Experimental limits on quarks, tachyons, and massive particles in cosmic rays

A. Marini, I. Peruzzi, M. Piccolo, and F. Ronga
Laboratori Nationali di Frascati dell' INFN, I-00044 Frascati, Rome, Italy

D. M. Chew,* R. P. Ely, T. P. Pun, and V. Vuillemin†
Lawrence Berkeley Laboratory, Berkeley, California 94720

R. Fries,‡ B. Gobbi, W. Guryn, Donald H. Miller, and M. C. Ross
Physics Department, Northwestern University, Evanston, Illinois 60201

D. Besset, S. J. Freedman,§ A. M. Litke, J. Napolitano,§ and T. C. Wang**
Department of Physics, Stanford University, Stanford, California 94305

Frederick A. Harris, I. Karliner,†† Sherwood Parker, and D. E. Yount
Department of Physics and Astronomy, University of Hawaii, Honolulu, Hawaii 96822
(Received 22 March 1982)

A large detector with high redundancy is used to search for various types of anomalous particles in cosmic rays at sea level. The detector is sensitive to zenith angles between 45° and 90°. Previously obtained limits on the fluxes of charge $\frac{1}{3}$ and $\frac{2}{3}$ particles are reduced to 2.9×10^{-10} and 2.6×10^{-10} cm^{-2}sr^{-1}sec^{-1}, respectively. The flux of ionizing tachyons is determined to be less than 2.4×10^{-9} cm^{-2} sr^{-1}sec^{-1}. The massive-particle flux limit we obtain is inconsistent with previous claims of such particles assuming that these particles are isotropic in zenith angle.

(i) Introduction. This paper presents results of a search for anomalous particles in cosmic rays obtained with a detector designed to search for fractionally charged particles produced in high-energy e^+e^- annihilation[1] at the Positron-Electron Project (PEP) at the Stanford Linear Accelerator Center. The detector as used for cosmic-ray studies is described in detail in a previous publication.[2]

Briefly, the detector consists of 24 segmented layers of plastic scintillator interleaved with large-area multiwire proportional chambers (MWPC's). Ten scintillation-counter layers are equipped with time-of-flight (TOF) readout. The acceptance for cosmic rays depends on the trigger requirements and analysis cuts for the specific application but the geometric admittance for cosmic rays is 4.0×10^3 cm^{2}sr. Figure 1 is a diagram of the detector which consists of two identical arms each covering one face of a cube. The range of cosmic-ray zenith angles is from 45° to 90°. Cosmic-ray particle properties are inferred from measurements of energy loss in plastic scintillators and velocity measurements by TOF. Good tracking reduces backgrounds from showers and interactions in the detector. The results reported here are from single-particle cosmic-ray experiments at sea level.

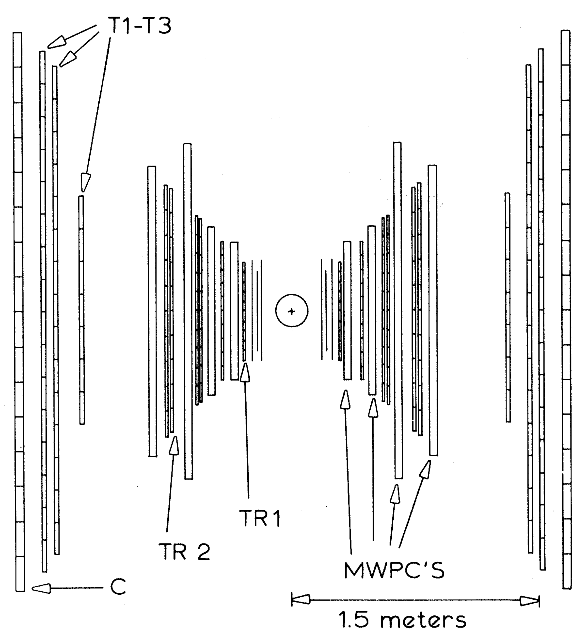

FIG. 1. Elevation view of the detector showing the two symmetric arms. T1–T3, and TR1 and TR2 are equipped with time-of-flight readout. The trigger is a hit in layer TR1, either arm, and layers TR2, both arms. Layers C are Lucite Cherenkov counters.

