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Search for New Massive Long-Lived Neutral Particles*

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Abstract

We have carried out a search for neutral hadrons with masses ≥ 2 GeV/c^2 and lifetimes $\geq 10^{-7}$sec. in the M4 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} those for production of ψ's by protons for comparable kinematic conditions. This is the most sensitive search to date for quasi-stable integrally charged quarks with masses ≥ 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 $\geq 10^{-7}$sec. and masses ≥ 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 may have a lifetime $\sim 10^{-6}$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 which were sensitive to integrally charged quarks with lifetimes $\geq 10^{-10}$ sec. 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 FNAL 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 M4 neutral beam at Fermilab we have carried out a search for quasi-stable neutral hadrons with masses ≥ 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 $m \cong [2cE^2 \Delta t/\ell]^{\frac{1}{2}}$. The flight time could be measured to an accuracy of better than 1 ns (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 M4 beam with its relatively large takeoff angle (7.25 mr) 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]

The calorimeter[5] used for the experiment had a total thickness of 900 gm/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 approx. $0.14(100/E)^{\frac{1}{2}}$ 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 std. dev. 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 rad. 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 square 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 vs 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 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 ns, 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 $\Delta t > 2$ ns and which were more than approx. 2 std. dev. above the neutron curve (Fig. 1). In the course of the experiment about 1.3×10^7 useful events (mostly neutrons) were recorded and analyzed. Typically there were ~ 2 candidates per 10^6 triggers. However these candidates were randomly distributed and did not lie along a band associated with a well-defined mass. Presumably these were mostly accidental coincidences of two low energy particles which gave a pulse height that simulated a higher energy particle or 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 1 gives 90% confidence level upper limits[7] for the invariant production cross section $E\, d^3\sigma/dp^3 \equiv p_L^{-1} d^3\sigma/dp_L d\Omega$. The range in p_T and $x_F \equiv 2p_L^*/\sqrt{s}$ are also given. The acceptance is centered near $x_F = 0$ so that central production is favored. 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 rad. lengths long so that photons from π^0's produced in the target could photop[illegible] the hypothetical particles. Cross section limits are given for each target in Table 1 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 gm/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 of approx. 2 mb for nucleons (about .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% confidence level upper limits as a function of the assumed interaction cross section per nucleon [$\sigma_T \equiv \sigma_T(Fe)/56$] for several values of the mass. When the total cross section is very small the limits increase because the particles have a lower efficiency for being detected in the calorimeter.[8]

In conclusion, we see no evidence for the production of long-lived neutral particles with masses ≥ 2 GeV/c^2. Our cross section limits in Table 1 are $\sim 10^{-1}$ of the limits for the production of charmed particles at Fermilab energies,[9] and $\sim 10^{-1}$ of the cross sections for the production of ψ's at comparable values of p_T (Ref. 10). If the total interaction cross section of the hypothetical particles is ~1 mb/nucleon, our limits are $\sim 10^{-3}$ those for ψ production (Fig. 2).[11] This result is the strongest evidence to date against the existence of quasi-stable integrally charged quarks.

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References and Footnotes

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2. J.C. Pati and A. Salam, Phys. Rev. D10, 275 (1974); J.C. Pati, Univ. of Maryland Tech. Report, 75-069.
3. L.W. Jones et al., Phys. Rev. 164, 1584 (1967).
4. J.A. Appel, et al., Phys. Rev. Lett. 32, 428 (1974).
5. L.W. Jones et al., Nucl. Instr. 118, 431 (1974).
6. Neutron production falls off approx. as $e^{-4.3p_T^2}$ for small p_T [J. Engler et al., Nucl. Phys. B84, 70 (1975)], while ψ production falls as $e^{-1.1p_T^2}$ [H. Snyder et al., submitted to Phys. Rev. Lett.].
7. The production cross section limits of Table 1 were obtained assuming: (a) production $\propto A^{1.0}$, (b) 100% efficiency of detection in the calorimeter, and (c) particle lifetime such that decay in flight may be neglected, (i.e., lifetime >> 10^{-7}sec).
8. 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.
9. 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 production cross sections for ψ's by 400 GeV protons. [E. Shibata, invited talk at the Vanderbilt University Conference on New Results in High Energy Physics, Nashville, 1976.]
10. The cross section for producing ψ's with 400 GeV protons is $E\, d^3\sigma/dp^3 = (2.6 \pm 0.6) \times 10^{-32}\, e^{-1.1p_T^2}$ cm^2.$(GeV^2$-nucleon) for $x_F \cong 0$. [H. Snyder et al., submitted to Phys. Rev. Lett.]
11. The upper limit from Table 1 for a mass of 3 GeV/c^2 corresponds to a total production cross section of 1.4×10^{-32} cm^2/nucleon if the hypothetical particles are produced with x_F and p_T distributions similar to those for ψ's. [H. Snyder et al., loc. cit.] If we also assume they have an interaction cross section ~1 mb, the limit in Fig. 2 corresponds to a total production cross section of 2×10^{-35} cm^2/nucleon.

