MEGA: A SEARCH FOR THE DECAY $\mu \rightarrow e\gamma$

R.D. Hartman, K.M. Stantz, and J.J. Szymanski
Indiana University Cyclotron Facility, Bloomington, Indiana 47408

We continue to play a major role in the MEGA rare muon-decay experiment at LAMPF.[1] The experiment is continuing production, with runs having taken place or scheduled during the summers of 1992-1995. Our efforts are presently concentrated on the analysis of the 1993 data set, which is the thesis data of IU student Keith Stantz. After a complete analysis, the sensitivity to the decay mode $\mu \rightarrow e\gamma$ will be somewhere in the range of 12-15 times better than the existing limit. The 1994 data set improves the sensitivity by another factor of approximately 3 and will be analyzed after the algorithms are fully developed for the 1993 analysis. Results for the 1992 data set, which were shown in last year's IUCF annual report, have now appeared in a conference proceedings.[2] We have also taken data to improve the measurement of the muon decay parameter ρ by a factor of three or better.

A short synopsis of the detector and trigger systems follows. The MEGA detector is cylindrically symmetric about the beam axis and is contained within a superconducting solenoid with clear bore 2.2 m long by 1.9 m in diameter and a 15-kG magnetic field. A positive muon beam of instantaneous stop rate 2.5×10^8/sec is brought to rest in a Mylar target that is located in the center of the detector. Each muon produces a positron via the dominant muon decay mode, $\mu \rightarrow e\nu\bar{\nu}$; the magnetic field confines these positrons within a radius of 30 cm from the beam center. This inner region is instrumented with eight cylindrical multiwire proportional chambers (MWPCs) and two scintillator arrays and serves as the positron (referred to as the electron) spectrometer.

Photons are detected in one of three independent, cylindrical photon spectrometers that surround the positron spectrometer. Photons are converted into e^+e^- pairs in one of two thin lead sheets located on the inner and outer radii of an MWPC. The MWPC determines in which lead layer the photon converted and is an essential part of the trigger signal. A barrel of scintillators is located just inside of the first lead layer for timing and trigger information. The outermost region of the photon spectrometer is instrumented with three layers of drift chambers, which provide tracking information to measure the pair energy.

The trigger system has two hardware trigger levels, which look exclusively at information from the photon spectrometers . A third-level, software trigger is done in a workstation farm consisting of 8 DEC station 5000-240's. The third-level trigger compares information in the positron and photon spectrometers and filters the incoming data by a typical factor of 20-30. The final rate to tape during the experiment was ~20-30 Hz.

In previous years, our group has built substantial portions of the hardware for the first- and second-level trigger systems. We are responsible for all aspects of the trigger system, as well as debugging the FASTBUS data-acquisition modules. A paper has been submitted to Nuclear Instruments and Methods describing the trigger system and associated electronics for the photon chamber readout.[3]

Our effort has moved into data analysis, with a large portion of the entire data analysis centered at IUCF. The following are the details of the IU contributions, a synopsis of the final 1992 data analysis, and a progress report on the 1993 analysis. The measurement of the muon decay parameter ρ is continuing and will not be presented here because the analysis does not presently involve IUCF personnel.

The decay $\mu \rightarrow e\gamma$ is separated from backgrounds by determining that the e and γ are produced at the same time, come from the same point in space, are produced back-to-back, and have an energy equal to half the muon rest mass, or 52.8 MeV. Thus, the parameters that the data analysis must determine are the energy, direction and decay time for each electron and photon considered in the analysis. In addition, the resolution functions in electron and photon energy, direction and decay time need to be determined (actually, it is the time difference between the electron and photon decay times that is relevant).

