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The Nature of the Soft Component of the Cosmic Radiation

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An inquiry is made into the nature of the corpuscular entities which possess the properties necessary to explain the soft component of the cosmic radiation on the basis of the recent theory of W. F. G. Swann. The conclusion is reached that the most likely entities are *protons* which lose energy according to the relation $-dE/dx=\lambda E+\alpha$, where α represents the energy lost per unit path by ionization, and λE the energy which goes into the production of secondaries in the amount that is actually observed in the form of showers.

SINCE the discovery of the latitude effect which demonstrated that there must be a corpuscular component of the cosmic radiation, there have been many attempts to find out what the nature of the corpuscular entities must be. The most complete treatment of this question has been given by A. H. Compton.[1] Compton has discussed the problem from the point of view that, to a large extent, the observed cosmic-ray particles are the primary entities themselves, and he has concluded that, at sea level, the hard component consists most probably of protons while the soft component may be ascribed to electrons. W. F. G. Swann[2] has discussed corpuscular theories from another point of view, namely, that the observed cosmic-ray particles are largely secondary in character, and that the number of secondary particles accompanying a primary one varies with the energy of the primary ray. If this view is adopted, then the considerations regarding the nature of the primary entities must be modified. It is the purpose of this paper to inquire into the nature of the primary entities from the point of view that the observed cosmic rays are largely secondary.

W. F. G. Swann has shown that the experimental data are well satisfied if it be assumed that the soft component of the cosmic radiation is corpuscular in nature and charged, and loses energy according to the relation $-dE/dx=\lambda E+\alpha$, where α represents the energy lost in the excitation and ionization of the atoms per unit of path, and λE is the energy which is lost by the production of secondaries. One of the numerical values of λ which results from these considerations is 0.3 per meter of water. It is our purpose to discover what the nature of the primary corpuscles must be in order that they should lose their energy according to this law with this value of λ. The only candidates which we need consider are protons and electrons, since particles of greater mass or larger charge will not be able to penetrate to any great depths into the earth's atmosphere.[1] The energy loss α is practically the same for both electrons and protons of high energy, and we cannot utilize its numerical value as a clue to the identity of the primary rays. Besides this constant energy loss, charged particles may lose

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[1] A. H. Compton, Proc. Phys. Soc. **47**, 747 (1935); Rev. Sci. Inst. **7**, 71 (1936).

[2] W. F. G. Swann, Phys. Rev. **47**, 575 (1935); **48**, 641 (1935); **50**, 1103 (1936).

energy by three processes: (a) by radiation, (b) by the production of pairs of electrons, and (c) by the production of showers. The cross sections for energy loss by processes (a) and (b) have been calculated by Bethe and Heitler,[3] and Nordheim.[4] The cross section for process (b) is only about 1/137 that for process (a). Although a theoretical mechanism for the production of showers has recently been given by Heisenberg,[5] and Oppenheimer,[6] the calculations are not as yet sufficiently detailed to give a value for the energy lost in this way. However, we may utilize the observations on the frequency of occurrence of showers to derive a value for this cross section in the following manner.

Let $F(E)dE$ be the number of primary rays of energy E crossing a unit area at sea level per second. The total amount of energy going into secondaries of these rays per unit path length is then $\int \lambda EF(E)dE$, where the integral is taken over all values of the energy. Let e be the average energy of a shower ray, and $R(N)$ be the frequency distribution of showers of N rays. For $R(N)$ we may take the experimentally determined form $R(N)=\gamma Z^2/N^3$,[7] and hence

$$\int \lambda EF(E)dE=\int_2^\infty eNR(N)dN=e\gamma Z^2/2.$$

Now the total flux of primary energy through our unit area is $\int EF(E)dE$. This energy will eventually all be dissipated in the excitation and ionization of atoms below sea level. If J is the average energy lost in producing one ion pair, and $I(x)$ the observed rate of ionization per unit volume caused by cosmic radiation at a distance x below sea level, then, neglecting the small amount of ionization produced below our unit area by secondary rays which originate above this area, the flux of primary energy is given by

$$\int EF(E)dE=J\int_0^\infty I(x)dx.$$

Thus we can find λ in terms of quantities which may be measured experimentally:

$$\lambda=e\gamma Z^2/2J\int_0^\infty I(x)dx.$$

A value for γ may be estimated from experiments by counters and by ionization methods. The counter observations are uncertain, on one hand, because of the difficulties in estimating the efficiency of a particular counter arrangement, and, on the other hand, the evaluation of the ionization experiments necessitates an uncertain extrapolation to the showers of smallest size. However, the values of γ obtained from the work of various observers[7, 8] vary from 0.7×10^{-5} sec.$^{-1}$ mole^{-1} to 5×10^{-5} sec.$^{-1}$ mole^{-1}, and we may take for these purposes the value of 2×10^{-5} sec.$^{-1}$ mole^{-1}. $I(x)$ may be taken from the observations of R. A. Millikan and his collaborators,[9] and we find, for the ionization produced by the soft component below sea level, the value of 7.1×10^4 ion pairs cm^{-2} sec.$^{-1}$. Assuming J as 32.2 ev, $Z^2=52$ for air, $e=10^8$ ev, we obtain $\lambda=0.16$ per meter of water.

