Search for New Massive Long-Lived Neutral Particles*

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We have carried out a search for neutral hadrons with masses $\gtrsim 2$ GeV/c^2 and proper lifetimes $\gtrsim 10^{-7}$ sec in the *M*4 neutral beam at Fermilab. The particle masses were determined from their flight time and kinetic energy. Our upper limits for the production cross section of such particles are 10^{-1} to 10^{-3} times those for the production of ψ's by protons for comparable kinematic conditions. This is the most sensitive search to date for quasistable neutral particles with masses $\gtrsim 2$ GeV/c^2.

Despite the many searches for new particles there is almost no evidence concerning the possible existence of neutral hadrons with lifetimes $\gtrsim 10^{-7}$ sec and masses $\gtrsim 1.5$ GeV/c^2. Such particles would not show up in searches which look for decay products, for example with a bubble chamber, nor can they be studied with conventional magnetic spectrometers. On the other hand, there is considerable theoretical motivation to search for such particles. For example, Han and Nambu[1] have proposed a version of the quark model with integrally charged quarks. Since these have fractional baryon number, the neutral quarks could be very long lived, perhaps absolutely stable if a neutral quark is the least massive. In the Pati-Salam model[2] integer-charge quarks might have a lifetime as long as 10^{-6} sec. Similarly if charm is absolutely conserved, the lowest-mass charmed particle would be stable and most previous charm searches would have failed.

Previous experimental searches for new long-lived particles include a cosmic-ray search[3] for massive hadrons which set total-production-cross-section limits of 10^{-31}–10^{-28} cm^2 for masses between 5 and 20 GeV, independent of the charge. A previous Fermilab experiment to search for massive particles with $q = \pm e$ set upper limits for the invariant cross section $E\,d^3\sigma/dp^3$ of 10^{-34} to 10^{-32} cm^2/GeV^2.[4]

In an experiment in the *M*4 neutral beam at Fermilab, we have carried out a search for quasistable neutral hadrons with masses $\gtrsim 2$ GeV/c^2. The masses of particles in the neutral beam were determined by measuring their flight times (with respect to the rf of the accelerator) and energies by means of a total absorption calorimeter.[5] From this information the mass of each particle can be determined from $m \cong [2cE^2\Delta t/l]^{1/2}$. The flight time could be measured to an accuracy of better than 1 nsec (or roughly the width of the rf "buckets" in the accelerator) over a flight path l of 0.59 km. The main difficulty in the experiment is the separation of any massive particles from the dominant neutron background. The *M*4 beam with its relatively large takeoff angle (7.25 mrad) was chosen to minimize this background, since it is likely that production cross sections for massive particles fall off more slowly with p_T than those for diffractively produced neutrons.[6,7]

The calorimeter[5] used for the experiment had a total thickness of 900 g/cm^2 of iron so that hadrons had a high probability of interacting and depositing essentially all their energy. The rms fractional energy resolution was approximately $0.14(100/E)^{1/2}$ for E in GeV. Phototubes placed on either side of the calorimeter collected light from alternate scintillators so that two independent measurements of the energy and time of flight were possible. Consistency (± 2 standard deviations in energy and time) between the two measurements was required; this eliminated events with anomalous timing caused by particles passing through the light pipes of the calorimeter. Scintillation counters ahead of the calorimeter were used to veto incident charged particles, and large counters over the calorimeter served to veto cosmic-ray extensive air showers. A segmented lead filter with a total length of 13.6 radiation lengths was placed between the production target and the calorimeter to remove most of the photons. Variable defining collimators were used to control the neutral-beam intensity at the calorimeter. Typically there were $\sim 10^3$ particles in a 2-mm^2 beam spot at the calorimeter with 4×10^{12} protons/pulse incident on the production target. The proton beam energy was 300 GeV.

Figure 1 shows a scatter plot of flight time versus energy for a small sample of events. The flight times are measured with respect to γ's. The majority of events are neutrons, but below

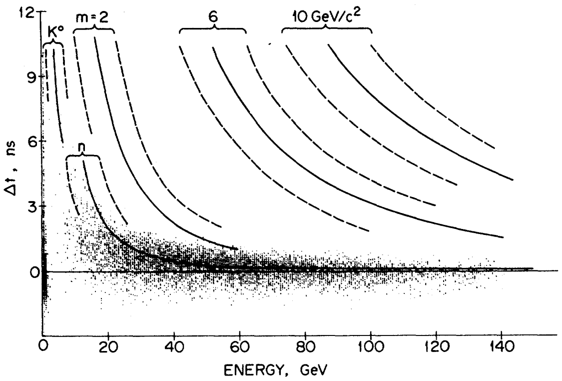

FIG. 1. Scatter plot of relative time of flight versus energy deposited in the calorimeter for a small sample of events. The solid curves show the expected loci for incident particles with various rest masses; the dashed curves indicate the expected spread (± 1σ) for a given mass.

