Double Cloud-Chamber Investigation of 500 m_e Particles in Cosmic Rays*

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The Princeton double cloud chamber was used to investigate the mass spectrum of long-lived cosmic-ray particles between the μ-meson and the proton masses. It was operated at two locations: (1) Echo Lake, Colorado (3250 m altitude and 42° geomagnetic latitude); (2) Princeton, New Jersey (sea level). The upper cloud chamber operated in a magnetic field of 5500 gauss. The lower chamber contained 7 copper plates of 1.27 cm thickness each. The range of a stopping particle was between 120 and 200 g/cm²Cu equivalent. No production layer was used. At Echo Lake a water Čerenkov counter was included in the counter arrangement to bias against μ mesons. The mass of every stopping particle was determined from momentum and range. A measurement of the ionization by droplet counting was possible in the upper chamber. No particle of about 500 electron masses was found in either run as compared to an equivalent flux of about 1000 stopped μ mesons at Echo Lake and 1500 stopped μ mesons at Princeton. These results are in disagreement with the Alikhanian experiment.

INTRODUCTION

THE existence of cosmic-ray particles of about 500 electron masses has been reported several times in the literature over the last ten years.[1–3] But it is primarily the work of Alikhanian *et al.*[2] which aroused so much interest in these particles. At 3200 m altitude and 32° geomagnetic latitude they operated two cloud chambers separated by a magnetic spectrometer in order to investigate the mass spectrum of cosmic radiation. The mass of particles stopping in the lower multiplate chamber was determined from momentum and range. The upper multiplate chamber served to detect the origin of the tracks. The range of stopping particles was between 55 and 96 g/cm² Cu equivalent. In a series of measurements Alikhanian *et al.* observed 255 μ mesons and 10 particles of about[4] 500 m_e (9 negative and 1 positive). These particles were not locally produced. Their apparatus was biased in favor of heavy particles. They calculated that the equivalent μ flux was 1160 μ mesons.

Since 1956 many attempts have been made to verify the existence of the X particle.[6–17] The present experiment is one of these. The first series of measurements has already been reported.[6,7] The main feature of the present experiment is that it duplicates almost exactly the Alikhanian experiment. The techniques used to detect particles are identical and, as far as our first series of measurements is concerned, it was carried out at almost the same altitude, geomagnetic latitude, and particle energy.

EXPERIMENTAL ARRANGEMENT

During the period 1957–1959 the Princeton double cloud chamber[5] was operated at two locations: (1) Echo Lake, Colorado (3250 m altitude and 42° geomagnetic latitude); (2) Princeton, New Jersey (sea level).

The upper chamber was in a magnetic field which averaged 5500 gauss and was used to measure the momentum of particles. It was filled with a mixture of 90% helium and 10% argon (by volume) so that ionization measurements by the method of droplet counting were possible. The lower chamber contained 7 copper plates, 1.27 cm thick each, representing a total range of 79.1 g/cm². It served to measure the range of stopping particles. Each chamber was photo-

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[1] J. G. Wilson, *Progress in Cosmic-Ray Physics* (Interscience Publishers, Inc., New York, 1954), Vol. II, Chap. II.

[2] A. I. Alikhanian, N. V. Shostakovich, A. T. Dadaian, V. N. Fedorov, and B. N. Deriagin, J. Exptl. Theoret. Phys. (U.S.S.R.) **31**, 955 (1956) [translation: Soviet Phys.—JETP **4**, 817 (1957)].

[3] G. K. Lindeberg, thesis, Princeton University, 1957 (unpublished).

[4] The particle of about 500 m_e will hereafter be called X particle.

[5] A. L. Hodson, J. Ballam, W. H. Arnold, D. R. Harris, R. R. Rau, G. T. Reynolds, and S. B. Treiman, Phys. Rev. **96**, 1089 (1954).

[6] *1958 Annual International Conference on High-Energy Physics at CERN* (CERN Scientific Information Service, Geneva, 1958), p. 153.

[7] P. A. Piroué, Thèse No. 1289, Université de Genève, 1958 (unpublished).

[8] J. W. Keuffel, R. L. Call, W. H. Sandmann, and M. O. Larson, Phys. Rev. Letters **1**, 203 (1958).

[9] E. Bierman, R. Lea, J. Orear, and S. Rosendorff, Phys. Rev. **113**, 710 (1959).

[10] R. Giacconi, H. Gursky, and A. Hendel, Bull. Am. Phys. Soc. **4**, 289 (1959).

[11] E. P. Hincks, Bull. Am. Phys. Soc. **4**, 7 (1959).

[12] M. Conversi, E. Fiorini, S. Ratti, C. Rubbia, C. Succi, and G. Torelli, Nuovo Cimento **9**, 740 (1958); **12**, 130 (1959); and Phys. Rev. **114**, 1150 (1959).