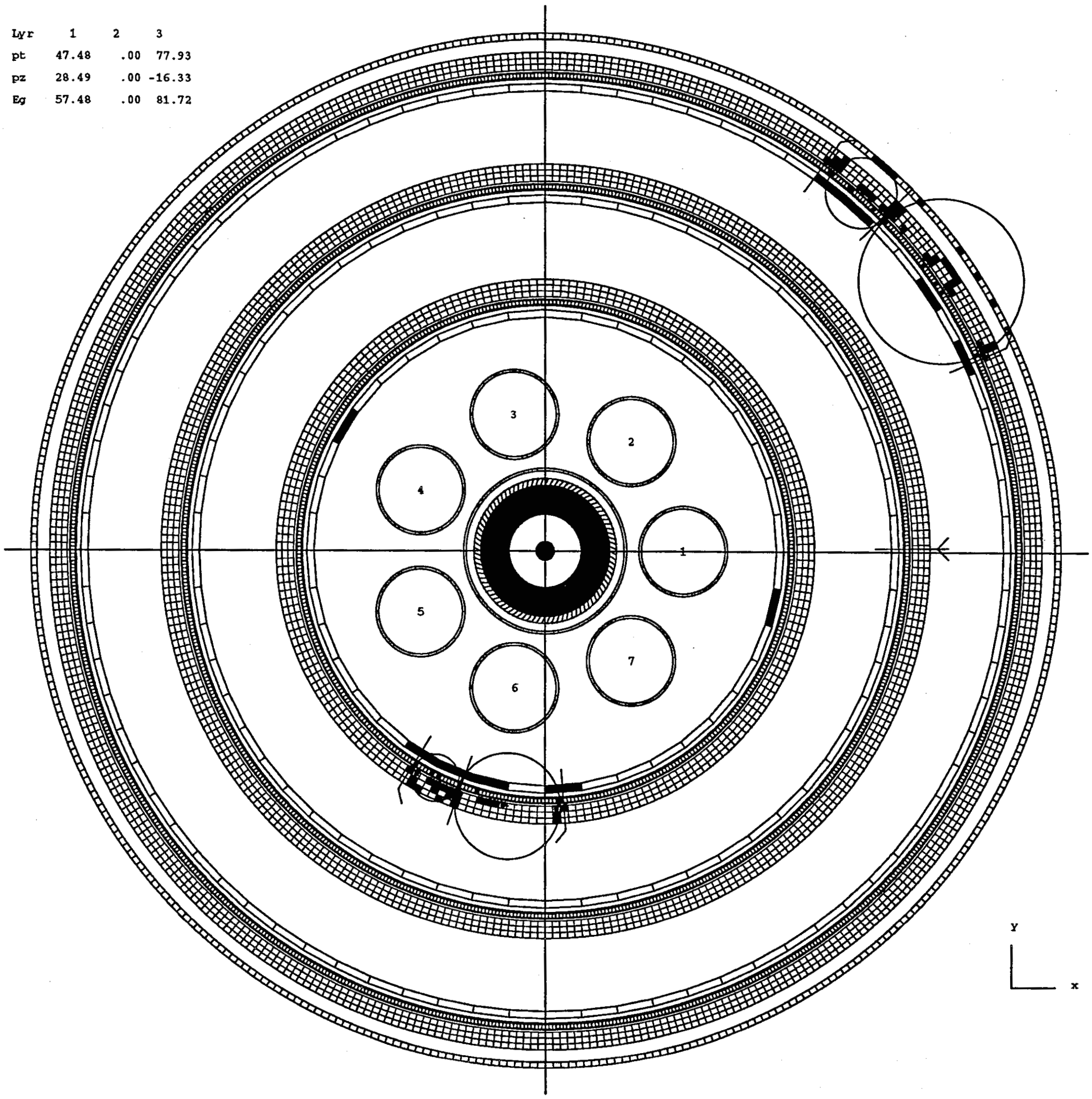
Thus, the major elements for a full analysis of the MEGA data are: an electron arm reconstruction code, a photon arm reconstruction code, precision timing algorithms and constants for both arms, alignment algorithms, and the analysis of many other calibration processes (for example, target location, delay-line calibration for the photon arm z information, electron scintillator ADC-timing correlations, etc.). In addition, substantial computing facilities and software infrastructure are needed to do production computing on the data set. Finally, the analysis of several subsidiary reactions is done to check the above codes.

There are two major IU analysis efforts: writing and debugging of the electron arm reconstruction code and the production running of reconstruction codes on the full MEGA data sets. The electron arm reconstruction is difficult because the electron arm runs at extremely high rates (more than 10^4 particles/mm^2/second) and the occupancy of the detector elements is high. Because the rates used in the 1993 run are a factor of three higher than in the 1992 run, a completely new electron-arm reconstruction code was needed for the 1993 data set.

