Chapter 3

Previous Determinations of Eta

3.1 Direct Measurements

In the 1960's there were several measurements of the upper part of the muon decay spectrum which, although they were basically measurements of ρ, also quoted a value for η by fixing $\rho = 3/4$; all had uncertainties of ± 0.5 or greater.[1,2,3] There was also an early measurement by Plano[4] which did a two parameter fit to ρ and η based on a measurement of the whole spectrum. His result was $\eta = -2.0 \pm 0.9$, which he discounted.

However, aside from the present one, the only *direct* η measurement of significant precision was that of Derenzo.[5] The method used was very different: a beam of π^+ and μ^+ was stopped in a 10-liter hydrogen bubble chamber. Observed were 2,070,000 μ^+ decay positrons, 6346 of which had $P_e \in (0.03, 0.13)\frac{1}{2}M_\mu c$, the region taken by Derenzo as sensitive to η. The result quoted was $\eta = -0.12 \pm 0.21$.

The use of a 4π visual detector filled with liquid hydrogen let Derenzo examine the extremely low-energy portion of the spectrum with less uncertainty than would have resulted

---

[1] J. Peoples, Nevis-147 (unpublished) (1966).

[2] B. A. Sherwood, Phys. Rev. **156**, 1475 (1967).

[3] D. Fryberger, Phys. Rev. **166**, 1379 (1968).

[4] R. J. Plano, Phys. Rev. **119**, 1400 (1960).

[5] S. E. Derenzo, Phys. Rev. **181**, 1854 (1969).

with the current apparatus for several reasons:

- Correction for Bhabha scattering was not needed when both secondaries had energies above 0.35 MeV (because their energies could be added together).
- Since there were no veto counters, there was no uncertainty in calculating the veto probability.
- Nuclear bremsstrahlung, scaling as Z^2, was less of a problem in hydrogen ($Z = 1$) than it is in carbon ($Z = 6$).
- The low density of liquid H_2 helped to reduce all energy-loss problems for Derenzo.
- Complete tracking information eliminated most external backgrounds.

On the other hand, there were problems which would be difficult to reduce significantly below their level in the Derenzo measurement, so this type of experiment is not a good candidate for an improved measurement of η. An example is the momentum-dependent measuring efficiency which Derenzo found to vary (in a somewhat non-monotonic manner) from 80% to 98% over the observed region of the spectrum.

In discussing Derenzo's experiment, it should be pointed out that a few improvements could be made to his analysis. The most significant change would be to correct for bremsstrahlung in the field of electrons. In hydrogen, where electron and nucleus have the same charge magnitude, this is comparable in size to the nuclear bremsstrahlung effect,[6] but correction was made for only the latter. It must be admitted that bremsstrahlung in the electron field is somewhat less likely for incident positrons with energies of only a few MeV, and so we must consider the problem in a bit more detail to justify this claim of similar effects. The justification is that most of the spectrum distortion arose from high-energy positrons which emitted a photon early in their trajectory and were then misjudged as having had a lower energy; at these high energies (typically 40 MeV), the cross section for bremsstrahlung in the field of electrons is only a few percent less than that in the

---

[6] E. Haug, Z. Naturforsch. **30 a**, 1099 (1975).

proton field. One should, therefore, almost double Derenzo's bremsstrahlung correction and thereby change the measured value of η by about -0.08. However, as long as one is reviewing the bremsstrahlung analysis, one should restore a minor term which Derenzo dropped from his bremsstrahlung formula,[7] shifting η by roughly $+0.02$.

Also, a small correction can be made because of the evolution of theory for the value of I_{adj} (the adjusted ionization potential) for hydrogen, which appears in the muon energy-loss equation by which Derenzo calibrates the density of the liquid hydrogen in his bubble chamber. This has evolved from 18.7 eV up to 21.8 eV.[8] The result is that Derenzo's liquid hydrogen was 2% denser than was calculated with the best value of I_{adj} available at that time. This would change the measured value of η by about -0.02.

Finally, one can consider the second-order radiative corrections.[9] These would change Derenzo's value by about -0.01. Combining all of these effects, one could more accurately quote the Derenzo result as $\eta = -0.21 \pm 0.21$. Since the net change is less than half the quoted uncertainty, the improvements are of only marginal significance. Also, had Derenzo quoted the correlated value for ρ using this corrected value, his answer would have been little different: $\rho = 0.7514 \pm 0.0026$ instead of $\rho = 0.7518 \pm 0.0026$.

