FERMILAB-Proposal-0533

Proposal to Measure the Rate of Formation of π-μ Atoms in $K_L^o \to \pi\mu\nu$ Decay

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I. Introduction

During the past year an experiment carried out at BNL (see Appendix A) has succeeded in detecting a number of examples of π-μ atoms. These hydrogen-like atoms are formed with a branching ratio of the order of 10^{-7} in the decay of the K_L^o into π, μ and ν. We propose herewith a continuation of the aforementioned experiment at Fermilab with the following aims in mind.

a) By making use of much higher energy K_L^o's it is possible to construct an experiment at Fermilab in which the branching ratio can be measured with much greater accuracy than is possible at BNL. This branching ratio is calculable to of the order of a few percent and has been evaluated by a number of theorists.(1) The calculated value is:

$$R = \frac{K_L \rightarrow (\pi\mu) + \nu}{K_L \rightarrow \pi\mu\nu} = (4.24 \pm .24) \times 10^{-7}$$

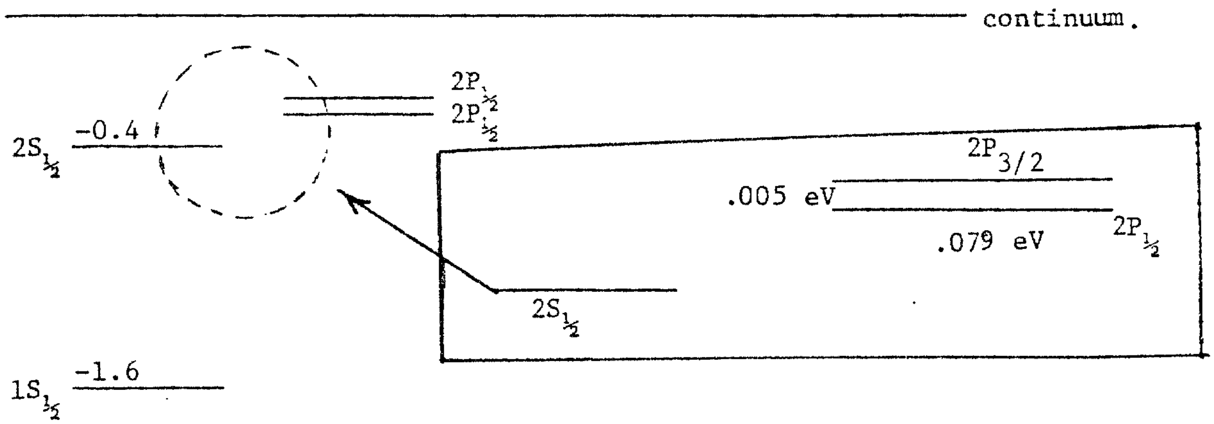
The error in these calculations depends largely on the value of f_+/f_- and is based on the measurement of that ratio by a Stanford-Santa Cruz Collaboration.(2) At present, the branching ratio obtained in the BNL experiment is about a factor of 5 lower than the prediction. If R does indeed differ significantly from the theoretically expected value then it may indicate an anomaly of sorts in the interaction between pion and muon.

b) It may be possible to determine the Lamb Shift by an experiment in which the 2S state is Stark quenched by passing the atoms through a region of magnetic field. At the high velocities obtainable at Fermilab these atoms can be made to experience electric fields in the billions of volts per centimeter.

c) As a byproduct of this experiment, we expect to examine in great detail that portion of the $K_L \rightarrow \pi\mu\nu$ Dalitz plot which corresponds to "almost bound" atoms. By this we mean K_L^o decays in which the relative momentum of pion and muon is of the order of 10 Mev/c or less.

II. Properties of π-μ Atoms

The reduced mass of the π-μ atom is 60.2 MeV. Thus its Bohr radius is 4.5×10^{-11} cm and its binding energy is -1.6 MeV. The lowest state is of course the $1S_{\frac{1}{2}}$ state. The energy levels of the states which are of interest in this experiment are as follows.



