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A SEARCH FOR LONG LIVED HEAVY PARTICLES

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We have performed a high sensitivity search for massive long-lived particles produced at 2.5mr by 400 GeV/c protons on a Beryllium target using time-of-flight, Cerenkov, and calorimetric techniques. A total of 10^{11} light particles ($\pi^-, K^-, \bar{p}$) was sampled at 70 GeV/c. This experiment places a limit of 1.1×10^{-37}cm^2/(GeV/c)^2/nucleon on the invariant cross section for the production of stable particles in the mass range of 4 to 10 GeV/c^2.

A search for new, massive, long-lived particles produced in collisions between 400 GeV/c protons and Beryllium nuclei has been performed at Fermilab. The apparatus was sensitive to particles with masses between 2 and 10 GeV/c^2 and with charge $\geq 2/3e$. This experiment was approximately three orders of magnitude more sensitive than previous searches of this kind[1] for masses ~ 5 GeV/c^2. This paper concentrates on the search aspect of the experiment. Other results will be reported elsewhere.

A strong motivation for this experiment was provided by the recent discovery[2,3] of the Υ(9.4), the τ(1.8) and the introduction of theories[4] requiring additional heavy quarks. These quarks are expected to produce a rich spectroscopy of new states with masses[5] greater than 4 GeV/c^2. Due to the conservation of the quantum number associated with the new quark, the lightest members of the new family of particles are expected to be stable against strong decays.

The rate at which these particles are expected to decay weakly into light particles is uncertain. The probability for decay can be expressed in terms of a mixing angle analogous to the Cabibbo angle[6]. Since this mixing angle might turn out to be quite small, there is a possibility that these particles are very long lived.

The experiment used the M6 Beam/Single Arm Spectrometer (SAS) Facility which formed a 2000' long spectrometer at 2.5 mr with respect to the Meson Laboratory Beryllium (8"x0.063"x0.063") target. The combined system had eight Cerenkov counters, a momentum bite of ±0.6%, and a solid angle of 0.5 μsr. Details of M6, SAS and the associated instrumentation are described elsewhere.[7]

The technique used to search for heavy new particles was the following:

a) A laboratory momentum of 70 GeV/c was chosen because a 5 GeV/c^2 mass particle produced at rest in the center of mass in 400 GeV/c collisions, has this momentum in the laboratory. Also at this momentum, there is a large time-of-flight difference between light particles and the masses of interest. The apparatus was set to accept negative particles to minimize the background of (anti-)nuclei.

b) Light particles ($\pi^-, K^-, \bar{p}$) were vetoed by three threshold Cerenkov counters C_1-C_3, set to count particles of masses below 1.3 GeV/c^2. A suppression of 10^{-7} was achieved in the trigger and an additional factor of 20 was achieved by off-line analysis. The trigger accepted any particle not vetoed by C_1-C_3 which counted in four trigger counters T_1-T_4, but not in halo counters H_1-H_3. Thus:

$$\text{Trigger}=T_1.T_2.T_3.T_4.\ (\overline{C_1+C_2+C_3})\ .\ (\overline{H_1+H_2+H_3}).$$

c) A differential Cerenkov counter was used to tag the anti-deuterons which formed the vast majority of the triggers. Similarly, anti-tritons were tagged with a second differential counter. Also, a threshold counter was set to count particles of mass less than 3.5 GeV/c^2, resulting in a rejection of anti-nuclei of 3.0×10^{-3}. Finally, another threshold counter was sensitive to masses ≤ 5.5 GeV/c^2.

d) The velocity of each particle which produced a trigger was measured by recording the time-of-flight at seven scintillation counter stations along a 1500' flight path. Pulse heights from all timing counters were also recorded to correct for slewing due to amplitude effects and to provide a measure of the charge of each particle.

e) A prescaled sample of light particle triggers was also taken in order to continuously monitor and calibrate the time-of-flight system.

The measured rms time resolution between pairs of counters was 250 psec, resulting in a rms mass squared resolution of

2.0 $(GeV/c^2)^2$ independent of mass. Thus, a 5 GeV/c^2 mass particle is 8σ from the nearest source of background, the anti-triton, and more than 11σ from the dominant background, the anti-deuteron. Figure 1a shows the mass squared plot of particles tagged as anti-deuterons by the differential Cerenkov counter.

The requirement of good time resolution limited the intensity to 3×10^6 particles per pulse. During the total exposure of 90 hours, 1.0×10^{11} light particles passed through the system. A total of 3.0×10^5 anti-deuterons was recorded.