3.2 Indirect Measurements

It is possible to determine combinations of α/A and β/A in muon decay by measuring P_{T_1}, the component of the decay positron's transverse polarization in the plane defined by the muon spin and positron momentum. An independent determination of α/A, β/A or a different combination gives one an indirect measurement of $\eta = (\alpha - 2\beta)/A$. This was

---

[7] H. W. Koch and J. W. Motz, Rev. Mod. Phys. **31**, 920 (1959).

[8] M. J. Berger and S. M. Selzer, in *Proceedings of Hawaii Conference on Charge States and Dynamic Screening of Swift Ions*, 1982, pp.57-74.

[9] A. V. Kuznetsov and N. V. Mikheev, Sov. J. Nucl. Phys. **31**(1), 136 (1980).

originally established by Kinoshita and Sirlin[10] and later emphasized by Scheck.[11]

Dropping terms linear in x_0 from our previous formula for $d^2\Gamma^{(0)}(x,\theta,\phi,\psi)/dx\,d(\cos\theta)$, one obtains

$$P_{T_1} = \frac{6(1-x)\eta + 16(1-\frac{3}{4}x)\frac{\beta}{A}}{6(1-x) + \frac{4}{3}\rho(4x-3) - \xi\cos\theta\left[2 - 2x + \frac{4}{3}\delta(4x-3)\right]} \, .$$

From this, the advantage of measuring P_{T_1}, rather than η directly, is immediately obvious: there is no suppression by an m_e/M_μ factor. The disadvantage, of course, lies in the difficulty of a polarization measurement. To equate such a polarization-derived value of the spectrum parameterization with spectrum shape measurements at mostly lower energy, the assumptions made are that the derivative-free, local, four-fermion point interaction suffices and that the low-energy spectrum shape is determined only by the Lorentz structure of the interaction.

A measurement of P_{T_1} has, in fact, been done;[12] this yielded a value of η with improved accuracy:

$$\eta = -0.011 \pm 0.085.$$

The value of η was extracted from measurements of P_{T_1} at eight energies, taking advantage of the slightly different energy dependence on η and β/A; the two parameters are still highly correlated in the fit. The values for α/A and β/A are somewhat less correlated; the values quoted were

$$\alpha/A = 0.015 \pm 0.052 \text{ and } \beta/A = 0.002 \pm 0.018 \, .$$

Another indirect approach is to exploit the relationships which exist between the muon decay parameters, using the combinations known to high accuracy to improve the limits on those which are less well known. H. Burkard *et al.* performed a global analysis, using experimental values for ξ'', ρ, δ, $\xi\delta/\rho$, ξ', α/A, α'/A, β/A and β'/A. The resulting limits

---

[10] T. Kinoshita and A. Sirlin, Phys. Rev. **108**, 844 (1957).

[11] F. Scheck, Phys. Rep. **44**, 188 (1978).

[12] H. Burkard *et al.*, Phys. Lett. **160B**, 343 (1985).

on α/A and β/A were

$$\alpha/A = 0.0004 \pm 0.0043 \text{ and } \beta/A = 0.0039 \pm 0.0062 \; ,$$

which in turn yield

$$\eta = -0.007 \pm 0.013 \; .$$

Burkard et al. do not include detailed information about the exact sources of the limits on particular parameters, and one might wonder whether there might be significant changes due to more recent values, such as the A. Jodidio et al. result[13] and erratum[14] for $\xi\delta/\rho$. Also, there were certain approximations; the correlation between the fitted value of ρ and η was ignored, giving results not quite consistent with the input data.

The first thing to note is that the input values for ξ'', α/A, α'/A, β/A and β'/A had little effect on any part of the fit because of their relatively low accuracy. The limits on β/A come mostly from the lower limit on $\xi\delta/\rho$ and the mathematical inequalities between the parameters; those on α/A come from the values for ρ, δ, $\xi\delta/\rho$, ξ' and, again, the mathematical inequalities, with most of the sensitivity being to the lower limit on ξ'. Thus, the fitted values for neither α/A nor β/A should have been much affected by the concerns mentioned above.

---

[13] B. Balke et al., Phys. Rev. **D34**, 1967 (1986).

