Title:

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NEUTRON-PROTON SCATTERING AT 10 MEV

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Measurement of the Angular Distribution
of Neutron-Proton Scattering at 10 MeV

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ABSTRACT

The relative angular distribution of neutrons scattered from protons was measured at an incident neutron energy of 10 MeV at the Ohio University Accelerator Laboratory. An array of 11 detector telescopes at laboratory angles of 0 to 60 degrees was used to detect recoil protons from neutron interactions with a CH₂ target. Data for 7 of these telescopes were obtained with one set of electronics and are presented here. These data, from 108 to 180 degrees for the center-of-mass scattering angles, have a small slope which agrees better with angular distributions predicted by the Arndt phase shifts than with the ENDF/B-VI angular distribution.

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1. Introduction

Despite the basic importance of neutron-proton elastic scattering, the angular distribution for elastic scattering below $E_n = 14$ MeV is still open to discussion and disagreement. For many purposes, the angular distribution is considered to be isotropic in the center-of-mass system, but in fact it is not. Hopkins and Breit¹ were prompted to write, "In the past, the assumption was made that below 10 MeV the n-p differential cross section was isotropic while above 10 MeV it was symmetric about 90° c.m. In fact, both of these assumptions are wrong." Recent evaluations, such as ENDF/B-VI,² theoretical models,^{3,4} and phase-shift solutions⁵ confirm that the differential cross section is anisotropic, but the amount of the anisotropy differs in these formulations. The situation at $E_n=10$ MeV is given in Figure 1, where we caution the reader to note the strongly suppressed zero on the ordinate. Even though all of these newer works agree that the distribution is anisotropic, they disagree on its magnitude by several percent. Although there is a large number of measurements at 14 MeV [e.g. Ref. 6], up to now, there have not been any measurements over a wide range of scattering angles at 10 MeV.

In addition to its importance in understanding the fundamental nucleon-nucleon interaction, data on the angular distribution of n-p elastic scattering is also important as a standard for determining neutron fluence through the use of proton-recoil counters. Proton recoils from neutrons incident on a material containing hydrogen are observed at some angle relative to the incident neutron beam, and the differential cross section for n-p scattering is necessary to relate the number of detected protons to the incident neutron fluence.

In this work, the relative angular distribution of n-p scattering is measured at $E_n = 10$ MeV. The differential cross section can be obtained from these relative values and from the angle-integrated cross section, which is known with great accuracy (0.2% in the ENDF/B-VI evaluation) from the well-measured total cross section less a very small correction for the radiative capture process ($n+p \rightarrow d + \gamma$).

2. Experiment

This experiment consisted of a source of quasi-monoenergetic neutrons, an hydrogenous target, an array of detectors for the recoil protons, and a monitor detector. Because deviations from anisotropy are small and high precision is desired in the data, the experiment will be described here in some detail.

Figure 2 presents the general layout of the experiment. Neutrons of nominally 10 MeV were produced with the Ohio University Accelerator Laboratory's T-11 tandem Van de Graaff accelerator. This facility allows for intense beam currents, short beam pulses, and a large and well-shielded target room. The neutron production reaction was $^2\text{H}(d,n)^3\text{He}$ at 0-degree neutron production angle. A beam of 7.27 MeV deuterons was chopped and bunched and directed to a 5.59 cm long gas cell containing deuterium at a pressure of nominally 244 kPa (35.4 psi). A tungsten foil (4.55 μm thick) separated the deuterium gas from the accelerator vacuum. The beam was stopped in a gold beam stop. Beam currents up to 5 μA were used, and the cell was cooled from the outside both by an air jet directed at the foil region of the cell and by a water channel on the circumference of the gold beam stop. The tungsten foil remained intact for over 2 weeks of beam required for the experiment.

