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Brief Reports

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Further evidence for heavy particles in the cosmic radiation

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In a continuation of a study of slow, penetrating cosmic-ray particles at sea level further evidence has been obtained for long-lived particles with mass$\approx(9/2)m_p$ and charge either exactly or approximately equal to unity. Also, in relatively complicated events, further possible examples of slow, accompanied, heavy particles with charge ≈ 0.7 were observed.

The apparatus that was used in this work is decribed in Ref. 1. Essentially, it comprises a telescope with six scintillator planes, two wide-gap spark chambers, and two steel absorbers. The scintillators provide time-of-flight data over a 2-m path length and also ionization measurements before and after traversal of a 68.4-g/cm^2 absorber. The trigger is a delayed coincidence which accepts slow ($\beta \lesssim 0.65$) particles which penetrate this absorber. This excludes nearly all cosmic rays and most single-particle triggers are caused by deuterons. Particle masses and charges are determined from the timing and pulse-height measurements. The telescope has undergone several modifications at various times but none between this, the last planned run, and the previous one which was reported in Ref. 1.

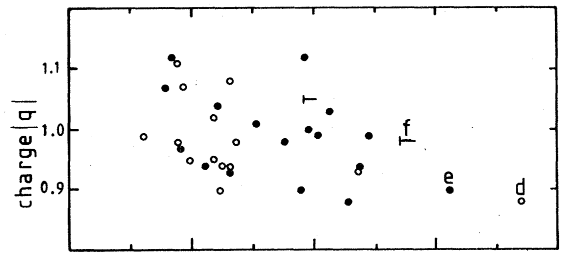

FIG. 1. Masses and charges of all unaccompanied particles observed in 4000 hours with $\beta \leq 0.60$. As in Ref. 1, for those events where the ionization beneath the main absorber did not exceed that above it by more than three standard deviations, a lower limit (90% confidence) for the mass is only given. Particles which stopped in the bottom absorber are indicated by open circles. The masses plotted here were deduced assuming unit charge in every case.

The results of the latest run for those events in which the spark chambers indicated no accompanying particles are shown in Fig. 1. Because this run was only a continuation of the previous one, the accuracies of the individual charge and mass measurements are unchanged from the earlier values of $\frac{1}{20}e$ and $\frac{1}{2}m_p$, respectively. Consequently, all but three of the events in Fig. 1 can be interpreted as normal nuclei. The three anomalous events, labeled d, e, and f, had measured speeds of 0.484c, 0.524c, and 0.551c, respectively. They are clean candidates for long-lived, heavy particles. Data obtained in previous runs of this experiment are consistent. The data of the last two runs are the most accurate and these have been combined in Fig. 2. Results from comparable experiments are not inconsistent with the interpretation of these events in terms of heavy particles.[1]

The average mass plotted for events b, c, d, and e is $(4.4\pm0.2)m_p$. The average charge for events a–f is 0.95 ± 0.03 in magnitude and reasonably con-

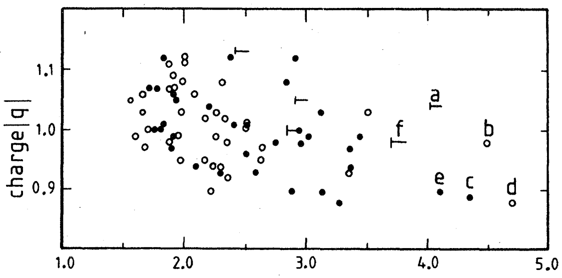

FIG. 2. Masses and charges of all unaccompanied particles with $\beta \leq 0.60$ which were observed in this run and the previous one (Ref. 1).

sistent with unity. If a charge of ± 0.95 is assumed for events b, c, d, and e then their average measured mass is $3.7m_p$.

Two explanations for events a–f are possible without invoking the existence of heavy particles. One involves multiparticle events and the other, which is more likely, involves unexpected timing errors. It was argued in Ref. 1 that both possibilities seem unlikely and the clumping of data points in Fig. 2 supports this. The argument given in Ref. 1 against timing errors hinged on the accuracy of the time-of-flight measurements being ≈400 psec. We now present further evidence, using stopping protons as particles of known speeds, which supports this. "Proton runs" were held during the experiment in order to calibrate the pulse-height measurements. They were identical to normal runs except that the main absorber was reduced in thickness to 15.5 g/cm^2 to enable slow protons to penetrate it whilst still stopping slow muons. The speed spectrum of protons able to penetrate the reduced absorber and reach the bottom triggering scintillator should ideally have a step at $\beta = 0.476$. In Fig. 3(a) the observed spectrum for protons is compared with the expected distribution (solid line) assuming a statistical accuracy of 300 psec for the time-of-flight measurements. The dashed curves show the effects of ±150-psec systematic errors. These data support the previous[1] estimate of 400 psec for the timing accuracy. In Fig. 3(b) the speed spectrum of protons with ranges (as deduced from pulse-height measurements in the bottom two scintillators) of 1.1–2.5 mm in the *bottom* absorber is compared to the expected distributions assuming again a 300-psec statistical error and ±150-psec systematic errors. These data also support the earlier estimate of the timing accuracy.

