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A Search for Protons in the Primary Cosmic-Ray Beam[1]

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It has been suggested that a large proportion of the cosmic rays found at sea level are protons. Now a charged particle is characterized by the fact that its ionization increases enormously towards the end of its range, so that, in the case of protons and alpha-particles large and measurable spurts of ionization should be produced in relatively short distances by those rays which are ending their journeys. If r is the distance from the end of the range to the point where the ionization per centimeter of path is σ, then, the fraction of the rays which, passing through a length l of a vessel containing gas at pressure p, produce therein spurts of ions greater in number than $lp\sigma$, is $(1-e^{-\mu r})$, or approximately, μr, where μ is the absorption coefficient of the radiation concerned. The assignment of a lower limit to the spurts which can be measured determines σ, and so r, through the aid of Bethe's theory; and, it becomes possible to calculate how many such spurts should be observed if the rays are protons. In an experiment based upon the foregoing principles spurts above an assigned size (7.2×10^4 ion pairs in one experiment, and 3.9×10^4 ion pairs in another experiment) produced in a small ionization chamber were measured. To eliminate alpha-particles the chamber was divided into two halves by horizontal partition, and only spurts occurring simultaneously in both halves were counted. Spurts produced by "showers" were recognized and eliminated by suitably arranged Geiger counters. A conservative interpretation of the results gives an upper limit for the number of protons present as five percent of the total number of cosmic rays at sea level, or 12 percent of the intensity of the hard component if Compton's estimate of the absorption coefficient and intensity of the hard component be used. If Millikan's values are adopted our estimate of the upper limit is six percent.

It has been suggested[2] that a large proportion of the cosmic-ray ionization observed at sea level and below is produced by protons of high energy which have penetrated the earth's atmosphere. This conclusion has been reached as a result of studies of the variation of the intensity of the cosmic radiation over the earth's surface. To reach the earth's surface at a given point, the particles must have both sufficient energy not to be deflected away by the earth's magnetic field and sufficient penetrating power to traverse the earth's atmosphere. It is observed, at sea level, that the cosmic radiation in the northern hemisphere increases in intensity with increasing geomagnetic latitude up to a latitude of about 50°. From there northward, it remains quite constant. A natural interpretation of these observations is that at 50° the particles with just enough energy to penetrate the earth's magnetic field have a range of just one atmosphere, and at higher latitudes, the particles of lower energy which are not excluded by the field can no longer reach the earth's surface because they are stopped within the atmosphere. Thus, we know the energy and the range of a particle which just reaches sea level at a latitude of 50° and we may apply the theo-

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[1] Presented at the Washington meeting of the American Physical Society, May, 1936.

[2] A. H. Compton and H. Bethe, Nature **134**, 734 (1934); A. H. Compton, Rev. Sci. Inst. **7**, 71 (1936); A. H. Compton, Proc. Phys. Soc. **47**, 747 (1935); J. Clay, Physica **3**, 332 (1936).

retical formulae of Bethe[3] and learn with what kind of particle we are dealing. The assumption that these particles are protons gives the closest agreement with observations. Such considerations, taken together with the observations on the east-west effect,[4] which show that at least some of the primary cosmic rays are positively charged, constitute a strong body of evidence in favor of protons as a constituent of cosmic radiation.

A proton of sufficiently high energy to function as a primary cosmic ray would in all regions where it possessed that energy function as regards ionization in a manner indistinguishable from an electron. Only near the end of its range would its ionization characteristics serve to differentiate it from a particle of equal charge but smaller mass. It has been pointed out by one of us,[5] however, that if protons function as cosmic rays the number of them which while passing through an ionization chamber of relatively small size were sufficiently near the end of their range to produce measurable spurts of ionization would be appreciable for experiments of reasonable duration. A measurement of this number provides information on the extent to which protons figure in the total observed cosmic radiation.

Suppose we consider spurts of ionization in the chamber which are greater than S ions per spurt. A spurt S may be considered as produced by a particle traveling a distance l in the ionization chamber with specific ionization σ, where l and σ are such that S equals $l\sigma$. By employing Bethe's formula[3] for the energy loss of protons, we can determine the range, r, that such protons will have after they pass through the chamber. Then, if n be the number of protons which traverse the chamber with path lengths l or greater, the number which will produce spurts of ionization greater than S is $n\mu r$, where μ is the coefficient of absorption of the proton beam.

