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RESEARCH PROPOSAL

LOS ALAMOS MESON PHYSICS FACILITY

HIGH PRECISION STUDY OF THE μ^+ DECAY SPECTRUM

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SUMMARY OF EXPERIMENT

A new high precision measurement of the μ^+ decay spectrum is proposed to test the extent that V-A governs the weak interaction. Measurements will be made with a time projection spectrometer using the surface muons from the stopped muon channel. Such a spectrometer combines high acceptance with good resolution and a wide dynamic range for measuring momenta. The measurement of momentum is absolute since it is made in a highly uniform accurately known magnetic field and is based on a rather complete 3-dimensional reconstruction of the trajectory of the positron as well as that of the muon from which it comes. Almost every entering muon can be made to stop in the gas of the chamber and its decay observed with an efficiency of almost 100%. Positron momenta from 3 to 53 MeV/c can be measured at the same time at a single magnetic field setting. The surface muons have a longitudinal polarization close to 100% and this is preserved by having the muons enter the spectrometer along its axis, parallel to its strong magnetic field. By measuring, with high statistics, the asymmetry of the positron emission over almost all of the momentum range the four parameters ρ, η, ξ and δ that describe the decay can be determined simultaneously with appreciably better precision than in any previous work.

PROPOSAL INFORMATION

Beam Area: Stopped Muon Channel

Beam Requirements:

Type of Particle: μ^+; some running with π^+ in the same channel.
Momentum Range: 29 MeV/c (Surface Muons)
Momentum Bite: $\Delta p/p = 1\%$
Solid Angle: 0.06 sterradians
Spot Size: 1 cm x 5 cm
Emittance: x-emittance = 0.7 cm-rad
y-emittance = 0.14 cm-rad
Intensity: 10^4 per second, time average
Beam Purity: e^+ less than μ^+; may require electrostatic separator.
Target: Muons will stop in the gas of the spectrometer.

Primary Beam Requirements: Standard

Running Time Required:

Installation Time Required: 2 weeks
Tune-up Beam: 2 weeks at 10^4 μ's/sec, time averaged.
Data Runs: Two periods of 2 weeks each; 10^6 seconds of good beam; repeat of this after analysis of first is complete.

Scheduling: Estimate ready to run before Jan. 10, 1980.

Scheduling should not be affected by the known present commitments of the group.

Major LAMPF Apparatus Required:

Time projection spectrometer, water cooling and magnet power.
LeCroy fast electronics; TDC's and ADC's; coincidence circuits.
The group expects to supply what isn't available from LEEP.
Data acquisition computer; PDP/11 or equivalent. Hut or trailer for electronics.

Shielding and Enclosures: Standard SMC arrangements should be adequate.

Special Services Required: Modifications to magnet, installation of magnet, water cooling and magnet power supply.

Space Required: 5 m x 5 m space near SMC for assembly and test of the spectrometer. Fig. 1 shows layout at SMC.

HIGH PRECISION STUDY OF THE μ^+ DECAY SPECTRUM

We propose a new high precision study of the μ^+ decay spectrum, more comprehensive than has been done before, with a view to testing more accurately than previously the extent to which V-A governs the weak interaction. We intend to measure both the energy spectrum and the energy dependence of the asymmetry of the e^+ emission from μ^+ decay, using a newly developed time projection spectrometer(1). Such a spectrometer combines a large acceptance with good resolution. The measurement of momentum is absolute since it is made in a highly uniform, accurately known magnetic field and is based on a rather complete 3-dimensional reconstruction of the trajectory of the positron as well as the muon from which it comes. An important feature of the spectrometer is its wide dynamic range. Positron momenta from 3 to 53 MeV/c can be measured at the same time at a single magnetic field setting.

We intend to use the surface muons from the stopped muon channel. These have a longitudinal polarization close to 100%, and we should be able to correct for any contamination of muons present from pions decaying in flight instead of from rest. This polarization will be preserved in our arrangement because the muons enter the spectrometer along its axis, parallel to its strong magnetic field. Almost every muon that enters the spectrometer will come to rest in the gas near its axis and almost every decay will be observed. For each muon the spin direction will be known and the angle of positron emission with respect to it measured. Thus, the asymmetry of the positron emission will be obtained over almost the entire momentum range so that the four parameters ρ,η,ξ and δ, that describe the decay, can be determined simultaneously with high statistics and appreciably better precision and reliability than in any other previous work. From these better limits on the interaction constants will be obtained.

