This is the final account of a measurement of the absolute cross section for the capture process $(n,d)\gamma$ at 185 MeV (Exp. 93). This experiment addresses the well known discrepancy between theoretical work$^1$ and measurements of the photodisintegration process $d(\gamma,p)n$ at $\theta_p=0^\circ$ obtained at Mainz.$^2$ The present experiment was proposed in 1979; intermediate reports and a description of the final experimental setup have appeared in the last two IUCF annual reports (see IUCF 1982 Annual Report p. 140 for the figure showing the details of the layout).

The $^7\text{Li}(p,n)^7\text{Be}$ reaction with a 2-g/cm$^2$ thick target was used as a neutron source, while a 6.4-cm thick container filled with liquid hydrogen constituted the capture reaction target. The hydrogen target was preceded by a scintillator (S0) and a wire chamber (W1) and followed by a second wire chamber (W2) in order to tag an event where an incident neutron converted into a charged particle inside the target volume. A scintillator of 4 cm $\times$ 4 cm, segmented into four elements, immediately following the second wire chamber, served as an entrance detector (S1), and was used to provide a time mark for valid events. At a distance of 2.2 m downstream, a 5-cm thick plastic scintillator (E) measured the energy of the charged particle. Immediately in front of this detector a scintillator hodoscope, divided into 15 $\times$ 23 cells of 2 cm by 2 cm served to determine the reaction angle. Spaced approximately equally between the entrance and energy detectors were two additional scintillators ($D_1$ and $D_2$) which were used to suppress accidental triggers. The lateral dimensions of the scintillators were chosen to measure reaction products with angles inside a cone of $\sim 7^\circ$ opening half-angle with a resolution of $\sim 0.5^\circ$. The thicknesses of the detectors and of the hydrogen cell were chosen such that the angular smearing by multiple scattering was less than $0.5^\circ$ for all particles of interest.

The neutron energy at the hydrogen target was $185 \pm 5$ MeV. In the time-reversed process, $d(\gamma,p)n$, this would correspond to a photon energy of $E_\gamma = 95 \pm 2.5$ MeV. The useful neutron flux at the target was $\sim 5 \times 10^5$ s$^{-1}$.

In order to derive a reliable value for the absolute cross section, the experiment was designed in such a way as to remove uncertainties due to neutron flux, hydrogen target thickness, and detector geometry. This was accomplished by observing the protons from the elastic "charge-exchange" scattering $(n,p)n$ concurrently with the deuterons from the $(n,d)\gamma$ reaction. The final result thus obtained is directly tied to the known value for charge-exchange nucleon-nucleon scattering.

Most of the more than 70 shifts of beam time devoted to Exp. 93 over the past few years were used for the solution of experimental problems. The final data-taking run occurred in January, 1983. Since then, a considerable effort has gone into the data analysis.

The event data, recorded on magnetic tape, were subjected in the sorting process to the following conditions: (1) discrimination against the low-energy tail of the incident neutron distribution by selecting the proper time between the firing of any of the entrance detectors and a cyclotron rf timing signal;
(ii) proper timing and energy signals in the two wire chambers to discriminate against background originating in the scintillators before and after the target; (iii) particle identification by selecting the respective loci for protons and deuterons in a display of time-of-flight between $S_1$ and $E$ detectors versus energy deposited in the $E$ detector and, for deuterons, (iv) a cut in timing and energy deposited in the two intermediate scintillators $D_1$ and $D_2$ to suppress the tail from low energy protons in the neighborhood of the deuteron particle locus. Low energy protons are produced by $(p,p')$ reactions in the target window and by nucleon-nucleon bremsstrahlung. Throughout this procedure the four entrance detector segments were treated separately. The events that passed the sorting were listed according to $x$ and $y$ coordinate in the hodoscope, resulting in 8 different two-dimensional arrays (4 entrance elements, each for protons and deuterons).

From the carefully measured dimensions of the setup and the known angular distributions of the processes $^7\text{Li}(p,n)^7\text{Be}$ and $p(n,p)n$, the shape of the proton distribution in $x$ and $y$ on the hodoscope was calculated for every entrance detector. By comparing the predicted distributions with the observed ones the hodoscope element that corresponds to $\theta=0^\circ$ could be experimentally determined. The same calculation, containing all effects from the finite target geometry, yielded a set of relative weights and centroid angles for every $S_1$-cell hodoscope-cell combination. Thus every such combination constitutes a measurement of the capture cross section $\sigma_{npdp}$ at a given lab angle $\theta_{lab}$, since

$$\sigma_{npdp}(\theta_{lab}) = \sigma_{npnp}(\theta_{lab}) \frac{d_f - C_d}{P_f - C_P} ,$$

where $\sigma_{npnp}(\theta_{lab})$ is the known elastic scattering cross section at $T_n=185$ MeV, $d_f$, $P_f$, $d_p$, $P_p$ are the numbers of deuterons and protons observed, $(f)$, with the target filled with liquid $H_2$ and, $(e)$, with the evacuated target, respectively, and $C$ is the relative normalization of the two runs. The ratio $d_f/d_p$ varied between 2.5 and 4 depending on $\theta$, while the term containing $P_p$ was usually very small.

