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Heavy particles in the cosmic radiation?

P. C. M. Yock
Department of Physics, The University of Auckland, Auckland, New Zealand

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Possible evidence of long-lived cosmic-ray particles with mass $\approx(9/2)m_p$ and charge either exactly or approximately equal to unity is reported.

Several experimental studies of long-lived cosmic-ray particles have yielded data which are not particularly easily accounted for in terms of well known particles.[1-13] These data have been variously interpreted as due to instrumental or statistical effects, chance coincidences, or possibly new particles. In this paper, data from a recently held 4000-h run of the slow-particle telescope described in Refs. 7 and 8 is reported. This telescope was designed to provide information on the masses and charges of slow ($\beta \sim \frac{1}{2}$), heavy ($m \gtrsim m_d$), long-lived ($\tau \gg 10^{-8}$ sec) particles traversing it. Some significant changes to the detailed design of the telescope were made for this run and the results obtained appear to strengthen significantly the case for long-lived particles with mass $\approx \frac{9}{2}\, m_p$ and charge either approximately or exactly equal to unity.

The telescope is shown in Fig. 1. It was operated as in previous runs. (Full details are given in Refs. 7 and 8.) For each event the outputs of the six photomultipliers were displayed sequentially on a single sweep of a Hewlett-Packard 183A oscilloscope running at 10 nsec/cm and photographed. For slow particles a delayed coincidence of signals from the top and bottom scintillators was required to trigger the oscilloscope and spark chambers. Particle speeds were obtained from the oscilloscope photographs with all timing measurements performed using the constant-fraction technique. The first four pulse heights for any particle were used as a measure of its ionization and, together with the speed measurement, yielded the particle's charge to an accuracy of about $\frac{1}{20}e$. The increase in ionization observed in the bottom-two scintillators, caused by the particle depositing energy in the main absorber, was used to deduce the particle's mass. The heavier a particle is, the less its increase in ionization. The accuracy of the mass measurement was typically $\frac{1}{2}m_p$. As in previous runs, the timing and pulse-height measurements were calibrated with fast muons and slow ($\beta \sim \frac{1}{2}$) protons, respectively. To enable slow protons to reach the bottom scintillators, the main absorber was reduced in thickness for proton runs.

As mentioned above, the telescope was modified somewhat following the previous run (reported in Ref. 8). The main absorber was increased in thickness in order to provide more accurate information on the masses of heavy particles. (In all previous runs data were obtained which are either suggestive of, or consistent with, particles of unit charge and mass $>m_t$.) Also, the fourth scintillator was moved from the bottom of the telescope to the center to improve the discrimination against multiparticle events. Figure 1 shows the telescope in its modified form.

The acceptance criteria for selecting single-particle events from the experimental data included five pulse-height constraints for each event, two timing constraints, and also either two or four further constraints (depending on whether or not the particle penetrated the bottom absorber) involving combined spark-chamber and timing data. With the modified geometry of

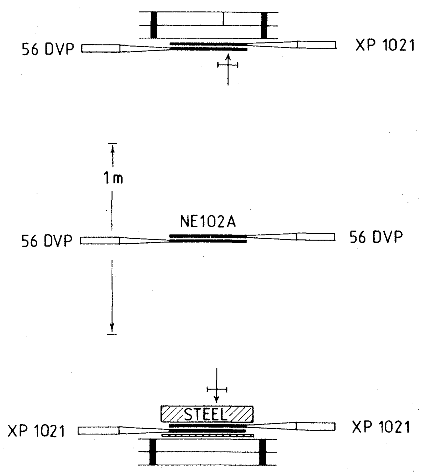

FIG. 1. The telescope as used for the present run. The scintillators and spark chambers are those described in Refs. 7 and 8. The air gap between the main absorber and the fifth scintillator is 3 mm wide. The thickness of the top absorber was 68.4 g/cm^2 for this run, and the bottom ~7 g/cm^2. The spark-chamber trajectory shown here is for particle b (see below). The arrows indicate its trajectory as predicted by the timing measurements.