Figure Captions

1. Scatter plot of relative time of flight vs 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 for a given mass.

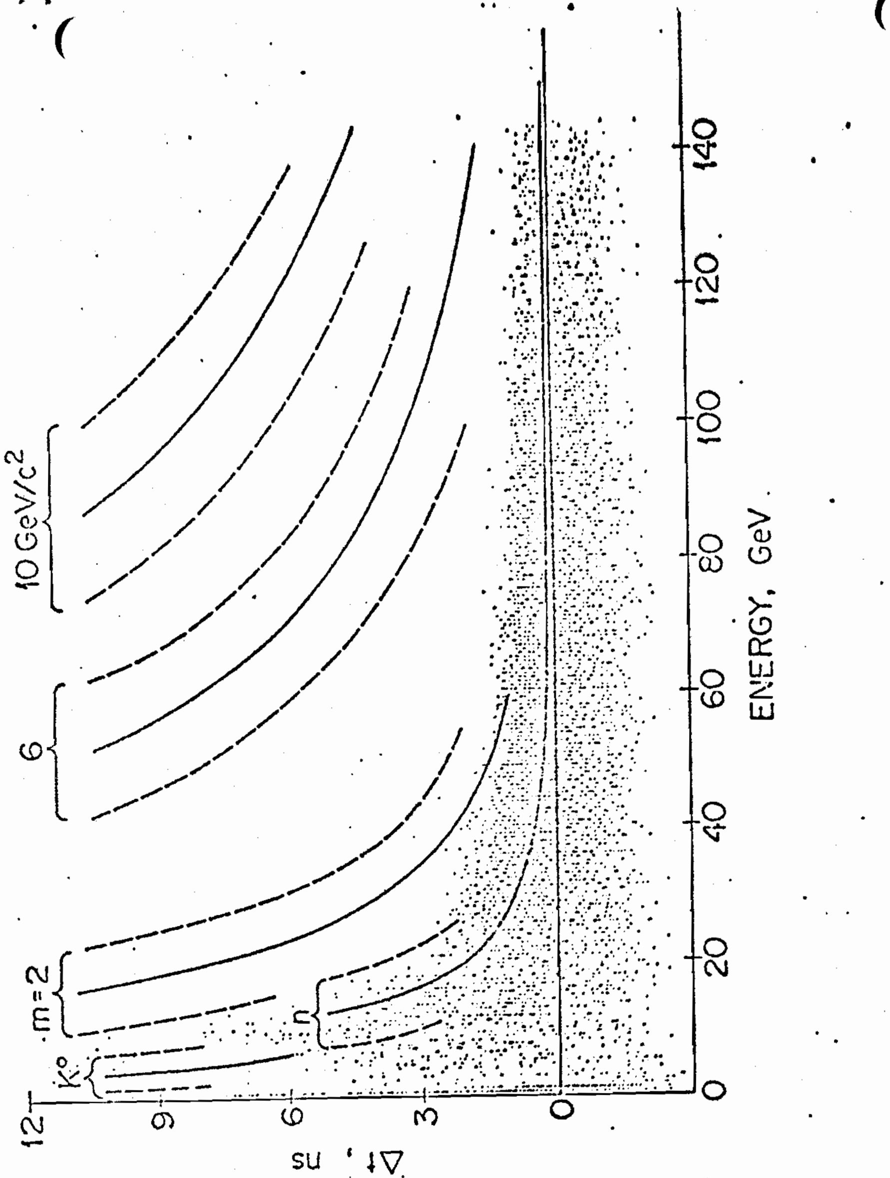
2. Invariant production cross section limits vs σ_T, the effective interaction cross section per nucleon.