[14] B. Balke et al., Phys. Rev. **D37**, 237 (1988).

Chapter 4

Experimental Apparatus

4.1 Spectrometer

The axial-focusing spectrometer used in this experiment, named "Comus" after the ancient Roman god of revelry, is similar in concept to the nuclear beta-ray spectrometers traditionally used in nuclide studies. An excellent, general reference on this type of spectrometer is that of Siegbahn.[1]

However, since muon decay energies are an order of magnitude higher, many aspects of the spectrometer had to be scaled up drastically. This higher-momentum design allowed some simplifications (such as a thicker "source" and a vacuum window), but also forced the sacrifice of certain refinements. In this last category are iron-free designs, helical collimators and the multitude of calibration sources which exist at energies of a few MeV.

A vertical cross section through the Comus spectrometer in shown in Figure 8. Two features of the spectrometer have been indicated for clarity, even though they do not lie on this vertical plane: the collimator-suspension cables (shown as dotted lines) and the four flux-return yokes of the magnet.

A general remark about the spectrometer design: it used a minimum of coincidence

---

[1] K. Siegbahn, in *Alpha-, Beta-, and Gamma-ray Spectroscopy,* edited by K. Siegbahn (North-Holland, Amsterdam, 1965), Vol. I, pp. 79-202.

counters for accepted particles and no drift chambers or other position-sensitive detectors. This was out of necessity; no more than about 50 mg/cm^2 of low-Z matter could be allowed before momentum selection in the spectrometer, if adequate corrections were to be possible for the resulting spectrum distortion. The e^+ had to pass through nearly this much material to escape the muon-stopping counter itself, on the average. Even in the detector, it is doubtful that the information gained by use of a tracking device would have justified the resulting scattering, annihilation, efficiency and geometry problems. A related remark is that the central region of Comus was evacuated to about 60 millitorr; interactions with the residual air were negligible.

4.1.1 Magnetic Field

The magnetic field was nearly symmetric around the spectrometer axis and roughly symmetric across the midplane bisecting that axis. It was, however, not a uniform field, the field strength instead following a bell-shaped curve along the axis, as plotted in Figure 9. There were significant radial components of the field at points off-axis and away from the midplane, as implied.

The large end pieces and 312-turn coil of the Comus electromagnet came from the former LBL 25-inch bubble chamber magnet. Four iron, flux-return yokes were added to reduce both the fringe field outside the spectrometer and the power requirements. (1400 amperes at 110 volts were needed for the highest momentum measurements after the yokes were installed.) The reduction in the fringe field made magnetic shielding for the photomultiplier tubes of the various counters more practical; with the yokes in place, none of the tubes had to be shielded against more than 150 gauss.

One problem associated with the fringe field was not completely eliminated—the deflection of the incoming muon beam. In the normal, data-taking configuration of Comus, the beam traveled near the spectrometer and perpendicular to its axis; it was vertically deflected at the highest field settings. The deflection that remained after shielding the beam line was corrected by unbalancing the last quadrupole magnet of the beam line with a current source, causing it to steer the beam. When one uses a single current source to effect this type of unbalancing act, it is, of course, necessary to adjust the main power supply for the "quad", so that the dipole component is superimposed on the same quadrupole strength as before.

Naturally, the iron-based design of the magnet resulted in nonlinear variation of the magnetic field with excitation. Nonlinearity first appeared at a tune momentum of about 30 MeV/c, but was not significant there. Magnet hysteresis was handled partly by basing calibrations on field measurements (rather than current) and partly by tuning the spectrometer with a set protocol (from higher to lower field values). Eddy currents, which were induced in the magnet end pieces whenever the field was changed, were allowed to decay for several minutes before data-taking commenced. Thus, the low-momentum portions of the spectrum were measured with stable spectrometer characteristics.

Even near the endpoint, the change in the field *shape* was at a barely noticeable level. The acceptance has been calculated to increase by no more than 0.3%; the momentum calibration, relative to the field at the center of the magnet, shifted upward by 0.06%. These effects would have had no major effect on the measurement of η, even if correction for them had not been made, as the spectrum shape is relatively insensitive to the overall momentum calibration and line shape.

4.1.2 Magnetic-Field Monitoring

The magnetic-field monitoring consisted of one Hall probe, together with three NMR probes whose overlapping ranges spanned the necessary region. The four probes were placed in geometrically similar positions in the magnet, away from edges of the iron yokes, and just outside the vacuum vessel. The placement is discussed further in Appendix B.

