Evidence That Protons are the Primary Particles of the Hard Component

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EXPERIMENTAL and theoretical investigations seem to have established the following facts with reasonable certainty: (1) The cosmic radiation in the atmosphere consists of two components, the hard and the soft. (2) The primary particles which produce the soft component are electrons whose behavior in the atmosphere is described by the multiplicative theory. (3) The hard component is secondary to some other form of primary radiation and it consists of particles of intermediate mass called mesotrons. (4) The soft component accounts for most of the observed intensity in the upper atmosphere but the hard component predominates at sea level and below.

For a complete interpretation of the cosmic radiation it is still necessary to make some statement regarding the nature of the primary particles which produce the mesotrons of the hard component, and for this purpose there already exists some experimental evidence. In the first place it is known that those primary mesotron-producing rays whose energies lie within the field-sensitive range are almost entirely positive. This conclusion is reached by making a quantitative comparison of the east-west asymmetry which measures the excess of positive over negative primaries with the latitude effect which measures the total charged component. The energy ranges involved in the two effects have been calculated by Lemaître and Vallarta, and the details of the calculations involved in deducing the relative numbers of positives and negatives have recently been given in this Journal.[1] It was concluded that *most probably all of the field-sensitive intensity at sea level was produced by positive primaries and within the probable errors not more than ten percent could be produced by negatives.* Although this analysis refers to the total field-sensitive intensity at sea level there is little doubt that the hard component alone is involved, since practically no field-sensitive soft component rays reach sea level.[2]

The second point bearing upon our problem is that the soft component primaries seem to be equally positive and negative and therefore distinct from the primaries of the hard component. The first evidence of this fact was found in a study of the E.-W. asymmetry of showers at mountain top elevations within the equatorial zone.[3] Using a triangular arrangement of counters affording a good resolution with respect to the zenith angle the asymmetry of the shower-producing rays incident at zenith angles of 35° and 49°, respectively, was found to be less than two percent on the summit of Nevado de Toluca, Mexico (atmospheric depth 6 meters of water). This slight asymmetry associated with the shower-producing radiation and presumably belonging to the soft component was to be compared with a fifteen-percent asymmetry of the total radiation at the same station. Furthermore the symmetry of the shower-producing radiation could not be ascribed to a failure on the part of rays whose energies were within the field-sensitive range to penetrate to the level of the instrument, for the same arrangement of counters showed a variation of shower intensity with latitude at that elevation. It was therefore necessary to assume an approximate equality in the numbers of positive and negative primaries of the shower-producing rays.

What is probably a more convincing experiment leading to this same conclusion was recently carried out in Panama by the writer[4] in collaboration with J. G. Barry. In this work the asymmetry of the total radiation was studied at very high elevations with instruments carried by free balloons. Four flights in which the average intensities from the eastern and western halves of the sky at 60° from the zenith were compared showed that the western intensity was only about seven percent greater than the eastern intensity, whereas if all of the primaries of the soft component had been positive an asymmetry of sixty percent would have been expected,

[1] T. H. Johnson, Rev. Mod. Phys. **10**, 230–235 (1938).
[2] See reference 1, p. 228.
[3] T. H. Johnson, Phys. Rev. **47**, 318 (1935).
[4] T. H. Johnson and J. G. Barry, Phys. Rev. **56**, 219 (1939).

according to a calculation based upon Lemaître and Vallarta's theory and Bowen, Millikan and Neher's[5] determinations of the latitude effect at high elevations. This lack of asymmetry in the radiation was also confirmed on two other flights by an analysis of the fluctuations in the measurements of the intensity during time intervals small compared with the rotation period of the instrument. If we assume that the asymmetry amounts to seven percent, a simple calculation shows that 44 percent of the intensity is produced by negative primaries and 56 percent by positive primaries. In making this deduction it has been assumed that the rays passing through the instrument have the directions of the primary rays which produced them and if an asymmetry in the primary radiation were masked by a subsequent diffusion of direction of the secondaries the conclusion might not be valid. In attempting to account for a diffusion of this nature the effect of the earth's field in deflecting the less energetic secondaries has been considered[6] but it was found that rays whose energies were great enough to allow them to be recorded by our instruments would lie entirely within 30° of the primary direction and half of the intensity would be confined to within about five degrees from that direction. Hence no appreciable masking of a primary asymmetry could be accounted for in this manner. The angular divergence between secondaries and their primaries arising out of the radiative and pair formation processes and from subsequent scattering have been studied in the case of heavy materials with cloud-chamber technique.[7] Even in this unfavorable case, where the scattering should be far greater than in air, most of the particles whose energy would allow them to be recorded in our instruments were confined to within ten or twenty degrees of the primary direction and in air we may expect a much closer concentration in direction of the secondary particles. There seems therefore to be no appreciable correction to be applied to our results from either of these effects and we are left with the conclusion *that the soft component is produced by primary electrons whose signs of charge are almost equally divided between positive and negative.** Since the mesotrons are produced by predominantly positive primary particles these cannot be the electrons of the soft component[8] but they must consist of some other form of primary particle. The instability of the mesotron excludes the possibility that secondary mesotrons are produced by other primary mesotrons and we are left with protons or other heavier nuclear particles as the only reasonable possibility.

Strictly speaking, the above analysis of the primaries of the hard component applies to only the ten percent of this component which displays field-sensitivity, or to about two percent of the total incoming cosmic-ray energy. On the other hand these field-sensitive mesotrons appear, on the basis of their absorption, to be those of the lowest energies and it would be most natural to assume that the remaining 90 percent of the mesotrons at sea level are also produced by protons of higher energies. Since we also know that no appreciable part of the mesotrons are produced by field-sensitive electrons it would be unnatural to assume that higher energy electrons could produce the field-insensitive mesotrons.

