[4]A review of additional data may be found in L. M. Lederman, in *Proceedings of the International Symposium on Lepton and Photon Interactions at High Energies, Stanford, California, 1975,* edited by W. T. Kirk (Stanford Linear Accelerator Center, Stanford, Calif., 1975), p. 265.

[5]J. Kirz, in AIP High Energy Physics Conference Proceedings, Vanderbilt University, Nashville, Tennessee, 1976 (to be published).

[6]See, for example, F. Halzen and K. Kajantie, Phys. Lett. 57B, 361 (1975); M. Bourquin and J. M. Gallard, Phys. Lett. 59B, 191 (1975).

[7]L. M. Lederman and S White, Phys. Rev. Lett. 35, 1543 (1975).

[8]G. R. Farrar and S. C Frautschi, Phys. Rev. Lett. 36, 1017 (1976); Minh Duong-van, SLAC Report No. SLAC-PUB-1604, 1975 (to be published); J. D. Bjorken and H. Weisberg, SLAC Report No. SLAC-PUB-1631, 1975 (to be published).

[9]G. Bohannon, private communication. The observed photon flux is 3 times the calculated bremsstrahlung flux.

[10]N. Kroll and W. Wada, Phys. Rev. 98, 1355 (1955).

[11]B. Alper *et al.*, Nucl. Phys. B87, 19 (1975); J. W. Cronin *et al.*, Phys. Rev. Lett. 31, 1426 (1973); B. V. Blobel *et al.*, Nucl. Phys. B69, 454 (1974); D. F. Cochran *et al.*, Phys. Rev. D 6, 3085 (1972).

[12]Our measured absolute π^+ yields at 800 MeV are a factor of 1.7 ± 0.4 lower than Cochran's yields (Ref. 11) at 730 MeV.

Detection of π-μ Coulomb Bound States*

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We have observed atoms consisting of a pion and a muon produced in the decay $K_L^0 \to (\pi\mu)_{\rm atom}\nu$. This represents the first observations of an atom composed of two unstable particles and of an atomic decay of an elementary particle.

We report herewith the detection of hydrogen-like atoms consisting of a negative (or positive) pion and a positive (or negative) muon in a Coulomb bound state. These pion-muon atoms are formed when the π and μ from the decay $K_L^0 \to \pi\mu\nu$ have sufficiently small relative momentum to bind. We have observed these atoms, produced at relativistic velocities, in the course of an experimental program at the Brookhaven National Laboratory alternating-gradient synchrotron.

The basic properties of these atoms are calculable by the formalism used to describe the hydrogen atom. The reduced mass of the system is 60.2 MeV/c^2, its Bohr radius is 4.5×10^{-11} cm, and the binding energy of the $1S_{1/2}$ state is 1.6 keV. To our knowledge, the first calculation of the branching ratio $R = [K_L^0 \to (\pi\mu)_{\rm atom} + \nu]/(K_L^0 \to {\rm all})$ was carried out by Nemenov,[1] who found that $R \sim 10^{-7}$, with the precise value depending upon the form factors of K_L^0 decay. We will present our results on R in a subsequent paper; only the evidence related to the detection of these atoms is discussed herein.

The prime motivations for the experiment are twofold. Firstly, the value R is proportional to the square of the π-μ wave function at very small distances and so an anomaly in its value may be indicative of an anomaly in the π-μ interaction. Secondly, by passage of the atoms through a magnetic field at high velocity ($\gamma \sim 10$) the $2S$ states should be depopulated through Stark mixing with the $2P$ states and consequent decay to the $1S$ states. The extent of this depopulation will be highly dependent upon the vacuum polarization shift (Lamb shift) of the $2S$ states relative to the $2P$ states and may, if measured with some accuracy, lead to a determination of the pion charge radius.