For the devices used in this experiment, the Hall probe accuracy was 0.25%, while that of the NMR was 0.001% from 5-40 MeV/c; the magnetic field gradients at the probe locations were substantial, but more accuracy was needed than that practical with a Hall probe. This led to a scheme to eliminate the field gradients locally, as discussed in Appendix B, so that NMR could be used. The probes themselves were of the LBL/CERN type, except that the preamplifier design was improved to allow operation at the low-field settings.

The Hall probe, on the other hand, provided a convenient monitor, was an aid in tuning the NMR and gave more reliable values near the endpoint. The absolute accuracy was only ±0.25% over the required range, but the long-term reproducibility (the relevant figure of merit, after calibration against the NMR) was ±0.06%. This Hall probe was sensitive only to the field component parallel to the spectrometer axis, but was placed where the other components were negligible.

4.1.3 Particle Trajectories

In order to explain the rest of the spectrometer design, particle trajectories in the magnetic field are first discussed. Cylindrical coordinates with the obvious convention are used. From the graphs in Figure 10, it is apparent that particles follow a spiral path with dr/dz almost constant, except near the center of the spectrometer where dr/dz changes sign abruptly. The total rotation of ϕ_s, the azimuthal angle of the trajectory in the spectrometer, is close to 90° for the accepted particles.

Also note the existence of a reasonably good ring-focus, a position at which particle paths with the same momentum intersect, independent of initial polar angle. The momentum-selection collimators were placed in this region.

However, as is usual for this spectrometer type, there is not a true focus at the detector position; the minimum radius of the detector, 5.08 cm, is just enough to contain almost all of the desired tracks. The radial distribution of these tracks is shown in Figure 11. as found by Monte Carlo in the absence of scattering.

4.1.4 Acceptance Characteristics

Since the η parameter is a characteristic of unpolarized muon decay, it is best measured with either unpolarized muons or a spectrometer which averages out the decay asymmetry.

A priori, one would probably prefer the unpolarized muon approach, simply using an unpolarized beam, or, failing that, stopping the beam in a depolarizing target. The former was not practical for this experiment, since the high stopping density of a surface muon beam was needed, and these beams are intrinsically polarized. The latter was not possible because an active target was needed to provide a target-detector coincidence signal for background rejection; plastic scintillator was the most practical choice, and this is only partially depolarizing.

A spectrometer acceptance that cancels spectrum components proportional to $\cos\theta$, where θ is the angle from the muon spin direction, has therefore been used. This condition will obviously be fulfilled if the acceptance is symmetric under 180° rotations around an axis at $\theta = 90°$. An axial-focusing spectrometer, with its azimuthal symmetry, meets this requirement for muon spins perpendicular to the axis. In fact, because of its higher symmetry, the muons can be allowed to precess around the axis—eliminating the need to control the fringe field of the spectrometer magnet at the muon position and reducing certain potential systematics. However, one must not be quite so casual: real collimators are not precisely centered, real spectrometers are not exactly perpendicular to the beam direction, and the real magnetic field may not lie precisely along the spectrometer axis at the muon's position. These potential systematics are discussed in Appendix A.

Once one has canceled the decay asymmetry, the next design requirement is that the transmission be fairly large; the probability that a muon will yield an event at low-momentum spectrometer tunes is low. This arises from the small momentum bite of the spectrometer (smaller at low-lying data points, being proportional to P_{tune}) and the concentration of the decay weight at high energies. On the other hand, spherical aberration limits the angular acceptance, if a good ring-focus is to exist at the momentum-selection collimators. The compromise between these requirements resulted in an angular acceptance that is roughly triangular, with a peak near 16.0° and extending between about 13.5° and 18.3°. This is plotted in Figure 12, averaged over the accepted momenta. At the peak accepted momentum, the solid angle is $\Omega/4\pi = 0.60$ %. The contour plot of Figure 13 shows how the angular and momentum acceptances are correlated, as found from calculated tracking results.

Averaged over angles, the line width is $\Delta P_{accept}/P_{tune} = 2.8\%$ (FWHM). The shape is shown in Figure 14; this is also averaged over starting positions on $T1$, but the shape is almost independent of this. A larger target, with resulting position dependence, could have been used in principle, but could have caused problems from any movement of the beam spot during data-taking.

