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$\mu^+ \rightarrow e^+\gamma$ and related rare decays

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The connection of rare decays to supersymmetric grand unification is highlighted, and a brief review of the status of rare decay experiments is given. The status of the MEGA experiment, a search for $\mu^+ \rightarrow e^+\gamma$, is reported. Some ideas for a new experimental arrangement that has the potential to reach a sensitivity of 10^{-14} are presented.

1. INTRODUCTION

The Standard Model of electroweak interactions gives a type a periodic table of the elementary fermions, where the periodicity is labeled by the family of the particle. The repetition of families is not understood, and neutral current transitions between the families appear to be forbidden experimentally. The Standard Model is a remarkably robust phenomenological theory that encompasses all current measurements and tempts us to look for process outside its sphere of applicability. As it is generally accepted that the Standard Model is not likely to be a complete description of nature, many extensions have been proposed.

Searching for the rare process $\mu^+ \rightarrow e^+\gamma$ is an excellent method to explore potential physics beyond the Standard Model of electroweak interactions because the process is predicted to be zero except when new physics is present. Even the addition of neutrino oscillations would produce only an immeasurably small rate. The observation of $\mu^+ \rightarrow e^+\gamma$ would imply the existence of new, heavy particles.

There have been many reviews of possible extensions of the Standard Model and their implications for the observation of rare decays [1]. Recently, the prejudice has grown within the physic community that supersymmetry is an extension that is likely to be related to nature. Barbieri, Hall, and Strumia [2] show that rare decays are signatures for grand unified supersymmetry and calculate the rates for $\mu^+ \rightarrow e^+\gamma$ and related processes for a wide range of parameters of these models. They conclude that $\mu^+ \rightarrow e^+\gamma$ has the largest rate by more than two orders of magnitude, and it ranges between the current experimental limit and 10^{-14}. With data from the MEGA experiment [3] at Los Alamos in analysis and new ideas on the horizon, $\mu^+ \rightarrow e^+\gamma$ seems ripe for a possible discovery.

Of course, $\mu^+ \rightarrow e^+\gamma$ is only one of several rare decays that address the same issues. The processes are complementary, and it would be necessary to investigate several before the underlying physics could be disentangled. In Table I, many related muon and kaon processes are listed along with their current limits (90% confidence) and the projections for ongoing experiments. When ideas for new experiments have been discussed, the future limit is shown in brackets.

2. STATUS REPORT ON MEGA

The experimental signature for an at-rest $\mu^+ \rightarrow e^+\gamma$ is a 52.8-MeV positron that is back-to-back and in time coincidence with a 52.8-MeV photon. The MEGA experiment, designed to search for it, has been described several times [4]. Briefly, it consists of a magnetic spectrometer for the positron and three pair spectrometers for the photon. The apparatus has been optimized for high rates and for good resolution to suppress backgrounds; the principal background is random coincidences. MEGA had three period when it took beam, one during each of 1993, 1994, and 1995. The data samples have a ratio of sizes of

Table 1
Current and proposed limits on rare decays

Process	Current Limit	Future Limit
$\mu^+ \to e^+\gamma$	5×10^{-11}	7×10^{-13} [1×10^{-14}]
$\mu^+ \to e^+e^+e^-$	1×10^{-12}	—
$\mu^- N \to e^- N$	8×10^{-13}	6×10^{-14} [1×10^{-16}]
$\mu^+ e^- \to \mu^- e^+$	3×10^{-7}	3×10^{-11}
$K^+ \to \pi\mu e$	2×10^{-10}	1×10^{-12}
$K_L \to \mu e$	2×10^{-11}	1×10^{-12}

roughly 1:2:3. The apparatus is mothballed and scheduled to be dismantled unless the analysis shows something surprising.

The total number of muons stopped in the apparatus was 1.5×10^{14} in roughly 10^7 s. There are 4.5×10^8 events on magnetic tape awaiting analysis. The analysis is proceeding in four stages. The first discards any event with insufficient detector interactions to reconstruct a candidate event; the second reconstructs the kinematic parameters of the particles; the third refines the reconstruction, and the last cuts away kinematically uninteresting events. At the time of this report, three-fourths of the data has been processed through the first phase with a reduction in the number of candidates by roughly a factor of 10. Only 7% of the data has been processed through step two to get a preliminary idea of the performance of the algorithms. As we shall see, the computer programs require improvements.

