AEC-ORO-2504-215

Muonium Formation Measurement in Dilute Argon Gas*

B. A. Barnett, C. Y. Chang, and G. B. Yodh
University of Maryland, College Park, Maryland 20742, USA

J. B. Carroll,† M. Eckhause, C. S. Hsieh,††
J. R. Kane, and C. B. Spence

College of William and Mary, Williamsburg, Virginia 23185, USA

Technical Report No. 74-079

UNIVERSITY OF MARYLAND
DEPARTMENT OF PHYSICS AND ASTRONOMY
COLLEGE PARK, MARYLAND

BLANK PAGE

Muonium Formation Measurement in Dilute Argon Gas*

B. A. Barnett, C. Y. Chang, and G. B. Yodh
University of Maryland, College Park, Maryland 20742, USA

J. B. Carroll,† M. Eckhause, C. S. Hsieh,††
J. R. Kane, and C. B. Spence
College of William and Mary, Williamsburg, Virginia 23185, USA

ABSTRACT

Direct precession measurements of the muonium atomic system have been made in argon gas at low pressures of 1290 and 2280 Torr. At the higher pressure the probability of muonium formation was found to be (85 ± 9)%, and a lower limit to the muonium relaxation time to be 2.8 ± 0.8 μsec. This rate of formation is in agreement with that predicted by Firsov and Byakov on the basis of muonium energy thresholds.

Hughes et al.[1,2] provided the first evidence that the muonium atomic system (μ^+e^-) is formed when they detected a muonium precession signal in argon gas at approximately 38,000 Torr. Since then other spin precession measurements have provided detailed information regarding muonium formation and relaxation rates in a small group of solid materials, including quartz, ice, solid carbon dioxide, silicon, and germanium[3,4,5]. We report here direct measurements of muonium in argon gas at low pressures of 1290 and 2280 Torr which are sensitive to both the degree of muonium formation and its time dependence. Future measurements might extend to gas admixtures consisting of argon gas seeded by specific concentrations of particular elements or molecules. The work described here offers a sensitive method by which a wide variety of reaction rates of a hydrogenlike atom might be studied in a inert environment.

Our measurements were made with the apparatus shown in Fig. 1. The backward-produced μ^+ beam from the SREL synchrocyclotron meson channel was brought to rest in the gas target region between counters 5 and 6. The stopping rate of this polarized beam was $20\mu^+$ per second per gram of target. Counter 5, which registered the arrival of charged particles in the gas target, consisted of a 25μ thick plastic scintillator supported on the upstream surface by 0.32 cm thick Lucite. Light from the scintillant was viewed from outside the chamber by an RCA C70133B phototube (12.7 cm diameter; gallium-phosphide first dynode). Counter 6, which operated as an anti-coincidence counter in the beam telescope, was a five-sided scintillator cup viewed through a conical Lucite lightguide by an RCA 4522 phototube. The surfaces of counters

5 and 6 facing the target region were exposed to the gas. The target chamber was designed to operate over the pressure range from vacuum to 3000 Torr. Ultra high purity argon gas (99.998%, 20 ppm O_2) was continuously flushed through the vessel at flow rates of 15 and 30 std cc/sec during the 1290 and 2280 Torr runs, respectively. The target cylinder was surrounded by an assortment of Helmholtz coils; perpendicular sets of bucking coils reduced the horizontal field at the target to less than 0.05G, while the circular pair of Fig. 1 were available to generate a vertical precession field. For most of the measurements, however, the precession field was provided entirely by the cyclotron fringing field of 3G.

A positive muon stopping in the target gas was identified by the fast coincidence signal $12\bar{3}45\bar{6}$ from the counters in the beam telescope. A second fast coincidence $\bar{2}3\bar{4}678$ within 3.6 μsec of the μ^+ stop signature signaled the appearance of the decay e^+. In the proper time sequence these signals formed the START and STOP input pulses to a 100 MHz time-interval meter (TIM) in which circuitry for protection against secondary muon events was incorporated.[6] The digital information from the TIM was stored in a 400 channel pulse height analyzer in which the initial 40 channels, corresponding to the region $t < 0$, were reserved for accidental events.

