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SMALL-ANGLE NEUTRON-PROTON SCATTERING AT 90 AND 290 MEV

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(Thesis)

September 14, 1954

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ABSTRACT

The relative differential neutron-proton scattering cross section has been measured in the range of center-of-mass angles from 5.1° to 36.0° for approximately 90-Mev neutrons and from 10.7° to 37.8° for approximately 290-Mev neutrons. The scattered neutrons were detected at small angles to the beam. Absolute values of the cross section have been obtained by normalization to prior results. The data indicate an angular distribution for 90-Mev neutrons that is symmetric about 90° in the center-of-mass system but an asymmetric distribution for 290-Mev neutrons, for which $d\sigma_{10^{\circ}}/d\sigma_{170^{\circ}}$ equals approximately 0.7.

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I INTRODUCTION

The determination of the nature of the nucleon-nucleon interaction is a basic problem of nuclear physics. One of the more productive sources of information has been the scattering of nucleons by nucleons. Low-energy investigations alone have led to two significant results: the spin dependence of nuclear forces[1] and the initial basis for the hypothesis of the charge independence of nuclear forces[2]. The low-energy data, however, can only determine two parameters of the interaction[3], so that any reasonable potential can be made to give the observed cross sections by a suitable choice of its range and depth. In order to determine the more detailed nature of the interaction, it is necessary to investigate the scattering at higher energies, where the de Broglie wave length in the center of mass of the two-nucleon system is of the order of or less than the range of the nuclear forces. This requires that the energy be greater than about 20 Mev.

A large number of investigations have been made of the n-p differential-scattering cross section in the high-energy region. In the vicinity of 90 Mev the techniques of electronic counting have been employed by Hadley, Kelly, Leith, Segrè, Wiegand, and York[4]; R. H. Fox[5]; and Selove, Strauch, and Titus[6]. Measurements have also been made by R. Wallace[7], utilizing nuclear emulsions, and by Brueckner, Hartsough, Hayward, and Powell[8], utilizing a cloud chamber. In the vicinity of 300 Mev De Pangher[9] has made a cloud-chamber measurement, and Kelly, Leith, Segrè, and Wiegand[10] have

employed counters. Other counter measurements have been made at 156 Mev by Randle, Taylor, and Wood[11]; at 180 and 220 Mev by Guernsey, Mott, and Nelson[12]; and at 400 Mev by Hartzler and Siegel[13]. All these methods have had the common feature of detection of the recoil proton from the n-p collision and determination of the angular distribution of scattered neutrons from the well-known kinematic relations[4]. As a consequence of the limitation imposed by the short range of the recoil proton for neutron angles near 0°, only the cloud-chamber measurement at 300 Mev was extended to angles of less than about 40° in the center-of-mass coordinate system.

At both 90 and 290 Mev, previous results indicated a large peak in the center-of-mass angular distribution of scattered neutrons at 180°. At 90 Mev the available data were interpreted as suggesting the possibility of a similar rise near 0°[14], whereas the 290-Mev results showed no peaking at small angles but indicated an approximately constant cross section from 15° to 45°[9]. The significance of the marked anisotropy of the differential cross sections in terms of the character of the n-p interaction can be shown in a qualitative manner through the use of the Born approximation applied to a central force[15]. The differential cross section is given in this approximation by

$$\frac{d\sigma}{d\Omega} = \frac{M^2}{\hbar^4}\left|\int_0^\infty \frac{\sin(Kr)}{Kr}\, V(r)\, r^2\, dr\right|^2,$$

where $K = \left|\vec{k}_{final} - \vec{k}_{initial}\right| = 2k \sin\left(\frac{\theta}{2}\right)$, M is nucleon mass, $k = p/\hbar$ is the relative propagation vector, and V(r) is the neutron-proton potential function for an ordinary force. Ordinary forces are forces that result in no interchange of either space or spin coordinates of the two interacting particles. The factor sin (Kr) in the integrand is an oscillating function of r. Therefore if many oscillations occur within the range of r for which

$V(r)$ is appreciably different from zero--i.e., within the range of the nuclear potential--the value of the integral is negligible. This condition exists for high energies where the de Broglie wave length, $\lambda = 1/k$, is small compared with the range of the nuclear force, and for large values of the scattering angle θ. As a result, the value of the integral is negligible except for small values of θ, and therefore the differential cross section for ordinary forces has a strong maximum at 0°. In the center-of-mass system, if a neutron is deflected through an angle θ in a collision, the proton recoils in the opposite direction at the angle $\pi - \theta$. If we consider the same collision for a pure exchange potential $P_M V(r)$ rather than for an ordinary potential $V(r)$, the emergent particles will have changed their identity, since for two-particle systems the effect of the space-exchange operator P_M is equivalent to reversing the sign of the relative coordinate. The neutron will consequently emerge at the angle $\pi - \theta$ and the proton at the angle θ. Therefore, since ordinary forces lead to a distribution peaked toward 0°, space-exchange forces lead to a distribution peaked toward 180°. It is then of interest to determine the behavior of the differential cross section over the entire range of scattering angles. This requires the extension of the range of measurement into the region where the major contribution to the scattering is from a force of ordinary nature.

The objective of this experiment was to measure the differential cross section in the previously uninvestigated region of small angles at 90 Mev, and to re-examine by an independent method this region at 290 Mev, which had been included in the investigation by DePangher. The angular distribution for n-p scattering was obtained by detecting the neutrons at small angles to the beam rather than by counting the recoil protons. This

detection was accomplished by inserting a polyethylene converter in front of a scintillation telescope, which was placed at the angle under consideration, so that the scattered neutrons were detected by counting the high-energy protons projected along the axis of the telescope from n-p scattering or neutron-induced nuclear reactions in this converter. The energy distributions of the neutron beams were broad, and the detector was rendered insensitive to the low-energy components by the introduction of an absorber between the counters of the coincidence telescope. Because the energy of the proton that was counted was not uniquely related to the energy of the scattered neutron, the reliability of this method was limited to small angles, where the energy of the scattered neutron is a slowly varying function of the scattering angle.

Since the initial report on the work[16], a cloud chamber study at 90 Mev has been completed by Chih,[17] and Hartzler et al.[18] have obtained small-angle cross sections for 400-Mev neutrons with a similar counter method.

II EXPERIMENTAL APPARATUS

General

The general layout of the apparatus is shown schematically in Fig. 1. The neutron beams employed were produced by interactions of the circulating beam of the 184-inch cyclotron with a target located at a radius corresponding to maximum particle energy. The beam was highly collimated and scattered from a target of liquid hydrogen. Scattered neutrons were counted at small angles to the beam by a detector mounted on a movable azimuth arm pivoted under the center of the target. Signals from the elements of the detector were transmitted over approximately 80 feet of coaxial cable to the counting area, where the major portion of the electronic equipment was located.

Neutron Beam

The 90-Mev beam was obtained by stripping 190-Mev deuterons on a 0.5-inch beryllium target. The energy distribution of the resultant neutrons has a peak at approximately 90 Mev and a width at half intensity of about 25 Mev,[4] as shown in Fig. 2. The 290-Mev beam was produced by forward-direction charge-exchange scattering of 345-Mev protons on a 2-inch beryllium target. The energy distribution of this beam has a peak at approximately 290 Mev and a width at half intensity of 60 Mev,[19] as is shown in Fig. 3.

The beam was collimated by a brass collimator 75 inches long, which was inserted in a port in the cyclotron shielding. The collimator was tapered so that the cross section subtended a constant solid angle at the beam source. The axis of the collimator was carefully aligned with the beam axis as determined by survey and the orientation of the completed