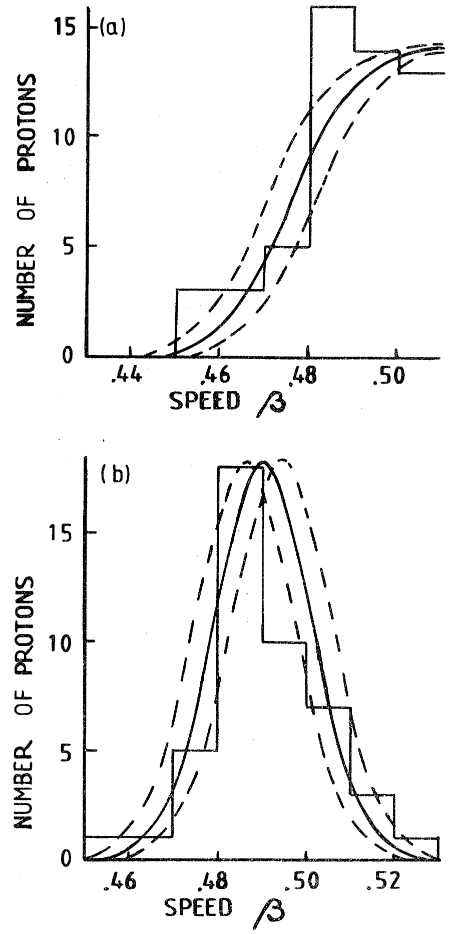

FIG. 3. Timing checks using stopping protons. In (a) the speed spectrum of protons capable of penetrating the reduced (15.5 g/cm^2) absorber and triggering the bottom scintillator is compared with spectra expected under various assumptions stated in the text. In (b) the observed spectrum for protons with ranges between 1.1 and 2.5 mm in the bottom absorber is compared with expected spectra.

The data of Fig. 3(a) were obtained in proton runs held in August 1979 and February 1980 while the data of Fig. 3(b) also include protons from a run held in April 1979. At least at these times any timing drifts must have been ≲100 psec. A more direct check for timing drifts is given by the "muon runs" which were held more frequently in order to calibrate the timing measurements and also to directly monitor any drifts. In Fig. 4 the quantity $\frac{1}{2}(\bar{\tau}_{15,\mu} + \bar{\tau}_{26,\mu})$, which is the average measured muon transit time within a constant, is plotted as a function of time. These data support the result found previously that timing drifts are ≲ 100 psec in this experiment.[1,2] The timing measurements were carried out by displaying and photographing the photomultiplier pulses on single sweeps of a

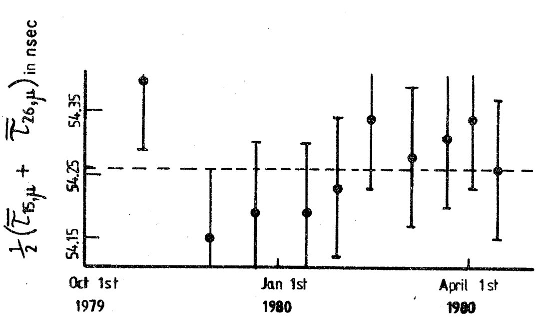

FIG. 4. The average measured muon transit time, within a constant, plotted as a function of time. The actual quantity which is plotted, i.e., $\frac{1}{2}(\bar{\tau}_{15,\mu} + \bar{\tau}_{26,\mu})$, is defined in Ref. 2. Each point is the average for a sample of about 20 muons, and the error bars correspond to the statistical distributions of these samples. The dashed line is the average value of the same quantity during the previous 4000 hours (i.e., for Ref. 1).

fast oscilloscope (Hewlett-Packard 183A) and measuring the spacings between them. A sample of these photographs, which were also used for the pulse-height measurements, has been reproduced elsewhere.[3] The accuracy of the method obviously depends on the characteristics of the oscilloscope, particularly of its time base. All effects of imperfections in the time base are of course included in the timing tests discussed above. A direct test of the long-term constancy of the time base using a crystal controlled oscillator for timing signals has been reported previously.[1,3] A further, independent test is possible using the spark-chamber trajectories for timing signals. This test provides an "on-line" check of the possibility that events a–f were tritons which were mistaken for particles with mass $\approx \frac{9}{2} m_p$ because the time base ran unusually slowly in these events. The required deviation of the time base away from its normal speed would result in tests (iv) and (v) of Ref. 2, which were normally used to reject multiparticle events, being systematically in error by +2.2 cm on average for these events. In fact, the average error was -1.5 ± 1.3 cm. This test, although not significant for any one particular event, has the advantage of applying to the actual sweeps in question.