The following relation governs the energy-angle distribution of the positron emission from fully longitudinally polarized muons from rest,(2)

$$dN(x,\theta) = \frac{d^3p}{(2\pi)^4}\frac{m_\mu E_0}{12} A \Bigg\{ 6(1-x) + 4\rho\left[\frac{4}{3}x - 1 - \frac{1}{3}\frac{m_e^2}{E_0^2 x}\right]$$
$$+ 6\eta\frac{m_e}{E_0}\frac{(1-x)}{x} \mp \beta\xi\cos\theta\Bigg[2(1-x)$$
$$+ 4\delta\left(\frac{4}{3}x - 1 - \frac{1}{3}\frac{m_e^2}{m_\mu E_0}\right)\Bigg]\Bigg\}$$

where the upper and lower signs refer to μ^- and μ^+, respectively; θ is the angle between the $e^\mp$ momentum and the spin direction of the $\mu^\mp$; $E_0 = (m_\mu^2 + m_e^2)/(2m_\mu)$ is the maximum $e^\mp$ energy; p and E are the momentum and energy of $e^\mp$; and $\beta = p/E$ is the corresponding velocity in units c and $x = E/E_0$.

The constant A is related to the muon lifetime, $\tau = (2.1997 \pm 0.0006) \times 10^{-6}$ sec.

The present situation is summarized in the table below, taken from a recent review by Sachs and Sirlin(2).

Decay parameter	V–A value	Experimental value
ρ	$\frac{3}{4}$	0.752 ± 0.003
η	0	-0.12 ± 0.21
$\vert\xi\vert$	1	$\geq 0.975 \pm 0.014$
δ	$\frac{3}{4}$	0.755 ± 0.009
$\vert P\vert$	1	1.00 ± 0.13

The same review quotes the following limits on the coupling constants,

$$\left(\frac{|g_i|^2 + |g_i'|^2}{|g_V|^2 + |g_V'|^2}\right)^{1/2} \leq 0.33 \quad (i = \mathrm{S, P})$$

$$\frac{|g_T|^2 + |g_T'|^2}{|g_V|^2 + |g_V'|^2} \leq 0.28$$

$$0.76 \leq \frac{|g_A|^2 + |g_A'|^2}{|g_V|^2 + |g_V'|^2} \leq 1.20$$

$$\mathrm{arc\,cos}\left(\frac{\mathrm{Re}(g_A{}^* g_V' + g_A' g_V{}^*)}{(|g_V|^2 + |g_V'|^2)^{1/2}(|g_A|^2 + |g_A'|^2)^{1/2}}\right) = (180° \pm 15°)$$

Although the measured values of the decay parameters are in good agreement with the V-A theory, the limits that can be placed on the other possible couplings are far from satisfactory.

Time Projection Spectrometer

Our version of the time projection spectrometer is based on an iron enclosed solenoid capable of providing a uniform magnetic field of 10,000 gauss over a cylinderical volume 140 cm in diameter, 80 cm long as shown in Fig. 2.

The muon beam enters through a 5 cm diameter hole in the center of one pole and moves along the axis of the magnet toward the other pole. Before entering the magnet the muons traverse a pair of Xe filled gas scintillation counters spaced 1 meter apart. Time of flight between these two counters is used to identify muons in the presence of electrons in the beam. Enough material is in the beam to bring the muons to rest in the gas near the center of the chamber.

At 10,000 gauss, none of the positrons from μ decay originating near the central axis can reach the cylindrical wall of the chamber. Backward emitted positrons move toward the entrance pole in helical paths until they strike the scintillation counter hodoscope that covers the useful area of this pole. The event trigger is a delayed coincidence between this hodoscope and the muon telescope. A delayed coincidence is required to assure that the positron comes from a muon at rest. The coincidence gate will remain open for 10 μs or so to capture a large fraction of the decaying muons. To determine the triggering efficency a double overlapped layer of scintillators will be used. The trigger will require an "or" from either scintillator, but pulses from both will be recorded and used to determine the efficiency of each. For the forward emitted positrons the trigger uses the signal from the sense wires of the time projection readout located at the farther pole. Fig. 3 shows the readout array. It consists of 36 identical hexagonal modules, each made to be a conventional proportional wire-pad readout. The proportional wires, with 1 cm spacing, read out one coordinate of the (x,y) plane; the pads, 8mm x 8mm square, spaced 1 cm apart along each wire, read out the orthogonal coordinate in the (x,y) plane. The elapsed time, after the trigger, of the arrival of the drift electrons at the wire is used to give the z coordinate, all for a given point of the trajectory (see Fig. 4). The