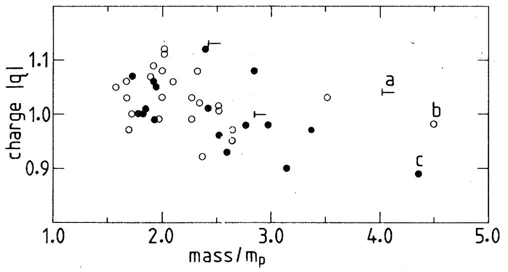

FIG. 2. Masses and charges for all particle observed in 4000 h with $\beta \leqslant 0.60$. For those events where the ionization beneath the main absorber did not exceed that above it by more than three standard deviations, a lower limit (90% confidence) for the mass is only given. Particles which stopped in the bottom absorber are indicated by open circles.

the present telescope, the acceptance criteria were changed in detail from those used in Ref. 8. Test (ii) was replaced with the requirement that $\tau_{24} - \frac{1}{2}\tau_{26} = \bar{\tau}_{24,\mu} - \frac{1}{2}\bar{\tau}_{26,\mu}$. Also, test (vii) was applied more strictly in the sense that all events with extra sparks (indicating accompanying particles) were rejected. With these modified tests the data reported here would seem to be sufficiently overconstrained to ensure, with negligible uncertainty, that they contain no contamination from multiparticle events. However, the nature of the cosmic radiation is such that it is difficult to give a quantitative estimate of this probability. The accuracy with which slow particles satisfied the timing tests in this run corresponds to a statistical accuracy ≈0.40 nsec for the time-of-flight measurements over the 2-m path length of the telescope. To this must be added drifts of $\lesssim 0.1$ nsec during the course of the experiment. These figures indicate a small but significant improvement in the accuracy of the timing measurements over those attained in previous runs. This improvement resulted from the modified pulse-clipping procedure used in this run.[14]

The masses and charges of all slow particles detected in 4000 h of running time and having measured values of $\beta \leqslant 0.60$ are shown in Fig. 2. All but three of the events in this diplot can be interpreted as being nuclei with $Z = 1$. The three anomalous events, labeled a, b, and c, had speeds of $(0.506 \pm 0.020)c$, $(0.467 \pm 0.017)c$, and $(0.515 \pm 0.020)c$, respectively. They are clean candidates for heavy particles with masses $\gtrsim \frac{9}{2} m_p$. Similar heavy-particle events were recorded in previous runs with this telescope, although these were subject to poorer resolution in the mass measurements. Data reported from closely comparable experiments[2,3,9] do not appear to rule out (or require) the interpretation of these events as particles with mass $\approx \frac{9}{2} m_p$.

The accuracies of the individual charge and mass measurements for deuterons and tritons may be deduced from the accuracies of the timing and pulse-height[8] measurements. For the data reported here they are approximately $0.05e$ and $0.5m_p$, respectively. The distribution of data points in Fig. 2 is in agreement with these expectations, except for points a, b, and c, which appear to lie clearly outside the triton distribution.

The masses of the particles plotted in Fig. 2 were computed from Eq. (3) of Ref. 8, assuming unit charge ($q = 1$) in every case. The computed mass for event c is $2.9m_p$ if the charge is taken to be its measured value, viz., $|q| = 0.89$. No evidence for particles with charge less than this was recorded in this run.

Figure 2 includes particles, plotted as open circles, which stopped in the bottom absorber. In Ref. 8 such events were included in the proton calibration runs only. Particle b stopped in the bottom absorber and its oscilloscope trace is reproduced in Fig. 3. The spark-chamber trajectory for this event, along with its trajectory predicted by the timing measurements, is shown in Fig. 1. The mass plotted for particle b in Fig. 2 is of course strictly a lower limit only, because this particle may have interacted in the main absorber. The same remark applies to all the open-circle events plotted in Fig. 2.

Two general explanations for events a, b, and c may possibly be given without invoking the existence of new, heavy particles. One possibility is that they are multiparticle events. There is, however, nothing which distinguishes these events in the way they satisfy the selection criteria for single-particle events from the other slow-particle events which assuredly are single-particle events. Furthermore, the spark-chamber trajectories do not hint at possible multiparticle interpretations for these events (in contrast to the possible fractional charge events reported in Ref. 8). The second possibility involves unexpected errors in the timing measurements. To account for events a, b, and c as tritons, time-of-flight mismeasurements $\gtrsim +1.1$ nsec are required for each event. In view of the above-quoted accuracy of the time-of-flight measurements, such errors seem most unlikely in a small sample of events. The required error corresponds to a 1.8% fluctuation in the speed of the oscilloscope's time base. To test for such fluctuations, a total of 200 single sweeps of the oscilloscope were photographed at intervals throughout the experiment with a 50-MHz crystal-controlled oscillator connected to the vertical

