Polarization of Protons by Scattering from Beryllium*

H. G. DE CARVALHO,† J. MARSHALL, AND L. MARSHALL
Institute for Nuclear Studies, The University of Chicago, Chicago, Illinois
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The polarization of high-energy protons scattered from beryllium has been investigated as a function of energy and angle of the scattered protons. It was found that the elastically scattered protons are much more strongly polarized than the quasi-free nucleon-scattered protons.

INTRODUCTION

THE possibility of spin polarization of high-energy nucleons was adumbrated in 1951 by an experiment of Wouters[1] who looked for such an effect to occur in *n-p* interactions. A couple of years later, large polarizations of high-energy proton beams were discovered by Oxley and co-workers[2] in the scattering of 220-Mev protons. In their experiments the fractional polarization of protons first scattered from a given element was estimated from the measured asymmetry of second scattering from an effective hydrogen target. Using first and second scattering angles of about 20° and 25° respectively, they measured polarizations of 20 percent for H, 45 percent for D, about 45 percent for Li, Be, B, and Cu, and about 25 percent for Al, Si, and Ag. The energy and angle of first scattering were such that for all these elements it was believed that the scattered protons were produced mainly by nucleon-nucleon scattering in the nucleus (hereafter called "quasi-free nucleon scattering") and to a negligible extent by diffraction scattering. Preliminary reports of the large polarizations found by Oxley *et al.* led us to look for a similar effect at 340 and 430 Mev. We made double-scattering experiments[3] with beryllium, both scatterings being made at about 30°. This investigation required energies and angles for scattered protons consistent with quasi-free nucleon scattering and showed zero asymmetry of double scattering within about four percent statistical error. Since the polarization varies as the square root of one-half the asymmetry, it follows that around 30° the polarization in beryllium due to quasi-free nucleon scattering is not larger than $(0.02)^{\frac{1}{2}}=15$ percent at these energies.

An important discovery in the field of high-energy proton polarization was made at Berkeley, and was reported at the October 1953 Physical Society meeting by Professor Emilio Segrè. He described preliminary results of his group indicating production of a high-energy polarized proton beam by small angle scattering from carbon. Following this event, the polarization of hydrogen for protons was measured,[4–6] with the aid of beams polarized by the method of small angle scattering.

Using a polarized 310-Mev beam, we investigated the polarization of beryllium by measuring the asymmetry of second scattering from an external beryllium target as a function of angle and energy. At each angle investigated, the marked increase in asymmetry with increasing energy of the scattered protons led to the conclusion[5] that the elastic scattering from the beryllium nucleus was the main polarized component and showed large polarization (up to 80 percent). Polarization by quasi-free nucleon scattering was apparently much less important, but no reliable decision could be made on the basis of those data[5] as to whether or not it was polarized at small angles.

Recently, measurements similar to those on beryllium have provided evidence that also for elements other than beryllium and over a range of energies, polarization by elastic scattering is much larger than polarization by quasi-free nucleon scattering. Evidence for large polarizations by elastic scattering of 133-Mev protons from carbon and uranium has been reported by Dickson and Salter.[6] A similar measurement on carbon for 310-Mev protons indicating strong polarization by elastic scattering has been made by Segrè and co-workers.[7]

An explanation of proton polarization by elastic scattering has been proposed[8] in terms of a spin-orbit interaction of proton and nucleus of the same magnitude as that assumed for the nuclear shell model. According to this explanation, one effect of the spin-orbit interaction is to cause the elastic scattering pattern to be shifted to somewhat smaller angles when the orbital angular momentum vector L is parallel to the proton spin and to somewhat larger angles when L is anti-

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† Now at the Conselho Nacional de Pesquisas, Rio de Janeiro, Brazil.

