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SEARCH FOR MASSIVE PARTICLE*

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Recent developments in strong-interaction theory have led to the speculation that there may exist particles associated with the basic representations of SU(3) and higher symmetry schemes.[1-3] In this picture mesons, baryons, and resonances are composite systems built up of these fundamental elements. The theoretical considerations indicate variously that these triplets could be fractionally charged,[1,2] could be stable, and are probably relatively massive.[3] This has provoked the purely experimental question: Are there metastable particles in nature which, because of their high mass and consequently low production probability, have to date escaped detection?

We report here the negative results of a search for particles of mass $3 \lesssim m \lesssim 7$ BeV produced by collisions of 30-BeV/c protons with Be and Fe nuclei. We depend on knowledge of the nuclear internal motion, studied in the preceding Letter,[4] to evaluate the relative probability of achieving c.m. energies sufficient to produce such particles. The essential signature we seek is mass, as defined by momentum and velocity. This differs from other experiments[5-7] which are based on the low ionization deposited by particles of charge $\frac{1}{3}e$ (quarks). Our experiment is also sensitive to quarks or, in fact, particles of any charge $q \geq \frac{2}{3}e$. The total flight path from the target is ~120 m, and this requires a stability which, although mass- and charge-dependent, is roughly $\tau \geq 10^{-7}$ sec.

A high intensity negative beam was defined at 4.5° from the G-10 target of the AGS. The beam layout is illustrated in Fig. 1. The momentum was defined to ±1% by dipole magnets D_1 and D_2 separated by a 4-ft by $\frac{1}{2}$-in. by $\frac{1}{2}$-in. collimator. Three additional momentum determinations were made by counter-defined trajectories through magnets D_3, D_4D_5, and D_6D_7. A set of quadrupoles (not shown) held the beam together for its ~100-m flight path to S_{10}. Vacuum pipes and helium bags were used where-ever possible. Since the center of the mass range to which we were sensitive is ~4 to 5 BeV, we set the beam momentum for 10 BeV/c in order to be near the peak in the laboratory spectrum expected at 5° on the basis of simple

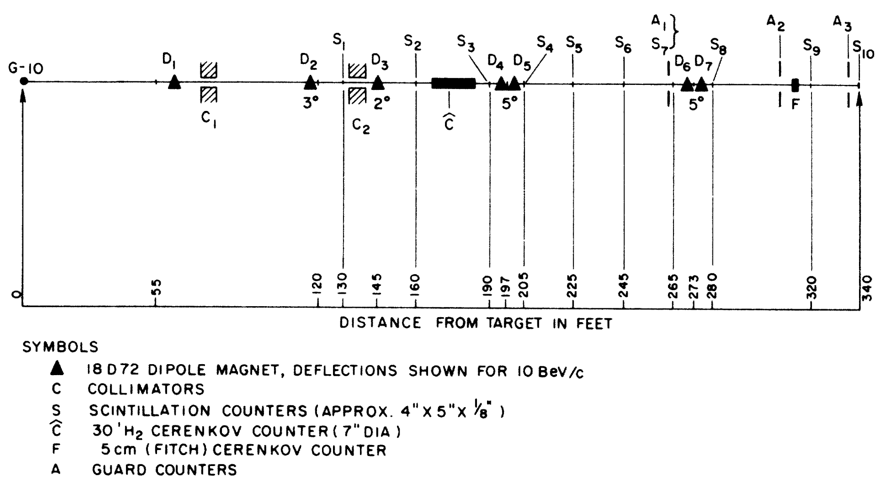

FIG. 1. Schematic beam layout.

phase-space considerations.

The mass of particles in the beam was determined by momentum selection and velocity measurements. The experiment was designed to detect one particle of mass $\gtrsim 3$ BeV/c in a beam of 10^{10} to 10^{11} light particles ($\beta = 1$). To achieve this sensitivity, the rejection of particles with $\beta = 1$ must be fairly sophisticated, capable of exposing very improbable combinations of processes which could masquerade as "slow" events. Such spurious events could, for example, be produced by the nuclear interactions in the scintillation counters; each pulse of $\sim 5\times 10^5$ pions produces 2000 such interactions in each of the $\frac{1}{8}$-in. thick counters.

The technique employed was essentially to require "almost independent" reconfirmation, several times along the flight path, that a candidate had a velocity $0.810 \leq \beta \leq 0.955$ and concurrently, many times, that this particle did not have $\beta \cong 1$. Repeated momentum definition served to disperse the nuclear debris generated along the beam.