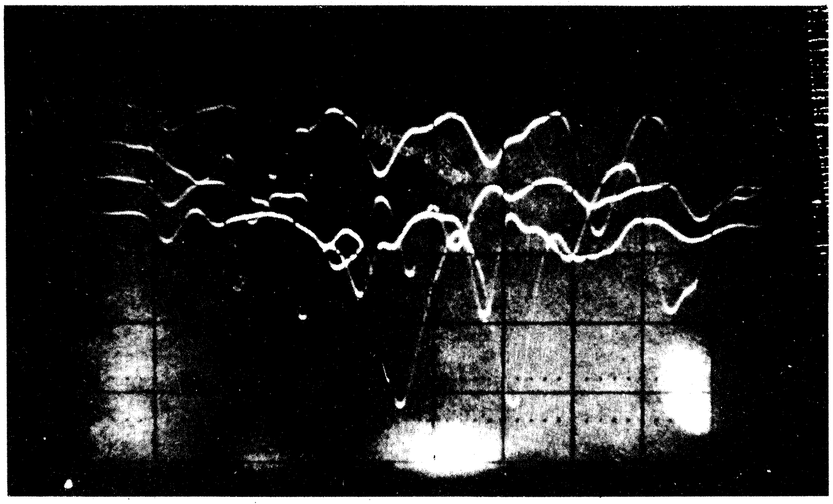

FIG. 3. Typical oscilloscope traces, including those for event b. Event b is the top one. The remaining three are all multiparticle events. This 25-h time exposure was taken in June 1979.

deflection plates. Amongst this relatively large sample, no fluctuations of the time base >0.60% were observed. No other malfunction involving only a single piece of equipment would account for the observations.

In view of the consistency of the results obtained in previous runs[7,8] with those reported here, it appears likely that future runs with the same equipment would produce further similar results. It is consequently suggested here that further studies of the cosmic radiation at sea level, perhaps employing different experimental techniques, be made to attempt to conclusively determine if there is a flux $\sim 3\times 10^{-9}$ cm^{-2} sec^{-1} sr^{-1} of slow, long-lived particles with charge exactly or approximately equal to unity and mass $\approx \frac{9}{2} m_p$ as the data reported here indicate. The replacement of solid absorbers with air-gap magnets may possibly improve the mass resolution achievable with cosmic-ray telescopes.[15] The flux of heavy particles indicated by the present studies could result from a threshold for pair production lying not far above present accelerator energies or from a heavy component in the primary cosmic-ray mix. The idea that the primary cosmic radiation may contain exotic particles has been mentioned by others.[16]

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[14] For this run each photomultiplier output was clipped with a 1-nsec-shorted cable and symmetrical, matched *T* connector. This resulted in a cleaner baseline for the oscilloscope trace, thus facilitating better timing and pulse-height measurements.

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International Conference on Cosmic Rays, Münich, 1975, edited by Klaus Pinkau (Max-Planck-Institut, Münich, 1975), Vol. 7, p. 2437. Such studies could also provide a test of the evidence reported in Ref. 8 for accompanied particles with charges distinctly smaller than unity. However, it is to be noted that, due to the presence of the accompanying particles in these events, the evidence appears weaker for them than that reported here for heavy particles with charge exactly or closely equal to unity. Millikan-type experiments may also provide useful data for these studies.

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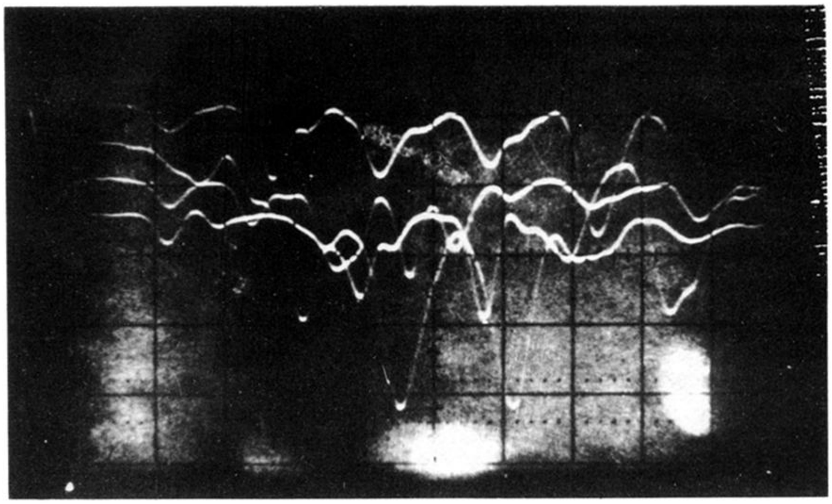

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