MEGA: Search for the Rare Decay $\mu^+ \rightarrow e^+\gamma$

M. D. Cooper, M. Brooks, A. V. Chernyshev, G. W. Hart, G. E. Hogan, M. A. Kroupa, V. D. Laptev, D. M. Lee, G. B. Mills, R. E. Mischke (P-25), F. J. Naivar, C. Pillai, J. C. Sturrock (LANSCE-6), P. S. Cooper (Fermi National Accelerator Laboratory), Y. Chen, M. Dzemidzic, A. Empl, E. V. Hungerford, III, K. Lan, B. W. Mayes, II, W. von Witsch (University of Houston), K. Stantz, J. Szymanski (Indiana University), C. Gagliardi, R. E. Tribble, X. Tu (Texas A&M University), D. D. Koetke, R. Manweiler, S. Stanislaus (Valparaiso University), K. O. H. Ziock (University of Virginia), L. E. Piilonen (Virginia Polytechnic Institute and State University)

Searching for rare decays like $\mu^+ \rightarrow e^+\gamma$ is a sensitive method to discover physics beyond the standard model of electroweak interactions because this model predicts their rates to be zero or immeasurably small. Even though no such transitions have been observed, most physicists believe that the standard model must be imbedded in a larger theory because of the number of unexplained constants it contains. Nearly all of the candidates for the larger theory predict rare decays to proceed at rates close to the current limits.

For a rare decay to be seen at a measurable rate, the process must be mediated by a new particle that is virtually exchanged between leptons and/or quarks. The structure of the electroweak theory is simpler if the mass scale for these new particles is below 1 TeV. The current experiments that are searching for rare decays are sensitive in the mass range between 50 GeV and 1 TeV, spanning the gap between direct production experiments and the 1-TeV scale. The possibilities for a discovery of great importance are nonnegligible. In the past two years, there has been intense speculation over one particular theory, supersymmetry. Supersymmetry postulates matching all of the known particles of spin ½ or 1 with superpartners that have either spin 1 or ½, respectively. These new particles can mediate the process $\mu^+ \rightarrow e^+\gamma$ and induce rates within the sensitivity range of the MEGA (muon decays to an electron and a gamma ray) experiment. These models predict that $\mu^+ \rightarrow e^+\gamma$ will be the largest rare decay. Supersymmetry can also be a low-energy reduction of a grand-unified theory, in which case the rates are felt to be large because of the high mass of the newly discovered top quark. If one samples supersymmetric models, the MEGA experiment spans about half of the potential parameter space with its branching-ratio sensitivity (90% confidence) down to 10^{-12}; the current limit is 5×10^{-11}.

The MEGA apparatus was described in the 1994 Physics Division progress report (M. D. Cooper et al., "MEGA: Search for the Rare Decay $\mu^+ \rightarrow e^+\gamma$," in "Physics Division Progress Report, January 1, 1994–December 31, 1994," G. Y. Hollen and G. T. Schappert, Eds., Los Alamos National Laboratory report LA-13048-PR [November 1995], p. 76). Only a brief recap will be repeated here. MEGA took advantage of the intense beams of the surface muons available at LAMPF (a 20-MHz average stop rate was used). The detector was contained in a large, warm-bore solenoid (1.5 T, 1.85 m$\varphi \times$ 2.9 m long) and consisted of two arms (Fig. II-37). The first, a set of special, cylindrical, proportional chambers, measured the kinematic properties of the decay electrons, and the other, the world's largest pair spectrometers, determined the same quantities for the photon. All of the charged particles arising from muon decay were confined by the magnetic field to the positron elements, leaving the photon counters in a relatively quiet environment. The MEGA collaboration, currently consisting of six university groups and two national laboratories, completed taking its data at the end of 1995. An intense analysis effort was begun to extract viable candidates from the stored events.

There are 4.5×10^8 events stored on tape from the three data runs that occurred during 1993–1995. These events are the remains of roughly 1.5×10^{14} muons that decayed in the detector during its 1.1×10^7 live seconds. Highly improbable events have been discarded in the hardware and software during the acquisition. The signature for $\mu^+ \rightarrow e^+\gamma$ is a 52.8-MeV photon and a 52.8-MeV electron that are back to back, from a common vertex, and in time coincidence, and the excellent resolution of the spectrometers at high rates allows the potential signal to be separated from the background. To establish which events might fit this description, sophisticated software is being used to reconstruct and sort the events.

