Search for massive, long-lived, fractionally charged particles produced by 300-GeV protons

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A search has been made for massive, long-lived, weakly interacting particles of fractional charge that could be produced by 300-GeV protons striking an aluminum target. The search was most sensitive to particles with a lifetime of about 100 μsec. These particles would have come to rest in the Caltech neutrino detector that was located halfway down the muon shield, and if they were massive enough and decayed into at least 5 GeV of visible energy in the calorimeter, they could have been detected. None were found. The 90%-confidence-level upper limit to the invariant cross section (times branching ratio R), $REd^3\sigma/dp^3$ [$cm^2/(GeV/c)^2$], is 4×10^{-39} (5×10^{-38}) for charge $(2/3)e$ ($(1/3)e$).

A search has been made for long-lived (25 μ sec $< \tau < 1$ msec) weakly interacting particles of rest mass greater than 5 GeV that are produced in the neutrino beam target, come to rest, and subsequently decay in the calorimeter portion of the Caltech-Fermilab neutrino detector.[1] The 253 m of steel, 3 m of Al, and 178 m of earth in front of the detector allow singly charged particles between 415 and 428 GeV to stop[2] in the calorimeter. Consequently, only particles of fractional charge $\frac{1}{3}e$ (between 46.1 and 47.5 GeV) and $\frac{2}{3}e$ (between 184 and 190 GeV) could do so. No such particles were observed during a six-hour parasitic run *(Caltech run No. 1626) during which time 1.39×10^{16} 300-GeV protons struck the 30-cm-long aluminum target of the "single-horn" neutrino beam. The calorimeter electronics, whose energy threshold was set at about 5 GeV, was gated off while the 20μsec-long burst of protons was striking the target and was gated on 75 μsec after the beginning of that burst for a duration of 14.925 msec. As a control, another gate (10 msec long) was opened two seconds before the arrival of the protons. I refer to these as the "beam gate" and "cosmic-ray gate," respectively. The electronic "dead time" was purposely set along enough so that no more than one event could be recorded per gate for each accelerator pulse. Only when the gating electronics sensed there was an accelerated beam would it generate a "beam gate" whereas a "cosmic-ray gate" was formed at every accelerator pulse. During this run there were 2097 beam gates and 2949 cosmic-ray gates, during which time the calorimeter electronics remained "alive" 2.6985 and 3.8725 sec, respectively. Had there been no events, these times would have been 31.298 and 29.490 sec, respectively.

COSMIC-RAY TIME DISTRIBUTION

The probability of a cosmic ray triggering the calorimeter in the time t is t/τ_0 where τ_0^{-1} is the cosmic-ray rate. Therefore, the probability that the electronics is still "alive" and capable of recording an event at that time is just the probability of getting zero events when $\bar{n}=t/\tau_0$ is expected, namely, $\exp(-t/\tau_0)$. Thus the cosmic-ray distribution is

$$\frac{\Delta N}{\Delta t}=R_0\exp(-t/\tau_0)\,, \quad (1)$$

where

$$\tau_0=(\text{CR live time}=3.8725\text{ sec})/(\text{CR gates}=2949)$$
$$=1.313\pm0.024\text{ msec}$$

and

$$R_0=\frac{(\text{CR gates}=2949)}{(\tau_0=1.313\pm0.024\text{ msec})}$$
$$=(224.7\pm4.1\text{ events})/(0.1\text{ msec}).$$

The first 5 msec of the cosmic-ray data are shown in Fig. 1(a) along with the expected curve Eq. (1).

