TABLE IV. Optical-model potential depths for $\lambda=0.8571$.

$V \backslash E$ (Mev)	50	140	260
V_{CR} (Mev)	-0.66	-12.1	-14.8
V_{SR} (Mev)	3.5	2.9	5.4
V_{SI} (Mev)	-4.2	1.7	-1.2
V_{CI} (Mev)	64	77	84

$$\mathrm{Re}[f(0)]=\frac{1}{32k}\sum_{I=0}^{1}\sum_{S=0}^{1}\sum_{J,l}(2I+1)\times(2J+1)\,{}^{S}R_{J,l}{}^{I}\sin(2\,{}^{S}\delta_{J,l}{}^{I}),$$

$$V_{CI}=\frac{3}{M\lambda^3}\mathrm{Im}[f(0)]=\frac{k}{M}\frac{3\bar{\sigma}}{4\pi\lambda^3},$$

$$[V_{SR}+iV_{SI}]=\frac{3}{M\lambda^3}\frac{1}{4k^2}f_1(0),$$

$$f_1(0)=\frac{1}{32ik}\sum_{I=0}^{1}\sum_{j,l,S=1}(2I+1)(2J+1)\times\{[1-{}^{1}R_{J,l=J}{}^{I}\exp(2i\,{}^{1}\delta_{J,l=J}{}^{I})]-(J-1)[1-{}^{1}R_{J,l=J-1}{}^{I}\exp(2i\,{}^{1}\delta_{J;l=J-1}{}^{I})]+(J+2)[1-{}^{1}R_{J,l=J+1}{}^{I}\exp(2i\,{}^{1}\delta_{J;l=J+1}{}^{I})]\},$$

k being the antinucleon momentum in the center-of-mass system; λ and $\rho(x)$ are defined in reference 7, and R is the amplitude of the reflected partial wave $[R=(1-T)^{\frac{1}{2}}]$.

In these expressions $\bar{\sigma}$ is the effective antinucleon-nucleon cross section given by

$$\bar{\sigma}=\tfrac{1}{2}[\sigma_{\bar{p}-n}{}^{\mathrm{abs}}+\sigma_{\bar{p}-p}{}^{\mathrm{abs}}]+\tfrac{1}{2}\gamma[\sigma_{\bar{p}-n}{}^{\mathrm{sc}}+\sigma_{\bar{p}-p}{}^{\mathrm{sc}}],$$

where γ is a factor that takes into account the effect of the Pauli principle upon nucleons inside the nucleus. This effect tends to forbid collisions with small momentum transfer, thereby decreasing the scattering in the forward direction.

A calculation of the γ factor has been performed considering a Fermi gas model of the nucleus and an N-$\bar{N}$ differential scattering cross section of the form $k[d\sigma(\theta)/d\Omega]=K+L\cos\theta+M\cos^2\theta$ which fits the measured angular distributions fairly well in the energy range considered here.[8] The results are shown in Table IV. Using these potentials, Fernbach *et al.* are now carrying out an optical-model calculation of the scattering of antiprotons from several light nuclei.

ACKNOWLEDGMENTS

We are indebted to Professor Geoffrey F. Chew for his invaluable advice and to Dr. Kenneth M. Watson for his help with the optical model.

[8] J. R. Fulco, University of California Radiation Laboratory Report UCRL-8416 (unpublished).

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p-n Asymmetries at 143 Mev*

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The asymmetry of neutrons produced by bombardment of C, Al, Cu, and Pb by 143-Mev polarized protons, at angles 20° to 70°, has been measured. The asymmetry is almost independent of target element but is inconsistent with that from a free *p-n* collision. The mechanism for the process is discussed.