The time spectrum of observed μ-e decay events was fit by a least-squares method to the single-frequency distribution

$$N(t) = N_0 e^{-t/\tau} [1 + 1/2\, R\, \alpha\, e^{-t/T} \cos(\omega t + \phi)] + B. \qquad (1)$$

In this expression, N_0 is the amplitude of decay events in the initial time channel, τ is the free muon lifetime of 2.2 μsec, T is the muonium relaxation time, B is a constant associated with accidental events, ϕ is the phase of the signal, and ω is the precession frequency for the $(F, M_F) = (1,1)$ state of muonium. The observed decay asymmetry is given by $1/2\ R\alpha$, in which R is the fraction of stopping muons which form muonium, 1/2 is the fraction of muonium formed in the $(F, M_F) = (1,1)$ state, and α is a measure of the free asymmetry coefficient anticipated under a condition in which the μ^+ remains free. An experimental value of $\alpha = 0.176 \pm 0.002$ was obtained in a separate μ^+ run in carbon at 30G in which a 10 cm x 15 cm x 0.32 cm sheet of graphite was positioned along a diagonal of the target cup. In this way the parameter α incorporated both the polarization of the beam emerging from the meson channel and corrections to the energy response and angular acceptance of the decay counters.

Figure 2 presents the first half of the spectrum at 2280 Torr after adjustments have been made at each channel for the background B and the muon decay exponential. Thus modified to the form $N_0[1 + 1/2\ R\ \alpha\ e^{-t/T}\cos(\omega t+\phi)]$ and grouped three channels per bin, the data show i) a strong precession signal at the muonium Larmor frequency $\sim eH/2m_e c$, and ii) a slow relaxation from the initial signal amplitude. No attempt was made to analyze this spectrum for evidence of two-frequency muonium precession since the beat structure would have evolved slowly for a field of 3G.[7] Table 1 lists the results of analysis for three target conditions: 1) argon gas at 2280 Torr, 2) argon gas at 1290 Torr, and 3) vacuum at 10^{-4} Torr. In fitting the function N(t) to the argon data we chose to simultaneously best-fit the parameters N_0, R, T, and ω while specifying the others.

In the case of the phase angle ϕ the geometrical value of 1.37 radians was used in the gas target analysis presented in Table 1. This value was supported by other least-squares calculations which included φ among the adjustable parameters. Because of the evident correlation between the parameters R and T in Eq. (1), a separate χ^2 study was made of this effect. Figure 3 displays a contour mapping of χ^2 for the variables (R,T) near the optimal position χ^2_{min}. The one standard deviation curve, corresponding to $\chi^2_{min} + 1$, is a measure of the parameter correlation.

The main results of the experiment were obtained at 2280 Torr in terms of a large and persistent muonium signal. A formation fraction of R = 0.85 $\pm$ 0.09 implies almost total production of the $(\mu^+ e^-)$ system in argon gas at low pressure. In particular, this signal is in excellent agreement with the prediction by Firsov and Byakov[8] of the probability for muonium production in argon. They estimated $0.81 < P < 0.86$ on the basis of an upper and lower energy threshold for muonium formation in argon.

When the chamber pressure was lowered to 1290 Torr, the muonium signal dropped noticeably. We interpret this change to be due to a rise in the relative significance of "deadlayer" events in which muons stopping in the scintillant of counter 5 and the surface of counter 6 precess as free muons. An empty target run at 10^{-4} Torr confirmed that stops in the scintillator material did not contribute to the muonium signal, in agreement with previous measurement.[9] For the analysis of the target-empty data, a low value of T was arbitrarily chosen in order to enhance the likelihood of observing a signal. The precession frequency was fixed at the value corresponding to a 3G field.

The type and concentration of impurities in an inert gas environment are known to control the rate at which the muonium polarization relaxes.[10] Our present system with its plastic counters in the target chamber is subject to a significant desorption of various gases. For this reason we attribute the stronger time dependence of muonium at the lower pressure and flow rate to a rise in the equilibrium level of impurities. At the higher pressure and flow rate the depolarization time T was observed to be on the order of the muon lifetime. This time more than likely would increase with an improvement in system cleanliness and gas purity. Even with the present conditions, however, useful chemical studies of muonium interactions with controlled amounts of impurities should be possible.