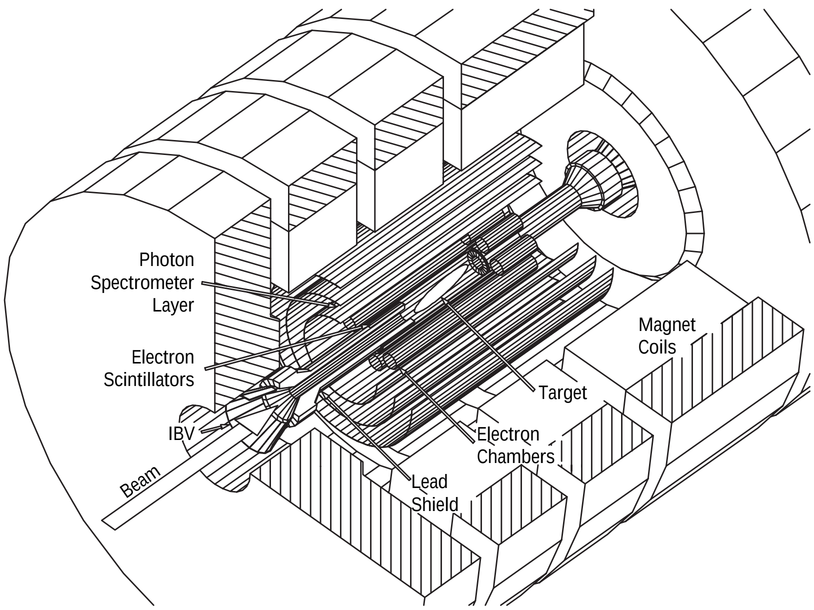

Fig. II-37. A simplified cutaway view of the MEGA apparatus. The detector is mounted inside a superconducting solenoid with a 1.5-T field. The muons enter along the magnetic field and stop in the target. Positrons from muon decays are detected in the eight cylindrical wire chambers and in the cylindrical arrays of scintillators surrounding the beam pipes. The three large cylinders are pair spectrometers for photon detection.

Four pieces of information are needed to measure a branching ratio. First, the energy, time, and geometrical scales of the detector must be calibrated so that the location of the signal is established. Second, the response functions of the detector elements must be determined so that the range of event properties (for example, the energies, times, and angles) for probable events is given by the resolutions. Third, the number of viable candidates, running anywhere from 0 to 100 in our sensitivity range, must be found. Last, the number of muon decays for which the detector was fully efficient $\mu^+ \rightarrow e^+\gamma$ needs to be determined.

The first two necessities of the analysis are given either from the data or from auxiliary measurements. The three simplest kinematic parameters to understand are the positron energy, the photon energy, and the relative time of decay. Figure II-38 displays the energy spectrum for positrons decaying at high rates (250 MHz instantaneously) in black. An idealization of this spectrum would be a roughly flat response up to 52.8 MeV and a precipitous step down to zero counts beyond that point. The experimental result shows that the energy is correctly calibrated to be 52.8 MeV, and the full-width half-maximum of the detector response is 0.7 MeV, as given by the 10%–90% points on the step function. In addition, there are a few percent of unphysical

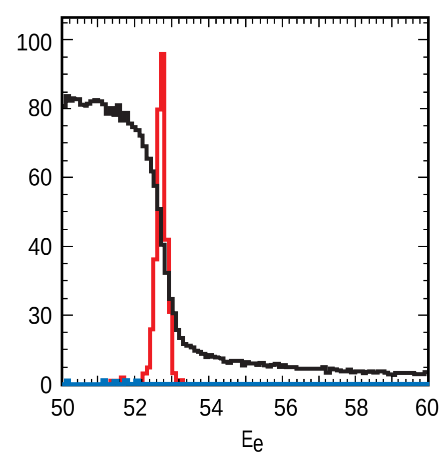

Fig. II-38. The Michel spectrum of normal muon decay at high rates is shown in black. The red curve is the signal expected for $\mu^+ \rightarrow e^+\gamma$ based on Monte Carlo simulations. The blue histogram contains the data with tight cuts on the time difference, the angle between the particles, and the photon energy.