INTRODUCTION

THE (p,n) reaction producing neutrons by proton bombardment of nuclei is primarily of interest as a source of neutrons from high-energy cyclotrons. It has usually been assumed that the process is an elementary collision with a neutron inside the nucleus. Early work on the polarization of the neutron[1] was consistent with this view. If this is indeed the case then the relation, which holds for elastic scattering, connecting the asymmetry of the outgoing neutrons from a polarized proton beam to the polarization of the neutrons from an unpolarized beam should still hold; this relation is $e=P_1P_2$. Thus it should be possible to compare directly the polarizations previously measured[1-3] with asymmetries. Roberts, Tinlot, and Hafner[3] and later Bradner and Donaldson[4] showed a deviation from the simple picture. They found a large asymmetry in the (n,p) reaction on carbon by polarized neutrons at 150 Mev, at 45° lab, of a sign opposite to the free *n-p* scattering. Stafford, Tournabene, and Whitehead[2] confirmed this by measuring the polarization of neutrons produced in the (p,n) reaction at 160 Mev. It is the purpose of this paper to extend this work by

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[1] R. G. P. Voss and R. Wilson, Phil. Mag. **1**, 175 (1956).
[2] Stafford, Tournabene, and Whitehead, Phys. Rev. **106**, 831 (1957).
[3] Roberts, Tinlot, and Hafner, Phys. Rev. **95**, 1099 (1954).
[4] H. Bradner and R. Donaldson, Phys. Rev. **99**, 890, 892 (1955).

measuring the asymmetries of neutrons produced in several elements and at several angles by the 150-Mev polarized proton beam of the Harvard cyclotron.

METHOD

The layout of the apparatus is shown in Fig. 1. The beam[5] is defined by brass plates 3 in. high and 1 in. wide, through which passed 3×10^7 protons per second. The beam then passed through an ionization chamber monitor to the targets which were chosen to be 10 Mev thick. The beam energy was determined[6] by range to be 148 ± 2 Mev, and the average polarization ($65\pm2\%$) was found by measuring the asymmetry from carbon and comparing with published data.[7,8]

The counter used was a large liquid scintillator[9] contained in an aluminum tank 3 in. wide, 6 in. high, and 25 in. long, carefully constructed to be symmetrical about a vertical plane through the center. The liquid was phenylcyclohexane with 4 g/liter of p-terphenyl in solution. The scintillator was viewed by five 5819 photomultipliers connected in parallel. Uniformity of light collection was achieved by adjusting the photomultipliers independently using a 2-mC source of Sr^{90}. The maximum variation was 5%, occurring at the counter ends. A 1-in. thick lead plate was placed between the counter and the targets to prevent scattered protons being counted. Any secondaries produced by the neutrons in this block were proportional in number to the incident neutrons and did not affect the observed asymmetry.

The counter was placed alternately to the left and to the right of the beam in the center of a large steel house which provided shielding from neutrons which came directly from the cyclotron itself. This shielding was 8 in. thick in the direction of the cyclotron. In spite of this and other shielding (shown in Fig. 1), the background neutrons exceeded the wanted neutrons by about a factor of four.

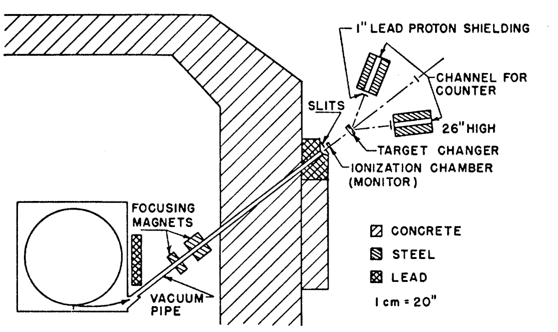

FIG. 1. Experimental layout to scale, showing the arrangement of the polarized proton beam and the shielding.

[5] G. Calame *et al.*, Nuclear Instr. **1**, 169 (1957).
[6] Palmieri, Cormack, Ramsey, and Wilson, Ann. Phys. **5**, 299 (1958).
[7] Alphonce, Johanssen, and Tibell, Nuclear Phys. **3**, 185 (1957).
[8] J. M. Dickson and D. C. Salter, *Proceedings of the International Conference on Nuclear Physics, Amsterdam, 1956* (Nederlande Natuurkundige Vereniging, Amsterdam, 1956).
[9] Thresher, Van Zyl, Voss, and Wilson, Rev. Sci. Instr. **26**, 1186 (1955).

