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# Search for new, long-lived, neutral particles

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We have searched for new particles of charge zero, a mass between 1.5 and 7.5 GeV/$c^2$, and lifetimes between $10^{-8}$ and $2\times10^{-6}$ sec, produced by 400-GeV/$c$ protons striking a beryllium target. The experiment looked for structure in the transverse-momentum spectrum of charged particles arising from decays in the Fermilab M3 neutral beam. No new particles were found. We place upper limits on the production cross section of any such particle.

Our understanding of high-energy physics has always been enhanced by the discovery of new particles. Hence it is important to search thoroughly for new particles over a wide range of possible masses, lifetimes, decay modes, etc. Many recent efforts have centered on charged particles, or on particles with very short lifetimes (less than $10^{-11}$ sec). We report here a null search for neutral particles, with lifetimes between $10^{-8}$ and $2\times10^{-6}$ sec, and with masses from 1.5 to 7.5 GeV/$c^2$.

Speculations about the existence of such a particle have come from several sources: if, for example, any of the generalized Cabibbo angles[1] governing the decay of new quarks were 1° or less, such a particle might have a lifetime in our range of sensitivity. A massive neutral lepton, lighter than the charged member of its doublet, might also be long lived,[2] as could Han-Nambu integrally charged quarks.[3]

The method we chose for the search was to create a neutral beam and study single charged particles arising from decays of particles in the beam. The momentum component transverse to the beam direction ($p_T$) of such a decay product is a sensitive function of the $Q$ value of the decay, and the $p_T$ spectrum shows a peak located just below the highest kinematically allowed $p_T$ value. This peak is quite sharp for a two-body decay, and becomes broader for higher decay multiplicities. Hence the presence of a new particle could be revealed as structure in the $p_T$ spectrum of single charged particles emerging from a neutral beam.

The experiment used the M3 neutral beam at Fermilab, which is shown in Fig. 1(a). The 400-GeV/$c$ proton beam struck a 12-in. Be target, followed by collimators and sweeping magnets to define the neutral beam, with a solid angle of $3\times10^{-8}$ sr. A 3-in.-thick piece of lead, followed by more collimators and magnets, removed $\gamma$ rays from the beam, which then consisted largely of neutrons and $K_L^0$'s in the ratio of 100:1. A halo of muons, several meters in radius, surrounded the beam, arising from pion and kaon decays near the Be target. Beginning 212 m from the target was an evacuated decay region that was 247 m in length. The detector[4] followed: a magnetic spectrometer that viewed the beam at a small angle. It was placed entirely above the vacuum pipe in which the beam traveled so that the beam was unperturbed except

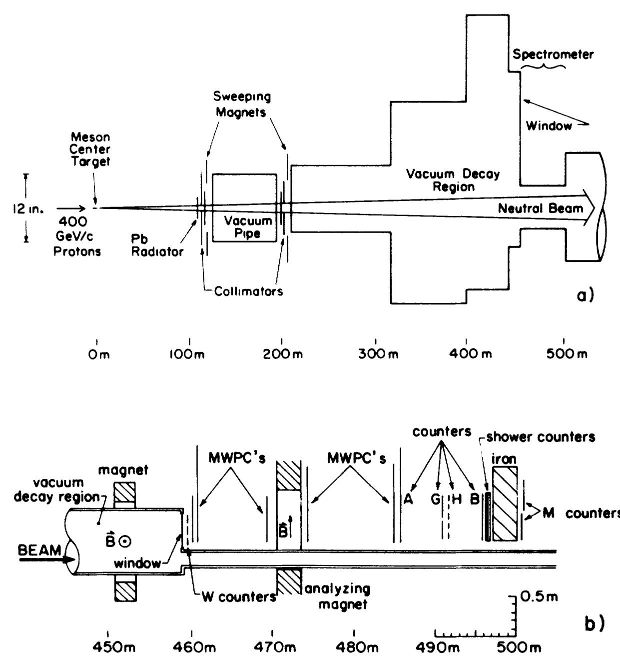


FIG. 1. (a) Elevation view of the M3 beam line, showing the lead radiator, collimators, sweeping magnets, and vacuum pipes. Also shown is the outline of the neutral beam. (b) Elevation view of the spectrometer, showing the proportional chambers, scintillation counters, shower counters, Fe muon filter, magnets, and the beam pipe.

