LA-UR- 87-2078

[illegible]

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36

LA-UR--87-2078

DE87 011767

TITLE: SEARCH FOR SPONTANEOUS CONVERSION OF MUONIUM TO ANTIMUONIUM

AUTHOR(S): B. Ni, K.-P. Arnold, F. Chmely, V. W. Hughes, S. H. Kettell, Y. Kuang, J. Markey, B. E. Matthias, H. Orth, H. R. Schaefer, K. Woodle, M. D. Cooper, C. M. Hoffman, G. E. Hogan, R. E. Mischke, L. E. Piilonen, R. A. Williams, M. Eckhause, P. Guss, J. Kane, J. Reidy and G. zu Putlitz.

SUBMITTED TO: The XI International Conference on Particles and Nuclei, Kyoto, Japan, April 20-24, 1987.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes.

The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

FORM NO 836 R4
ST NO 2629 5/81

MASTER

(To be published in the Proceedings of the XI International Conference on Particles and Nuclei, Kyoto, Japan, April 20-24, 1987.)

SEARCH FOR SPONTANEOUS CONVERSION OF MUONIUM TO ANTIMUONIUM

(Presented by Vernon W. Hughes)

B. Ni, K.-P. Arnold, F. Chmely, V.W. Hughes
S.H. Kettell, Y. Kuang, J. Markey, B.E. Matthias,
H. Orth, H.R. Schaefer, and K. Woodle
Yale University

M.D. Cooper, C.M. Hoffman, G.E. Hogan,
R.E. Mischke, L.E. Piilonen, and R.A. Williams
Los Alamos National Laboratory

M. Eckhause, P. Guss, and J. Kane
College of William and Mary

J. Reidy
University of Mississippi

and

G. zu Putlitz
University of Heidelberg

ABSTRACT

We have searched for spontaneous conversion of muonium (M) to antimuonium ($\bar{M}$) by a method involving detection of high-Z muonic X rays. A beam of M atoms with keV energies, produced by electron pickup by μ^+ from a foil, travels in vacuum and in a magnetic field-free environment to a high-Z target. The event signatures used were a double coincidence of two muonic X rays of the target material and a triple coincidence that also required detection of secondary electrons ejected when M strikes the target. Partial analysis of our 8 x 10^6 triggers indicates upper limits on the effective M →$\bar{M}$ four-fermion coupling constant of $G_{M\bar{M}} \lesssim 30\ G_F$ (90% C.L.) and $G_{M\bar{M}} \lesssim 8\ G_F$ (90% C.L.), respectively, from the two signatures. This begins to probe predictions of the left-right symmetric theory with a doubly-charged Higgs triplet.

I. INTRODUCTION

The possibility of the spontaneous conversion of the muonium atom (M or μ^+e^-) to its antiatom, antimuonium ($\bar{M}$ or μ^-e^+), was first suggested by Pontecorvo in 1957.[1] In analogy to the (K^0, $\overline{K^0}$) system, in which two different neutral degenerate particles (particle and antiparticle) are coupled by the weak interaction and hence become mixed, Pontecorvo remarked that the composite atom M should be mixed slightly with $\bar{M}$ due to a second-order weak coupling ($\mu^+e^- \to \nu\bar{\nu} \to \mu^-e^+$)-two different neutrinos, ν_e and ν_μ, were not known at that time-and furthermore might perhaps be coupled by a direct interaction.

In the past 30 years there have been a number of theoretical discussions and speculations about the $M \to \bar{M}$ conversion. These include the suggestion of the existence of primitive leptons and of an associated multiplicative law of muon number conservation, which would allow the $M \to \bar{M}$ conversion,[2,3] and the observation of the close relationship of the $M \to \bar{M}$ conversion to neutrinoless double beta decay and hence the possible occurrence of this conversion due to a massive Majorana neutrino or due to a doubly charged Higgs triplet,[4] both processes being allowed by the left-right symmetric theory of the electroweak interaction.[5] Usually a Hamiltonian term for a 4-Fermion interaction of the V-A type is chosen to represent the $M \to \bar{M}$ conversion:

$$\mathcal{H}_{M\bar{M}} = \frac{G_{M\bar{M}}}{\sqrt{2}} \bar{\psi}_\mu \gamma_\lambda (1 + \gamma_5) \psi_e \bar{\psi}_\mu \gamma^\lambda (1 + \gamma_5) \psi_e + \text{h.c.} \qquad (1)$$

in which $G_{M\bar{M}}$ is a coupling constant characterizing the strength of the interaction. The left-right symmetric theory with a Δ^{++} Higgs particle (Fig. 1) predicts the value $G_{M\bar{M}} \lesssim 10\, G_F$, in which G_F is the Fermi coupling constant.

