$+\Gamma(K^+ \to \mu^+ \nu')]$ will be much larger than the experimental value 1.9×10^{-5} [R. Macek *et al.*, Phys. Rev. Lett. 22, 32 (1969)], since the helicity argument no longer applies. Hence, we should set $m'' > 500$ MeV. With these values of m'' and m' the limit $m_{\nu_\tau} \lesssim 250$ MeV, obtained by examination of the high-energy end of the e or μ spectrum from τ decay, is not affected since $m'', m' \gg m_{\nu_e}, m_{\nu_\mu}$.

[15]If the reported data are not due to statistical fluctuation, they can be separated into two groups, one the low-energy group and the other the high-energy group. Certainly, the interaction (1) describes the low-energy group pretty well. But whether this grouping is a statistical fluctuation or a real effect is unknown at present. These points were stressed by H. Primakoff (private communication).

[16]In gauge theories, the charge radius is not a gauge-invariant quantity. Our estimate of this quantity is performed in a special gauge, e.g., in the 't Hooft-Feynman gauge.

[17]See, for example, J. E. Kim, thesis, University of Rochester, 1975 (unpublished).

[18]D. A. Dicus, E. W. Kolb, V. L. Teplitz, and R. V. Wagoner, in Proceedings of the International Conference on Neutrino Physics and Neutrino Astrophysics, West Lafayette, Indiana, 28 April–2 May 1978 (to be published), consider possible searches for ν' in a heavy-liquid bubble chamber.

[19]See, for example, J. E. Kim, Phys. Rev. D 16, 172 (1977).

Search for Long-Lived Heavy Particles

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We have performed a high-sensitivity search for massive long-lived particles produced at 2.5 mrad by 400-GeV/c protons on a beryllium target using time-of-flight, Cherenkov, 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)$^2\cdot$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 $\geq \frac{2}{3}e$. 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 $\Upsilon(9.4)$ and the $\tau(1.8)$, 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. Because of 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 *M*6 beam single-arm spectrometer (SAS) facility which formed a 2000-ft.-long spectrometer at 2.5 mrad with respect to the meson laboratory beryllium (8 in. ×0.063 in. ×0.063 in.) target. The combined system had eight Cherenkov counters, a momentum bite of ±0.6%, and a solid angle of 0.5 μsr. Details of *M*6, SAS, and the associated instrumentation are described elsewhere[7] and schematically summarized in Fig. 1.

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 those with the masses of interest. The apparatus was set to accept negative particles to minimize the background.

(b) Light particles ($\pi^-, K^-, \bar{p}$) were vetoed by three threshold Cherenkov counters, C1–C3, 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 C1–C3 which counted in four trigger counters T1–T4, but not in halo counters, H1–H3. Thus

$$\text{Trigger} = \text{T1}\cdot\text{T2}\cdot\text{T3}\cdot\text{T4}\cdot\overline{(\text{C1}+\text{C2}+\text{C3})}\cdot\overline{(\text{H1}+\text{H2}+\text{H3})}.$$

(c) Two differential Cherenkov counters, D1 and D2, were used to tag the antideuterons which formed the vast majority of the triggers. Similarly, antitritons were tagged with a third differential counter, D3. Also, a threshold counter, C4, was set to count particles of mass less than 3.5 GeV/c^2, resulting in a rejection of antinuclei of 3.0×10^{-3}. Finally, another threshold counter, C5, 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, S1–S7, along a 1437-ft. 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 calorimeter at the end of the system was used to study the hadronic nature of the candidate particles.

