LIMIT ON THE PRESENCE OF HEAVY STABLE FUNDAMENTAL PARTICLES IN THE PRIMARY COSMIC RADIATION*

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An upper limit for the flux of heavy stable fundamental particles in the primary cosmic radiation is presented which is about two orders of magnitude less than that suggested to explain the anomalous cosmic-ray muon spectrum.

Cosmic-ray muons have traditionally been thought to originate in the decays of pions and kaons produced in the interactions of the primary radiation with atmospheric nuclei. This model predicts that the flux of sea-level muons, with energies in excess of about 50 GeV, should increase with increasing zenith angle; the dependence would be approximately proportional to the secant of the zenith angle at these very high energies.[1] Although the effect has been confirmed for muon energies extending up to at least 300 GeV,[2,3] recent measurements of the muon flux for sea-level energies in excess of 1000 GeV have found no zenith angle dependence.[4] As a possible explanation of this apparent violation of the model, Callan and Glashow[5] propose the existence of particles called U's that (1) are stable, (2) are singly charged, (3) have a rest mass greater than about 4 GeV/c^2 and so would not have been detected in accelerator experiments,[6] (4) do not interact strongly with atomic nuclei, and (5) make up 0.1% of the entire primary radiation. Particles that possess these properties would not be distinguishable from muons in experiments that measure the muon flux and would dominate the muon spectrum at very high energies. It is the purpose of this Letter to present an experimentally measured upper limit for the flux of U's in cosmic rays, and thus to demonstrate, under the assumption of a plausible primary spectrum of U particles, the unacceptability of this hypothesis as an explanation of the measured zenith angle dependence of the very high-energy muon spectra.

A search for massive, long-lived particles in cosmic rays has been concluded at the Brookhaven National Laboratory. The experimental arrangement has been described by Kasha and Stefanski,[7] and a detailed account of the experiment is being prepared for publication. In brief, the experiment consisted of a mass spectrograph: The particle mass was determined from a simultaneous measurement of the particle's time of flight and momentum. The search was carried out at a zenith angle of 75° facing due north at a geomagnetic latitude of 40°52′N. An upper limit of 2.4×10^{-4} (m^2 sr sec)$^{-1}$ was established for the heavy-particle flux for particles with velocities in the range $0.5c$-$0.75c$. Calculations based on the predicted properties of the U particles indicate that a flux of about 10^{-2} (m^2 sr sec)$^{-1}$ is required if these particles are to be responsible for the measured muon flux at energies above 1000 GeV. The measured upper limit on the heavy-particle flux then disproves the U-particle hypothesis.

Calculations of the flux of U's detectable by the experiment had to take into account the effects of the earth's magnetic field and atmosphere on the proposed U component of the primary radiation. Two considerations had to be taken into account: First, the experiment would have detected only particles with sufficient energy to penetrate the atmosphere and reach sea level with velocities in the range $0.5c$-$0.75c$. Second, because of their deflection in the earth's magnetic field, many low-energy particles do not reach the earth's surface. This low-energy cutoff, which is usually referred to as the geomagnetic cutoff, must be low enough to guarantee that U's might be present at sea level with momenta and velocities that could be measured by the spectrograph.

The U particles passing through the atmosphere will lose energy by ionization. Since the spectrograph is aimed at a zenith angle of 75°, the particles must penetrate about four times the depth of the atmosphere of air to reach the apparatus. Ionization losses in air[8] are about 2 MeV (g/cm^2)$^{-1}$ and thus the U's lose about 8 GeV

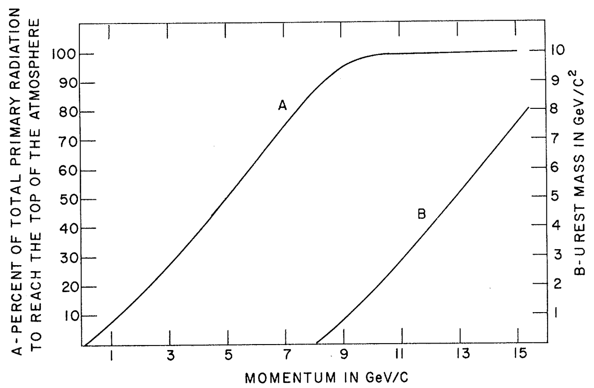

FIG. 1. Curve A, geomagnetic cutoff at 41.8°N latitude. Curve B, lower bound of the range of momenta studied in the experiment as a function of rest mass of the U's.