For μ and n, various estimates have been made. For example, Compton,[2] invoking Eckart's[6] analysis of the variation of the cosmic-ray ionization with elevation quotes, for μ, 0.08 per meter of water, and an intensity of the proton beam equal to 40 percent of the total cosmic-ray intensity. Millikan and his collaborators[7] give for the hard component of the radiation a value, among others, of $\mu=0.078$ per meter of water and an 81 percent intensity. Other estimates[8] do not differ greatly from these.

Experimental Procedure. Experiments to detect the spurts of ionization caused by protons were carried out in a thin-walled, cylindrical brass chamber 15.4 cm high and 6.7 cm in diameter, filled with nitrogen to a pressure of 14.7 atm. In order to eliminate the effects of alpha-particles, the chamber was divided in half by a thin copper diaphragm, placed horizontally, and only those spurts of ionization were measured which occurred simultaneously in both halves of the chamber. Each half of the chamber was furnished with an electrode to collect the ions and two FP–54 vacuum tube electrometers with photographic recording were employed. To minimize the statistical fluctuations in the ionization a potential of 450 volts was applied to the chamber. The presence of showers of electrons which passed through both halves of the chamber was recognized and the effect eliminated by the use of a system of Geiger-Müller counters whose discharges were recorded on the same photographic paper as the electrometer records. The arrangement of the counters and the chamber is represented diagrammatically to scale in Fig. 1. A group, B, of four counters, 10 cm long, were connected in parallel and placed as close as possible to the ionization chamber A. These counters acted as a master counter for the groups C and D. Groups C and D each consisted of seven counters, 20 cm long, and were arranged to record independently when any two or more counters in a group were discharged. Thus, a mark was made upon the photographic paper when at least one counter of group B and at least two counters of group C were simultaneously discharged, and similarly for group D. To increase the probability that a shower of rays be recorded, under each of the groups C and D were placed 0.6 cm of Pb which could scatter the shower radiation backward. It is intended to describe in detail the electrical circuits used for these purposes in a separate publication by one of us (W. E. R.).

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[3] H. Bethe, Zeits. f. Physik **76**, 293 (1932).

[4] T. H. Johnson, Phys. Rev. **48**, 287 (1935).

[5] W. F. G. Swann, Phys. Rev. **49**, 478 (1936).

[6] C. Eckart, Phys. Rev. **45**, 851 (1934).

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

[8] Cf., e.g., T. H. Johnson, Rev. Sci. Inst. **4**, 639 (1933).

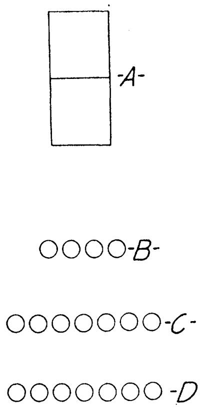

FIG. 1. Arrangement of ionization chamber and counters.

The observations were divided into two series. In the first, extending over a period of 175 hours, only those spurts of ionization of more than 7.2×10^4 ion pairs in each half of the chamber were counted. This limit corresponds to a specific ionization of the proton of 678 ion pairs per cm at atmospheric pressure after applying a small correction of the order of ten percent for lack of saturation.[9] The residual range of such a proton is 1010 cm, or $1010\text{ cm}-309\text{ cm}=701$ cm after it has passed through the chamber, and the proton would have an energy of 4.5×10^7 electron volts. The total number of cosmic rays which traverse the chamber and have path lengths in each half greater than half the length of the chamber is 300 per hour.[10] Hence we would expect to find during the 175 hours of observation 15 spurts of ionization, if Compton's estimate of μ and of the fraction of the rays which are protons is taken, or 30 spurts on Millikan's estimate. Actually we observed only twelve spurts of ionization of these sizes, of which ten were accompanied by discharges of the counters, leaving only two possible protons. This is considerably smaller than the expected number and we must conclude that such protons are not present to an appreciable extent. We also note that the counter arrangement used here is quite efficient for the detection of showers of rays which produce these amounts of ionization. However, it is reasonable to suppose that even the two spurts unaccompanied by counts were showers which the counters did not record.

