Spin Correlation and Analyzing Power Measurements for Neutron-Proton Radiative Capture at $T_n = 183$ MeV

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(Received 16 February 1993)

We have measured the spin correlation coefficient (C_{NN}) and the neutron and proton analyzing powers (A_n and A_p) for the $\vec{n}\vec{p} \to d\gamma$ reaction at a neutron beam energy of 183 MeV. Calculations of the spin correlation are particularly sensitive to the treatment of mesonic and isobaric currents. Predictions that include both explicit photon couplings to exchanged mesons and intermediate isobar states, and relativistic correction terms in the Hamiltonian, agree well with our data, thus demonstrating the quantitative accuracy of present treatments of meson-exchange currents at moderate momentum transfer ($q \sim 1$–$2\ \mathrm{fm}^{-1}$).

PACS numbers: 25.40.Lw, 24.70.+s

Deuteron photodisintegration (or its inverse, neutron-proton radiative capture) is one of the most fundamental of nuclear reactions. Against the backdrop of a well-understood electromagnetic interaction in this simplest of nuclear systems, one can test the level of theoretical understanding of "correction" terms that pervade all treatments of more complex nuclei and reactions: e.g., explicit coupling to non-nucleonic degrees of freedom and relativistic corrections to the amplitude. In particular, the importance of relativistic (especially spin-orbit) terms in the Hamiltonian [1,2] has been highlighted by recent differential cross section measurements for $np \leftrightarrow d\gamma$ [3–6], which also removed troublesome discrepancies among earlier experiments.

The goal of our experiment was to test the quantitative accuracy of theoretical treatments of those electromagnetic currents in which the photon couples *explicitly* to exchanged mesons [meson exchange currents (MEC)] or to intermediate nucleon resonances. These currents are to be distinguished from those that are *implicitly* included, via the Siegert theorem [7], in any nucleon-nucleon (NN) Hamiltonian which satisfies the continuity equation. In order to reproduce photodisintegration and electrodisintegration cross sections at low energies ($E_\gamma \ll 100$ MeV) it is sufficient to include the Siegert MEC terms in addition to photon coupling to the proton. At the other extreme, $E_\gamma > 1$ GeV, standard descriptions of explicit MEC effects are known [8] to be inadequate to account for the observed energy dependence of the photodisintegration cross section. Our intent was to test theory at an intermediate energy ($E_\gamma \sim 100$ MeV), high enough that explicit non-nucleonic currents are important, but low enough to validate their treatment in terms of a few light exchanged mesons (π, ρ, ω) and only the $\Delta(1232)$ nucleon resonance [whose role is included via "isobaric currents" (IC)].

To this end we have performed the first measurement of the transverse spin-correlation coefficient C_{NN} for $np \to d\gamma$, an observable chosen for its sensitivity to MEC and IC. The spin correlation is defined by $C_{NN} = (\sigma_{\uparrow\uparrow} - \sigma_{\uparrow\downarrow})/(\sigma_{\uparrow\uparrow} + \sigma_{\uparrow\downarrow})$, where $\sigma_{\uparrow\uparrow}$ ($\sigma_{\uparrow\downarrow}$) is the cross section for parallel (antiparallel) orientation of the neutron and proton spins, when both are normal to the reaction plane. The sensitivity of C_{NN} to MEC and IC can be understood in terms of its manifest dependence on the np spin state. At low energies, where the disintegration cross section is dominated by photon coupling to the proton, the transition is predominantly $E1$, coupling the $^3S_1$ ground state of the deuteron to ^3P_J (predominantly parallel spin) states of the np system; for these transitions, C_{NN} ranges from 0 to +1. Non-nucleonic currents, which increase in strength with increasing energy, drive the weaker $M1$ transitions to spin-singlet np states (e.g., $^3S_1 \to {}^1S_0$, $^3D_1 \to {}^1D_2$), for which C_{NN} has the extreme value -1. Thus, even small additional currents can have a significant effect on the spin correlation. This model-independent qualitative argument is confirmed by detailed calculations performed by Schmitt and Arenhövel [9], who also show that C_{NN} is rather insensitive to the choice of NN potential, in contrast to the marked sensitivity of the differential cross section to MEC, IC, *and* NN potential choices.

