# Influence of the Earth's Magnetic Field on Air Showers

R. J. NORMAN
*Physics Department, University of Melbourne, Melbourne, Australia*
(Received November 1, 1955)

Cocconi has estimated that the deflection of air shower particles in the earth's magnetic field should produce some ellipticity of shower structure, with the major axis in the E–W direction. Experimental evidence is advanced to show that the variation in shower structure at sea level is less than 4%, which compares favorably with Cocconi's theoretical value of ~2% and proves that, at low altitudes, the displacement of particles from the shower axis produced by the earth's magnetic field is negligible in comparison with Coulomb scattering.

IT has been estimated by Cocconi[1] that the influence of the earth's magnetic field on the electrons (±) of an extensive air shower may not be negligible in comparison with the displacement of these particles from the shower axis due to Coulomb scattering. The calculations indicated that the lateral distribution of electrons around the shower axis should be not circular but elliptical, with the major axis in the east–west direction and, at sea level, twice as long as the minor axis. The earlier calculation of Cocconi was subsequently corrected[2] and the effect at sea level was re-estimated to be about 2%. However, in a recent investigation at 2634 meters (where the effect is considered to be larger) Chaloupka,[3] using counter telescopes inclined at 45°, found approximately 20% more shower particles arriving from E–W than from N–S directions. Since any ellipticity of shower structure at sea level would have complicated the interpretation of a shower experiment which we are performing in this laboratory at present, a preliminary analysis of our results was undertaken to assess the magnitude of this effect at sea level.

The experimental arrangement consisted of three proportional counters,[4] 0.05 square meter in area, arranged radially at the corners of a 5-meter equilateral triangle, one side of which was in the E–W direction, where the ellipticity is expected to be greatest. The remaining two sides lay in directions 30° E of N and 30° W of N, thus recording substantially the effect in the N–S direction. Triple coincidences from the counters were amplified and displayed on cathode-ray tubes where they were registered by a recording camera. The counters have been checked continually with the 46.7-kev γ-ray line from Ra D+E+F and have held their calibration over the course of the experiment.

The integral burst ratio distribution $A$ in Fig. 1 was constructed from the ratios of the pulse sizes (shower densities) in counters 1 and 2 lying in the E–W direction. The slope of such a distribution has been shown[5] to be independent of the shower size-frequency exponent γ, and dependent only upon the lateral structure function. The burst ratio distributions for pairs of counters lying in the three different directions are given by curves $A$, $B$, $C$ in Fig. 1, and the departure of each from the average distribution (full curve) may be

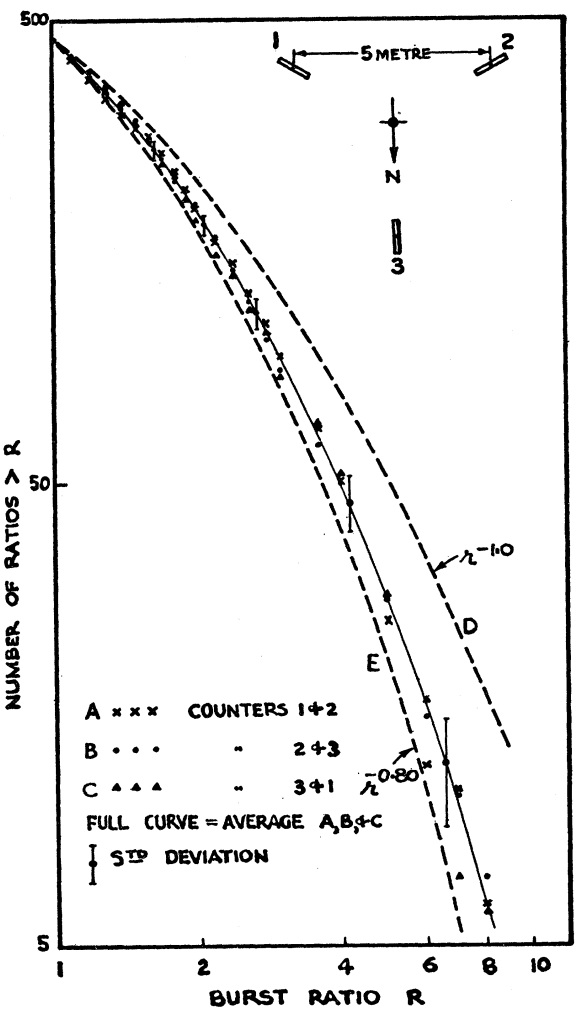


FIG. 1. Experimental distributions $A$, $B$, and $C$, obtained from counter pairs lying in different directions, are compared with two distributions $D$ and $E$ calculated for shower lateral structures of $r^{-1.0}$ and $r^{-0.80}$, which are more or less steep respectively than the average experimental lateral structure of $r^{-0.85}$.