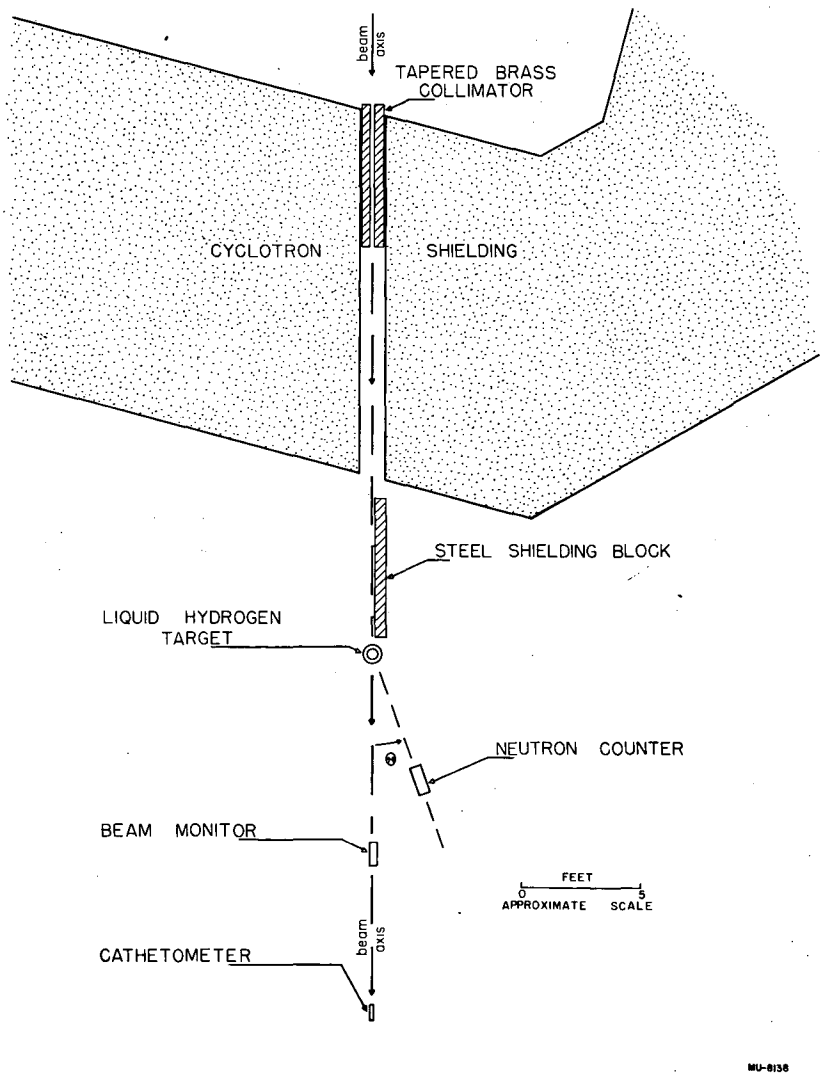

Fig. 1. Schematic diagram of experimental arrangement.

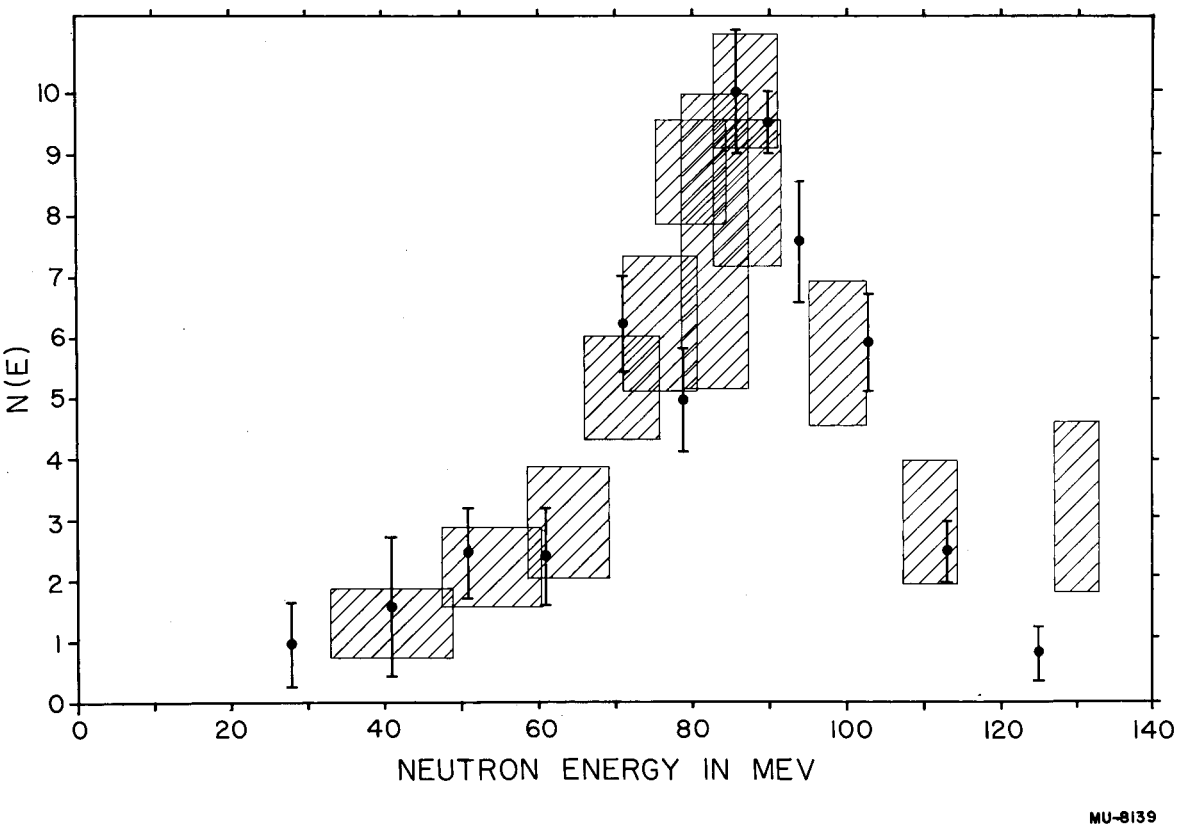

Fig. 2. Energy distribution of the primary neutrons in the beam obtained by stripping of 190-Mev deuterons on 0.5-inch-thick beryllium. The vertical bars and shaded rectangles indicate the data obtained by the two methods of Hadley et al[4].

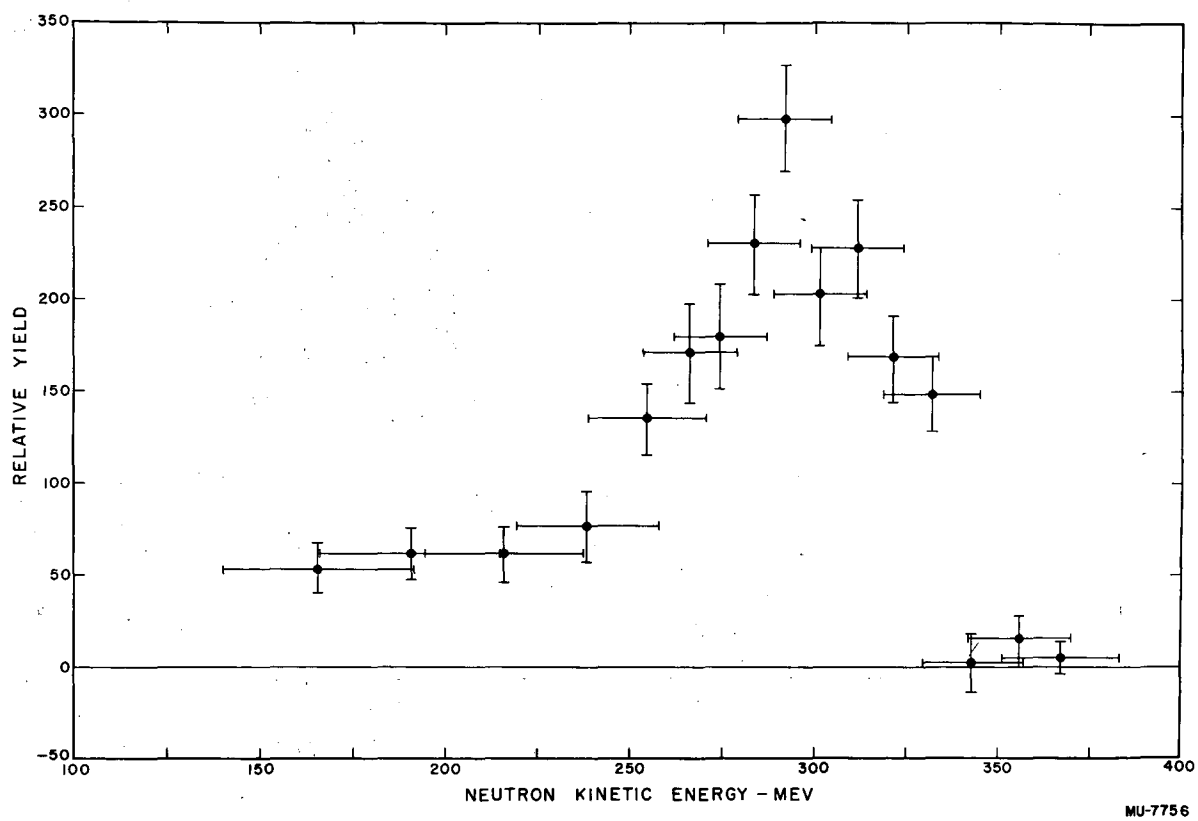

Fig. 3. Energy distribution of the primary neutrons in the beam obtained by charge-exchange scattering of 345-Mev protons on 2.0-inch-thick beryllium obtained with a 35-channel magnetic spectrometer by Cladis, Hess and Ball[19].

collimator was fixed. At the position of the scattering target the beam was 3.4 inches high by 0.9 inch wide.

A steel shielding block 6 ft long by 6 in. high by 3 in. wide was placed close to the beam on the same side as the counters to reduce background. This block was aligned by screw-motion supports so that its face was 0.1 inch from the edge of the beam as defined by the extension of the collimator geometry. The face of the block adjacent to the beam was machined plane, and had a step 0.1 inch deep and 1 foot long at the end nearest the scattering target, to reduce the possibility of its consituting a source of scattered particles that could reach the counters.