A measurement of C_{NN} requires that the neutron beam and proton target be simultaneously polarized. By reversing the beam and target spins independently, one can then extract simultaneously C_{NN} and the neutron and proton analyzing powers, A_n and A_p, defined as $A = (\sigma_\uparrow - \sigma_\downarrow)/(\sigma_\uparrow + \sigma_\downarrow)$, where the arrow indicates the spin state for the appropriate nucleon (the spin of the other nucleon has been summed over). Though the analyzing powers are not particularly sensitive to MEC and IC effects, they may help constrain other ambiguities in the calculations.

The experiment was performed at the Indiana University Cyclotron Facility, utilizing the polarized neutron facility (PNF) and polarized proton target (PPT) described in Refs. [10,11]. The secondary neutron beam had a mean energy of 183 MeV (corresponding to E_γ = 95 MeV), an average flux of 5×10^6/s, and a vertical polarization in the range 0.5–0.6. The average polarization of the "spin refrigerator" PPT was 0.42. The target material was Yb-doped yttrium ethyl sulfate [$Y(C_2H_5SO_4)_3 \cdot 9H_2O$, or "YES"] crystals of total thickness 1.0 g/cm^2, with a hydrogen content of 55 mg/cm^2. The considerable number of heavy contaminant nuclei in the target necessitated taking background data with a second target (the "dummy"), which simulated the nonhydrogenous contents of the YES crystal. The background was only $\sim$10% of the $np \to d\gamma$ yield since the bombarding energy was just slightly above the π^0 production thresholds for the heavy contaminant nuclei. To optimize the statistical precision of our results, we spent $\sim$25% of our total data acquisition time on the dummy target.

For $np \to d\gamma$ events, both reaction products were detected in coincidence using the apparatus illustrated in Fig. 1. The deuterons were confined kinematically to a laboratory-frame cone of $\sim 9°$ half-angle about the beam. They were identified in a forward detector array consisting of a 3.2 mm thick ΔE scintillator, four multiwire proportional chambers (MWPC), and a 70 mm thick E scintillator, sufficient to stop all deuterons of interest. A 6.4 mm thick veto scintillator, V, placed directly behind

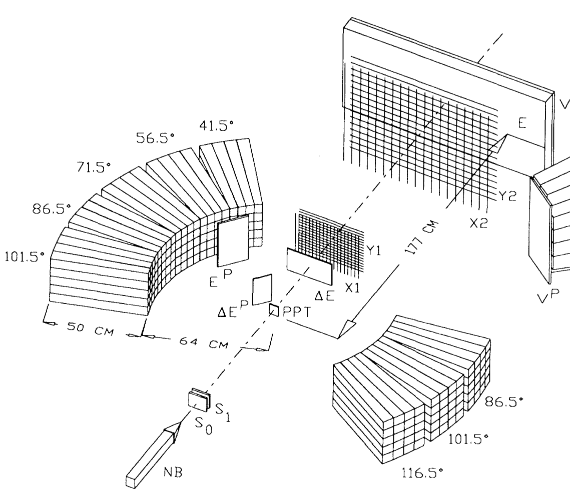

FIG. 1. Scale rendering of the experimental setup. Each stack of Pb-glass detectors is labeled by its central laboratory polar angle. Details are discussed in the text.

the E detector, was used to identify and veto the abundant high-energy protons produced by the neutron beam. (A sample of high-energy proton events was recorded for detector monitoring purposes.) The photons were detected in an array of 160 Pb-glass Cherenkov counters, arranged in stacks of 20 counters each, covering the angles $\theta_{\rm lab} = 34°$–$109°$ to the left of the beam and $79°$–$124°$ to the right. Two pairs of Pb-glass detector stacks were placed symmetrically about the beam axis to allow study of potential instrumental asymmetries. The hardware trigger for an $np \to d\gamma$ event required that the upstream (S_1) and downstream (V) vetoes did not fire, while the ΔE and E detectors, at least one Pb-glass detector, and at least three out of the four wire planes ($X1$, $Y1$, $X2$, $Y2$) fired in coincidence.

Several in-beam polarimeters allowed for continuous monitoring of the polarization of the primary proton beam, secondary neutron beam, and PPT. A polarimeter for the primary beam, based on pd elastic scattering [12], preceded the neutron production target. The neutron polarization was monitored via np elastic scattering in a polarimeter [10] downstream of the setup shown in Fig. 1. In addition, the beam *and* target polarizations were determined by observing np elastic scattering from the PPT at $\theta_{\rm cm} \simeq 70°$. For the latter polarimeter, the recoil proton was detected in the ΔE^P-E^P scintillator telescope, to the left of the beam in Fig. 1, in coincidence with an elastically scattered neutron in a sixteen-segment liquid scintillator counter, N^P, on the right. The scintillator V^P vetoed charged particles entering N^P. The spin-correlation coefficient and analyzing powers for np elastic scattering are known at the energy and angles relevant to this polarimeter [10,13].