Table Caption

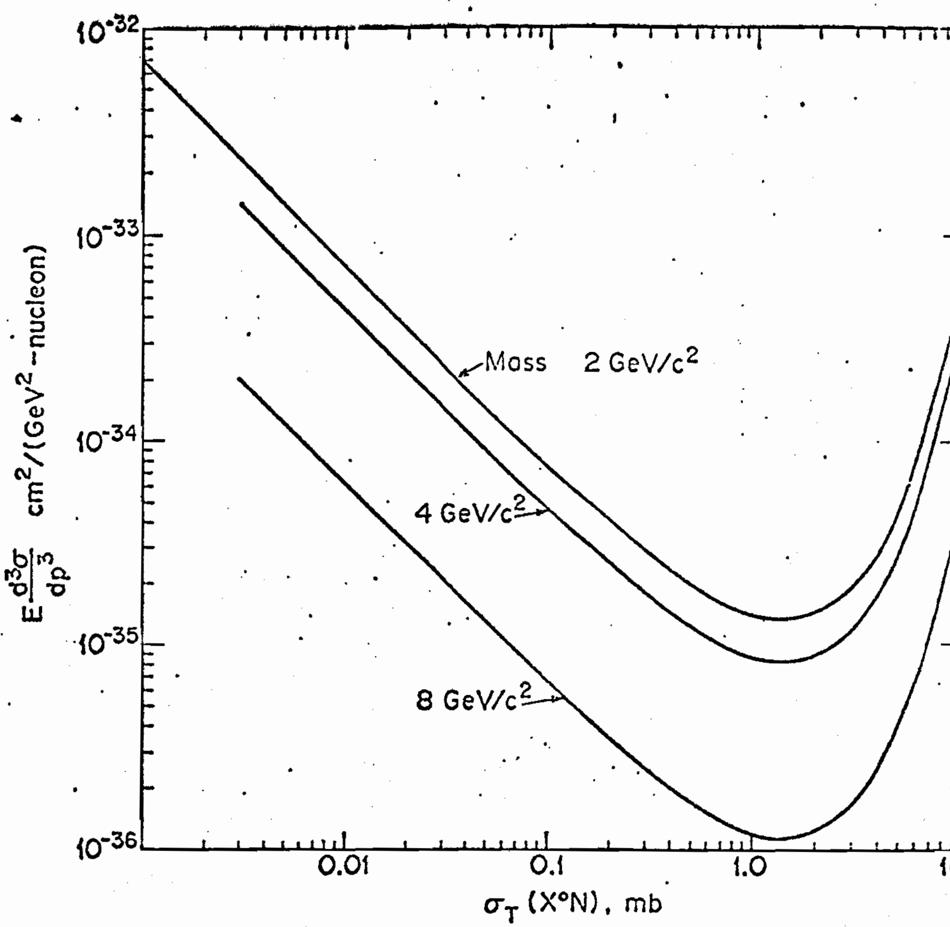
1. Invariant production cross section limits (90% conf.) per nucleon for the beryllium and tantalum targets.

Table 1

Mass (GeV/c^2)	Range in p_T (GeV/c)	Range in x_F	$E\,d^3\sigma/dp^3$ (cm^2/GeV^2-nucleon) Be Target	Ta Target
2	0.13 — 0.32	-0.05 — 0.09	1.1×10^{-32}	9.1×10^{-33}
3	0.20 — 0.48	-0.08 — 0.14	3.5×10^{-33}	3.7×10^{-33}
4	0.26 — 0.64	-0.11 — 0.18	1.5×10^{-33}	1.2×10^{-33}
6	0.39 — 0.96	-0.16 — 0.27	5.3×10^{-34}	5.3×10^{-34}
8	0.52 — 1.12	-0.22 — 0.27	1.9×10^{-34}	2.1×10^{-34}
10	0.65 — 1.14	-0.27 — 0.17	1.1×10^{-34}	2.4×10^{-34}
12	0.78 — 1.15	-0.33 — 0.04	1.3×10^{-34}	2.9×10^{-34}



10 GeV/c²
6
m=2
n
K°
ENERGY, GeV
0
20
40
60
80
100
120
140
Δt, ns
12
9
6
3
0



$E\frac{d^3\sigma}{dp^3}$ cm²/(GeV²–nucleon)
10⁻³²
10⁻³³
10⁻³⁴
10⁻³⁵
10⁻³⁶
Mass 2 GeV/c²
4 GeV/c²
8 GeV/c²
0.01
0.1
1.0
10
σ_T (X°N), mb