The logic handled the output from ten beam-defining scintillation counters, one gas and one liquid Čerenkov counter, and three guard counters having rectangular holes for beam passage. The logic was divided into three main elements (see Fig. 2):

(a) Early veto system.—A 10-m long threshold Čerenkov counter (C) filled with ethylene at 30 psi counted pions with an efficiency $\gg 99\%$. The signal from this Čerenkov counter, together with the signals from the three guard counters, were sent into a mixing circuit which gave twelve identical outputs of 25 nsec width. These were used as anticoincidence gates at the discriminators of the ten scintillation counters and the liquid Čerenkov counter F. This arrangement reduces the rate from discriminators ($D_F, D_1, \cdots, D_{10}$) by a factor ~100, thus permitting the subsequent logic to work at a very low rate — an important feature in obtaining a high rejection rate for $\beta = 1$ particles.

(b) Time-of-flight ($\beta = 1$) veto system. —Coincidence circuits 41, 42, 43, 44, and 45 counted the surviving prompt ($\beta = 1$) particles ($\pi^-, K^-, \bar{p}$) with a resolving time of 4 nsec and an efficiency of about 99% per pair. The outputs from these five pairs of prompt coincidence circuits were added in a mixing circuit (OR), which gave, simultaneously, twelve gates of 35-nsec width for rejection of $\beta = 1$ events.

(c) Delayed coincidence and Fitch Čerenkov ($\beta \neq 1$) system.—Coincidence circuits, 21, 22, 23, 24, and 25 stretched the output pulses from discriminators D_1, D_2, D_3, D_9, and D_{10} from 3 nsec to 25 nsec. Two 56AVP photomultipliers viewed a wide-band velocity-selecting Čerenkov counter F, made after the design of Fitch.[8] The index of refraction of a glycerine-water mixture was adjusted to accept particles between $\beta = 0.81$ and $\beta = 0.96$. The efficiency in this band was measured to be 90%, whereas the efficiency for $\beta = 1$ particles was found to be 10%. Coincidence circuits 47, 48, 49, 50, and 51 were delayed to accept particles between $\beta = 0.81$ and $\beta = 0.96$, but to reject $\beta = 1$ particles.

In addition, a pair of 35-nsec wide pulses from OR were delayed with respect to each other by a 35-nsec cable and were sent into the delayed coincidence circuits as veto gates. This insured that the circuits had zero dead time for rejecting the $\beta = 1$ particles, and that any $\beta = 1$ particle within ±35 nsec of a "slow" particle would also serve to reject the event. The coincidence circuit 53 insured that the "slow" particle had been transmitted through the eleven counters and had a β between 0.81 and 0.96. The output from coincidence circuit 53 was used to open an 80-nsec gate for pulses from counters S_1, S_2, S_3, S_5, S_6, S_8, S_9, and S_{10}. This arrangement was made to reduce the random counting rates for the subsequent time-of-flight analysis. Additional outputs from 53 were used as gating signals on the time-to-pulse height logic.

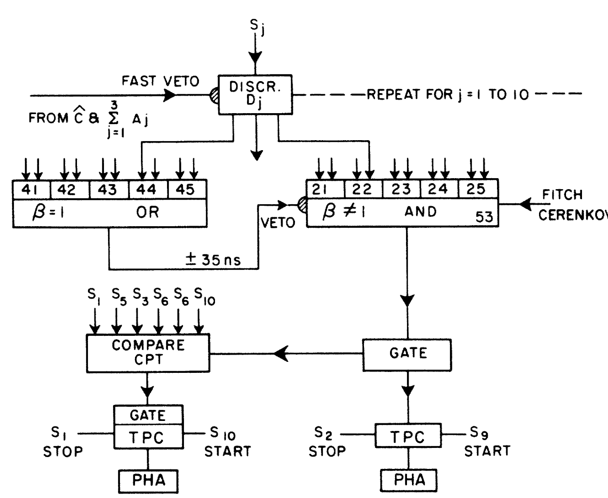

FIG. 2. Electronic logic.

A special circuit, *CPT*, compared the time-of-flight between the three pairs S_1S_5, S_3S_8, and S_6S_{10}, each of which had a 33-m separation (100 nsec for $\beta=1$). The comparator passed a pulse if these flight times were within 1.0 nsec of one another.

In summary, an event must have a momentum established via its trajectory, narrowly defined through four bending magnets by eleven counters; must not be accompanied by particles spraying into the guard counters; must be separated in time from any $\beta=1$ particle by ±35 nsec; must not trigger any of the five pairs of $\beta=1$ coincidence circuits; must not give a pulse in the 10-m gas Čerenkov counter; must have a velocity between 0.81 and 0.96 as determined both by delayed coincidences and by the angular cone of Čerenkov radiation produced in the Fitch counter; and must have the same velocity to $\pm1\%$ in three different flight intervals.