In general, the reconstruction algorithms trade improving the resolution of the particles for maximizing the efficiency and suppressing backgrounds. This paper gives a progress report prior to the latest improvements that are currently under development. The three easiest response functions to measure are the photon energy resolution, the positron-photon timing, and the positron energy resolution. Each is done with a different technique.

The primary beam conditions with stopping muons do not contain any sharp photon lines. In order to get a sharp photon line, negative pions are stopped in polyethylene. They charge exchange roughly 50% of the time and produce a slowly moving π^0 that, in turn, decays into two photons. If one selects those photons that happen to be nearly back-to-back, one gets a narrow line at 55 MeV from the lower energy photon, quite near the endpoint of the location of any possible photon from $\mu^+ \to e^+\gamma$. The spectrum of such events is shown in Fig. 1. The energy resolution is near that predicted.

The relative time resolution can be measured by looking for the allowed process $\mu^+ \to e^+\gamma\nu\nu$. This internal bremsstrahlung correction to ordinary muon decay can only be seen easily at low rates where the random backgrounds are greatly reduced. The timing spectrum is shown in Fig. 2. Improvements in calibration constants are expected to improve the timing to be nearly 1 ns

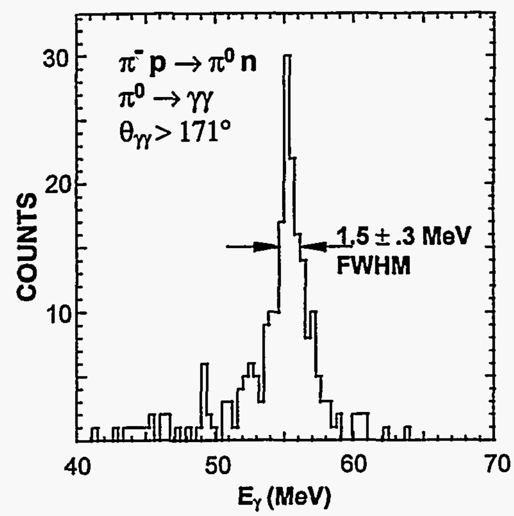

Fig. 1. Photon energy response for 55-MeV gamma rays from π^0 decays.