A weighted least squares fit to the time information for each heavy particle trigger determined the velocity of the particle and hence the mass squared of the particle. The associated Cerenkov counter information was used to place the event into one of five classes: a) light particle; b) anti-deuteron; c) anti-triton; d) mass <3.5 GeV/c^2 but not a, b or c; and e) massive (≥ 3.5 GeV/c^2) particle candidate.

Mass plots were constructed for each of the 5 Cerenkov counter classes for those events which traversed at least 5 stations and gave an acceptable chi-square. For the sample of anti-deuterons, 95% survived these cuts. Event profiles were examined for every candidate event. These profiles contain the results of the fit, the pulse height from each time-of-flight counter, the status of all Cerenkov counters and hodoscopes, and the status of several beam structure monitors.

To determine the efficiency of the system for measuring particles in the 4 to 6 GeV/c^2 mass range, the spectrometer momentum was tuned to +30 GeV/c. Deuterons at this momentum register as 4.4 GeV/c^2 particles with momentum of 70 GeV/c. The result of that study is shown in Fig. 1b. The appearance[8] of a clear deuteron peak at a "mass" of 4.4 GeV/c^2 at the expected level demonstrates the system's sensitivity to slow particles. Furthermore, appropriate cable delays introduced to simulate particles in the 4 to 10 GeV/c^2 mass range demonstrated an essentially 100% trigger efficiency over this range.

The results of the mass search analysis are shown in Fig.1c for the analysis cuts described above. Of 350,000 triggers, 1500 events survive the cuts. Two-thirds of these appear to be anti-deuterons and most of the rest are light particles. It can be seen that there are three events with masses in the vicinity of 5 GeV/c^2. An examination of the profiles of two of these events indicates timing counter inconsistencies plus a missing threshold Cerenkov tag set for masses $\leq$5.5 GeV/c^2. The third event does show signs of being an acceptable 5 GeV/c^2 event. However, this candidate registered in only five of the possible seven timing stations. For the sample of anti-deuteron events, 85% of those which fired at least five stations also fired six or more stations. A requirement of six stations for this plot would have removed all three of the potential candidates. The calorimeter information indicated that all three candidates were hadrons. Furthermore, the leakage of anti-deuterons expected in Fig.1c at masses $\geq$4.6 GeV/c^2 is estimated from the Cerenkov identified anti-deuterons to be ~0.5 events. We conclude, therefore, that there is at most one candidate particle of 5 GeV/c^2 mass, which is consistent with the level of background.

The above result establishes an upper limit of:

$$E \frac{d^3\sigma}{dp^3}\bigg|_{x_m, p_\perp = 0.175} = 1.1\times10^{-37}\,\mathrm{cm}^2/(\mathrm{GeV}/c)^2/\mathrm{nucleon}$$

at the 90% confidence level for the production of long-lived particles in the mass range from 4 to 10 GeV/c^2. Here x_m is the Feynman x value for a particle of mass m with longitudinal momentum of 70 GeV/c. For 5 GeV/c^2 particles, x_m=0. For a mass of 8 GeV/c^2, the $|x|$ value is ~0.3. If the x-dependence for massive particles is similar to that of light particles, $\sim(1-x)^4$, the cross section limit could be extrapolated to x=0 for masses different from 5 GeV/c^2. For an 8 GeV/c^2 particle, this extrapolation increases the above cross section limit by a factor of ~4.

This calculation relies on the following assumptions:

1) The invariant cross section[9] for the reaction $p+Be\to\pi^-+X$ at 400 GeV/c for pions entering the apparatus at an $x = 0.175$ and $P_\perp = 0.175$ GeV/c is 5.7 mb/(GeV/c)^2/nucleon.
2) The absorption cross section for the new massive particle is not significantly larger than the absorption cross section for π^-.
3) The particle is absolutely stable. If the particle is unstable, then the above limit must be multiplied by the factor $\exp[(26M/\tau)(\mathrm{nsec}/(\mathrm{GeV}/c^2))]$, where M is the mass and τ is the proper lifetime. For example, for a 5 GeV/c^2 particle, this factor produces a significant degradation of sensitivity for lifetimes less than about 5×10^{-8} sec.

For comparison with experiments at 0° it is useful to extrapolate this result to $P_\perp = 0$. A shallow $P_\perp$ dependence[10] is indicated by results on J/ψ production, Υ(9.4) production, and high mass dimuon continuum production by incident hadrons. This extrapolation is expected to increase the limit by $\lesssim 30\%$.