30 GeV there is a significant fraction of kaons and photons. Superimposed on the scatter plot are the loci of particles with masses m_K, m_n, 2 GeV/c^2, 6 GeV/c^2, and 10 GeV/c^2. The dashed curves indicate the rms mass resolution calculated from the energy resolution of the calorimeter and the time resolution. The latter was ± 0.88 nsec and was determined primarily by the width of the rf bunches. The mass resolution was such that it was just possible to resolve kaons and neutrons near 10 GeV.

Candidates for massive particles were events with $\Delta t > 2$ nsec and which were above the $m = 2$ curve (Fig. 1). There were a total of 28 candidates in the 1.3×10^7 events (mostly neutrons) that were recorded and analyzed. However these candidates were randomly distributed and did not lie along a band associated with a well-defined mass. Presumably they were mostly accidental coincidences of two low-energy particles which gave a pulse height that simulated a higher-energy particle or they were the tail of the normal neutron distribution.

The numbers of candidates in each mass band were counted. From this, the number of protons incident on the production target, the solid angle subtended by the collimators, and the energy range over which candidates were accepted, upper limits on the production cross section for each value of the particle mass could be determined. Table I lists the number of candidates within ± 1σ for different masses and the corresponding invariant cross sections, $E\,d^3\sigma/dp^3 \cong p_L^{-1} \times d^3\sigma/dp_L\,d\Omega$. As there is no evidence for the production of a particle with a well-defined mass, 90%-c.l. (confidence level) upper limits on the production cross section are also quoted.[8] The ranges in p_T and $x_F = 2p_L^*/\sqrt{s}$ are also given. The

TABLE I. Invariant-production-cross-section limits.[a]

Mass (GeV/c^2)	p_T range (GeV/c)	x_F range	Observed[b] events	$E\,d^3\sigma/dp^3$[c] observed	$E\,d^3\sigma/dp^3$[d] 90%-c.l. limit	Target
2	0.13–0.32	− 0.05–0.09	14[e]	7.7×10^{-33}	1.1×10^{-32}	Be
			4[e]	4.5×10^{-33}	9.1×10^{-33}	Ta
3	0.20–0.48	− 0.08–0.14	10	2.8×10^{-33}	3.5×10^{-33}	Be
			3	1.6×10^{-33}	3.7×10^{-33}	Ta
4	0.26–0.64	− 0.11–0.18	6	8.5×10^{-34}	1.5×10^{-33}	Be
			1	3.1×10^{-34}	1.2×10^{-33}	Ta
6	0.39–0.96	− 0.16–0.27	5	2.8×10^{-34}	5.3×10^{-34}	Be
			1	1.4×10^{-34}	5.3×10^{-34}	Ta
8	0.52–1.12	− 0.22–0.27	1	4.9×10^{-35}	1.9×10^{-34}	Be
			0	...	2.1×10^{-34}	Ta
10	0.65–1.14	− 0.27–0.17	0	...	1.1×10^{-34}	Be
			0	...	2.4×10^{-34}	Ta
12	0.78–1.15	− 0.33–0.04	0	...	1.3×10^{-34}	Be
			0	...	2.9×10^{-34}	Ta

[a] Invariant cross sections in cm^2/GeV^2 per nucleon.

[b] Events within a band ± 1σ of the mass contour in the energy–time-delay space of Fig. 1.

[c] Most probable invariant cross sections *if* the observed events were due to a new particle (see text).

[d] 90%-c.l. upper limits to the invariant cross sections for each mass.

[e] Observed events only for the band between m and $m+\sigma$ (Fig. 1); 2–3 times as many events were seen between m and $m-\sigma$ from the tail of the neutron distribution.

