spectrum a similar splitting appears (naturally with the peaks somewhat shifted).[4]

The double peak may be explained by the splitting of the state $L_{3'}$ by spin-orbit interaction. The observed value of about 0.2 ev agrees well with the theoretical estimate by Roth and Lax.[3]

The correctness of this interpretation is supported by measurements on Ge - Si alloys: the splitting diminishes with increasing content of Si (e.g., in an alloy with 22% atomic percent of Si the energy interval of the peaks a, b in the reflection curve is only 0.15 ev; in Si it was not observable at all).[5] Similar double peaks were also found[5] in the reflection spectra of GaAs (the peak a is at 2.94, b at 3.20 ev), GaSb (2.00; 2.48), InAs (2.53; 2.82), InSb (1.82; 2.38); the general features of our interpretation are here in good accord with theoretical expectations as was kindly pointed to us by Phillips.[6]

It may be expected that the corresponding spin-orbit splitting in the Γ point should also be observable optically; however, in the absorption spectrum of Ge determined by Dash and Newman[7] this is not apparent. This point deserves further experimental investigations.

For help in our work and valuable discussions we thank A. Abrahám, F. Lukeš, J. C. Phillips, Z. Trousil, and B. Velický.

[1]H. R. Philipp and E. A. Taft, Phys. Rev. 113, 1002 (1959).

[2]J. C. Phillips, J. Phys. Chem. Solids 12, 208 (1960).

[3]L. M. Roth and B. Lax, Phys. Rev. Letters 3, 217 (1959).

[4]At our suggestion F. Lukeš from the University of Brno determined the absorption index k of germanium by the method of D. G. Avery [Proc. Phys. Soc. (London) B65, 425 (1952)]; his preliminary results confirm our observations. He found the peaks in the k curve at about 2.11 and 2.32 ev (private communication).

[5]J. Tauc and A. Abrahám, Proceedings of the Conference on Semiconductor Physics, Praha, 1960 (to be published).

[6]J. C. Phillips (private communication).

[7]W. C. Dash and R. Newman, Phys. Rev. 99, 1151 (1955).

PROTON HELICITY FROM Λ DECAY

Robert W. Birge and William B. Fowler*
Lawrence Radiation Laboratory, University of California, Berkeley, California
(Received August 22, 1960)

When Λ hyperons are produced with K^0 mesons in $\pi^- - p$ reactions there is a large up-down asymmetry of the decay products with respect to the production plane.[1] The angular distribution of the decay pion from a completely polarized hyperon at rest can be written as[2]

$$dN = (1/4\pi)(1 + \alpha \cos\chi)d\Omega,$$

where $d\Omega$ is the solid angle of the pion momentum vector $\vec{P}_\pi$, and χ the angle between $\vec{P}_\pi$ and the spin of the hyperon. The constant α is given by

$$\alpha = 2 \,\mathrm{Re}(A^*B)/(|A|^2 + |B|^2),$$

and characterizes the degree of mixing of parities in the decay. A and B are the amplitudes for decay into $s_{1/2}$ and $p_{1/2}$ final states of the pion-nucleon system. The quantity $\alpha\overline{P}$, which has the possible values $0 \leq |\alpha\overline{P}| \leq 1$, is a measure of the up-down asymmetry and has been experimentally shown[3] to be $\geq 0.73 \pm 0.14$. This large asymmetry can exist only if the Λ's are highly polarized in the production process and if there is nonconservation of both parity and charge conjugation in the decay process.

Another necessary consequence of parity nonconservation in the decay process is a longitudinal polarization of the decay proton from unpolarized Λ's decaying at rest. It can be shown that this longitudinal polarization equals $-\alpha$.[4]

Fortunately, this longitudinal polarization of the proton, referred to the center of mass of the Λ, appears as a partial transverse polarization in the laboratory system when a Λ decays in flight and, hence, can be measured by a suitable scattering experiment. In this way the helicity of the proton can be obtained, whereas in the $\alpha\overline{P}$ experiments only the lower limit to the magnitude can be determined. The sign of α was determined in an experiment of Boldt et al.,[5] who found $\alpha = +0.85^{+0.15}_{-0.21}$, based on 54 selected events from a total of 257 in a multiplate cloud chamber.