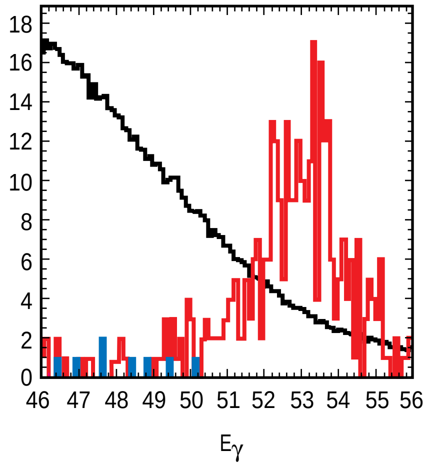

Fig. II-39. The photon spectrum from bremsstrahlung at high rates is shown in black. The red curve is the signal expected for $\mu^+ \rightarrow e^+\gamma$ based on Monte Carlo simulations. The blue histogram contains the data with tight cuts on the time difference, the angle between the particles, and the positron energy.

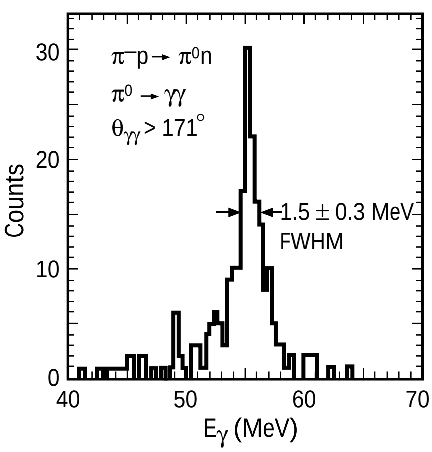

Fig. II-40. A spectrum from $\pi^0 \rightarrow \gamma\gamma$ with the angle between the gamma rays greater than 171°. Each π^0 is produced by stopping a π^- in a CH_2 target.

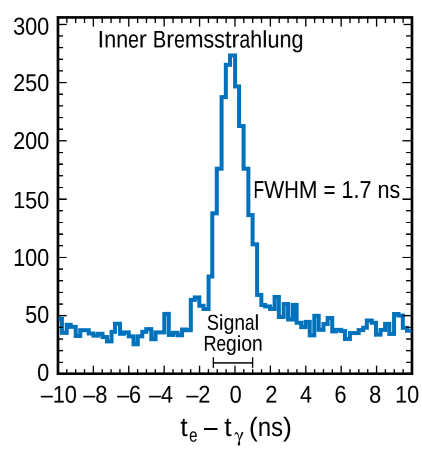

Fig. II-41. The timing spectrum that indicates the presence of coincidences of positrons and photons from the expected process $\mu^+ \rightarrow e^+\gamma\nu\nu$.

events at a higher energy that are caused by confusion of the pattern-recognition code by extra hits in this high-rate environment; these unphysical events represent a small inefficiency for finding the signal.

The corresponding energy spectrum for the photons is shown in black in Fig. II-39. This spectrum, whose origin is bremsstrahlung ($\mu^+ \rightarrow e^+\gamma\nu\nu$), is expected to fall rapidly as the energy approaches the 52.8-MeV endpoint. Again, there are some unphysical high-energy events that represent extra background. This spectrum contains no distinct features to use as a calibration. To overcome this deficiency, photons are measured from the decay $\pi^0 \rightarrow \gamma\gamma$. If the π^0 is made from stopping pions via the process $\pi^- p \rightarrow \pi^0 n$, the energies of the two gamma rays range from 54.92 to 82.96 MeV. By selecting only decays with an angle of at least 171° between the photons, nearly monoenergetic gamma rays of 55 MeV are isolated, as seen in Fig. II-40. Again, the energy calibration is seen to agree with its predicted value, and the resolution is 1.5 ± 0.3 MeV.

The primary background to the $\mu^+ \rightarrow e^+\gamma$ process is random coincidences between a positron from one muon decay and a photon from a second muon decay via the $\mu^+ \rightarrow e^+\gamma\nu\nu$ process. At the full beam intensity, the prompt coincidences from $\mu^+ \rightarrow e^+\gamma\nu\nu$ are completely swamped by the accidentals. However, if the beam intensity is greatly lowered and the magnetic field is somewhat reduced, a clear peak is observed at a time difference of zero (Fig. II-41). This feature demonstrates that the timing is correctly prepared. The observation of the peak demonstrates that the apparatus can observe a real coincidence process.

At this time, the collaboration has analyzed the 1993 data, which represent one-sixth of the total sample. Each event must be reconstructed by a very-time-consuming program that converts the detector signals into particles whose kinematic properties are known. For this subset of the data, the equivalent of 30 Hewlett-Packard 100-MHz workstations have computed continuously for one month at Indiana University, Los Alamos, and Texas A&M University.