---

[1] G. Cocconi, Phys. Rev. **93**, 646 (1954).
[2] G. Cocconi, Phys. Rev. **95**, 1705 (1954).
[3] P. Chaloupka, Phys. Rev. **96**, 1709 (1954); and Czechoslov. J. Phys. 4, 508 (1954).
[4] R. J. Norman, Australian J. Phys. **8**, 419 (1955).
[5] I. D. Campbell and J. R. Prescott, Proc. Phys. Soc. (London) **A65**, 258 (1952).

judged in relation to the two dashed curves. These were calculated on the basis of an electron density at a distance $r$ from the shower axis varying as $r^{-1.0}$ for $D$ and as $r^{-0.80}$ for E, representing structure functions which are more or less steep respectively than the average experimental value of $r^{-0.85}$. The lateral shower structure is the same in each of the three directions, within the experimental error of 4%. This places an upper limit of error on Cocconi's second calculation of approximately 2%, and shows that the effect of the earth's field on shower structure at sea level is negligible compared with Coulomb scattering.

PHYSICAL REVIEW VOLUME 101, NUMBER 4 FEBRUARY 15, 1956

# Analysis of the Small-Angle Elastic Scattering of High-Energy Protons by Carbon*

WARREN HECKROTTE
*Radiation Laboratory, University of California, Berkeley, California*
(Received November 14, 1955)

The usual treatment of the high-energy elastic scattering of protons by nuclei has been extended to include relativistic Coulomb corrections and a complex nuclear spin-orbit potential. With these additions it is possible to obtain a good fit of the experimental results on the polarization of high-energy protons scattered elastically by carbon for small scattering angles. In addition, it is possible to deduce the sign of the nuclear spin-orbit potential from the high-energy data alone. The significance of the imaginary spin-orbit potential is discussed.

## INTRODUCTION

THE elastic scattering and polarization of high-energy protons by nuclei has been studied previously by several authors.[1,2] In this note the small-angle polarization is examined somewhat more closely. In particular, relativistic effects arising through the Coulomb interaction are calculated and, in addition, the nuclear spin-orbit potential is generalized to be complex. The relativistic correction manifests itself as a spin-orbit potential, and it will appear that this additional potential has a noticeable effect on the polarization of the proton for small angles of scattering.[3] This, together with the generalization of the nuclear spin-orbit potential as complex, makes possible a good fit of the small-angle polarization data for carbon and a deduction of the sign of the nuclear spin-orbit potential from the high-energy data alone.[4] By limiting our considerations to small angles, we minimize model-dependent features (e.g., the shape of the potential well), which tend to be more marked at larger angles.

## COULOMB SPIN ORBIT POTENTIAL

To order $(v/c)$ the relativistic corrections to the Hamiltonian[5] arising from the Coulomb potential are given by

$$V=-\frac{i\hbar c^2}{4m^2c^4}\nabla V_c\cdot\mathbf{P}+\frac{\hbar c}{2m^2c^4}(\mu-\tfrac{1}{2})\boldsymbol{\sigma}\cdot(\nabla V_c\times\mathbf{P}),\quad(1)$$

where $V_c$ represents the Coulomb potential and $\mu$ is the magnetic moment of the proton. The nonspin-dependent term makes a small contribution and will be ignored. The spin-dependent terms arise from the magnetic-moment interaction and the Thomas precession. The contribution of a similar term from the potential will be ignored since it can be considered as being included with the usual nuclear spin-orbit potential. Similarly we can neglect the contribution of Eq. (1) coming from the Coulomb potential inside the nucleus. The additional spin-orbit potential obtained from Eq. (1) is thus given by

$$V=(-)\frac{\hbar^2Ze^2}{2m^2c^2}\frac{(\mu-\frac{1}{2})}{r^3}\boldsymbol{\sigma}\cdot\mathbf{L};\qquad r>R=\text{radius of charge distribution}$$
$$=0;\qquad r<R.$$

With the inclusion of this term in the Hamiltonian, the scattered amplitude will have the form,

$$f(\theta)=A_c+B_c\boldsymbol{\sigma}\cdot\mathbf{n}+C_c\boldsymbol{\sigma}\cdot\mathbf{n}+A_n+B_n\boldsymbol{\sigma}\cdot\mathbf{n}.$$

The vector $\mathbf{n}$ is the unit vector normal to the plane of scattering and is taken to be positive for scattering to the right. The amplitude $(A_c+B_c\boldsymbol{\sigma}\cdot\mathbf{n})$ represents the Coulomb scattering of a proton from a point charge; $(A_n+B_n\boldsymbol{\sigma}\cdot\mathbf{n})$ represents the nuclear scattering modified in the usual way by the presence of the charge distribution. $C_c$ is the spin-dependent correction to the

* This work was performed under the auspices of the U. S. Atomic Energy Commission.
[1] Fernbach, Heckrotte, and Lepore, Phys. Rev. **97**, 1059 (1955).
[2] R. M. Sternheimer, Phys. Rev. **97**, 1314 (1955).
[3] This particular point was discussed with reference to neutrons by J. Schwinger, Phys. Rev. **73**, 487 (1948).
[4] The sign of the polarization has of course been deduced by the measurements of L. Marshall and J. Marshall, Phys. Rev. **98**, 1398 (1955).
[5] L. Rosenfeld, *Nuclear Forces* (Interscience Publishers, Inc., New York, 1949), p. 315.