The measurement of velocity was made on two 100-channel pulse-height analyzers, which print out the flight time between S_1 and S_{10} (with *CPT* requirement) and between S_2 and S_9 (no *CPT* requirement) for each event.

The system was calibrated in the positive-polarity beams using the copious production of deuterons and tritons which could be made to sweep the velocity band as the beam momentum was varied. This possibility enabled the experimental location of the gate edges and efficiencies. The efficiency for detection of particles in the mass range defined by the momentum and velocity band is given in Fig. 3.

Table I shows the resulting counts and pion flux in the mass search from 3 to 7 BeV/c^2. Stainless steel (as well as Be) was employed as a proton target in order to use the results of Fermi motion studies.[4] The search from

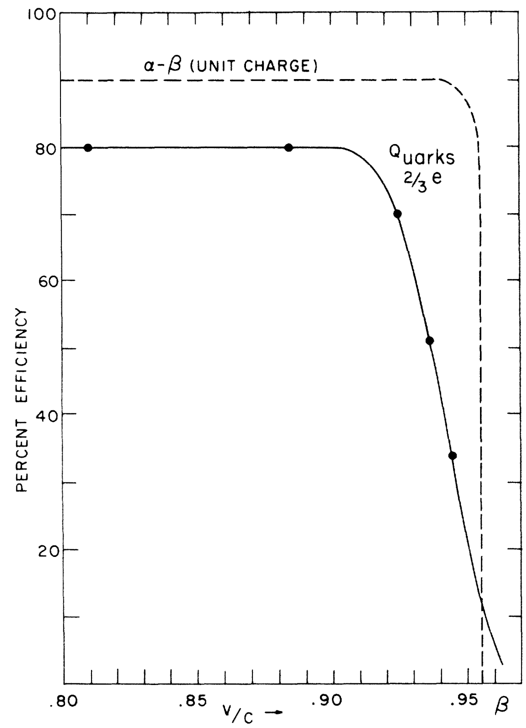

FIG. 3. Efficiency versus particle velocity for $q=e$ and $q=\frac{2}{3}e$. The latter was determined by attenuating all input signals by 2 before sweeping the positive d^+ and t^+ particles through the relevant velocity range.

2 to 3 BeV/c^2 is reported in the following Letter.[9] Since the pion production is rather well known in terms of absolute cross sections, the simplest statement of results is the cross section limit on production of particles in this mass range:

$$\frac{d^2\sigma}{d\Omega dp}(p+\mathrm{Be})<1.5\times10^{-36}\ \mathrm{cm^2\ sr^{-1}\ (BeV/}c)^{-1}$$

per Be nucleus,

Table I. Summary of the runs.

Target	Momentum (BeV/c)	Pion Flux	No. of candidates[a]
Stainless steel	10.0	1.6×10^{10}	0
Beryllium	9.0	2.4×10^{10}	3 correlated near $m=2.8$ 3 uncorrelated near $m=2.8$ 0, $m\geq3$

[a]At 10 BeV the mass sensitivity begins at $m\geq3$ BeV. Correlated events are those which define the same mass in both S_1-S_{10}, and S_2-S_9 records (see Fig. 1). The candidates near $m=2.8$ BeV are associated with an uncorrelated background, but could possibly represent $\bar{t}$ (see reference 9).

$$\frac{d^2\sigma}{d\Omega dp}(p+\mathrm{Fe}) < 3\times10^{-36}\ \mathrm{cm}^2\ \mathrm{sr}^{-1}\ (\mathrm{BeV}/c)^{-1}$$

per Fe nucleus.

A model-dependent but perhaps more useful interpretation is in terms of a production reaction involving triplets,[1-3] although the results have wider application. In these models the triplets are produced via reactions like

$$p+N \to p+N+\alpha+\bar{\alpha}, \tag{1}$$

or

$$p+N \to N+\bar{\alpha}+\beta, \tag{2}$$

where α, β are quarks or integrally charged singlets and triplets.[3]

In Reaction (1) we can compare the α or β yields with production of $\bar{p}p$ pairs.[4] The probability of having a c.m. energy sufficiently high (by virtue of nuclear motion) to produce particles of mass $m=(W_0-2)/2$ BeV is shown as a function of (single-particle) nuclear momentum in Fig. 3 of reference 4. Also shown in that paper (Fig. 2) is the incident proton energy required to produce $\bar{p}$ at threshold as a function of nuclear momentum. Thus, 5-BeV particles made in Reaction (1) ($W_0=12$ BeV) require the same internal momentum as $\bar{p}$ production by ~2-BeV protons. Figure 2 of reference 4 then teaches us that 5-BeV α's would be suppressed by at least 10^{-5} relative to pion production. We have estimated the further reduction due to phase space and dynamics by using the same equations as in $\bar{p}$ production with an additional factor of $(m_p/m_\alpha)^2$ to represent the possible effect of a propagator in Reaction (1). The results are shown in Table II. The yield due to Reaction (2) is crudely estimated by applying an energy shift to results of the first calculation. These yields are really qualitative in nature and are quite sensitive to almost everything near the cutoff, $m_\alpha \sim 5m_p$ in this experiment. For example, the omission of the $(1/m_\alpha)^2$ term would increase the yields considerably.

