 3(b) show, on a
logarithmic scale, the $t_f - t_{d^*}$ spectra after all software cuts
have been applied to other variables (except neutron energy)
for the PPT and the dummy target, respectively. The latter
spectrum reveals two background peaks of approximately
equal size, resulting from quasifree $A(n,d\gamma)$ events on the
dummy target and from free $p(n,d)\gamma$ events initiated on the
$\Delta E$ scintillator. This background ($\sim10\%$) was removed by
subtracting the (normalized) dummy data from the PPT data,
resulting in a very clean, narrow peak that corresponds to the
$p(n,d)\gamma$ events induced on the hydrogen component in the
PPT, as shown in Fig. 3(c).

Figure 4 shows the $\phi_{open}$ spectra for the PPT with partial
cuts (event origin, particle identification, and timing correla-
tion) and all cuts (except those on neutron energy and copla-
narity itself). The former spectrum exhibits a significant ac-
cidental coincidence background, whose dependence on
$\phi_{open}$ (roughly sinusoidal) reflects the detector acceptance:
Both the d and $\gamma$ detectors had maximal acceptance for par-
yield wire chamber hits (with substantially less efficiency than the deuterons) if they occurred within 600 ns after the arrival of a valid event. Their energy depositions in the in-beam scintillators would not have surpassed the thresholds, eliminating corruption of TDC information and adding only a small amount of integrated charge (within the experimental resolution) to the ADC information when they arrived within the 140 ns ADC gate width for a valid event.

A substantial additional source of multiple hit events occurred during four data cycles taken in the second of the three production runs. The extra problem in these cycles was later traced to an intermittent cable connection in the electronic "clear" circuit, which was intended to reset ADC’s, TDC’s, and wire chamber readout initiated by a scintillator-Čerenkov counter coincidence, when that coincidence was not subsequently accompanied by (slower) signals from three of the four MWPC’s. The failing cable resulted in unclered data being inadvertently recorded in place of the appropriate ADC and TDC information if the next (uncorrelated) event satisfied both the intermediate and the final logic requirements. In the case of the wire chambers, the unclered hit information was recorded together with the appropriate hits produced by the valid event.

In order to investigate the impact of these problems, in the final production run we purposely removed the MWPC requirement at the trigger logic, thereby eliminating the need for the clear circuit. We instead used a coincidence register bit to record whether at least three MWPC’s had fired for each event. The wire chamber hit information was recorded as usual. These data allowed us to simulate in software replay both the ordinary multiple-hit events and the events corrupted by the clear circuit failure, by suitably combining successive events stored on tape. The result of this simulation showed that essentially none of the events with corrupted ADC’s and TDC’s, caused by the clear circuit failure, could have passed all of the software cuts described in Sec. III B 1. The net effect of the clear circuit failure was thus a reduction in the electronic efficiency for $np \to d\gamma$ events during cycles 18–21, which was shown to be spin independent within statistics. These cycles were excluded from the data sample used for evaluation of absolute differential cross sections.

In the simulation we reproduced the observed properties of the ordinary multiple-hit events well by combining only the MWPC hits for a chain (two or more) of successive events, whenever all but the last in the chain were accompanied by fewer than three MWPC’s. Because the ADC and TDC information was uncorrupted, good events could be efficiently recovered by an algorithm that passed any event in which at least one, among all possible combinations of MWPC ray tracings, satisfied all of the $np \to d\gamma$ criteria. Application of this algorithm to the artificially corrupted events in the simulation proved highly successful: The valid $np \to d\gamma$ events were recovered with $\leq 0.5\%$ loss and with $\leq 1.5\%$ gain of apparent (but invalid) $np \to d\gamma$ events for each Pb-glass stack and each $np$ spin state. We thus used this multiple-hit event recovery scheme in all of our data analysis, and it provided about 25% of our final $np \to d\gamma$ event sample. The fact that this recovered fraction was the same, within statistics, whether we used loose or tight software cuts to identify the events provides evidence that the
multiple-hit events did not suffer from any significant deterioration of resolution.

### C. np polarimeter data analysis

#### 1. Identification of np events

The np elastic scattering events were identified in software via the following cuts: (a) neutron beam energy, (b) software threshold on the neutron detector pulse height, (c) particle identification (using $E_N$ vs $\Delta E_P$ pulse heights to select protons), (d) np timing correlation, and (e) accidental coincidence subtraction.

A small fraction ($\approx 18\%$) of events accepted by the np polarimeter detectors and satisfying the above cuts arose from quasi-free $A(n,np)$ reactions on contaminant nuclei in the PPT. This background was subtracted by acquiring np polarimeter data using the dummy target, in a way similar to that described in Sec. III B 1.