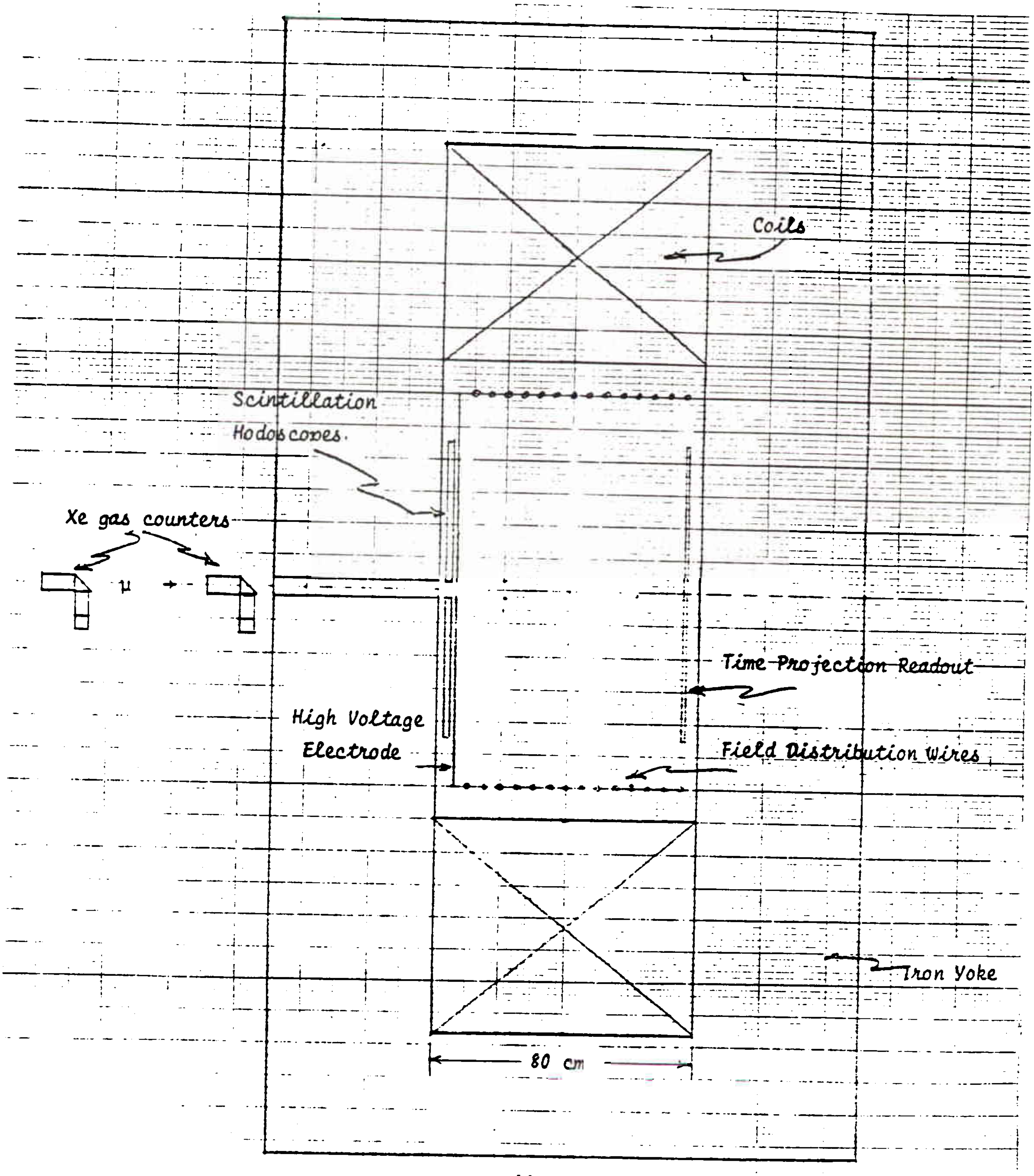

Fig. 2. The Time Projection Spectrometer

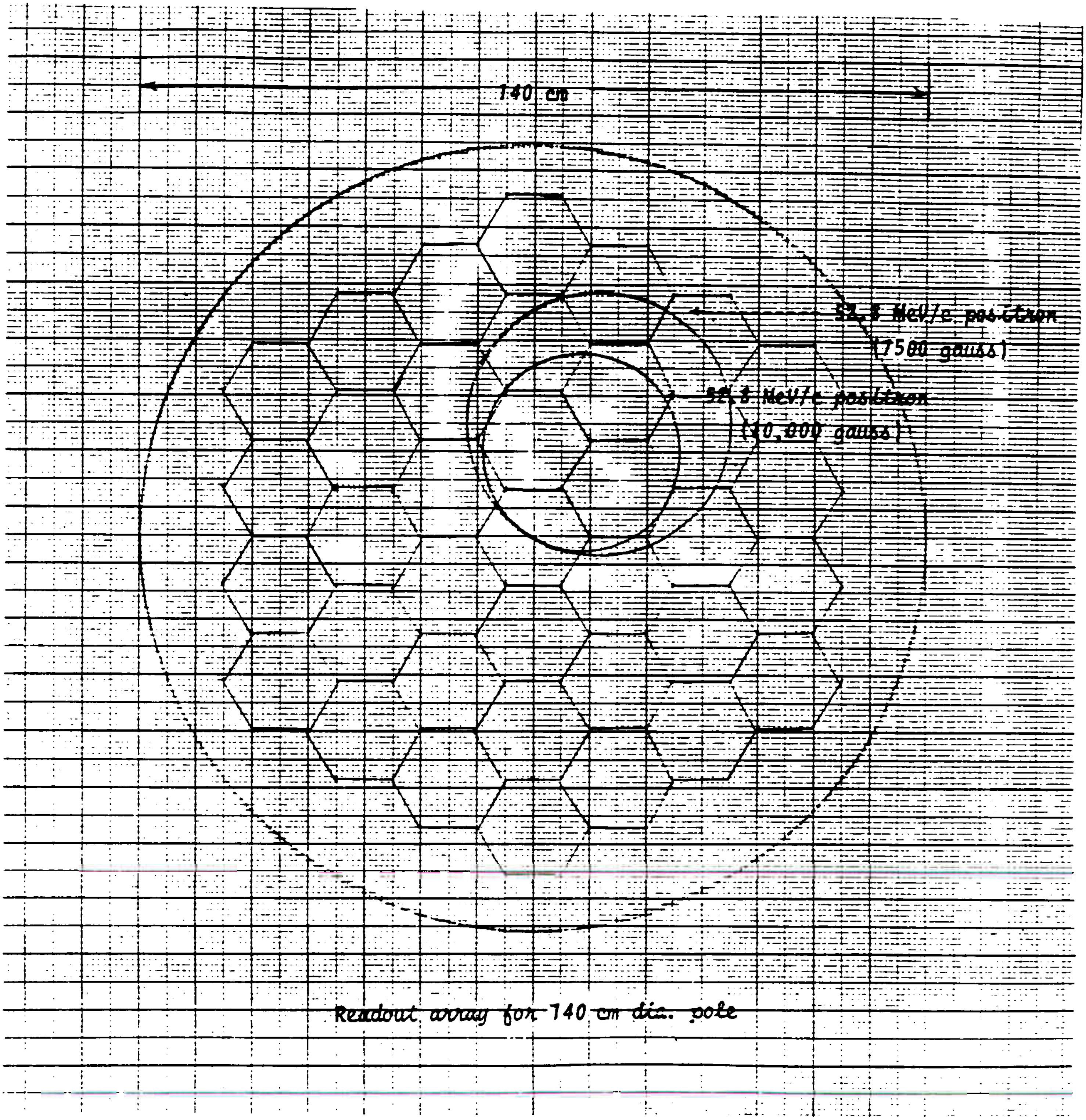

Fig. 3. Hexagonal Readout Array
for Time Projection Spectrometer

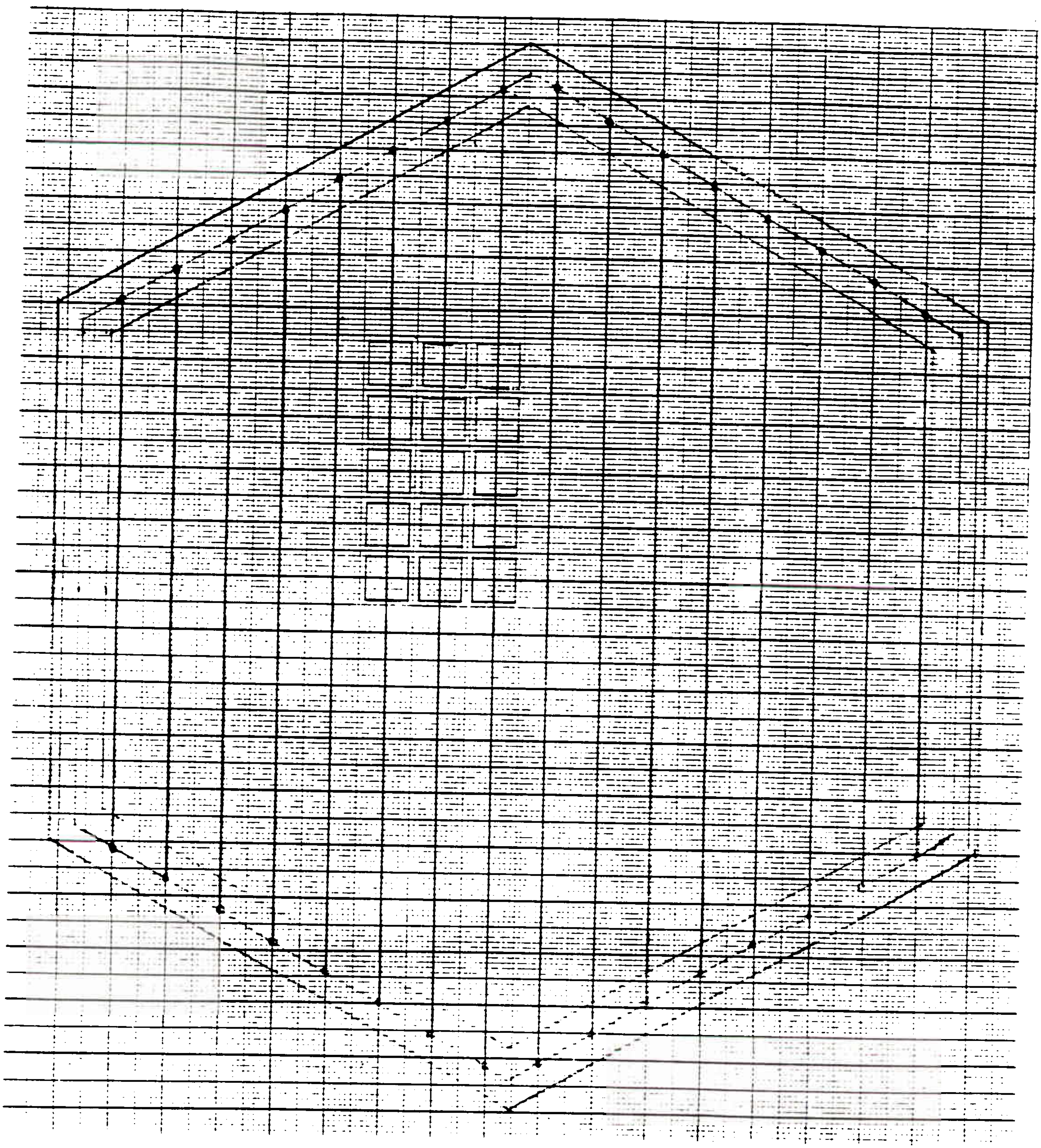

FIGURE 4: Hexagonal Module showing wires with 1 cm spacing and a section of the pad readout

central (37th) hexagon is designed to measure circles of 1 cm radius or less. It will have the same external dimensions, e.g. 10 cm on a side, but the wire spacing will be 0.5 cm, and the pads, 4mm x 4mm square, will be spaced 0.5 cm apart along the the wires. At 10,000 gauss a 1 cm radius of curvature corresponds to a cutoff for the perpendicular component of the momentum of 3 MeV/c. To do better at the low energy end of the spectrum we intend to operate at lowered magnetic fields, possibly with chamber gas at reduced pressure to give less multiple scattering. Since the required muon beam intensities are modest, we intend to collimate the beam with a 1 cm x 5 cm slit to facilitate triggering on low energy positrons.

The modules will be arranged for precise positioning over the pole surface. The aim is to know the position of every wire and every pad to 10 microns. This will be done by careful layout and surveying and by making use of the self-calibrating properties of the spectrometer.