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

The measured rms time resolution between pairs of counters was 250 psec, resulting in a rms mass-squared resolution of 2.0 $(\text{GeV}/c^2)^2$ in-

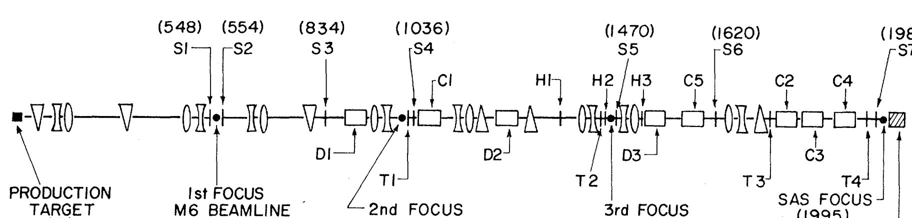

FIG. 1. Schematic of the *M*6 beam/SAS facility—not to scale. The position along the beam line in feet is given in parentheses for critical components. T1-T4 are trigger counters, H1-H3 are halo counters, S1-S7 are timing counters, and C1-C5 and D1-D3 are threshold and differential Cherenkov counters, respectively.

dependent of mass. Thus, a 5-GeV/c^2 mass particle is 8σ from the nearest source of background, the antitriton, and more than 11σ from the dominant background, the antideuteron. Figure 2(a) shows the mass-squared plot of particles tagged as antideuterons by the differential Cherenkov 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 $\times 10^5$ antideuterons 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 square of the mass of the particle. The associated Cherenkov counter information was used to place the event into one of five classes: (a) light particle; (b) antideuteron; (c) antitriton; (d) mass < 3.5 GeV/c^2 but not a, b, or c; and (e) massive ($\geq$ 3.5 GeV/c^2) particle candidate.

Mass plots were constructed for each of the 5 Cherenkov counter classes for those events which traversed at least five stations and gave an acceptable χ^2. For the sample of antideuterons, 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 Cherenkov counters and hodoscopes, and the status of several beam-structure monitors.

To determine the efficiency of the system for measuring particles in the 4–6-GeV/c^2 mass range, the spectrometer momentum was turned 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. 2(b). 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. 2(c) for the analysis cuts described above. Of 350 000 triggers, 1500 events survive the cuts. Two-thirds of these appear to be antideuterons 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 Cherenkov 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 antideuteron 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 antideuterons expected in Fig. 2(c) at masses $\geq$ 4.6 GeV/c^2 is estimated from the

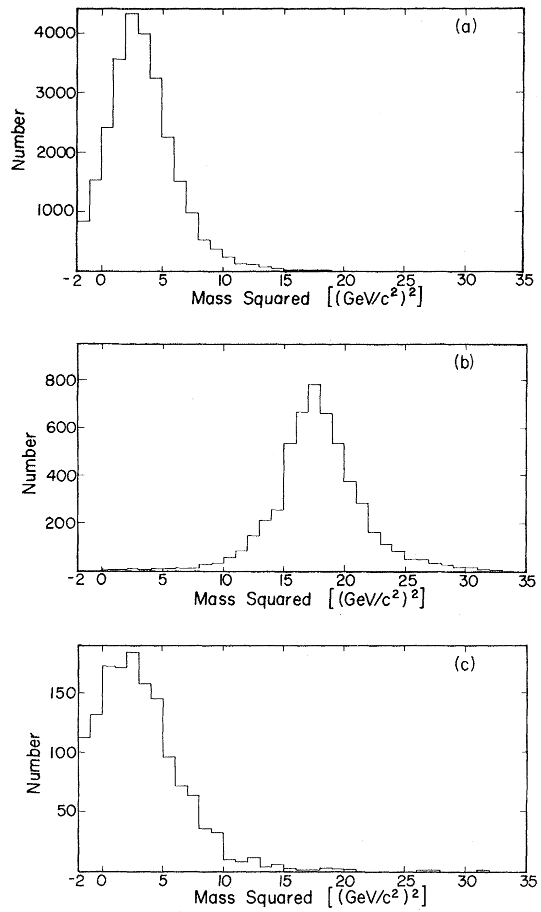

FIG. 2. (a) A mass squared plot of antideuterons representing 10% of the total data sample. (b) A sample of 30-GeV/c deuterons analyzed as if they were 70-GeV/c momentum particles demonstrating the effectiveness of the system to record particles in the 4–5-GeV/c mass range. (c) Mass squared plot of the complete sample of candidate events. The peak at low mass squared represents light particles and antideuterons that leak through the rejection criteria. The three potential candidates appear in the region between 26 and 32 (GeV/c^2)^2.