In the course of an experiment designed to produce Ξ particles[6] from a high-momentum (1.1-Bev/c) K^- beam[7] impinging on the Berkeley

30-inch propane chamber, about 20 000 Λ's were produced. A fraction of these (about 800 events) were observed to decay and have a subsequent scattering of the proton within the liquid of the chamber. This constituted a considerably larger sample of events than had been obtained by Boldt et al.; hence it seemed worth while to repeat the experiment because of its fundamental nature. Preliminary and incomplete results of this experiment have already appeared elsewhere.[8]

All events visually identified as Λ's were measured, and the relevant data were then calculated on an IBM-650 computer. A constraint program was used to find the best fit to the data, taking into account transverse momentum balance and coplanarity of the Λ's with respect to the production origin as well as the "Q" of the decay. In addition, the ionization of all tracks was visually checked for consistency with measured momentum and particle assignments. Above about 800 to 900 Mev/c there was difficulty separating θ^0's from Λ's, and those events were deleted.

A major difficulty was encountered because the proton track, prior to scattering, was often too short to measure the momentum accurately. Because very large errors were assigned to these tracks, the constraint program could not readily compute reliable values for the momenta, yet these values were needed to obtain the asymmetry parameter in the scattering process. For this reason, we assumed an elastic scattering and used the momentum obtained from the scattered prong instead. The events were accepted only when the proton momenta calculated by this method (after appropriate corrections for energy loss by ionization) were consistent with the values needed to give the right Q for the Λ. In most cases the scattered proton stopped in the chamber and a very accurate momentum determination could be made; unfortunately, however, these low-momentum events are just those where the asymmetry from scattering by carbon is quite small. Therefore these events do not help to measure the initial polarization of the proton.

In order to eliminate possible inelastic scattering events an acceptance cutoff was made in the scattering angle at a point where the elastic scattering cross section still dominates the inelastic processes. Even in those events in which both the incoming and outgoing momenta could be well measured, it was impossible to detect excitation into the low-lying levels of carbon; therefore, the cutoff procedure was used for all events.

This procedure was necessary because the asymmetry parameter for inelastic scattering can be of opposite sign to that of elastic scattering in certain angular regions. Those events with two prongs that appeared to be hydrogen scatterings were subjected to an additional constraint program to determine whether they were indeed elastic hydrogen scatterings.

As a result of rejecting θ-like events, inelastic scattering, poorly measured events, events with large kinks in the tracks, and events in which all tracks were too short to be measured accurately or the momentum was obviously too low for analysis, only 212 events remained for further analysis. Finally, all single Λ's without visible production origins were eliminated from the sample, leaving 183 events. Of these, 36 were cases in which the proton was scattered by hydrogen in the propane and the remainder were elastic carbon scatterings.

It is difficult to see how any bias can creep into the selection of these events even with such a high filtering factor, because the sign of the polarization is not an obvious quantity when the event is viewed in a bubble chamber picture.

The following procedure was then used to analyze the selected events. First, for each event the angle between the spin of the proton and the direction of motion of the proton in the laboratory system was computed in a manner prescribed by Stapp.[9] The sine of this angle multiplied by the magnitude of the original longitudinal polarization ($-\alpha$) is the magnitude of the transverse polarization. Second, correction was made for the precession of the proton spin in the magnetic field of the bubble chamber prior to the scattering event. The rate of precession of the spin was computed according to the equations derived by Ford and set forth in the paper by Nelson et al.,[10] namely,

$$\omega_s = \frac{e\vec{B}}{m_0\gamma c}[1+(\tfrac{1}{2}g-1)\gamma] - \frac{\vec{v}}{v}(\gamma-1)(\tfrac{1}{2}g-1)\frac{e\vec{B}\cdot\vec{v}}{m_0\gamma c v},$$

where $\vec{B}$ = magnetic field, $\vec{v}$ = velocity of the proton, and $\frac{1}{2}g = 2.79275$. Third, because of spin-orbit forces, the scattered intensity is proportional to $1+(-\alpha\vec{P}_1)\cdot\vec{P}_2(\theta)$, where $-\alpha\vec{P}_1$ is the transverse polarization of the incoming proton at the position of the scattering (as determined by the above transformation) and $P_2(\theta)$ is the asymmetry parameter in the scattering process. The direction of $P_2(\theta)$ is along the normal to the scattering plane, $\vec{\eta}_2 = \vec{k}\times\vec{k}'/|\vec{k}\times\vec{k}'|$. The magnitude of $P_2(\theta)$ is a function of incoming momentum and scattering angle and has been determined experimentally elsewhere. For example, with an initial transverse polarization downwards, $P_2(\theta)$ is determined as

$$P_2(\theta) = (N_R - N_L)/(N_R + N_L),$$

where N_R and N_L are the number of protons scattered to the right and to the left. (The angle ϕ between P_1 and P_2 is 0 deg and 180 deg, respectively.) In. Figs. 1 and 2 the values of $P_2(\theta)$ are summarized as a function of laboratory-system momentum and scattering angle for protons scattered by carbon and hydrogen, obtained from references available in the literature and by private communication. A list of references from which these data were taken is available on request. Data from these charts were put into the memory of the computer and intermediate values obtained by interpolation. A dashed line in Fig. 1 indicates the elastic cutoff. Below 300 Mev/c the asymmetry parameter P_2 was set equal to 0, even though at very low momenta P_2 again becomes finite. This condition eliminated another 63 events and left only 120 events of significance.