4.1.5 Target-Area Layout

The vacuum vessel in the target area, as elsewhere, was constructed of aluminum. This was desirable to reduce the scattering and showering of charged particles, and the gamma rays from radiative muon decay and bremsstrahlung produced no high-energy fluorescence X rays. Those X rays which were produced had energies below 1.6 KeV and extremely short attenuation lengths, so that few escaped the aluminum itself. Thus, annoying backgrounds in the target-area anti-counters were minimized. A drawing of the target area is shown in Figure 15, to aid in understanding the discussion that follows.

$T1$— μ^+-stop Counter

$T1$ was constructed of NE110 plastic scintillator with height x width of $\frac{1}{2}$" x $\frac{3}{4}$", and thickness of 0.0838 cm; its long dimension was rotated by about 45° around the vertical so that it presented a roughly half inch square face toward both the beam and the spectrometer acceptance. It served several purposes:

- a target for stopping muons;
- in coincidence with Tb, a count of stopping muons;
- one input to the event trigger;
- a time-of-flight coincidence for background rejection; and

- a way to reject many events scattering out of the target plane (using the large energy deposition typical of such events).

In order to perform these functions, several conflicting requirements had to be met. $T1$ had to be:

- thin and of low-Z material to minimize bremsstrahlung and scattering;
- thick enough to stop the incident muons;
- of a material that would depolarize the muons, reducing problems from spectrometer asymmetries;
- small enough that the spectrometer's acceptance was nearly constant over it;
- large enough to contain most of the beam spot, giving an adequate event rate and reducing edge effects.

In the compromise solution chosen, $T1$ did cause significant spectrum distortions due to intrinsic physical processes, and these will be discussed in Chapter 5. Systematic effects due to muon polarization were not completely eliminated, as stopping muons retain 25% of their original polarization in plastic scintillator,[2] but this represents a factor of four improvement. The edge effects of $T1$ were reduced by collimating the beam just upstream of the target area.

In future references to this counter, mention will be made of $T1_\mu$ and $T1_e$. These are logic signals in the electronics; $T1_\mu$ is produced by large pulses in $T1$, and $T1_e$ by the relatively small ones, corresponding roughly to stopping muons and escaping positrons, respectively. The separation is not perfect, with about 4% of decay positrons passing through enough scintillator to generate the $T1_\mu$ signal.

---

[2] J. Brewer, private communication.

Tb Counter

This counter was 1" square and positioned perpendicular to the muon beam, 1" upstream from the center of $T1$; the thickness was 0.0769 cm. It served three functions:

- Large signals from muons which passed through Tb, generating the logic signal Tb_μ, were used in coincidence with $T1_\mu$ to count muon stops in the target. This eliminates the ambiguity in $T1_\mu$.
- Small signals from the positrons which passed through Tb, generating the logic signal Tb_e, were used in anti-coincidence with $T1_e$ in the event trigger; this eliminated the possibility that a beam e^+ could Bhabha scatter a target electron into the spectrometer acceptance, or itself be scattered into it. While Monte Carlo calculations predict this effect to be negligible, the anti-counter provided additional security. Also rejected were decay positrons from muons stopped in Tb.
- The incident muon momentum was degraded, allowing them to stop at the desired location in $T1$.

$A1$, $A2$, $A3$ Anti-counters

It is possible for an $e^\pm$ to enter the acceptance of the spectrometer in other than a direct line from the target; this could happen by scattering/showering from the walls of the vacuum vessel after a decay in $T1$. The increased path length of this indirect path would seldom be enough to reject the events by the time-of-flight discrepancy, so the $A1$, $A2$ and $A3$ anti-counters were positioned to intersect the path of most possible scatters in the target area. The exception to this is scattering from the thin, flat light guide of $T1$. Even in this case, only a small area near $T1$ is vulnerable, and, being thinly constructed of low-Z material (Lucite), the problem is further minimized. The remaining small correction is included in the target-area Monte Carlo calculation.

The other purpose served by these counters (mostly by $A1$ and $A2$) is to reject the majority of events with a substantial Bhabha scatter in $T1$. This is discussed in more detail in Section 5.1.3. Note that Bhabha scattering and bremsstrahlung of high-energy particles in $A1$ and $A2$ can, themselves, contribute low-energy events. These events are, in principle, self-vetoing, but add to the large number of events that must be rejected by $A1$ and $A2$. A few scatters from the $A1$ bevel pass the applied cuts, but almost all of those from $A2$ are vetoed by $A1$.