There is also other independent evidence that electrons do not produce mesotrons. Neddermeyer and Anderson[9] and Street and Stevenson[10] have found that penetrating particles (mesotrons) are not in general associated with rays which produce showers (electrons), and a sensitive test of the absence of penetrating rays in electron-produced showers has recently been made by Jánossy.[11] What evidence exists for the

[5] I. S. Bowen, R. A. Millikan, and H. V. Neher, Phys. Rev. **53**, 855 (1938).

[6] T. H. Johnson, Phys. Rev. **56**, 226 (1939).

[7] E. C. Stevenson and J. C. Street, Phys. Rev. **49**, 425 (1936); see also reference 11.

* *Note added in proof.*—A recent flight has been made for detecting the contribution to our counting rate from showers originating in the air above and in the batteries beneath the counters, events to which the counter train would not be directionally selective. For this purpose the counters were alternated between an in-line arrangement similar to that used for measuring the asymmetry and an out-of-line arrangement with nearly the same spacing between counters. This flight showed that less than one-fifth of our counts could be attributed to showers.

[8] There seems to be no reason to suspect that positive electrons should be more efficient in producing mesotrons than negative electrons, and even if this were the case the above argument would still be valid because of the rapid multiplication of the soft component with the production of both positive and negative electrons by primary electrons of either sign.

[9] S. H. Neddermeyer and C. D. Anderson, Phys. Rev. **51**, 884 (1936).

[10] J. C. Street and E. C. Stevenson, Phys. Rev. **52**, 1003 (1937).

[11] L. Jánossy, Proc. Camb. Phil. Soc. **34**, 614 (1938).

production of mesotrons in showers[12] can be interpreted by the assumption that the mesotron-producing rays are either mesotrons or protons.

The position of the knee of the latitude effect is also in opposition to the assumption that mesotrons are produced by electrons, and it agrees better with the assumption that the mesotrons are produced by protons. The knee occurs at 40° latitude where the critical energy for electrons is 7.5 Bev. On the other hand the energy required for a mesotron to pass through the atmosphere is only about 2 Bev if the known ionization losses are taken into account. If the mesotrons were produced by electrons some of them should acquire the full energy and the knee of the latitude effect would be expected to occur above 50° latitude. On the other hand if protons are the primary mesotron-producers their critical energy for 40° latitude is 6.4 Bev and the maximum energy which a proton of that energy could impart to a mesotron in a head-on collision is only 3.1 Bev. The energy lost by a mesotron in passing through the atmosphere might be brought into agreement with this value if all types of energy losses were taken into account.

Experiments by Montgomery, Montgomery, Ramsey and Swann[13] have indicated that not more than five percent of the rays at sea level can be primary protons and similar upper limits to the proton intensity have been established by cloud-chamber analyses.[14] An absence of protons to this extent, however, cannot be taken as an objection to the assumption of primary protons for these would probably be prevented from reaching sea level because of nuclear absorption. A cross section of the order of πr_0^2 (the Thompson cross section) is equivalent to an absorption coefficient of 1.0 per meter of water or to a probability of 1 : 25,000 that a ray will reach sea level. Absorption coefficients of this order have been found for rays producing large bursts, nuclear evaporations, and neutrons and it is possible that some of these phenomena could also be ascribed to primary protons.

[12] J. C. Street, J. Frank. Inst. **227**, 765 (1939); see also accompanying papers by W. Bothe and W. F. G. Swann.
[13] C. G. Montgomery, D. D. Montgomery, W. E. Ramsey and W. F. G. Swann, Phys. Rev. **50**, 403 (1936).
[14] P. M. S. Blackett and J. G. Wilson, Proc. Roy. Soc. **A160**, 304 (1937); see also reference 11.

As a final argument for the existence of primary protons it may be shown[15] on the basis of very general and plausible assumptions regarding the electrical potentials in the space surrounding the source of cosmic rays that protons with high energy could be generated, regardless of whether the initial energy was acquired by (a) electrons or (b) protons. In case (a) the electron current would leave the source charged to a high positive potential and, in the electrostatic field thus created, the electrons would lose part of their energy and protons from a surrounding gaseous envelope would be accelerated. When equilibrium is established the two currents would just balance and at all distances from the source this condition would be expressible by the equation

$$\rho^+ v^+ = \rho^- v^-, \tag{1}$$

where ρ^+ and ρ^- are the space densities of positive and negative particles and v^+ and v^- are their average velocities. At great distances the space charge set up by the two kinds of particles must also cancel for otherwise, as Swann[16] has pointed out, potential differences irreconcilable with the observed passage of charged particles through space would develop. This consideration leads to the condition

$$\rho_\infty{}^+ = \rho_\infty{}^-, \tag{2}$$

where $\rho_\infty{}^+$ and $\rho_\infty{}^-$ are space charge densities at any suitably large distance from the source. Combining (1) and (2) we obtain

$$v_\infty{}^+ = v_\infty{}^-. \tag{3}$$

The ultimate velocities of the two types of particles are equal and consequently their energies must be in proportion to their rest masses. Thus the protons should have energies two thousand times greater than the electrons and they alone would be able to penetrate through the earth's field. The result is similar in the case (b), but the problem is complicated if the ionic conductivity of interstellar space is taken into account. However this does not necessarily seem to invalidate the above explanation of the origin of the proton component and it may also provide some interpretation of the origin of the soft component.

[15] T. H. Johnson, Phys. Rev. **54**, 385 (1938).
[16] W. F. G. Swann, Phys. Rev. **44**, 124 (1933).