While the foregoing results present, in the opinion of the writers, conclusive evidence, it was felt of interest to make an independent estimate of the possible number of protons based upon spurts of smaller size. The chief interest of such an estimate arises from the possibility of a proton disappearing by some nuclear collision act before its energy had become reduced to a value corresponding to production of spurts of ionization of the size assigned. Such a failure of the protons to die a natural death will of course invalidate the arguments above presented. The smaller the sizes of the spurts upon which the arguments are based, the more into the high energy region do we drive any proposed assumption as to disappearance of protons by nuclear encounters. Unfortunately when dealing with spurts of small size certain complicated considerations become involved which prevent the conclusion reached from depending upon considerations as clear-cut and definite, as those applicable to the experiments already cited. However, even for these spurts of smaller size the final evidence seems conclusive.

In the second series of experiments measurements were made of the number of spurts greater than 3.9×10^4 ion pairs occurring in 92.4 hours. This limit corresponds to 360 ions/cm at atmospheric pressure and would be produced by a proton of range 5100 cm and energy 1.0×10^8 electron volts. The expected number of spurts greater than this limit would be 55, using Compton's values, and 108, using those of Millikan. The number of spurts of this size observed was 62, of which 25 were accompanied by discharges of the counters. However, we must examine this result in more detail before we may draw a proper conclusion. First, the smaller spurts of ionization which we are now considering occur with a sufficient frequency that we begin to measure purely accidental coincidences between the two halves of the vessel. Of the 62 spurts counted, we estimate that 14 of them are accidental and should be disregarded. Secondly, the probability that a shower will be recorded by the counters will be lower than in the first series of observations, since the numbers of rays involved are smaller, and we should apply a correction to the number of bursts which are accompanied by counts.

In Fig. 2 are shown the frequency distributions

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[9] E. F. Cox, Phys. Rev. **45**, 503 (1934).

[10] J. C. Street and E. H. Woodward, Phys. Rev. **46**, 1029 (1934).

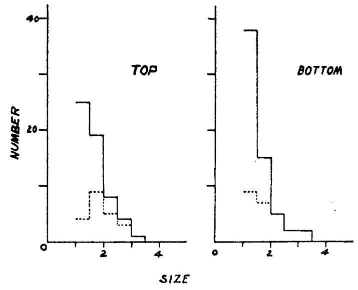

FIG. 2. Distribution in size of spurts of ionization occurring simultaneously in both halves of the chamber. Full line, all spurts; dashed lines, those spurts which were accompanied by counts.

of the bursts of ionization in each half of the chamber, together with those of the bursts which were accompanied by counter discharges. The similarity of these distribution curves to those obtained in a large double ionization chamber[11] is striking, and suggests that here we are dealing with the same phenomenon, and therefore that the spurts observed in the small ionization chamber are really caused by sprays of the electron type and not by protons. Particularly noteworthy is the fact that on the average the ionization produced in the top half of the chamber is larger than in the lower half, a circumstance which is easily explained as caused by the spreading out of a bundle of rays. A proton passing through the vessel would be expected to give a slightly larger ionization in the bottom half.

We may attempt to estimate the probability that the counters will record a shower, in the following way. Let the probability that group B be discharged be P_B, and let us assume P_C and P_D similarly for groups C and D. Then the probability that groups B and C are discharged and group D is not is $P_BP_C(1-P_D)$. Similarly for groups B and D and not C we have $P_BP_D\ (1-P_C)$, and finally, for all three, $P_BP_CP_D$. The ratio of the number of bursts of a given size recorded as accompanied by group C to the number of bursts accompanied by both groups C and D is then $(1-P_D)/P_D$. Thus we can calculate from the data P_C and P_D. The probability π, that a burst will be accompanied by some counter discharge will then be

$$\pi = P_B(P_C+P_D-P_CP_D). \qquad (1)$$

Table I shows the results of such a computation. Although the data are rather meager, it is evident that P_C and P_D are not low even for the smaller sizes of spurt.

