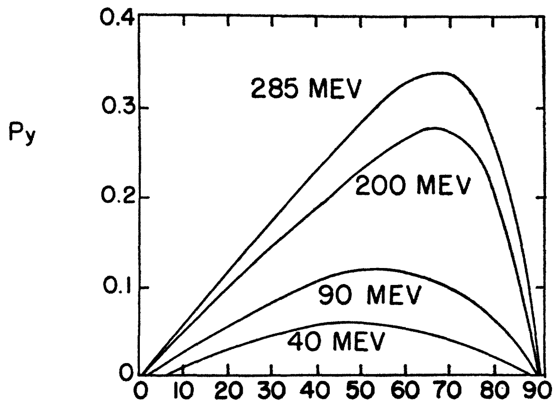

FIG. 1. The polarization $P_y(\theta, \phi=0)=[Q(\theta)/I(\theta)]$ as a function of scattering angle θ (c.m. system) for a single n-p collision at laboratory energies of 40, 90, 200, 285 Mev.

$(\theta_1, \phi_1=0)$ are the coordinates of the second target with the first target as origin and the incident beam as z-axis. (θ_2, ϕ_2) are the coordinates of the twice-scattered neutrons with the second target as origin and a z-axis defined by the two targets; ϕ_2 is measured from the plane of the first scattering. $I_1(\theta_1)$, $I_2(\theta_2)$ are the differential cross sections with polarization terms omitted.

Although polarization effects vanish in the Born approximation, the higher angular momentum states in a partial wave analysis can profitably be so calculated since interference terms with states of lower angular momentum (computed exactly) do not vanish. Accordingly, the calculations were carried out using the phase shifts of Christian and Hart in the $^3S_1$, $^3D_1$, $^3D_2$, and $^3D_3$ states, with all higher states included in the Born approximation.

Q_1 and Q_2 are equal (at the same angle and energy), provided that, in a partial wave analysis, all Wronskian conditions on the phase shifts of the coupled equations are satisfied. In Fig. 1, values of $Q(\theta)/I(\theta)$ are plotted as a function of center-of-mass angle for any single n-p scattering. One can see from the equations of Wolfenstein[3] that $Q(\theta)$ is antisymmetric about $\pi/2$ for odd or even parity states alone (hence zero at $\pi/2$), but symmetric for odd-even interference terms. Detection of azimuthal asymmetry at $\pi/2$ would therefore indicate the presence of both odd and even terms, and so disprove the "even" exchange hypothesis. In the case of p-p scattering, the $\pi/2$ point should of course give no polarization regardless of the assumed interaction since the even triplet states are not present.

It is of interest to note that almost the entire energy dependence of the polarization $Q(\theta)/I(\theta)$ lies in the differential cross section $I(\theta)$. This behavior is not entirely surprising since $Q(\theta)$ is determined principally by the $^3S-^3D$ interference terms; the S phase shifts decrease and the D increase with increasing energy apparently in such a way as to leave $Q(\theta)$ almost independent of energy between 90 Mev and 285 Mev.

With energies of 220 Mev and 160 Mev for the two scatterings, respectively, the ratio $J(\phi_2=0)/J(\phi_2=\pi)$ is 1.12 ± 0.03 at $\theta_1=65°$, $\theta_2=60°$. The ±0.03 is based on an estimate of the accuracy to which the phase shifts are known.

Although the problem has been formulated for two scatterings of a neutron beam, the first scattered beam could just as well have arisen from a (p,n) reaction. This follows from the equality of polarization of the two scattered particles and from the invariance of the scattering amplitude under the substitution $\theta\rightarrow\pi-\theta$ and $\phi\rightarrow\phi+\pi$ because of the exchange dependence assumed. A similar argument for the second scattering shows that the scattered intensity of the protons at any angle is the same as that of the neutrons. In an accompanying letter, Wouters[4] reports an experiment in which a beam of polarized neutrons was produced by a (p,n) reaction in LiD and detected by means of an n-p scattering. The resulting asymmetry agrees in sign and order of magnitude with the foregoing calculations. The experiment was also carried out with LiH as first target; for this case no significant asymmetry was detected.