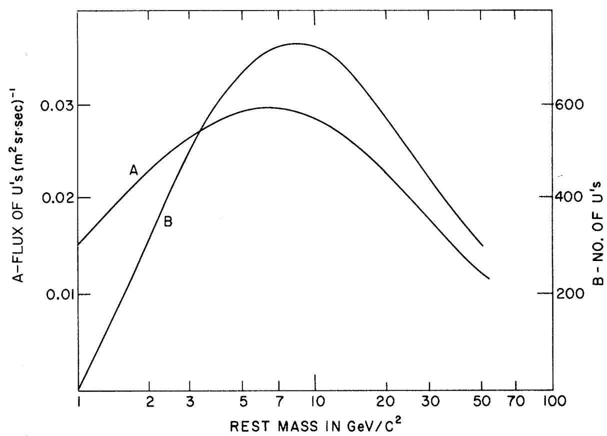

FIG. 2. Curve A, the flux of U's with velocities between $0.5c$ and $0.75c$ at sea level and incident at 75° to the vertical. Curve B, the number of U's that the experiment should have detected if these particles are the source of the anomalous effects in the very high-energy muon momentum spectrum.

in energy in getting from the top of the atmosphere to the spectrograph. Furthermore, particles of mass M with velocities between $0.5c$ and $0.75c$ will have energies between $1.16M$ and $1.51M$. Therefore, the range of primary U-particle energies studied in the experiment is given by

$$E=(8+1.16M) \text{ to } E=(8+1.51M), \tag{1}$$

where M is in GeV/c^2 and E is in GeV.

The fraction of total primary radiation that reaches the top of the atmosphere at 41.8°N latitude[9] is shown as a function of particle momentum in Fig. 1, curve A. Since the spectrograph was aimed due north at 75° to the vertical, the particles that reached the spectrograph entered the atmosphere at a slightly higher latitude than where they were detected. This correction of about 0.9° in geomagnetic latitude was taken into account in Fig. 1, curve A. In Fig. 1, curve B, the lower bound of the range of primary particle momenta studied in the experiment is shown as a function of U rest mass. A comparison of curves A and B in Fig. 1 indicates that, since the U rest mass must be greater than a few GeV/c^2, there is no attenuation of the U-particle flux due to the earth's magnetic field.

Having established the range of primary energies studied in the experiment and that particles with these energies will reach sea level, the flux of U's at sea level can be calculated if the energy spectrum of U's in the primary radiation is known. It is generally believed that the primary particles acquire their energy by being accelerated by the magnetic fields within the galaxy. In this respect U's and protons would be treated as if they were alike and, therefore, the spectrum of primary U's would exhibit the same momentum dependence as the spectrum of primary protons. Since U's must make up 0.1% of the primary radiation, the momentum spectrum of primary U's incident on the atmosphere would be given by[10]

$$N(>p)\simeq 8/p^{1.55}, \tag{2}$$

where p is the particle momentum in GeV/c and N is the number of particles/m^2 sr sec with momentum greater than p. The flux of U's can be calculated from (2) using the range of energies given in (1); the results are shown in Fig. 2, curve A.

The number of U's that the experiment would have detected during its 690 h of running is determined from the flux of U's and the acceptance of the spectrograph and is shown in Fig. 2, curve B. This curve shows that at least 100 U's should have been detected in the experiment if the rest mass of the U particle is greater than a few GeV/c^2. Only eight possible heavy particles were detected in the experiment: Calculations indicate that these are consistent with background. Therefore, the anomalous effect in the very high-energy muon spectrum cannot be explained by the existence of U particles.

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[1]P. H. Barrett, L. M. Bollinger, G. Cocconi, Y. Eisenberg, and K. Greisen, Rev. Mod. Phys. 24, 133 (1952).

[2]W. F. Nash and A. W. Wolfendale, Phys. Rev. Letters 20, 698 (1968).

[3]R. J. Stefanski, R. K. Adair, and H. Kasha, Phys. Rev. Letters 20, 950 (1968).

[4]H. E. Bergeson, J. W. Keuffel, M. O. Larson, E. R. Martin, and G. W. Mason, Phys. Rev. Letters 19, 1487 (1967).