(ii) Search for quarks in cosmic rays. The charge of particles passing through the detector is inferred from

the Bethe-Bloch formula,

$$-\frac{1}{\rho}\frac{dE}{dX}=\frac{Q^2}{\beta^2}f(\beta) ,$$

where $(-1/\rho)\,dE/dX$ is the energy loss, Q is the particle charge in units of the electron charge, and $f(\beta)$ is a material-dependent function slowly varying in the velocity ($\beta=v/c$). The detector is triggered by a particle passing through scintillation layers TR1 and TR2 shown in Fig. 1. All scintillation counters have a photomultiplier tube at each end. For a trigger hit both tubes must have pulse heights above $\frac{1}{30}$ the pulse height of a minimum-ionizing $Q=1$ particle. The single-counter time resolution is 150 psec. An overall charge resolution of $\pm 3.5\%$ was determined with a sample of clean cosmic-ray events. Our cosmic-ray quark-search analysis procedure is described in detail in Ref. 2.

In a run of 1.5×10^6-sec live time we find no evidence for particles with either $Q=\frac{1}{3}$ or $\frac{2}{3}$. For this run the detector was located outside but adjacent to the PEP shielding tunnel. That is, only one direction of incidence was shielded. In Fig. 2 the flux limits from this experiment are combined with the limits from a previous run made while the detector was inside the PEP tunnel. The total live time for all the data reported is 2.3×10^6 sec.

Table I compares our results to other seraches for quarks in cosmic rays at large zenith angles. We emphasize that the present search is unique because it combines sensitivity over a wide range of zenith angles with sensitivity over a significant range of particle velocities.

(iii) Search for tachyons in cosmic rays. Several cosmic-ray experiments have searched for particles traveling faster than light (tachyons) since it was first pointed out that their existence is not ruled out by the equations of relativity. Nearly all the searches sought to discover charged particles preceding the relativistic front of air showers originating high in the atmosphere.[6] Positive evidence has been reported by some authors but none of these observations were confirmed by subsequent experiments and sources of systematic errors have been identified.[7]

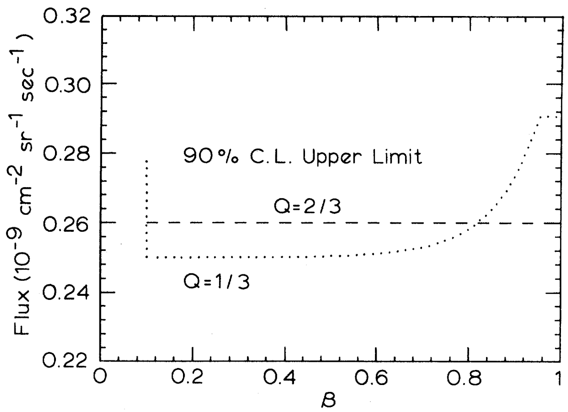

FIG. 2. Flux limits for particles with charge $|Q|=\frac{1}{3}$ and $\frac{2}{3}$ as a function of velocity.

To our knowledge, there are only two previous tachyon searches which attempted to directly measure velocity.[8,9] Both used a time-of-flight method and large-area plastic scintillators. The results of Ref. 8 apply to charged particles with velocities greater than $1.6c$ which are able to deposit $\geqslant 4$ MeV/cm in three plastic scintillators. The flux limit obtained was $\Phi_t\leqslant 2.2\times 10^{-5}\ \mathrm{cm^{-2}\,sr^{-1}\,sec^{-1}}$.

Since charged-particle velocity is measured directly in our detector we simply search for tracks with anomalously high β as a signal for tachyons. The largest background is due to ordinary cosmic-ray particles which begin to shower while passing through the detector producing multiple hits in the counters. With more than one hit in a counter the inferred counter hit will be early in time making the velocity

TABLE I. Searches for fractional charge at large zenith angles.

