TABLE II. Horizontal and vertical components in milliradians for the angles between the tracks *ab*, *cd*, and *ce*.

| | $\theta_{ab}$ | $\theta_{cd}$ | $\theta_{ce}$ |
|---|---|---|---|
| *H* | 2.4±0.2 | 5.5±0.2 | 1.5±0.2 |
| *V* | 0.6±0.6 | 5.6±0.8 | 1.8±0.8 |

body decay in flight has occurred we find $15\leqslant Q(\mathrm{He}^{*3})\leqslant 250$ Mev and $3\leqslant Q(\mathrm{He}^{*4})\leqslant 65$ Mev, where the limits take into account estimated errors in momenta and angles consistent with the ionization and scattering measurements.

If we consider the decay in flight of an excited state of He, we can rule out ordinary nuclear excitation on a lifetime basis, since one should expect lifetimes less than $10^{-16}$ sec. On the other hand, the observed time of flight and $Q$ value for $\mathrm{He}^{*3}$ suggest the excited state to be of the type involving a bound hyperon; either (*i*) $\mathrm{He}^{*3}=\Lambda^{+}+p+n$ or (*ii*) $\mathrm{He}^{*3}=2p+\Lambda^0$. Type (*i*) should have $Q$ value of ~240 Mev while (*ii*) should have ~170 Mev. We believe the formation of the latter in reaction (4) with the production of a $\pi^-$ the most likely interpretation. Another, though less likely a possibility, would be the mesonic decay mode of either $\mathrm{He}^{*3}$ or $\mathrm{He}^{*4}$ [of either type (*i*) or (*ii*)] in which a $\pi^0$ meson is emitted. However, the formation of $\mathrm{He}^{*3}$ seems more likely than $\mathrm{He}^{*4}$ since the latter involves a pick-up reaction.[3] This case provides some evidence for the formation of an excited nucleus by addition of positive charge to a breakup fragment.

We wish to thank Professor J. B. French for helpful discussion and Miss P. Hull for her assistance in scanning.

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[1] This is corroborated by the Li star; if *d* was a $\pi$ of $Pc=2.76$ Bev, the momentum of *b* should increase by $M_{\mathrm{nucleon}}/M_{\pi}$ and the Li star should show a narrow cone of at least 3 tracks; this is not the case. (We imply here equal velocities for all particles.)

[2] The minimum ionizing track emitted from the first star could be the $\pi^-$ indicated below.

[3] Professor J. B. French has estimated the pick-up process and finds it is improbable at our energy due to the large momentum transfer involved. The charge-exchange process without meson production is almost certainly equally improbable.

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# Polarization of High-Energy Deuterons*

OWEN CHAMBERLAIN, EMILIO SEGRÈ, ROBERT TRIPP,
CLYDE WIEGAND, AND THOMAS YPSILANTIS
*Radiation Laboratory, Department of Physics, University of California, Berkeley, California*

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In analogy to experiments on proton polarization,[1–4] we obtained a polarized deuteron beam by the same scattering method. The trajectories of 167-Mev deuterons as produced by the cyclotron are essentially the same as those of 312-Mev protons if the magnetic field of the steering magnet is properly adjusted and the deuteron beam enters the cave through the same channel as the proton beam.

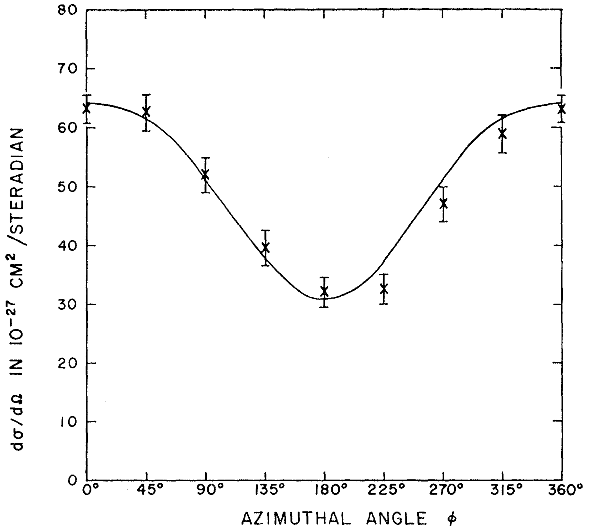

FIG. 1. Differential cross section *versus* azimuthal angle Φ for polarized deuterons scattered elastically by carbon.