We used as a monitor an argon-filled ionization chamber detecting the polarized proton beam. Since the background was large, and was not caused by the polarized proton beam, this was not necessarily a reliable monitor. Background counts were therefore taken at frequent intervals, by use of a remote target changer. No variation in normalized background rate was observed, and any variation would have been averaged by this procedure. The background subtraction was straightforward for the background neutrons were unaffected by the presence of a target.

The counter was used with an ordinary 10^{-7}-sec amplifier, which fed five discriminators in parallel, set at 20, 30, 40, 50, and 60 v. These enabled counts to be taken averaging over a successively larger spectrum of neutron energies. These settings remained constant for all angles and no changes in pulse height were observed.

The effective energies to be attached to these channels were measured by measuring the total cross section in a 15.6-in. carbon block of the scattered neutrons.[9] By comparison of the total cross section with measured data, an energy could be determined. This was found to be very closely the same at all the angles for the same discriminator bias. A small correction was necessary for the lack of perfect geometry.

The targets were adjusted so that the protons lost 10 Mev in them, and were of adequate purity.

ALIGNMENT AND SYSTEMATIC ERRORS

The beam slit was adjusted to be 1 in. wide and 3 in. high and to include the most intense, and uniform, beam. The beam line was then determined by a beam photograph 6 ft behind the slit; at this position the beam was 4 in. wide at the extremes of the intensity pattern but symmetrical. The precision of determining the center of this beam pattern is estimated as 0.2 in. and is the major uncertainty in the alignment procedure. Although the counter was changed from side to side several times for each angle, the complete alignment procedure was repeated for only two angles—20° and 30°—but with complete reproducibility.

The energy is known to change with position across the beam[6] and so is the polarization; other systematic errors could be caused by a nonuniform counter, a change of counter gain with position, and errors in background subtraction. We have calculated these effects to be small and have somewhat arbitrarily added an error of 0.01 to all the statistical errors and 0.02 for the 60° and 70° points in order to take account of these systematic errors.

DATA

The data-taking procedure was as follows: Counts were taken for 10-min intervals with successively Cu target, background, Al target; counts were taken for

TABLE I. Sample data. Numbers given are (counts×64); superscripts are counts. Data were taken in the "North 70°" arrangement.

Time	20 volts	30 volts	40 volts	50 volts	60 volts	Monitor
Background:						
10 min	592^{0}	291^{22}	136^{48}	69^{57}	31^{32}	1913.87
10 min	584^{18}	290^{40}	134^{61}	70^{11}	31^{25}	1906.80
Cu target in:						
10 min	718^{37}	350^{50}	161^{27}	81^{12}	35^{61}	1906.02
10 min	722^{22}	351^{34}	164^{27}	82^{50}	37^{16}	1925.05

two such cycles. The counter was then moved to the same angle on the other side, and counts were taken for four cycles. Then the counter was moved back to the original side and two more cycles taken. The whole process was repeated for the Cu and Pb targets and for other angles.

Table I shows a sample section of data. The asymmetries were simply derived from these, by the formula $e=(R-L)/(R+L)$, but were then corrected to apply to a 100% polarized beam by dividing by 0.65. The results are in Table II.

DISCUSSION

In Fig. 2 our data for the asymmetry at two effective energies for carbon are plotted. On the same graph we plot the points for the polarization of the neutron measured at Harwell with a comparable bombarding energy. Within the poor statistics, there is agreement between the polarization and the asymmetry. Also plotted are the (n,p) asymmetries of Roberts *et al.*,[3] similarly corrected to apply to a 100% polarized beam. We plot here only their data with carbon in both scatterers. Their other data are comparable.

It should be noted that the 30° point falls below a smooth curve through the others; this fact persists for all the elements. It is possible that this is an alignment error, since the data for all the elements were taken with the same alignment; the discrepancy is, however, within the assigned error. We also note that the asymmetry is essentially the same for all elements.

According to the most elementary ideas, we might consider that the neutron production from proton bombardment is caused by an elementary p-n collision inside the nucleus. Indeed, neutrons produced in the forward direction are mostly high-energy neutrons, corresponding to this process and to the large exchange term in the n-p scattering. Mandl and Skyrme[10] have made detailed calculations of this process and obtain good agreement with experiment at 160 Mev, both in energy spectrum and angular distribution.