[1] L. F. Wouters, Phys. Rev. **84**, 1069 (1951).
[2] Oxley, Cartwright, and Rouvina, Phys. Rev. **93**, 806 (1954).
[3] Marshall, Nedzel, and Marshall, Phys. Rev. **93**, 927 (1953).
[4] Chamberlain, Segrè, Tripp, Wiegand, and Ypsilantis, Phys. Rev. **93**, 1430 (1954).
[5] Marshall, Marshall, and De Carvalho, Phys. Rev. **93**, 1431 (1953); De Carvalho, Heiberg, Marshall, and Marshall, Phys. Rev. **94**, 1796 (1954).
[6] J. M. Dickson and D. C. Salter, Nature (to be published).
[7] Chamberlain, Segrè, Tripp, Wiegand, and Ypsilantis, reported by Clyde Wiegand, invited paper at the Washington Meeting of the American Physical Society, May 1954 [Phys. Rev. **95**, 644 (1954)].
[8] E. Fermi, Nuovo cimento, April 1954, exact calculation privately communicated; W. Heckrotte and J. V. Lepore, Phys. Rev. **95**, 1109 (1954); B. J. Malenka, Phys. Rev. **95**, 522 (1954); Snow, Sternheimer, and Yang, Phys.Rev. **94**, 1073 (1954).

parallel. At angles near the elastic diffraction minima, these shifts in the elastic scattering pattern move the diffraction minima for the two cases apart in such a way that the polarization changes violently from positive to negative to positive with increasing scattering angle in the region of a diffraction minimum.

At least this is true if one assumes a potential well with a sharp edge. For an actual nucleus, one supposes that the edge is not well defined, and consequently, that the polarization will show dips instead of changes in sign near the diffraction minima. In agreement with the predictions of the spin-orbit coupling hypothesis, a strongly marked dip has been reported in the polarization by elastic scattering of 310-Mev polarized protons from aluminum.[7]

In the case of the lightest nuclei, the concept of a sharp-edged potential well is even less realistic and one might expect the dips in the polarization curve to be less evident. In the case of carbon[7] and beryllium[9] for elastic scattering of 310-Mev protons, the dips have been looked for and are not as yet in evidence.

As for quasi-free nucleon scattering, investigations made on carbon show that both *p-p* and *p-n* nonexchange collisions[10] at 310 Mev produce about 25 percent maximum polarization. The *p-n* exchange collision produces about 25 percent maximum polarization at 310 Mev[10] and about 20 percent maximum polarization at 120 Mev.[11] These data give additional confirmation to the conclusion that polarization by quasi-free nucleon scattering is in fact small compared with polarization by elastic scattering.

In part, the present paper is a more complete report on the earlier work at 310 Mev,[5] containing as well more data which have accumulated in the meantime. Furthermore, it is a report of a similar set of measurements on polarization by elastic scattering of 435-Mev protons polarized from beryllium.

EXPERIMENTAL

Two mechanisms are known by which fast protons scattered from nuclei can be polarized, namely by scattering of the incoming proton from the whole nucleus, a phenomenon in which all the component nucleons cooperate, and secondly by quasi-free nucleon collision, an event which to some extent resembles a free nucleon-nucleon collision. A complicating feature of the second mechanism is that the target nucleons have a momentum distribution characteristic of the nucleus which contains them.

The cooperative scattering apparently is complicated[12] in that the nucleus can be left in any of several excited states differing very little in energy. Groups of protons scattered in such a way as to leave the nucleus in different excited states have small energy differences compared with their kinetic energy of 300 or 400 Mev. Consequently, the cooperative scattering has a fine structure beyond the sensitivity of the measurements to be described here. In the present paper we call the entire cooperative phenomenon "elastic" for want of a detailed understanding of the process. The work to be reported here mainly gives information on polarization by the so-called elastic scattering.

An unpolarized beam, such as the circulating beam of the cyclotron, is one for which the expectation value of the spin in any direction is zero. Such a beam may be polarized by undergoing a spin dependent scattering. In this event there is no asymmetry of total number of scattered protons but there is an asymmetry of number of scattered protons of given spin direction, that is, for a given direction of scattering the scattered protons have a net polarization. The polarization at a given angle, $P(\theta)$, is defined as the difference between the fraction of the protons scattered with spin up and the fraction with spin down.

In general, if a polarized beam undergoes a spin-dependent scattering the probabilities for protons to be scattered on opposite sides of the beam will be different. For a scattering in the horizontal plane, the asymmetry, A, is defined as twice the difference between the numbers scattered to the right and to the left, divided by their sum. It is well known that the asymmetry resulting after the second scattering is maximal in the plane defined by the first scattering. There is no resultant asymmetry in a plane normal to the plane of the first scattering, and this fact is used to test that the detecting apparatus is properly aligned.