The normalizations of runs were obtained from either the integrated charge of the primary proton beam or the "neutron flux" measured with the last two scintillators in the setup. The two agreed with each other, except in cases where there was an obvious explanation for a discrepancy. The combination of the two yielded a reliable relative normalization between runs with target full or empty.

Corrections to the data take into account the measured deadtime (1-7% correction), the measured efficiency for the two wire chambers (90-98%), and a inefficiency due to an experimental problem of a hodoscope element for protons, (2%). In addition, a correction (2%) arises in the background subtraction since in runs with the full target, the energy distribution of the upstream background deuterons is modified by passage through the hydrogen.

Numerous checks on the resulting body of data have been performed. Using the sum of all valid protons and deuterons, an angle-integrated cross section was calculated for each of the 95 single runs that comprise the total experiment. No systematic drift as a function of time was found. However, the most likely candidates for statistically significant fluctuations were compared to the run dependence of all applied corrections, to time dependent changes in the sorting conditions that were required, and to the occurrence of
instrumental problems during the run. No significant correlations were found. Possible contributions from accidental coincidences were determined to be negligible. The efficiency of the wire chambers and the rate of rejection of events with an ambiguous hodoscope pattern (multiple fires) were found to be the same for protons and deuterons (they thus cancel). The data contributed from any one of the four entrance detectors were compared with each other and found to agree within statistics, as was the case for data from the different regions in the hodoscope with 2, 3 or 4 layers of scintillator being fired by an event.

The data from all runs were then combined and the final lab cross section was calculated. A change of the hodoscope cell number that corresponds to \( \theta = 0^\circ \) by one unit in any direction affected the final result only within statistics, as was the case when either half of the hodoscope was ignored in calculating the final angular distribution. The lab cross section was then converted to the center-of-mass and by detailed balance the cross section for the time-reversed process was calculated. The final result is displayed in Fig. 1 (solid dots). The error shown contains the statistical error and a 2% contribution due to an uncertainty in the background subtraction.

The most serious uncertainty in this measurement is caused by the "known" cross section for \( p(n,p)n \) to which our measurement is related. It turns out that in the kinematic region in which we are interested \( p(n,p)n, 0^\circ, 200 \text{ MeV} \) serious discrepancies exist between parametrizations of the nucleon-nucleon interaction and scattering data. In our analysis we chose an analytical expression for \( \sigma_{nnpp} (\theta) \) that has a shape determined by phase shift analyses but is normalized to fit the available data, resulting, at \( \theta = 0^\circ \), in a value of \( \sigma_{nnpp, \text{lab}} = 50.0 \text{ mb/sr} \).

The open-square point in Fig. 1 represents the photo-disintegration measurement at \( \theta_p = 0^\circ \) (Ref. 2) which originally stimulated the present experiment; the two measurements agree with each other within statistics.

In Fig. 2 we compare the present measurement (cross hatched region) with all currently available experimental information (References listed in the figure caption).

Also shown in Fig. 1 is the result of Partovi's classical calculation\(^1\) from 1964 (solid line) in comparison with two more recent investigations. The dashed line represents a calculation by Hwang\(^3\) which, to our understanding, is different from Partovi's in the explicit incorporation of gauge invariance, the choice of reference frame and the number of multipole terms. The dot-dash curve has been obtained...
by Laget\textsuperscript{4} by expanding the reaction amplitude in terms of leading diagrams. Shown here is a revised calculation, after a sign error in Ref. 4 has been eliminated\textsuperscript{5}. These calculations all start from a phenomenological parametrization of the nucleon-nucleon interaction and it would seem that one should be able to calculate nucleon-nucleon radiative capture reliably on such a basis. However, as can be seen in Fig. 1, there are serious discrepancies between all theoretical approaches and the data, indicating that our understanding of even the most fundamental system in nuclear physics is quite limited. In addition, it seems not at all clear how the various calculations differ in their physical content. The result of this experiment indicates the need for a concentrated theoretical effort to clarify the situation.

\textsuperscript{*}Present address: CERN, CH-1211 Geneva 23, Switzerland.
\textsuperscript{†}Present address: TRIUMF, Univ. of British Columbia, Vancouver, B.C. V6T 2A3 Canada.


5) J.M. Laget, private communication.