The K_L^0 particles which give rise to our "atomic beam" are produced by a 30-GeV proton beam striking a 10-cm beryllium target (see Fig. 1). A large vacuum tank and a connecting evacuated beam channel lead out to the detection equipment. A 4-ft steel collimator prevents any direct line of sight from the detector system to the target. This is to prevent background particles, in par-

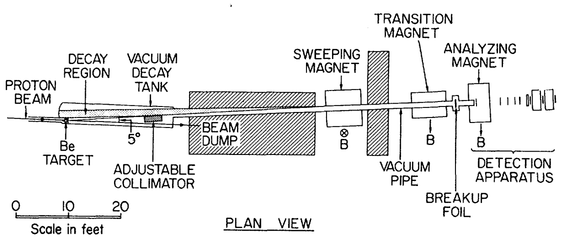

FIG. 1. Experimental arrangement at the alternating-gradient synchrotron.

ticular $K_L{}^0$'s, from approaching the neighborhood of our detectors.

Those $K_L{}^0$'s which decay within the shaded area in the vacuum tank give rise to decay products which may, if properly oriented in their direction of motion, travel down the channel. In order to remove charged particles, we have interposed two magnets along this channel. The first of these, labeled the "sweeping magnet," bends horizontally and has an integrated field strength of 8 kG m. The second magnet (originally intended to induce transitions between the 2S and 1S states of these atoms) is called the "transition magnet" and bends vertically with an integrated field strength of 36 kG m. Those charged particles which survive have very high momenta or are given a significant deflection before entering the detector region.

We have then a beam consisting largely of γ rays (resulting from π^0's which are in turn the products of kaon decays), highly energetic pions and muons, and occasional atoms. The momentum spectrum of the atoms coming down the channel has no appreciable contribution above about 5 GeV/c.

To dissociate the atoms and make their detection possible, we interpose a thin aluminum foil just before the end of the vacuum channel (see Fig. 2). Ionization of an atom takes place through a series of sequential transitions through the states having highest angular momentum for any given principal quantum number. We have calculated the thickness of foil required to break up a 1S atom to be 0.010 in. of aluminum. In the course of the experiment data was taken with foil thicknesses of 0.030 and 0.250 in. of aluminum.

The pion and the muon, now uncoupled, exit from the foil at the same velocity (with momenta in the ratio of their rest masses) and in almost perfect spatial coincidence. The opening angle between them at a typical atomic momentum of 3 GeV/c, neglecting the multiple scattering in the foil, should be less than 0.5 mrad. The projected multiple scattering of each particle in a 0.030-in. aluminum foil is about (1.3 GeV/c)/p mrad. Thus the angle between pion and muon upon emerging from a 0.030-in. foil should be about 2 mrad. The angle between them in the case of a 0.250-in. aluminum foil is about 5 mrad.

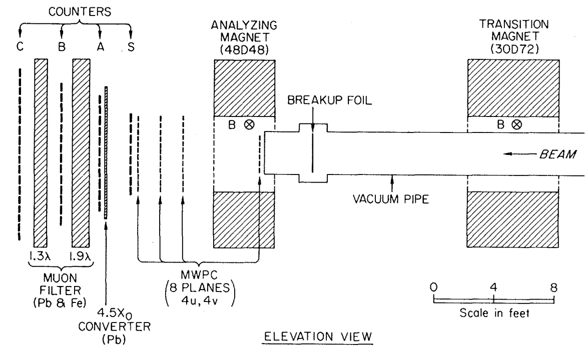

FIG. 2. Detection apparatus.

We next introduce these two coincident particles into a horizontal field which serves to separate them vertically. We terminate the vacuum channel with a thin Mylar window where the separation between the pion and muon is about a centimeter for a typical atom. Just beyond the window we place a multiwire proportional chamber made of two planes (planes 1 and 2) to allow the reconstruction of the vertical (x) and horizontal (y) coordinate of each of the particles. Each of these planes is constructed of a set of wires inclined at 60° to the vertical. At the point where the pion and the muon traverse these planes they are directly above one another and separated by a vertical distance Δ which is closely correlated to the sum of their momenta.