For an annular counter to be highly efficient, care must be taken to avoid insensitive areas near the inner radius. Multiple light guides could have solved this problem under different circumstances, but space constraints precluded this for $A1$ and $A2$. The alternate solution was to divide each annular counter into several thin rings, so that total internal reflection could be achieved, even for light coming from very near the inner radius of each ring. The rule that must be obeyed by each ring follows from simple optics and geometry:

$$n\frac{r_i}{r_o} > 1 ,$$

where n is the index of refraction of the scintillator, while r_i,r_o are the inner and outer radii of the ring, respectively. Subdivision into three rings was adequate for $A1$, while five were required for $A2$ because of its smaller inner radius.

4.1.6 Collimators

$K1$

$K1$ consists of two aluminum tanks of lead shot, surrounding the vacuum vessel downstream of the target. It shields the spectrometer against particles from the beam line, decaying muons which missed the target, as well as from positrons originating in the target and making large-angle scatters from material near the target area.

$K2$

The large front collimator, $K2$, provided mostly protection against high-energy particles creating showers in the rear part of the spectrometer, thereby contaminating low-energy measurements; it consists of 33.3 radiation lengths of lead. An aluminum plate is on the back of the collimator, and aluminum also covers the beveled surface.

$K2$ does not set the minimum acceptance angle in the spectrometer as it might appear; this is determined by the downstream collimators. The chance that high-energy particles striking the edges of $K2$ would contribute low-energy events was thus greatly reduced.

K_3

This collimator is a lead ring, beveled on its inner radius. It partially determines the high-momentum edge of the acceptance, substantially narrowing the resolution. The need to have more than one exit baffle is typical of axial-focusing spectrometers.

K_4, K_5, C_1, C_2

These collimators are near the ring-focus of the spectrometer and are the primary determining factors of the acceptance. With a non-active collimator slit, especially one which is beyond the strongest magnetic field, there is a danger that high-energy particles will pass through the edges of the collimator without much scattering and be accepted. Since low-energy particles would be scattered more, they would have less chance of being accepted; hence, the measured spectrum would be distorted.

The anti-counter on the inner radius of the slit is $C1$, that on the outer radius is $C2$. The counters were both constructed from $\frac{1}{4}''$ scintillator, placed on the bevels of the $K4$ and $K5$ lead collimators, respectively. $C1$ and $C2$ have no reflective wrappings on the surfaces facing the slit, a practice which is desirable to eliminate an inactive covering and possible because all other unwrapped counters in the vicinity are also veto counters. It is topologically necessary, of course, that the light guide for $C1$ cross the slit between the counters; for this reason, the Lucite portion of the light guide did not begin until after the crossing. Most events in which the light guide was struck were thus rejected, and they caused little difficulty.

The light guides on both counters cause an additional complication: optical considerations leave a gap on each counter where the guide bends away from the scintillator ring. One result is that some unvetoed trajectories miss the $T2$ trigger counter. These constitute about 1% of the number of good events and have to be considered in the analysis of $\overline{T2} \cdot T3 \cdot T4$ events. The line shape is also somewhat affected.

One other detail about $C1$ and $C2$ is that, while positioned beyond the strongest magnetic fields, the field strength in their vicinity is still enough that a fairly high-momentum particle from the detector or vacuum window is required to reach them. This is important since low-momentum $e^{\pm}$ are frequently backscattered from the detector shower. Had these counters been placed in a region of very low field near the detector, events would have been vetoed in an energy-dependent (and difficult-to-calculate) manner, with no resultant advantage. Vetoes by $e^{\pm}$ and gamma rays from the detector can still occur, of course, but the fraction of vetoed events is small and relatively independent of energy.

4.1.7 A, B, C, D Anti-counters

These four counters, each covering 90° of azimuthal angle, together make a cylinder of scintillator around the region through which accepted trajectories travel. Several purposes are served:

- Many high-momentum particles from $T1$ hit the outer radius and back plate of the vacuum vessel, as well as the spectrometer magnet, and some particles from the resulting showers mimic good events. Impacts on these counters by the primary particles vetoed many such events.