We wish to thank Professors R. T. Siegel and P. H. Steinberg for enlightening discussions and suggestions. We are also grateful to Dr. G. H. Miller and Mr. M. Mattie for their help with the performance of this experiment. In addition we acknowledge the work and assistance of the William and Mary machine shop and the SREL synchrocyclotron staff. SREL is supported by the National Science Foundation, the National Aeronautics and Space Administration, and the Commonwealth of Virginia.

References

* Research supported in part by the U.S. National Science Foundation and the Atomic Energy Commission.

† Present address: Lawrence Berkeley Laboratory, Berkeley, California 94720

†† The results presented here constitute part of a thesis to be submitted in partial fulfillment of the requirements for the Ph.D. degree of the College of William and Mary.

1. V. W. Hughes, D. W. McColm, K. Ziock, and R. Prepost, Phys. Rev. Letters 5, 63 (1960).
2. V. W. Hughes, D. W. McColm, K. Ziock, and R. Prepost, Phys. Rev. A 1, 595 (1970).
3. G. G. Myasishcheva, Yu. V. Obukhov, V. S. Roganov, and V. G. Firsov, Sov. Phys., JETP 26, 298 (1968).
4. D. G. Andrianov, G. G. Myasishcheva, Yu. V. Obukhov, V. S. Roganov, V. G. Firsov, and V. I. Fistul', Sov. Phys., JETP 29, 643 (1969).
5. J. H. Brewer, K. M. Crowe, F. N. Gygax, R. F. Johnson, B. D. Patterson, D. G. Fleming, and A. Schenck, Phys. Rev. Letters 31, 143 (1973).
6. M. Eckhause, R. T. Siegel, and R. E. Welsh, Nucl. Instr. and Methods 43, 365 (1966).
7. I. I. Gurevich, I. G. Ivanter, E. A. Meleshko, B. A. Nikol'skii, V. S. Roganov, V. I. Selivanov, V. P. Smilga, B. V. Sokolov, and V. D. Shestakov, Sov. Phys., JETP 33, 253 (1971).
8. V. G. Firsov and V. M. Byakov, Sov. Phys., JETP 20, 719 (1965).
9. G. G. Myasishcheva, Yu. V. Obukhov, V. S. Roganov, and V. G. Firsov, Sov. Phys., JETP 5, 227 (1967).
10. R. M. Mobley, J. M. Bailey, W. E. Cleland, V. W. Hughes, and J. E. Rothberg, J. Chem. Phys. 44, 4354 (1966).

Figure Captions

Fig. 1. Experimental arrangement for muonium measurements. The counters labeled 1 through 8 consist of Pilot B scintillants coupled to photomultiplier tubes.

Fig. 2. First half of the muonium precession curve for argon at 2280 Torr corrected for background and the exponential decay of the muon. Each bin represents 3 channels, or 30 nsec.

Fig. 3. The correlation of parameters R and T is presented in terms of a χ^2 contour mapping of these parameter in the vicinity of the best-fit position. Contours 1σ and 2σ show the values of R and T at one and two standard deviations away from the best-fit point.

TABLE 1

Results of Data Analysis for Muonium Formation

Run No.	Target	Pressure (Torr)	N_0	R	T (μ sec)	ω (μsec^{-1})	B (Per Channel)	χ^2 Normalized[a]
1	Argon	2280	844 ± 2	0.85 ± 0.09	2.8 ± 0.8	26.3 ± 0.1	32	1.05
2	Argon	1290	789 ± 3	0.64 ± 0.16	0.7 ± 0.3	25.9 ± 0.4	57	1.18
3	Vacuum	10^{-4}	1250 ± 4	0.07 ± 0.12	0.25	26.4	114	0.91