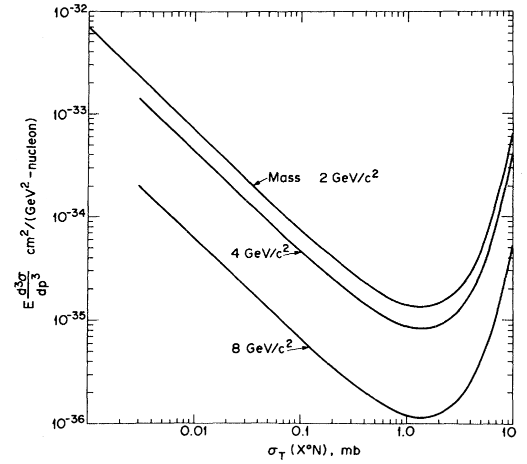

FIG. 2. Invariant-production-cross-section limits versus σ_T, the effective interaction cross section per nucleon.

acceptance is centered near $x_F = 0$ which has been found to favor the production of massive particles such as the $\bar{d}$ and ψ. Two production targets were used at different times in the experiment, a 20-cm beryllium target and a 10-cm tantalum target. The latter was 30 radiation lengths long so that photons from π^0's produced in the target could photoproduce the hypothetical particles. Cross-section limits are given for each target in Table I assuming direct production by protons only, since the evaluation and significance of cross sections for production by secondaries are uncertain.

Runs were also taken with a 960-g/cm^2 iron absorber in the beam ahead of the calorimeter. It is plausible to expect massive new particles to have total interaction cross sections which are small compared to neutrons. (ψ's, for example, have a total cross section ~ 2 mb for nucleons or about 0.05 times the nucleon-nucleon cross section.) Thus the absorber would selectively remove neutrons, and in these runs we were able to open the collimators to pass much more beam. Our production-cross-section limits for new particles are then a function of the total interaction cross section in the absorber and detector. In Fig. 2 we show 90%-c.l. upper limits as a function of the assumed interaction cross section per nucleon [$\sigma_T \equiv \sigma_T(\mathrm{Fe})/56$] for several values of the mass. When the interaction cross section is very small the limits increase because the particles have a lower efficiency for being detected in the calorimeter.[9]

In conclusion, we see no evidence for the production of long-lived neutral particles with masses $\gtrsim 2$ GeV/c^2. Our cross-section limits in Table I are ~ 10^{-1} of the limits for the production of charmed particles at Fermilab energies[10] and ~ 10^{-1} of the cross sections for the production of ψ's at comparable values of p_T (Ref. 7). If the total interaction cross section of the hypothetical particles is ~ 1 mb/nucleon, our limits are ~ 10^{-3} times those for ψ production (Fig. 2). If the hypothetical particles are produced with x_F and p_T distributions similar to those for ψ's, the upper limit from Table I for a mass of 3 GeV/c^2 and a Be target corresponds to a total production cross section ~ 2.5×10^{-32} cm^2/nucleon. If we also assume that they have an interaction cross section of ~ 1 mb, the limit in Fig. 2 corresponds to a total production cross section of ~ 2.5×10^{-35} cm^2/nucleon. Our result is the strongest evidence to date against the existence of quasistable integrally charged quarks.

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[6] Neutron production falls off approximately as $\exp(-4.8p_T)$ for small p_T [J. Engler *et al.*, Nucl. Phys. B84, 70 (1975)], while ψ production falls off as $\exp(-1.6 \times p_T)$ [H. D. Snyder *et al.*, Phys. Rev. Lett. 36, 1415 (1976)].

[7] The cross section for producing ψ's by 400-GeV protons on beryllium is in agreement with $E d^3\sigma/dp^3 = 3.9 \times 10^{-32} \exp(-1.6p_T)(1-|x_F|)^{4.3}$ cm^2/GeV^2 per nucleon (Snyder *et al.*, Ref. 6).

[8] The production cross section limits of Table I were obtained assuming the following: (a) production proportional to $A^{1.0}$, (b) $\approx 100\%$ efficiency of detection in the calorimeter, and (c) particle lifetime such that decay in flight may be neglected (i.e., lifetime $\gg 10^{-7}$ sec).

[9] In calculating the efficiency of the calorimeter we required that the particle interact in the first half so that most of its energy would be deposited in the calorimeter.

[10] The current limits for production of charmed mesons by protons with their subsequent decay into final states with two charged particles are roughly equal to the production cross sections for ψ's by 400-GeV protons [E. Shibata, in Proceedings of the Second International Conference at Vanderbilt University on New Results in High Energy Physics, Nashville, Tennessee, 1–3 March 1976 (to be published)].