BEAM DISTRIBUTION

The beam data are shown in Fig. 1(b). The solid curve of the latter figure is the cosmic-ray curve Eq. (1) with R_0 normalized to the number of beam gates:

$$R_0(\text{beam})\text{ pred. via CR}=\frac{(\text{beam gates}=2097)}{(\tau_0=1.313\pm0.024\text{ msec})}$$
$$=(155.2\pm2.8\text{ events})/(0.1\text{ msec}).$$

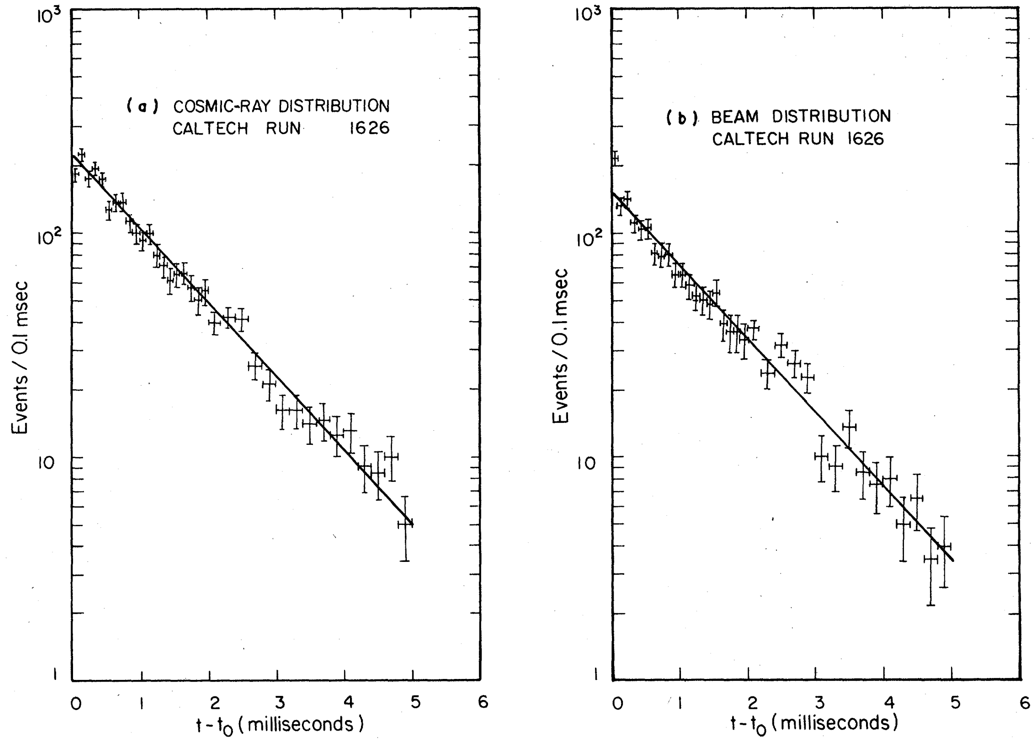

FIG. 1. (a) Cosmic-ray time distribution for first 5 msec ($t_0 = 75$ μsec). (b) Beam-events time distribution for first 5 msec ($t_0 = 75$ μsec).

The agreement is good except for the first 100-μsec bin. Figure 2 is an expanded view of this interval and shows that the entire excess of beam events occurs at 25 μsec. This excess was caused by the infrequent noise in the beam-gate triggering electronics. (It happened only 60 times during the entire run.) Its effect was to start a beam gate at 25 μsec *before* the arrival of the proton burst rather than at 75 μsec after. As a consequence, the high instantaneous counting rate in the calorimeter during the beam burst caused the equipment to trigger on the first event near the beginning of the burst and thus to produce a "spike" of 60 events in a 1-μsec-wide bin at 25 μsec. After subtracting these 60 events from the beam distribution and correcting the corresponding live time by subtracting 60×25 μsec from it, one can test the hypothesis that the beam distribution is caused by only cosmic rays and thus is of the form of Eq. (1) where

$$\tau_0\,(\text{beam}) = \frac{[\text{live time} = 2.6985\ \text{sec} - (60 \times 25\ \mu\text{sec})]}{(\text{beam gates} = 2097 - 60 = 2037)}$$

$$= 1.324 \pm 0.029\ \text{msec}$$

and

$$R_0(\text{beam}) = \frac{(\text{beam gates} = 2037)}{(\mu\tau_0 = 1.324 \pm 0.029\ \text{msec})}$$

$$= (153.8 \pm 3.4\ \text{events})/(0.1\ \text{msec}).$$

These numbers are consistent with the predicted ones, 1.313 ± 0.024 msec and 155.2 ± 2.8 events/0.1 msec.