Neutrons produced near 0-degrees were collimated by tungsten and copper collimators, which served also as shielding for all but one of the detector telescopes. The design philosophy of the collimation and shielding was to form a collimated beam of diameter greater than that of the CH₂ foil (10 mm) such that the neutron flux would be approximately uniform over the area of the foil and such that the maximum neutron flux would be incident on the foil. The former requirement led to the design of an approximately double-tapered collimator with the waist of the collimation close to the half-way point between the gas cell (source) and the CH₂ foil (sample); the collimation near the sample was intended to clean up scattered neutrons and to put a sharper edge on the neutron radial profile well outside the diameter of the sample. The latter requirement necessitated a short source-sample separation. At the same time, maximum shielding of the detectors was crucial inasmuch as (n,p) and (n, α) reactions in one of the silicon detectors could produce charged particles which would be detected by the other member of the telescope, an event which would be confused with the desired coincident DE-E events from recoil protons from the sample. Data presented below will show that even with the shielding used, such events were identified. To maximize the shielding, tungsten was used as much as possible within budgetary constraints. Neutrons below 1 MeV were not believed to be a problem inasmuch as their interactions in silicon, copper, and tantalum do not produce charged particles with any significant probability. Neutron transport calculations were made to assess the efficacy of the shielding and they showed that single scatterings of source neutrons could be important. Hence shielding was introduced to reduce the flux of these neutrons (see, for example, the wedge-shaped shields in Fig. 2).

Components located in the direct neutron beam (or where there could be significant numbers of scattered neutrons) were designed to reduce the number of charged particles produced. Tantalum was the material of choice as a compromise of acceptable nuclear properties, cost and ease of fabrication. A 0.25 mm piece of tantalum covered the collimator to stop charged particles produced in the aluminum entrance window and in the throat of the copper collimator inside the chamber. The CH₂ foil was mounted on tantalum of the same thickness. An additional charged-particle baffle was provided by yet another piece of tantalum immediately downstream of the CH₂ foil.

The CH₂ foil was commercial polypropylene. Two thicknesses were used: a single layer of 1.55 mg cm⁻² and a thick target consisting of 5 layers, which was useful for enhancing the signal-to-background at the forward recoil angles. The thickness and uniformity of the single layer were measured by measuring with a silicon surface-barrier detector the spectrum of alpha particles passing normally through the foil. Two alpha sources were used, a ²⁴¹Am source and the high quality ²³⁹Pu source mentioned below. The uniformity of the single layer was better than 10%. Another factor of importance was the flatness of the CH₂ foil for two reasons. First, at the angles of 48 and particularly 60 degrees, the maximum energy loss of the recoil protons was significant and a wavy foil would be equivalent to a foil of non-uniform thickness. Second, the foil was mounted on the upstream side of a tantalum holder with a 10 mm diameter hole in it, and at the larger angles (60-degrees in this case) the holder could have obscured part of the foil if it were not flat on the tantalum.

Detector telescopes consisted of Delta-E and E silicon surface barrier detectors with a tantalum collimator of 12 mm diameter in between the two. The detectors were nominally 150 mm² in area. Their thicknesses, given in Table 1, were chosen in

general to minimize their mass (and therefore the number of background counts due to neutron reactions with the silicon), although some compromises needed to be made so that existing detectors could be used. There were 11 of these telescopes as shown in Figure 2, and they were positioned on a machined semicircular aluminum ring at symmetric angles to enable the identification and quantification of any left-right asymmetry in the neutron beam or the CH₂ target. All of the detectors were tested prior to the experiment with a range of biases to determine at what low bias their charge collection was incomplete. In the experiment, the biases were kept well above these minimum values.

The electronics, illustrated schematically in Figure 3, used standard preamplifiers and NIM modules. Signals from the detectors at laboratory angles of 0, 12, 24, and 36 degrees were multiplexed into a common amplifier and ADC system. Those at 48 and 60 degrees were multiplexed into another system, and because the results suggest that there might have been a slightly different efficiency (or dead time) in these two channels, we report only the more extensive data from the first.