A helium-filled bag of 0.004-inch vinyl plastic occupied the region traversed by the beam from the hydrogen target to a point in the rear of the neutron counter, in order to reduce the background of particles scattered by air.

The beam was monitored by a bismuth fission counter placed in the beam to the rear of the scattered-neutron counter.

Targets

For the measurements at 90 Mev, the target consisted of 1.0 g/cm^2 of liquid hydrogen, contained in a cylindrical vessel of 0.004-inch stainless steel with vertical axis. The target assembly had previously been employed in another experiment[20], and was modified for this experiment by the alteration of the vacuum-jacket windows to accommodate the rectangular-cross-section neutron beam. An identical empty target assembly was employed to determine the contribution of neutron counts from the hydrogen-containing vessel and the vacuum-jacket windows, which consisted of 0.17 g/cm^2 of steel and 0.07 g/cm^2 of dural, respectively. The interchange was accomplished by a lateral translation of the targets by a mechanism that could be remotely controlled from the counting area.

For the measurements at 290 Mev, the target consisted of 2.8 g/cm^2 of liquid hydrogen contained in a rectangular double-walled box constructed of polystyrene foam. The beam traversed a total of 0.6 g/cm^2 of wall thickness, which was approximately constant over a height equal to twice the depth of the liquid hydrogen. The contribution of counts from neutrons scattered by the end walls was then determined by lowering the target assembly to a point where the neutron beam was above the surface of the hydrogen. The raising and lowering of the target was accomplished by a motor-driven elevator that could be remotely controlled from the counting area.

Neutron Counter

A schematic diagram of the neutron counter is shown in Fig. 4, and the specifications of the components employed at the two neutron energies are listed in Tables I and II. A photograph of the counter is shown in Fig. 5.

The neutrons actually counted were those that were "converted" in the polyethylene converter or in the portions of Counters 1 and 2 adjacent to the converter. The term "converted neutron" refers to a neutron that yields a high-energy proton in the forward direction by n-p scattering or nuclear interaction. These recoil protons were counted in coincidence in Counters 2 and 3. In order to reject charged particles originating in other processes, counts coincident in Counters 1, 2, and 3 were determined and subtracted from the 2-3 coincidences. The neutron-counting efficiencies obtained were of the order of 1/2%.

Absorber 1 consisted of a thickness of copper sufficient to prevent protons from reaching the scintillation counters directly. Scintillation Counter 1 consisted of a thin plate of plastic scintillant mounted in a reflecting aluminum box with 0.001-in. aluminum foil windows and viewed by two 1P21 photomultiplier tubes at opposite ends. The dimensions of the

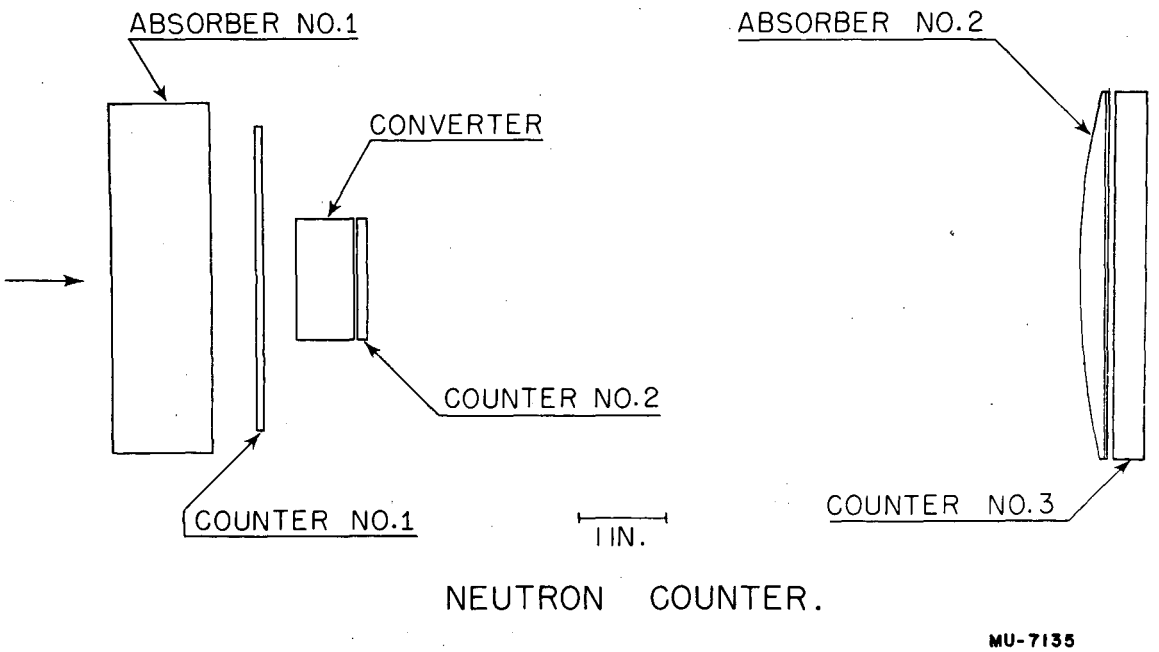

Fig. 4. Arrangement of components of neutron counter.

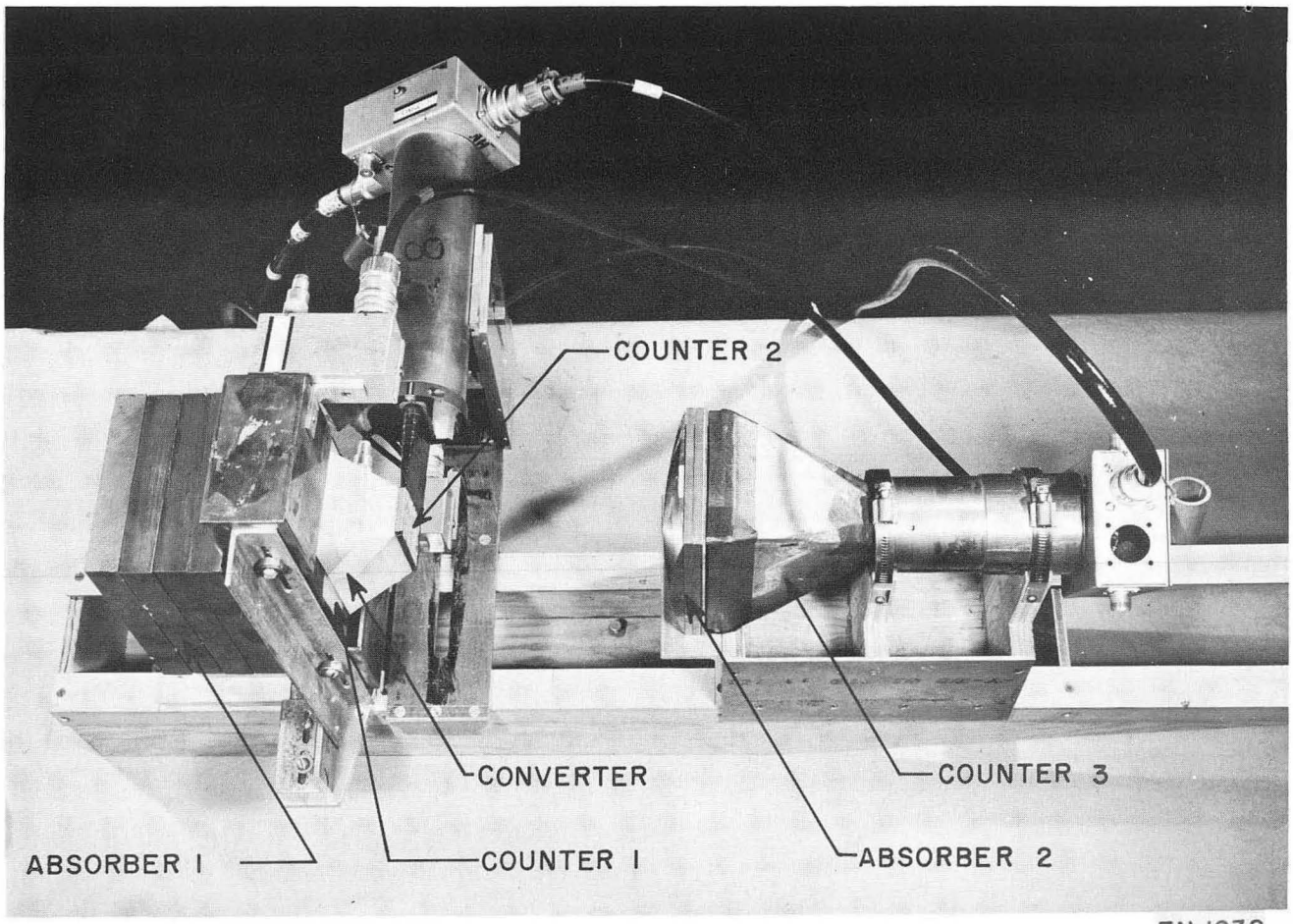

Fig. 5. Photograph of neutron counter. Converter and absorbers shown are those employed for the 290-Mev measurement.