- Even if the primary particles hit inactive material (such as the faces of the $K3$ or $K4$ collimators) rather than these counters, they were sometimes struck by a particle in the resulting shower or, more frequently, by an annihilation gamma ray, and still vetoed the event.

- Some events, in which a hard Bhabha scatter occurred in $T1$, were rejected when the spectrometer was tuned to accept the lower-momentum member of the pair. This, of course, was when such rejection was most needed.

- Some external backgrounds, such as cosmic-ray showers, were also vetoed by these counters. This is in addition to the rejection provided by the time-of-flight coincidence.

4.1.8 Detector

In coincidence with $T1_e \cdot \overline{Tb_e}$, the detector provided the event trigger. It also gave a measure of the energy of the incident particle and, by virtue of its division into three geometrical regions, allowed the study of background events. This will be elaborated below.

Counters $T2$, $T3$, $T4$

These counters were positioned slightly downstream of the spectrometer vacuum window in the order listed:

- $T2$: 4"ø, 0.365 cm thick scintillator
- $T3$: 6"ø, 0.310 cm thick scintillator
- $T4$: an annular scintillator, with an outer diameter of 8" and an inner diameter of 4"; it is 0.318 cm thick. Because of the hole in its center, this counter was equipped with two separate light guides and phototubes, so that no areas were insensitive. An analog sum was performed on the outputs of the two tubes.

Together, these counters divide the 8"ø detector surface into three regions:

1. $T2 \cdot T3$
2. $\overline{T2} \cdot T3 \cdot T4$
3. $\overline{T3} \cdot T4$

The size and location of the counters were chosen so that most good events struck the $T2 \cdot T3$ region; the purpose of the other regions was to study contaminating events for comparison with the calculated corrections.

NaI Detector

The cylindrical NaI(Tl) crystal has a diameter of 8" and a length of 10"; one inch corresponds to 0.98 radiation lengths. It provided an energy measurement of the detected particle, including the annihilation and bremsstrahlung γ's in the detector shower, when corrected for energy deposition in the upstream counters and other material.

Unfortunately, the same high-Z components which allow efficient conversion of γ-rays tend to backscatter low-energy e^+. Backscattering, along with energy absorption, also occurred in the window of the NaI detector, consisting of aluminum, MgO reflective powder and a certain amount of rubber and plastic. Thus, although the resolution of the NaI crystal for a low-energy γ-ray is 8.4%, the resolution for low-energy charged particles is worse and has a long tail toward low measured energy. The situation was helped by backscattered particles passing through the $T2$, $T3$ and/or $T4$ counters a second time and depositing additional energy.

Even with only modest energy resolution, however, the NaI was extremely valuable. Particles with higher-than-expected energy were efficiently rejected—very important at low P_{tune} settings. At moderate-to-high P_{tune} settings, most contaminating particles had much lower energy than the desired ones, and the energy resolution was sufficient to reject a large fraction.

4.1.9 M_1, M_2

These counters (not illustrated) were positioned opposite to the spectrometer acceptance and separated from each other, so that positrons originating from $T1$ could cause a coincidence between them. Thus, a diagnostic was provided on the rate of muons stopping in, or near, $T1$, independent of that counter. The solid angle subtended by the coincidence was such that the rate was larger than that of good events in the lower part of the spectrum: the solid angle was 0.0068% of 4π steradians.

4.2 Electronics

The high-speed logic for the experiment consisted mostly of 100 MHz NIM modules and was reasonably simple. The event trigger was chosen to minimize bias to the extent consistent with a reasonable data-taking rate: $T1_e \cdot \overline{Tb}_e \cdot (T2 + T4)$. The discriminator settings for these signals, except for Tb_e, were set conservatively, allowing almost all serious cuts on the data to be done off-line.

A simplified diagram of the trigger electronics is shown in Figure 16; coincidences formed for the various scalers are not shown, nor are various coupling elements to eliminate DC-offset levels and the like. The discriminators used were mostly of LeCroy types 821Z and 621Z, except for an LBL-designed constant-fraction discriminator for the NaI. The LeCroy units were not internally terminated, which eliminated the need to split the signal between the ADC's and discriminators.

The anti-counter electronics were quite simple: each anti-counter had an ADC and a TDC, and was connected to a CAMAC scaler. Most were also monitored in various combinations by visual scalers. The NaI electronics were a straightforward analog sum of the outputs from the four phototubes; a constant-fraction discriminator on this formed the TDC stop, while ADC's recorded the individual outputs, as well as the sum.