Cherenkov-identified antideuterons 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

$$(Ed^3\sigma/dp^3)|_{x_m, p_\perp = 0.175} = 1.1\times10^{-37}\ \text{cm}^2/(\text{GeV}/c)^2\cdot\text{nucleon},$$

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: (1) The invariant cross section[9] for the reaction $p+\text{Be}\to\pi^- + X$ 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 assumed to be not significantly larger than the absorption cross section for π^-. There was a total of 0.89 interaction lengths of material for protons in the system. (3) The particle is assumed to be absolutely stable. If the particle is unstable, then the above limit must be multiplied by the factor $\exp\{[26\ \text{nsec}/(\text{GeV}/c)^2]M/\tau\}$, 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, $\Upsilon(9.4)$ 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 $\Upsilon(9.4)$, 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 $\sim\frac{1}{10}$ 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 either that their production is significantly suppressed relative to what would be expected from the size of the $\Upsilon(9.4)$ 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 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.

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[8] In Fig. 2, the mass squared scale is systematically low by a few percent. This is due to imprecisions in the TDC and spectrometer momentum calibrations.

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[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 nonzero mixing angle between the heavy quark and the light quarks or by conventional beta decay (see Cahn, Ref. 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).

Search for Direct Electron Production in *p-p* and *p*-Be Collisions at 12 GeV/*c*

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We have made a systematic search for direct e^+ and e^- production in p-p and p-Be collisions at 12 GeV/c incident proton momentum. Data were collected at c.m. angles of 20°, 35°, 63°, and 84°. We find no evidence for the previously reported rise in the ratio e/π at low momentum transfer. The data are consistent with zero direct electron production from other than previously known sources.

Leptons produced directly in hadron-hadron collisions have been the subject of intense study in recent years.[1] The approximately constant e/π ratio of 10^{-4} observed at center-of-mass energy $\sqrt{s} > 20$ GeV and transverse momentum $P_T > 1$ GeV/c has been explained by a fit which includes a signficant amount of charmed-particle production.[2] However, the reported rise in this ratio for $P_T < 1$ GeV/c observed at both the CERN intersecting storage rings[3] with $\sqrt{s} = 53$ GeV and at the Brookhaven National Laboratory alternating-gradient synchrotron[4] with $\sqrt{s}$ as low as 4.5 GeV cannot be explained in the same way. Indeed, some experiments near or below charm threshold have reported null results.[5-7] We report here the results of a systematic search for direct e^+ and e^- production in proton-proton and proton-beryllium collisions at four c.m. angles (20°, 35°, 63°, 84°) in this region of momentum transfer and at an incident proton momentum of 12 GeV/c ($\sqrt{s} = 4.9$ GeV). These data partially overlap those of Ref. 4 but have been obtained by a different technique.

The experiment was performed using the external proton beam of the zero-gradient synchrotron (ZGS) at Argonne National Laboratory. A schematic diagram of the experimental setup is shown in Fig. 1. Secondary particles produced in a target of hydrogen or beryllium at positions *T*1, *T*2, *T*3, or *T*4 were selected by a two-stage spectrometer viewing targets at position *T*2. Different production angles were investigated by moving the target upstream or downstream to positions *T*1, *T*3, or *T*4 and then restoring secondary particles of the desired momentum to the spectrometer axis by a septum magnet *M*1. Data were obtained with a 0.40-cm-long beryllium target at all four production angles and from a 10-cm-long liquid hydrogen target at position *T*2, corresponding to a 35° c.m. production angle.

The spectrometer was evacuated except in the target region, which was filled with helium at atmospheric pressure. The momentum bite of the spectrometer was set at 3% by a collimator at the intermediate focus. The spectrometer subtended a solid angle from 0.05 to 1 msr for the