MEASUREMENT OF THE SPIN CORRELATION COEFFICIENT AND ANALYZING POWERS FOR THE $p'(6,d)y$ REACTION AT $T_n \approx 183$ MeV

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The goal and motivation of this experiment have been described in the previous annual report. Briefly, this experiment is a measurement of the spin correlation coefficient, $A_{yy}(\theta)$, and the neutron and proton analyzing powers ($A_{y0}(\theta)$ and $A_{0y}(\theta)$) for the $p'(6,d)y$ reaction at $T_n \approx 183$ MeV. We are primarily concerned with measuring $A_{yy}$ with sufficient precision ($\pm 0.05$) to provide a quantitative test for theories incorporating meson-exchange current and isobar current effects in reaction calculations for this two-nucleon system.

Last year, substantial progress was made, and this experiment is now near completion. In June 1991, after several development runs, our request for 119 shifts of beam time to finish data acquisition was approved. We performed the first production run (43 shifts) in August 1991, the second (38 shifts) in December 1991, and the third (38 shifts) in February 1992. Overall, all production runs were successful, despite a number of detailed technical problems that occurred during some of them. In this report, results from our initial analysis of the data are presented.

The experiment was performed in the Polarized Neutron Facility at IUCF. A 200-MeV polarized proton beam incident on an LD$_2$ target produced vertically polarized neutrons via the D$(p,\bar{n})2p$ reaction. Neutrons emitted near $10^\circ$ from the proton beam (in the plane of proton polarization) passed through a sweep magnet (to remove charged particles from the secondary beam) and then through a 2-meter long collimator. The collimated neutron beam had an average energy of 183 MeV and typical polarization of 50-60% (depending on the primary proton beam polarization); the neutron beam size at the polarized proton target (PPT) was about 4.8 by 6.8 cm, slightly smaller than the target itself (5 by 7 cm). The PPT is of the spin refrigerator type, using a Yb-doped yttrium ethyl sulfate (Y(C$_2$H$_5$SO$_4$)$_3$:9H$_2$O or “YES”) crystal. The typical target polarization was 42%. The total thickness of the target was 1 g/cm$^2$, while the hydrogen content was only 55 mg/cm$^2$. The considerable number of heavy nuclei in the target necessitated taking background data with a second target (the “dummy”) which simulated the non-hydrogenic contents of the
PPT. The background amounted to about 10% of the total $d\gamma$ coincidence yield, requiring that about 25% of our total data-acquisition time be spent on the dummy target, to optimize the statistical precision of the observables.

Figure 1 shows the detector setup. For $p'(n',d)y$ events, the outgoing deuterons were detected by a series of charged particle detectors centered along the neutron beam axis, including a $\Delta E$ scintillator (3.2-mm thick), four multi-wire proportional chambers ($X_1, Y_1, X_2, Y_2$), and an $E$ scintillator (70-mm thick). A $V$ scintillator (6.4-mm thick) was used to veto events where the charged particle did not stop in the $E$ scintillator. The coincident $\gamma$-rays were detected by an array of 160 Pb-glass Cerenkov counters (8 stacks,

Figure 1. Scale rendering of the detector setup. Each stack of Pb-glass detectors is labeled by its central laboratory polar angle. Details are discussed in the text.
each containing $4 \times 5$ counters), ranging from $34^\circ$ to $109^\circ$ on the beam left side, and $79^\circ$ to $124^\circ$ on the right. Two pairs of Pb-glass stacks were placed symmetrically about the beam to allow evaluation of instrumental asymmetries. For the purpose of detector monitoring, pre-scaled $(\bar{n},p)$ events were also recorded, by requiring all of the in-beam scintillators ($\Delta E$, E and Veto) to fire, along with at least 3 of the 4 wire chambers. Also recorded were cosmic events, which fired one of 5 plastic scintillator paddles (not shown) placed on top of Pb-glass stacks, in coincidence with one or more Pb-glass counters, to monitor and calibrate the gains of the Pb-glass counters. The target and beam polarizations were measured via n-p elastic scattering in a separate polarimeter viewing the PPT, by detecting outgoing protons with $\Delta E^P$ and $E^P$ scintillators on the left, and neutrons with an array of 16 liquid scintillator cells ($N^P$) on the right (see Fig. 1). The plastic scintillator $V^P$ in front of the liquid scintillator cells was used to veto charged ejectiles. The relative neutron beam flux was monitored independently for each beam-target spin combination by two pairs of in-beam scintillators (only the front pair, $S_0$-$S_1$, is shown in Fig. 1), by requiring the front paddle (charged particle veto) not to fire, and the back paddle to fire. Additional polarimeters not shown in Fig. 1 provided independent continuous on-line monitoring of both the primary proton and secondary neutron beam polarizations.

In analyzing the data, we define $\bar{p}(\bar{n},d)\gamma$ events via software cuts on the following information:

a) Event origin – Wire chamber information was used to ray-trace outgoing charged particles back to the target plane to eliminate events which originated outside the target area.

b) Particle identification – Deuterons were distinguished from protons by plotting time-of-flight of particles (from $\Delta E$ to E scintillator) vs. pulse height in the E scintillator, or by $\Delta E$ vs. E pulse heights.

c) Photon energy – The energy of photons from $\bar{p}(\bar{n},d)\gamma$ ranged from 70 to 120 MeV over the angle range covered. The pulse-height resolution of the Pb-glass detectors was about 30%. A software cut at 30 MeV was applied to eliminate low-energy $\gamma$'s.