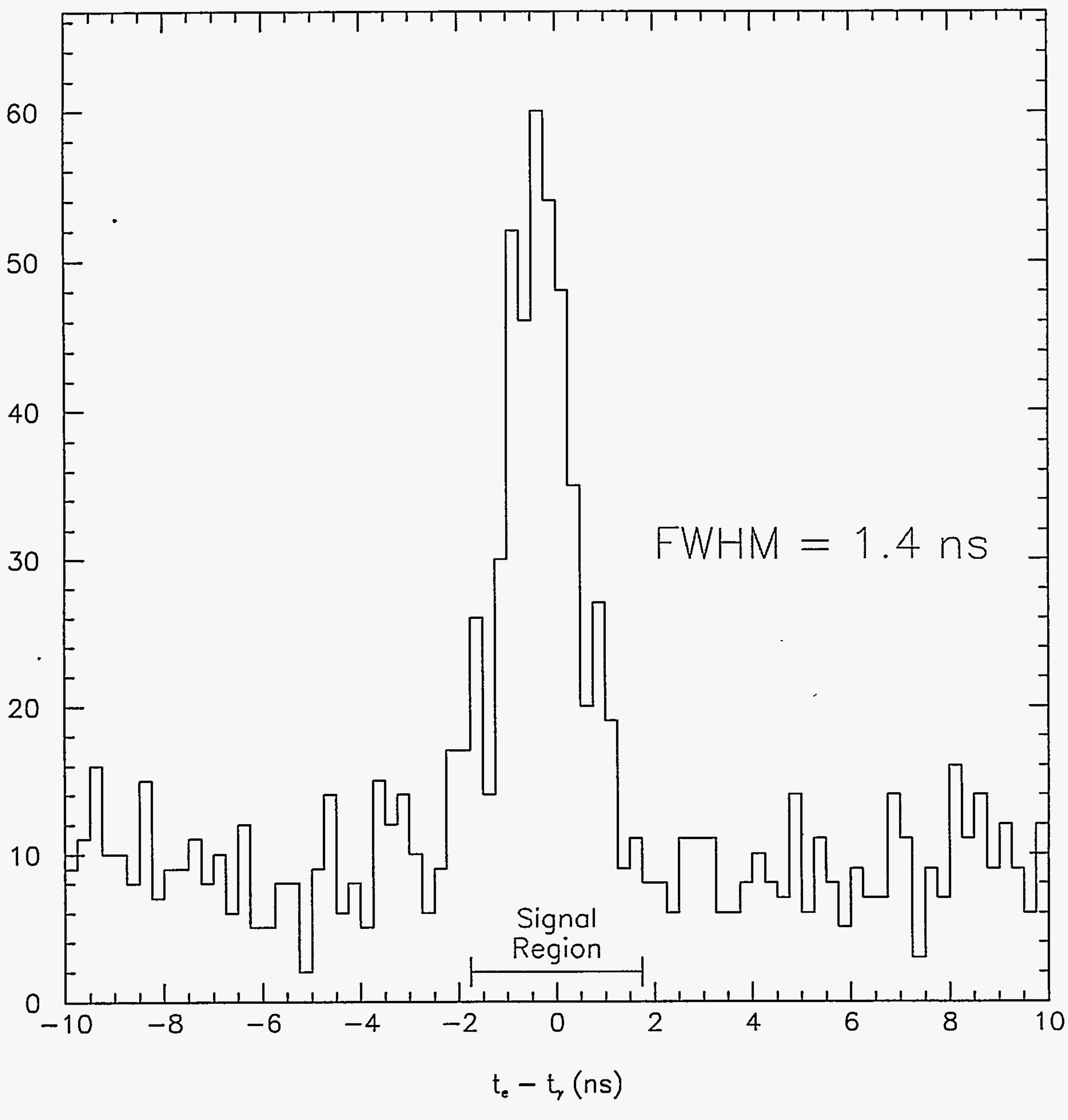

Fig. 2. Positron-photon timing for the process $\mu^+ \rightarrow e^+\gamma\nu\nu$ process at low rates.

FWHM. Observation of this decay is reassuring because it is the proof that the detector sees some events that it should.

At low rates it is possible to reconstruct the positrons to observe the kinematic edge of the positron energy spectrum. The resolution is given accurately by the energy difference between the 10 and 90% points on the edge. We get about 500 keV FWHM as shown in Fig. 3. One of our refining algorithms will remove the differences in the position of the edge due to non-uniformities in the magnetic field.

