DETECTION OF π-μ COULOMB BOUND STATES

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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 π-μ atoms are formed when the π and μ from the decay 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 A.G.S.

The basic properties of these atoms are calculated 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 state is 1.6 keV. To our knowledge, the first calculation of the branching ratio $R = \frac{K_L \to (\pi\mu)_{Atm}^{+}\nu}{K_L \to ALL}$ 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° 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. First, 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 passing the atoms through a magnetic field at high velocity 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 2P states relative to the 2S states and may, if measured with some accuracy lead to a determination of the pion charge radius.

The K_L° particles which give rise to our "atomic beam" are produced by a 30 GeV proton beam striking a 10 cm beryllium target (see Figure 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 particular K_L°'s from approaching the neighborhood of our detectors.

Those K_L°'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 kilogauss meters. 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 kilogauss-meters. Those charged particles which survive have very high momenta or are given a significant deflection before entering the detector region.

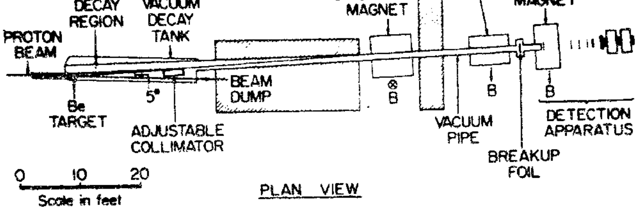

Fig. 1. Experimental arrangement at the A.G.S.

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 about 5 GeV/c.

To dissociate the atoms and make their detection possible, we interpose a thin aluminium foil 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 π-μ atom to be 0.025 cm of aluminium. In the course of the experiment, data was taken with foil thickness of 0.075 cm and 0.625 cm of aliminium.

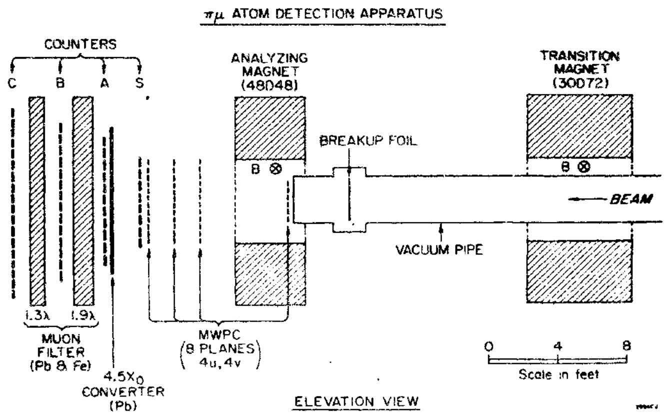

Fig. 2. Detection Apparatus.

The pion and the muon, now uncoupled, exit 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 milliradians. The projected multiple scattering of each particle in a 0.030'' aluminium foil is about (1.3/p (GeV)) milliradians. Thus the angle between pion and muon upon emerging from a 0.075 cm foil should be about two milliradians. The angle between them in the case of a 0.625 cm aluminium foil is about 5 miliradians.

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 and horizontal 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 ±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'' 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 non-adjacent 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 .8 and 3.5 centimeters. 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 nanoseconds 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 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 1.35 cm.

b) The horizontal separation at the foil must be less than 0.50 cm.

c) The measured vertical angle between the two tracks as they leave the foil must be less than 0.025 radians.

d) The measured horizontal angle between the two tracks as they leave the foil must be less than 0.004 radians.

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.

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 ±2.5 cm. We insist then that all of our tracks of interest point back to 22.5 cm wide fidicial 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 $\alpha = \frac{P_\pi - P_\mu}{P_\pi + P_\mu}$ 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 abovementioned

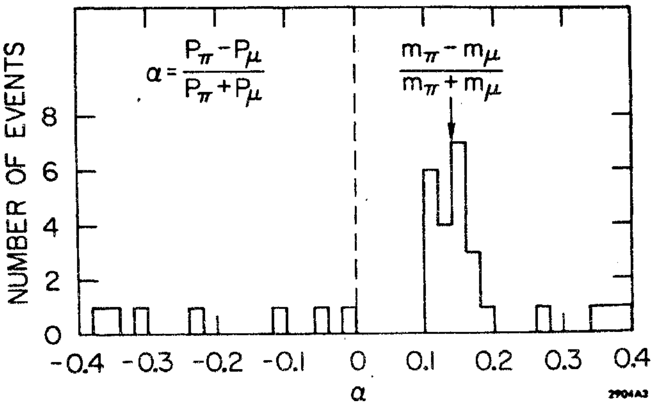

Fig. 3. A plot of the parameter α indicating the detection of π-μ atoms.

tests, is flat within 30% from α = −0.4) to α = +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 $\alpha = \frac{m_\pi - m_\mu}{m_\pi + m_\mu} = 0.14$ The data shows a clear peak at the predicted point containing a total of 21 events with an estimated background of 3 events. The width of the peak is consistant with that expected from measurement errors.

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

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