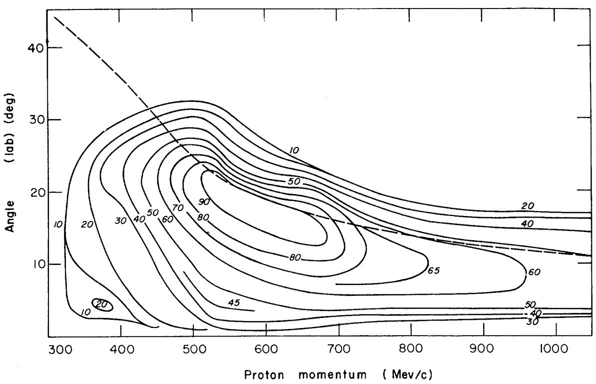

FIG. 1. Curves of constant asymmetry for elastic scattering of protons from carbon as a function of laboratory-system momentum and scattering angle. Dashed line indicates cutoff where elastic-scattering cross section still dominates inelastic scattering.

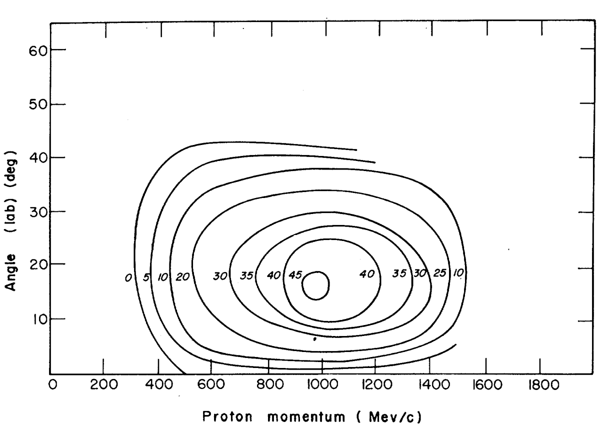

FIG. 2. Curves of constant asymmetry for proton-proton scattering as a function of laboratory-system momentum and scattering angle.

Finally, the probability that a proton scatter to the right is $N_R/(N_R + N_L) = \frac{1}{2}(1 - \alpha P_i)$, where $P_i = P_1 P_2 \cos\phi$ for the ith event. The product of all of these independent probabilities is the likelihood function

$$L = \prod_i (1 - \alpha P_i),$$

which may be plotted as a function of α to obtain the most likely value for the magnitude and sign of α.

In Fig. 3 the natural logarithm of L is plotted for 120 events.

Although these data indicate that $\alpha = -0.45 \pm 0.4$,[11] the relevant question to be answered here is the sign of α and not the magnitude (which is already known to be $\geq 0.73 \pm 0.14$). Hence one may state that our value is three standard deviations away from $\alpha = +0.73$. The ratio of the likelihood function at $\alpha = -0.73$ to that at $\alpha = +0.73$ is 65:1; for $\alpha = \mp 0.45$ the ratio is 12:1. The negative sign for α implies positive helicity for the proton in contradiction to theoretical speculations[12] based on the universal Fermi interaction, and to the experimental findings by Boldt et al.,[5] whose results are plotted in the same graph as a dashed

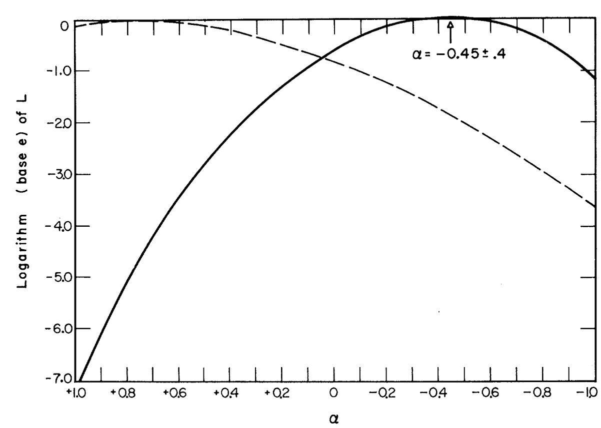

FIG. 3. Natural logarithm of the likelihood function L as a function of α. The longitudinal polarization of the proton from Λ^0 decay is $-\alpha$. Solid curve is this work. Dashed line is that of Boldt et al.[5] This experiment indicates $\alpha = -0.45 \pm 0.4$.