#### 2. Determination of the beam and target polarizations

Using the extracted np polarimeter yields vs np spin state, the beam and target analyzing power asymmetries $e_n$, $e_p$, and spin correlation asymmetry $e_{np}$ for np elastic scattering were determined:

$$e_n = (N_{11}-N_{14}+N_{12}+N_{13})/(N_{11}+N_{14}+N_{12}+N_{13}),$$

$$e_p = (N_{11}-N_{14}-N_{12}+N_{13})/(N_{11}+N_{14}+N_{12}+N_{13}),$$

$$e_{np} = (N_{11}+N_{14}+N_{12}+N_{13})/(N_{11}+N_{14}+N_{12}+N_{13}),$$

where the spin-dependent yields $N_{ij}$ are defined as in Sec. I. The beam and target polarizations $P_n, P_p$ could then be deduced from these asymmetries using absolute analyzing power $(A_n, A_p)$ and spin correlation $(C_{NN})$ values measured for np elastic scattering at 183 MeV in a previous experiment [10,11], with absolute normalizations (of uncertainty $\pm 3\%$ for each analyzing power and $\pm 6\%$ for $C_{NN}$) tied to $pp$ elastic scattering [10].

The measured $e_n$ and $e_p$ asymmetries have substantial sensitivity to small errors in determining the neutron detector angles (since $A_n$ and $A_p$ vary rapidly as a function of angle within our range [11]) and to instrumental asymmetries in our left-right asymmetric polarimeter (arising, for example, from PPT field effects). In contrast, $C_{NN}$ asymmetries are explicitly left-right symmetric and far less sensitive to field effects, since an average is taken over the two PPT spin directions. Furthermore, for np elastic scattering in our angular range, $C_{NN}$ is known [10,11] to vary very weakly with angle: $C_{NN}=0.780, 0.732,$ and $0.690$ at the angles $\theta_{n}^{lab}=33.3^\circ, 36.4^\circ,$ and $39.5^\circ$, respectively, of the three neutron detector columns. For the above reasons, we extracted the product $P_n P_p$, needed to determine $C_{NN}$ for $np \rightarrow d \gamma$, directly from the np polarimeter spin correlation asymmetry:

$$P_n P_p = \frac{e_{np}(\theta)}{C_{NN}(\theta)}.$$

(3.1)

For individual polarizations, we used the following formulas:

$$A(\theta) = \sqrt{\frac{e_n(\theta) e_p(\theta) C_{NN}(\theta)}{e_{np}(\theta)}},$$

(3.2)

$$P_n = \frac{e_n(\theta)}{A(\theta)},$$

(3.3)

$$P_p = \frac{e_p(\theta)}{A(\theta)}.$$  

(3.4)

In extracting $P_n$ and $P_p$, in this way, we ignore the small (few parts in $10^5$) charge-symmetry-violating difference [11] between $A_n(\theta)$ and $A_p(\theta)$ for elastic scattering.

The analysis described above was performed separately for NRM and AFP data and for the three neutron detector columns. Small NRM-AFP differences ($\sim 0\%$, $9\%$, and $16\%$, for columns 0, 1, and 2, respectively) were observed in the extracted values of beam polarization $P_n$ and the analyzing power $A$, but not in $P_n P_p$, which must reflect the existence of systematic errors associated with the PPT holding field, even after corrections were made in software for the gain shifts observed in the neutron detectors. These errors may arise from the bending of the outgoing proton trajectories in the field, although the proton detectors were made large enough, in principle, to accept the deflected protons for either field orientation. In any case, we assume that the averaging of NRM and AFP results cancels such field-dependent errors to a high degree of accuracy. That this is a good assumption is borne out by the averaged results presented in Table I, where the extracted polarizations are all shown to be independent (within the specified statistical uncertainties) of neutron detector column number, and the extracted analyzing power angular dependence agrees well with earlier measurements [10,11].

For the above reasons, for cycles 1–13 (the first of the production runs), where only NRM data were obtained, we used the np polarimeter results extracted from column 0 only, since here the field effect appears negligible; for cycles 14–28, where there were both NRM and AFP data, we used the results extracted from all three columns and averaged over AFP and NRM modes.
D. Evaluation of absolute cross sections for \( np \rightarrow d\gamma \)

The absolute cross sections have been evaluated from the data taken in the final production run only, where the various efficiency and correction factors were best understood. The c.m. frame cross section for \( np \) radiative capture \((d\sigma/d\Omega)\) was deduced from

\[
\frac{d\sigma}{d\Omega} = \frac{J}{4\Delta\Omega N_{H}\eta_{d}\eta_{\gamma}} \sum_{i=1}^{4} \frac{Y_{i}}{F_{i}L_{d}\lambda_{d}T_{i}},
\]

(3.5)

where \( Y_{i} \) is the \( np \rightarrow d\gamma \) yield measured for the \( i \)th \( np \) spin state and for a given Pb-glass detector stack; \( J \) is the Jacobian factor converting the laboratory cross section to the center-of-mass frame; \( \Delta\Omega = 0.127 \) sr is the laboratory solid angle of each Pb-glass stack front face as viewed from the center of the target; \( N_{H} = 3.29 \times 10^{22} \) cm\(^{-2} \) is the number of free hydrogen atoms per unit area in the PPT; \( \eta_{d} \) is the combined efficiency for all the four wire chambers to detect a deuteron \((\eta_{d} = 0.978 \pm 0.001) \) for both the PPT and dummy target runs); \( \eta_{\gamma} \) is the photon detection efficiency for a given Pb-glass stack; \( \eta_{s} \) is the combined efficiency of software cuts used to extract the \( np \rightarrow d\gamma \) events from the data; \( F_{i} \) is the neutron beam intensity (neutrons/s) for the \( i \)th spin state, averaged over all the PPT bombardments; \( L_{d} \) and \( \lambda_{d} \) are the electronic and computer live time for the \( d\gamma \) events obtained with the PPT for the \( i \)th spin state; and \( T_{i} \) is the total data acquisition time for the \( i \)th spin state for the PPT.