[5]C. G. Callan and S. L. Glashow, Phys. Rev. Letters 20, 779 (1968).

[6]D. E. Dorfan, J. Eades, L. M. Lederman, W. Lee, and S. C. C. Ting, Phys. Rev. Letters 14, 999 (1965).

[7]H. Kasha and R. J. Stefanski, Tenth International Conference on Cosmic Rays, Calgary, Canada (to be published), paper HE35.

[8]D. M. Ritson, Techniques of High Energy Physics, edited by R. E. Marshak (Interscience Publishers, Inc. New York, 1961), Vol. V, p. 526.

[9]The data for Fig. 1, curve A, are taken from G. Lemaître and M. S. Vallarta, Phys. Rev. 43, 87 (1933).

[10]The proton energy spectrum is given in W. R. Weber, Handbuch der Physik 46, 181 (1967), Part II.

PION FORM FACTOR AND $\pi\pi$ DIFFRACTION CROSS SECTION FROM CONSISTENCY RELATIONS AMONG pp, $p\bar{p}$, πp, AND $\pi\pi$ DIFFRACTION CROSS SECTIONS*

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Consistency relations among pp, $p\bar{p}$, πp, and $\pi\pi$ diffraction scattering cross sections and the pion and nucleon form factors are derived on the basis of the multiple-quark-scattering picture of elastic scattering of hadrons. The pion form factor is found to be similar to the nucleon form factor and the charge radius of the pion is $r_\pi \cong 0.65$ F in agreement with experimental evidence. The differential cross section for $\pi\pi$ diffraction scattering is found to be 4/9 times that of πp.

Interesting consistency relations among the leading diffraction peaks for pp, $p\bar{p}$, πp, and $\pi\pi$ scattering and the form factors of p and π are suggested from the systematics of the multiple-quark-scattering picture of high-energy elastic scattering of hadrons.[1] These consistency conditions are of greater generality than the multiple-quark-scattering picture from which they are drawn.[2] By means of these consistency relations, the form factor of π and the differential cross section for $\pi\pi$ diffraction scattering may be determined from the pp, $p\bar{p}$, and πp diffraction cross sections and the form factor of p. The results are that the pion form factor is found to be very similar to the nucleon form factor, and that the differential cross section for $\pi\pi$ diffraction scattering is 4/9 times the πp diffraction cross section. The charge radius of the pion is calculated to be $r_\pi \cong 0.65$ F, in good agreement with the best experimental values.[3,4]

In the self-consistent multiple-quark-scattering analysis of pp scattering, the amplitude for single (charge-independent) quark-quark diffraction scattering f_{QQ} is self-consistently determined from $d\sigma_{pp}{}^1/dt$, the pp cross section in the region of the first diffraction-scattering slope.[1] We have

$$f_{pp}{}^1(t) \simeq [3G_p(t)]^2 f_{QQ}(t), \tag{1}$$

and

$$d\sigma_{pp}{}^1/dt \simeq |f_{pp}{}^1(t)|^2. \tag{2}$$

The superscript 1 indicates that a quantity refers to the first diffraction-scattering slope for the process that is indicated by the subscripts, e.g., $d\sigma_{pp}{}^1$. $G_p(t)$ is the single-quark form factor of p.

Similarly, the single (charge-independent) quark-antiquark ($Q\bar{Q}$) scattering amplitude is self-consistently determined by fitting the first diffraction slope of the elastic $p\bar{p}$ cross section,

$$f_{p\bar{p}}{}^1(t) \simeq [3G_{\bar{p}}(t)]^2 f_{QQ}(t). \tag{3}$$

The single-$\bar{Q}$ distribution in $\bar{p}$ is the same as the single-Q distribution in p; so $G_{\bar{p}}(t) = G_p(t)$. The amplitude for the first diffraction slope for πp scattering involves a combination of QQ and $Q\bar{Q}$ single-scattering amplitudes,

$$f_{\pi p}{}^1(t) \simeq 3G_\pi(t) G_p(t)[f_{QQ}(t) + f_{Q\bar{Q}}(t)]. \tag{4}$$

$G_\pi(t)$ is the single-Q form factor of π, which is the same as the single-$\bar{Q}$ form factor of π. Similarly, the leading diffraction slope in $\pi\pi$ scattering involves a combination QQ, $Q\bar{Q}$, and $\bar{Q}\bar{Q}$ sin-