Beginning in 1968 several experiments[6] have established upper limits on $G_{M\bar{M}}$, with the best presently quoted limit being $G_{M\bar{M}} \leq 20\ G_F$ (90% C.L.). Except for one experiment in which the reaction $e^- + e^- \rightarrow \mu^- + \mu^-$ was looked for with two colliding e^- beams of 525 MeV per beam, all the experiments reported to date have sought as the signal of the $M \rightarrow \bar{M}$ conversion the muonic X rays which would be produced following the collision of $\bar{M}$ with a target atom.

The present paper reports a more sensitive experiment of this latter type and gives the preliminary results based on the data analysis to date.[7] Finally, a discussion of a possible more sensitive experiment to search for the $M \rightarrow \bar{M}$ conversion using the recently discovered thermal muonium is given.

II. THE $(M,\bar{M})$ SYSTEM AND PRINCIPLE OF THE EXPERIMENT

In the absence of external electromagnetic fields, M and $\bar{M}$ have the same ground state energy levels as determined from a Hamiltonian $\mathcal{H}_0$ including the electromagnetic interaction. The postulated weak interaction $\mathcal{H}_{M\bar{M}}$ of Eq. (1) will have diagonal matrix elements in the (F, M_F) representation coupling M and $\bar{M}$:

$$\langle \bar{M}(F,M_F)|\mathcal{H}_{M\bar{M}}|M(F,M_F)\rangle \equiv \frac{\delta}{2} = 1.0 \times 10^{-12}\ \frac{G_{M\bar{M}}}{G_F}\ \text{eV}, \tag{2}$$

in which F, M_F are quantum numbers for total angular momentum and its z-component, respectively. The eigenstates of the $(M,\bar{M})$ system with the total Hamiltonian $\mathcal{H}_0 + \mathcal{H}_{M\bar{M}}$ will then be $(|M\rangle \pm |\bar{M}\rangle)/\sqrt{2}$.

If M is formed at time t = 0, then in vacuum and in the absence of an external electromagnetic field, a component of $\bar{M}$ will develop with time so that the state wave function will be

$$|\psi(t)\rangle = a(t)|M\rangle + b(t)|\bar{M}\rangle, \tag{3}$$

where $a(0) = 1$ and $b(0) = 0$. First-order perturbation theory for degenerate states gives:

$$b(t) = \frac{\delta}{2i\hbar} t \tag{3a}$$

$$|b(t)|^2 = \frac{\delta^2}{4\hbar^2} t^2 \tag{3b}$$

In the presence of an external magnetic field H, a Zeeman energy term $\mathcal{H}_Z$ must be added to $\mathcal{H}_0$ and the resulting Breit-Rabi energy level diagrams for M and $\overline{M}$ are shown in Fig. 2. The degeneracy of M and $\overline{M}$ states with the same (F, M_F) values, present with $\mathcal{H}_0$ alone, is now removed, and hence the development with time of the $\overline{M}$ component in ψ is reduced.[8] This reduction in b(t) due to H is much more pronounced for states 1 and 2 than for states 3 and 4. Indeed, for $H \lesssim 10$ mG ($H \lesssim 500$ G), $|b(t)|^2$ is reduced for states 1 and 2 (3 and 4) by less than 10% of its value for $H = 0$.

The principle of our experiment involves the formation of M at time $t = 0$ through an electron capture by μ^+ from a foil. The resulting beam of M atoms travels in vacuum and in a magnetic field-free region until it strikes a high-Z target. During the flight time to the target, an $\overline{M}$ component of the wave function will develop if $\mathcal{H}_{M\overline{M}}$ exists. Upon striking the target, a muonic atom $Z\mu^-$ will be formed with a probability proportional to $|b(t)|^2$. The resulting cascade of muonic atom characteristic X rays is taken as the signal of an $M \rightarrow \overline{M}$ conversion. In addition, a count in proper time sequence is required from a detector indicating that the $(M,\overline{M})$ system has struck the target.

