other required rule is that no transitions are allowed from a solid band on the left to a dashed band on the right since this does not leave behind a $3d^7$ core state. Our single-particle representation of the many-electron states thus gives us a simple model for displaying the lowest excitations needed to describe both the localized optical spectrum and the bandlike conduction in NiO.

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SEARCH FOR MASSIVE PARTICLES IN THE COSMIC RADIATION AT SEA LEVEL*

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We have found no evidence for the existence of long-lived, massive particles in the cosmic radiation at sea leavel. The experimental limit for masses above 2 BeV/c^2 is 2.2×10^{-8} particles (cm^2 sr sec)$^{-1}$.

A search has been made at sea level for massive, long-lived particles that might be present in the cosmic radiation. The experiment, shown schematically in Fig. 1, consists of measuring the velocity of particles capable of traversing an aluminum absorber. For velocities measurably smaller than the speed of light, this corresponds to imposing a lower limit on the mass of the traversing particle. The velocity range accessible to our experiment is from 0.5 to 0.9c. The absorber is 195 g/cm^2 of aluminum which corresponds, for the above range of velocities, to a lower limit on the mass of 30 to 0.65 BeV/c^2.

The detectors are nine plastic scintillation counters each 36 in. long, 12 in. high, and 1 in. thick. Each counter is viewed by two RCA 7746 photomultipliers, one at each end. The counters are arranged vertically in banks of three giving detection areas of 36×36 in.^{2} and the banks are equally spaced at 14-ft intervals. The zenith angle for the central axis is 84°, and the solid angle subtended is 0.01 sr. A trigger is generated by the fast logic when there are signals from

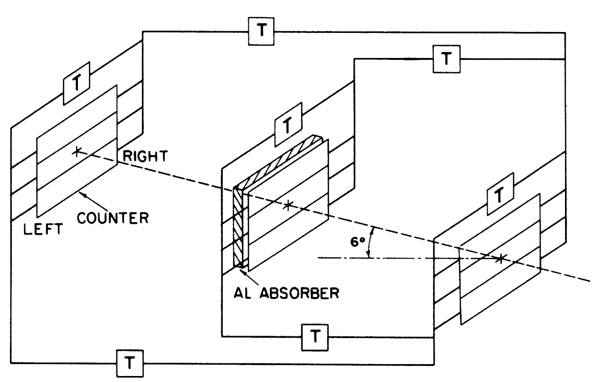

FIG. 1. Schematic of experimental setup and time-measurement arrangement. Each box labeled T indicates measurement of the time interval between the two signals entering the box.

both ends of each bank in coincidence. The timing requirements are left very broad, running over 50 nsec. Once a trigger occurs, the following information is stored: (1) time of flight between the first and the last, and the second and the last banks of counters, both from the right and left sides of each bank, (2) the time difference between the pulses from the left and right end of each bank of counters, (3) the pulse heights from each end of the three banks of counters, and (4) which of the 18 phototubes gave an output pulse during a 200-nsec interval centered around the trigger.

The correct time of flight between two banks of counters is obtained by averaging the left and right time intervals. The position of the traversal is computed from the time difference between the left and right signals for each counter bank. The velocity of the particles is computed using the same path length for all particles since the correction for the actual path is at most 0.6%.

The velocity range observed in this experiment is from $0.5c$ to $1.5c$. Since most, if not all, of the single-particle events which produce a trigger are muons, the time-of-flight spectrum is sharply peaked about $\beta = 1.0$. Figure 2 shows the time-of-flight distribution as obtained using the first and last bank of counters. The time of flight obtained using the middle and last banks is only used as a consistency check. The full width at half-maximum of the $\beta = 1.0$ peak is about 1.5 nsec. The full flight path corresponds to 29 nsec at the speed of light. The main problem lies in distinguishing the events on the tail of this muon time-of-flight distribution from events which are really slow, massive particles. To reduce timing errors associated with "walk," all events with pulse heights less than 0.25 V are removed from the data. (The discriminators are set at 0.1 V, and the average pulse height for a minimum ionizing particle is 0.5 V.) Events are also removed for which the positions determined in each of the three counters do not fit a straight line. The above cuts of the data remove about 11% of the single-particle events and the "live time" for the experiment is corrected for their removal. The rejected events are shown by the shaded area in Fig. 2. The peaking of the velocity spectrum at the high end is due to vertical showers simulating single-particle events. In addition, there are multiple-particle events in which two or more counters in a bank give an output. These events are not considered as possible candidates for massive particles since the timing measurements are ambiguous. Because of this, the experiment is not sensitive to massive particles which might be associated with electromagnetic showers or other multiple-particle events.