Table I

Dimensions of Active Volumes of Scintillation Counters

Counter	Neutron Energy (Mev)	Dimensions (in.) Height	Width	Thickness
1	90	4.0	3.5	0.080
	290	5.6	4.1	0.500
2	90	2.2	1.4	0.118
	290	2.2	1.4	0.118
3	90	6.6	4.2	0.375
	290	6.6	4.2	0.750

Table II

Absorber Specifications

Absorber	Neutron Energy (Mev)	Thickness (g/cm^2)	Substance
1	90	25	Cu
	290	103	Cu
2 (shaped portion)	90	1.8 (max.)	Al
	290	15.7 (max.)	Cu
2 (uniform portion)	90	1.8 (max.) 1.0 (min.)	Cu
	290	13.8 (max.) 6.5 (min.)	Cu

scintillant were such that no undeflected particle could traverse Counters 2 and 3 without having traversed Counter 1. The converter was polyethylene, and at 90 Mev was 1.74 g/cm^2 in thickness and had the same cross section perpendicular to the path of the scattered neutrons as the active volume of Counter 2. The distance from the center of the target to the center of the converter was 70 in. for laboratory angles of 5.0° and 2.5° and 40 in. for angles of 5.0° and larger. At 290 Mev the converter was 6.53 g/cm^2 in thickness and had the form of a rectangular-base truncated pyramid, as shown in Fig. 5, to assist in increasing the counting rate. The distance from the center of the target to the center of the converter was 58 in. for all angles. Scintillation Counter 2 was a thin liquid counter optically coupled to a 5819 photomultiplier by a lucite light pipe extending from the edge of the active volume. Both counters were made as thin as possible consistent with the requirements of sufficient pulse amplitude and uniformity over the extent of their active volumes, in order that the greatest number of neutron counts could be related to neutrons converted in the converter. The ratio between neutron counts obtained with the converter in and counts with the converter out was approximately 4.5. Absorber 2 determined the low-energy cutoff, or the minimum energy that a neutron in the beam could have and still be counted after scattering. As the energy of the scattered neutron is a function of the scattering angle according to the relation,

$$E'(E,\Theta) = E \Big/ 1 + \left(1+\frac{E}{2Mc^2}\right) \tan^2 \Theta ,$$

where M is mass of neutron, the maximum thickness of this absorber was varied with angle so as to correspond to the range of a proton with energy $E'(E, \Theta)$. The absorber consisted of a shaped portion, employed at all angles,

and a uniform-thickness portion, which could be varied with angle. The shaped portion was thickest in the center and was shaped so that, to good approximation, the "minimum energy to count" would be independent of the angle to the axis of the telescope with which the recoil proton emerged from the converter. In determining the shape of the absorber, it was assumed that most of the recoil protons were from n-p processes in the converter. Consideration was given to the dependence on angle of both the recoil proton energy and the average thickness of converter and counter material traversed by the proton. Counter 3 consisted of a plate of plastic scintillant mounted in a reflector lined with aluminum foil and viewed by a 5819 photomultiplier. The approximation that the minimum-energy-to-count be independent of the angle with which the recoil proton emerged from the converter required that the distance from the converter to Counter 3 be large compared with the transverse dimensions of the converter. In order to satisfy this requirement and maintain the maximum counting rate, the cross section of Counter 3 was made as large as possible within the limitations imposed by the estimated single-count rate and its effect on the accidental 2-3 coincidence rate.

Electronic Apparatus

A block diagram of electronics is shown in Fig. 6, from which power supplies have been omitted for simplicity. Signals, taken directly from the last dynode of each photomultiplier, were first amplified by two Hewlett-Packard 460-A distributed amplifiers in the immediate vicinity of the counters before transmission over coaxial transmission lines to the counting area. This initial amplification was to reduce the effect of pickup. In the counting area the signals were further amplified by one 460-A amplifier in each channel and applied to the inputs of two double-coincidence circuits

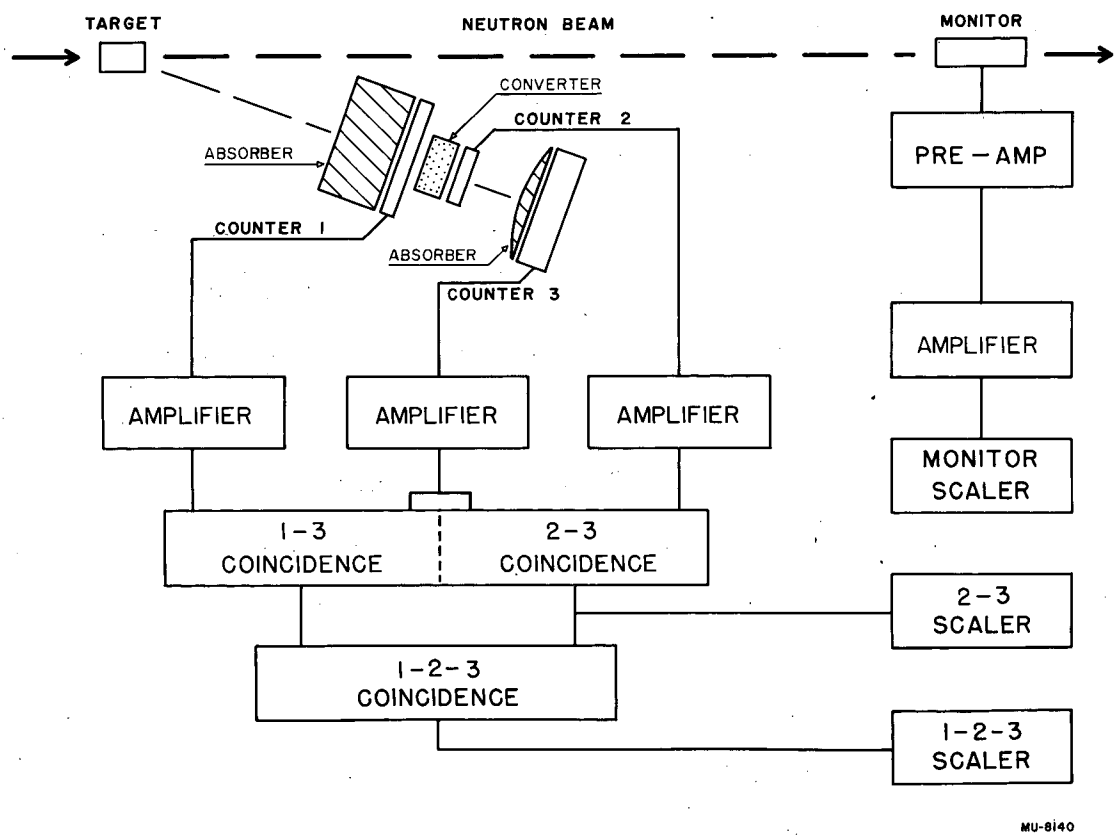

Fig. 6. Block diagram of electronics. Power supplies are not shown.

of the Garwin type[21], having a resolving time of the order of 4×10^{-8} sec with the input pulses employed. The 1-3 coincidence and 2-3 coincidence output signals were approximately 1 μ sec in width and 10 volts amplitude, and were fed to a double-coincidence circuit to provide 1-2-3 coincidence signals. This circuit was of conventional type with a resolving time of the order of 2 μ sec. The 2-3 and 1-2-3 coincidence signals were each fed directly to scalers.

III EXPERIMENTAL PROCEDURE

Preparatory Procedure

The preparation for a typical run consisted of the following steps, arranged in chronological order.

The edge of the internal neutron-producing target, collimator axis, and cathetometer axis were aligned optically. Then the shielding block, target center, and zero-azimuth index were aligned on the determined beam axis with the cathetometer. Photographic plates preceded by a few g/cm^2 of polyethylene converter were exposed in the neutron beam at the ends of the steel shielding block, target center, and cathetometer to check this alignment.

Curves of counting rate versus discriminator bias and collection voltage were obtained for the bismuth fission monitor and operating values were selected. In order to obtain counting rates that would allow preparatory steps to be accomplished in a reasonable time, the converter and Absorber 1 were removed and subsequent tests were made by counting recoil protons from a polyethylene target of standard thickness. The use of a standard target permitted relatively rapid comparison of the performance of the apparatus at different runs or at different times within a run.

With photomultiplier voltages set at reasonable values, the time delays of the signals in each channel were equalized by the insertion of short lengths of cable to maximize the 1-3 and 2-3 coincidence counts per unit beam, where unit beam was determined by an arbitrary number of monitor counts. Operating points for the photomultiplier voltages were obtained on the plateaus of curves of coincidence counts per unit beam versus applied voltage. These plateaus were determined by independently varying the voltages

applied to Counters 1 and 2 while the voltage on Counter 3 was held constant at a reasonable value, and similarly by varying the voltage applied to Counter 3 while the voltages applied to Counters 1 and 2 were held constant at the values determined from the preceding step.

Additional preparatory steps or tests on the performance of the equipment that were not required at each run are described in a subsequent section.