III. EXPERIMENTAL ARRANGEMENT AND DATA

The experiment was performed at the Los Alamos Meson Physics Facility

(LAMPF), and a schematic diagram of the apparatus is shown in Fig. 3. A separated subsurface μ^+ beam[9] with momentum $p_\mu = 10$ MeV/c and intensity 3×10^5 μ^+/sec (average) from the stopped muon channel (SMC) was incident on a 20 μm plastic scintillator followed by a thin (0.75 μm) Al foil, where M is formed with kinetic energies principally between 1 and 20 keV. Following a region with a transverse H of 1.5 kG to sweep out μ^+, the M beam travels a distance of 280 cm, with 206 cm magnetically shielded to $H \lesssim 20$ mG, and are stopped on a 1 μm thick Bi target, which was evaporated onto a 2 mil aluminized mylar backing and coated with 75A of MgO. The M detector is based on emission of secondary electrons from the Bi target which are then focused and accelerated onto a microchannel plate detector. The K_α and L_α X rays from Biμ^- are detected with the LAMPF NaI(Tℓ) crystal box detector[10] (Fig. 4), modified to extend its low energy threshold to below 2 MeV. The $\overline{M}$ event signature was defined as a triple coincidence of a Biμ^- L_α X ray, Biμ^- K_α X ray, and a count in the M detector (Fig. 5). Extensive neutron shielding with iron, concrete, and borated polyethylene was employed to reduce the background counts in the crystal box detector arising from neutron capture γ rays.

Studies were made with a 16 MeV/c μ^- beam incident on a Bi target to observe the spectra of Biμ^- X rays with the crystal box detector and to measure its detection efficiency. Figures 6(a) and 6(b) show the spectra observed for the upper and lower energy γ rays observed and exhibit clearly the K_α and L_α Biμ^- X rays. The detection efficiency for these two coincident X rays is about 4%. A two-dimensional display of the energy spectrum is shown in Fig. 7.

Extensive background studies were made with the crystal box detector during the development of the experiment and during data-taking under various conditions of accelerator off, accelerator on, μ^+ beam on, and sweeping magnet on. The usual operational trigger requirement on the crystal box detector is that there be two coincident photons ($\Delta t = \pm 30$ ns) in nonadjacent rows of crystals, each with energy above 2 MeV, and a total energy $\lesssim 20$ MeV in the detector. A background trigger rate of about 12 per sec (average) was observed, with the most relevant condition of accelerator on, muon channel open, but μ^+ beam detuned for low transmission. The majority of this background is believed to be due to correlated γ rays originating from n capture.

The detection efficiency of the muonium detector and its noise background were also studied. The secondary electron coefficient γ (number of secondary electrons per incident H^+) was measured for H^+ in the kinetic energy range from 2 to 50 keV incident on different materials in an auxiliary experiment at Oak Ridge National Laboratory. For Bi with a 40Å coating of MgO, γ was greater than 5 in the relevant energy range above 15 keV. Studies of the collection efficiency of our actual detector (Fig. 5), using secondary electrons from a U α source, indicated that the detection efficiency for M would be about 50%. Subsequent analysis of data from our experiment gave the value (46 ± 1)%. The time delay between M striking the target and a signal from the microchannel plate is from 40 to 90 ns due to the secondary electron transit times. This time delay is involved in the triple coincidence signal from $M \rightarrow \overline{M}$ conversion and hence is important. It has been determined from a Monte Carlo calculation. The background noise rate in the M counter is about 1 kHz due principally to thermionic emission from the large area target (cathode).

The basic data-taking mode to search for the M →$\bar{M}$ conversion utilizedthe trigger condition on the crystal box detector mentioned above and recorded time and pulse amplitude from each NaI(Tl) crystal in the detector for subsequent off-line analysis. The time and amplitude of the microchannel plate pulse of the M detector, which was not incorporated in the trigger, was recorded in a ± 250 ns range about each trigger. Data were taken with Bi, Bi + MgO, and U targets–about 42%, 42%,and 16%, respectively. About 8 x 10^6 triggers were obtained in 180 hours of data-taking.

IV. PRELIMINARY DATA ANALYSIS AND RESULTS

For orientation on the data analysis it is useful to estimate the signal rate to be expected if $G_{M\bar{M}} = G_F$, which is done in Table I.