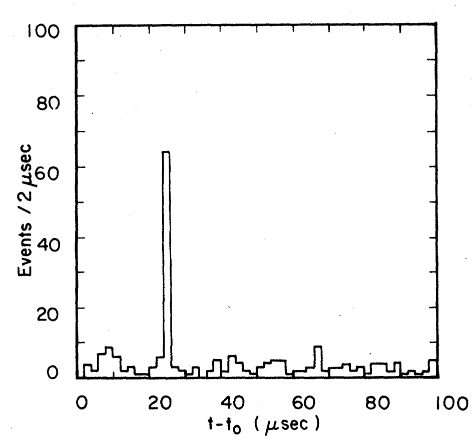

FIG. 2. Expanded time distribution of the first 100 μsec of beam distribution.

INVARIANT DIFFERENTIAL CROSS SECTION–UPPER LIMIT (90% CONFIDENCE LEVEL)

How large a "signal" could have been missed by statistical fluctuation? If there were B long-lived particles of lifetime $\tau=\lambda^{-1}$ that stopped in the calorimeter and decayed R fraction of the time so as to deliver more than 5 GeV to the calorimeter, one would expect the beam-plus-cosmic-ray background distribution to be of the form

$$\frac{\Delta N}{\Delta t}=\frac{G}{\tau_0}\left(1+\lambda\tau_0\frac{BR}{G}e^{-\lambda t}\right)$$
$$\times\exp\left\{-\left[\frac{t-t_0}{\tau_0}+\frac{BR}{G}(e^{-\lambda t}\;-e^{-\lambda t})\right]\right\}\,, \qquad (2)$$

where G is the number of beam gates, t_0 is the beginning time of the gate relative to the beam burst (considered as a δ function in time), and τ_0^{-1} is the cosmic-ray background rate. Figure 3 compares this distribution for some typical values of BR and τ with the first 1.4 msec of the beam distribution. The spurious 60 events at 25 μsec have been subtracted. For each value of τ one can form a χ^2 function and determine how large BR can be made before the χ^2 value reaches its 10%-probable value. Here, account has been taken of the 20-μsec width of the beam. This value of BR shown

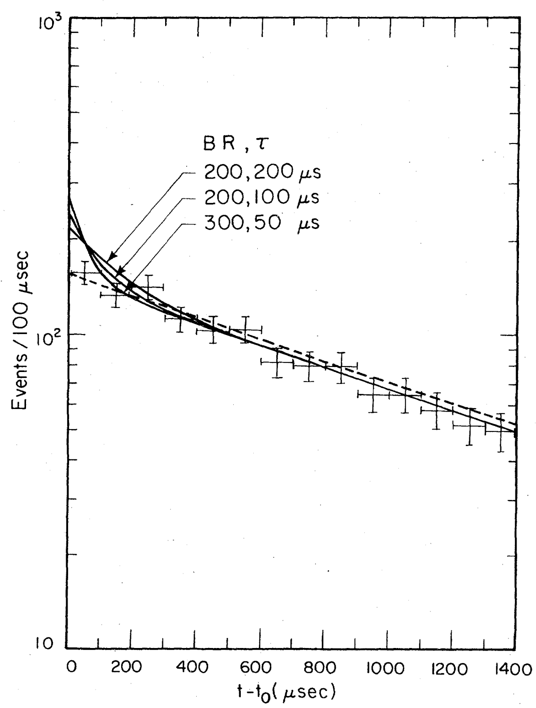

FIG. 3. Typical expected time distribution for the number of long-lived particles B (times their branching ratio R) compared with the first 1400 μsec of beam data.