Relative Cross-Section Data

At each laboratory angle considered, measurements were made of 2-3 coincidence counts per unit beam and 1-2-3 coincidence counts per unit beam for the following arrangements of the experimental apparatus:

1. Hydrogen target - converter in
2. Dummy target - converter in
3. Hydrogen target - converter out
4. Dummy target - converter out

The angle was changed after each sequence, and the counting time allotted was regulated so that a set of measurements including all considered angles could be repeated a large number of times during a run in order to minimize the effect on the relative cross sections of any drift in counter or monitor efficiency. This procedure also served as a check on the over-all performance of the apparatus by providing a measure of the reproducibility of the data.

Tests of Apparatus

For each of the two liquid-hydrogen targets employed, the ratio of neutron counts per unit beam obtained with the hydrogen target empty to those obtained with the dummy target was measured at 5° laboratory angle and was assumed to be independent of angle.

The counting efficiency of the thin anticoincidence counter was determined by removing Absorber 1 and the converter and placing the counters so that a scattered proton would traverse them in the order 2-1-3. Because Counter 2 presented a smaller cross section to scattered particles than Counter 1, a comparison of the 2-3 and 1-2-3 coincidence counts per unit beam provided a means of determining the efficiency of Counter 1. This was found to be 100 ± 2%.

The change in neutron energy with scattering angle amounted to about 10% for the range of angles measured. A measurement was made of the effect on the counting rate at a given angle of a change of about 10% in the minimum-energy-to-count as determined by the thickness of absorber 2. The observed change of about 20% in neutron counts per unit beam due to hydrogen was in agreement, within statistics and the experimental uncertainty of the known neutron energy spectra, with that calculated on the assumptions of (1) a 1/E energy dependence of the conversion process and (2) a minimum-energy-to-count that was independent of the angle with which the recoil proton emerged from the converter. This energy dependence was based on the known behavior of the total n-p cross section as a function of energy[12] and the similar behavior expected on the basis of the Goldberger model[23] for high-energy protons ejected from carbon. In view of this agreement, it was considered reasonable that these assumptions were valid to good approximation, and therefore that the sensitivity of the neutron counter did not vary appreciably over the range of angles measured from that predicted on the basis of a 1/E energy dependence of the conversion process.

The contribution from accidental coincidences to the counting rate was determined to be negligible at both energies. At 90 Mev the number of neutron counts from hydrogen per unit beam was constant, within counting statistics

of 2%, over a fivefold variation of beam intensity. At 290 Mev the beam intensity and counting rates were about 1/10 those at 90 Mev, and no difficulty from accidental coincidences would have been expected. A check was made with one input of the 2-3 coincidence delayed by one rf cycle of the cyclotron. The instantaneous single-counting rates of the two counters were therefore unaltered, but any coincidence count would of necessity be due to the chance occurence within the resolving time of the coincidence circuit of two pulses not related to the same particle. This check indicated that the contribution from accidentals was less than 1% of the observed rate.

IV REDUCTION OF DATA

Relative Differential Cross Section in Laboratory System

The number of neutron counts per unit beam, R, for any experimental arrangement is given by

$$R = \frac{N_n}{N_{mon.}} = \frac{N_{2-3} - N_{1-2-3}}{N_{mon.}},$$

where for a given period of scattering

N_{2-3} = number of 2-3 coincidence counts observed,

N_{1-2-3} = number of 1-2-3 coincidence counts observed,

$N_{mon.}$ = number of monitor counts observed/256. (The counting rate of the bismuth fission monitor was such that it was convenient to define a unit of beam in terms of the scaling multiple of 256.)

If the various experimental arrangements are then indicated by the subscripts

H for hydrogen target,

D for dummy target,

i for converter in,

o for converter out,

the number of neutron counts per unit beam due to hydrogen at the laboratory angle Θ is given by

$$\Delta H_{\Theta} = \left[R_{H,i} - R_{D,i}\right]_{\Theta},$$

and the number of neutron counts per unit beam due to hydrogen that can be specifically attributed to the converter is given by

$$\delta H_{\Theta} = \left[\left(R_{H,i} - R_{D,i}\right) - \left(R_{H,o} - R_{D,o}\right)\right]_{\Theta}.$$

The uncorrected relative differential cross section in the laboratory system determined in these two ways is then given by

$$\Delta H_{\Theta} / \Delta H_{\Theta'} \quad \text{and} \quad \delta H_{\Theta} / \delta H_{\Theta'}$$

where Θ' is the reference angle, i.e., that angle at which the relative cross sections were normalized to the previous data of Hadley et al. at 90 Mev[4] and of Kelly et al. at 290 Mev[10]. The reference angle was 17.6° at 90 Mev and 17.9° at 290 Mev.

Because the energy of the scattered neutrons depends on the scattering angle, these ratios must be corrected for the approximate 1/E energy dependence of the conversion process. The energy of the scattered neutron is given, in the nonrelativistic approximation, by $E \cos^2 \Theta$, where E is the energy of the neutron in the beam. The correction factor corresponding to the angle Θ is then given in this approximation by

$$F = \frac{1}{E \cos^2 \Theta'} \Big/ \frac{1}{E \cos^2 \Theta} = \frac{\cos^2 \Theta}{\cos^2 \Theta'} .$$

<u>Conversion to Center-of-Mass System and Normalization</u>

The center-of-mass relative differential cross section $d\sigma_{\theta}/d\sigma_{\theta'}$ at the angle θ is then obtained by application of the relationship

$$\frac{d\sigma(\theta)}{d\sigma(\Theta)} = \frac{1}{4 \cos \Theta} \quad \frac{\left[1 + \left(E/_{2Mc^2}\right) \sin^2 \Theta\right]^2}{\left(1 + E/_{2mc^2}\right)} ,$$

where M is mass of neutron. The center-of-mass angle θ corresponding to the laboratory angle Θ is given by

$$\theta = 2 \tan^{-1} \left[1 + E/_{2Mc^2}\right]^{\frac{1}{2}} \tan \Theta .$$

The relative cross section is then placed on an absolute scale by normalization to the previous data at the angle θ' to give the center-of-mass differential cross section for n-p scattering at the center-of-mass angle θ in units of 10^{-27} cm^2/steradian.

V RESULTS AND DISCUSSION OF ERROR

A summary of the data is given in Tables III, IV, and V for 90-Mev neutrons and in Tables VI, VII, and VIII for 290-Mev neutrons. For each angle considered the following quantities are listed:

(a) neutron counts from hydrogen per unit beam for each run;

(b) neutron counts from hydrogen per unit beam relative to the same quantity at the reference angle for each run;

(c) the statistically weighted average for all runs of the data of (b);

(d) the center-of-mass relative differential cross section;

(e) the normalized center-of-mass differential cross section in 10^{-27} cm^2/steradian.

In Fig. 7 the 90-Mev center-of-mass differential cross section, obtained with 60 Mev as the minimum neutron energy to count is plotted in conjunction with results of the prior work at larger neutron angles[4,5,6,7,8] and with the recent results of Chih[17], which includes the region of small angles. A similar plot for the 290-Mev cross section, obtained with 200 Mev as the minimum neutron energy to count, is given in Fig. 8, showing the data in relation to the prior results of Kelly et al.[10] and De Pangher[9].

The angular resolution of the neutron counter, obtained from consideration of the finite extent of both the source of scattered neutrons and the converter, was dependent upon the scattering angle. For 90-Mev neutrons the resolution in the center-of-mass system was approximately $\pm$ 3° at 10° and $\pm$ 5° at 36°. For the measurement at 5° the target-converter distance was increased to give a resolution of about $\pm$ 1.5°. For 290-Mev neutrons the resolution was approximately $\pm$ 3 at 10° and $\pm$ 6 at 37.8°.

