The Determination of the Energy Spectrum of Primary Cosmic Rays

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WHILE in principle many effects depending on the action of the earth's magnetic field can be used for the determination of the energy spectrum of the primaries,[1] there are in fact two serious difficulties which stand in the way of a successful attack. One is that all intensity measurements must be made within the atmosphere which, again because of unwelcome phenomena related to the passage of high energy primaries through matter, acts mainly so as to blur the pure magnetic effect we are interested to know. The other is that some of the best-known magnetic effects most readily accessible to experiment, notably the latitude and the longitude effects, are notoriously insensitive to the primary energy spectrum. This difficulty would of course persist even if unwanted confusions due to the atmosphere could be eliminated by making observations clear at the top of the atmosphere. Hence the need of devising a simple experiment to satisfy the following requirements.

(a) The observations of the pure magnetic effect on which the deduction of the primary energy spectrum is to be based should be as slightly affected as possible by the earth's atmosphere.

(b) The pure magnetic effect in question should be sensitive to the primary energy spectrum, but independent of the presence of positive and negative primaries and of their ratio.

We now propose to show that the experimental investigation of the azimuthal effect, at the proper geomagnetic latitude, satisfies both of these requirements and is eminently suited for the determination of the primary spectrum. By "azimuthal effect" we understand the variation of intensity at a fixed zenith angle and for different azimuths.[2] By "intensity" we understand the number of particles in that direction per unit time.

At this point it becomes necessary to recall some of the fundamental results of the theory of the allowed cone[3] of cosmic rays resulting from the action of the earth's magnetic field on charged particles. The allowed cone is made up of the totality of all directions from which charged particles of a given energy may arrive at a given point of the earth. It consists of the "main cone" or "cone of full light" within which all directions are allowed, the "shadow cone" and the Störmer cone, outside of which all directions are forbidden. In the terminology we have adopted, the "penumbra" is the region between the main cone and the shadow cone within which certain patches or bands of directions are allowed and the rest forbidden. It is the existence of the penumbra which makes possible the determination of the primary energy spectrum in the manner to be suggested presently. The penumbra is not important at all latitudes.[4] Near the equator the region intermediate between the main cone and the Störmer cone is almost all dark, and the cone of full light is practically the whole allowed cone. At high latitudes the region in question is almost all lighted, the dark regions being relatively unimportant, and the shadow cone is practically the entire allowed cone. But at intermediate latitudes (between 10° and 40° geomagnetic) the penumbra makes a significant contribution.[5]

The banded structure of the penumbra gives rise to a series of humps in the azimuthal effect, which will be all the more marked the greater the number of primaries of low energy as compared with those of high energy. It is thus clear that, bearing in mind the existence of the penumbra, the azimuthal effect is in principle suitable for the determination of the primary spectrum. These contentions are fully borne out by R. Albagli Hutner's very complete determi-

[1] See, for example, the discussion by T. H. Johnson, Rev. Mod. Phys. **10**, 193 (1938).

[2] The azimuthal effect without taking into account the influence of the penumbra is discussed by G. Lema tre and M. S. Vallarta, Phys. Rev. **50**, 493 (1936).

[3] For a summary see reference (1), or M. S. Vallarta, J. Frank. Inst. **227**, 1 (1939). A more extensive review is given by M. S. Vallarta, *An Outline of the Theory of the Allowed Cone of Cosmic Radiation* (University of Toronto Press, 1938).

[4] E. J. Schremp, Phys. Rev. **54**, 157 (1938).

[5] R. Albagli Hutner, Phys. Rev. **55**, 15 (1939); **55**, 614 (1939).

nation of the penumbra at 20°,[5] to whose original papers the reader is referred for details and methods of analysis. A glance at her results (Figs. 3 to 6, reference 5) shows at once that the banded structure of the penumbra should make itself felt in the north to west quadrant, for positive primaries, and in the north to east quadrant, for negative, in which quadrants the energy range from 0.385 to 0.500 Störmers (8.8 to 14.9×10^9 ev for electrons) will be explored. Measurements of the azimuthal effect in the two quadrants from east to west through north would thus give the necessary data for the determination of the primary energy spectrum. That the azimuthal effect is indeed sensitive to the particular function describing the primary spectrum has also been shown by her. In the absence of obnoxious atmospheric phenomena, an experiment of the kind proposed here could easily distinguish, at a zenith angle of 50°, between a primary spectrum K/E^2 and $K/E^{2.5}$ for either positive or negative particles.

It remains to discuss now how far the proposed experiment could be expected to yield the necessary data when atmospheric phenomena, i.e., the generation and absorption of secondaries, is taken into account. An important feature of the proposed experiment is that, since the zenith angle is constant, the length of the air path is also constant. Let us now assume that the hard secondaries are mesotrons and the soft ones electrons (positive and negative) and examine how they would act as messengers of the primaries in an experiment of the kind we are discussing. First of all it is certain that the former will keep the direction of their progenitors. Will they be able to carry their message to an instrument within the atmosphere? How many hard secondaries will there be to each primary?

To answer these questions we have to rely on the theory of the mesotron as developed up to the present. To begin with, since the length of the air path is constant, and since the lifetime of a mesotron depends only on its energy, being quite ample, in the range of energies involved, to cover the distance between the top of the atmosphere and the point where the measuring instrument is placed, it seems certain that the mesotron will arrive at the triple coincidence counter apparatus without trouble. Conditions do not seem so favorable as far as the soft secondaries are concerned. For here, although the conservation of direction, which is a first requisite for the success of the experiment, is still largely assured if these secondaries are formed in a cascade process, and although it is possible to predict, with the help of the cascade theory, how many soft secondaries are produced out of a primary of given energy traversing a given thickness of air, it is not so easy to see how many secondaries would reach the triple coincidence counter generated by a single primary. Estimates can, however, be made, and in any case the soft primaries could be filtered off, in which case the experiment would yield only the energy spectrum of the primaries responsible for the production of hard secondaries. The final decision on this problem, however, rests in the hands of the quantum theory of high energy processes.

In view of these considerations, it would seem that an experiment of the kind discussed here warrants a serious effort. Dr. A. Banos, Jr., one of our former students and a valued collaborator, has agreed to carry out the experiment in Mexico City (geomagnetic latitude 29°, altitude 2240 m above sea level). The experiment will be made with a set of triple coincidence counters, with automatic recording, so designed as to make the complete turn of the horizon, while measuring simultaneously zenith angles from 15° to 75° by intervals of 15°. Since high precision is aimed at, it is intended to keep the instrument in continuous operation for at least six months. Its results will be awaited by many of us with great interest. The counters used in this experiment have been manufactured by the Massachusetts Institute of Technology under the directions and from designs of Professor Robley D. Evans, to whom we are deeply indebted for his cooperation.