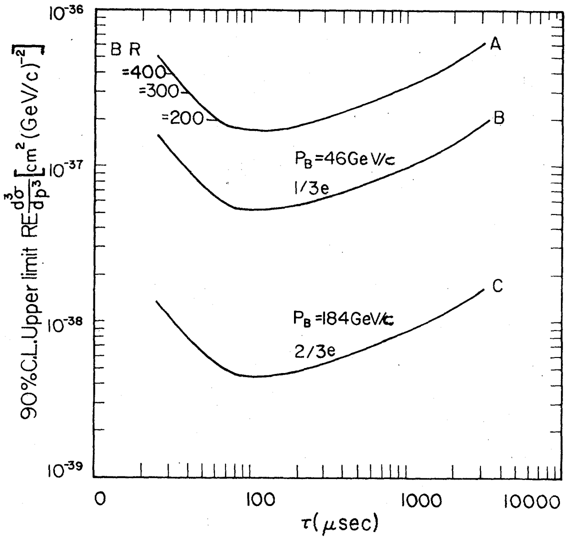

FIG. 4. Curve A shows the value of BR that gives a χ^2 value with a confidence level of ten% vs mean life. B and C show the 90%-confidence-level upper limits to the invariant cross section (times R), $REd^3\sigma/dp^3(0°)$, vs τ for $\frac{1}{3}e$ charged particles of $P_B=46$ GeV/c and for $\frac{2}{3}e$ charged particles of $P_B=184$ GeV/c, respectively.

in curve A of Fig. 4 vs τ enables one to establish an upper limit to the product of invariant differential cross section $E(d^3\sigma/dp^3)$ and branching ratio R, as a function of meanlife τ, by means of a relation of the form

$$RE\frac{d^3\sigma}{dp^3}\bigg|_{\text{at }0°}=\frac{BR}{N_0N_Tf_{\text{MS}}\Delta\Omega P_B\Delta P_B}\,. \qquad (3)$$

Here N_0 is the number of incident protons, N_T the number of target nucleons per cm^2, $\Delta\Omega$ the solid angle subtended from the target by the calorimeter, and P_B and ΔP_B the momentum and its interval of the fractionally charged particles that come to rest throughout the calorimeter. f_{MS} is the fraction remaining after multiple scattering and is estimated by assuming that the production cross section varies as $e^{-6p_\perp^2}$.

The actual form of $RE(d^3\sigma/dp^3)$ is more complicated than Eq. (3) because there are two targets, one the primary (1-mean-free-path-long aluminum) located 944 m from the calorimeter ($\Delta\Omega_1$ $=2.52$ μsr) and the second, the beam dump at the end of the neutrino beam decay tube located 544 m from the detector ($\Delta\Omega_2=7.60$ μsr). The protons that do not interact in the first target strike the second one with their full energy while some of the others emerge from the first target and strike the second one with reduced but still effective energy. This phenomenon of thick targets has been studied quantitatively in Ref. 3 and ap-

TABLE I. P_B and ΔP_B are the momentum and its spread for the particles with charge $\frac{2}{3}e$ and $\frac{1}{3}e$ that come to rest in the detector. $N_0^{(1)}$ and $N_0^{(2)}$ are the numbers of incident protons that strike the neutrino target and the beam dump. $N_T^{(1)}$ and $N_T^{(2)}$ are the number of target nucleons per cm^2 and $\Delta\Omega^{(1)}$ and $\Delta\Omega^{(2)}$ the solid angles subtended by the detector at these two places. The estimated fractions of particles originating at these points that remain after multiple scattering are $f_{MS}^{(1)}$ and $f_{MS}^{(2)}$.

Charge	$\frac{2}{3}e$	$\frac{1}{3}e$
P_B	184 GeV/c	46.1 GeV/c
ΔP_B	5.8 GeV/c	1.4 GeV/c
$N_0^{(1)}$	1.39×10^{16} protons	1.39×10^{16} protons
$N_0^{(2)}$	1.02×10^{16} protons	1.02×10^{16} protons
$N_T^{(1)}$	5.0×10^{25} cm^{-2}	5.0×10^{25} cm^{-2}
$N_T^{(2)}$	5.0×10^{25} cm^{-2}	5.0×10^{25} cm^{-2}
$f_{MS}^{(1)}$	0.62	0.87
$f_{MS}^{(2)}$	0.62	0.87
$\Delta\Omega^{(1)}$	2.5×10^{-6} s	2.5×10^{-6} s
$\Delta\Omega^{(2)}$	7.6×10^{-6} s	7.6×10^{-6} s
$P_B\Delta P_B$	1060 (GeV/c)^2	66.4 (GeV/c)^2
$(1)\equiv N_0^{(1)}N_T^{(1)}f_{MS}^{(1)}\Delta\Omega^{(1)}$	1.08×10^{36} cm^{-2}	1.51×10^{36} cm^{-2}
$(2)\equiv N_0^{(2)}N_0^{(2)}f_{MS}^{(2)}\Delta\Omega^{(2)}$	2.38×10^{36} cm^{-2}	3.35×10^{36} cm^{-2}
$P_B\Delta P_B[(1)+(2)]$	3.68×10^{39} cm^{-2} (GeV/c)^2	3.22×10^{38} cm^{-2} (GeV/c)^2