In order to polarize and analyze the deuteron beam we have used carbon as scatterers *A* and *B*. After the second scatterer we have measured the intensity of the scattered beam as a function of $\phi$. We have endeavored to limit ourselves to elastically scattered deuterons by the use of absorbers, as in the proton work.

It has been shown by Lakin and Wolfenstein[5] that the most general intensity distribution produced by polarized deuterons is:

$$I(\theta,\phi)=I_0(\theta)+A(\theta)\langle T_{20}\rangle +[B(\theta)\langle T_{21}\rangle+C(\theta)|\langle T_{11}\rangle|]\sin\theta\cos\phi +D(\theta)\langle T_{22}\rangle\sin^2\theta\cos 2\phi. \quad (1)$$

The incident deuterons travel in the $z$ direction and have been polarized by scattering in the $x$, $y$ plane. $I$, $A$, $B$, $C$, $D$ are polynomials in $\cos\theta$ and the $T_{ik}$'s are expectation values, for the beam before it undergoes the second scattering, of quantities such as

$$T_{21}=-\tfrac{1}{2}\sqrt{3}[(S_x+iS_y)S_z+S_z(S_x+iS_y)],$$
$$T_{11}=-\tfrac{1}{2}\sqrt{3}(S_x+iS_y),$$
$$T_{22}=-\tfrac{1}{2}\sqrt{3}(S_x+iS_y)^2,$$

where **S** is the spin operator for the deuteron.

Experimentally we have found $I(20°,\phi)$ as in Fig. 1. An analysis of this scattering gives

$$I(20°,\phi)=p+q\cos\phi+r\cos 2\phi, \quad (2)$$

with $p=50.3\pm2.2$, $q=15.3\pm1.9$, and $r=-1.8\pm3.6$ in units of $10^{-27}$ cm²/steradian. The errors are based on counting statistics only, and are valid for the ratios

$p:q:r$ but not necessarily for the absolute values of these parameters. Measurements at smaller values of $\theta$ give similar results with smaller values of $q/p$.

This equation agrees well with Eq. (1) and shows that the coefficient of $\cos 2\phi$ is very small or zero, at least in the cases investigated up to now.

A possible explanation which is consistent with the usual spin-orbit model has been pointed out by Dr. M. Ruderman. If it is assumed that the deuteron polarization originates in an $\mathbf{L}\cdot\mathbf{S}$ coupling which acts in the scattering process in addition to a central force, and if the magnitude of the spin-orbit potential is small compared to the central part, it then follows that the $\cos 2\phi$ term is negligible because $\langle T_{22}\rangle$ is very small.

It must be noted that the description of the polarization of a deuteron beam is substantially more complicated than the similar description for particles of spin $\frac{1}{2}$, and that our analysis gives only a small part of the relevant information.

* This work was done under the auspices of the U. S. Atomic Energy Commission.

[1] Oxley, Cartwright, and Rouvina, Phys. Rev. **93**, 806 (1954).

[2] Chamberlain, Segrè, Tripp, Wiegand, and Ypsilantis, Phys. Rev. **93**, 1430 (1954). Figure 1 of the reference paper is applicable to the present work and the same notations are used throughout.

[3] Marshall, Marshall, and de Carvalho, Phys. Rev. **93**, 1431 (1954).

[4] J. M. Dickson and D. C. Salter, Nature **173**, 946 (1954).