If the first and second scattering are equivalent, the asymmetry after the second scattering may be used to evaluate the polarization due to the first scattering of a previously unpolarized beam. The relationship is $P=(\frac{1}{2}\text{ asym})^{\frac{1}{2}}$. If a first scattering produces the polarization $P_1(\theta)$ and a second scattering would produce

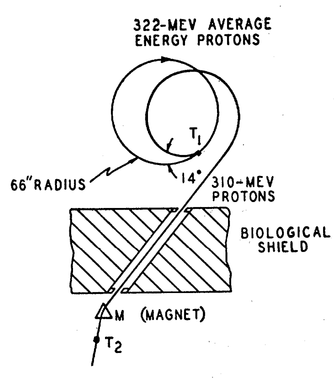

FIG. 1. Plan view of 450-Mev synchrocyclotron showing trajectory of proton beam.

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[9] De Carvalho, Heiberg, Marshall, and Marshall, reported by J. Marshall, invited paper at the Washington Meeting of the American Physical Society, May 1954 [Phys. Rev. 95, 644 (1954)].

[10] H. Bradner and R. Donaldson, Phys. Rev. 95, 1701 (1954).

[11] A. Roberts and J. Tinlot, reported by John Tinlot, invited paper, Washington meeting of the American Physical Society, May 1954 [Phys. Rev. 95, 644 (1954)].

[12] Karl Strauch, Rochester Conference on High Energy Physics, January, 1954 (University of Rochester, Rochester, 1954).

$P_2(\theta)$ in an unpolarized beam, the effect of the two in succession is to produce an asymmetry given by asym$=2P_1(\theta_1)P_2(\theta)_2$.

The plane of the first scattering was the plane of the rotating (unpolarized) cyclotron beam. Only protons scattered to the right at a well defined angle and energy could reach the experimental area, owing to the combined selective action of the collimating system (Fig. 1) and analytical action on the long proton trajectory by the magnetic field of the cyclotron and its fringing field. For the first scattering, the angle and energy loss corresponded to an elastic scattering.

For the lower energy experiments, an internal beryllium target (specified as T_1 in Fig. 1) was placed at 66 inches radius corresponding to 322-Mev average energy protons in the cyclotron. For the higher energy experiments, the internal beryllium target was placed at 76 inches corresponding to 440-Mev average energy protons. A beam of protons scattered from the beryllium target T_1 at angle θ_1 to the right was analyzed in the fringing field of the cyclotron and emerged through the shield into the experimental area.

After the collimated beam was further analyzed by a magnet M in the experimental area, it was incident on the second beryllium scatterer. The asymmetry of second scattering was measured with counters mounted on a framework which held them and swung them symmetrically about the beam as an axis. The description and method of alignment of this framework has been extensively discussed in a previous paper,[13] as has also the method of location of the deflected beam. Also included is a description of the method of adjustment of the scintillation counters in multiple coincidence. We omit further details here.

The spectrum of protons scattered from beryllium at a small angle θ may be roughly described as shown in Fig. 2. The elastically scattered protons are represented as a line, of slightly less than the incident energy E_1, whose width is determined by straggling in the

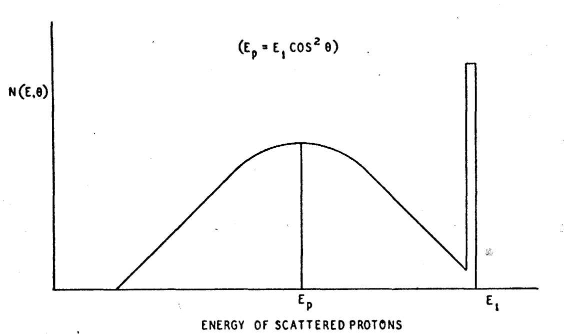
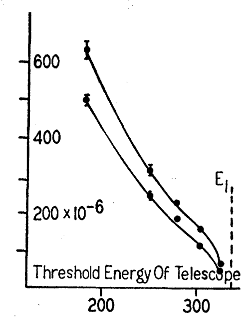


FIG. 2. Schematic diagram showing energy spectrum of protons scattered at angle θ when incident proton beam of energy E_1 strikes a nucleus. The line spectrum represents elastically scattered protons. The continuous spectrum at lower energies represents quasi-free nucleon scattered protons.