Inasmuch as the initial production of atoms is proportional to $|\psi(0)|^2$, the initial population should be roughly 8/9 in the $1S_{\frac{1}{2}}$ state and 1/9 in the $2S_{\frac{1}{2}}$ state. The initial production in higher state is negligible.

III. Method for Producing π-μ Atoms

The atoms will be produced by first generating a well collimated high energy K_L^o beam in vacuum and then examining the neutral decay products of that beam after a distance of about 1000 feet of decay path. The proposed beam is the M-3 beam out of the meson lab. It appears straightforward to take a neutral beam at about 1 milliradian relative to the proton beam and allow it to travel for a distance of the order of 1000 feet to the experimental apparatus. The beam will be collimated to produce a spot which is 6" high and 18" wide at the detector. It appears reasonable to expect a flux of 10^7 K_L^o per pulse in the momentum band from 50 GeV/c to 150 GeV/c. The vacuum system will be constructed so as to be a tube which tapers out to one meter in diameter at the detector region.

Because of the large flux of particles in the beam we expect that the detector will only be able to detect those atoms which are at least six inches outside of the beam spot at the detector. The proposed geometry for detection of these atoms will be described in Part V.

IV. Breakup of Atoms in Foil

Detection of the atoms proceeds by first breaking them up in a thin foil and then magnetically examining the separated pion and muon. We have calculated the amount of foil needed to break up an atom as about 30 milligrams/cm^2 and the recent experiment at BNL indicated that .030 of Al broke up all incident atoms. After the atom is broken up, the pion and muon emerge from the foil with a relative momentum of the order of 1 MeV/c. Hence the signature of one of these atoms is the appearance after a foil of a pion and muon which are nearly spatially coincident and have momenta in the ratio of their rest masses.

V. Overall Setup

In Figure 1 we show a detailed sketch of the experimental apparatus. The beam is carried out to the detection apparatus in a long, cylindrical vacuum pipe which broadens out to a diameter of one meter as it reaches the detectors. The beam first passes through a sweeping magnet having a 1m. x 1m. aperture and a BL of 10 KG - meters. The magnetic field in this magnet is horizontal and its purpose is to vertically separate those π-μ pairs which originate in K^o_L decays but are not bound. A foil is then introduced into the vacuum tank after this magnet and serves to dissociate any atoms which hit it. These dissociated atoms then enter the second magnet, identical to the first but with vertical field and the pion and muon are separated horizontally. At the point where the pion and muon are separated by at least two centimeters for a 100 GeV atom the upper portion of the vacuum is terminated by a thin window. Immediately thereafter we interpose two proportional planes each of which measure the x and y coordinate of both the pion and muon. The two particles are then passed through the third magnet which gives them each a further horizontal kick. Again their directions are measured by means of a set of proportional planes. Finally the particles pass through a set of trigger counters (including a lead sheet for showering electrons), a steel muon filter and another set of muon counters.

VI. The Trigger

The trigger system consists of three picket fence arrays of scintillation counters with a 1" thick sheet of lead against the second of these arrays. We require that there be two A counters struck, two B counters struck and at least one C counter struck. Each of the A and B counters will be 2" wide and we will insist that a gap of at least one counter exist between the two tracks at those planes. We will then read all of the data into a buffer memory associated with a simple fast-processing microcomputer system.

In the microcomputer system, sixteen of which will be on line to the data acquisition module we will determine the separation between the two tracks (if there are indeed two) in the first MWPC's and abort the event if this separation does not lie between 2 and 8 cm. horizontally and less than 1 cm vertically. For those events which remain, we will compute tracks both before and after the second magnet and determine the momenta of the pion and muon. Further cuts will be done off-line when the data is analyzed in detail.

VII. Flux Calibration

Calibration and monitoring of the K_L^o flux can be accomplished by detection of non-bound π-μ pairs with large relative momentum ($\sim$ 100 MeV/c). These pairs constitute a major component of the K_L^o decay products and will be detectable through precisely the same trigger as we use for atoms. As near as we can tell, there appears to be no problems inherent in the flux measurement. As a byproduct we can very easily explore the Dalitz plot for low relative momentum corresponding to "almost-bound" pairs.