A reliable *relative* measure of the incident neutron flux was needed to normalize the $np \to d\gamma$ and polarimeter yields for each combination of beam and target spin directions. Two separate neutron flux monitors, placed upstream and downstream of the detector setup, independently measured this flux. Each monitor consisted of two scintillators of cross sectional area larger than the beam size, with the front scintillator in each case serving as a charged-particle veto. (The neutron beam, NB, was approximately 7 cm high by 5 cm wide at the target location, matching the dimensions of the PPT.) Only the upstream monitor, S_0-S_1, is indicated in Fig. 1.

The two primary goals of the data analysis were to eliminate background events from the $np \to d\gamma$ yields by employing a number of kinematic correlations, and to identify and control the size of systematic errors. For $np \to d\gamma$ event selection, cuts were made on the following observables: (1) event origin deduced from MWPC ray tracing of the forward charged particle; (2) particle identification via ΔE, E, and time-of-flight measurements; (3) photon energy deposition in the Pb-glass detectors; (4) coplanarity of the detected deuteron and photon; (5) agreement of the observed θ_d vs θ_γ and E_d vs θ_γ correlations with two-body kinematics; and (6) d-γ time difference. Cuts (1) and (6) proved most effective in eliminating $np \to d\gamma$ events induced on hydrogen in the ΔE scintillator rather than in the PPT. The d-γ time difference was measured over a time range that allowed us to monitor (and subsequently subtract) accidental coincidences between a charged particle and a photon. The quantitative effect of the software cuts and the cleanliness of $np \to d\gamma$ selections are illustrated in Fig. 2.

Systematic errors in the results were kept small in comparison with the statistical uncertainties. This required special procedures to account for effects associated with the magnetic holding field of the PPT. This 0.059 T field was reversed every 15 min to flip the proton spin. Although all photomultiplier tubes used were magnetically shielded, the target field reversal still produced appreciable gain changes in the Pb-glass and neutron detectors. These changes were monitored via the observed shifts in the pulse height spectra of cosmic ray muons in the Pb-glass counters and of protons scattered into the neutron detectors during auxiliary measurements of pp scattering. The gain shifts were corrected in replay software, as was the small ($< 0.5°$) magnetic deflection of the deuteron trajectories as they exited the target. In addition, $\sim 30\%$ of our data were taken in a configuration where the proton target polarization and magnetic holding field were *antiparallel*, so that the sign of any instrumental asymmetry associated with the holding field would be reversed. With this precaution, we found that analysis of all the data with the software field corrections *disabled* produced negligibly different results from those obtained (and reported below) with the field corrections on.

Systematic errors that might arise in the normalization of the data (i.e., from the beam and target polarization and relative flux measurements) were also studied. The largest by far was the 10% normalization uncertainty in the experimental C_{NN} values for np elastic scattering [10,13] used in determining the product of beam and target polarizations. This uncertainty leads to a 10% systematic uncertainty in our value for C_{NN} for $np \to d\gamma$ and a 5% uncertainty in our analyzing powers, still only half as large as the typical statistical uncertainties in each case. Other systematic effects from the normalization of the data were on the (1–2)% level. With regard to instrumental asymmetries, for each of the two pairs of geometrically symmetric Pb-glass detector stacks, the results from the left and right stacks were in agreement within statistical uncertainties, and we report their average value below.

Our experimental results for the spin-dependent observables are compared with theory in Fig. 3, which also includes a sample of cross section data [3–6]. The only previous polarization measurements at this energy, those