Charm Threshold in Electron-Positron Annihilation

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Available data on new mesons discovered at SPEAR are sufficient to determine the spectrum of low-lying charmed mesons and to provide a complete description of the threshold structure of R in the framework of the charmonium model. A number of simple tests are proposed to confirm the charm interpretation.

Recent observation at SPEAR of the reaction $e^+e^- \to (K^\mp\pi^\pm$ or $K^\mp\pi^\mp\pi^\pm\pi^\pm)$ + (recoil, strangeness ± 1)[1] strongly suggests that the long-awaited charmed mesons have been found. The identified $K\pi$ and $K\pi\pi\pi$ systems appear as 6–7 standard deviation enhancements at 1.865 ± 0.010 GeV. A large signal is also observed in recoil against the 1.865 state for recoil invariant masses in the range 1.96 to 2.20 GeV. All of this comes from analysis of data taken in the "threshold region," 3.90 GeV $\lesssim W \lesssim$ 4.60 GeV, with little or no evidence for the enhancements at $W \gtrsim$ 5–6 GeV.

Choosing the mass of the state seen in recoil to be 2.02 GeV in accord with Ref. (1), these new data permit resolution of two important issues: (1) The charmed pseudoscalar D^0 lies at 1.865 GeV, *below* the vector D^{*0} at 2.02 GeV. (2) The rich structure in R observed between 3.7 and 4.5 GeV is completely consistent with the charmonium model, generalized to include coupling to decay channels. Furthermore, we can estimate masses of all other low-lying charmed mesons, the D^* branching ratios, and the exclusive channel contributions to ΔR, the charmed component of R. We propose a number of tests of this "charm interpretation" of the SPEAR results.

Systematics of charmed mesons.—As we argue shortly, $M_{D^0} = 1.865$ GeV and $M_{D^{*0}} \cong 2.020$ GeV. From the quark model, $M_{D^+} - M_{D^0} = M_{K^0} - M_{K^+}$ and $M_{F^+} - M_{D^0} = M_\varphi - M_{K^*}$. Thus, $M_{D^+} = 1.870$ GeV, $M_{D^{*+}} = 2.025$ GeV, $M_{F^+} \cong 2.00$ GeV, and $M_{F^{*+}} \cong 2.15$ GeV. A linear-potential model calculation[2] places the center of gravity of the charmed P states 550 MeV above the S states. Spin-dependent splittings among the P states can be taken from the strange-meson system (the reduced masses are reasonably close). The estimated P-state masses are $D_P(1^1P_1) \simeq 2.5$ GeV, $D_{P0}(1^3P_0) \simeq 2.4$ GeV, $D_{P1}(1^3P_1) \simeq 2.6$ GeV, and $D_{P2}(1^3P_2) \simeq 2.6$ GeV.

These considerations set the following thresholds in e^+e^- annihilation below 4.5 GeV: $W_{DD} = 3.73$ GeV, $W_{DD^*} = 3.885$ GeV, $W_{FF} = 4.00$ GeV, $W_{D^*D^*} = 4.04$ GeV, $W_{FF^*} = 4.15$ GeV, $W_{F^*F^*} = 4.30$ GeV, $W_{DD_P} \simeq W_{D^*D_{P0}} \simeq 4.4$ GeV, and $W_{DD_{P1}} \simeq 4.5$ GeV.

There is no phase-space inhibition for the decay modes $D_P \to D^*\pi$, $D_{P0} \to D\pi$, $D_{P1} \to D^*\pi$, and $D_{P2} \to D\pi, D^*\pi, F^+\overline{K}$.[3] However, phase space for $D^* \to D\pi$ is limited, and $D^* \to D\gamma$ can be competitive. Note that $F^{*+} \to F^+\gamma$ is the only observable mode of the $C = S = 1$ vector. These are sensitive to all relevant mass differences. We computed $\Gamma(D^* \to D\pi)$ by two quite different methods: (i) calculation of the amplitude using the model of Eichten *et al.*[4]; (ii) assuming SU(4) symmetry and relating to $\Gamma(K^* \to K\pi)$. Good agreement between the two methods establishes insensitivity to dynamical details. Radiative ($M1$) transitions are computed from the nonrelativistic quark model.[2,5] Results are listed in Table I.

Charmed-meson production in e^+e^- annihilation.—Recently we presented a dynamical model for $e^+e^- \to$ charmed mesons,[4] based on a universal interaction (linear potential) responsible for both quark binding and hadronic decay. The annihila-