VIII. Rate Estimate and Running Time Request

At 3 x 10^6 K_L/pulse (see Appendix B), 10 second repetition rate, 1000 feet decay path, and 10% geometrical acceptance, we would detect one $K_L \rightarrow (\pi\mu)_{atom} + \nu$ event per hour at the predicted branching ratio.

The acceptance is based on Monte Carlo calculations with the spectrometer shown in the figure, using measured[ ] K_L spectra. For purposes of computing the fraction of K_L's decaying in the 1000' pipe a momentum of 150 GeV/c has been used.

On this basis, we request 500 hours of running time to measure the Branching Ratio R, including time for trigger studies and calibration running.

IX. Equipment Request

We request that the Laboratory provide two of the three large aperture magnets, the modifications to M3 (including the opening up of the aperture and the decay pipe to and through the magnets), a data acquisition computer, and fast electronics. The experimenters will provide the third magnet, the detector hardware and its interfacing to the computer.

References

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[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 $K_L^0 \to (\pi\mu)_{\text{atom}}\nu$. 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 $R = [K_L^0 \to (\pi\mu)_{\text{atom}} + \nu]/(K_L^0 \to \text{all})$ 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-

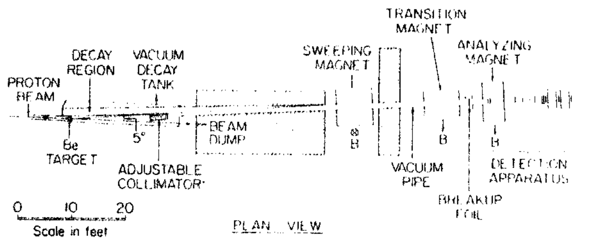

FIG. 1. Experimental arrangement at the alternating-gradient synchrotron.

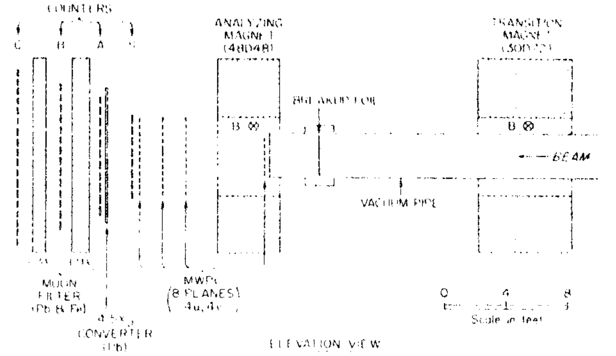

FIG. 2. Detection apparatus.

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 2*S* and 1*S* 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 1*S* 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.

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

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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.

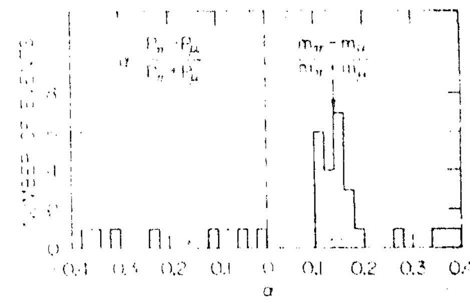

FIG. 3. A plot of the parameter α indicating the detection of π-μ atoms.

(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.

We would like to express our appreciation to the Brookhaven National Laboratory alternating-gradient synchrotron staff and to L. Birkwood, J. Bjorken, S. Drell, G. Donaldson, M. Faessler, M. K. Gaillard, D. Hitlin, B. Kincaid, D. Ouimette, M. Prasad, C. Rasmussen, A. M. Rushton, J. Tannis, A. Tilghman, J. D. Walecka, S. Wojcicki, and C. Zupancic for valuable assistance.