[a]Interval of analysis: 326 channels

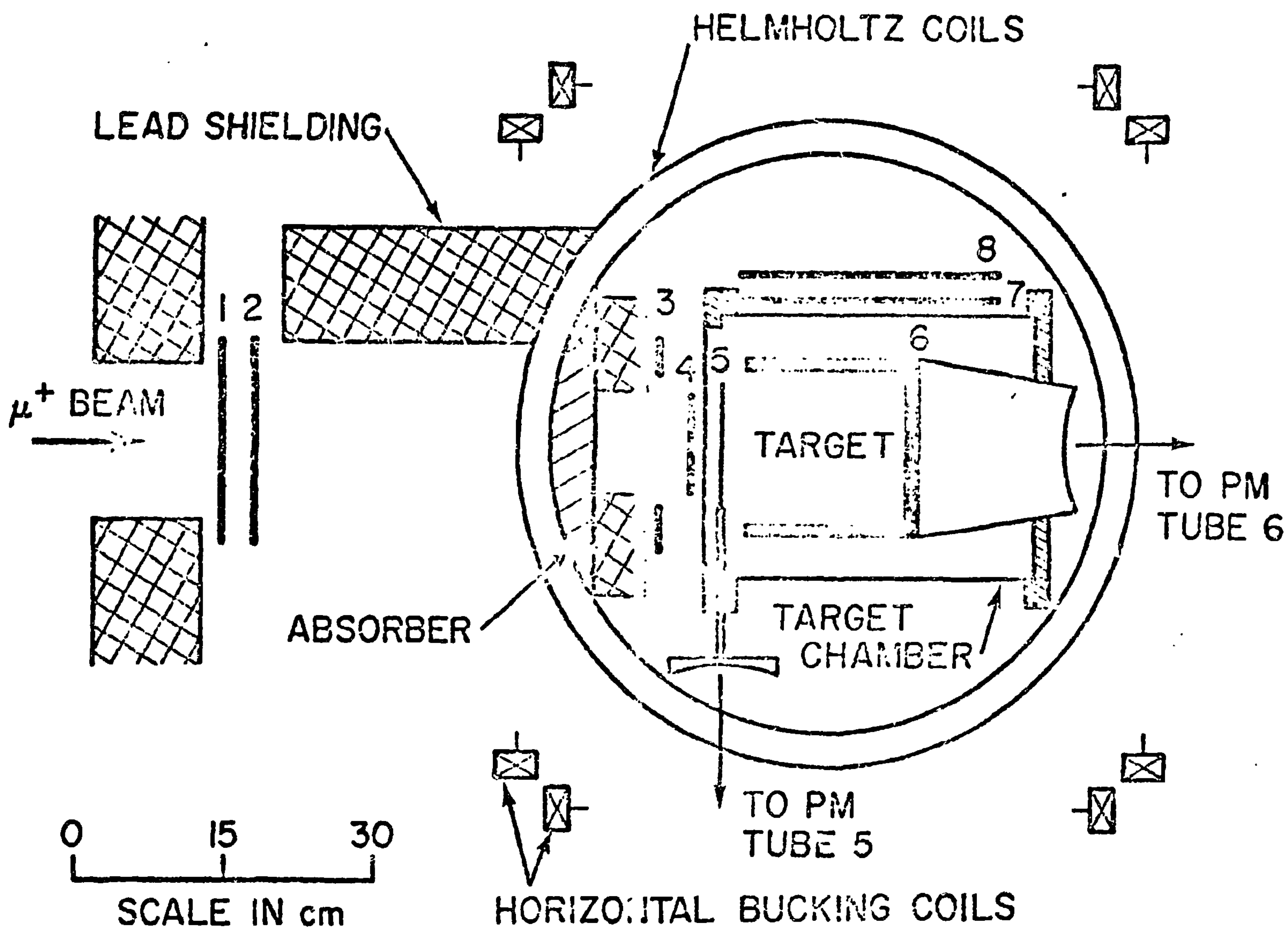

HELMHOLTZ COILS
LEAD SHIELDING
1 2
3
4
5
6
7
8
μ+ BEAM
TARGET
TO PM
TUBE 6
ABSORBER
TARGET
CHAMBER
TO PM
TUBE 5
0
15
30
SCALE IN cm
HORIZONTAL BUCKING COILS