Once \( d\sigma/d\Omega \) is known, we use the principle of detailed balance to convert this quantity to the c.m. deuteron photodisintegration cross section, \( d\sigma/d\Omega \), via

\[
\frac{d\sigma}{d\Omega} = \frac{2}{3} \frac{K_{p}}{K_{\gamma}} \frac{d\sigma}{d\Omega},
\]

(3.6)

where \( K_{p} \) and \( K_{\gamma} \) are the proton and photon c.m. momenta, respectively.

The estimation of the factors \( F_{i}, \eta_{d}, \) and \( \eta_{s} \) involved nontrivial analyses and calibrations, as briefly discussed below.

1. Neutron beam intensity \( F \)

The absolute calibration of the neutron beam intensity was based on the known differential cross section \([16]\) and the observed yields of \( np \) back-angle elastic scattering events induced in the PPT and in the auxiliary CH\(_{2}\) target. During the experiment, we acquired events triggered by forward-going protons (prescaled by a factor of 400) simultaneously with the \( np \rightarrow d\gamma \) events (see Sec. II D). Software cuts on neutron beam energy, event origin, particle identification, and veto \((V)\) detector pulse height and timing were used to identify protons as \( np \) backscattering candidates. Most \((\sim 80\%)\) of these candidate events arose from quasifree scattering on contaminant nuclei in the PPT \((\sim 55\%)\) or from reactions induced on other materials (e.g., the \( \Delta E \) scintillator) along the beam path \((\sim 25\%)\). Thus the dummy target subtraction was critical for determining the true elastic scattering yields associated with the hydrogen in the PPT.

The \( np \) backward elastic scattering cross section and its normalization uncertainty \([16]\) is \((d\sigma/d\Omega)_{np}^{ab} = (31.2 \pm 3.1) \) \(\mu b/sr\), averaged over the illuminated solid angle \((0.158 \text{ sr})\) of the forward charged particle detectors. Using the above information and the measured lifetimes and wire chamber detection efficiencies, we deduced an average intensity \( F = (3.70 \pm 0.37 \pm 0.41) \times 10^{6} \) neutrons/s. This was obtained with an average primary proton beam current of 205.7 nA. The two errors quoted for \( F \) are both systematic errors and are due, respectively, to the normalization uncertainty in the \( np \) scattering cross section and to the uncertainty in the effective dummy target vs PPT thickness ratio \((= 1.00 \pm 0.04); \text{ see Ref. } [11]\). As a cross-check on the above result, we also took data (subject to less quasifree contamination) with CH\(_{2}\) and with C targets (see Sec. II), whose thicknesses were more accurately known than those of the PPT and dummy target. Using the same methods as above, from these data we deduced \( F = (3.66 \pm 0.37) \times 10^{6} \) neutrons/s, normalized to the same primary beam current as measured in a Faraday cup, in good agreement with the PPT result. The 10% error in the latter value of \( F \) is predominantly due to the \( np \) cross section normalization uncertainty. In our experiment we found that the neutron flux \((F_{n})\) was proportional to the primary beam current \((I_{p})\) monitored by the Faraday cup, and to a good approximation the proportionality constant was independent of the \( np \) spin state \( i \). We thus used the values \( F_{i} = (3.66 \pm 0.37) \times 10^{6} \) \[(\text{neutrons/s}) \times (I_{p}/205.7 \text{ nA})\] in the evaluation of \( np \rightarrow d\gamma \) cross sections.

2. Software cut efficiency \( \eta_{s} \)

The software efficiency was estimated only for the MWPC "perfect"-hit data, where there was no ambiguity in ray tracing. Although the procedure described below for evaluating \( \eta_{s} \) is not applicable for the recovered multiple-hit data, we do not expect any significant differences in the distribution of events with respect to kinematic variables, and therefore in \( \eta_{s} \), between events with and without accidental extra MWPC hits. This view is supported by the observation that the "perfect"-hit and the multiple-hit samples give the same (within statistics) ratio of yields with tight vs loose software cuts, for each of the eight Pb-glass detector stacks (the ratio averaged over eight stacks is 0.79). In the following analysis, we estimate the efficiency only for the loose cuts which were actually used to extract cross sections.