[5] W. Lakin and L. Wolfenstein (unpublished). We thank the authors for having shown us the manuscript.

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# Mechanism of Proton Polarization in High-Energy Collisions*

Owen Chamberlain, Emilio Segrè, Robert Tripp,
Clyde Wiegand, and Thomas Ypsilantis
*Radiation Laboratory, Department of Physics, University of California, Berkeley, California*

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RECENT experimental evidence has accumulated showing that high-energy collisions of protons with various nuclei induce a considerable polarization in proton beams[1-3] and mechanisms have been proposed to account for this effect.[4-9] We have tried to investigate this phenomenon experimentally and we present here a brief summary of our results.

For the sake of discussion we shall distinguish three types of collisions: (a) elastic collisions in which the struck nucleus is left unexcited; (b) inelastic collisions in which the struck nucleus is left in an excited state; (c) the limiting case (quasi-elastic) in which the impinging proton can be considered to collide with a specific nucleon of the target and recoils almost as in a free nucleon-nucleon collision.

The theory proposed in references 4 through 7 applies specifically to elastic collisions and should be applicable especially to diffraction scattering. This we have tested by measuring the differential cross section for left and right scattering for a polarized 300-Mev proton beam obtained as described in reference 2. The scatterers studied are carbon, aluminum, calcium, and iron, as well as several others less completely.

One of the important requirements of the experiment is that the scattering be elastic. This is at least partially achieved by using a detecting telescope with enough absorber to exclude all protons that have suffered an appreciable energy loss in the target. In Fig. 1, we show absorption curves for the scattered protons taken at an angle $\theta = 9°$ for left and for right scattering from carbon. The curves show the effect of nuclear absorption and also the end of the range of the protons. From curves of this type one can derive values of the asymmetry $e$ as a function of the energy of the scattered protons. The asymmetry shows an increase at high energy which indicates a high degree of polarization of the protons scattered elastically, as predicted.[4-7] However, our resolution in energy (limited by range straggling) is insufficient to distinguish the fluctuations in cross section corresponding to the levels of the residual nucleus. Fortunately, for small $\theta$, diffraction scattering accounts for most of the scattering cross section and it is possible, by using a thick absorber in the telescope, to obtain scattering curves that show the characteristic diffraction pattern.[10] This is shown in Fig. 2, in which left and right scattering are plotted separately. The corresponding values of $e$ are plotted in Fig. 3 and show fluctuations which we think are due to the operation of the $\mathbf{L}\cdot\mathbf{S}$ coupling as expected.[4-7] The minimum is not as pronounced as predicted by the simplified theories,[4-7] but there are probably two causes for this: Experimentally the lack of energy and angular resolution does not permit measuring elastic scattering only; theoretically the simplified models

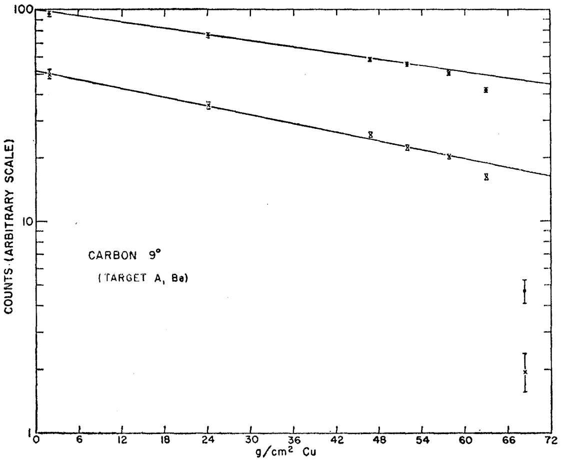

FIG. 1. Counting rate as a function of the absorber thickness in the counter telescope. Target $B$: carbon; beam polarization 0.64, $\theta = 9°$. Dots: left scattering; crosses: right scattering. Proton energy 300 Mev.