Such a readout is capable of locating where the muon stops and can verify that the emitted positron comes from this point. We will be able to reconstruct the positron trajectory rather completely, and so determine its momentum as well as the angle with respect to the spectrometer axis. Since the spin of the muon is aligned along this direction by the magnetic field, we obtain rather directly for each event, the momentum as well as the angle of emission of the positron with respect to the muon spin direction, as required for the asymmetry measurement.

Muon Polarization

The muon channel will be tuned to 29 MeV/c momentum to accept predominantly surface muons. Since surface muons come from pions decaying at rest they ought to be 100% polarized in the longitudinal direction. We say 100% because this is the value expected if the two component theory of the neutrino is correct. Besides the surface muons, our beam will include some muons coming from pions decaying in flight, with less than 100% polarization. The contamination has been calculated by Tschalär according to a plausible model of the beam and target arrangements and shown to be small. We can check such estimates experimentally by carrying out measurements with the muon beam tuned above and below the surface muon momentum. An appropriate subtraction can correct the effect.

We will have to study the possible depolarization of the muons after they come to rest in the gas of the chamber. It is well known that muons that are moving slowly or are "at rest" readily capture electrons and form muonium. In a transverse field a rapid depolarization occurs for muons stopping in most materials except metals. However, in a strong longitudinal magnetic field, the muon spin decouples from that of the electron in muonium, and the muon spin tends to remain aligned with the magnetic field (Paschen-Back effect). At 10,000 gauss the muon is 98.8% polarized in the field direction. This is the value for free muonium, but it may be affected by the interactions with the gas in which it is moving. To study this effect we will want to compare the asymmetry found with that obtained with the muons stopping in a metal target where the depolarization, if any, should be much less. The point is that in metals muonium is very short-lived and the muons behave as if they were essentially free. For muons stopping in gas the depolarization should be greater for low field operation and we should be able to use our low field data to correct for the effect.