Data from the crystal box detector, without the M detector, were analyzed first. The raw data from the crystal box for each trigger were first processed to incorporate the energy and time calibration information.A candidate signal event required an X ray at the K_α energy of Biμ^- of 6.0 MeV ± 10% and a second X ray at the L_α energy of 2.6 MeV ± 10% in coincidence within the detector resolving time of 5 ns. Furthermore, to reduce the possibility that the two X rays originate from a single higher energy particle, we require that the angle between the two X rays be greater than 57°. A partial background subtraction was made of events associated with the spectrum obtained with the plug in the muon beam line. Scaling the result of analysis of a small fraction of the data, we estimate 235 candidate signal events corresponding to a signal rate of 580 μHz. With a 90% C.L. this corresponds to $G_{M\bar{M}} \lesssim 30\ G_F$ from this preliminary analysis.

When we add the additional requirement that a count be present from the M counter in proper delayed coincidence, the scatter plot of γ_1 and γ_2 energies is shown in Fig. 8. Preliminary analysis gives 8 candidate events corresponding to a signal rate of 20 μHz and to the limit $G_{M\bar{M}} \leq 8\ G_F$ (90% (C.L.). The candidate events are believed to be due to background processes.

The final analysis based on a maximum likelihood calculation will soon be completed and published.

With the recent discovery of the abundant formation of thermal muonium,[11] a much more sensitive experiment to search for the $M \rightarrow \bar{M}$ conversion can be designed. The principal advantages provided by a thermal muonium source from SiO_2 are the increased number of M atoms formed and their localization in a relatively small spatial region so they can be observed throughout their lifetime by a large acceptance detector. It would seem that the preferred method would be to look for a fast e^- from a region with M atoms, indicating the $M \rightarrow \bar{M}$ conversion. A magnetic spectrometer with MWPC detector planes might be located downstream of the region where M is formed, or, alternatively, M might be formed within a magnetic spectrometer with a cylindrical geometry. Estimates indicate that a sensitivity at the level of $G_{M\bar{M}} = 10^{-2}\ G_F$ might be achieved.

ACKNOWLEDGEMENTS

This research was funded in part by U.S. Department of Energy (Yale University, Los Alamos National Laboratory), National Science Foundation (College of William and Mary, University of Mississippi) and the Deutsche Forschungsgemeinschaft (University of Heidelberg).

REFERENCES

1. B. Pontecorvo, Sov. Phys. - JETP 6, 429 (1958).
2. G. Feinberg and S. Weinberg, Phys. Rev. Lett. 6, 381 (1961); C.N. Yang, J. Tiomno, Phys. Rev. 79, 495 (1950); G. Feinberg, P. Kabir, and S. Weinberg, Phys. Rev. Lett. 3, 527 (1959); N. Cabibbo and R. Gatto, Phys. Rev. Lett. 5, 114 (1960).
3. E. Derman, Phys. Rev. D19, 317 (1979).
4. A. Halprin, Phys. Rev. Lett. 48, 1313 (1982).
5. R.N. Mohapatra, J.D. Vergados, Phys. Rev. Lett. 47, 1713 (1981); R.N. Mohapatra, in Quarks, Leptons, and Beyond, ed. by H. Fritzsch (Plenum Publishing Co., 1985), p. 219.
6. J.J. Amato, et al., Phys. Rev. Lett. 21, 1709 (1968); W.C. Barber, et al., Phys. Rev. Lett. 22, 902 (1969); G.M. Marshall, et al., Phys. Rev. D25, 1174 (1982); G.A. Beer, et al., Phys. Rev. Lett. 57, 671 (1986).
7. B. Ni, et al., Bull. Am. Phys. Soc. 32, 1069 (1987); B.E. Matthias, et al., Bull. Am. Phys. Soc. 32, 1069 (1987); C.J. Barnett, et al., Bull. Am. Phys. Soc. 32, 1031 (1987).
8. G. Feinberg and S. Weinberg, Phys. Rev. 123, 1439 (1961); D.L. Morgan, Jr., Yale University Ph.D. Thesis 1966 (unpublished); D.L. Morgan, Jr., and V.W. Hughes, Phys. Rev. D2, 1389 (1970); D.L. Morgan, Jr., and V.W. Hughes, Phys. Rev. A7, 1811 (1973).
9. A. Badertscher, et al., Nucl. Instr. and Meth. A238, 200 (1985).
10. R.D. Bolton, et al., Nucl. Instr. Meth. 188, 275 (1981); G.H. Sanders, et al., Nucl. Instr. Meth. 180, 603 (1981); R.D. Bolton et al., Phys. Rev. Lett. 53, 1415 (1984).
11. A.P. Mills, Jr., et al., Phys. Rev. Lett. 56, 1463 (1986); G.A. Beer, et al., Phys. Rev. Lett. 57, 671 (1986).