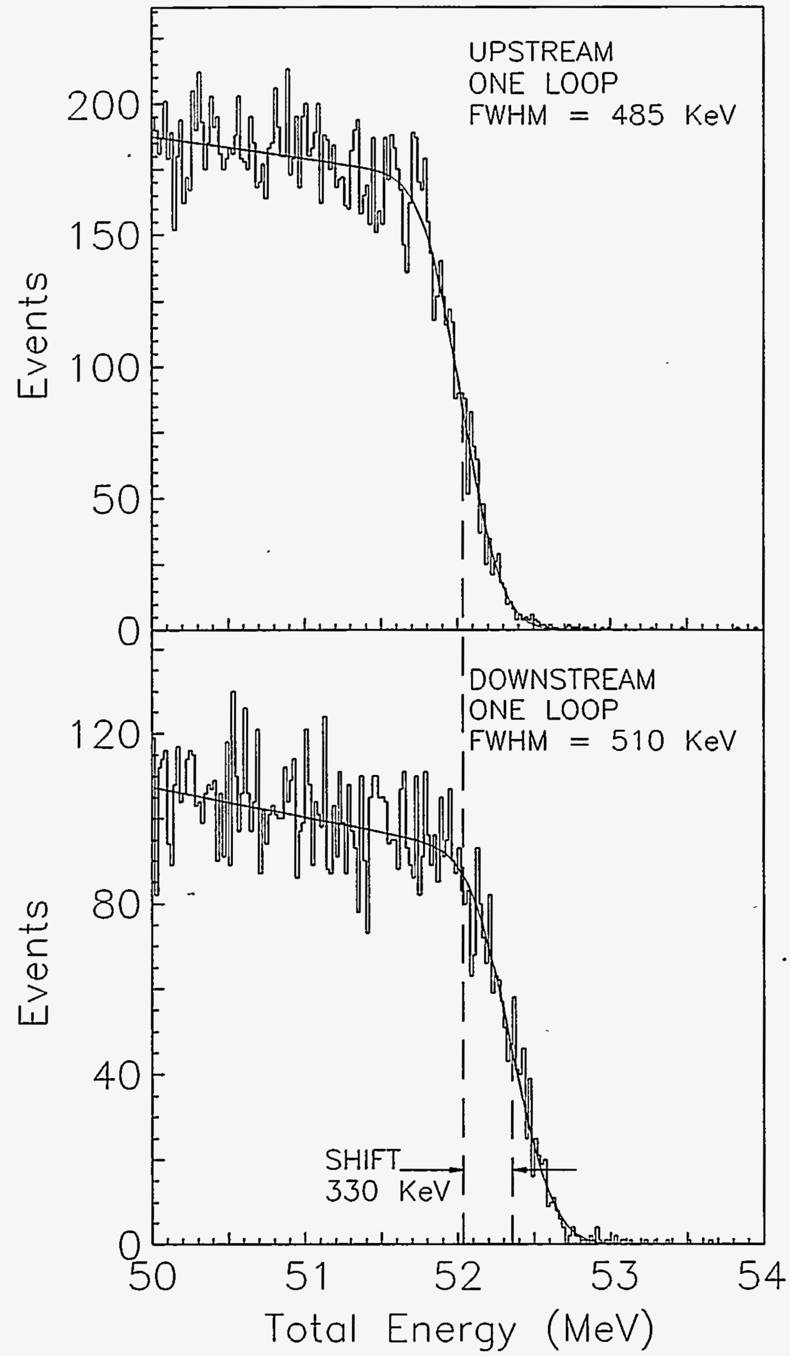

Fig. 3. Positron energy spectrum at low rates.

At high rates, the positron spectrum acquires a high-energy tail due to the improper reconstruction of unphysical events made from random hits in the detector; these are shown in Fig. 4 along with a liberal demarcation of the signal region. The signal region is shown centered at