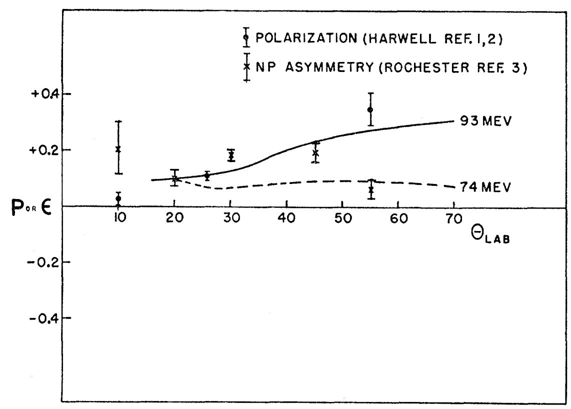

FIG. 2. The asymmetry in neutron production from carbon for effective energies of 74 and 93 Mev (solid and dashed lines), This is compared with the (n,p) asymmetries of Roberts *et al.*, and the polarizations of Voss and Wilson and of Stafford *et al.*

Thus it becomes of interest to compare our data with those expected from free p-n collisions, which is done in Fig. 3. The polarization or asymmetry in p-n collisions can be inferred from that in n-p collisions using charge symmetry. The free n-p scattering curve is an interpolation between the accurate 95-Mev data[11] and 350-Mev data.[12] The line passes through the less complete data of Roberts *et al.*[3] Also plotted on the same curve are the data[4] (from a different energy of 235 Mev) of quasi-elastic p-n asymmetries where the event was specified by a 90° p-n coincidence. The curve for free p-n collisions is slightly modified by the internal

TABLE II. Neutron asymmetries from 100% polarized protons of energy 143 Mev.

Effective neutron energy (Mev): Target	Angle	74±6	77±6	81±6	86±6	93±6
Carbon	20°	0.10	0.10	0.10	0.10	0.10
	30°	0.04	0.08	0.07	0.09	0.09
	40°	0.09	0.10	0.15	0.14	0.21
	50°	0.12	0.13	0.20	0.25	0.26
	60°	0.06	0.20	0.25	0.28	0.25
	70°	0.06	0.10	0.20	0.26	0.30
Aluminum	20°	0.09	0.08	0.10	0.09	0.11
	30°	0.06	0.03	0.09	0.07	0.08
	40°	0.09	0.08	0.10	0.12	0.17
	50°	0.11	0.20	0.23	0.24	0.32
	60°	0.26	0.11	0.18	0.28	0.30
	70°	0.15	0.11	0.18	0.28	0.30
Copper	20°	0.07	0.08	0.08	0.11	0.12
	30°	0.13	0.12	0.10	0.12	0.11
	40°	0.08	0.08	0.11	0.17	0.18
	50°	0.14	0.17	0.21	0.23	0.26
	60°	0.23	0.21	0.26	0.26	0.29
	70°	0.08	0.11	0.15	0.26	0.21
Lead	20°	0.08	0.12	0.08	0.10	0.08
	30°	−0.01	0.00	0.05	0.08	0.09
	40°	0.09	0.12	0.17	0.13	0.26
	50°	0.18	0.20	0.26	0.25	0.34
	60°	0.21	0.20	0.25	0.28	0.25
	70°	0.13	0.18	0.28	0.32	0.43
Total error assigned to all points in column:		±0.02	±0.02	±0.02	±0.03	±0.06

[10] F. Mandl and T. H. R. Skyrme, Proc. Phys. Soc. (London) **A65**, 101 (1952).

[11] Stafford, Whitehead, and Hillman, Nuovo cimento **5**, 1589 (1957).

[12] Siegal, Hartzler, and Love, Phys. Rev. **101**, 838 (1956).