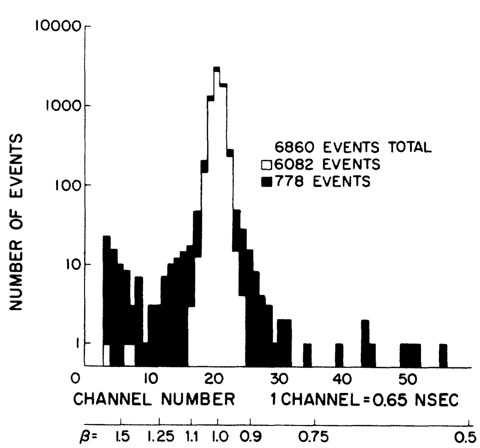

FIG. 2. Time-of-flight spectrum. Events in black are those removed by pulse-height and linear-fit cuts.

The experiment was run for 157 h. (This figure includes corrections for the events removed.) No events were observed with a velocity between 0.5 and $0.9c$. Taking one event as an upper limit, the flux of massive particles is computed to be $\leq 2.2 \times 10^{-8} (\text{cm}^2 \text{ sr sec})^{-1}$. This upper limit can be compared with some recent results in cosmic-ray work. Bergeson et al.[1] have measured muon intensities as a function of zenith angle at energies greater than 1000 BeV. Their results do not agree with theories which assume that the muons are produced entirely by pion and kaon decay in the upper atmosphere. In an attempt to explain this discrepancy, Callan and Glashow[2] suggested that the particles observed may in fact not be muons but a new particle which they call U. They hypothesized that the U is a singly charged particle with no strong interactions whose mass must be greater that 2.5 BeV/c^2 so as not to have been found in accelerator experiments. In addition, the U is assumed to be a stable component of the primary cosmic radiation. The spectrum of U's can be calculated using two assumptions: (1) that they are accelerated in space by the same mechanism as cosmic-ray protons and therefore obey a power-law momentum spectrum with the same exponent, -1.6,[3] (2) that the flux of U's at momenta greater than 1000 BeV/c accounts for essentially all the particles seen in the experiment of Bergeson et al. These two assumptions lead to a momentum spectrum for the U's of

$$N = 3 \times 10^{-3} p^{-1.6},$$

Table I. Summary of the velocity range accepted by the apparatus and the expected flux of U's in that range for various possible values of the U mass.

Mass (BeV/c^2)	Range of β accepted by apparatus	Kinetic energy at sea level (BeV)	Momentum at[a] top of atmosphere (BeV/c)	Flux predicted[b] in accepted momentum range $N=3\times10^{-3}p^{-1.6}$ (10^{-6} particles/cm^2 sr sec)	Experimental limit on flux in accepted momentum range (particles/cm^2 sr sec)
2	0.8-0.9	1.3-2.6	18.5-19.8	3	2.2×10^{-8}
5	0.7-0.9	2.0-6.5	21.8-25.5	7	
10	0.6-0.9	2.5-13.0	27.4-36.2	6	Same limit
20	0.55-0.9	4.0-26.0	37.8-57.4	5	for all
30	0.5-0.9	4.5-39.0	47.0-79.1	4	values of
40	0.5-0.9	6.0-52.0	55.0-100	3	the mass.
50	0.5-0.9	7.5-65.0	63.0-119	3	
100	0.5-0.9	15-130	100-222	1	

[a]At the zenith angle of 84° used in this experiment, there is 8 $\mathrm{kg/cm}^2$ of air from the top of the atmosphere to sea level. See C. W. Allen, Astrophysical Quantities (The Athlone Press, University of London, London, England, 1963), p. 120.

[b]Predicted on the basis of the experiment of Bergeson et al. (Ref. 1) and the proposal of Callan and Glashow (Ref. 2).

where p is the relativistic momentum of the U's in BeV/c and N is the flux of U's with a momentum greater than p in $(\mathrm{cm}^2\ \mathrm{sr\ sec})^{-1}$.

Table I summarizes the velocity range accepted by the apparatus and the expected flux of U's in that range for various possible values of the U mass. The observed upper limit on the flux is given in the last column. We conclude that our results clearly rule out the U hypothesis as a possible explanation of these anomalous, high-energy, cosmic-ray-muon fluxes. This conclusion agrees with that published previously by Kasha and Stefanski[4] using results obtained with a magnetic spectrometer.

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