The efficiencies corresponding to most of the individual software cuts (event origin, particle identification, \( E_{\gamma}, \Delta \theta \), and \( E_{d} \) vs \( \theta_{d}; \text{ see Sec. III B}) \) could be determined by taking the difference between two \( \Phi_{\text{open}} \) distributions (after background and accidental coincidence subtraction). Specifically, we compared the distribution for events satisfying all of the software cuts (except for the \( \Phi_{\text{open}} \) cut itself) to that for events satisfying all but the one cut of interest. A narrow peak centered at 180° in this difference spectrum (containing the events removed specifically by the one cut of interest) would indicate that this cut caused a loss of \( np \rightarrow d\gamma \) events, and the lost yield was then determined from the peak area (over the range 147°-\( \pm \Phi_{\text{open}} = 213°\)). This approach could not be used to determine the effects of the \( \Phi_{\text{open}} \) cut itself or of the \( t_{\gamma} \Delta E \) cut, where it conflicts with the procedure for subtracting accidentals. In these cases, we estimated the losses by fitting the observed peaks with Gaussian distributions and calculating how much of the Gaussian fell outside the corresponding one-dimensional loose gates.
FIG. 5. $np \rightarrow d \gamma \phi_{open}$ spectra satisfying all but one of the software cuts, and failing: (a) the deuteron particle identification cut; (b) the $E_d$ vs $\theta_d$ cut.

Shown in Fig. 5 are two $\phi_{open}$ difference spectra containing events removed by a single cut, namely, the particle identification cut in (a) and the $E_d$ vs $\theta_d$ cut in (b). In the former case, the loss peak is obvious, but it is not in the latter. To evaluate the losses quantitatively in each case, we have subtracted one-half of the summed background in the two neighboring regions, $80^\circ \leq \phi_{open} \leq 147^\circ$ and $213^\circ \leq \phi_{open} \leq 280^\circ$, from the counts inside the $\phi_{open}$ peak region defined above. We thus calculated the relative event losses due to each individual cut. We found that the deuteron particle identification cut and the $E_d$ vs $\theta_d$ cut caused the largest losses [(4.7 ± 0.3)% and (2.3 ± 0.6)% respectively], probably arising in both cases from the reaction tail in the E scintillator. All other cuts combined caused a loss of (4.2 ± 1.3)%.

It is conceivable that some good events were lost due to correlated effects of more than one cut, so that they would show up only in spectra of events simultaneously failing two or more cuts. We have investigated such correlations in the analysis and have found that the loss of good events which failed simultaneously the deuteron particle identification cut and the $E_d$ vs $\theta_d$ cut was (1.2 ± 0.3)%, and the losses which simultaneously failed any combination of cuts were negligible.

By concentrating on events that fail only one cut or only one of the combinations of two or more cuts at a time in the above prescription, we have defined mutually exclusive losses for the various cuts and their combinations; i.e., no single event can show up in more than one of the loss peaks.

FIG. 6. View from above of the PPT showing the YES target and its Kel-F frame, the stainless steel inner Dewar wall (of thickness $d=0.025$ cm), and the slatted copper plates that were used to aid in the target cooling. The slots in the Cu plates (introduced to minimize eddy current effects) have not been taken into account in the photon attenuation calculations; rather we have simply used an appropriate average thickness ($d=0.25$ cm) of copper. Not shown is an outer aluminum Dewar of radius 14.6 cm and thickness 0.146 cm.

It is thus appropriate to sum the losses as estimated above. The total software cut efficiency for MWPC single-hit data is thus estimated to be $\eta_{r}=0.876 \pm 0.014$, where the uncertainty is statistical.

3. Photon detection efficiency $\eta_{\gamma}$

The photon detection efficiency for a given Pb-glass stack is defined as $\eta_{\gamma}=N/N_0$, where $N_0$ is the number of $d \gamma$ photons originally emitted toward the front face of the stack and $N$ is the number actually detected. The efficiency includes the effect of materials inside the PPT Dewar (see Fig. 6), which could convert the photons to $e^+e^-$ pairs before they reached the Pb-glass detectors. For example, using the photon absorption curves in Ref. [17], it was calculated that photons headed for the 86.5° Pb-glass stacks had a probability of (22±4)% for such premature conversion. This probability was smaller for the other stacks. The resulting $e^+e^-$ pairs would be bent by the PPT holding field and could be scattered by the materials in the PPT. However, the simulations referred to below indicate that most of the electrons and positrons would still strike the targeted or neighboring Pb-glass counters and would still be recorded as $d \gamma$ photons.

In order to determine the $d \gamma$ photon detection efficiency for the experiment, the GEANT [18] simulation package was used. The simulation used the exact geometry of the Pb-glass
TABLE II. \( np \to d \gamma \) cross sections at \( T_n=183 \) MeV and their uncertainties.

<table>
<thead>
<tr>
<th>( \theta_\gamma ) (lab)</th>
<th>( \theta_{p,c.m.} )</th>
<th>Jacobian ( J )</th>
<th>Yield ( Y )</th>
<th>( \eta_\gamma )</th>
<th>( d\sigma^\gamma/d\Omega ) (( \mu b/sr ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>116.5</td>
<td>48.9</td>
<td>1.409</td>
<td>2476±68</td>
<td>0.887±0.040</td>
<td>6.03±0.17±0.29</td>
</tr>
<tr>
<td>101.5</td>
<td>62.0</td>
<td>1.232</td>
<td>5730±104</td>
<td>0.890±0.040</td>
<td>6.07±0.11±0.29</td>
</tr>
<tr>
<td>86.5</td>
<td>76.0</td>
<td>1.058</td>
<td>6716±108</td>
<td>0.873±0.040</td>
<td>6.24±0.12±0.30</td>
</tr>
<tr>
<td>71.5</td>
<td>91.2</td>
<td>0.900</td>
<td>3491±78</td>
<td>0.902±0.040</td>
<td>5.33±0.12±0.26</td>
</tr>
<tr>
<td>56.5</td>
<td>107.7</td>
<td>0.766</td>
<td>3630±77</td>
<td>0.914±0.040</td>
<td>4.66±0.10±0.22</td>
</tr>
<tr>
<td>41.5</td>
<td>125.5</td>
<td>0.662</td>
<td>3328±74</td>
<td>0.905±0.040</td>
<td>3.72±0.08±0.18</td>
</tr>
</tbody>
</table>