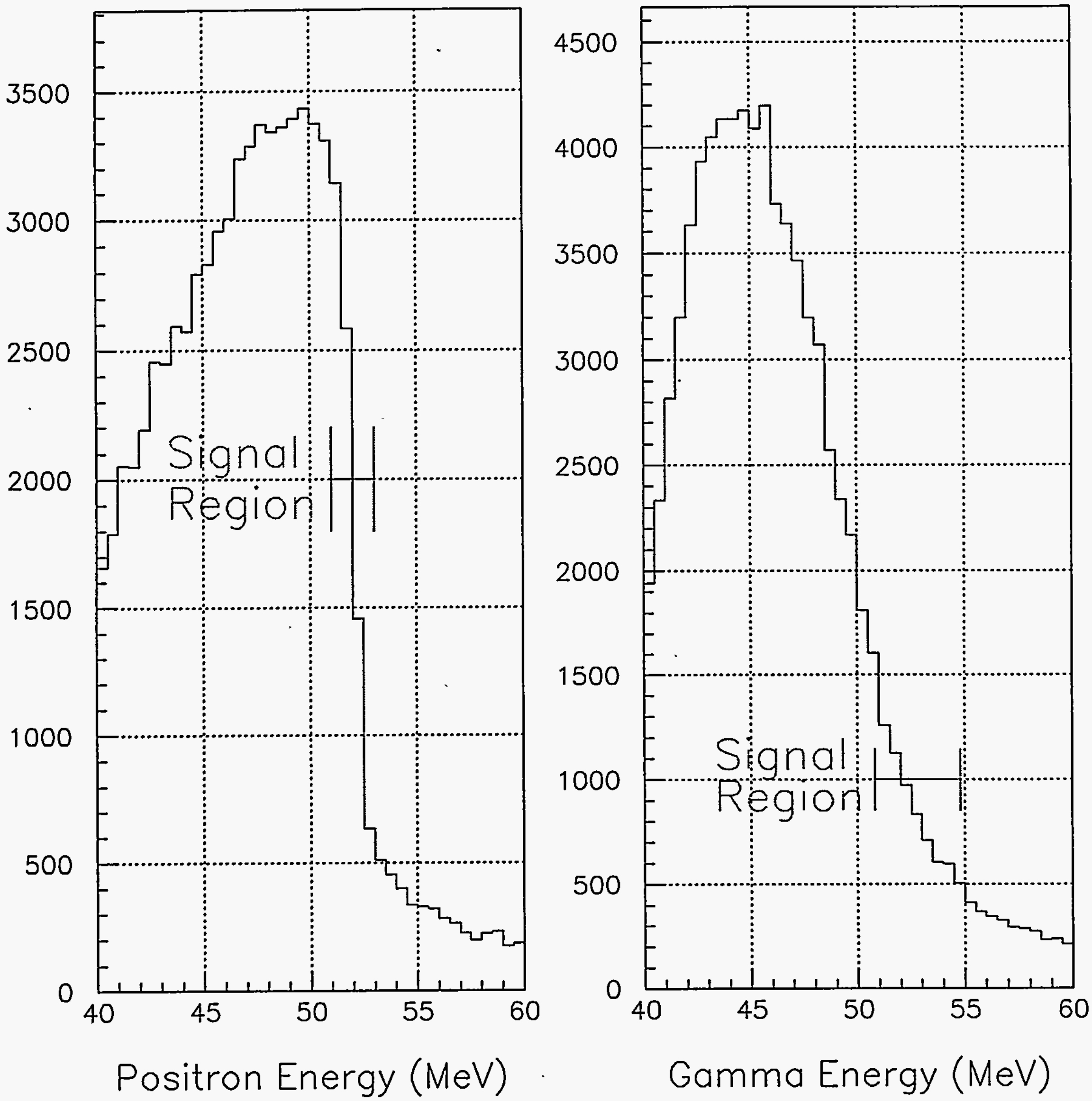

Fig. 4. Positron and photon energy spectra from high-rate muon data

52 MeV because energy loss has not been restored on an event-by-event basis. The photon energy spectrum also contains many unphysical events. Algorithms to remove the vast majority of these events are under development; they have been identified as originating from two separate photons and are readily isolated.

Figure 5 plots the photon energy versus the positron energy with cuts on the relative time and opening angle. No events are observed in the signal region for this small sample of the data. The absence of signal corresponds to a branching-ratio limit of $<7 \times 10^{-11}$, a value close to the published value and background free. This value is expected to improve substantially once the data is reprocessed by the new programs. The goal of 7×10^{-13} for the full data set is still possible.