 

for decays. The products of these decays passed through a thin window and entered the spectrometer, shown in Fig. 1(b). It consisted of five multiwire proportional chambers and a magnet for measuring particles' trajectories and momenta, five hodoscopes of scintillation counters to identify and trigger on decays of interest, a set of shower counters for electron identification, and finally, a 3-m-thick Fe wall followed by another hodoscope of scintillation counters to veto halo muons.

Just before particles entered the spectrometer they passed through a magnet which gave them a 210-MeV/$c$ momentum impulse in the vertical direction: negatively charged particles were bent downwards. This momentum kick was introduced to reduce the copious $K_L^0$ decays from entering our data sample. Since the maximum transverse momentum of a $K^0$ decay product is 229 MeV/$c$, the vast majority of such particles, rising out of the beam to enter the spectrometer, were redirected downwards, if negatively charged, by this magnet. By using the scintillator hodoscopes of our spectrometer to trigger only on negative particles that were still rising, we then accepted only particles with $p_T > 210$ MeV/$c$ to comprise our data set, i.e., decay products of particles heavier than the $K^0$.

Our data were collected in two runs. The first, as described above, had $1.6\times10^{17}$ protons on target. The second, a search for neutral leptons, was taken with 4.5 m of Fe in the beam to absorb hadrons, and had $1.0\times10^{17}$ protons impinging on the target, with an effective beam solid angle of $3\times10^{-6}$ sr. For the lepton run the vertically bending magnet at the beginning of the spectrometer was turned off. Both positively and negatively charged particles were accepted.

The data analysis consisted of first choosing those triggers for which the pattern of struck wires in the proportional chambers was really that of a rising, negatively charged particle. The particle's trajectory was extrapolated back to see if it actually came from the beam, and the transverse momentum $p_T$ was calculated from the particle's momentum and the angle it made with the center line of the beam. Only particles that intersected the beam in the last 100 m of the decay region were kept for further consideration. Finally because muons of momentum $< 5$ GeV/$c$ would be absorbed in the muon filter, we conservatively demanded that particle momenta be $> 10$ GeV/$c$.

With this analysis complete we expected three kinds of background events to remain in the data: $K^0$ remnants in the region of $p_T = 215$ MeV/$c$, particles arising from neutron interactions with the residual gas of the evacuated decay volume, and beam halo muons that happened to cross the beam and then were absorbed in the iron of the muon filter. We isolated each of these background sources and measured their characteristic $p_T$ spectra in the following ways. We monitored $K^0$ decays throughout the data collection by forming a special trigger that demanded that there be a single particle traversing the spectrometer, but did not require that it be rising or of negative charge. We recorded 1/1024 of these triggers. They were dominated by $K_L^0$ decay products, and allowed us to measure experimentally their $p_T$ spectrum. To study neutron interactions we let air into the beam pipe until the products of these interactions dominated the other background sources and then measured the $p_T$ spectrum. For the muon component we measured the $p_T$ shape by collecting events while triggering only on muons. For the normalization of this background source, we used a previous measurement of the absorption of muons by 3 m of iron.[5]

The data of our hadron search, the $p_T$ spectrum of observed particles, is shown in Fig. 2. The spectrum is smooth. A fit to the sum of muon and neutron backgrounds in the range $0.6 < p_T < 1.65$ GeV/$c$, is also shown. The shapes of the two background sources were held constant in the fit, with normalizations consistent with their experimental uncertainties. The agreement is excellent, having a $\chi^2$ of 40 for 32 degrees of freedom. We conclude that no new particles exhibit themselves as structure in this data.