The electron-arm reconstruction algorithm starts with a prediction of the path a 52.8 MeV electron has to follow if it is from a $\mu \rightarrow e\gamma$ event. The point where the photon converts into an e^+e^- pair is used, as well as timing information in the electron scintillators. Sections of 1, 2 or 3 chambers are identified that should have hits, and chamber hit information is collected for each chamber section. The chamber information is of varying quality, due to electrically dead wires, noise induced in the electronics, ineffiencies and rate effects. Two-dimensional tracks, in the form of circles, are then constructed. This portion of the algorithm is called "filter2b," and will be discussed more below.

After suitable circular tracks are found in the electron chambers, hits are sought in the third dimension (parallel to the beam direction), and a full 3-dimensional helix is reconstructed. Special care is used to insure the chamber information used in the helix reconstruction is likely to be real, i.e., not caused by noise. The algorithm outlined above shows great promise of delivering high reconstruction efficiency in the high rate environment.

In support of the electron-arm reconstruction code development effort, our group has developed 3-dimensional graphics software to display events in the electron arm. This software was initially developed using hardware and software provided by the Center for



```
Lyr     1       2      3
pt    47.48    .00  77.93
pz    28.49    .00 -16.33
Eg    57.48    .00  81.72
```

Figure 1. An end view of a $\pi^0 \rightarrow \gamma\gamma$ event. There are no hits in the electron spectrometer for these events. Hits in drift chambers, MWPCs and scintillators are shown.

Innovative Computing Applications at Indiana University. We applied for funding to acquire our own 3-D graphics system, and received funding from the Indiana University Computing Services. An HP 9000-715/100 workstation with 3-D graphics accelerator was purchased. This computer is not only used for graphics, but is the staging platform for the filter production running described below.

The photon-arm reconstruction code used for the 1992 data will be used for all data sets. The increased muon stopping rate does not significantly increase the photon-arm rates.

One of the important measures of the performance of the photon-arm detectors is the energy resolution, which is measured by producing π^0's with a stopped π^- beam. Both the photons from π^0 decay are reconstructed, as shown by the example event in Fig. 1. Events