\( ^a \)Denoting the angle between the proton momentum and that of the photon in the center-of-mass frame.

\( ^b \)The first error in \( d\sigma^\gamma/d\Omega \) is statistical; the second is systematic, derived by adding in quadrature the relative uncertainties in those quantities (except the yield \( Y \) and the neutron intensity \( F \)) shown on the right hand side of Eq. (3.5). We have not included an overall (i.e., angle-independent) normalization uncertainty of \( \pm 10\% \), due primarily to the uncertainty in the absolute \( np \) elastic scattering cross section, which was used to determine the absolute neutron intensity \( F \).

Arrays (Fig. 1) and a simplified model (Fig. 6) of the materials in the PPT. It incorporated the relevant interaction processes for the photons and their secondary particles in the surrounding materials, and the PPT holding field effect, under the assumption of a uniform magnetic field of 0.059 T with radius of 15 cm centered at the target.

In the simulation, photons were emitted from the target isotropically. Their energies were determined as a function of emission angle from \( np \to d \gamma \) kinematics. For each photon emitted from the target, the simulation tracked the photon and all its secondary particles (i.e., shower) with energies above 0.5 MeV (lower-energy particles contributed negligibly to the total amount of Čerenkov radiation) and recorded energies deposited by these particles in each of the 160 Pb-glass cells. The pulse height in each Pb-glass detector should be approximately proportional to the deposited energy. The pulse height resolution (FWHM) for individual Pb-glass detectors was approximately 45% at \( E=50 \) MeV, averaged over the volume of the detector, according to an analysis of the cosmic-ray pulse height spectra taken in the experiment. Since the pulse height resolution is proportional to \( E^{-1/2} \), the simulated pulse height was formed by randomizing the deposited energy \( E \) (in MeV) according to a Gaussian distribution with a FWHM of 0.45(\( E/50 \))\(^{1/2} \). The requirement for photon detection was the same as in the real experiment, namely, that there be at least one Pb-glass cell whose pulse height exceeds 18 MeV. The cell with the largest pulse height was chosen to determine the photon's angular information.

The calculated photon detection efficiencies \( \eta_\gamma \) for individual Pb-glass stacks are given in Table II, where the uncertainties are dominated by estimated systematic errors (e.g., errors in the PPT model and in the simulation). The typical efficiency obtained using the GEANT code is 0.89 ±0.04. This is only slightly smaller than the results (0.91) of a very simple calculation using only photon attenuation lengths, in which it was assumed that every photon converted inside the Pb-glass was detected.

According to the simulation, among the events detected by the Pb-glass stacks, a small but sizable portion (≈20% for the 86.5° and 101.5° stacks, and a much smaller portion for the other stacks) were due to the electrons and positrons from conversion inside the PPT, rather than to the direct \( d \gamma \) photons. However, according to our calculation and analysis, these electrons and positrons pass the \( np \to d \gamma \) software cuts with almost the same efficiency as the \( d \gamma \) photons.

The results of the evaluation of absolute \( np \to d \gamma \) differential cross sections are shown in Table II and Figs. 7, 8, and are discussed in Sec. V.

IV. RESULTS

Shown in Figs. 7, 8 and Table III are our results for the differential cross section \( d\sigma/d\Omega \), the neutron and proton analyzing powers \( A_n \) and \( A_p \), and the spin correlation coefficient \( C_{NN} \) at \( T_n=183 \) MeV. The results have been extracted including both the MWPC "perfect"-hit and multiple-hit events, and are based on the loose \( np \to d \gamma \) software cuts. For the spin observables, the error bars represent statistical uncertainties only, but for \( d\sigma/d\Omega \) we have added in quadrature all systematic uncertainties other than that governing the overall absolute normalization. The systematic er-

FIG. 7. \( d\gamma \to np \) cross section results of this experiment (in open squares, for which the error bars represent the quadratic sum of all the statistical and systematic uncertainties except the ±10% overall normalization uncertainty). Also shown are previous available data and recent theoretical calculations by Jaus and Woolcock using the Paris N-N potential in impulse approximation with relativistic corrections (dashed curve), plus meson-exchange currents (solid curve).
errors for the spin observables, including the overall normalization uncertainties, are small compared to the statistical uncertainties, and will be discussed in detail in Sec. V.