The relative solid angles for detecting particles from the CH₂ target were determined by a precision ²³⁹Pu alpha-particle source.⁸ This source has a ²³⁹Pu purity of 99.9766%, and is uniform to $\pm 0.5\%$ over a diameter of 12.59 mm. It was placed in the same position as the CH₂ foil, behind the 10 mm diameter Ta collimator. The Delta-E detectors were removed for this determination of relative solid angles. The spread in solid angles was less than 7% and 6 of the telescopes were within $\pm 1\%$ of each other.

3. Data Processing and Analysis

Event data for each of the 11 telescopes were obtained using a series of ADC's interfaced to a personal computer. The entire data acquisition system, including software, was designed by D.E. Carter. A software interrupt, responsible for processing and storing of the raw ADC data, was compiled with the main acquisition software. Pulse height (E) and time-of-flight (TOF) signals, representing the time difference between a beam pickoff and an E- ΔE coincidence, were recorded as event data. A router signal associated with each event was used for telescope identification. After processing by the interrupt, events were added to a 32K event buffer and later written to disk.

In order to determine relative n-p cross sections, event data were first sorted according to detector. Data reduction was accomplished using the PAW (Physics Analysis Workstation) software developed at CERN. With the aid of PAW, raw two-dimensional E vs. ΔE spectra were formed for each telescope. (See Fig. 4) A polygonal gate was then drawn around the region of the spectrum containing the elastically scattered protons. In most cases, the boundaries of this region were fairly unambiguous. However, precise gating proved more challenging at the larger angles due to kinematic broadening. An additional cut on time-of-flight was attempted but it was found that elastic proton counts were contained even in the tails of the TOF peak. Thus the final results contain no secondary gating. An identical procedure was used for sorting and replaying the background event data.

One-dimensional spectra for foreground and background were generated by summing the bins contained in the two-dimensional E- ΔE gate. Typical foreground and background spectra for a detector at 36 degrees are shown in Fig. 5. The counts with no CH₂ are

typical of the low backgrounds observed in most of the detectors. An indication of sample-out to sample-in counts for the region of summed counts is given in Table 2, where we see that, for all detectors from 0 to 36 degrees, the signal exceeded the background by factors of 10 to 40. Although the 0-degree detector was subject to high backgrounds from (n,z) reactions on Si, these events could be isolated from the elastic protons due to their negative Q-values. The background spectra were then normalized and subtracted from the foreground. Normalization factors were determined from the ratio of foreground and background neutron monitor counts. Relative solid angles for each telescope, determined using the ^{239}Pu alpha source, were then used to normalize the final background subtracted spectra.

Because of the importance of knowing no recoil protons were lost, that is that none fell outside the region of summation, different size regions were summed. The net counts varied little with reasonable choices of summation regions, and an estimated uncertainty for the summation window chosen was included in the overall uncertainties.

The possibility of losing counts through nuclear interactions in the silicon detectors (either Delta-E or E) or through multiple scattering was investigated. Using known reaction cross sections,⁹ the loss due to nuclear reactions was found to be less than 0.1%. Extrapolation of the values of Ref. 10 give similar results. Multiple scattering was investigated with the TRIM code of Ziegler,¹¹ and losses of less than 0.1% were predicted. Thus at 10 MeV incident neutron energy, we believe that any corrections to or data due to these two loss mechanisms are negligible.

The present data set consists of a total of 8 runs with the CH2 sample in and 4 runs with a blank. The relative yields of proton recoils (target in minus target out, suitably normalized) were obtained then for these 8 data sets. Because the conditions of the monitor were not identical for the 8 runs, the relative yields needed to be normalized to each other. This was done by requiring the same, weighted sum of the detector telescopes from 0 through 48 degrees. The data at 60-degrees comprised only the thin target measurements and were therefore not used in this normalization.

Finally, the eight runs were combined by weighted average of the results. Normalization of the runs to the angle-integrated cross section was accomplished as described below.