[13] I. B. McDiarmid, Phys. Rev. **115**, 1016 (1959).

[14] G. G. Fazio and M. Widgoff, Phys. Rev. **116**, 1263 (1959).

[15] G. G. Fazio and D. M. Ritson, Phys. Rev. **116**, 1267 (1959).

[16] L. Gilly, B. Leontic, A. Lundby, R. Meunier, J. P. Stroot, and M. Szeptycka, *1960 Annual International Conference on High-Energy Physics at Rochester* (Interscience Publishers, Inc., New York, 1960), p. 808.

[17] V. Cook, D. Keefe, L. T. Kerth, P. G. Murphy, W. A. Wenzel, and T. F. Zipf, (to be published).

graphed by two cameras at a stereoscopic angle of 17°. Particles which traversed the upper chamber and stopped in the lower one had a range between 120 and 200 g/cm^2 Cu equivalent.

The expansion of both chambers was counter-controlled. The experimental setup is shown in Fig. 1. Trays of Geiger counters are represented by A, B, C, D, E, and F. Trays A, B, and C are in coincidence. They insure that the incident particle is within the useful solid angle. Trays D, E, and F are in anti-coincidence. Counter D insures that only stopping particles will trigger the chambers while counters E and F are guard counters to eliminate wide showers. At Echo Lake a water Čerenkov counter functioning as a velocity selector was included in the counter arrangement in order to bias against very fast particles, thereby enhancing the number of heavy particles detected compared with the number of μ mesons. It was used in anticoincidence. Since the events reported by Alikhanian showed a complete lack of local production, no production layer was used. Therefore the chambers were primarily triggered by single particles stopping in the lower chamber.

Our apparatus was biased in favor of the detection of heavy particles since the magnetic field sweeps out some of the light particles that would have stopped in the lower chamber. The Čerenkov counter and multiple scattering added to this bias. For each run we calculated the ratio R of the recording efficiencies of the X particles and the μ mesons. The number of X particles is then compared to the "equivalent μ flux" which is the number of stopped μ mesons multiplied by the ratio R.

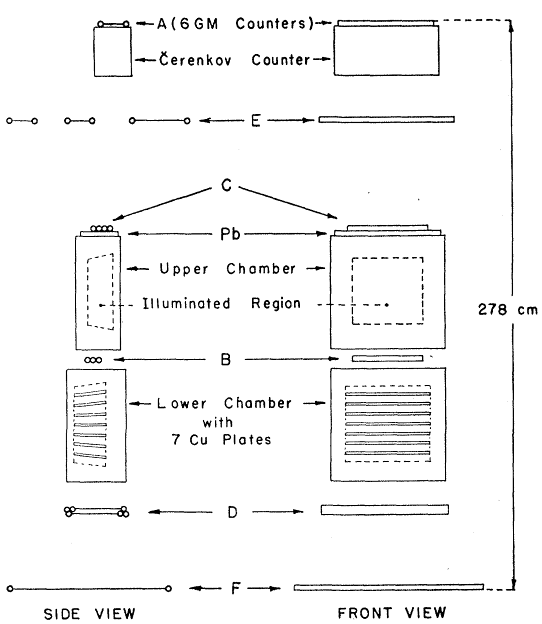

FIG. 1. Experimental setup for the Echo Lake run. The Čerenkov counter was not used at Princeton.

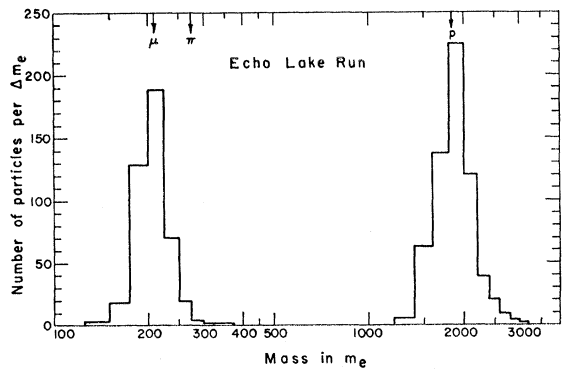

FIG. 2. Mass histogram representing the distribution of measured masses for the particles observed at Echo Lake. The mass interval Δm_e is 25 m_e for the μ mesons and 200 m_e for the protons.

ANALYSIS PROCEDURE

The mass of a stopping particle was determined from momentum and range. The conditions of acceptance of an event were the following:

(1) The four stereoscopic photographs (two per chamber) must be of good quality and the track of the particle must appear on each photograph.

(2) The track ionization in the upper chamber must be consistent with the mass of the particle as determined from momentum and range.

(3) The track in the upper chamber must be properly aligned with the track in the lower chamber, taking into account the fringing magnetic field between chambers.

(4) In the lower chamber scattering angles and ionization between plates must be compatible with the mass of the particle as determined from momentum and range.