Figures II-38, II-39, II-42, and II-43 are a set. For the four primary variables that characterize the kinematics, these figures show the raw data (black), the expected signal based on Monte Carlo simulations (red), and the data cut tightly on the three other variables not displayed in the particular figure (blue). The structure in the uncut, relative-time spectrum is an artifact of the on-line filter; otherwise it would be flat. These figures allow the observation of several points. First, the evolution of the full spectrum to a few events is seen as the severe cuts are imposed to isolate the signal. Second, the number of events in the signal region is seen to be zero. Third, the distinct character of the signal is easily identified. Last, the proximity of candidates to the signal region can be evaluated.

The energies of photons and positrons for events that are within ±1.0 ns of being in coincidence and that have an angle between them of at least 178.1° are plotted in Fig. II-44. There are no events inside the box that indicates the signal region. The number of muon decays in the sample is 2.3×10^{13}. Taking Poisson statistics and the detector acceptance into account, a new limit for the branching ratio (90% confidence) for $\mu^+ \rightarrow e^+\gamma$ is established to be 4×10^{-11}. This value represents a slight improvement over the previous best limit of 5×10^{-11}, a result that was based on subtracting 50 events of background. These results are preliminary and may be improved by the imposition of cuts on kinematic properties not considered here; this work is in progress. It is hoped that when the remaining techniques for background reduction have been employed, the result for the remaining five-sixths of the data will be background-free and will get close to the desired sensitivity. Of course, the exciting possibility of actually observing a $\mu^+ \rightarrow e^+\gamma$ signal remains.

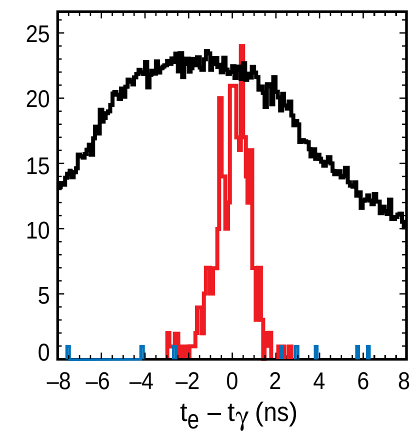

Fig. II-42. The relative timing spectrum at high rates is shown in black. The red curve is the signal expected for $\mu^+ \rightarrow e^+\gamma$ based on Monte Carlo simulations. The blue histogram contains the data with tight cuts on the angle between the particles, the positron energy, and the photon energy.

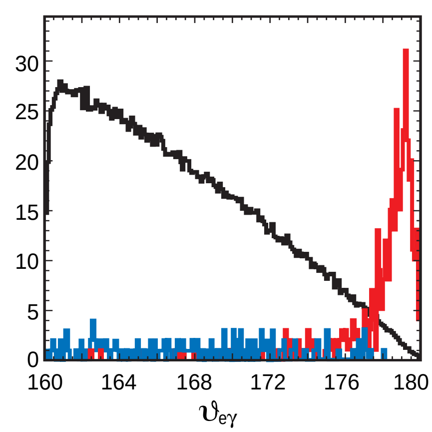

Fig. II-43. The spectrum of angles between the positron and photon at high rates is shown in black. The red curve is the signal expected for $\mu^+ \rightarrow e^+\gamma$ based on Monte Carlo simulations. The blue histogram contains the data with tight cuts on the time difference, the positron energy, and the photon energy.

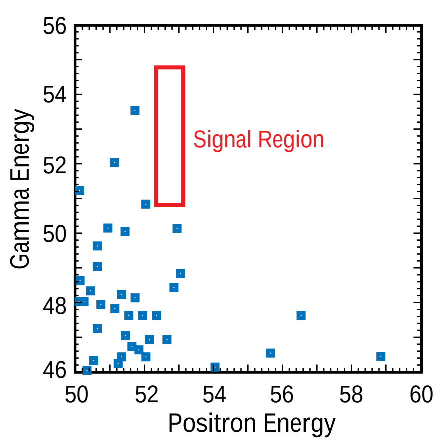

Fig. II-44. The photon energy plotted versus the electron energy for a set of events that are nearly back to back and in time coincidence. The empty box is where a potential $\mu^+ \rightarrow e^+\gamma$ signal should be.