Table I. Estimated Signal Rate for $G_{M\bar{M}} = G_F$.

(The signal rate is proportional to $G^2_{M\bar{M}}$)

Quantity	Value
Intensity, I_μ, of μ^+ beam ($p_\mu = 10$ MeV/c) ($I_p = 800\ \mu$A, average)	$3 \times 10^5\ s^{-1}$ (aver)
Number of M formed per sec at foil ($M/\mu^+ = 0.04$)	$1.2 \times 10^4\ s^{-1}$ (aver)
Number of M stopped at target ($d\Omega = 10^{-3}$)	$10\ s^{-1}$ (aver)
$\bar{M}$ probability/atom* $\lvert b\rvert^2$ of Eq. (3b)	2×10^{-6}
Yield of two X rays	0.8
Detection efficiency for two X rays	0.04
Total signal rate (with crystal box detector alone)	$6 \times 10^{-7}\ s^{-1}$ (aver)
Total signal rate (with M detector also)	$3 \times 10^{-7}\ s^{-1}$ (aver)

*This value incorporates an estimate of the reduction in $\lvert b\rvert^2$ due to the magnetic field.

FIGURE CAPTIONS

Figure 1 $M \rightarrow \overline{M}$ conversion via exchange of doubly charged Higgs bosons Δ^{++}, Δ^{--}.

Figure 2 Breit-Rabi energy level diagrams of M, $\overline{M}$ ground-states with hyperfine structure interval a.

Figure 3 Schematic diagram of apparatus used to search for $M \rightarrow \overline{M}$ conversion.

Figure 4 The LAMPF crystal box detector.

Figure 5 Muonium detector. When the $(M,\overline{M})$ system strikes the target, secondary electrons are liberated and electrostatically collected onto the microchannel plate for detection.

Figure 6 Measured spectra of (a) Biμ^- K_α X ray, and (b) Biμ^- L_α X ray. Spectrum (a) is the plot of the highest energy γ ray for the coincidence trigger requirement, and the lower energy peak at the L_α X ray energy occurs because the K_α X ray can be missed.

Figure 7 Scatter plot of K_α, L_α X rays of Biμ^-.

Figure 8 Scatter plot of $(M,\overline{M})$ data γ_1, γ_2 with triple coincidence requirement.