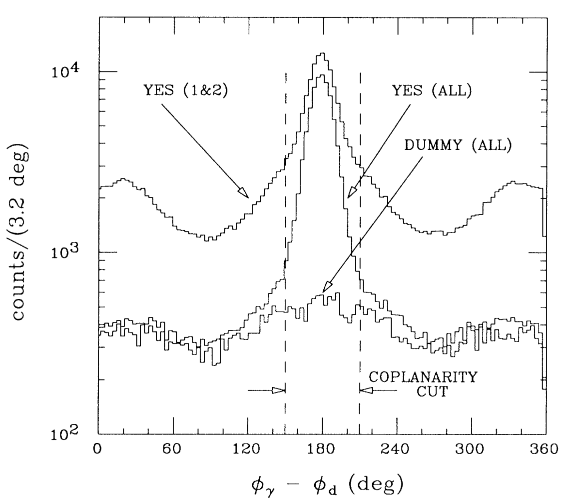

FIG. 2. Spectra of the coplanarity variable $\phi_\gamma - \phi_d$ displayed for various conditions. "YES (1&2)" represents data taken with the YES target after cuts 1 and 2 have been applied (see text), while "YES (ALL)" has all cuts (except coplanarity) applied. The difference between these two spectra results largely from the removal of accidental d-γ coincidences by the application of the additional cuts. The sinusoidal shape of the background for "YES (1&2)" reflects the detector acceptances for d and γ singles. The "DUMMY (ALL)" spectrum represents background measured with a hydrogen-free target.

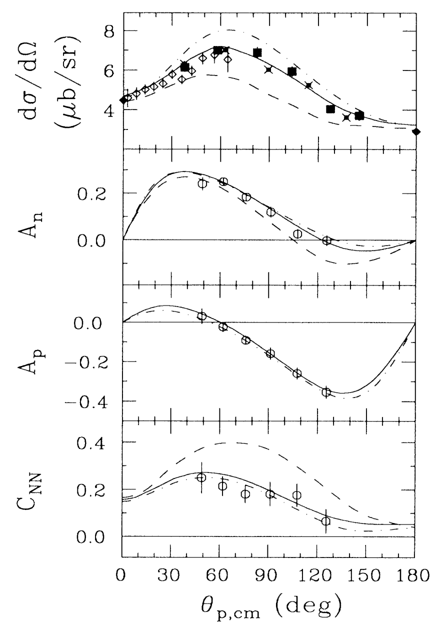

FIG. 3. Observables for $d\gamma \to np$ at $E_{cm} = 95$ MeV: Results for A_n, A_p, and C_{NN} from this work (open circles, statistical errors only), along with cross section results from Ref. [3] (filled squares), Ref. [4] (open diamonds), Ref. [5] (crossed circles), and Ref. [6] (filled diamonds). The theoretical curves are discussed in the text.

for A_n [3], are in good agreement with our results, but have uncertainties larger by a factor of ~ 3.5 and so are not shown in Fig. 3. The dashed curves in Fig. 3 represent calculations of Jaus and Woolcock [14] using the Paris NN potential in an impulse approximation, along with a relativistic correction from the spin-orbit operator; the latter correction is necessary to obtain agreement with the forward-angle cross section data [4]. The solid curves represent a calculation that includes, in addition, explicit coupling between the photon and an exchanged meson (π, ρ, or ω) or an intermediate-state $\Delta(1232)$. The data clearly favor the second calculation. The dot-dashed curves result from a similar calculation by Schmitt and Arenhövel [9], in which the Bonn coordinate space potential was used, rather than the Paris potential. We see in Fig. 3 the strong sensitivity of the spin correlation coefficient to MEC and IC effects, together with its relative insensitivity to the choice of the NN potential. The relativistic correction included in all the above calculations has a discernible effect on C_{NN}, and significantly improves the agreement of the calculations with our measurements.

The new spin observable data presented here, combined with the high quality cross section [3–6] and photon asymmetry [15,16] data collected over the past decade, place tremendous constraints on model calculations. The excellent agreement of the Jaus and Woolcock calculation [14] with the experimental results for all four observables in Fig. 3 is significant, and demonstrates great recent progress in our quantitative understanding of neutron-proton radiative capture at intermediate energies. Similar calculations also reproduce very well measurements of the photon asymmetry Σ [15,16] over a range of energies up to and including the region of the $\Delta(1232)$ resonance; the photon asymmetry displays a sensitivity to MEC and IC similar to that of C_{NN} [9,14]. These quantitative successes at moderate momentum transfers ($q \sim 1$–$2\ \mathrm{fm}^{-1}$) make the failures [8] of the meson-exchange theory at higher q all the more significant.

We would like to acknowledge the contributions of K. Komisarcik and J. Vanderwerp, who operated the liquid deuterium neutron production target and built many of the scintillation counters. We also acknowledge A.M. Nathan and M.A. Lucas for their assistance in tagged-photon tests of the Pb-glass detectors at the University of Illinois. This work was supported in part by the National Science Foundation under Grants No. PHY-9015957 (Indiana), No. PHY-8611395 (Hope College), and No. PHY-9103794 (Kentucky).

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