Expt.	Range of zenith angles	Flux ($\mathrm{cm^{-2}\,sr^{-1}\,sec^{-1}}$) (90% C.L.) $Q=\frac{1}{3}$	β	$Q=\frac{2}{3}$	β
Ref. 3	$45°\leqslant\theta\leqslant 90°$	$\leqslant 2.3\times 10^{-10}$	$\beta\simeq 1$	...	...
Ref. 4	$75°\leqslant\theta\leqslant 90°$	$\leqslant 1.7\times 10^{-8}$	$\beta\simeq 1$	$\leqslant 1.7\times 10^{-8}$	$\beta\simeq 1$
Ref. 5[a]	$\theta\simeq 84°$	...	...	$\leqslant 5.1\times 10^{-8}$	$0.5\leqslant\beta\leqslant 0.9$
This expt.	$45°\leqslant\theta\leqslant 90°$	$\leqslant 2.9\times 10^{-10}$	$0.6\leqslant\beta\leqslant 1.0$	$\leqslant 2.6\times 10^{-10}$	$0.1\leqslant\beta\leqslant 1.0$
		$\leqslant 2.5\times 10^{-10}$	$0.1\leqslant\beta\leqslant 0.6$		

[a] This experiment was designed to detect slow massive particles. Though pulse-height information was retained, efficiencies and results for fractional charge were not discussed.

systematically high. To reduce this background and to ensure accurate velocity measurements, we require at least eight time measurements along the track and not more than two hits in TOF counters not associated with the track. Figure 3 shows the veloticy distribution from a 1-h-long run before and after the above cuts are applied. The final distribution has a tail towards low velocities expected from slowly moving cosmic-ray particles. After the cuts the high-velocity region of the distribution is consistent with a Gaussian shape. The full width at half maximum of the Gaussian is 0.042, giving a velocity resolution of ±1.8%.

For a run of 8×10^5 sec we observe six events with velocity greater than $1.1c$ and none above $1.2c$. If the resolution is Gaussian we expect only $\simeq$0.04 events above $1.1c$. Examination of the events above $1.1c$ shows that in each case, a shower developed but it stayed close enough to the particle path to pass the imposed cuts. The shower is clearly indicated by the dE/dX distribution along the track. Although we believe that these events are due to ordinary particles, we exclude the region of β from 1.1 to 1.2 for determining the flux limit. The cuts for the tachyon search reduce our acceptance to $1.2\times10^3\ \mathrm{cm^2\,sr}$. Thus we obtain a tachyon flux limit of

$$\Phi_t \leq 2.4\times10^{-9}\ \mathrm{cm^{-2}\,sr^{-1}\,sec^{-1}},\quad \beta \gtrsim 1.2,\quad 90\%\ \mathrm{C.L.}$$

To be seen in our detector the tachyon must deposit at least as much energy as a relativistic $Q=\frac{1}{3}$ particle. This corresponds to an energy loss of about 0.23 MeV/cm in scintillator plastic. Whether or not the hypothetical tachyon ionizes in plastic scintillator is not certain. For example, Lemke[10] suggests that the ionization energy loss may be considerably less than that for ordinary minimum-ionizing particles. Efficiencies for the trigger and for the analysis of lightly ionizing particles are discussed in Ref. 2. This experiment was carried out while our detector was enclosed by the PEP shielding tunnel. Thus the tachyon must penetrate $\simeq 250\ \mathrm{g/cm^2}$ concrete shielding blocks to reach our detector.

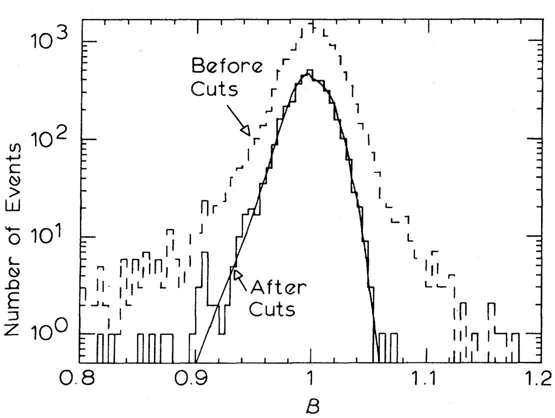

FIG. 3. Velocity distribution from a 1-h run. The smooth curve is a fit to a Gaussian plus an exponential. The data after cuts are consistent with a Gaussian tail at high velocities.

