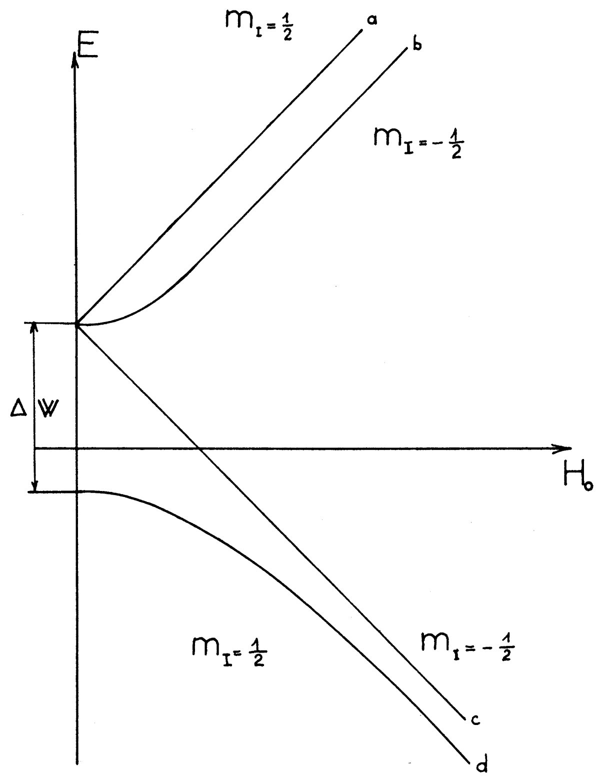

FIG. 1. Energy levels of a hydrogen atom in an applied magnetic field.

where β is a Bohr magneton and ΔW the zero-field splitting. A will have an appreciable value except if $2\beta H_0 \gg \Delta W$.

The behavior of a system with two energy levels E_b and E_d perturbed by a Hamiltonian $\mathcal{H}_1$ such that $(b|\mathcal{H}_1|d) = A\cos\omega t$ with ω in the vicinity of $(E_b - E_d)/\hbar$ can be described as that of a fictitious spin $K = \frac{1}{2}$ with a gyromagnetic ratio γ', placed in a dc field H_0' perpendicular to a rotating field of amplitude H_1', those quantities being defined through

$$\gamma' H_0' = \omega_0, \quad \gamma' H_1' = A/2. \qquad (2)$$

The interchange of the populations between the states b and d corresponds to the reversal of the polarization K_z of the fictitious spin K. The conditions for that reversal are[1]

(1) $dH_0'/dt \ll \gamma' H_1'^2$,

(2) $\Delta H_0' = H_0'(\text{in}) - H_0'(\text{out}) \gg H_1$,

where $H_0'(\text{in})$ and $H_0'(\text{out})$ are the values of the fictitious dc field H_0' crossed by the spin K upon entering and leaving the radio-frequency region of length Δx, with the condition $\gamma' H_0'(\text{in}) < \omega < \gamma' H_0'(\text{out})$. Transposed to the real system, these conditions become

$$(1) \quad \frac{d}{dt}\frac{(E_b - E_a)}{\hbar} \cong \frac{\Delta(E_b - E_a)}{\Delta x \cdot \hbar}\frac{dx}{dt} \ll \beta^2 H_1^2/\hbar^2,$$

where dx/dt is the mean velocity of hydrogen atoms of the order of 2×10^5 cm/sec;

$$(2) \quad \Delta\omega = \Delta(E_b - E_d)/\hbar \gg \beta H_1/\hbar.$$

The choice of the frequency ω and thus of the field H_0, such that $E_b(H_0) - E_d(H_0) = \hbar\omega$ is a compromise between the necessity to minimize the influence of stray fields from the cyclotron and to keep an appreciable value for the matrix element $(b|S_z|d)$; ω = 2400 Mc/sec seems to be reasonable. The length Δx being of the same order as the radio-frequency wave length $\lambda = 12$ cm, if one chooses $\Delta\omega \sim \omega/100$ the two inequality conditions (1) and (2) will be satisfied with H_1 = 1 gauss.

If the populations of the states b and d were equalized rather than interchanged by the rf field, the resulting proton polarization $\langle I_z \rangle / I$ would only be $\frac{1}{2}$.

[1] F. Bloch, Phys. Rev. 70, 460 (1946).