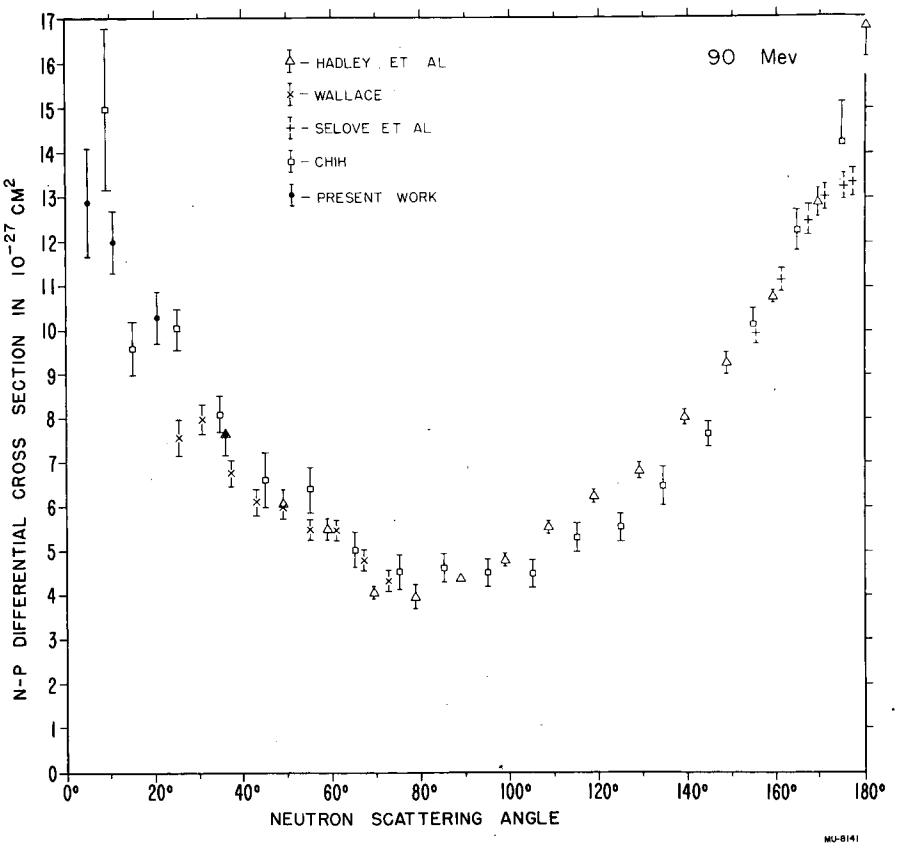

Fig. 7. 90-Mev differential neutron-proton cross section in the center-of-mass system in 10^{-27}cm^2/steradian.

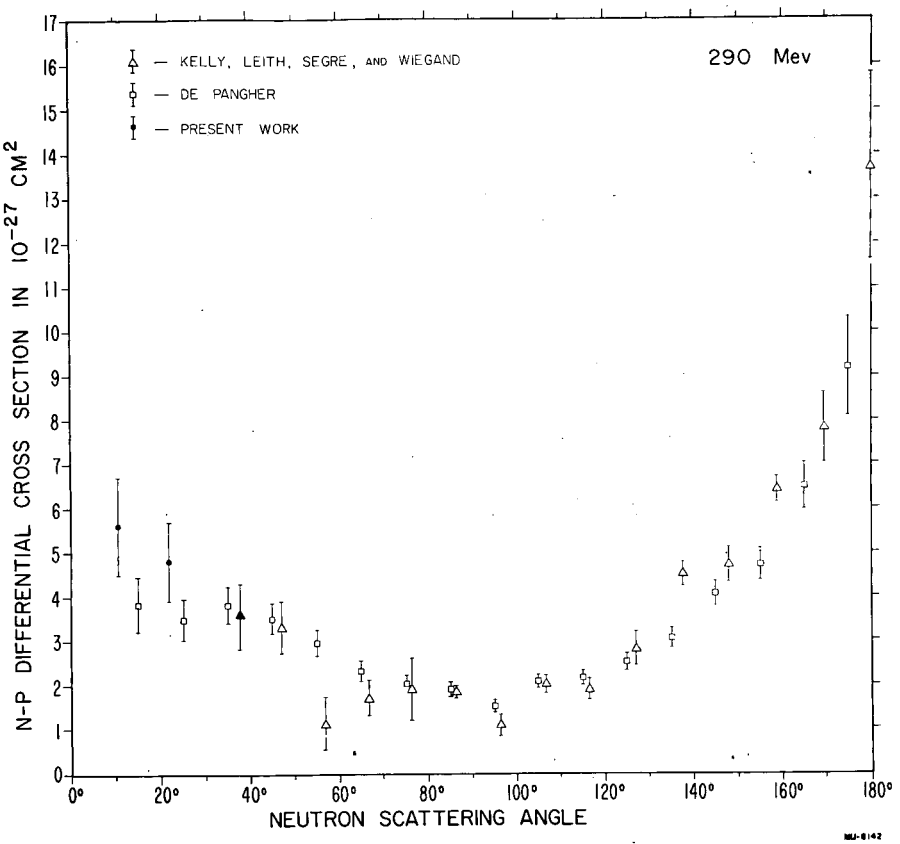

Fig. 8. 290-Mev differential neutron-proton cross section in the center-of-mass system in 10^{-27}cm^2/steradian.

As a further check on the reliability of the method, a determination was made at all considered angles of both $\Delta H_{(H)}$, the number of neutron counts due to hydrogen with the converter in place, and $\delta H_{(H)}$, the number of neutron counts per unit beam with converter in less the number of counts with the converter removed. The relative differential cross sections obtained by these two methods are in excellent agreement, as is shown in Fig. 9 for 90 Mev and Fig. 10 for 290 Mev. The normalized cross sections shown in Figs. 7 and 8 are those determined from the first method.

In order to ascertain whether the relative differential cross sections were particularly sensitive to the value of the minimum energy for detection of the scattered neutrons, a measurement was made with this energy set at two different values for each of the neutron beams employed. At 90 Mev this low-energy cutoff was 60 Mev for the major portion of the measurement, and a check was made at 66 Mev so that neutrons constituting approximately 15 % of those counted at 60 Mev were not included in the measurement. The relative cross sections obtained were in good agreement, as is shown in Fig. 11. At 290 Mev the low-energy cutoff was selected at 200 Mev, and a check was made at 225 Mev. The relative cross sections obtained were in agreement at 21.4° but could not be considered to be in agreement at 10.7°, where the difference between the two values is equal to three times its statistical standard deviation, as is shown in Fig. 12. Portions of both the 200-Mev and 225-Mev cutoff data were obtained at each of two different runs. No anomalous behavior of the apparatus was indicated, and values of the relative cross sections were consistently higher at the 225-Mev cutoff than at the 200-Mev cutoff. Approximately 25% of the neutrons counted with a 200-Mev cutoff are not counted when this is increased to 225 Mev, so that a difference between the measured cross sections, which are averages over the energy spectrum of the counted neutrons, is not precluded.

The errors shown in all figures and tables are the standard deviations of the counting statistics, and for the normalized data include the statistical error introduced by the fitting to previous results.

At 90 Mev it was determined experimentally that the contribution of neutron counts from recoil protons scattered from the hydrogen target did not exceed 5%. These protons can yield high-energy neutrons in the forward direction by inelastic collisions with the Cu nuclei of Absorber 1. The determination was accomplished by making a measurement of $\Delta H_{(H)}$ with Absorber 1 displaced towards the hydrogen target from its normal position. A comparison of the observed change in $\Delta H_{(H)}$ with that expected from the alteration of geometry then yields an upper limit to counts from this source. The greatly reduced counting rate at 290 Mev made a similar experimental determination impractical, but an estimate of this effect indicates an upper limit of the same order of magnitude at this energy. From the experimental inelastic cross section of Cu for 305-Mev protons[22] approximately 35% of the incident protons experienced an inelastic collision before their energy was reduced to a value lower than the minimum-energy-to-count. The findings of G. Bernardini et al.[23] on the number and energy of protons resulting from inelastic collisions of 300-Mev neutrons incident on emulsion nuclei indicate that approximately 20% of the proton collisions yield neutrons of energy greater than 200 Mev in the forward direction. Therefore, about 7% of the recoil protons from the hydrogen target yield neutrons that may subsequently convert and be counted.

The effect of this proton contribution on the relative cross section at 90 Mev is negligible because the numbers of scattered neutrons and recoil protons at a given angle are approximately equal. At 290 Mev, for small neutron angles, the number of recoil protons is approximately 1.5 times the number of scattered neutrons. Consequently, an error of about

3% in the direction of too large a relative cross section is introduced in the measured values from this source. The data presented in the tables and figures are the measured values, to which no correction for this error has been applied.

Other systematic errors were estimated to be small compared with the statistical uncertainty of the measurements.

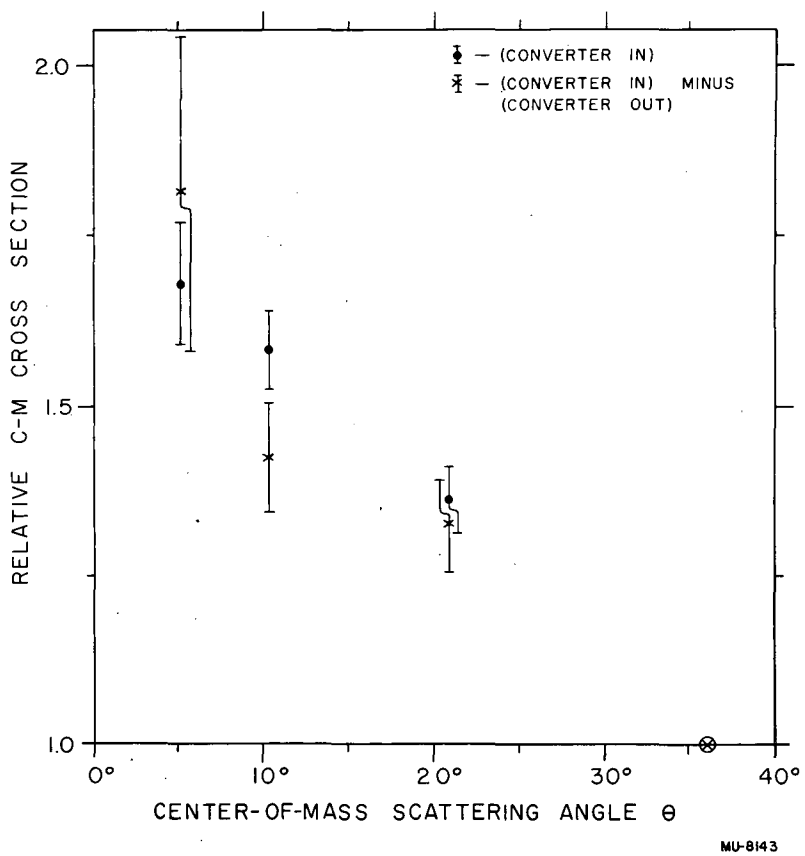

Fig. 9. Ratio of the 90-Mev differential neutron-proton cross section in the center-of-mass system at the angle θ to that at 36°, as obtained (a) with the converter in, (b) by the difference between converter-in and converter-out data.