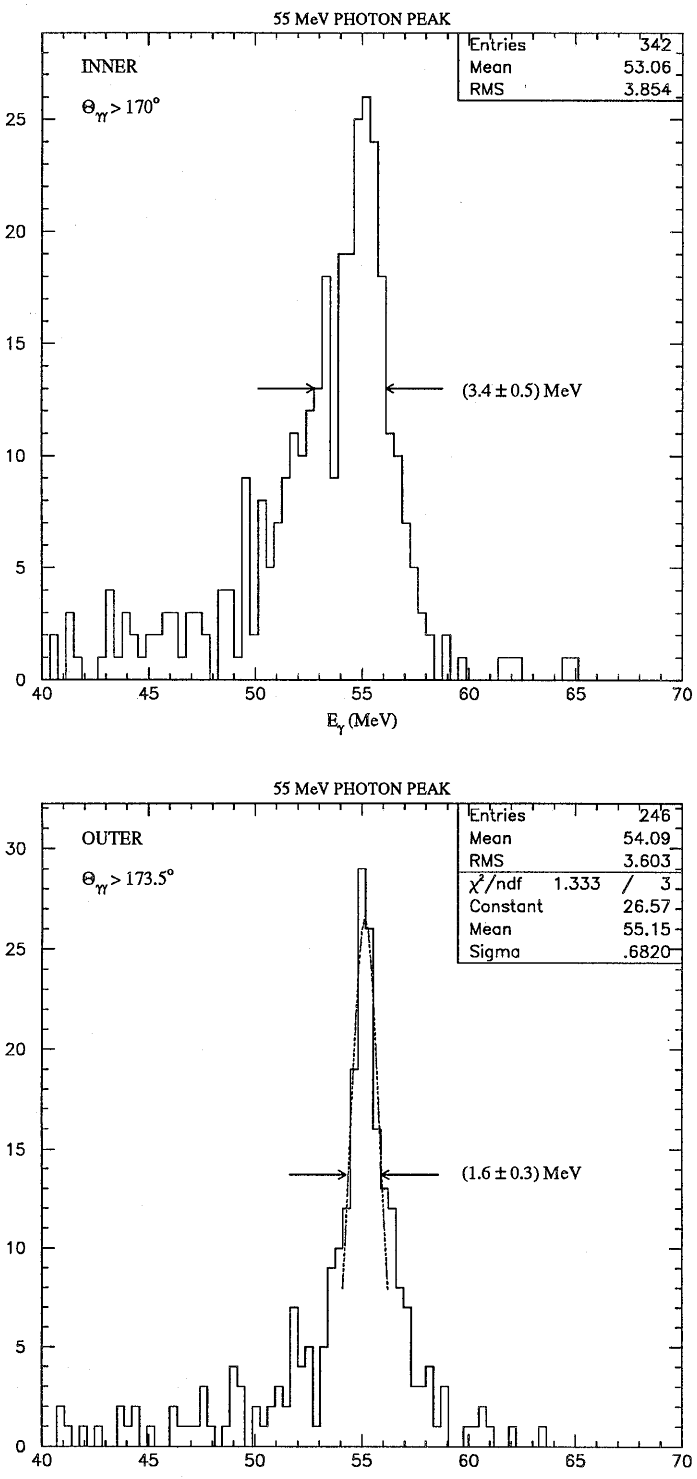


Figure 2. Reconstructed energy for the 55-MeV gamma ray produced by a $\pi^0 \rightarrow \gamma\gamma$ decay for two photons separated by 180°. The plot is shown separately for events where the photon converted in the inner and outer Pb layers of the photon spectrometers.

are selected that have the two photons separated by 180°. At 180° separation, one of the photons has an energy of 55 MeV; the response of the detector to the 55-MeV photon is shown in Fig. 2.

One of the important geometric parameters used in the analysis is a detailed knowledge of the target location. This is necessary to align the photon direction properly with the electron direction; a small change in the target position results in a large change in the direction of the electron with respect to the target. We have developed an algorithm at IU that finds the target position to within 1 mm. Equivalently, the angle the target is slanted with respect to the beam is found to within 0.1°. The algorithm relies on a statistical method to find the target, where the intersection points of many tracks are found, and the centroid of the distribution of intersection points is assumed to be the target position. This statistical algorithm was necessary because muon-decay events have a single charged-particle track, not multiple tracks that can be traced to a common origin.

We have taken on the task of production running of the MEGA data. It makes sense for us to do this task, because we have the largest computing power available in the collaboration (on the HP 9000-700 series workstations), expertise in the filter algorithms (particularly the electron reconstruction code) and people who can run filter jobs and monitor the results. The first task, "filter2b," was outlined above. The purpose of "filter2b" is to decide if chamber hits with sufficient quality exist in the correct places to further consider the event.

To run the filter codes on our workstation cluster, we had to port many tens of thousands of lines of code from VAX-VMS to HP-UX. The 1993 data set consists of approximately 80 8-mm tapes containing approximately 900 runs, so there is a large logistics problem to handle the data tapes and the large number of output files. This required a high level of automation of our filtering procedures to avoid errors. The HP 715/100 graphics workstation was the tape-staging platform. IUCF purchased a dual 8-mm tape drive and the MEGA collaborators purchased 2-4 GB disk drives to complete the data staging hardware. Among the constants needed for "filter2" are dead-wire lists for the electron chambers, which were produced by IU undergraduate student Chris Keslin. The production filtering will occur during summer, 1995. The second and final stage of filtering, which is the full reconstruction of kinematic variables for the photon and electron, will start soon thereafter.

The timing resolution function of the MEGA detector is measured using the decay $\mu \rightarrow e\gamma\nu\bar{\nu}$ (muon inner-bremsstrahlung decay). Figure 3 shows a spectrum of the time-difference taken between the positron and photon spectrometers for inner-bremsstrahlung decay. This spectrum was produced during the summer of 1994 by Ted Forringer, who was a Research Experience for Undergraduates student at IUCF at the time. The peak near zero time difference clearly shows the presence of the muon inner-bremsstrahlung decay in the data set. The observation of this decay mode proves that the detector is capable of measuring a process that has a single muon decaying into a positron and a gamma, as for $\mu \rightarrow e\gamma$. The resolution is expected to improve to 1 ns or better after walk corrections in the positron scintillators are made and the optimal use of all scintillator times is included.