IV. Results

Results were obtained for eight runs as shown in Figure 6. The data have been displaced for clarity and they have been normalized to a 166-degree average value of 78 mb/sr. We note the excellent consistency of the results at a given angle. Also these results are consistent with a preliminary experiment performed four months previous to the production experiment.

Results are combined in Figure 7, where we continue to keep separate the right and left detectors at the same angle. The points here are displaced with the right detector being displaced to the left and the left detector to the right. Again we see excellent agreement between right and left detectors at a given angle.

The angular range of these data is probably not large enough for a useful Legendre polynomial fit to normalize to the angle-integrated cross section. We have fit the

data with polynomials of order 1 and 2, and, clearly from Figure 7, a first order Legendre polynomial would be sufficient. More data at smaller center-of-mass angles will be required for a good normalization of the fit.

We conclude from the data in Figure 7 that the shape of the angular distribution we measure is more consistent with the Arndt phase-shift prediction than with that of ENDF/B-VI.

Our future plans include remeasurement of the relative angular distribution of n-p scattering with electronics that treat each angle equally. We believe then that reliable data can be obtained for laboratory angles of 48 and 60-degrees. Data at other incident neutron energies would also be of interest, and in particular, we would like to study the scattering at 14-MeV with the same detectors and electronics to compare results with those obtained in other laboratories (e.g. Ref. 6).

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Table 1

Detector thicknesses in microns (those with thicknesses of 300 microns or greater are given as nominal thicknesses as specified by the manufacturer)

Angle	Delta E	E
0	265	500
12L	300	1000
12R	300	1000
24L	146	1000
24R	157	1000
36L	171	500
36R	162	500
48L	78	1000
48R	75	1000
60L	15	91
60R	15	92

Table 2

Typical ratios of counts in the proton-recoil area with target out to those with target in, suitably normalized, for the 1-layer CH₂ sample. For the 5-layer sample, the ratios were lower by about a factor of 5.

Angle	CH ₂ out/CH ₂ in
0	0.095
12L	0.026
12R	0.028
24L	0.030
24R	0.039
36L	0.092
36R	0.074

Figure captions:

Figure 1. Angular distribution of the cross section for neutron-proton scattering at $E_n=10$ MeV according to the ENDF/B-VI evaluation,² the earlier work of Hopkins and Breit,¹ and the recent phase-shift solution of Arndt.³

Figure 2. Experimental arrangement showing the neutron source, neutron collimation, evacuated scattering chamber, CH₂ sample location, and the array of 11 DE-E counter telescopes.

Figure 3. Schematic diagram of the electronics. Note the multiplexing of signals so that all Delta-E signals go to one ADC and all E-signals to another.

Figure 4. Two-dimensional display of pulse-height spectra for Delta-E and E detectors for the telescope at 24-degrees. The proton recoils fall in a group around which a region of interest is drawn. Counts are summed in this region. (a) CH₂ as sample; (b) Blank.

Figure 5. Projection of the two-dimensional spectrum of Figure 3 onto the E-pulse-height axis. This spectrum is compared with the normalized sample-out spectrum and shows that the background level was very low.

Figure 6. Data for the 8 runs normalized to each other and to an average cross section of 78 mb/sr at 166 degrees. The data at each angle have been displaced for clarity.

Figure 7. Combined data on n-p scattering at the 7 angles investigated. The consistency of results for detectors on the right and left side of the beam indicates that there was very little left-right asymmetry in the beam and the sample.

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NP Angular Distributions

Figure 1

PLAN VIEW : N-P SCATTERING EXPERIMENT

Figure 2

Telescopes 1-7

E delta-E timing (control room)

Figure 3

Figure 4a

Figure 4b

Normalized background on foreground for detector 6 (Run 522)

Figure 5

NP Angular Distribution

Figure 6

NP Angular Distribution

Figure 7