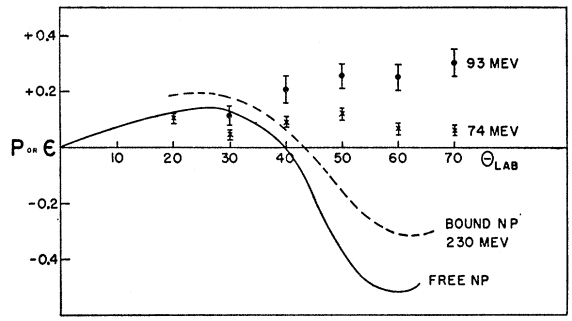

FIG. 3. The asymmetry in neutron production from carbon compared with that in free *p-n* scattering at 150 Mev and bound *p-n* scattering at 230 Mev, at the equivalent angle.

momentum distribution of the neutrons inside the nucleus. This causes an averaging of ϵ over angles of $\pm 10°$, but the effect on ϵ is less than 10%.

There is passable agreement at angles up to 30° lab (60° c.m. for the *p-n* system). At angles larger than this, the quasi-elastic *p-n* scattering measured by Bradner still shows qualitative agreement with the free *p-n* scattering and could show exact agreement within our knowledge of *n-p* scattering. When only the neutron is defined there is disagreement even as to sign. This disagreement is accompanied by a further disagreement. For a free *p-n* collision the energy of the neutron varies as $E \cos^2\theta$, where θ is in the laboratory system; thus at 60° lab we expect an energy distribution peaked at 37 Mev, with a spread about this value to the momentum distribution. This is not the case. Thus we expect the 90-Mev neutrons to come from a different process than the 37-Mev neutrons; those of lower energy might sometimes come from a *p-n* collision, explaining the lower average asymmetry.

In a search for other possible mechanisms for neutron production at wide angles, we can compare with other processes. We note, for example, that the polarization or asymmetry in elastic scattering experiments is linear with angle in the small-angle region once Coulomb effects are taken into account,[7,8] and is concave to the angle axis; in contradistinction, the asymmetry plot here is convex to the axis. In two other experiments this convex shape is found. Firstly, a study of the asymmetry of pickup deuterons from polarized protons in the reaction $C^{12}(p,d)C^{11}$,[13] and in the asymmetry of α particles in the elastic p-α scattering at backward angles, which we here write as $p(\alpha,p)\alpha$. In each of these cases also, a naive approach would be to assume a direct interaction. Stafford *et al.*[2] have suggested that this asymmetry, or in their case polarization, is due to an interaction of the incoming proton, or outgoing neutron, with the nucleus as a whole. We envisage this classically as a two-stage process, of a *p-n* production in the forward direction followed by an elastic scattering (or vice versa). The nuclear spin orbit coupling then produces the large asymmetry. The *p-n* production then occurs at a small angle and the neutron energy is higher than that given by a free *p-n* collision. The two-stage process will be a small effect at small angles where the direct process has a large cross section, but becomes large at angles (and outgoing energies) where the direct process has a reduced cross section. Thus there will always be a transition from the case of a predominantly direct process at small angles to a predominantly indirect process at large angles for any reaction where the direct process falls off steeply with angle. This will hold whether or not the indirect process is due to interaction with the nucleus as a whole. Polarization still equals asymmetry, but the curve is convex towards the angle axis.

Squires[14] has considered the above-mentioned process for the (p,n) reaction. He claims that it is not possible to obtain agreement with a nuclear potential, but that multiple nuclear collisions must be considered. This corresponds to the second stage of the indirect process considered above being caused by nucleon-nucleon interactions. However, Greider[15] has obtained good agreement in the related reaction $C^{12}(p,d)C^{11}$ using the interaction with the nuclear potential. These two facts seem contradictory, and neither treatment explains the difference between Bradner's quasi-elastic scattering and the free *p-n* scattering. Thus the matter cannot be regarded as settled.

One of the purposes of this experiment was to study the feasibility of obtaining highly polarized neutron beams; these have been used by Stafford *et al.*[2,11] It is now certain that the asymmetry, and probably therefore the polarization, varies very fast with energy, and great care must be taken in any experiment using such a beam.

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[13] P. F. Cooper, Jr., thesis, Harvard University, 1957 (unpublished).

[14] E. J. Squires, Proc. Phys. Soc. (London) **72**, 433 (1958).

[15] K. Greider, thesis, University of California, 1958, UCRL 8357 (unpublished).