The values of λ for the processes (a) and (b) may be calculated from the known expressions. Table I contains the values of λ for these methods of energy loss for protons and electrons in units of meter^{-1} of water. The value of λ which is to be compared to the 0.3 m^{-1} deduced from the theory of W. F. G. Swann is the sum of the λ's for all processes of energy loss with the exception of the energy lost by ionization and excitation of atoms along the path. Thus, even if we postulate that electrons are unable to produce showers, the total, theoretical λ for electrons is too large. On the other hand, if we assume that showers are not produced by protons, the theoretical value of λ is much too small. Thus it appears that *the soft component of the cosmic radiation consists of*

TABLE I. *Values of λ in meter^{-1} of water for energy lost by various processes.*

<table>
<tr><th>Energy loss by</th><th>Electrons</th><th>Protons</th></tr>
<tr><td>Radiation</td><td>2.2</td><td>$2.2/(1840)^2$</td></tr>
<tr><td>Pair Production</td><td>0.0073</td><td>$0.0073/(1840)^2$</td></tr>
<tr><td>Showers</td><td colspan="2">0.16</td></tr>
</table>

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[3] H. Bethe and W. Heitler, Proc. Roy. Soc. **A146**, 83 (1934).

[4] L. Nordheim, J. de phys. et rad. **6**, 135 (1935).

[5] W. Heisenberg, Zeits. f. Physik **101**, 533 (1936).

[6] J. R. Oppenheimer, paper delivered at the Harvard Tercentary Conference (1936).

[7] C. G. Montgomery and D. D. Montgomery, Phys. Rev. **50**, 490 (1936), and earlier references there given.

[8] H. Geiger and O. Zeiller, Zeits. f. Physik **97**, 300 (1935); J. C. Street and R. T. Young, Phys. Rev. **47**, 572 (1935).

[9] I. S. Bowen, R. A. Millikan and H. V. Neher, Phys. Rev. **44**, 246 (1933).

primary protons which lose their energy according to the law $-dE/dx=\lambda E+\alpha$, *where* λE *represents the energy loss by the production of showers.* The value of 0.16 for λ derived from shower data differs from the 0.3 required by Swann's theory only by a factor of two, well within the uncertainty of the data involved in calculating it. For example, if γ is taken as 4×10^{-5} sec.$^{-1}$ mole^{-1}, or e as 2×10^{8} ev, values well within the range of the observations, the λ calculated from shower production will agree exactly with that required by theory.

This hypothesis can explain, naturally, an east-west effect due to positively charged particles, which increases with altitude as does the soft component, although the detailed explanation of this effect is much more complicated than is suggested here. The hypothesis is not in contradiction with the recent experiments attempting to detect a proton component of the cosmic radiation,[10] since the actual number of protons passing through an area at sea level will be small compared to the number of secondary rays which accompany them. Thus, although the earth's magnetic field will affect the soft component of the radiation before it enters the atmosphere, and so produce the latitude and azimuthal effects, the cosmic-ray particles which will be observed will be, for the most part, positive and negative electrons: the shower particles which the primary protons have produced.

The recent theory of shower production of Heisenberg[5] results in the conclusion that about half of the energy lost by a primary ray in producing a shower will go into neutrinos, and it would seem necessary to take this into account by multiplying e, the energy of a shower ray, by a factor of two. However, this is not necessary, since again half, approximately, of the energy which passes through a unit area will also go into the production of neutrinos and not into the eventual production of ionization. Thus to the approximation considered here, the presence or absence of neutrinos does not influence the result.

The validity of the above choice of protons for the soft component primaries rests, of course, upon the assumption that Bethe and Heitler's theoretical formula for the radiation of fast electrons is correct for the energy range here involved. In the past, considerable doubt has been cast upon it, and several modifications[11] of the expression have been suggested. It is not our purpose to discuss these here except to point out that the recent results of Anderson and Neddermeyer[12] restore some confidence in the correctness of the formula. If the formula is proved to be invalid, however, the suitability of protons for the soft component is not affected, but we may also have to admit the possibility of electrons; electrons, however, which *do not lose energy proportionally to their energy*, and the corpuscular theory would have to be generalized to take this into account.

Thus, with due regard for the possible objections outlined above, the most probable entities which behave in a manner necessary to satisfy the requirements of the corpuscular theory of W. F. G. Swann for the soft component of the cosmic radiation are protons which produce secondaries in the numbers which are actually observed as showers. In conclusion, the authors wish to express their deep appreciation to Professor Swann for much valuable discussion, advice and criticism.

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[10] C. G. Montgomery, D. D. Montgomery, W. E. Ramsey and W. F. G. Swann, Phys. Rev. **50**, 403 (1936); R. B. Brode, H. G. MacPherson, and M. A. Starr, Phys. Rev. **50**, 581 (1936); C. G. Montgomery and D. D. Montgomery, Phys. Rev. **50**, 975 (1936).

[11] J. R. Oppenheimer, Phys. Rev. **47**, 44 (1935); L. W. Nordheim, Phys. Rev. **49**, 189 (1936); W. F. G. Swann, Phys. Rev. **49**, 829 (1936).

[12] C. D. Anderson and S. H. Neddermeyer, Phys. Rev. **50**, 263 (1936).