The effects of variations of the main supply voltage were considered and discounted as the cause of the unusual results for events a–f.[4]

It appears that, as far as can be determined from this particular experiment, there is a strong case for the presence of a flux $\sim 2\times 10^{-9}$ cm^{-2} sec^{-1} sr^{-1} of long-lived ($\tau \gg 10^{-8}$ sec) primary or secondary cosmic-ray particles with charge ±1, mass $= (4.4 \pm 0.2) m_p$, and $\beta \leq 0.6$ at sea level. The data are also consistent with a charge $\approx \pm 0.95$ and a mass $\approx 3.7 m_p$. The observed flux is not inconsistent with results of other similar experiments.[1] If the particles are stable, the flux requires[5] a concentration $\sim 10^{-23}$ heavy particles/nucleon in matter, and this is not ruled out by searches which have been made for small concentrations of charge +1 heavy particles in matter.[6]

It is reemphasized here that proton, deuteron, and triton fluxes determined from this experiment are in reasonable agreement with fluxes reported by other groups at similar momenta, and that events a–f were indistinguishable from protons, deuterons, and tritons in the way they satisfied the selection criteria for single-particle events.[1,2] The latter remark does not apply to the remaining events discussed below.

During the present run three possible examples in relatively complicated events of slow, heavy, accompanied particles were observed. For the first two the measured masses and charges were $> 5.3 m_p$ and $> 2.8 m_p$ (90% confidence limits), and $\pm 0.75 \pm 0.05$ and $\pm 0.70 \pm 0.05$, respectively. In both of these events the spark chambers exhibited extra sparks indicating that either they were uninteresting multiparticle events or that they were slow, heavy, fractionally charged particles which were preceded by other, presumably causally related, particles. In any case, these two events are very similar to events A and B of Ref. 2 and the observations warrant further work with equipment more suited to handling multiparticle events. One further event, for which the oscilloscope trace is shown in Ref. 3, had measured values of charge $= \pm 0.89 \pm 0.06$ and mass $= (12.8 \pm 2.5) m_p$ assuming unit charge and $(9.3 \pm 3.0) m_p$ assuming a charge of $\pm 0.89 \pm 0.06$. For this event there were no visible sparks in the spark chambers and this probably indicates the passage of several particles through the chambers during their sensitive time (~ 50 μsec). This event could either have been several particles combining to produce the seemingly single-particle oscilloscope trace shown in Ref. 3, or it could have been a very heavy, preceded particle. A cloud-chamber event observed some years ago was not dissimilar to this event.[7] Again, further work, including Millikan-type studies, would be of use.

Note added. After this manuscript was submitted for publication I was informed of a recent CERN experiment [A. Bussiere *et al.* Nucl. Phys. B174, 1 (1980)] in which possible evidence for the production in *pN* collisions of particles with charge −1 and mass 4.3 ± 0.1 GeV/c^2 at a rate $\simeq 10^{-11}$ × the pion production rate is reported. In a similar Fermilab experiment [D. Cutts *et al.*, Phys. Rev. Lett. 41, 363 (1978)] the published (mass)^2 spectrum reveals events at this mass and at a similar rate, but the background from $\bar{d}$'s and $\bar{t}$'s is significant. These accelerator results, taken together with the cosmic-ray data presented and referred to here on particles with mass $\simeq \frac{9}{2} m_p$, indicate that fairly heavy long-lived particles may be produced in *NN* collisions with a cross section which grows rapidly with energy between a few hundred GeV and several TeV. Further discussion along these lines has been given elsewhere [P. C. M. Yock, Phys. Rev. D 22, 2805 (1980)].

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[1] P. C. M. Yock, Phys. Rev. D 22, 61 (1980). This paper refers to earlier studies carried out at Auckland and also elsewhere by other groups.

[2] P. C. M. Yock, Phys. Rev. D 18, 641 (1978).

[3] P. C. M. Yock, in *High Energy Physics—1980,* proceedings of the XXth International Conference on High Energy Physics, Madison, 1980, edited by L. Durand and L. G. Pondrom (AIP, New York, 1981). The photographic reproductions shown here are sharper than the one in Ref. 1.

[4] The critical components are the oscilloscope and the power supply (Fluke 415B) for the photomultipliers. Similar instruments were tested with a Variac transformer, and also the main supply was monitored with a Dranetz power-line-disturbance analyzer. It is noted here that the apparatus ran continuously (no equipment or power failures) throughout the 4000 hours of the present run and for the preceding 3000 hours, and also that it was operated in a room maintained between 23 and 28° C.

[5] L. W. Jones, Rev. Mod. Phys. 49, 717 (1977).

[6] R. A. Muller *et al.*, Science 196, 521 (1977); P. F. Smith *et al.*, Nucl. Phys. B149, 525 (1979).

[7] Yunnan Cosmic Ray Group, Sci. Sin. 16, 123 (1973).