Beam Deflector

It is desirable to have each event as uncluttered by additional particles as possible while it is being read out. This can be done with a pulsed electric field beam deflector which is arranged to move the beam off the entrance slit of the spectrometer while the event is read out. Allowing 10 μs for the muon to decay and 15 μs for the drift, the required hold time for each event is about 25 μs.

The deflector is triggered by the Xe counters in the beam on either an electron or a muon so that once a particle enters others are excluded for 25 μs. If a trigger signalling the decay of a stopped muon is received, the time projection readout is initiated and the trigger system inactivated until the readout is complete. The electronic design calls for a 250 μs readout time. Thus, we should be able to record up to 3 events per 750 μs beam burst. Since there are 120 of these per second, the event rate can be as much as 360 per second. Such operation calls for a beam rate of from 10^3 - 10^4

per second, and would be capable of ignoring a substantial number of positrons in the beam. This system makes it possible to collect 10^8 clean events in 10^6 seconds of solid running time.

TIME PROJECTION SPECTROMETER

SPECIFICATIONS

Magnet	
Pole diameter	140 cm
Pole gap	80 cm
Nominal magnetic field	10 kg
Field uniformity	<0.1%
Gas	CH_4 at 1 atmos
Electric field	E/p = 0.5 volts/cm/Torr
Drift length	70 cm
Drift voltage	30 kv
Drift time	15 μs

Trigger: Time of flight between two Xe gas filled scintillation counters for the muons in delayed coincidence with a double overlapped scintillation counter hodoscope for the positrons. The delayed coincidence gate is from 0.5 - 10.0 μs.

Fraction of muons stopping in the chamber	.92
Acceptance for backward emitted positrons	.55

Momentum resolution:

From measurement of a single turn, at the end point, 52.8 MeV/c	$\Delta p/p$ = 0.22% rms
averaged over the Michel spectrum	$\Delta p/p$ = 0.39% rms

Muon beam: 29 MeV/c surface muons from the stopped muon channel

Intensity: 10^4 - 10^5 per second, instantaneous;
10^3 - 10^4 per second, time average

Event rate: 120 - 360 per second, time average

Running time: 10^6 seconds

Total events collected: 1.2 - 3.6 x 10^8

Performance

We have carried out Monte Carlo calculations to estimate the acceptance and resolution and other aspects of the performance of the spectrometer.

The calculation takes into account energy loss and range straggling of the muons entering the spectrometer. It takes into account multiple scattering of the positrons in the chamber gas. The momentum measurement is made by determining the radius of curvature from each triplet of points obtained by measuring at 2 cm intervals along the x,y projection of the trajectory. For N such triplets $\Delta p/p$ is taken to vary as $(N)^{-1/2}$.

The following conditions were imposed:

1) Chamber gas CH_4 at 1 atm
2) Magnetic field, 10,000 gauss
3) Energy loss in Xe counters and windows of the vacuum transport, 2.2 MeV.
4) Muons accepted if they stop within ±16 cm from center of spectrometer.
5) Minimum radius of curvature in (x,y) plane accepted, 1.0 cm
6) Minimum length of arc measured, 1/2 turn; maximum length, 1 full turn.
7) Measurement accuracy $\delta x = \delta y = 0.02$ cm rms, $\delta z = 0.2$ cm rms

In the Table 1 we give the calculated momentum resolution and acceptance for positron momenta a) averaged over the Michel spectrum, and b) near the end point, between 42.0 and 52.8 MeV/c. Various ranges of azimuthal angle of positron emission are taken because the resolution improves as this angle approaches 90°. The data in this region would give the best determination of the momentum spectrum. However, for the determination of the asymmetry the more forward and backward angles are important.

TABLE 1

ACCEPTANCE AND RESOLUTION OF THE TIME PROJECTION SPECTROMETER

Gas: CH_4 at 1 atm

Field: 10,000 gauss

μstops: ±15.7 cm from center

Radius of Curvature: $R \geqq 1.0$ cm

Fraction of turn measured: $1/2 \leqq n \leqq 1.0$

Measurement accuracy: $\delta x = \delta y = 0.02$ cm rms, $\delta x = 0.2$ cm rms