d) Coplanarity – The difference in azimuthal angles of the deuteron and the photon was restricted to $180^\circ \pm 30^\circ$. This cut eliminated most of the background from quasi-free $A(\bar{n},d)\gamma$ reactions induced on contaminant nuclei in the PPT.

e) $\theta_d$ vs. $\theta_\gamma$ – The observed photon angle was used to calculate the expected deuteron angle, using two-body kinematics. The difference between this value and the measured deuteron angle was restricted to $\pm 3^\circ$.

f) $E_d$ vs. $E_\gamma$ – This correlation is also determined by two-body kinematics.

g) Timing – A cut was placed on $t_\gamma - t_{\Delta E}$ to select $\bar{p}(\bar{n},d)\gamma$ initiated on the PPT. The time resolution was sufficient ($\sim 1$ ns FWHM) to discriminate against $p(\bar{n},d)\gamma$ events initiated on the $\Delta E$ scintillator itself.

h) Accidental subtraction – Accidental coincidences between a charged particle from one beam burst and a photon from the next were recorded and then subtracted from the prompt coincidences.

As an example of the cleanliness of the event selection, Fig. 2 shows the $\phi_\gamma - \phi_d$ spectra for the the PPT with partial (a), b) and g) ) and all (except coplanarity itself) cuts, and for the DUMMY target with all cuts (normalized to the same neutron flux as
Figure 2. The $\phi_\gamma - \phi_d$ spectra for the polarized target (PPT) with partial (event origin, particle identification and timing) and all (except coplanarity itself) cuts, and for the DUMMY target with all cuts (normalized to the same neutron flux as was used the PPT). Data are from the August 1991 run only.

was used for the PPT). As we can see, after all cuts and the dummy data subtraction, there is a very clean peak centered at $180^\circ$ in the $\phi_\gamma - \phi_d$ distribution, as expected from the two-body kinematics for the p(n,d)$\gamma$ reaction.

Special care was taken to correct and cancel systematic errors associated with the magnetic holding field of the PPT. Inside the target wall (radius 15 cm) the field was approximately 580 G. Outside the target wall, the field decreased rapidly with distance, and varied from a few tenths of a Gauss to a few Gauss near the photomultiplier tubes of the various detectors. The field was reversed every 15 minutes to reverse the proton polarization of the target. Although all photomultiplier tubes in this experiment were magnetically shielded, the change in residual magnetic field caused by the target field

![Graph showing $\phi_\gamma - \phi_d$ spectra for PPT and DUMMY targets with different cuts.](image)
reversal produced gain shifts in the PMT’s attached to the Pb-glass detectors, and the neutron detectors used for the polarimeter. The cosmic ray events allowed us to track and correct for the gain shifts of Pb-glass detectors, which ranged from 5% to 20%. The gain changes in the neutron detectors were measured in a separate run, utilizing a secondary proton beam (obtained by turning off the PNF sweeping magnet). We then observed p-p elastic scattering coincidences induced on the flux monitor scintillator, with the forward protons traveling to the neutron detectors along paths that did not traverse the PPT dewar. By reversing the PPT field the usual way, we observed neutron detector gain shifts of 1-2%, which will be corrected in software. The magnetic holding field also deflected the paths of charged particles as they exited the target, but for deuterons of interest this effect is small (0.5° at maximum) and easily calculable. In addition to correcting for the effects of the target field, we took a large fraction of the data with the holding field anti-parallel to the proton target polarization, to compare with data acquired with the holding field parallel to the proton polarization. This will allow us to study and cancel any residual field-dependent systematic errors.

The preliminary results of this experiment, the neutron and proton analyzing powers $A_{y0}$, $A_{0y}$, and the spin correlation coefficient $A_{yy}$, are shown in Fig. 3 (represented by filled circles). Also shown in Fig. 3 are theoretical calculations (curves), and a sample of previous cross section data at this energy. The only previously measured spin observable at this energy is the neutron analyzing power (not shown). Our measurement of neutron analyzing power is in good agreement with that data but exceeds its statistical precision by a factor of 3.5. The dashed curves represent a calculation by Jaus and Woolcock\textsuperscript{3} using the Paris potential in impulse approximation, along with a relativistic correction to the spin-orbit operator (this correction is necessary to obtain agreement with the forward cross section data). The solid curves represent a calculation that includes, in addition, explicit coupling between the photon and an exchanged meson ($\pi$, $\rho$, or $\omega$) or an intermediate $\Delta$ (1232). The data clearly favor the second calculation. The dot-dashed curves represent a similar calculation by Schmitt and Arenhövel,\textsuperscript{4} but using the Bonn R-space potential. From Fig. 3 we see the considerable sensitivity of the spin correlation coefficient to the exchange and isobar currents, and its relative insensitivity to the choice of NN potential. The agreement of the Jaus and Woolcock calculation with the data for all four observables is excellent, signifying the advanced state of our understanding of neutron-proton radiative capture at this energy.

We are now in the final stages of data analysis. The main task is to understand all important sources of systematic errors and estimate their sizes. We would also like to optimize our replay to reduce statistical uncertainties. Finally, a calibration of the detection efficiency for $(n,d)\gamma$ events would allow us to deduce the absolute differential cross section. We expect to finish data analysis by fall of 1992.

Figure 3. Preliminary results of $A_{y0}$, $A_{0y}$, and $A_{yy}$ for radiative capture from this work (filled circles), along with cross section results from Cameron et al.,$^5$ (filled squares), De Sanctis et al.,$^8$ (crossed circles), Meyer et al.,$^6$ (open diamonds), and Hughes et al.,$^7$ (filled diamond). The theoretical curves are discussed in the text. Data from all of the production runs on the present experiment have been included here.