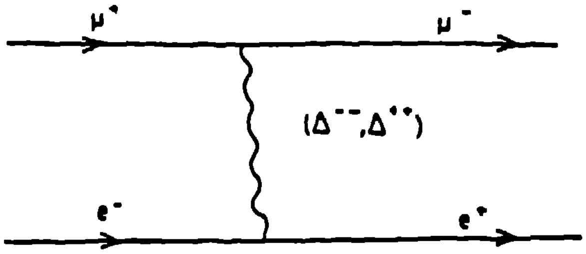

FIGURE 1

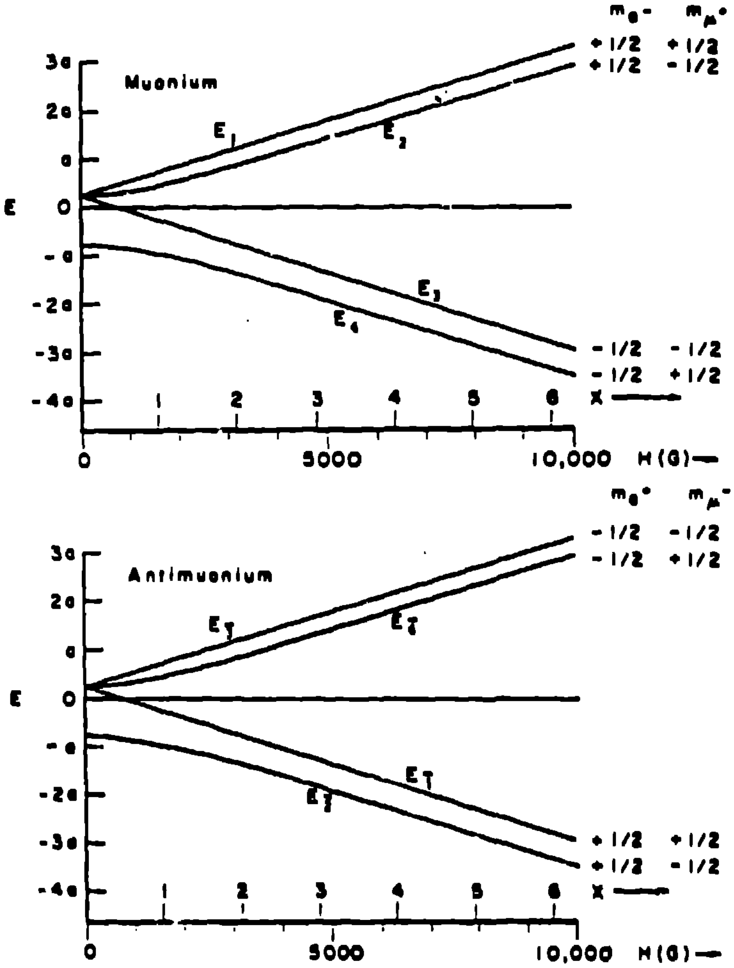

FIGURE 2

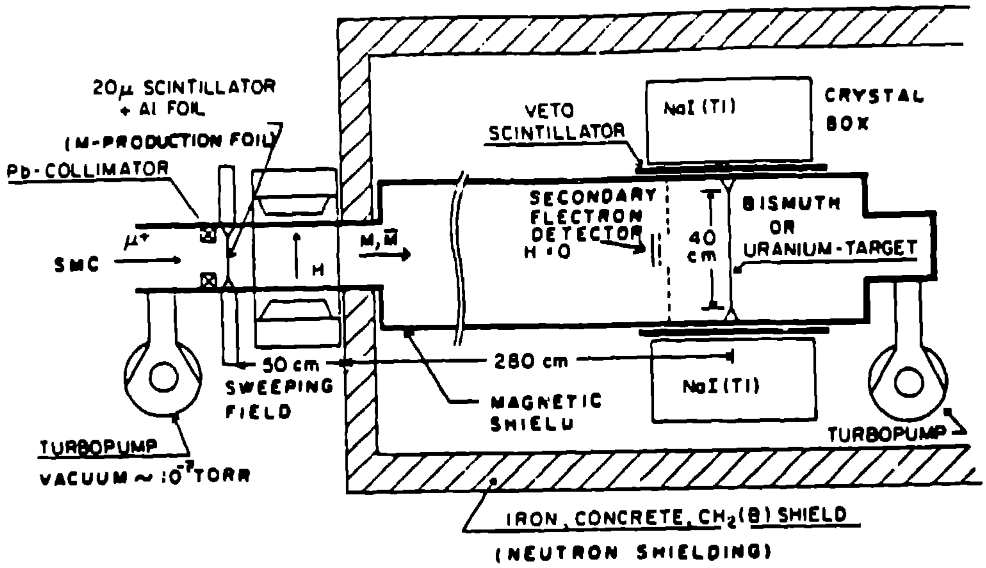

FIGURE 3

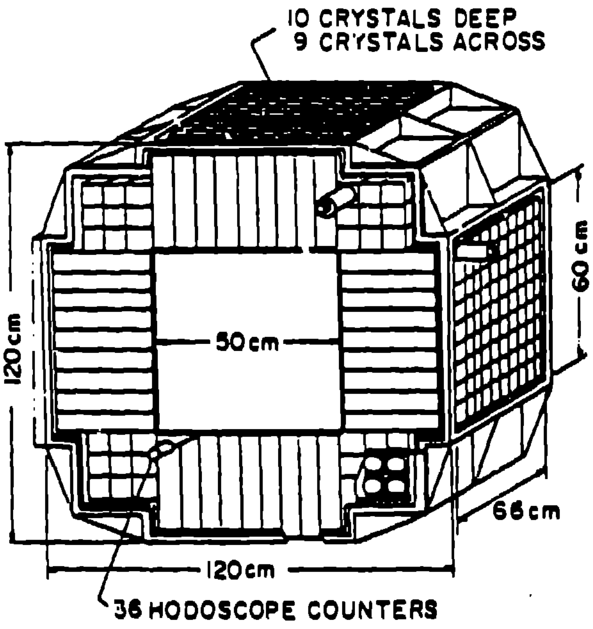

FIGURE 4