A more refined interpretation of the results could be obtained by calculating the polarization from the D(p,n) reaction, here assumed equivalent to a scattering of protons by free neutrons. The failure to detect asymmetry with the LiH target does not seem particularly disturbing since scattering from neutron bounds in Li^7 might reasonably be expected to yield less polarization than would scattering from free neutrons, sufficiently less to escape detection in Wouters' experiment.

The experimental results, although consistent with the "even" theory, are not of sufficient precision to allow one on this basis to rule out interaction in the odd triplet states. This point is under further investigation in the hope that a quantitative argument can be made.

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[1] R. S. Christian and E. W. Hart, Phys. Rev. **77**, 441 (1950).
[2] L. Wolfenstein, Phys. Rev. **76**, 541 (1949).
[3] L. Wolfenstein, Phys. Rev. **75**, 1664 (1949).
[4] L. Wouters, Phys. Rev. **84**, 1069 (1951).

Detection of the Azimuthal Polarization of the n-p Interaction at 150 Mev

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A DOUBLE-SCATTERING experiment for the purpose of measuring the polarization due to the noncentral n-p interaction at high energy is in progress at this laboratory. The azimuthal effect appears notably as a change in the right/left ratio of second scattered flux intensity as the scattering angles are altered; the concurrent paper[1] presents the theoretical predictions concerning the magnitude of the effect in an ideal experiment.

The principal problem encountered in a double-scattering experiment in the 150-Mev region is the large accidental background in the azimuthal counter array caused by single scattered particles. In order to circumvent this, the first scattering (p,n) is performed inside the 184-inch cyclotron vacuum tank, utilizing the excellent neutron collimating features of the concrete shielding. The "neutron" target is a cast LiD block, which can be moved along the center line of the emergent neutron beam by means of a sliding probe. It thus intercepts the circulating proton beam at various radii corresponding to a range of first scattering angles of 0° to 45°. This geometrical arrangement has the advantage that the emergent neutron beam has almost the same energy at any angle; it also makes possible normalizing the system to 0°, where clearly no polarization is to be expected. LiH has also been used to show that the predominent contribution to the polarization effect is indeed a result of the relatively "free" deuteron neutron.

The second scattering (n,p) is performed by the orthodox carbon-paraffin difference method; the proton detectors consist of coincidence scintillation counter telescopes subtending a wide aperture ($\sim$8°). Four such telescopes detect the second scattered particles at the azimuthal angles 0° (right), 90° (up), 180° (left), and 270° (down). The scattering angle for all four is fixed at 30°, the theoretically optimum angle, throughout the experiment. Thus, the external second scattering apparatus operates under essentially constant conditions, and the independent variable is the first scattering angle.

The theory of the concurrent paper predicts no polarization at 45° lab angle, with a maximum asymmetry at 30°; quantitatively, this is expressed as a right/left second-scattered flux ratio of 1.12 or, as is more convenient, 12 percent polarization. Experimentally, account must be taken of the masking caused by Li neutrons; a rough yield measurement indicates that a multiplying factor of two to three should be applied to the measured numbers.

The results exhibit a reasonably unique pattern of behavior; various "false" polarization mechanisms have been hypothesized, but none can entirely match this pattern:

(1) The azimuthal flux distribution is consistently sensitive to changes in first scattering angle and scatterer material.

(2) No consistent changes appear in up/down ratios outside probable error for any scatterer.

(3) The carbon (second-scatterer) data show no angular dependence in right/left ratio for either LiD or LiH; thus there exists an experimental situation in which no polarization is observed by the adopted rules of procedure and analysis.

(4) The LiD first-scatterer, paraffin second-scatterer data exhibit a consistent increase in right/left ratio from 0° to 30°, and a decrease from 30° to 45°. Calculated from the change in the paraffin-carbon difference, the former amounts to an observed polarization of 6.5 percent (±2.4 percent) and the latter change corresponds to 7.5 percent (±4.5 percent).

(5) The LiH data show no comparable changes in left/right ratios, indicating that at least the major part of the effect must be attributed to the *D* neutrons.

These results thus correspond to an "ideal" polarization of 15 percent to 20 percent; they are interpretable as showing the existence of noncentral forces in the high energy *n-p* interaction. Considering the probable errors, they do not disagree with the theoretically calculated magnitude.

Extensive improvement of the method is underway with the intent of more closely tracing the polarization curves in greater detail.

The author wishes to thank Professors E. O. Lawrence and R. L. Thornton for their suggestions and continued interest. This research was performed under the auspices of the AEC.