The $p_T$ spectrum of our lepton search is shown in Fig. 3. The spectrum is smooth, and in the region $0.3 < p_T < 0.9$ GeV/$c$ both the lepton-search data and the muon background data vary approximately as $\exp(-7.3p_T)$. We conclude that the events shown in Fig. 3 are due to the muon background, and that these data show no evidence for neutral leptons.

Our data enable us to put an upper limit on the cross section with which a new particle could be produced in proton + Be collisions, if it had a mass between 1.5 and 7.5 GeV/$c^2$ and a lifetime between $10^{-8}$ and $2\times10^{-6}$ sec. We have calculated these upper limits by first making a Monte Carlo simulation of the experiment and predicting the size and shape of the $p_T$ spectrum that would be seen in the decay of such a particle.[6] By fitting to the data a function that is a sum of the three background sources plus the Monte Carlo–generated decay spectrum, we calculated the upper limits.

Figure 4 presents these upper limits. Since the shape

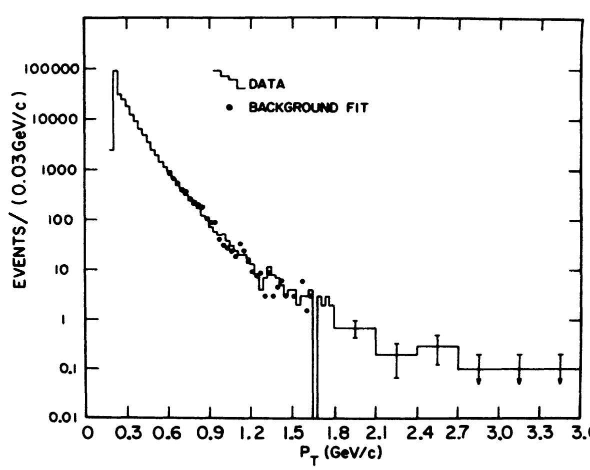


FIG. 2. Hadron-search data. The histogram is the data points, and the dots are a fit of the sum of the background sources described in the text.

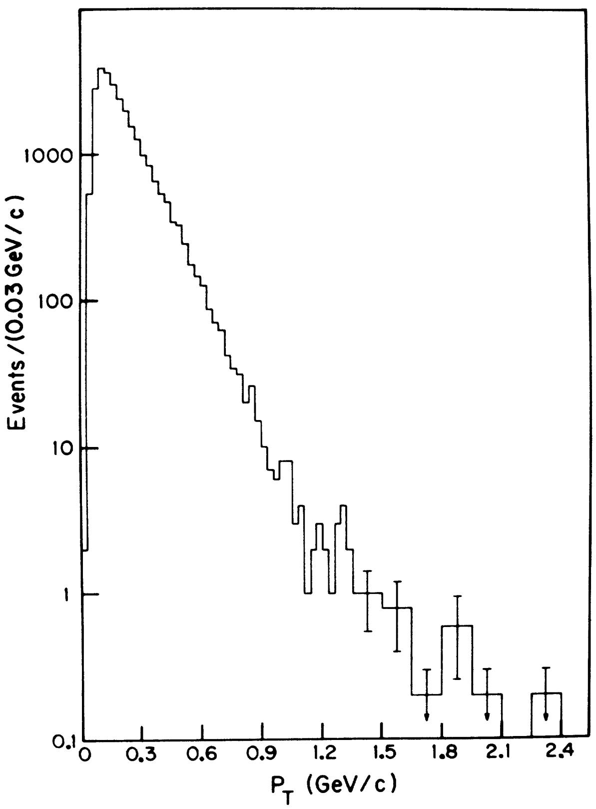


FIG. 3. Lepton search data. In the region $0.3 < p_T < 0.9$ GeV/$c$ this data is proportional to $\exp(-7.3p_T)$, as is the measured muon background.