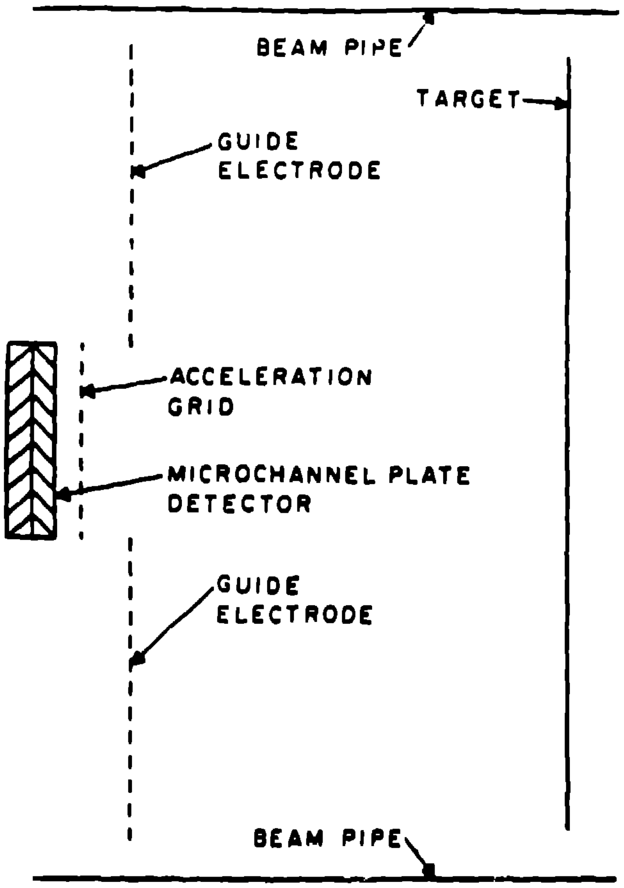
BEAM PIPE
TARGET
GUIDE ELECTRODE
ACCELERATION GRID
MICROCHANNEL PLATE DETECTOR
GUIDE ELECTRODE
BEAM PIPE

FIGURE 5

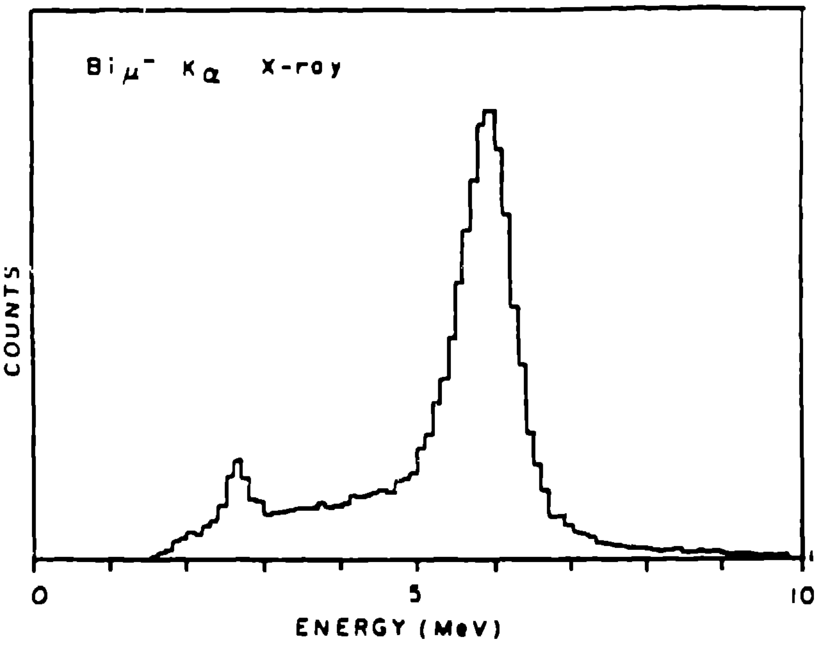

FIGURE 6(a)