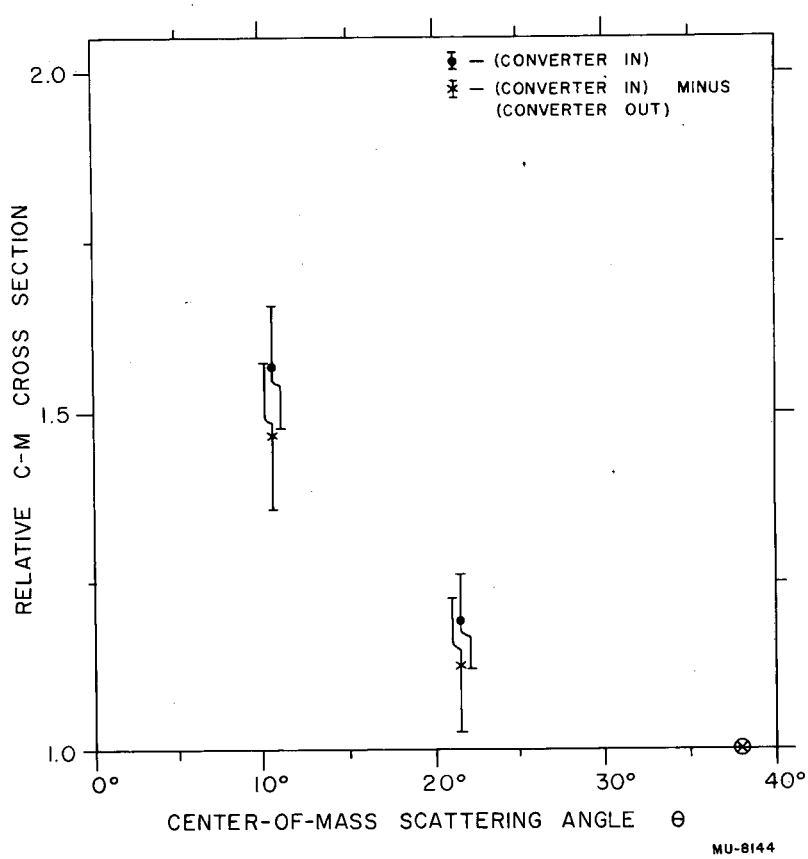

Fig. 10. Ratio of the 290-Mev differential neutron-proton cross section in the center-of-mass system at the angle θ to that at 37.8° as obtained (a) with the converter in, and (b) by the difference between converter-in and converter-out data.

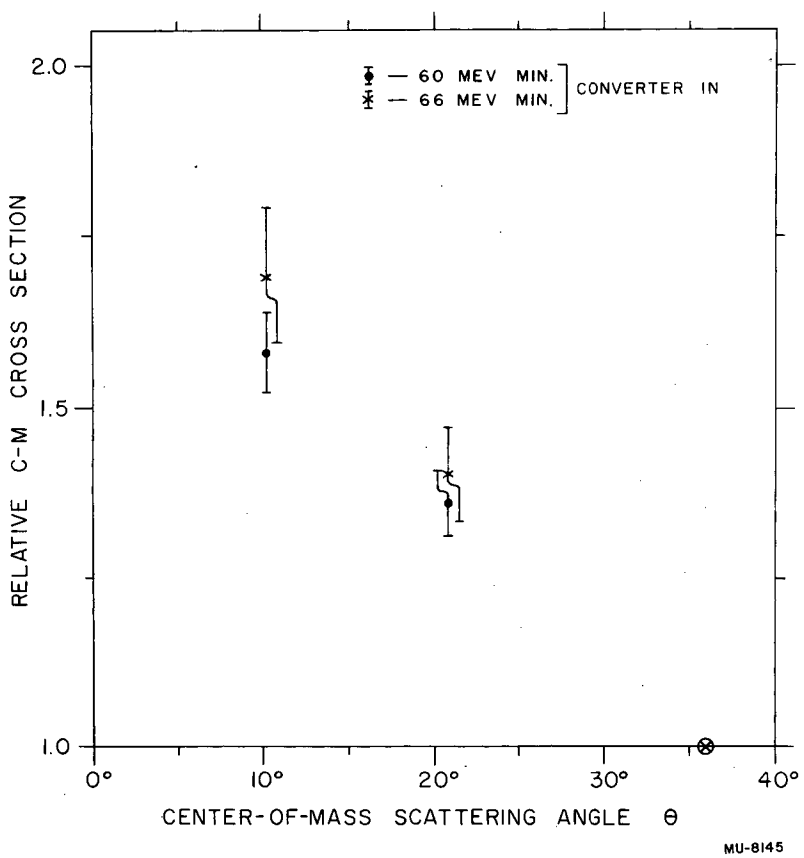

Fig. 11. Ratio of the 90-Mev differential neutron-proton cross section in the center-of-mass system at the angle θ to that at 36° for values of the minimum neutron energy to count of 60 and 66 Mev.

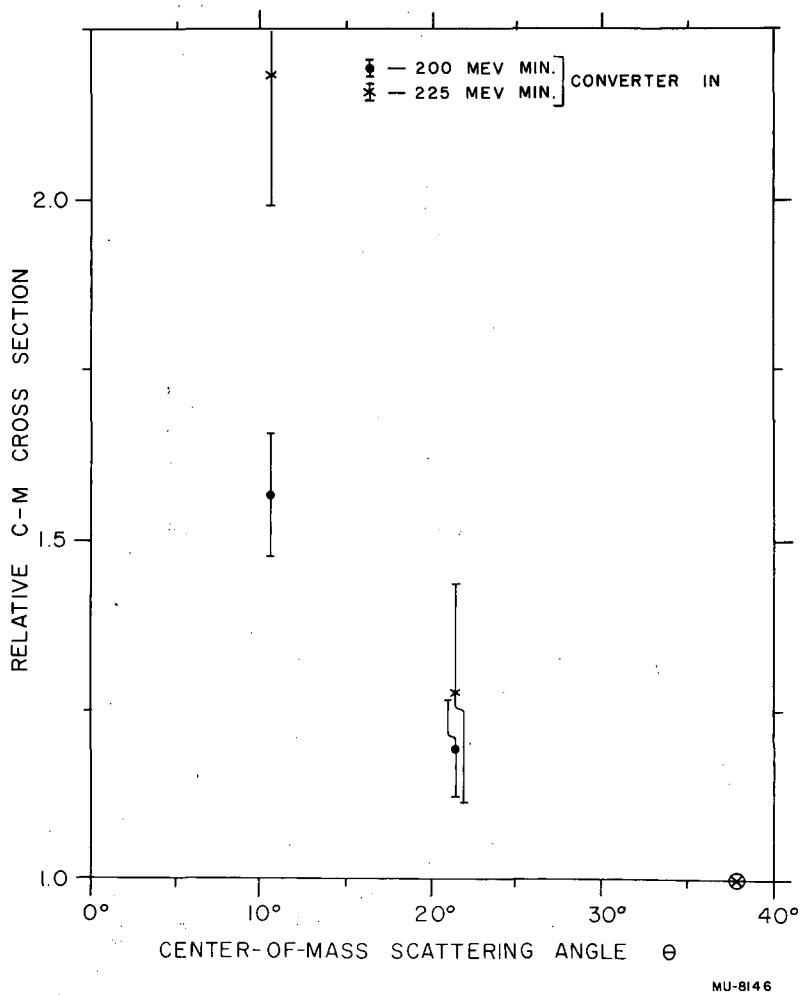

Fig. 12. Ratio of the 290-Mev differential neutron-proton cross section in the center-of-mass system at the angle θ to that at 37.8° for values of the minimum neutron energy to count of 200 and 225 Mev.