[13] Marshall, Marshall, Nagle, and Skolnik, Phys. Rev. **95**, 1020 (1954).

FIG. 3. Absorption curve (see reference 5) for doubly scattered protons (337-Mev protons scattered at 14°R from Be emerge with 331-Mev energy and are scattered a second time at $\theta_2=23°$ from 2-in. thick Be), showing counting rate left and right *versus* thickness of copper absorber. The elastic scattering cross section is not well measured by these data because the scattered protons are enormously attenuated in a complicated way by the copper absorber. However, since the attenuation is the same to left and right owing to the fact that counters and absorbers are rotated about the beam, the asymmetry of scattering is measured in a precise way.



scatterer. The quasi-free nucleon scattering is a broad band whose center of gravity is the energy of a free p-p scattering, $E_p=E_0\cos^2\theta$, whose shape is determined by the momentum distribution of the target nucleons in the nucleus.[14] At the highest energies, the quasi-free nucleon scattering becomes indistinguishable from elastic scattering. As the scattering angle decreases, the center of gravity of the quasi-free nucleon scattering, E_p, approaches the elastic scattering energy, so that more protons are scattered with energies in the elastic region. The situation would become quite ambiguous except for the fact that as the scattering angle decreases, elastic scattering becomes the major phenomenon, i.e., the area of the elastically scattered "line" becomes large compared with the area of the broad band. So for example at 310 Mev and at 10°, it is estimated that about 70 percent of the protons scattered from beryllium are elastically scattered.

To examine the asymmetry of the elastically scattered protons, as compared with the asymmetry of all scattered protons, varying thicknesses of copper are placed in front of the counters which detect scattered protons. When the copper absorber is very thin, almost all protons scattered by the two mechanisms are counted. As the absorber is made thicker, more and more of the quasi-free nucleon-scattered protons fail to reach the counters, so that one measures protons of which an increasingly larger fraction is elastically scattered. For the greatest thicknesses of absorber, the protons detected are almost entirely elastically scattered. At small enough angles, the elastic scattering dominates, and even for small amounts of absorber, or no absorber at all, the measured asymmetry is due mostly to elastically scattered protons. Figure 3 shows the behavior of the counting rates to the right and the left as the thickness of copper absorber is increased.

The dependence of asymmetry on scattering from Be as found by this procedure is shown for 310-Mev protons in Fig. 4 and for 430-Mev protons in Fig. 5. At all angles for which sufficient measurements were made, the asymmetry appears to rise to high values

[14] Cladis, Hess, and Moyer, Phys. Rev. **87**, 425 (1952).

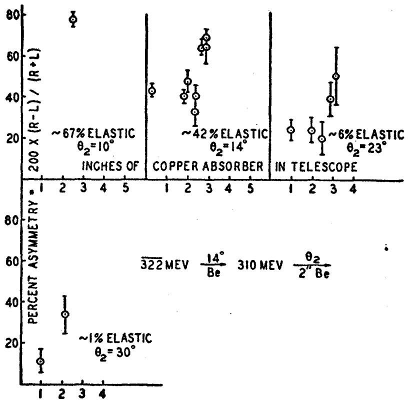


FIG. 4. Asymmetries measured for second scattering of protons from beryllium, as a function of thickness of copper in the detecting telescope, and as a function of laboratory angle, for 310-Mev, 55 percent polarized protons.

with increasing thickness of copper, from which the conclusion is drawn that the elastic scattering component is strongly polarized, and in fact, considerably more polarized than the nucleon-scattered protons.

The asymmetry as measured for small thicknesses of copper is large at small angles and small at large angles, varying roughly as the fraction of elastically scattered protons. This observation also supports the conclusion that the elastic scattering is considerably more strongly polarized than the quasi-free nucleon scattering.

The fraction of elastic scattering has been estimated using the elastic cross sections of beryllium measured by Richardson *et al.*[15] together with the differential cross sections for total scattering from beryllium as measured in the present experiment. The latter were measured directly by the triple or quadruple coincidence rate (two counters in incident beam plus one or two counters in scattered flux) divided by double coincidence rate (two counters in incident beam). The cross sections so measured were of 3 percent or 4 percent statistical accuracy but had a somewhat poorer over-all accuracy owing to the necessity to correct for loss of protons by nuclear scattering in the beryllium and copper. These estimated corrections ranged from 8 percent to 35 percent. Estimates of the percentage of elastic scattering so obtained are given in Fig. 4.