Fig. 1

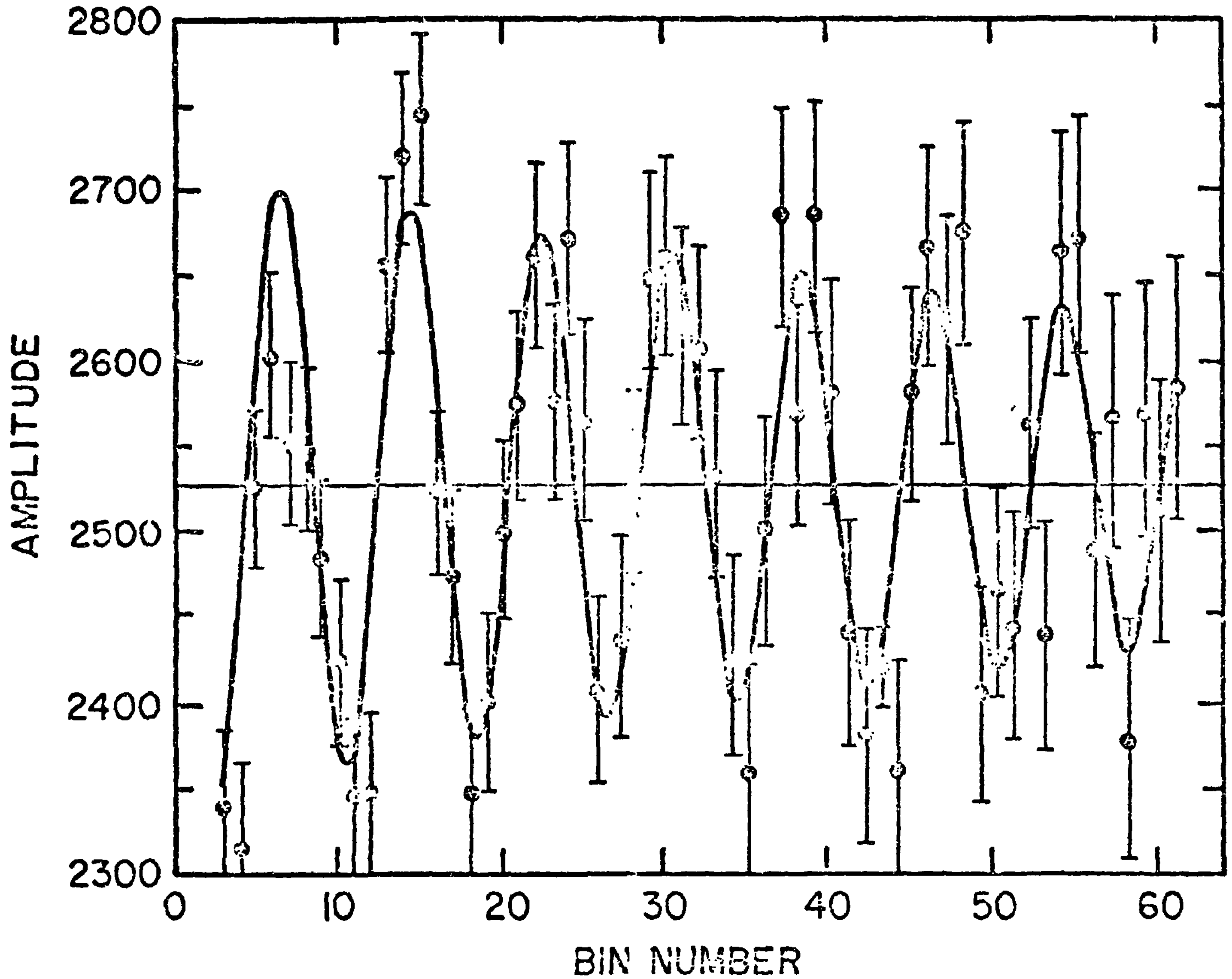
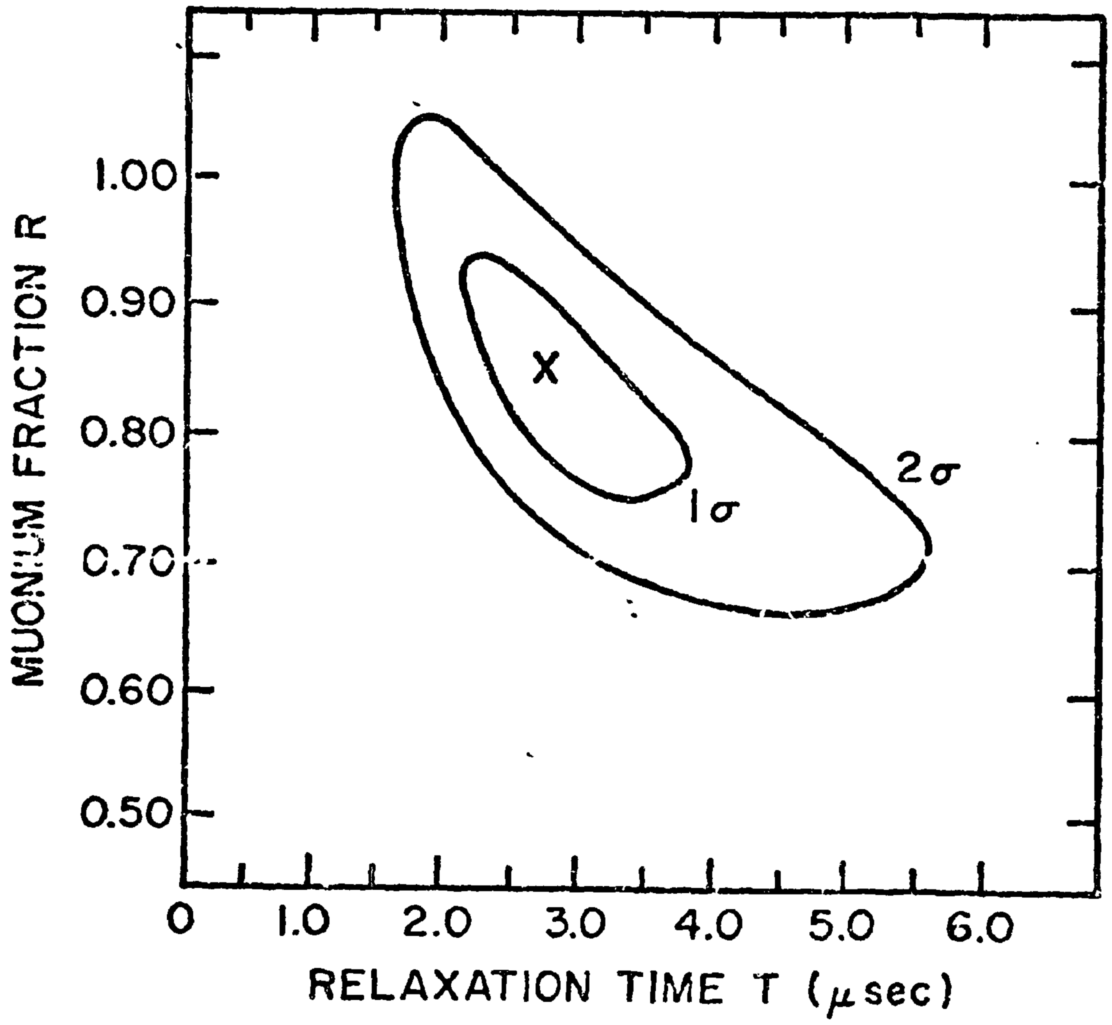

2800
2700
2600
2500
2400
2300
AMPLITUDE
0
10
20
30
40
50
60
BIN NUMBER

Fig. 2



MUONIUM FRACTION R
1.00
0.90
0.80
0.70
0.60
0.50
X
1σ
2σ
0
1.0
2.0
3.0
4.0
5.0
6.0
RELAXATION TIME T (μsec)

Fig. 3