of the spectrum depends somewhat on the decay multiplicity, we have assumed a two-body decay. Figure 4(a) shows the upper limit as a function of the mass of the parent if the parent's lifetime were $3\times10^{-8}$ sec; Fig. 4(b) shows the dependence on lifetime if the mass were 3 GeV/$c^2$. The results are shown for both the neutral-hadron and neutral-lepton searches. The curves correspond to the 90% confidence-level upper limit for the invariant cross section per nucleon, at Feynman $x$ of the parent of 0.2. Also shown are the results of other neutral-particle searches. The present experiment has several orders of magnitude more sensitivity than the only comparable neutral-hadron search (Gustafson *et al.*[7]) and one or more orders more sensitivity than the neutral-lepton searches of Benvenuti *et al.*[8] and Bechis *et al.*[9] To plot the data of these three experiments in Fig. 4(a), it was necessary to make lifetime corrections (to $3\times10^{-8}$-sec lifetime) to the data of Gustafson *et al.* and Benvenuti *et al.* at $x=0.2$.

If we assume a three-body decay in the Monte Carlo simulation, with a flat Dalitz-plot distribution, the upper limits would increase by a factor of 1.5.

In summary, we have performed a search for long-lived neutral hadrons and leptons produced in collisions between 400-GeV/$c$ protons and beryllium nuclei. Our method is insensitive to branching ratio or type of decay product, and the sensitivity of our search is only weakly dependent upon decay multiplicities. This sensitivity is typically several orders of magnitude better than previous experiments.

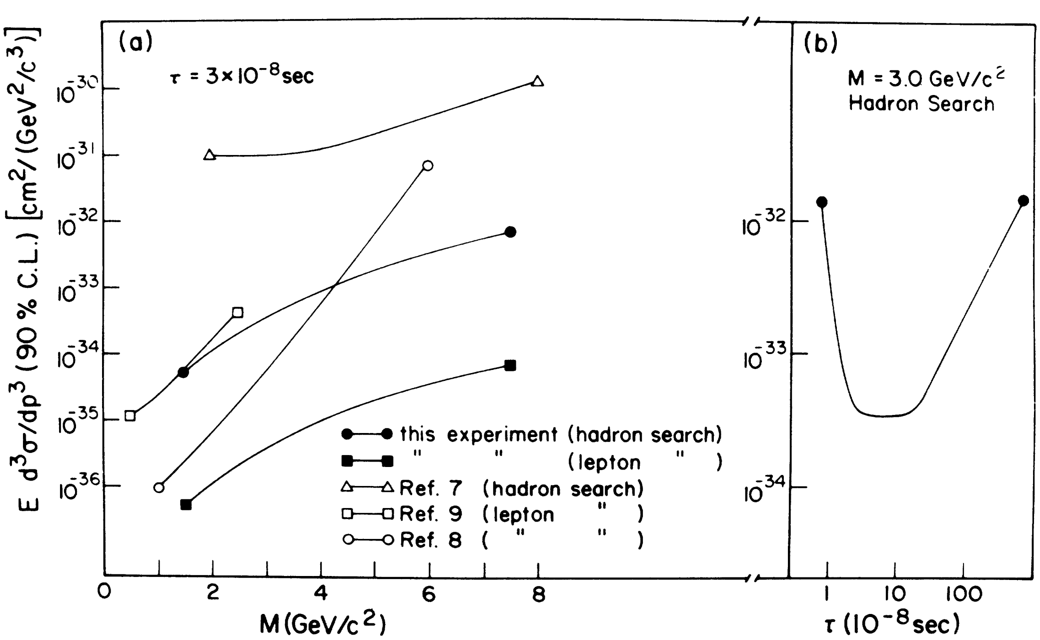


FIG. 4. Upper limits on the particle production. Shown in this figure are the upper limits set by this experiment on heavy-neutral-particle production invariant cross sections. The results of other relevant experiments are also shown. In all cases, the cross section for a particle produced at $x=0.2$ and $p_T=0$ is quoted. (a) shows the upper limits as a function of mass at a lifetime of $3\times10^{-8}$ sec. (b) shows the dependence on lifetime of the hadron upper limits at a mass of 3 GeV/$c^2$.

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