The polarization was estimated from the relationship $2P_1(\theta_1)P_2(\theta)=\text{asym}$. For example, the polarization of the 310-Mev proton beam may be calculated from the largest asymmetry observed for the case of $\theta_2=14°$. In this case, both first and second scatterings are elastic and at the same angle so that, except for a small difference in energy between the first and second scattering, $P_1(\theta_1)=P_2(\theta_2)$. One finds about 65 percent asymmetry in Fig. 4 from which $P=(\frac{1}{2}\times 0.65)^{\frac{1}{2}}=55$ percent polarization for the 310-Mev beam.

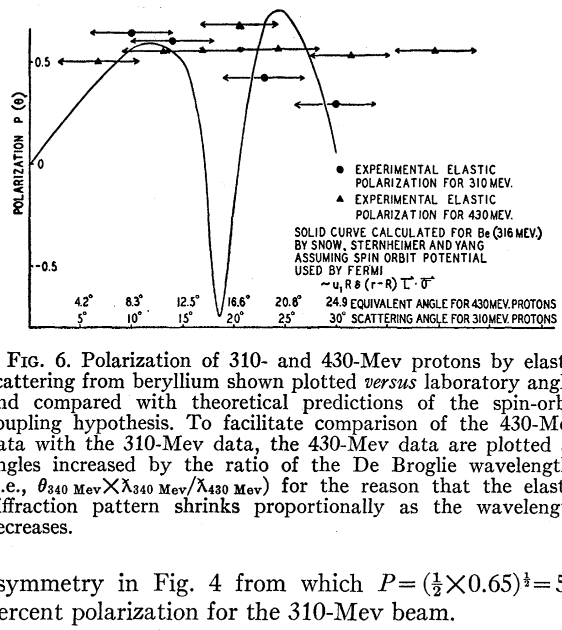


FIG. 6. Polarization of 310- and 430-Mev protons by elastic scattering from beryllium shown plotted *versus* laboratory angle, and compared with theoretical predictions of the spin-orbit coupling hypothesis. To facilitate comparison of the 430-Mev data with the 310-Mev data, the 430-Mev data are plotted at angles increased by the ratio of the De Broglie wavelengths (i.e., $\theta_{340\text{ Mev}}\times\lambda_{340\text{ Mev}}/\lambda_{430\text{ Mev}}$) for the reason that the elastic diffraction pattern shrinks proportionally as the wavelength decreases.

The 429-Mev beam was produced by elastic scattering at an estimated angle of about 5°. Its polarization is calculated from the asymmetry of elastic second scattering at 5.6°, for which case first and second scatterings are approximately equivalent. Since at this angle most of the scattering is elastic, the measured asymmetry probably does not increase much with thickness of copper, and consequently, one can use an asymmetry found for small thicknesses. We find an asymmetry of 45 percent in Fig. 5 and consequently, we estimate that $P=(\frac{1}{2}\times 0.45)^{\frac{1}{2}}=47$ percent polarization for the 429-Mev beam. In a similar way the polarization of the 439-Mev beam is found to be 55 percent from the data at 14° second scattering angle.

With the known beam polarizations and the maximum measured asymmetries at each angle, one readily evaluates the polarization of the elastically scattered component as a function of angle. These are shown

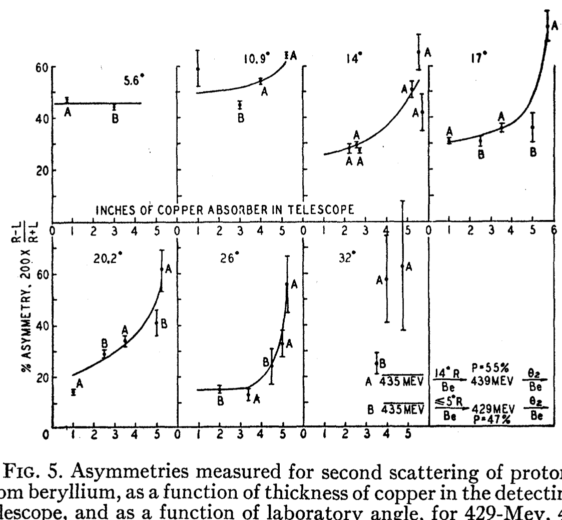


FIG. 5. Asymmetries measured for second scattering of protons from beryllium, as a function of thickness of copper in the detecting telescope, and as a function of laboratory angle, for 429-Mev, 47 percent polarized protons and for 439-Mev, 55 percent polarized protons.