4.2.1 $T1$ Electronics

$T1$ presented several non-trivial problems, mostly because the counter had to detect a small positron pulse which followed a large muon pulse, usually by less than a few microseconds. Thus, the counter not only needed a large dynamic range, but had to have very little signal-correlated noise, e.g. afterpulsing and cable reflections. A further complication came from the thinness of the scintillator through which the exiting positrons could be allowed to pass. With an average positron signal involving only 15 photoelectrons, Poisson statistics added significantly to the width of the pulse-height distribution. Combined with variations in path length through the scintillator (arising from muon straggling and the wide range of accepted track angles with respect to $T1$—recall that the normal to the $T1$ plane was rotated from the spectrometer axis), the total variation in positron pulse heights for good events was large. This increased the vulnerability of the counter to noise problems.

The problems were addressed in several ways:

- The photomultiplier tube was selected for low noise and afterpulsing; an Amperex XP-2230 was found to be a significant improvement over the RCA 8575 tubes used on the other counters. The output of the tube was clipped to reduce the tail of the muon pulse.

- For a portion of the data, two discriminators triggered on the positron signal, the second level being set 2.8 times as high as the first. Both were recorded in separate TDC's. The first, with the low threshold, would fire on almost any positron exiting $T1$, but was vulnerable to recording an extraneous pulse in the TDC before the desired positron pulse arrived. This same discriminator was used for the event trigger.

- The high-threshold discriminator, on the other hand, missed some positrons, but rarely triggered on afterpulsing, reflections and noise. Thus, a restrictive time-of-flight cut could still be made off-line for those events in which the first $T1$ TDC was stopped prematurely. The combination was much more desirable than either possibility by itself.

- The positron discriminators were placed in the experimental area near the $T1$ counter, minimizing problems with cable reflections and noise pickup; the analog signals to the electronics room were amplified at this same location.

4.2.2 Time-Correlation Electronics

A valuable diagnostic in a muon decay experiment is the time correlation between the arrival of a muon and the detection of a decay positron. For this reason, a nanosecond-resolution clock (of TRIUMF design and construction) was used to measure the time, up to 4.1 μs, between the arrival of a muon and the triggering of an event.

When the mean time between muon arrivals is not much greater than the time-out period of the clock, the situation is complicated by muon pile-up in the target, and it is not possible to assign an event to a particular muon with certainty. That was the case in this experiment to some extent, with a mean interval between muons of, typically, 20 μs. Thus, to reduce distortions in the diagnostic information—such as the exponential decay of the muons with the correct lifetime—electronics were needed to correct for this pile-up. This is standard in the field of muon-spin resonance (μSR) and will not be discussed here in detail.

The electronics used to label events in which a pile-up problem had occurred, and to regulate start/stop pulses to the clock, consisted of a quad-width NIM module designed and constructed at LBL for use in μSR experiments. The pulses to the clock were internally gated by fast ECL logic, specifically MECL III. The other logic was from the slower MECL 10K series, except for the microsecond-scale time gates which were implemented with Schottky TTL timing chips. The timing performance of such a specialized design is better than can be obtained with the usual crate or two of standard NIM electronics.

4.3 Data-Acquisition System

Data were taken with a PDP-11/60 computer linked, through Unibus and a Kinetic Systems 3912 crate controller, to a single CAMAC crate. Events were written onto 1600 BPI magnetic tape in blocks of 16, with a readout of the scalers added to the end of each buffer. The recorded data for normal (i.e. not scaler or comment) events were mostly the ADC and TDC information for all counters (excepting $M1$ and $M2$, for which the coincidence was only scaled), plus information on the timing of the muon and positron, relative to previous muons and positrons.

The PDP-11 used the TRIUMF program DA[3] to read out the CAMAC crate and to write the data to tape. Each event required 1 ms to acquire, resulting in a computer

---

[3] T. Miles and A. Satanove, IEEE Trans. Nucl. Sci. **NS-30**, 3746 (1983).

deadtime of no more than a few percent for the usual runs. The on-line analysis was performed by MULTI[4] on a time-available basis. This is a flexible system which allows substantial modification of the analysis task without recompilation.

---

[4] Fermilab MULTI User's Guide, PN-97.5.