Table III

90-Mev Data Obtained with the Converter In

And a Minimum Neutron Energy to Count of 60 Mev

Lab. Angle Θ (deg.)	Date	ΔH_{Θ}	$\Delta H_{\Theta}/\Delta H_{17.6^\circ}$	Wtd. Av.	$d\sigma_{\theta}/d\sigma_{36^\circ}$	C.M. Angle θ (deg.)	$d\sigma/d\Omega$ ($10^{-27}cm^2$)
2.5	*12-7-53	127.2 ± 10.4	1.60 ± .14	1.60 ± .14	1.68 ± .14	5.1	12.9 ± 1.2
5.0	12-5-53	113.1 ± 5.0	1.46 ± .08	1.51 ± .06	1.58 ± .06	10.3	12.0 ± 0.7
	12-7-53	123.6 ± 7.3	1.56 ± .10				
	*12-7-53	125.4 ± 8.7	1.58 ± .12				
10.0	12-5-53	102.2 ± 4.4	1.32 ± .07	1.32 ± .05	1.36 ± .05	20.8	10.3 ± 0.6
	12-7-53	103.8 ± 3.9	1.31 ± .06				
17.6	12-5-53	77.4 ± 2.3				36.0	7.6 ± 0.4
	12-7-53	79.3 ± 2.0					

* The data in these rows have been corrected by the ratio between solid angle subtended by the neutron counter for the angular range of 5.0° — 17.6° and that for the angular range 2.5° — 5.0°.

Table IV

90-Mev Data Obtained with the Converter In

And a Minimum Neutron Energy to Count of 66 Mev

Lab. Angle Θ (deg.)	Date	ΔH_{Θ}	$\Delta H_{\Theta}/\Delta H_{17.6^\circ}$	$d\sigma_{\theta}/d\sigma_{36^\circ}$	C.M. Angle θ (deg.)
5.0	12-5-53	101.2 ± 5.5	1.61 ± .10	1.69 ± .10	10.3
10.0	12-5-53	86.0 ± 4.0	1.36 ± .07	1.40 ± .07	20.8
17.6	12-5-53	63.0 ± 1.8			36.0

Table V

90-Mev Data Obtained from the Converter-In Minus Converter-Out Subtraction

And a Minimum Neutron Energy to Count of 60 Mev

Lab. Angle Θ (deg.)	Date	δH_{Θ}	$\delta H_{\Theta}/\delta H_{17.6^\circ}$	Wtd. Av.	$d\sigma_{\theta}/d\sigma_{36^\circ}$	C.M. Angle θ (deg.)
2.5	*12/7/53	108.5 ± 13.0	1.73 ± .22	1.73 ± .22	1.81 ± .23	5.1
5.0	12/5/53	73.2 ± 6.1	1.16 ± .11	1.36 ± .08	1.42 ± .08	10.3
	12/7/53	95.6 ± 9.4	1.52 ± .16			
	*12/7/53	97.3 ± 8.0	1.55 ± .14			
10.0	12/5/53	80.2 ± 5.3	1.27 ± .10	1.28 ± .07	1.32 ± .07	20.8
	12/7/53	80.0 ± 4.5	1.28 ± .09			
17.6	12/5/53	63.2 ± 2.7				36.0
	12/7/53	62.7 ± 2.6				

* The data in these rows have been corrected by the ratio between solid angle subtended by the neutron counter for the angular range of $5.0^\circ - 17.6^\circ$ and that for the angular range $2.5^\circ - 5.0^\circ$.

Table VI

290-Mev Data Cbtained with the Converter In

And a Minimum Neutron Energy to Count of 200 Mev

Lab. Angle Θ (deg.)	Date	ΔH_{Θ}	$\Delta H_{\Theta}/\Delta H_{17.9^o}$	Wtd. Av.	$d\sigma_{\theta}/d\sigma_{37.8^o}$	C.M. Angle θ (deg.)	$d\sigma/d\Omega$ ($10^{-27}cm^2$)
5.0	1/22-25/54	4.55 ± .53	1.17 ± .16	1.52 ± .09	1.56 ± .09	10.7	5.6 ± 1.1
	2/15-17/54	5.60 ± .34	1.70 ± .15				
	4/14-18/54	4.25 ± .20	1.61 ± .12				
10.0	1/22-25/54	4.85 ± .20	1.25 ± .15	1.16 ± .07	1.19 ± .07	21.4	4.3 ± 0.9
	2/15-17/54	3.47 ± .28	1.06 ± .11				
	4/14-18/54	3.20 ± .24	1.21 ± .11				
17.9	1/22-25/54	3.88 ± .29				37.8	3.6 ± 0.7
	2/15-17/54	3.29 ± .22					
	4/14-18/54	2.64 ± .15					

Table VII

290-Mev Data Obtained with the Converter In

And a Minimum Neutron Energy to Count of 225 Mev

Lab. Angle Θ (deg.)	Date	ΔH_{Θ}	$\Delta H_{\Theta}/\Delta H_{17.9^\circ}$	Wtd. Av.	$d\sigma_{\theta}/d\sigma_{37.8^\circ}$	C.M. Angle θ (deg.)
5.0	2/15-17/54	4.10 ± .27	2.61 ± .33	2.12 ± .18	2.18 ± .19	10.7
	4/14-18/54	3.30 ± .21	1.86 ± .24			
10.0	2/15-17/54	1.75 ± .29	1.12 ± .21	1.23 ± .16	1.27 ± .16	21.4
	4/14-18/54	2.45 ± .36	1.38 ± .25			
17.9	2/15-17/54	1.57 ± .15				37.8
	4/14-18/54	1.77 ± .19				

Table VIII

290-Mev Data Obtained from the Converter-In Minus Converter-Out Subtraction

And a Minimum Neutron Energy to Count of 200 Mev

Lab. Angle Θ (deg.)	Date	δH_{Θ}	$\delta H_{\Theta}/\delta H_{17.9^{\circ}}$	Wtd. Av.	$d\sigma_{\theta}/d\sigma_{37.8^{\circ}}$	C.M. Angle θ (deg.)
5.0	1/22-25/54	3.59 ± .56	1.18 ± .23	1.42 ± .11	1.46 ± .11	10.7
	2/15-17/54	3.58 ± .50	1.34 ± .23			
	4/14-18/54	3.80 ± .23	1.56 ± .15			
10.0	1/22-25/54	3.95 ± .61	1.30 ± .25	1.08 ± .10	1.12 ± .10	21.4
	2/15-17/54	2.45 ± .36	0.92 ± .17			
	4/14-18/54	2.73 ± .29	1.12 ± .15			
17.9	1/22-25/54	3.05 ± .36				37.8
	2/15-17/54	2.68 ± .28				
	4/14-18/54	2.43 ± .19				

VI CONCLUSIONS

The data at 90 Mev, when compared with the cross sections at larger angles, show a marked symmetry of the angular distribution of scattered neutrons about 90°. This had been explained by Christian and Hart[14] in terms of a potential that is half-ordinary and half-exchange, $\frac{1}{2}(1+P_M)V(r)$, frequently termed the Serber potential. P_M, the space-exchange operator, has the value of $+1$ for even-parity states and -1 for odd-parity states of orbital angular momentum. Therefore this potential has the value zero for odd angular momentum states and yields no scattering in these states; the differential cross section is therefore symmetrical about 90°. The phenomenological treatment by Case and Pais[25], who employ an $\vec{L}\cdot\vec{S}$ interaction in triplet states, and by Jastrow[26], who employs a repulsive hard core in the singlet states, seek to provide a possible single potential for both n-p and p-p interactions. Both treatments have the common feature that the additional types of interactions introduced to obtain theoretical agreement with the observed isotropic p-p angular distribution leave unaltered the fact that the calculated n-p angular distribution is dominated by a Serber potential.

At 290 Mev the results are in disagreement with those of De Pangher[9] with respect to the value of the cross section at approximately 10° center-of-mass relative to its value at approximately 40°. The De Pangher data indicate a cross section that is approximately constant over the range of angles from 15° to 35°, whereas the results of this experiment indicate a cross section at 10° that is $1.56 \pm .09$ times that at 38° (See Fig. 10). There is a qualitative agreement, however, in an absence at 290 Mev of the symmetry of the differential cross section about 90° observed at 90 Mev;

the difference between the two experiments is one of degree that is not outside the limits of the combined experimental errors. (See Fig. 8). Recent results in the 400-Mev range[18] also exhibit a similar behavior at small neutron angles. This lack of symmetry at the higher energy must then require a departure from the half-ordinary, half-exchange Serber potential, which has provided the basic character of the angular distribution of n-p scattering, and the consequent inclusion of an appreciable contribution from scattering in angular momentum states of odd parity.

At the present time the n-p differential scattering cross section for 90-Mev neutrons is known with a reasonable degree of certainty. Preliminary reports of work at Harvard (93 Mev) for the mid- and large-angle range and at Harwell (104 Mev) for the small-angle range indicate an agreement with prior data and with the results here reported. The results in the 300-Mev region are, however, not as complete. This is particularly so in the region of small angles. The statistical accuracy of the absolute cross sections of this experiment was limited by the large uncertainty in the value determined by Kelly et al.[10] at the common angle. Further, there is a disagreement between the results of this experiment and those of De Pangher[9] in the relative values of the cross sections at angles less than 40° in the center-of-mass system.

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