ASYMMETRY IN SCATTERING OF 150-Mev POLARIZED PROTONS IN NUCLEAR EMULSIONS*

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The use of a volume of emulsion in the dual role of scatterer and detector (with the attendant large available solid angle and high angular resolution) appears to contain some unique features as a method for measuring the polarization of high-energy protons. We have in mind especially situations in which the proton beams are of low intensity, and/or in which the beam shape is unfavorable or poorly known; for example, the measurement of proton polarization in π-p scattering, photoproduction and photodisintegration reactions, etc.

Grigor'ev[1] has observed polarization in the "quasi-elastic" scattering of 570-Mev protons and neutrons in nuclear emulsions, and Friedman[2] has extensively investigated the polarization of 316-Mev protons in scattering, both elastic and inelastic. Both investigators found appreciable polarization effects at some angles, but the difficulty of extracting statistically significant data has so far rendered the method of limited usefulness as a polarization analyzer. Thus in such experiments, several thousands of hours of scanning are needed to measure polarization with a relative error in the range 5-10%.[2] At the energies of those experiments, the scattering is predominantly inelastic, and the effects correspondingly smaller and more difficult to interpret.

In the observations reported below, we have succeeded in circumventing some of these difficulties. A stack of 600-micron Ilford G-5 emulsion pellicules was exposed to an integrated flux of 3×10^3 protons/cm^2 from the Harvard Cyclotron.[3] The protons, of initial energy 149 $\pm$3 Mev, emerged from the cyclotron after scattering through 15° by an internal carbon target and had an initial polarization P_0=(72±3)%. By decreasing the proton energy to this value, we are able to utilize a relatively large range of angles in which the scattering is predominantly elastic. Our main results to date include the following:

(a) A new technique for polarization measurements using nuclear emulsions. The rather small background and relatively small angular spread in the original beam (< ±1°) have permitted a new method of scattering analysis. This consisted simply in measuring the projected angle of every proton track at a distance of 23 mm from the edge of the emulsion, and comparing the distribution with that observed at 3.5 mm from the edge. All tracks with the expected grain count at the greater distance deviating by > 5° from the original beam direction were ascribed to a single scattering in the emulsion; the 2.5-mm distribution provided the (small) background correction, as well as the original beam direction. The results, shown in Figs. 1 and 2, represent 2410 scatterings obtained in about 200 hours of scanning time.

The measurement has yielded a large degree of polarization, with an average P of (0.6 ±0.06) for the scattering between 5° and 12° of protons of average energy 135 Mev. Since both P and $d\sigma$ are quite large in this angular region it will be possible to use an "along-the-track" method of scanning for scatterings when the beam is not

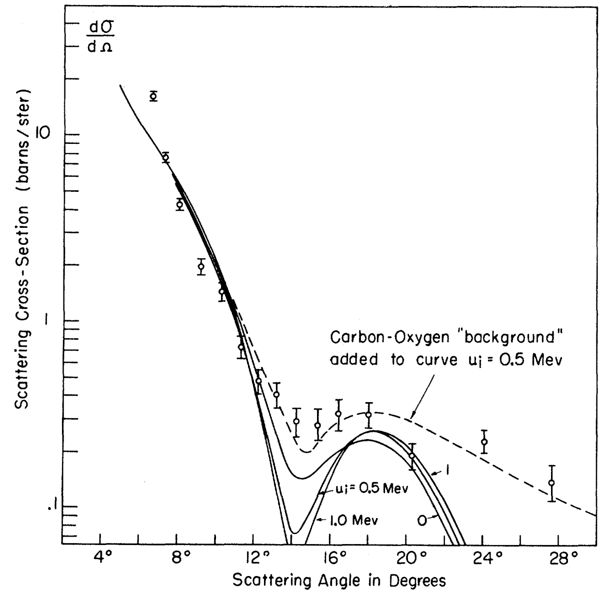

Fig. 1. Angular distribution of proton scattering in nuclear emulsion. The solid curves of both figures are for Ag plus Br, not taking into account the C and O in emulsion, computed by Sternheimer.[6] The broken curve is an estimate, based on the Harwell measurements [Dickson, Rose, and Salter, Proc. Phys. Soc. (London) A68, 361 (1955)] of proton scattering by C and O, for emulsion including all of its constituents.