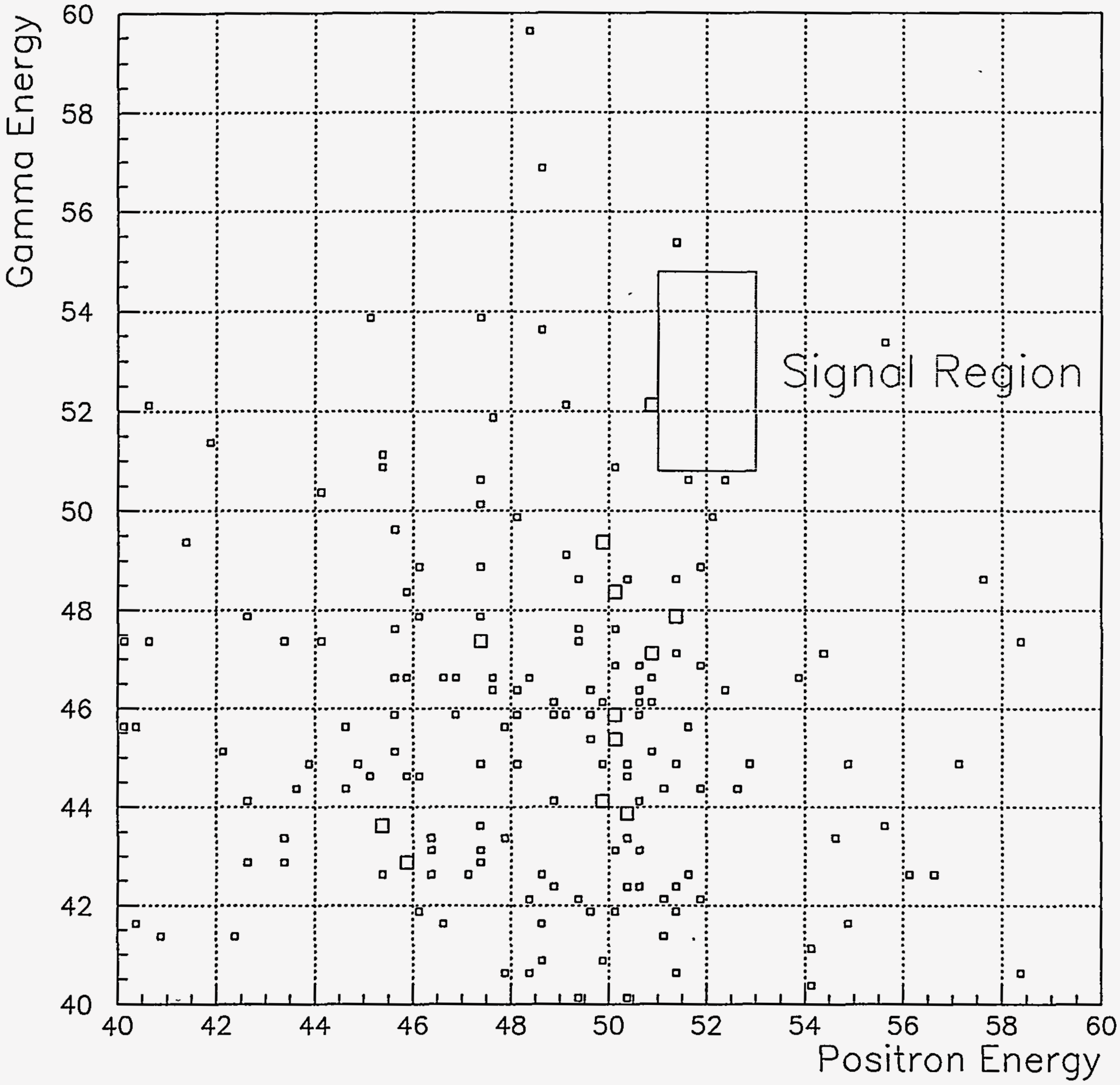

Fig. 5. Photon energy versus positron energy with cuts on timing and back-to-back angle from high rate data.

It is clear that the data in Fig 5 is background free only by luck. To achieve our final result, the new algorithms mentioned above must be implemented. We estimate that a factor of 50–100 in background suppression should be achieved straightforwardly.

3. IDEAS FOR A NEW $\mu^+ \to e^+\gamma$ EXPERIMENT

With the excitement being generated by the possibilities associated with supersymmetry, it is useful to speculate on how one might go beyond the results from MEGA. The following is not a worked out proposal with simulations but is a set of plausibility arguments that indicate that it is worth searching for a design that might reach a sensitivity of 10^{-14}, near the lower limit of the current supersymmetry estimates.

Any experiment that hopes to reach such a sensitivity will need at least an order of magnitude more muon stops than are currently available if it is to be done within reasonable fiscal constraints. Such a source has already been proposed [5], though its realization is definitely in the future. This source might be used for a variety of experiments and could be viewed as a facility. Hence, I will assume the availability of 10^{10} stopping muons in the experiment.

The essential limitations experienced by MEGA were threefold, the duty factor of the accelerator, the efficiency of the photon detector, and the rate in the positron arm. The duty factor should be dealt with by using a machine with greater than 50% duty factor. In MEGA, the photons were detected with pair spectrometers because of the better resolution relative to inorganic crystals and the immunity to low energy neutron capture. New advances in inorganic crystal technology offers the possibility of returning to these devices for getting the kinematic parameters of the photons. They offer essentially 100% efficiency, as opposed to 4%, and their faster characteristic time will minimize the influence from piled up signals.

