ARE ALL COSMIC-RAY MUONS REALLY MUONS ?

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We propose the existence of a new component of cosmic radiation to explain the recent discovery[1] that cosmic rays found in deep mines do not satisfy the "secθ law."[2] This component must make up about one thousandth of the primary flux and must consist of stable, massive, charged particles without strong interactions.

Energetic particles found deep underground are normally assumed to be muons produced by the chain: primary proton + atmospheric nucleus → energetic pion or kaon → muon. It is an inescapable consequence of this hypothesis that sea-level muons with energies much greater than 100 GeV must have a secθ angular distribution where θ is the zenith angle (this is because high zenith-angle pions spend a longer time in rarefied atmosphere and have a better chance of decaying before being absorbed).[2,3] However, recent observations[1] of cosmic rays at slant depths of 2000-8000 ft of rock (corresponding to sea-level muon energies of 10^3-10^4 GeV) reveal that the flux depends only on slant depth (i.e., energy), but not significantly on zenith angle, in violent disagreement with the secθ law.

This result might be explained by the action of a new production mechanism for muons which is either direct or mediated by very short-lived particles.[4] Any explanation along these lines must involve a radical departure from conventional physics. With this in mind, we wish to propose an alternative, and also radical, resolution of the problem: that a new, stable, charged particle lacking strong interactions exists and is present in primary cosmic radiation. We call this new particle U. These new particles will be seen in deep mines along with secondary muons, and they are not readily distinguished from muons. Because the primary radiation is isotropic, the deep-mine flux of U's is a function of slant depth only. If the U flux is large enough, the angular distribution of particles seen in deep mines is explained.

What are the properties of these U particles? Evidently, they are penetrating particles with no strong interactions. They are singly charged, or else their anomalous ionization would have been detected. Because no new stable particles have been discovered in accelerator experiments, the U's must be heavier than 2.5 GeV. To explain the failure of the secθ law, most of the particles seen below 2000 ft must be U's. Taking into account their range-energy relation and the known primary proton flux, we conclude that about one thousandth of the primaries with energies of 10^3 to 10^4 GeV are U's. It seems imperative to make a direct measurement of the mass of energetic particles seen in deep mines in order to test this hypothesis.

It is usually assumed that primary particles are accelerated by galactic magnetic fields, which should treat protons and U's similarly. Thus one would expect that 10^{-3} of all the primaries are U particles. This means that detectable quantities of U particles should have accumulated on Earth. What would be their fate? Positive U's, when they stop, bind electrons to form atoms chemically identical with hydrogen, but heavier. We estimate, assuming a constant cosmic flux over the earth's life, that 10^{-14} of the hydrogen in sea water should be this new "isotope." A combination of known isotope separation techniques and mass spectroscopy seems capable of detecting such a contaminant. Negative U's will bind to atomic nuclei with Z protons to form new "isotopes" of chemical species $Z-1$. Those stopping in the atmosphere will mostly convert nitrogen to heavy carbon, while those stopping in the sea will form heavy nitrogen. The eventual fate of these heavy "isotopes" is obscure to us, though some geologic or metabolic process could well concentrate them.

We can give no firm theoretical reason for the existence of the U particle. However, it should be noted that certain renormalizable models of weak interactions could involve just such stable particles as we imagine. These are the "box models" invented by Kummer and Segrê.[5]

Our explanation of the deep-mine experiment is undeniably radical, since it requires that the particles seen deep underground not be muons. However, any explanation of the experiment requires new physics of one kind or another. Let us convince the reader that this is so.

It is clear that the electromagnetic production of muon pairs by the primary protons or their progeny cannot compete with the strong production of pions which then decay. Of course, there could be a primary component of energetic photons, of mysterious origin. If they were 100 times as copious as primary protons in the 10^3- to 10^4-GeV range, they would produce enough muons to explain the deep-mine experiment. Unfortunately, such a photon flux would produce far more energetic electron showers than are seen.

One may also imagine a direct strong coupling between muon pairs and hadrons, somehow effective only at high energies. But then energetic muons would be strongly scattered and could hardly be expected to reach the surface of the earth.

Next, one may invoke the long-sought intermediate vector boson, W. If its mass is less than 30 GeV, then it may be produced by 1000-GeV primaries. Its dimensionless coupling constant in this case is less than α, and it is unlikely that enough would be made to give the required isotropic muon flux. On the other hand, if it is much heavier than 30 GeV, it can only be produced by the most energetic primaries, which are very scarce.

Enough W's may be produced if they are given new, strong, quadratic couplings to hadrons.[6] However, this hypothesis is not without its difficulties, for it appears to destroy universality and it leads to the appearance of unobserved neutral lepton currents. Although these difficulties may be surmountable, the resulting theory certainly represents a radical departure.

Finally, one may conjecture the existence of a brand-new strangeness quantum number and a new family of hadrons which decay by weak interactions. Accelerator experiments tell us that these particles must be heavier than a few GeV. Like strange particles, they would be produced strongly in pairs and would decay weakly. If their lifetimes were so short that they would decay before interacting, they could provide a source of isotropic muons. To explain the deep-mine experiment the new particles must be produced, at high energies, one tenth as copiously as pions, and they must have a large branching ratio into muons. We regard this as a conceivable but unlikely possibility.

This brief survey of possible explanations shows that they all involve new particles and new interactions. Our proposal is no more radical than any other, is fascinating in the technological and scientific vistas it opens, and has the virtue of being easily tested by relatively simple cosmic-ray experiments.

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

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

[3] At the lower energies studied in Ref. 1, the secθ law is not fully effective for the muonic progeny of kaons. As the authors of Ref. 1 demonstrate, even if all the "muons" descended from kaons, their result could not be explained.

[4] This explanation is proposed in Ref. 1.

[5] W. Kummer and G. Segrè, Nucl. Phys. 64, 585 (1965).

[6] T. Ericson and S. L. Glashow, Phys. Rev. 133, B130 (1964).