After leaving the analyzing magnet, the pion and the muon continue through a series of three further pairs of proportional chambers, each constructed of wires at $\pm 60°$ to the vertical. In each of these planes the x and y coordinates of each track can be localized to about ± 1 mm. Following the last of these chambers, we have, in sequence, a bank of 11 counters (S bank), a sheet of 1-in.-thick lead to induce showering of electrons, a bank of 15 counters (A bank), a lead and steel wall embodying 1.9 mean free paths of absorber, another bank of 19 counters (B bank), a wall comprising 1.3 free paths of absorber, and a final bank of 23 counters (C bank). The absorber removes muons below a momentum of 0.9 GeV/c and about 90% of the pions. The first crude indication that an event of interest has passed through the detector comes when we obtain a trigger indicating simultaneous counts in two S counters, two nonadjacent A counters, one or more B counters, and one or more C counters. We next examine planes 1 and 2 to determine rapidly whether two tracks passed directly above one another within the experimental resolution and with Δ lying between 0.8 and 3.5 cm. We then remove, through the use of our on-line computer, all events in which more than four tracks passed through the first plane. The residual events are logged for further study. The information recorded includes the timing of all counters, the pulse height on each of the A counters, and the positions of the tracks as they pass through the eight planes.

We carry forth the analysis of the data by subjecting each event to a sequence of tests, each of which must be passed before it can be considered a valid candidate for a π-μ atom. The geometrical characteristics of these tests have been determined through a study of the e^+-e^- pairs which are created by γ rays impinging on the foil and the muons which come down the vacuum channel when the sweeping and transition magnets are turned off. The tests are as follows:

(1) All counters involved in a trigger must be time coincident within ± 2 nsec after correction for flight times of the various particles.

(2) The four counters which define the muon track must lie on a straight line within the limits of Coulomb scattering in the absorber. Only one track may penetrate to the C bank.

(3) The pulse height on each of the A counters must be less than 2.5 times that produced by a minimum ionizing particle.

(4) Each of the tracks must have a momentum not less than 0.9 GeV/c.

(5) After the two tracks are reconstructed back through the magnet, we can determine the x and y projections of their apparent separation and the apparent angle between them as they left the foil. The cuts are as follows: (a) The vertical separation at the foil must be less than 0.45 in. (b) The horizontal separation at the foil must be less than 0.20 in. (c) The measured vertical angle between the two tracks as they leave the foil must be less than 0.025 rad. (d) The measured horizontal angle between the two tracks as they leave the foil must be less than 0.004 rad.

(6) Our study of the e^+-e^- pairs indicates that the vertical spacing, Δ, between the two tracks in planes 1 and 2 is predictable to a wire spacing given the momenta of the two particles. We reject all candidates which do not conform to this constraint within ± 2 wire spacings.

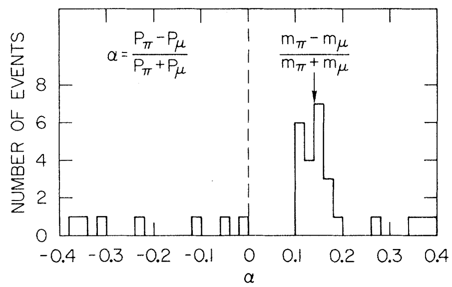

FIG. 3. A plot of the parameter α indicating the detection of π-μ atoms.

(7) By studying the e^+-e^- pairs we have ascertained that we can project our tracks back to the vicinity of the collimator with a horizontal spatial resolution of ± 1.0 in. We insist then that all of our tracks of interest point back to a 9-in.-wide fiducial region near the collimator, missing both the collimator itself and the walls of the vacuum channel.

(8) Finally, we insist that the sum of the pion and muon momenta be no more than 5 GeV/c.