The rate in the positron detector can be dealt with by examining the sensitivity formula

$$S\ (90\%\ \text{C.L}) = 2.3/M\ ,$$

where

$$M = (\Omega_0/4\pi) \bullet \varepsilon_\gamma \bullet \varepsilon_p \bullet E_c \bullet R \bullet T\ ,$$

and Ω_0 is the overlap solid angle, ε_γ is the gamma-ray detection efficiency, ε_p is the positron detection efficiency, E_c is the cut efficiency, R is the average stop rate, and T is the live time. If the rate is as high as suggested above, then the solid angle can be small as it is the product that determines the sensitivity. Hence, a small solid-angle, special-purpose spectrometer can be used for the positron. In particular, it can have small momentum acceptance to reduce the rate so that the probability of pileup is small. The small solid angle allows for a small photon detector too, which is an important cost containment feature. Small solid angle spectrometers can also have very good energy resolution necessary to suppress random backgrounds. The positron energy is where a spectrometer can be built with qualitatively improved resolution. Any detector that can suppress the random backgrounds will easily suppress the prompt background from $\mu^+ \to e^+\gamma\nu\nu$.

A potential layout is shown in Fig. 6. It features a 180° spectrometer for the positron instrumented with Si strip detectors. The angle is chosen to be 90° with respect to the beam and the muon polarization direction because this angle is independent of the model for the interaction driving $\mu^+ \to e^+\gamma$. The photon arm is a segmented array of inorganic crystals protected by a magnet to sweep away the charged-particle flux. Table 2 gives some specifications for the detector elements that have a reasonable chance of being achieved; the common symbols used are θ for angular resolution and τ for resolving time.

If all these resolutions are achieved and the apparatus can collect data for 2×10^7 s, then the

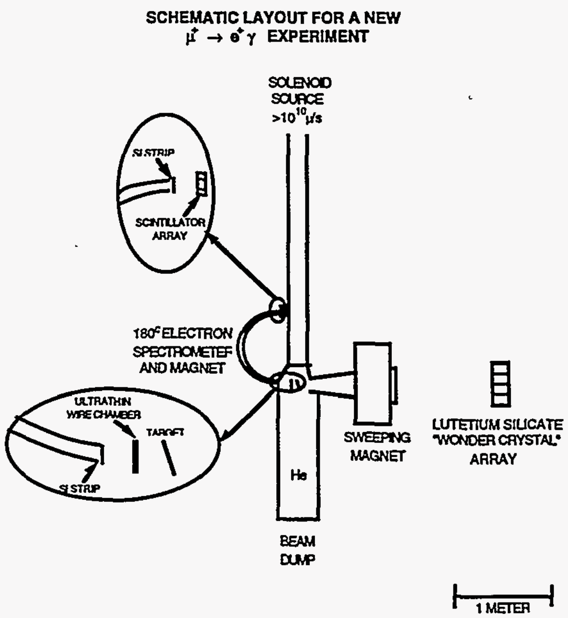

Fig. 6. Schematic layout for the idea for an improved $\mu^+ \to e^+\gamma$ search.

Table 2
Component specifications for the $\mu^+ \to e^+\gamma$ idea

Component	Specifications
Beam	10^{10} μ^+/s, beam dump shielded from the photon detector
Target	<7° w.r.t. beam, $\sigma_{\mathrm{ms}} = 3 \times 10^{-3}$ rad.
Proton spectrometer	$\sigma_{E\gamma}$ = 1.7% at 50 MeV, $\sigma_\theta = 2 \times 10^{-3}$ rad., σ_τ = 300 ps, Depth = 15 X_0, No. of crystals = 2000, $\Omega/4\pi$ = 0.005, $R_\gamma\tau$ (pileup) = 0.02, $R_\gamma\tau$ (trigger) = 10^{-4}
Positron spectrometer	$\sigma_{Ee} = 10^{-4}$ at 50 MeV, $\sigma_\theta = 3 \times 10^{-3}$ rad, σ_τ = 300 ps, $\Delta p/p = 2 \times 10^{-3}$, $\Omega/4\pi$ = 0.005, B = 0.5 T, $R_e\tau$ (trigger) = 10^{-3}

branching ration sensitivity (90% C.L.) should be10^{-14} with less than 1 event of background. There are many concern that must be addressed with detailed simulations before such an idea can be turned into a proposal. However, if the details are clarified, the future looks bright for continued progress on searching for $\mu^+ \to e^+\gamma$. Similarly, effort is currently being expended to work out a much improved $\mu^- N \to e^- N$ experiment [6]. Hence, the field of rare decays is alive and well, with much exciting progress ahead.

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