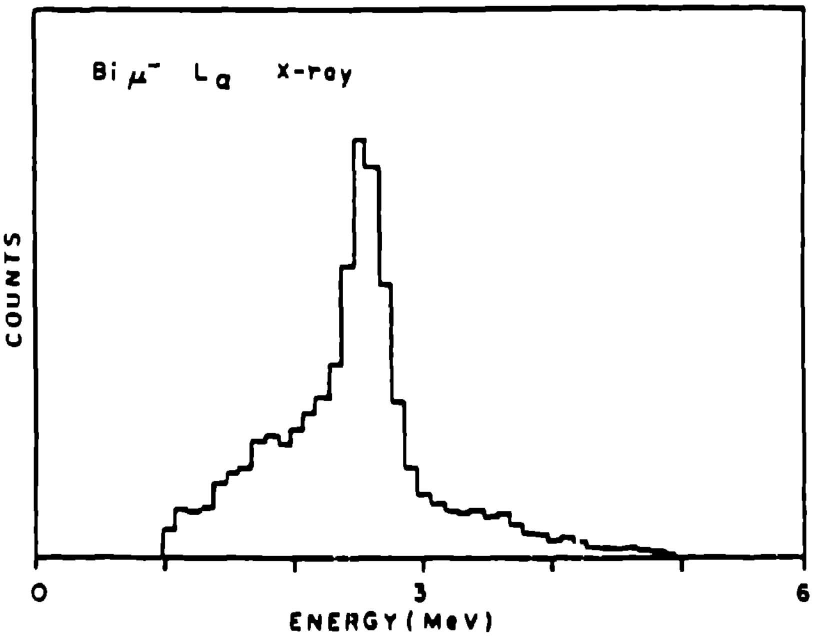

FIGURE 6(b)

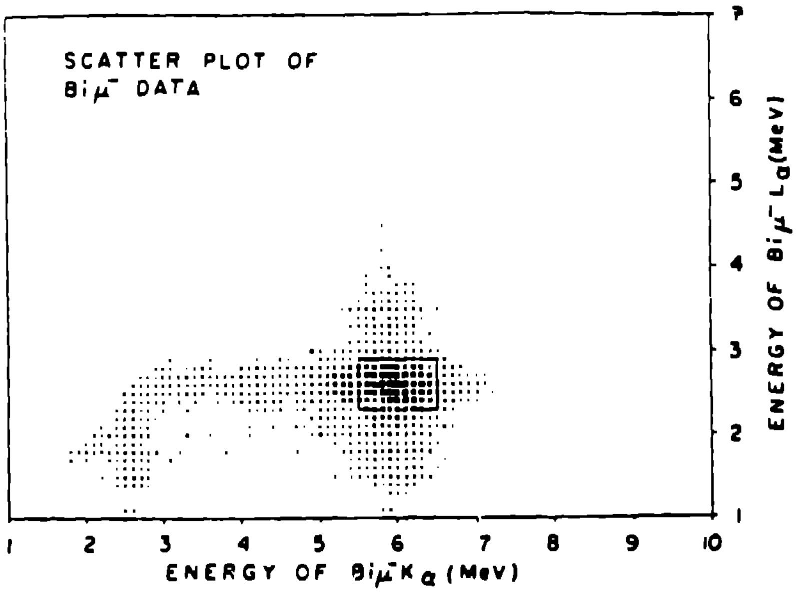

FIGURE 7

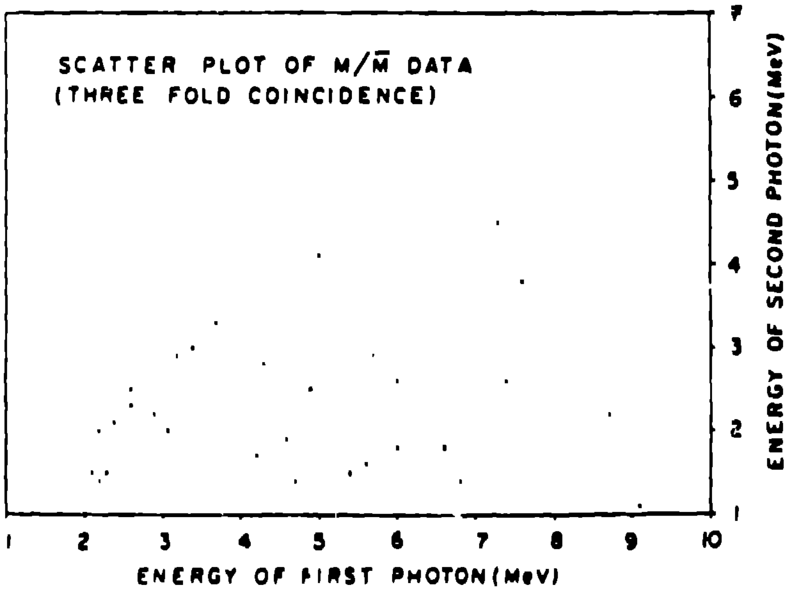

FIGURE 8