(5) The particle must not have undergone any visible nuclear interactions in the plates.

(6) The particle must have stopped well within the limits of the illuminated region.

The six conditions were checked by visual inspection. In the case of conditions (2)–(4), and (6) detailed measurements were made only for approximately 5% of the events, chosen at random. However, we were consciously biased in favor of X particles. For instance, if momentum and range measurements gave a mass between the proton and the μ-meson masses, a detailed study of origin, scattering and ionization was performed even if one or more of the above six conditions was not met. This bias was introduced in order to make sure that no X particle was accidentally overlooked. A π or μ meson leaving the illuminated region without stopping or a π meson undergoing a nuclear interaction will appear to have an anomalously high mass as determined from momentum and range alone.

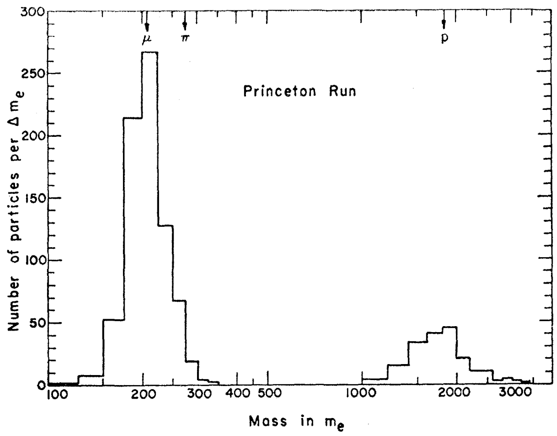

FIG. 3. Mass histogram for the Princeton run. The mass interval Δm_e is the same as in Fig. 2.

RESULTS

Echo Lake run (for which the ratio R of the recording efficiency of mass-500 particles to μ mesons was 2.4 ± 0.4). Among 16 300 pictures we found 432 μ mesons (possibly including a few π mesons), 620 protons and no particle of intermediate mass. Figure 2 shows the corresponding histogram. Therefore no particle of about $500m_e$ was observed as compared to an equivalent μ flux of $2.4\times432\approx1000$ μ mesons.

Princeton run (for which $R=2.0\pm0.3$). Among 8400 pictures we observed 760 μ mesons (also possibly including a few π mesons), 187 protons and no particle of intermediate mass. Figure 3 shows the corresponding histogram. For this run the equivalent μ flux was about 1500 μ mesons.

In both runs the range of a stopping particle was between 120 and 200 g/cm^2 Cu equivalent.

INTERPRETATION OF THE RESULTS

In order to compare the results of the present experiment with those of the Alikhanian experiment, we shall evaluate the 95% confidence interval for the X-particle flux relative to the μ flux.

Let F_μ be the μ-meson flux, F_X the $500m_e$ particle flux, and A their ratio:

$$A=F_X/F_\mu. \tag{1}$$

The distribution of particles in time is given by the Poisson distribution:

$$e^{-m}m^r/r!, \tag{2}$$

where r is the number of particles observed in a given time and m is $\bar{r}$, the mean of the distribution. As, according to the Alikhanian experiment, the X particles are not locally produced (similar to μ mesons), it has become customary to compare the X-particle flux with the μ flux. If the number of X particles relative to the total number of X and μ mesons is measured then the binomial distribution should be used:

$$P_{ns}(p)=[n!p^s(1-p)^{n-s}]/s!(n-s)!, \tag{3}$$

where n is the number of trials, i.e., the number of X particles and μ mesons observed, s is the number of successes, i.e., the number of X particles observed, and p is the probability of the event "X." In these conditions it is easy to show that

$$A=p/R(1-p), \tag{4}$$

where R is the ratio of the recording efficiency of X particles to μ mesons. The parameter p is obviously not known. All we can do is to find an estimate p^* of p. It is quite straightforward to show that the maximum likelihood estimator p^* of p is the sample proportion

$$p^*=s/n, \tag{5}$$

and therefore

$$A^*=p^*/R(1-p^*). \tag{6}$$

The problem is now to determine a confidence interval[18] $p_1\leqslant p\leqslant p_2$ corresponding to a confidence coefficient β. The interval $A_1\leqslant A\leqslant A_2$ is then obtained from (4). If p is the chance of success in one trial, it is ordinarily assumed that the relative chances of $0, 1, \cdots, n$ successes in n trials are distributed according to the magnitudes of the successive terms of the expansion

$$(q+p)^n=\sum_{i=0}^{n} P_{ni}=1, \tag{7}$$

where $q=1-p$. The expected number of successes is np. Let s be the observed number of successes ($s\neq0$). In order to find the confidence interval $p_1\leqslant p\leqslant p_2$ with confidence level $\epsilon=1-\beta$, one may select p_1 so that the sum T of the last $n+1-s$ terms of (7) is $\frac{1}{2}\epsilon$. Likewise, p_2 is then selected so that the sum D of the first $s+1$ terms of (7) is $\frac{1}{2}\epsilon$. The quantities p_1 and p_2 are therefore solutions of the two following equations:

$$T=\sum_{i=s}^{n}\binom{n}{i}p_1{}^i(1-p_1)^{n-i}=\frac{\epsilon}{2}, \tag{8}$$

$$D=\sum_{i=0}^{s}\binom{n}{i}p_2{}^i(1-p_2)^{n-i}=\frac{\epsilon}{2}. \tag{9}$$

Numerical values of p_1 and p_2 are obtained from tables.