As can be seen from Table III, the left-right symmetric Pb-glass stacks at $\theta_{\mathrm{lab}}=86.5^\circ$ and $101.5^\circ$ give statistically consistent results for all three spin observables and the cross section, indicating that no significant instrumental asymmetry existed in this experiment. Thus, in Figs. 7, 8 we present results averaged over the left-right symmetric stacks. In deducing the averaged cross sections, we have treated the statistical errors for the left and right stacks as independent, but the systematic errors for the two as completely correlated.

Note that both the theoretical predictions and our measurements (see Fig. 8) for the neutron and proton analyzing powers adhere well to the relation $A_n(\theta_{p,\mathrm{c.m.}}) = -A_p(\theta_{p,\mathrm{c.m.}})$, which should hold in the absence of interfering amplitudes from isospin-0 and isospin-1 $np$ states. While such mixing is forbidden for strong interaction processes by charge symmetry [11], it could arise in principle for the electromagnetic $np \rightarrow d\gamma$ reaction, e.g., from $E1-M2$ interference. In practice, however, the most important transitions ($E1$ and $M1$) for this reaction both proceed from isospin-1 ($^3P$ and $^1S$, respectively) states, so that the observed relationship between $A_n$ and $A_p$ is not surprising.

For comparison with our data, also shown in Figs. 7, 8 are previous measurements for the cross section [3,19–21] and neutron analyzing power [3]. Our cross section results agree well with all recent measurements at overlapping angles, within our $\pm 10\%$ normalization uncertainty. Our neutron analyzing power results are also in good agreement with the previous data of Cameron et al. [3], but exceed their statistical precision by a factor of approximately 3.5.

In Figs. 7, 8 we also show recent predictions by Jaus and Woolcock [6] and by Schmitt and Arenhövel [2]. The dashed curves represent calculations by Jaus and Woolcock using the Paris $N-N$ potential in impulse approximation, along with a relativistic correction to the spin-orbit operator (which is necessary to obtain agreement with the forward angle cross section data). The solid curves, also from Jaus and Woolcock, include additional effects due to explicit coupling between the photon and an exchanged meson ($\pi$, $\rho$, or $\omega$) or an intermediate $\Delta$ (1232). These MEC and IC corrections clearly introduce very significant changes in the predicted values of $C_{NN}$ and $d\sigma/d\Omega$, and they must be included to reproduce our measured values. The dot-dashed curves in Fig. 8 represent similar calculations by Schmitt and Arenhövel, but using the Bonn coordinate-space $N-N$ potential. Using four different $N-N$ potentials (Bonn, Paris, Nijmegen, and Argonne V14), Schmitt and Arenhövel have shown [2] that all of the observables reported herein are relatively insensitive to the choice of $N-N$ distorting potential.

The relativistic correction included in all the above calculations has a discernible effect on $C_{NN}$ (as well as on the forward differential cross section) [2] and significantly improves the agreement of the calculations with our measurements.

<table>
<thead>
<tr>
<th>$\theta_{\mathrm{lab}}$ (deg)</th>
<th>$\theta_{p,\mathrm{c.m.}}$ (deg)</th>
<th>$d\sigma/d\Omega$ ($\mu$b/str)</th>
<th>$A_n$</th>
<th>$A_p$</th>
<th>$C_{NN}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>41.5</td>
<td>125.5</td>
<td>3.72±0.20</td>
<td>0.011±0.020</td>
<td>-0.347±0.028</td>
<td>0.073±0.050</td>
</tr>
<tr>
<td>56.5</td>
<td>107.7</td>
<td>4.66±0.24</td>
<td>0.014±0.018</td>
<td>-0.244±0.026</td>
<td>0.234±0.046</td>
</tr>
<tr>
<td>71.5</td>
<td>91.2</td>
<td>5.33±0.29</td>
<td>0.129±0.020</td>
<td>-0.147±0.028</td>
<td>0.187±0.050</td>
</tr>
<tr>
<td>86.5 ($L$)</td>
<td>76.0</td>
<td>6.02±0.32</td>
<td>0.227±0.020</td>
<td>-0.112±0.029</td>
<td>0.187±0.051</td>
</tr>
<tr>
<td>86.5 ($R$)</td>
<td>76.0</td>
<td>6.46±0.34</td>
<td>0.204±0.020</td>
<td>-0.085±0.028</td>
<td>0.230±0.049</td>
</tr>
<tr>
<td>101.5 ($L$)</td>
<td>62.0</td>
<td>6.25±0.34</td>
<td>0.225±0.022</td>
<td>0.019±0.032</td>
<td>0.283±0.056</td>
</tr>
<tr>
<td>101.5 ($R$)</td>
<td>62.0</td>
<td>5.90±0.32</td>
<td>0.259±0.022</td>
<td>-0.058±0.031</td>
<td>0.246±0.055</td>
</tr>
<tr>
<td>116.5</td>
<td>48.9</td>
<td>6.03±0.34</td>
<td>0.255±0.024</td>
<td>-0.017±0.035</td>
<td>0.239±0.061</td>
</tr>
</tbody>
</table>
The new data for $\vec{n}\vec{p}\rightarrow d\gamma$ from this experiment, together with the previous high quality cross section [3,19–21] and photon asymmetry [4,22] data collected over the past decade, place very strong constraints on model calculations. The excellent agreement of the full (i.e., including MEC and IC corrections) Jaus-Woolcock calculation with our results and previous data for all four observables in Figs. 7, 8 is very significant, demonstrating great recent progress in our quantitative understanding of neutron-proton radiative capture at intermediate energies. Similar calculations by Arenhövel et al. also reproduce the measurements of the photon asymmetry $\Sigma$ [4,22] over a range of energies up to the region of the $\Delta$ (1232) resonance. The photon asymmetry displays a sensitivity to MEC and IC effects similar to that of $C_{NN}$, but is more sensitive to the choice of $N$-$N$ potential, especially to the strength of the tensor force. These quantitative successes at moderate momentum transfer ($q \sim 1–2$ fm$^{-1}$) make the failures [5] of meson-exchange models of photodisintegration at higher $q$ all the more significant.

