EVALUATION OF ABSOLUTE CROSS SECTIONS FOR THE $\vec{p}(\vec{n},d)\gamma$ REACTION AT $T_n \cong 183$ MeV

C. Bloch, S.M. Bowyer, T.W. Bowyer, W.W. Jacobs, H.O. Meyer,
S.F. Pate, E. Pierce, J. Sowinski, S.E. Vigdor, C. Whiddon,
S.W. Wissink, and G. Xu
Indiana University Cyclotron Facility, Bloomington, Indiana 47408

P. Jolivette
Hope College, Holland, Michigan 49423

M.A. Pickar
University of Kentucky, Lexington, Kentucky 40506

The data acquisition for E328 (Spin Correlation and Analyzing Power Measurements for Neutron-Proton Radiative Capture at $T_n = 183$ MeV) was completed in February 1992. Since then detailed analysis of the data has been performed, and the results for the spin observables were published.[1] Our measurements for the spin observables A_n, A_p, and C_{NN} agree well with theoretical predictions by Jaus and Woolcock[2] and by Schmitt and Arenhövel,[3] demonstrating great recent progress in the quantitative understanding of meson exchange current (MEC) and isobar current (IC) effects in neutron-proton radiative capture at intermediate energies.

Although the primary goal of this experiment was to measure the spin correlation coefficient and analyzing powers, an accurate determination of the absolute cross sections for this reaction can be achieved from the acquired data, and can provide further constraints on theoretical model calculations. The results of our current analysis for the cross sections are shown in Fig. 1, together with data from previous measurements.[4−6] In the figure both statistical and systematic errors (except an overall normalization uncertainty of 10% due to uncertainty in the elastic n-p scattering cross sections used to extract the neutron flux) are included by adding them in quadrature. The cross sections and their errors are also summarized in Table I.

We deduce the cross sections for n-p radiative capture and its inverse, photodisintegration, respectively by

$$\frac{d\sigma^c}{d\Omega} = \frac{YJ}{\Delta\Omega N_H F \eta_\gamma \eta_d \eta_s L_{d\gamma} P_\gamma T} \tag{1}$$

and

$$\frac{d\sigma^\gamma}{d\Omega} = \frac{2}{3}\frac{K_p^2}{K_\gamma^2}\frac{d\sigma^c}{d\Omega} \tag{2}$$

where Y is the p(n,d)γ yield (background- and accidental-coincidence-subtracted) for a given Pb-glass detector stack (for a detailed description of the detector setup, see Ref. 1); J is the Jacobian factor converting the lab cross section to the center-of-mass cross section; $\Delta\Omega = 0.1267$ sr is the lab solid angle of each Pb-glass stack front face with respect to the target, $N_H = 3.29 \times 10^{22}/\text{cm}^2$ is the number of free hydrogen atoms per unit area in the polarized proton target (PPT); $F = (3.66 \pm 0.37) \times 10^6$ neutrons/second is the average

d(γ,p)n
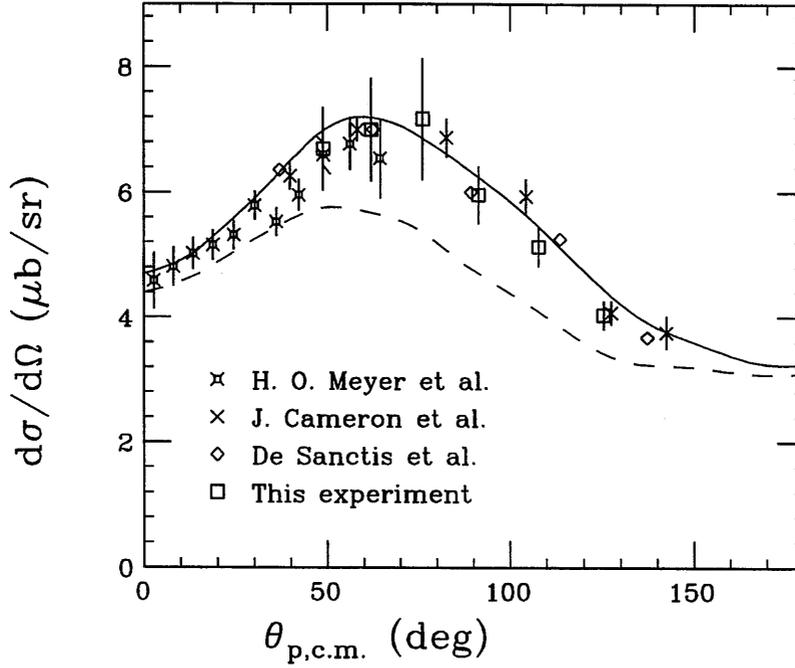
Figure 1. Extracted d(γ,p)n cross section (squares) at $E_\gamma \cong 95$ MeV. Also shown are data from previous measurements,[4-6] and calculations by Jaus and Woolcock using the Paris potential in an impulse approximation, including relativistic corrections (dashed curve), and in addition, including MEC and IC effects (solid curve).

neutron flux used; $\eta_\gamma = 0.86 \pm 0.04$ is the photon detection efficiency for a Pb-glass detector stack; $\eta_d = 0.978 \pm 0.001$ is the combined deuteron detection efficiency for the four wire chambers; $\eta_s = 0.868 \pm 0.015$ is the efficiency of software cuts used to select the p(n,d)γ events; $L_{d\gamma} = 0.9175$ is the electronic live time for the dγ event stream with the PPT; P_γ is the probability that a photon from the p(n,d)γ reaction survives attenuation along its path from the PPT to the Pb-glass detectors; $T = 3.895 \times 10^6$ s is the data acquisition time for the PPT. In equation (2), K_p and K_γ are the proton and photon c.m. momenta, respectively.