Our conclusion, obtained by comparing Table I and Table II, is that the existence of metastable particles in the mass range up to ~5 BeV and with unit charge is very unlikely. Particles of charge $\frac{2}{3}e$ can only be excluded up to a mass ~4.5 BeV due to the decreased phase space for particles of the correspondingly lower momentum. Metastable particles which do not require pair production can be excluded up to a mass of 7 BeV, if produced with a cross section greater than $\sim10^{-35}$ cm^2. These results are in agreement with earlier searches for unit-charge heavy particles,[10,11] but are at least 100 times more sensitive.

Table II. Yield of α's with 3×10^{10} π^- counts.

m_α	Yield Eq. (1)	Yield Eq. (2)
$4.0m_p$	120	200
$4.5m_p$	9	20
$5.0m_p$	~1	3

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OBSERVATION OF ANTIDEUTERONS*

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Using a high-transmission mass analyzer designed to search for unitary-symmetry triplets,[1] we have observed the production of antideuterons in 30-BeV proton-beryllium collisions.

The search was made in a $4\frac{1}{2}$-deg beam described in the preceding Letter. This communication also described the logic designed to suppress $\beta=1$ particles and their residue while recording beam-defined particles of $0.81<\beta<0.96$. To bring antideuterons into the sensitive velocity band, the beam was tuned to momenta between 4.5 and 6 BeV/c. We also report on a search for antitritons in the momentum interval near 9.0 BeV/c.

The evidence for antideuterons is contained in the graphs of Fig. 1. Table I summarizes all the negative-beam runs. Events which satisfy the logic have the velocity recorded in two time-of-flight systems, S_1S_{10} (210 ft) and S_2S_9 (170 ft). In S_1S_{10} there is the additional requirement of constant velocity across each of three

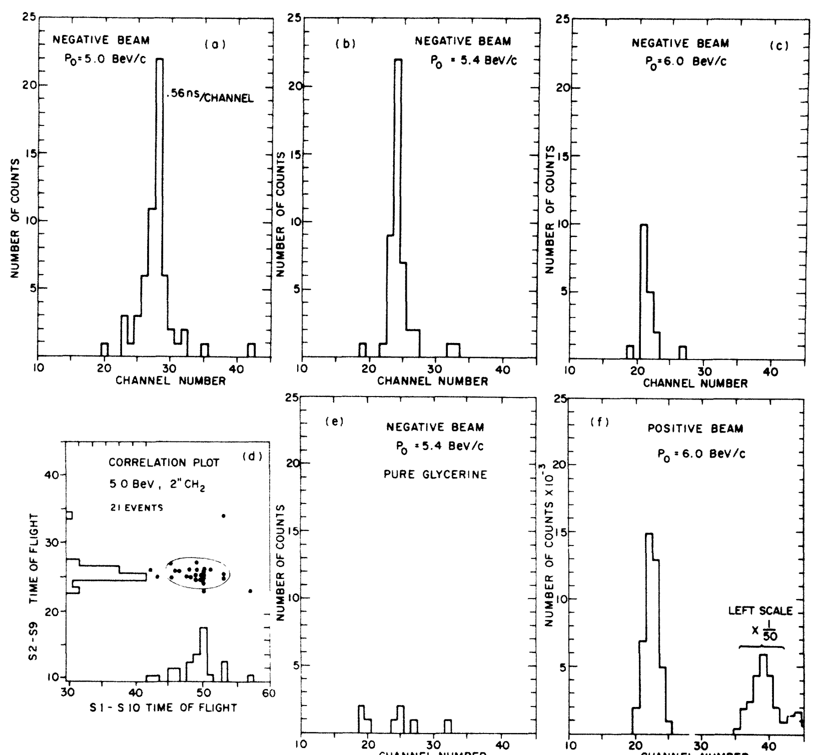

FIG. 1. Time-of-flight spectra between counters S_2 and S_9 (180 ft) for particles of the indicated momenta. The data of Figs. 1(a), 1(b), 1(c), 1(e), and 1(f) were taken in consecutive runs during which the time-to-channel calibration was ~0.55 nsec channel. The normalizations are given in Table I, except for 1(e) which should be divided by two to compare with 1(b). The resolution oval indicated in 1(d) is obtained from graphs like 1(f).