Having subjected all of the recorded data to these tests, we arrive at a residue of 33 events. For each of these events we plot (in Fig. 3) the parameter $\alpha = (P_\pi - P_\mu)/(P_\pi + P_\mu)$, where P_π is the pion momentum and P_μ is the muon momentum. A study of this parameter through an examination of e^+-e^- pairs indicates that the acceptance of our apparatus, modified by the above-mentioned tests, is flat within 30% from $\alpha = -0.4$ to $\alpha = +0.4$. None of our acceptance tests bias us toward one or another sign of α. Hence, any bump in this plot would indicate a strong correlation between pion and muon momenta; in particular, the atoms should be characterized by a value of $\alpha = (m_\pi - m_\mu)/(m_\pi + m_\mu) = 0.14$ The data show a clear peak at the predicted point containing a total of 21 events with an estimated background of three events. The width of the peak is consistent with that expected from measurement errors.

We conclude that we have observed Coulomb bound states of pions and muons.

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[1]L. L. Nemenov, Sov. J. Nucl. Phys. 16, 67 (1973) [Yad. Fiz. 16, 125 (1973)].

Observation of Elastic Neutrino-Proton Scattering*

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We have observed thirty events of the process $\nu p \to \nu p$ with a background expectation of seven events. The neutral-current to charged-current ratio $\sigma(\nu p \to \nu p)/\sigma(\nu n \to \mu^- p)$ is measured to be 0.17 ± 0.05 for $0.3 < q^2 < 0.9$ (GeV/c)^2 where $-q^2$ is the square of the four-momentum transfer to the proton.

Because of its simplicity, one of the most interesting weak neutral-current reactions is the elastic scattering of neutrinos by protons. Previous searches[1] for this reaction have been hampered by high neutron background, poor pion-proton separation, and/or low statistics. The addition of shielding does not necessarily eliminate the neutron-background problem because of the presence of ν-induced neutrons in equilibrium with neutrinos. In this experiment the problem is significantly alleviated by using a detector of such large size that ν-induced neutrons can be absorbed or detected through their interactions in the outer regions of the detector.

The experiment was performed at Brookhaven National Laboratory in a "wide-band" horn-focused neutrino beam. The target-detector [Fig. 1(a)] consists of twelve calorimeter modules containing a total of 33 tons of liquid scintillator.[2] Each module [Fig. 1(b)] is segmented into sixteen cells which are viewed at each end by phototubes. For an energy deposition greater than 3 MeV in a given cell, precise timing and the energy depositions are recorded for each tube. This information determines the position of the source of the energy deposition along the cylinder to ± 10 cm and its timing to ± 0.5 nsec.

The front half of the detector utilizes a close-packed geometry to be fully sensitive to neutrons and charged particles entering from the sides, top, and bottom. For example, a neutron passing through the detector would signal itself by colliding with protons in several, separated cells. The last half of the detector has four large drift chambers[3] interspersed among the calorimeters. Each chamber contains two x planes and two y planes so that the angle as well as position of any tracks exiting from a module may be determined. We have measured a single-gap efficiency of 98% for particles with angles of up to 60° relative to the beam direction. The entire apparatus is housed in a blockhouse of 1.5-m-thick heavy concrete to shield against neutrons. A 2.4-m$\times$3.5-m liquid scintillation counter upstream of the first calorimeter is used to veto charged particles.

The calorimeters and drift chambers are continuously calibrated by accepting beam-associated muons along with neutrino-induced triggers; in addition, vertical cosmic-ray events, recorded between machine bursts, monitor the pulse height and timing of each phototube in the system.

To estimate the cosmic-ray background, the detector is activated between beam bursts for a period of time equal to the duration of the beam

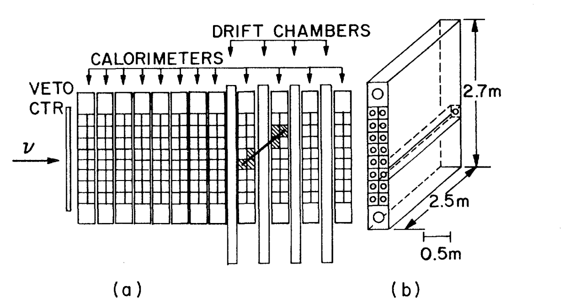

FIG. 1. (a) Side view of the apparatus showing a typical recoil proton event. (b) Diagram of a single calorimeter module.