The special case $s=0$ is of particular importance since no X particle was found. When $s=0$, $p^*=s/n=0$, but it does not follow that $p=0$. The interval $p_1\leqslant p\leqslant p_2$ for a confidence level ϵ becomes $0\leqslant p\leqslant p_2$, where p_2 is

[18] See, for example, R. S. Burington and D. C. May, Jr., *Handbook of Probability and Statistics with Tables* (Handbook Publishers, Sandusky, Ohio, 1953).

obtained from the equation

$$D=\sum_{i=0}^{0}\binom{n}{i}p_2{}^i(1-p_2)^{n-i}=(1-p_2)^n=\epsilon. \quad (10)$$

The result is

$$p_2=1-\epsilon^{1/n}, \quad (11)$$

and from (4) and (11) we find

$$A_2=(1/R)(\epsilon^{-1/n}-1). \quad (12)$$

The 95% confidence interval for the X-particle flux relative to the μ-meson flux is obtained from (12) with $\epsilon=1-\beta=0.05$. For the Echo Lake run $n=432$ and $R=2.4$; hence $A_2\approx0.3\%$. For the Princeton run $A_2\approx0.2\%$ ($n=760$ and $R=2.0$).

CONCLUSION

On the basis of the results obtained at Echo Lake alone where the whole experimental arrangement was very similar to Alikhanian's, we find that there is less than 1% chance that Alikhanian's sample and our sample were drawn from the same population. If, furthermore, we include the similar results obtained at Princeton we can only arrive at the conclusion that Alikhanian's evidence that the $500m_e$ particle flux amounts to 0.5% of the μ-meson flux is not supported by the results of this experiment.

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Theory of Nuclear Matter*

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The methods of quantum statistics previously developed by the author are applied to the determination of properties of the ground state of nuclear matter. An expansion in powers of the pair-function of quantum statistics is made and expressions are derived for the momentum distribution, pair-correlation function, binding energy, and effective single-particle energies. The leading terms of these expressions can be interpreted in terms of an effective two-body interaction, and a model of nuclear matter which consists of interacting quasi-particles whose energies are the effective single-particle energies is thereby suggested. The theory is compared with Brueckner's theory and also with Landau's phenomenological theory of the Fermi liquid.

INTRODUCTION

THE nuclear many-body problem began in the nineteen-thirties with the observation that the binding energy per nucleon as measured for nuclei over the full range of the periodic table is roughly constant and of order −8 Mev. This property is in direct contrast with the behavior of a system with long range forces in which the energy increases with the square of the number of particles. It was therefore deduced, even before any scattering experiments were performed, that nuclear forces are short-ranged. With respect to the constant nuclear binding energies it was said that nuclear forces lead to "saturation." The nuclear many-body problem later took on an additional spect when careful measurements of nuclear radii showed that the central density of nuclei was also essentially constant for all nuclei with nucleon number. $A\gtrsim30$. As a consequence of these observations, the concept of nuclear matter was introduced, in which both the Coulomb forces between protons as well as surface effects were assumed to be absent, since the additional complications presented by these effects are easily understood in a quantitative sense. In nuclear matter the number of neutrons equals the number of protons and these two different states are characterized by the two projections of the isotopic spin quantum number $I=\frac{1}{2}$.

With the concept of nuclear matter one is able to direct full attention towards understanding the phenomenon of the saturation of nuclear forces, and in fact one may consider the problem of infinite nuclear matter in this idealization. It is a solution of this problem to which the efforts of the present paper are directed.

An important measurable property of large nuclei is the momentum distribution $\langle n(k)\rangle$ of the nucleons. Although measurements of $\langle n(k)\rangle$ do not abound in the literature, it is known for light nuclei that there is a long tail in the distribution.[1] For very heavy nuclei, however, it is expected that the momentum distribution falls off rapidly for momentum values $k\gtrsim k_F$, where k_F is the maximum momentum of the corresponding ideal Fermi gas. This expectation is based upon the success

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[1] E. M. Henley, Phys. Rev. 85, 204 (1952); J. B. Cladis, W. N. Hess, and B. J. Moyer, Phys. Rev. 87, 425 (1952).