(iv) Search for massive particles in cosmic rays. A previous cosmic-ray experiment[11] provides evidence for a singly charged particle with mass $\simeq$4.2 GeV at sea level. Interestingly, there may be evidence for a similar particle produced at accelerators.[12] The measurements of Ref. 11 were made at sea level for zenith angles near the vertical and velocities in the range $0.48 \leq \beta \leq 0.60$. The observed flux is approximately $2\times10^{-9}\ \mathrm{cm^{-2}\,sr^{-1}\,sec^{-1}}$.

In an effort to confirm this result we search for massive particles in data obtained while the detector was outside of the shielding tunnel. A 30-g/cm²-thick vertical steel absorber $60\times60\ \mathrm{cm^2}$ in the center of the detector makes the total thickness of the apparatus comparable to the absorber thickness in Ref. 11.

To search for slowly moving particles we apply the following cuts:

(1) The track must intersect at least five TOF counters with hits in both phototubes.

(2) The trigger condition must be satisfied by the intersected TOF counters (layers TR1 and TR2).

(3) The track must pass through the steel absorber.

(4) Average β (determined from a linear fit through the TOF data) must be less than 0.80.

From a total of $\simeq 7\times10^6$ triggers, these cuts select about 1300 events.

The analysis is directed towards selecting events which correspond to particles with large values of M/Q^2, M being particle mass. We proceed by testing each event against the hypothesis that it was caused either by a proton or a deuteron. We emphasize, however, that if β is too large ($\beta \gtrsim 0.65$) we are insensitive to the difference between a deuteron and a triton or any other particle more massive than a deuteron. We fit the TOF data to a function of position along the track with the incident-particle velocity as a free parameter. Whenever the track crosses a scintillator, MWPC, or the steel absorber, the change in velocity is calculated from the relation

$$\Delta\beta = \Delta t \left(-\frac{1}{\rho}\frac{dE}{dx} \right)_{\mathrm{avg}} \frac{Q^2}{M} \frac{(1-\beta^2)^{3/2}}{\beta} ,$$

where Δt is the material thickness and $[(-1/\rho)\times(dE/dx)]_{\mathrm{avg}}$ is the calculated average energy loss of a unit charged particle with velocity β.[13] For a given track we use this procedure to determine if the TOF data are consistent with the particle being a proton by requiring the fit χ^2 be less than 3 per degree of freedom. The 230 tracks remaining from our 1300 selected tracks which are not consistent with the proton hypothesis are examined further. Approximately 90% of these are associated with showers or interactions in the detector and not genuine slowly moving particles. All the other events are consistent with being produced by deuterons. (For more details of the procedure see Ref. 14.) Thus we have no evidence for particles with mass any greater than that of a deuteron, although we cannot exclude tritons from our observed events.

We calculate our sensitivity using a Monte Carlo technique. For a given mass, the sensitivity goes to zero at low velocities where the particle does not penetrate the detector far enough to generate a trigger. It goes to zero at high velocities where heavier particles are indistinguishable from deuterons. For particles of mass 4.26 GeV, the optimum velocity is $\beta \simeq 0.51$ where the sensitivity is about 90% (i.e., there is a 90% probability that a particle with mass 4.2 GeV would not be identified as a deuteron). The running time with the steel absorber in place was 1.5×10^6 sec. The steel does not cover the entire fiducial volume at the center of our detector reducing our admittance by 20%. Half the particles must pass through the concrete shielding tunnel on one side of the detector, and we include only particles incident from the opposite direction. The resulting flux limit is shown in Fig. 4 compared to the result presented in Ref. 11. Our limit is inconsistent with the flux presented in Ref. 11 if we compare directly. With our acceptance, running time, and sensitivity, the result presented in Ref. 11 implies that we should have observed four events. The probability of seeing none in less than 2%. However, the zenith-angle dependence of the massive particle flux is uncertain and it may be incorrect to compare the two results directly. For example, if we assume the massive particles have the same zenith-angle distribution as deuterons, we can normalize the two experiments based on the observed number of deuterons in each. From Fig. 2 in Ref. 11 we obtain a vertical deuteron flux of