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Appendix B

The Proposed Modifications to the M3 Line

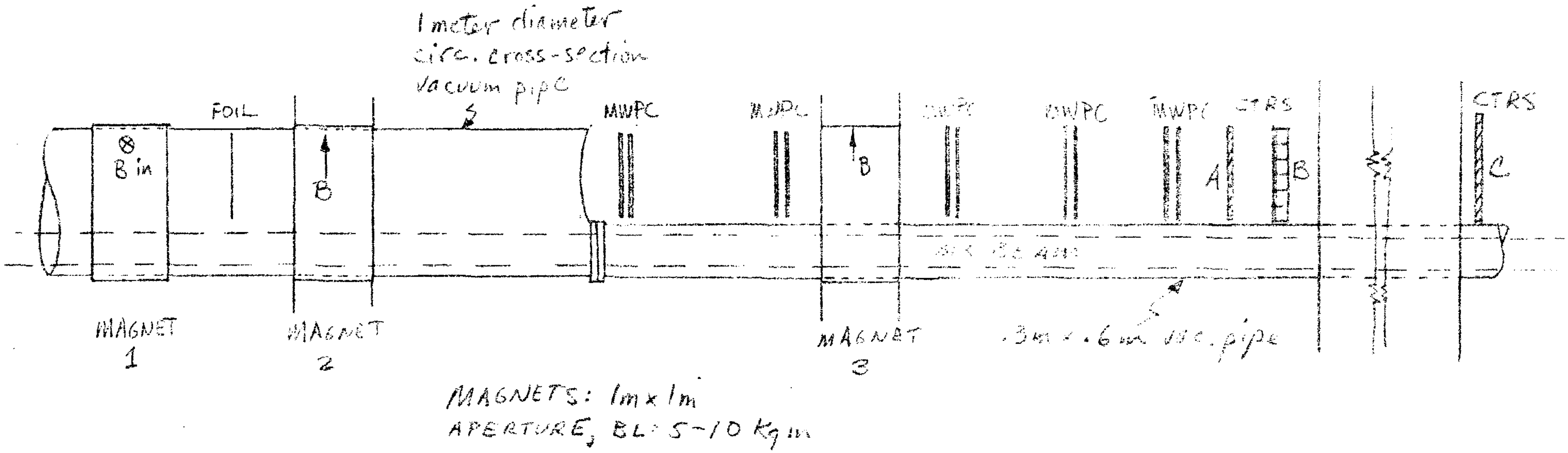
Preliminary discussions with Meson Lab Staff have uncovered no major obstacles to producing a beam of the size and flux required. The primary collimator gives a solid angle of $\pm.42 \times \pm.17$ mrad which corresponds to an 18.1 x 7.3 inch beam at 1800 feet. The present limiting apertures are collimating and sweeping stations further downstream. The modifications consist primarily of removing these elements and of connecting vacuum pipes which are presently separated to provide a continuous vacuum decay path from about 700 feet to the apparatus, to be located in the present M3 Wonder Building. The cost of this effort appears quite modest as no new building construction is required.

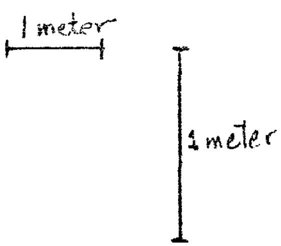
The remaining limitation is the alignment of the 14" pipe which brings the beam to the Meson Detector Building. The fixed and at present unknown alignment of this pipe relative to the center of the M3 beam may prevent full utilization of the above-mentioned solid angle. The rate estimates in the proposal have therefore been made with a rather conservative flux of 3×10^6 K_L/pulse.

It should be pointed out that even at that level M3 would be the most intense and highest-energy K_L source likely to be available for some time and its potential utility would extend far beyond the scope of the present proposal. The beam, coupled with the non-forward pair spectrometer herein proposed would make accessible as yet untapped areas of K° physics. Among the possibilities are:

1. Finite-t regeneration of K_S's at high energies.
2. K-induced high-p_T phenomena.
3. The search for other ultra-rare K_L decays.

Members of the present collaboration are studying seriously the feasibility of using the proposed setup to explore these areas.





PROPOSED π-μ ATOM SPECTROMETER
(SIDE VIEW)