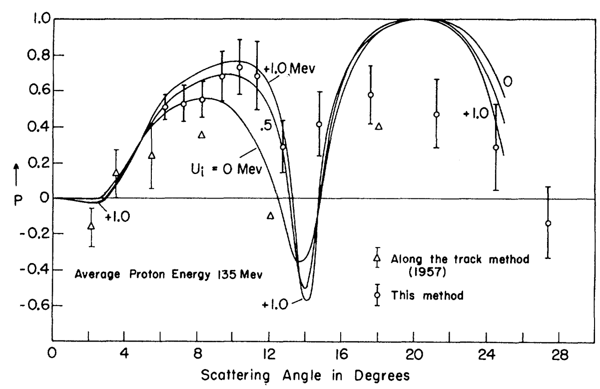

Fig. 2. P *vs* Θ. The points, obtained from the observed right-left asymmetry in the number of scatterings, have been corrected for the initial beam polarization, for angular spread due to multiple scattering, for the difference between the projected and space angle of scattering, and for an assumed sinφ azimuthal angular dependence of the polarization. The triangles correspond to our old "along-the-track" measurements.[9] For the observations above 6°, obtained in this way, we have not indicated the very large statistical uncertainty (to avoid confusion); each of these points is based on only 15-20 scatterings. The old observations (triangles) required an order-of-magnitude greater observation time that the results of our new technique.

collimated and the background is appreciable. The method will not be useful at lower energies, since polarization in the scattering by most nuclei falls off sharply at lower energies.[4] It will be useful for higher proton energies, however, since polarized protons can be slowed down to 150 Mev without appreciable depolarization.[5]

Furthermore, the technique can be applied to other elements by comparing the track distribution, as observed in the emulsion, with and without some scattering material interposed in the beam.

(b) Evidence on the nuclear spin-orbit potential. The curves in Figs. 1 and 2 were computed by Sternheimer[6] for $Z=41$, corresponding to the average Z for Ag and Br. These curves indicate the possibility of obtaining additional useful information concerning the nature of the nuclear spin-orbit potential. Indeed, if we consider the region below 14°, our experimental points speak somewhat in favor of the curves calculated with finite imaginary spin-orbit potential.[7] However, since, as pointed out by Bethe,[8] it is $|u|$ which is responsible for the shape and magnitude of polarization, it will be necessary to establish the value of the real part before any definite conclusions can be drawn concerning the magnitude of the imaginary spin-orbit potential.

(c) Polarization in small-angle scattering. In our first observations, previously reported,[9] scatterings were observed by following each proton track. Since each track had, on the average, only a 4% probability of exhibiting a scattering before leaving the emulsion, the extraction of a statistically significant result required lengthy and laborious scanning. These results, shown as triangles in Fig. 2, show a negative polarization $-(0.16\pm0.10)$ in the angular region of Coulomb scattering, around 2°.

A negative polarization at small angles is to be expected,[8,10] as a result of interference between the (repulsive) Coulomb scattering and the nuclear spin-orbit interaction. Relatively crude arguments would indicate a fairly large effect,[11] although the more refined computations of Sternheimer[6] reduce the expected effect below the experimental indications. Since our first report on the small-angle polarization,[9] the Uppsala group[12] has reported $P=-(0.067\pm0.02)$ at 2° in oxygen at the same energy.[13] Although the large uncertainty makes it difficult to be sure of the magnitude, we have additional indications that our observations in the "Coulomb region" may represent a real effect. This evidence comes from observations of asymmetries which develop in the angular distribution of the beam in passing through the emulsion, as well as from multiple-scattering measurements on individual tracks. The interpretation of such observations is complicated by the difficulty of distinguishing between multiple and single (or plural) scattering effects in the angular region of interest. Work is in progress towards the development of methods of observation and interpretation appropriate to this angular range.

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[2] J. Friedman, Phys. Rev. 104, 794 (1956).

[3] We are indebted to Professor K. Strauch and R. Wilson for their cooperation.

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[6] R. M. Sternheimer, Phys. Rev. (to be published).

[7] W. Heckrotte, Phys. Rev. 101, 1406 (1956).

[8] H. A. Bethe, Ann. Phys. 3, 190 (1958).

[9] B. C. Maglić and B. T. Feld, Padua-Venice Conference on Mesons and Recently Discovered Particles (Italian Physical Society, Bologna, 1957), p. XVI-1.

[10] To our knowledge, the first suggestion came from J. Cassels, Proceedings of the Fifth Annual Rochester Conference on High-Energy Physics, 1955 (Interscience Publishers, Inc., New York, 1955), p. 158.

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[12] Alphonce, Johansson, and Tibell, Nuclear Phys. 4, 672 (1957).

[13] J. Friedman (private communication) also finds indications, on closer examination of his published data,[2] of such an effect.

BETA DECAY OF THE Λ†

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In the course of studying a large number of decays of hyperons, produced in our hydrogen bubble chamber by 1.23-Bev/c pions, we have found an unambiguous case of a Λ undergoing