line, and contrary to our own preliminary results.[8]

A second way of determining the sign of α is to measure the right-left asymmetry directly. The result obtained in this manner is $(N_R - N_L)/(N_R + N_L) = 20/120 = 0.16 \pm 0.091$. The computed value for this ratio, $(-2\alpha\langle P_1 P_2\rangle_{av}/\pi)$, based on the average of the product of the input polarization $-\alpha P_1$ and the asymmetry parameter $P_2(\theta)$, is 0.16 for $\alpha = 1.0$, and 0.07 for $\alpha = -0.45$. The experimental asymmetry is in agreement with both of these values.

Finally, we have computed the quantity $D = -\sum_i P_i \cos\phi_i$ as suggested by Bowen et al.,[13] so that these data may be combined with other results. The value obtained here is $D = -2.79$, to which may be added Bowen's -0.142.

Every effort has been made to detect errors in the experiment, to the extent that the signs and magnitude of the polarization of the individual events making up the most significant part of the data have been checked numerous times. Although these data disagree with previous measurements of the sign of α, we have no other choice but to present the results as they now stand.

It is with pleasure that we acknowledge the work done by Howard White and his group in programming the computer and processing all the data. Dr. Cyril Henderson collaborated with us on a preliminary version of this experiment. We are indebted to Dr. Wilson Powell and to all the members of the 30-inch propane chamber group, and to the staff of the Bevatron for their part in making a successful run of the chamber.

We thank the many scanners and technicians for their help in the analysis. Discussions with Dr. Francis Muller and Dr. Oreste Piccioni were most helpful, as well as discussions with many other people too numerous to list.

*Now at Brookhaven National Laboratory, Upton, New York.

[1]F. S. Crawford, M. Cresti, M. L. Good, K. Gottstein, E. M. Lyman, F. T. Solmitz, M. L. Stevenson, and H. K. Ticho, Phys. Rev. 108, 1102 (1957); F. Eisler, R. Plano, A. Prodell, N. Samios, M. Schwartz, J. Steinberger, P. Bassi, V. Borelli, G. Puppi, G. Tanaka, P. Woloschek, V. Zoboli, M. Conversi, P. Franzini, I. Mannelli, R. Santangelo, V. Silvestrini, D. A. Glaser, C. Graves, and M. L. Perl, Phys. Rev. 108, 1353 (1957).

[2]T. D. Lee, J. Steinberger, G. Feinberg, P. K. Kabir, and C. N. Yang, Phys. Rev. 106, 1367 (1957).

[3]Frank S. Crawford, Jr., Lawrence Radiation Laboratory (private communication), results from experiments in reference 1.

[4]T. D. Lee and C. N. Yang, Phys. Rev. 108, 1645 (1957); R. Gatto, University of California Radiation Laboratory Report UCRL-3795, June, 1957 (unpublished); J. Leitner, Nuovo cimento 8, 68 (1958).

[5]E. Boldt, H. S. Bridge, D. O. Caldwell, and Y. Pal, Phys. Rev. Letters 1, 256 (1958).

[6]W. B. Fowler, R. W. Birge, P. Eberhard, M. L. Good, W. M. Powell, and H. K. Ticho, reported at the Ninth Annual International Conference on High-Energy Physics, Kiev, 1959 (unpublished).

[7]P. Eberhard, M. L. Good, and H. K. Ticho, Lawrence Radiation Laboratory Report UCRL-8878, August, 1959 (unpublished).

[8]R. W. Birge and W. B. Fowler, Bull. Am. Phys. Soc. 4, 355 (1959). The results reported at the meeting from a larger sample of events already indicated a negative value of α, inconsistent with the value given in the Abstract.

[9]Henry Stapp, University of California Radiation Laboratory Report UCRL-8096, December, 1957 (unpublished).

[10]D. F. Nelson, A. A. Schupp, R. W. Pidd, and H. R. Crane, Phys. Rev. Letters 2, 492 (1959).

[11]The error was obtained by taking the value of α when the logarithm of the likelihood function equals -1/2.

[12]R. P. Feynman and M. Gell-Mann, Phys. Rev. 109, 193 (1958); E. Sudarshan and R. Marshak, Phys. Rev. 109, 1860 (1958); J. J. Sakurai, Nuovo cimento 7, 649 (1958).

[13]T. Bowen, C. R. Sun, and A. E. Werbrouck, Princeton University Report NP-7079, December, 1958 (unpublished).