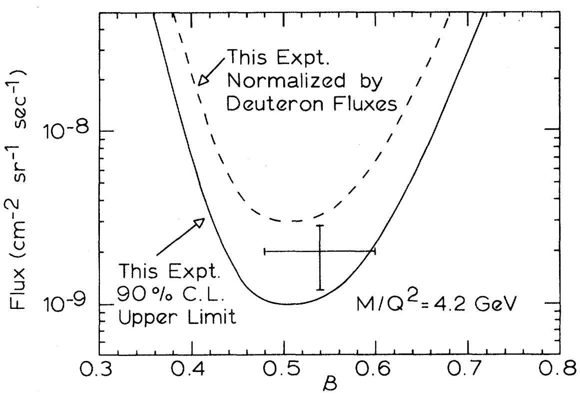

FIG. 4. Flux limits for unit charged particles with mass 4.2 GeV as a function of velocity. The curves include the efficiency of the analysis procedure for identifying particles with mass 4.2 GeV.

$\simeq 3 \times 10^{-8}$ cm^{-2} sr^{-1} sec^{-1}. Using the number of particles in the present experiment found to be consistent with the deuteron hypothesis we obtain a flux, for $0.50 \leq \beta \leq 0.60$, of $\simeq 10^{-8}$ cm^{-2} sr^{-1} sec^{-1}. This estimate includes the efficiency of discriminating deuterons from protons but neglects the increase in the number of deuterons due to misidentification of particles of higher mass. With this relative normalization we expect to see only about one massive particle and the inconsistency between the two experiments is no longer significant. This comparison is also displayed in Fig. 4.

Finally, we note that similar limits apply to particles with mass greater than 4.2 GeV. In this case, the cutoff of sensitive β decreases to lower β as the mass increases. The high-β cutoff is unchanged. For more details, see Ref. 14.

---

[*]On leave from University of Paris VI, Paris, France.

[†]Present address: EP Division, CERN, Geneva, Switzerland.

[‡]Present address: Physics Department, Indiana University, Bloomington, Ind.

[§]Present address: Physics Div., Argonne National Laboratory, Argonne, Ill.

[**]Present address: High Energy Physics Inst., Beijing, Peoples Republic of China.

[††]Present address: Dept. of Physics, Univ. of Illinois, Champaign-Urbana, Ill.

[1]A. Marini *et al.*, Phys. Rev. Lett. 48, 1649 (1982).

[2]J. Napolitano *et al.*, Phys. Rev. D 25, 2837 (1982).

[3]T. Kifune *et al.*, J. Phys. Soc. Jpn. 36, 629 (1974).

[4]R. B. Hicks *et al.*, Nuovo Cimento A 14, 65 (1973).

[5]P. Franzini and S. Shulman, Phys. Rev. Lett. 21, 1013 (1968).

[6]For a brief review of searches for tachyons preceding air showers see L. W. Jones, Rev. Mod. Phys. 49, 717 (1977). Recent air-shower searches are reported in F. Ashton *et al.*, in *Proceedings of the Fifteenth International Conference on Cosmic Rays, Ploudiv, 1977,* edited by B. Betev (Bulgarian Academy of Sciences, Sofia, 1977), Vol. 7, p. 370; P. Bhat *et al.*, in *16th International Cosmic Ray Conference, Kyoto, 1979, Conference Papers* (Institute of Cosmic Ray Research, University of Tokyo, Tokyo, 1979), Vol. 6, p. 135.

[7]J. R. Prescott, J. Phys. G 2, 261 (1976).

[8]F. Ashton *et al.*, Nucl. Instrum. Methods 93, 349 (1971).

[9]H. Hanni and E. Hugentobler, in *Tachyons, Monopoles, and Related Topics,* edited by E. Recami (North-Holland, Amsterdam, 1978).

[10]H. Lemke, Lett. Nuovo Cimento 17, 6 (1976).

[11]P. C. M. Yock, Phys. Rev. D 22, 61 (1980); 23, 1207 (1981). See references cited in these papers for previously reported evidence for massive particles.

[12]A. Bussiere *et al.*, Nucl. Phys. B174, 1 (1980); D. Cutts *et al.*, Phys. Rev. Lett. 41, 363 (1978).

[13]A. M. Bakich and L. S. Peak, Nucl. Instrum. Methods 148, 167 (1978).

[14]J. Napolitano, Ph.D. thesis, Stanford University, 1982 (unpublished).