[15] Richardson, Ball, Leith, and Moyer, Phys. Rev. 86, 29 (1952).

plotted in Fig. 6. The polarizations for the higher-energy beams are plotted there, also, and in fact are plotted at an angle increased by the ratio of the De Broglie wavelengths for 310 and for 430 Mev, accordingly as the elastic diffraction pattern shrinks with increasing energy. For comparison with the predictions of the spin-orbit coupling hypothesis,[8] the polarization of beryllium calculated for the lower energy is plotted. Although it would be preferable to recalculate this curve for the higher energy, yet one expects that probably it will be very much the same in its major features.

One sees that large dips in the elastic polarization curve are not in evidence. Higher proton intensities and, correspondingly, measurements with better angular resolution are needed to prove or disprove the existence of small dips. The present data suggest that a nuclear potential with smooth features such as a Gaussian would give a somewhat better description of the elastic polarization in light nuclei.

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Changes in Amplitude of the Cosmic-Ray 27-Day Intensity Variation with Solar Activity*

PETER MEYER AND J. A. SIMPSON
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois

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Both cosmic-ray neutron and ionization-chamber intensity observations reveal that the amplitude of the 27-day recurring intensity variation has been changing over an interval of several years. A method for studying this phenomenon using ionization chamber data for the period 1936–1946 and neutron intensity data for 1951–1953 is described which not only selects preferentially the 27-day variations but also selects the variations which are world wide.

The amplitude of the 27-day intensity variation over these years displays minima and a maximum closely related in time to the minima and maxima of the approximately 11-year cycle in general solar activity. Thus, these results provide additional, and independent, evidence that solar active regions are responsible for producing the mechanism which controls the 27-day cosmic-ray primary intensity variations.

I.

IN continuing the study of the 27-day recurring intensity variations[1,2] we have observed that the amplitude of this variation displays a remarkable decrease over the years 1951 to 1954. A network of widely distributed neutron intensity monitors was completed in 1951 to detect this world-wide variation in the low-energy portion of the primary cosmic radiation spectrum. It was clear from the measurements in 1951 that the amplitude of the variation was 4–5 times larger than the amplitude at high primary particle energy as measured by shielded ion chambers. In later years the relative amplitudes of the variations in the low and high energy parts of the primary spectrum have become increasingly difficult to measure because of the decline in the amplitude of the variations over these years.

Since individual solar regions have been associated with the 27-day recurring variations in 1951, and since the synodic rotation period for equatorial regions of the sun is $\sim$27 days, we have searched for an association between the decline of amplitude in the intensity variations and the changing level of solar activity over the $\sim$11-year solar "cycle." In this paper we propose to investigate this change of amplitude and demonstrate that a close association exists between this phenomenon and the general level of solar activity.

II.

The decline in amplitude of the mean daily 27-day neutron intensity is most readily demonstrated by using a method devised by Chree[3] for the analysis of recurrences of geomagnetic character figures. The method requires adding together the intensity of all days that display a maximum (or minimum) intensity. These days are called day zero. The summation is carried over the preceding and following days out to day n, where n extends beyond the period of the variation being investigated. This superposition of data will display any recurrence tendency among the maxima of mean daily intensities and give the average period of the recurrence. The Chree-type curves shown in Fig. 1 have been obtained for 10 neutron intensity maxima from eight months of data in 1951, 22 neutron maxima in

* Assisted by the Office of Scientific Research, Air Research and Development Command, U. S. Air Force.

[1] For example, A. T. Monk and A. H. Compton, Revs. Modern Phys. **11**, 173 (1939). A complete list of publications through 1951 is found in the review article by H. Elliot, *Progress in Cosmic Ray Physics* (North-Holland Publishing Company, Amsterdam, 1952), Chapt. VIII.

[2] J. A. Simpson, Phys. Rev. **94**, 426 (1954) and references therein.

[3] C. Chree, Trans. Roy. Soc. (London) **A212**, 75 (1913).