plied to this case. For example, by assuming that each proton loses $\frac{1}{3}$ of its energy each time it interacts, one estimates that the composition of the proton beam that strikes the second target consists of 37% at 300 GeV, 37% at 200 GeV, and 18% at 133 GeV. Furthermore, only the first mean free path of the second target (the beam dump) is considered as being effective for producing the weakly interacting particles that can come to rest in the calorimeter. The proton threshold energies are 199 and 65 GeV for producing stopping particles of rest mass 5 GeV [the momenta of which are 184 GeV/c (of charge $\frac{2}{3}e$) and 46.1 GeV/c (of charge $\frac{1}{3}e$)]. Only one of such pair-produced particles is detectable per event.

Table I summarizes the values of the quantities in

$$RE\frac{d^3\sigma}{dp^3}\bigg|_{\text{at }0^\circ}=\frac{BR}{P_B\Delta P_B}(N_0^{(1)}N_T^{(1)}f_{MS}^{(1)}\Delta\Omega^{(1)}+N_0^{(2)}N_T^{(2)}f_{MS}^{(2)}\Delta\Omega^{(2)})^{-1} \quad (4)$$

that together with the BR values of Fig. 4(a) allow one to determine the 90%-confidence-level upper limit of $RE[d^3\sigma(0°)/dp^3]$ vs τ. This latter quantity is plotted in Fig. 4(b) and 4(c) and summarizes the results of the experiment.

An early search for massive (5 to 15 GeV/c^2) long-lived particles in cosmic rays was made by Jones *et al.*[4] and an upper limit of their flux was established to be 10^{-10} (cm^2/sec sr)$^{-1}$. Since the data taking of my experiment there have been numerous searches for long-lived particles at accelerators. Appel *et al.*[5] found no long-lived, singly charged, forward moving, massive particles produced by 300-GeV protons in some 5.5×10^7 secondary particles. Their value of the upper limit of $d\sigma/dp d\Omega$ per nucleon was in the range of 0.02 to 4.4 μb/(GeV/c/ sr). Gustafson *et al.*[6] looked for neutral particles to be produced with $0.13<P_T<1.15$ GeV/c. The upper limit of $E(d^3\sigma/dp^3)$ was 10^{-32} to 10^{-34} cm^2/(GeV/c)^2. Antreasyan *et al.*[7] looked at a P_T of 2 GeV/c (4 GeV/c) ($\theta=77$ mr) for charge $\frac{1}{3}e$ ($\frac{2}{3}e$) particles. They determined upper limits of 5.1×10^{-39} (8.8×10^{-39}) cm^2/(GeV/c)^2 for charge $\frac{1}{3}e$ ($-\frac{1}{3}e$) and 1.3×10^{-39} (2.2×10^{-39}) cm^2/(GeV/c)^2 for charge $\frac{2}{3}e$ ($-\frac{2}{3}e$), respectively. Other searches[8] for quarks, done earlier, generally were at smaller momentum transfer and had less sensitivity. Finally, while this manuscript was in preparation, the experiment of Cutts *et al.*[9] presented a 90%-confidence-level upper limit for $|Ed^3\sigma/dp^3|=1.1\times10^{-37}$ cm^2/(GeV/c)^2 per nucleon for massive particles between 2 and 10 GeV/c^2 with charge $\geq\frac{2}{3}e$. Although my experiment could have detected particles of $\frac{1}{3}e$ charge, it would not have been able to detect massive quarks because the quark-gluon interaction was expected to be so strong that they would have been absorbed before reaching the detector.

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