V. SYSTEMATIC ERRORS FOR THE $\vec{n}\vec{p}\rightarrow d\gamma$ RESULTS

Sources of systematic error for our $\vec{n}\vec{p}\rightarrow d\gamma$ spin observable results have been studied extensively. Among the many potential sources considered, we found that only three contributed appreciably: (a) the PPT holding field and its reversal, (b) spin-dependent removal of events by software cuts, and (c) uncertainty in the absolute $C_{NN}$ values for $np$ elastic scattering used in the extraction of $np$ polarimeter results. Below we discuss in turn the systematic errors caused by each of these factors.

A. PPT field effects

As was mentioned in Secs. II and III, the PPT holding field caused gain shifts in certain detectors and bending of the deuteron trajectories. We made corrections in the software for both these effects (see Sec. III A). In addition, we acquired data with the PPT in AFP mode, as well as in NRM mode, to partially cancel the remaining field effects.

Upper limits on the level of residual-field-dependent instrumental asymmetries have been estimated in two independent ways. The target analyzing power and spin correlation asymmetries due to instrumental effects were measured directly, by acquiring three cycles of data with the PPT unpolarized, but the holding field being reversed as usual (see Sec. II E). The results are close to zero. For example, the absolute value of the $np\rightarrow d\gamma$ target “asymmetry” $\epsilon^x_p$ (defined as the relative difference in cross sections for the holding field direction up vs down), averaged over the eight Pb-glass stacks for these three cycles is 0.024±0.011. Assuming $|\epsilon^x_p|\leq 0.035$, it is calculated that the upper limits of field-dependent systematic errors for $A_n$, $A_p$, and $C_{NN}$ in a given angle bin (before summing over AFP and NRM data) are less than $\pm 0.005$, $\pm 0.083$, and $\pm 0.020$, respectively. The second method compared polarized target data analyzed separately for NRM and AFP modes, with results shown in Fig. 9. The summed $\chi^2$ value characterizing the agreement between these two sets of spin observable results is 24.1 for a total of 24 data points, suggesting no significant systematic discrepancies. The NRM-AFP differences averaged over the eight Pb-glass stacks for $A_n$, $A_p$, and $C_{NN}$ are $-0.002\pm 0.015$, $-0.029\pm 0.022$, and $0.010\pm 0.039$, respectively.

We have used the 1σ statistical fluctuation limits on the results of the above two methods to estimate field-dependent systematic errors in $A_n$, $A_p$, and $C_{NN}$, as determined from the NRM and AFP data alone. In our experiment the ratio between the data acquisition times for AFP and NRM was 3.0/7.0. Because the field effects in these two modes act in opposite directions, summing the AFP and NRM data cancels out the field effects to a large extent, leaving residual errors about 40% as large as those estimated for NRM and AFP alone. After summing NRM and AFP data and combining the results derived via the above two methods, the field-dependent systematic errors for $A_n$, $A_p$, and $C_{NN}$ are taken to be $\pm 0.002$, $\pm 0.020$, and $\pm 0.008$, respectively, independent of angle in each case.

B. Spin-dependent removal of events by software cuts

The efficiency of the loose software cuts for selecting $\vec{n}\vec{p}\rightarrow d\gamma$ events was only (87.6±1.4)% (see Sec. III D). Systematic errors will arise if removal of the events by these cuts is spin dependent. In order to estimate the size of such systematic errors, we also extracted $\vec{n}\vec{p}\rightarrow d\gamma$ spin observables with a set of tight software cuts [see Figs. 2(a)–2(h)]. Only the neutron time-of-flight (hence secondary beam energy) gate was left unchanged between the two sets of cuts. We then compared the results corresponding to the tight cuts to the results for the statistically independent events removed upon going from the loose to the tight cuts. The summed $\chi^2$ value obtained by comparing these differences to zero is 26.7 for 24 points.
Detailed comparisons suggest some possible small systematic differences between the loose- and tight-cut results, and these are more likely due to spin-dependent removal of events with the tight software cuts (efficiency \( \approx 71\% \)) rather than with the loose cuts. (Although the background is somewhat higher with the loose cuts, the spin observables turn out to be fairly insensitive to background subtraction errors.) We therefore feel the results extracted with the loose cuts are less prone to spin-dependent errors than are the tight-cut results. We take half of the observed rms differences (averaged over the eight Pb-glass stacks) between the tight- and loose-cut results to estimate the systematic errors due to the spin-dependent removal of events by the loose cuts. The associated systematic errors for \( A_n \), \( A_p \), and \( C_{NN} \) are \( \pm 0.006 \), \( \pm 0.013 \), and \( \pm 0.019 \), respectively.