[1] Don R. Swanson, Phys. Rev. **84**, 1068 (1951).

Neutron Stars in Krypton*

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CONTINUING the preliminary survey of neutron stars in various gases,[1] approximately 200 neutron stars have been observed in an 8-inch Wilson cloud chamber filled with krypton to about one atmosphere of pressure. The neutrons were produced in the forward direction by 240-Mev protons bombarding Cu or Be targets in the Rochester cyclotron. The cloud chamber was placed about 25 feet from the target behind 9 feet of copper collimation which passed a neutron beam of circular cross section $2\frac{3}{4}$ inches in diameter. The energy spectrum of the neutron beam from a Be target had its maximum at about 190 Mev with a width of approximately 70 Mev at half maximum.[2]

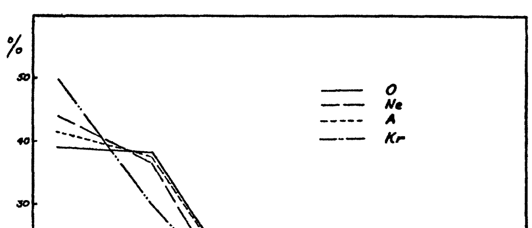

FIG. 1. Percent of stars observed *vs* number of prongs.

The prong distribution found for the Kr stars together with those previously reported for O, Ne, and A[1] are presented in Fig. 1,

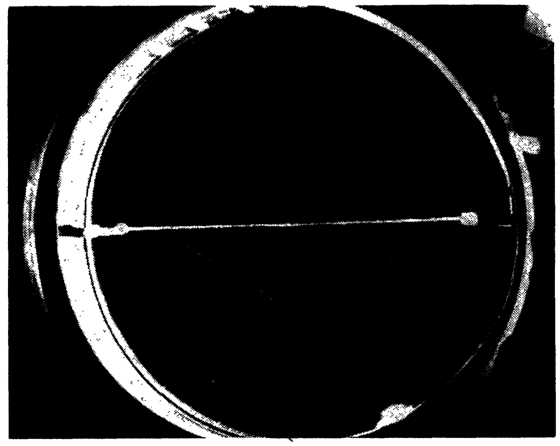

FIG. 2. 4-prong neutron star in krypton.

according to which the distribution for the three lighter gases is rather similar, whereas the relative number of stars with two prongs is found to be considerably higher in Kr.

An attempt to obtain a classification of the ejected charged particles has been made by a combined judgment of the track width and density and the number of delta-rays. Light or medium ionizing tracks with few ($\lesssim 2$) delta-rays per inch were called protons, charge $= |e|$. Light or medium ionizing tracks with many ($\gtrsim 4$) delta-rays per inch and heavily ionizing tracks were called alphas, charge $= 2|e|$. Recoiling residual nuclei were not counted as either protons or alphas. For example, the 4-prong Kr star in Fig. 2 would be treated as 2 protons, 1 alpha, and a recoil. On this basis the alpha to proton ratios found for Kr and, for comparison, those previously found for O, Ne, and A are as follows:

	2-prong stars	3-prong stars	4-prong stars
O	2.68	1.57	2.82
Ne	2.14	1.35	1.30
A	0.88	0.98	0.84
Kr	0.11	0.29	0.21

The Kr ratios bear out the downward trend with increasing atomic number suggested by the corresponding ratios found for O, Ne, and A.

The alpha to proton ratio for star particles ejected in reactions produced by slow negative π-mesons is reported by Menon, Muirhead, and Rochat,[3] who for the heavy nuclei in photographic emulsions found a value of 0.3 and for the light group of nuclei 1.55 (or 1.0 by a more indirect method). The tendency in our table is in fair agreement with these results; however, the 2-prong stars show rather high values in the light gases and a low value in Kr. A reasonable explanation would be that one must expect that the low energy tail of the neutron distribution will induce more (n,α) than (n,p) reactions in light elements, whereas the yield of (n,α) reactions by low energy neutrons will be small in heavy elements due to the high potential barrier. For 3- and 4-prong stars the contribution of low energy neutrons is likely to be smaller, and here the agreement with the emulsion values is quite good. The relatively high ratio for 4-prong O stars can be understood on the basis of an alpha-particle structure for the O nucleus.