Fraction of μ's stopping within ±15.7 cm of center: 0.683

	AVERAGE OVER MICHEL SPECTRUM		E_e >42.0 MeV	
ANGULAR RANGE θ DEGREES	FRACTION OF POSITRONS MEASURED	$\left\langle \frac{\delta p}{p} \right\rangle$	FRACTION OF POSITRONS MEASURED	$\left\langle \frac{\delta p}{p} \right\rangle$
0 - 180	0.838	0.0070	0.655	0.0030
15 - 165	0.827	0.0069	0.652	0.0030
30 - 150	0.776	0.0053	0.656	0.0028
45 - 135	0.669	0.0046	0.619	0.0027
60 - 120	0.490	0.0041	0.466	0.0024
75 - 105	0.257	0.0039	0.257	0.0022

The most precise way to measure the spectrum is to use the data in the range $60^o \leqq \theta \leqq 120^o$. In this case the geometrical acceptance is practically constant over the full range of x except for $0 \leqq x \leqq 0.10$ as Table 2 shows. The Monte Carlo calculation used 100,000 events.

TABLE 2

GEOMETRICAL ACCEPTANCE

$60^o \leq \theta \leq 180^o$

X	ACCEPTANCE
0.00 - 0.10	0.316
0.10 - 0.20	0.485
0.20 - 0.30	0.493
0.30 - 0.40	0.480
0.40 - 0.50	0.498
0.50 - 0.60	0.494
0.60 - 0.70	0.490
0.70 - 0.80	0.494
0.80 - 0.90	0.480
0.90 - 1.00	0.492

Figure 5 shows the positron x distribution as obtained by the Monte Carlo calculation for $60^o \leq \theta \leq 120^o$. The cutoff at low x is due mainly to the cutoff $R \leq 1.0$ cm.

Figure 6 shows the positron azimuthal angle θ obtained by the Monte Carlo calculation for $0^o \leq \theta \leq 180^o$. The 1 cm x 5 cm aperture in the scintillation counter hodoscope is the cause of some loss of events for backward emitted positrons.

```
HIST  1      ELECTRON X DISTRIBUTION
TOTAL POINTS      48950      FIRST MOMENT      .7001

UNDRFLOW          0
     0.000        0
      .040       22
      .080      104  X
      .120      207  XXX
      .160      333  XXXX
      .200      474  XXXXXX
      .240      656  XXXXXXXX
      .280      874  XXXXXXXXXXX
      .320     1035  XXXXXXXXXXXXX
      .360     1226  XXXXXXXXXXXXXXX
      .400     1462  XXXXXXXXXXXXXXXXXX
      .440     1753  XXXXXXXXXXXXXXXXXXXXXX
      .480     2043  XXXXXXXXXXXXXXXXXXXXXXXXXX
      .520     2150  XXXXXXXXXXXXXXXXXXXXXXXXXXX
      .560     2513  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      .600     2719  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      .640     2771  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      .680     3093  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      .720     3351  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      .760     3419  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      .800     3480  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      .840     3680  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      .880     3793  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      .920     3899  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      .960     3893  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
OVERFLOW          0
```