The significance of this limit for the existence of a long-lived particle carrying a new quantum number depends on the assumed properties of the production cross section. If the production of this particle is related to the mechanism for producing the Υ(9.4), this particle should be produced with a similar cross section. The invariant cross section for Υ production at x=0 and $P_\perp = 0$ has been measured[11] to be 1.1×10^{-36} cm^2/(GeV/c)^2/nucleon, assuming a branching ratio to dimuons[12] of 5%. The limit established in this experiment is ~1/10 of the measured Υ production. Moreover, it is believed that the production of states carrying the bare quantum number should be enhanced over the bound quark-antiquark state[13]. Failure to detect these states implies that either their production is significantly suppressed relative to what would be expected from the size of the Υ(9.4) cross section or that the particles are not stable and decay with a lifetime less than $\sim5\times10^{-8}$ seconds[14].

We would like to express our thanks to the many people at the Fermi National Accelerator Laboratory who have contributed to the successful operation of this experiment. Particular thanks are due to Hoshang Vaid, Ron Miksa, Roger Strong and to Cordon Kerns and his associates for their technical assistance. This work was supported in part by the U.S. Department of Energy, The National Science Foundation Special Foreign Currency Program and the Istituto Nazionale di Fisica Nucleare, Italy.

REFERENCES

1. J. A. Appel *et al.*, Phys. Rev. Lett. **32**, 428(1974); H. R. Gustafson *et al.*, Phys. Rev. Lett. **37**, 474(1976).

2. S. W. Herb *et al.*, Phys. Rev. Lett. **39**, 252(1977).

3. M. Perl *et al.*, Phys. Rev. Lett. **35**, 1489(1975).

4. B. W. Lee and S. Weinberg, Phys. Rev. Lett. **38**, 1237(1977); R. N. Cahn, Phys. Rev. Lett. **40**, 80(1978); R. N. Mohapatra and D. P. Sidhu, Phys. Rev. **17**, 1876 (1978); A. DeRujula, H. Georgi, S. L. Glashow, Harvard Pre-print HUTP-77/A028 (unpublished) and Annals of Physics (to be published); H. Georgi *et al.*, Phys. Rev. Lett. **40**, 692(1978).

5. See for example: D. B. Lichtenberg, J. C. Wills and J. T. Kiehl, Phys. Rev. Lett. **39**, 1592(1977).

6. M. Kobayashi and T. Maskawa, Progr. Theor. Phys. **49**, 652(1973); J. Ellis, M. K. Gaillard, D. V. Nanopoulos and S. Rudaz, CERN Report No. CERN TH. 2346, 1977 (unpublished).

7. D. S. Ayres *et al.*, Phys. Rev. D **15**, 3105(1977).

8. In Fig. 1, the mass squared scale is systematically low by a few percent. This is due to imprecisions in the TDC and spectrometer momentum calibrations.

9. D. Cutts et al., Phys. Rev. Lett. **40**, 141(1978); F. Taylor *et al.*, Phys. Rev. D **14**, 1217(1976).

10. J. G. Branson et al., Phys. Rev. Lett. **38**, 1331(1977); J. G. Branson *et al.*, Phys. Rev. Lett. **38**, 1334(1977); D. M. Kaplan *et al.*, Phys. Rev. Lett. **40**, 435(1978).