C. Normalization uncertainty in \( np \) elastic scattering \( C_{NN} \)

The absolute normalizations for all the polarization results reported here are based on that determined for \( C_{NN} \) in \( np \) elastic scattering in previous experiments [10,11] that utilized the IUCF polarized neutron facility. The \( C_{NN} \) calibration in these earlier experiments is subject to an overall normalization uncertainty of \( \pm 6\% \) \([10]\), yielding overall normalization uncertainties of \( \pm 3\% \), \( \pm 3\% \), and \( \pm 6\% \), respectively, in \( A_n \), \( A_p \), and \( C_{NN} \) measured for \( np \to d\gamma \).

D. Summary of systematic errors

Detailed estimates of other systematic errors are given in Ref. [23]. The total systematic errors in the relative angular distributions for the \( np \to d\gamma \) spin observable results \( A_n \), \( A_p \), and \( C_{NN} \), deduced by adding in quadrature those errors from all sources studied, are no greater than \( \pm 0.007 \), \( \pm 0.024 \), and \( \pm 0.022 \), respectively, in any angle bin. The combined systematic errors are in all cases substantially smaller than the statistical uncertainties. In addition to the systematic errors mentioned above, the \( np \to d\gamma \) spin observable results \( A_n \), \( A_p \), and \( C_{NN} \) are also subject to overall normalization uncertainties of \( \pm 3.2\% \), \( \pm 3.3\% \), and \( \pm 6.5\% \), respectively. These errors are dominated by the \( np \) scattering \( C_{NN} \) calibration uncertainty described above.

VI. CONCLUSIONS

Measurements of observables for the \( np \to d\gamma \) reaction can be used to test our understanding of various important aspects of the strong interaction in the \( N-N \) system. In particular, both simple physical arguments and more sophisticated theoretical calculations [2,6] have suggested that, in the intermediate-energy range, the normal-component spin correlation coefficient \( C_{NN}(\theta) \) for this reaction is particularly sensitive to electromagnetic currents in which the photon couples explicitly to exchanged mesons (MEC’s) or to intermediate \( \Delta \) resonances (IC’s). This sensitivity has motivated us to measure \( C_{NN}(\theta) \) at \( T_n = 183 \text{ MeV} \), in order to provide a quantitative test for theoretical calculations that incorporate such effects. Our experiment represents the first measurement ever made of two-spin observables in photodisintegration. While measuring \( C_{NN} \), we have also simultaneously measured differential cross sections \( d\sigma/d\Omega \), and neutron and proton analyzing powers \( A_n \) and \( A_p \).

Our results have been compared with recent theoretical calculations, as well as with previous data for cross sections and neutron analyzing powers. Our cross section results agree well with previous measurements made in the last decade. Our neutron analyzing power results also agree well with the data obtained by Cameron et al. [3], but exceed their statistical precision by a factor of 3.5. Most significantly, our results are in excellent agreement with theoretical predictions made (before our experiment) by Jaus and Woolcock, incorporating MEC and IC effects, as well as relativistic corrections [6]. The modifications to \( C_{NN} \) that arise from the latter three ingredients are all considerable and are all required in order to obtain the excellent agreement with our measurements. The quantitative agreement found for all measured observables signifies great recent progress in our understanding of MEC, IC, and relativistic effects in the \( N-N \) system. Similar theoretical calculations incorporating MEC, IC, and relativistic effects by Schmitt and Arenhövel [2] also agree well with our spin observable data, although they overpredict the cross sections for \( \theta_{p,\text{c.m.}} \approx 90^\circ \) by \( \sim 20\% \).

In this experiment we have only measured the normal-component spin correlation coefficient \( C_{NN} \). Other spin correlation coefficients, such as \( C_{LL} \) and \( C_{SS} \) (which have not yet been measured), are also expected to be sensitive to MEC and IC effects [2,6]. To provide further constraints on theoretical calculations, it is thus desirable to measure these observables with precision comparable to that obtained in the present experiment. Measurements of tensor polarization observables for deuteron photodisintegration [2] would also be helpful in identifying deficiencies in conventional theory based on nucleon, meson, and isobar degrees of freedom. The failure of such theories, which include only relatively light mesons and only the \( \Delta(1232) \) among nucleon resonances, in reproducing the energy dependence of \( d(\gamma,p)n \) total cross sections at \( E_\gamma > 500 \text{ MeV} \) [5] makes it imperative for future spin experiments (including additional \( C_{NN} \) measurements) to explore an energy range above that of the present experiment, where the conventional theory may begin to break down. It will be a challenge to see whether deuteron photodisintegration results over such a broad energy range can eventually be explained within the framework of an extended conventional theory including additional mesons and nucleon resonances in the description, or whether a more efficient treatment can be developed based on quark degrees of freedom.

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