FIGURE 5: Positron x distribution for $60^0 \leq \theta \leq 120^0$

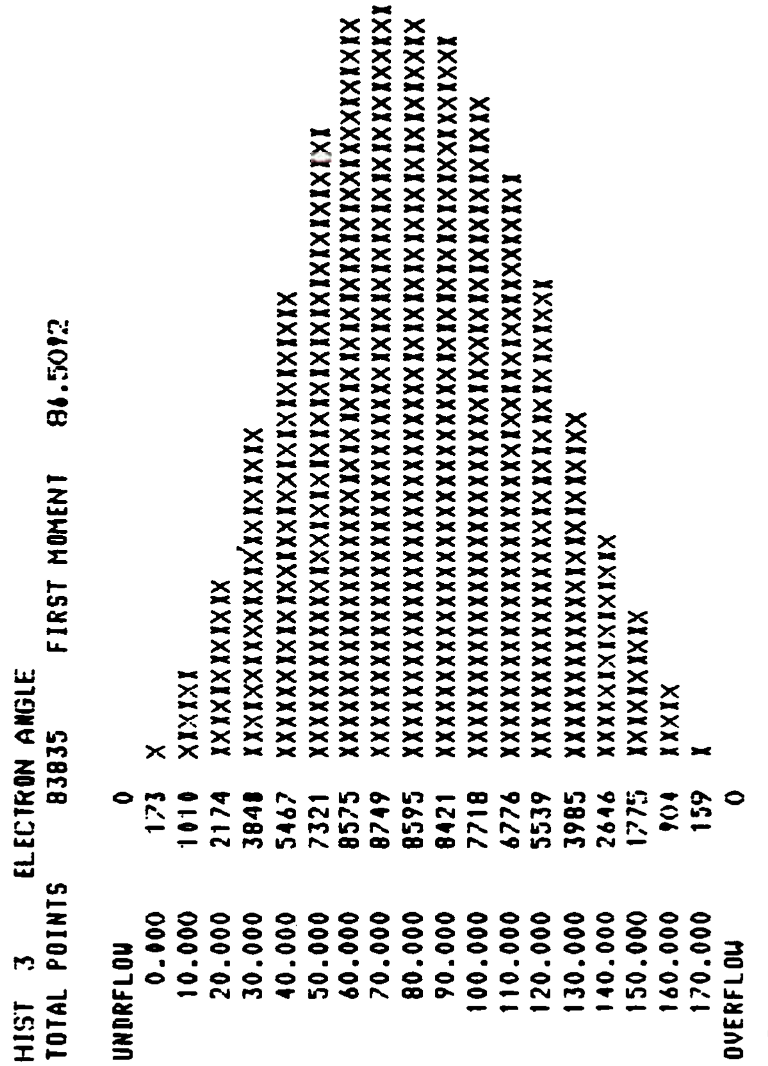

FIGURE 6: Angular distribution of positrons for acceptance with $0^0 \leq \theta \leq 180^0$

Precision of the Measurement

The most precise determination of ρ is that by Peoples[4], who gave the value 0.7503 ±0.0026 based on an analysis of 1.1×10^6 events using a sonic spark chamber and covering a momentum range from 13.6 to 53.6 MeV/c. According to Peoples the uncertainty in ρ due to statistical fluctuations is $\sqrt{6/N}$. This imposes an uncertainty of 0.0022 on ρ. To do better requires some 100 fold more events and corresponding efforts to keep the systematic errors down.

The systematic errors in Peoples' experiment were estimated to be ±0.0014. However, the principal contribution to this was uncertainty in spark chamber efficiency (±0.0010) which should not be a factor in our case. Besides the internal radiative corrections, which are well known, corrections have to be made for external bremsstrahlung, Bhabba scattering, and positron annihilation in flight. In our case, since the positron moves in a homogenous gaseous medium, the corrections required can be made to the required accuracy in a reliable way. The principal limitation on the experiment is that the momentum measurement must be free of systematic errors to 1 part in 10^4. This requires knowing the magnetic field to this level of accuracy. The use of nuclear magnetic resonance (NMR) probes for surveying and shimming the field and for monitoring it during the running makes this level of accuracy accessible without special difficulty. For an absolute measurement of the momentum the corresponding requirement on the measurement of R would be to establish the location of wires and pads to an accuracy of 10 μ. This could be quite troublesome and would require exceptional care in laying out the pads, surveying their positions, and guarding against expansions and distortions.

However, an absolute measurement is not required since the decay parameters ρ,η and δ depend on x, the relative energy of the positron with respect to the end point of the spectrum. Thus, systematic errors would arise if there were differences in the scale of lengths over the range covered by the measurements. These differences can be reduced dramatically by utilizing the scaling property of the spectrometer that allows the momentum range to be covered at constant R by varying H.

Thus, the required accuracy in the spectrum can be obtained by using the readout at a distance of 30 to 36 cm from the axis. This is the region where the 52.8 MeV/c positions are read out at 10,000 gauss for $60^{o} \leqq \theta \leqq 120^{o}$.

The same wires and pads will read out 5.28 MeV/c positions if the field is reduced to 1000 gauss and it is clear that the whole spectrum, except for very low energy positrons, can be obtained with identical accuracy by measuring with a series of magnetic fields. The chief limitation on our experiment will be in processing so many events.

We can expect to break new ground in the measurement of η. In this case the most precise measurement is that by Derenzo(5) who obtained $\eta = -0.12 \pm 0.21$ using a liquid hydrogen bubble chamber in which he examined 2.07×10^{6} μ^{+} decays. He gave particular emphasis on decays with positrons of momentum less than 7.1 MeV/c. The statistical accuracy can be estimated from $\delta\eta = 125/\sqrt{N}$. Thus, 10^{6} events gives $\delta\eta = 0.125$ about 1/2 that obtained by Derenzo. With 10^{8} events we can bring the statistical accuracy down to ± 0.0125.

The measurement of δ requires a measurement of the asymmetry over θ. Here the previous best measurement is that of Fryberger(6) who obtained $\delta = 0.752 \pm 0.009$ by measuring 5×10^{5} events with a spark chamber spectrometer. His accuracy was largely statistical and again we improve on this an order of magnitude by going to 10^{8} events. In our case systematic errors could be worrisome but come under control because of the great amount of redundancy our spectrometer provides. We have a check on the accuracy of the measurements because the spectrum obtained from partial ranges of the polar angle ϕ and the azimuthal angle θ must always be that derived from the precise spectrum obtained from the constant R measurement. In this sense the spectrometer is self-calibrating to a level of $\Delta p/p \simeq 10^{-4}$.

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