To find the probability π, it is necessary to obtain also P_B. We may distinguish two extreme cases. First, it may be supposed that the spreading of the shower is negligible, so that it is sufficient, for the calculation of P_B, to assume that all the rays of the shower travel along the same line. Secondly, it may be supposed that the spread of the shower is large enough so that the shower always covers the entire area of the lower half of the chamber. We may expect the correct value of P_B to lie between the extreme values calculated from these two assumptions. Now, the solid angle subtended by the counter group B at a point within the top of the ionization chamber is about one-fourth of the solid angle subtended by the bottom of the ionization chamber. Therefore, for the first case cited above, P_B would be $\frac{1}{4}$. For the second case, P_B would be given by the expression:

$$P_B = 1-(1-\tfrac{1}{4})^n, \qquad (2)$$

where n is the number of rays in the shower.[12] For the first group of sizes of spurts in Table I—that is, those spurts with sizes in the lower half of the chamber, between 3.9×10^4 and 5.8×10^4 ion pairs—the mean value of n is about 7, and P_B would be 0.86, from Eq. (2). Thus, we can set the limits of P_B, for the group of smallest spurts, corresponding to our two extreme assumptions as

$$0.25 < P_B < 0.86.$$

By Eq. (1), using the values of P_C and P_D found in Table I, we then estimate that

$$0.21 < \pi < 0.76.$$

We should expect the correct value of π to be closer to the lower limit than the upper, since the cloud chamber observations of Stevenson and Street[13] on the angular spread of showers of the order of seven rays show that more than 70 percent of the shower electrons lie within a cone of vertical angle 10°. A value of π equal to 9/27 would mean that all of the spurts observed, in the group of smallest sizes, were showers of electrons.

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[11] C. G. and D. D. Montgomery, Phys. Rev. **49**, 705 (1936).

[12] C. G. and D. D. Montgomery, Phys. Rev. **48**, 786 (1935).

[13] E. C. Stevenson and J. C. Street, Phys. Rev. **49**, 425 (1936).

Such a value of π is in every way reasonable. For the groups of larger sizes, π would be larger as is observed. Thus there is no evidence for the occurrence of any spurts of ionization other than those produced by "showers."

Hence in conclusion, as already stated, the experiments with larger spurts would require, in the 175 hours of observation, 15 spurts of a size greater than or equal to that assigned if Compton's estimate of μ and of the fraction of the rays which are protons is taken, or 30 spurts on Millikan's estimate. Only two spurts possibly explicable by protons were observed in these experiments. While the experiments with spurts of smaller size are not as conclusive, they are in every way consistent with the conclusions reached from the spurts of larger size. It is concluded that the observations here described place upon the number of protons which can be present in the cosmic radiation at sea level a much lower limit than that which has been assigned for them. We may set a conservative upper limit to the number present as 5 percent of the total number of cosmic rays at sea level, or 12 percent of the intensity of the hard component if Compton's estimate of the absorption coefficient and intensity of the hard component be used. If Millikan's values are adopted our estimate of the upper limit is 6 percent. These experiments do not, however, exclude protons as being the initiators of what is observed as the hard component of the cosmic radiation provided that the actual number of protons present is considerably less than the number of rays measured by counters as representative of the hard component. To utilize this loop hole of escape it would be necessary to assume that the protons act chiefly through the agency of secondaries produced along their paths in a manner such as has been proposed by one of us as representative of the mechanism of the corpuscular theory of cosmic rays.[14]

TABLE I. *Distribution in size, in the lower half, of spurts occurring in both halves of the chamber.*

Size in units of 3.9×10^4 ion pairs	No. of spurts, observed	No. of accidentals, estimated	No. of spurts accompanied by counts			P_C	P_D
			Groups *B* and *C* only	Groups *B* and *D* only	Groups *B*, *C* and *D*		
1–1.5	38	11	2	4	3	3/7	3/4
1.5–2.0	15	3	1	1	5	5/6	5/6
2.0–2.5	5	0	0	1	4	4/5	1
2.5–3.0	2	0	0	0	2	1	1
3.0–3.5	2	0	0	0	2	1	1
Total	62	14	3	6	16		

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[14] W. F. G. Swann, Phys. Rev. **48**, 641 (1935).