11. W. R. Innes *et al.*, Phys. Rev. Lett. **39**, 1240(1977).

12. E. Eichten and K. Gottfried, Phys. Lett. **66B**, 286(1977).

13. See for example Fig. 5 and discussion of F. Halzen and S. Matsuda, Phys. Rev. D **17**, 1344 (1978).

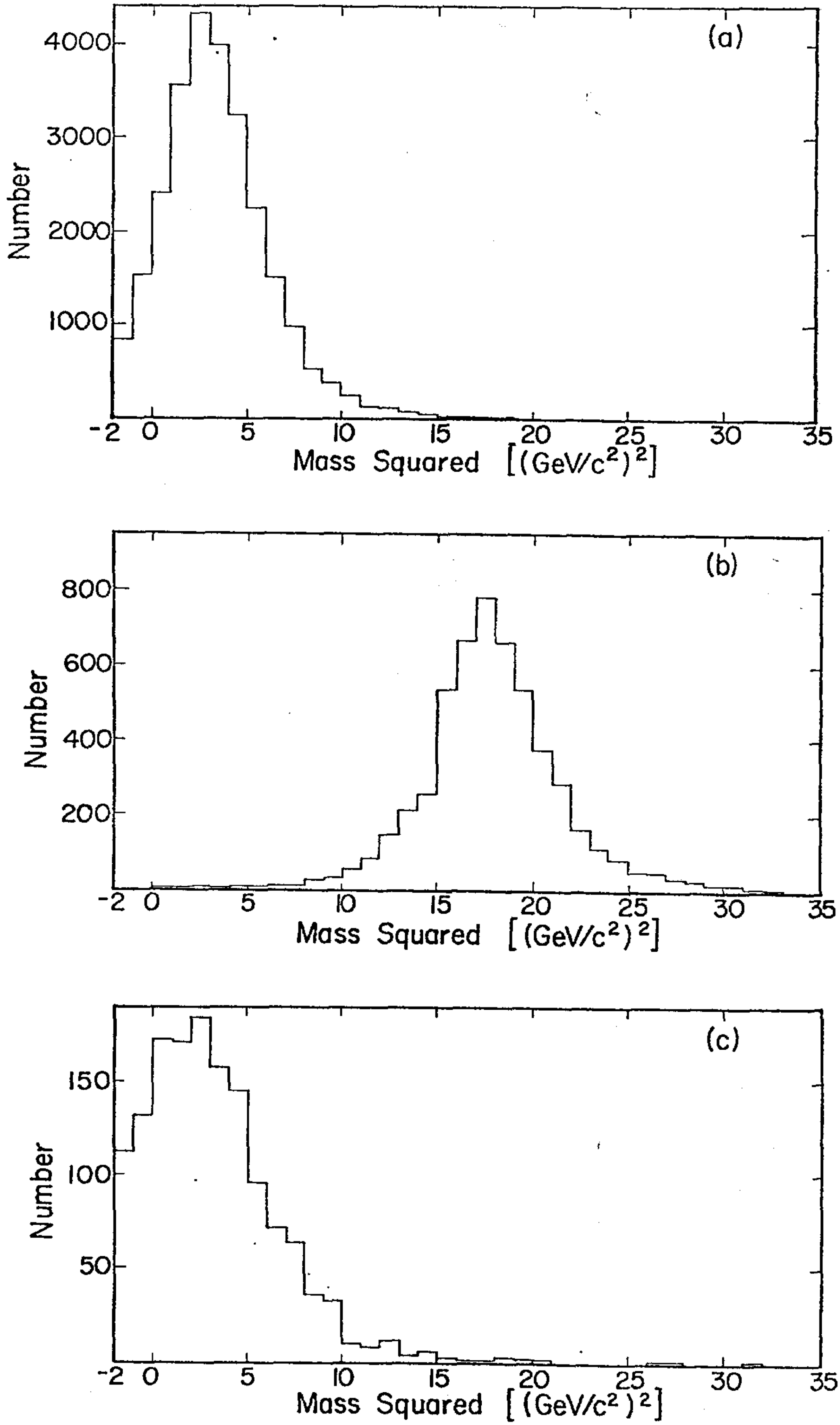
14. The lightest member of this family of particles is expected to be singly charged. The weak decay of this particle could be explained by a non-zero mixing angle between the heavy quark and the light quarks or by conventional beta decay (see R.Cahn, reference 4) if the neutral particle turns out to be the lightest one. In the latter case the charged particle will live long enough to be detected with full sensitivity unless the mass splitting is anomalously large ($\gtrsim 50$ MeV/c^2).

FIGURE CAPTIONS

Figure 1: a. A mass squared plot of anti-deuterons representing 10% of the total data sample.

b. A sample of 30 GeV/c deuterons analyzed as if they were 70 GeV/c momentum particles demonstrating the effectiveness of the system to record particles in the 4 to 5 GeV/c^2 mass range.

c. Mass squared plot of the complete sample of candidate events. The peak at low mass squared represents light particles and anti-deuterons that leak through the rejection criteria. The three potential candidates appear in the region between 26 and 32 $(GeV/c^2)^2$.


(a)
Number
4000
3000
2000
1000
-2 0 5 10 15 20 25 30 35
Mass Squared [(GeV/c²)²]
(b)
Number
800
600
400
200
-2 0 5 10 15 20 25 30 35
Mass Squared [(GeV/c²)²]
(c)
Number
150
100
50
-2 0 5 10 15 20 25 30 35
Mass Squared [(GeV/c²)²]