The estimation of Y, F, η_γ, η_s and P_γ involves certain non-trivial analyses and calculations, as discussed below. The p(n,d)γ yield Y was extracted with a software cut, among others,[1] on the neutron time-of-flight $TOF = T_{rf} - T_{\Delta E} + \Delta T_d$, where T_{rf} and $T_{\Delta E}$ are the time for the RF signal and ΔE scintillator, respectively, and ΔT_d is the calculated flight time of deuterons from the PPT to the ΔE scintillator, which is a function of gamma angle. The cut selects incident neutrons in the energy range 170-193 MeV (average 183 MeV). An analogous cut was used to select events from the prescaled sample of forward-going

energetic protons that we collected at the same time as the dγ events. From these proton events we determined the detected yield of n-p elastic scattering events from the PPT, in order to deduce the absolute neutron flux F by normalization to known n-p differential cross sections.[7] Most of the observed proton yield arose from reactions on contaminant nuclei in the PPT, rather than from free n-p scattering. It was thus critical to perform a proper subtraction of the background using a dummy target to isolate the free-scattering contribution. As a crosscheck on our knowledge of the relative target thicknesses of PPT vs. dummy target, we followed a similar procedure to extract the neutron flux from runs with CH_2 and C targets of more precisely known thicknesses. The two procedures agreed, giving $F = (3.66 \pm 0.37) \times 10^6$ n/s. The systematic error here is dominated by the uncertainty in absolute n-p elastic scattering cross sections extracted from the program SAID-91 (Ref. 7): $(d\sigma/d\Omega)_{np} = (31.2 \pm 3.1)$ mb/sr averaged over our acceptance.

The software cut efficiency for p(n,d)γ events can be determined by looking at the coplanarity $\phi_{open} = \phi_d - \phi_\gamma$ distributions satisfying all but one of the software cuts on other variables. The peak centered at 180° in this spectrum was used to determine the effective loss of p(n,d)γ events by comparing peak areas with and without specified cuts. We found that the deuteron particle identification cut caused the dominant loss (5.0%, probably arising from the reaction tail in the E scintillator). All other cuts combined caused a loss of 8.2%. The total software cut efficiency is then estimated to be $\eta_s = 0.868 \pm 0.015$.

The photon detection efficiency η_γ for each Pb-glass detector stack has been estimated so far by simple calculations taking account of the path length available through Pb-glass for each γ incident angle of interest. This path length determines the photon conversion probability and the probability of collecting sufficient Čerenkov light from the subsequent electromagnetic shower to surpass the hardware threshold set at $E_\gamma \sim 18$ MeV. The counters were sufficiently deep (50 cm) to give 100% detection efficiency near the middle of the stack over the entire E_γ range of interest. However, edge effects reduce the overall calculated efficiency of each stack to $\eta_\gamma = 0.86 \pm 0.04$, in good agreement with the measurements made with a tagged photon beam at the University of Illinois.[8]

Photons generated in the target had a significant probability (up to 22% for the worst case) for converting in material between the event vertex and the Pb-glass detectors. This attenuation factor has been calculated for each γ angle bin. However, some fraction of the generated e^+e^- pairs from these intermediate conversions would still be detected in the Pb-glass. The fraction that would still trigger np$\rightarrow$dγ events is complicated by bending of the e^+ and e^- in the PPT holding field. We are currently working on a detailed calculation of the attenuation losses. In the meantime, we have assumed that $1 - P_\gamma$ for each Pb-glass stack is half ($\pm$ half) of the calculated intermediate conversion probability. The uncertainty in P_γ dominates the angle-dependent systematic errors shown in Table I.

Our cross section results are in good agreement with previous measurements of p(n,d)γ (Ref. 4-6), and also in good agreement with theoretical calculations by Jaus and Woolcock.[2]

Table I

p(n,d)γ cross sections at T_n=183 MeV and their errors.

θ_γ (lab)	θ_p (c.m.)	Jacobian J	Yield Y	P_γ	$d\sigma^\gamma/d\Omega$ ($\mu b/sr$)
116.5	48.9	1.409	2445 ± 68	0.925 ± 0.075	$6.69 \pm 0.18 \pm 0.64$
101.5	62.0	1.232	5730 ± 104	0.905 ± 0.095	$7.00 \pm 0.12 \pm 0.81$
86.5	76.0	1.058	6716 ± 108	0.889 ± 0.111	$7.17 \pm 0.13 \pm 0.96$
71.5	91.2	0.900	3491 ± 78	0.948 ± 0.052	$5.96 \pm 0.14 \pm 0.44$
56.5	107.7	0.766	3630 ± 77	0.975 ± 0.025	$5.13 \pm 0.11 \pm 0.28$
41.5	125.5	0.662	3328 ± 74	0.980 ± 0.020	$4.04 \pm 0.09 \pm 0.21$

Note: The first error in $d\sigma^\gamma/d\Omega$ is statistical, the second is systematic. The 10% systematic uncertainty in neutron flux F (primarily due to the uncertainty in n-p scattering cross sections extracted from SAID-91) is not included.

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