The full set of reconstruction codes has been developed for the 1992 data set. The decay $\mu \rightarrow e\gamma$ has been sought using the 1992 data set, for which a candidate event is shown in Fig. 4. Cuts are made in time and e-γ opening angle, and the photon energy is plotted versus the electron energy for candidate events. Events from the decay $\mu \rightarrow e\gamma$ will have E_γ and E_e both equal to 52.8 MeV, within the resolutions, and will thus show up in

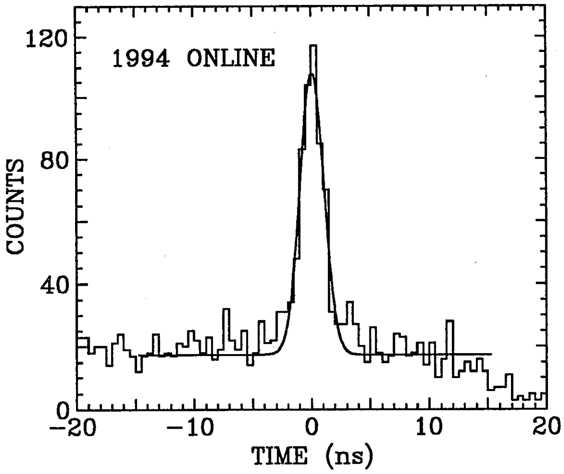


Figure 3. Timing spectrum determined by inner-bremstrahlung decay of the muon.

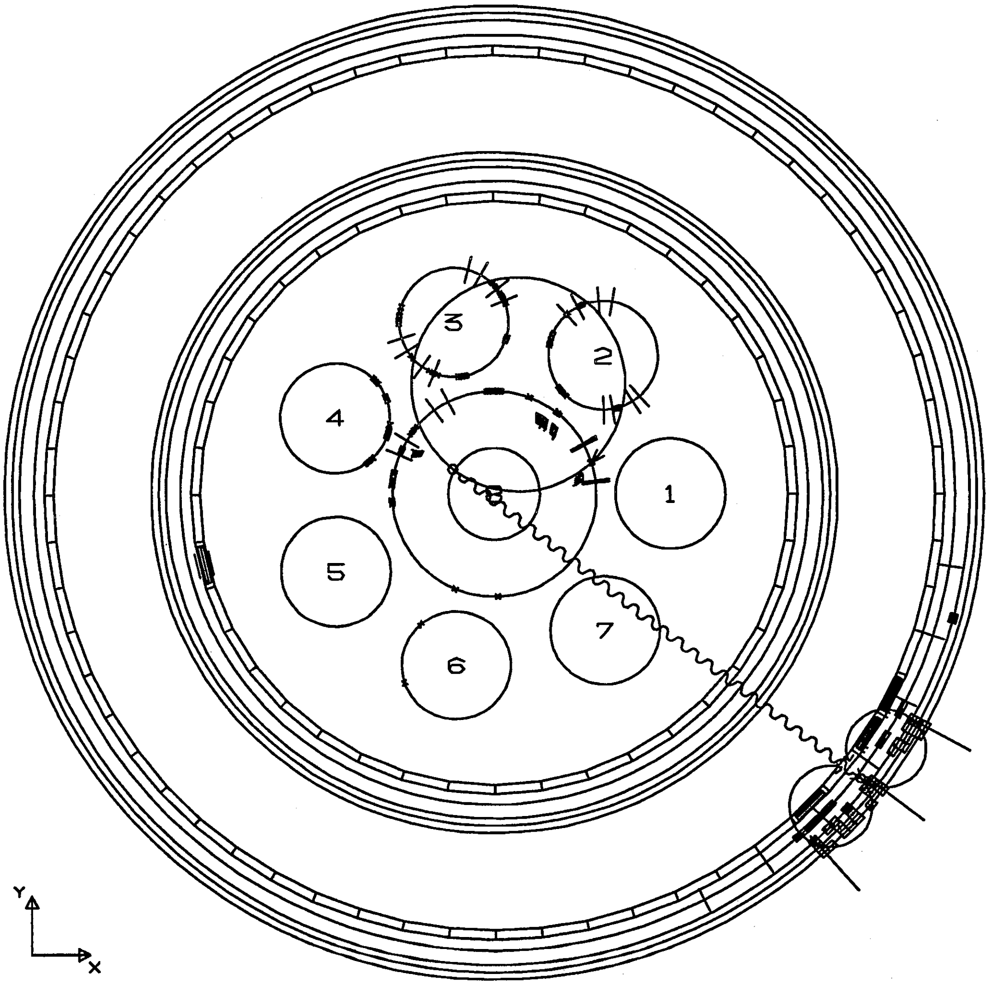


Figure 4. One of the best $\mu \to e\gamma$ candidate events from the 1992 data. This event was rejected by the timing cut.

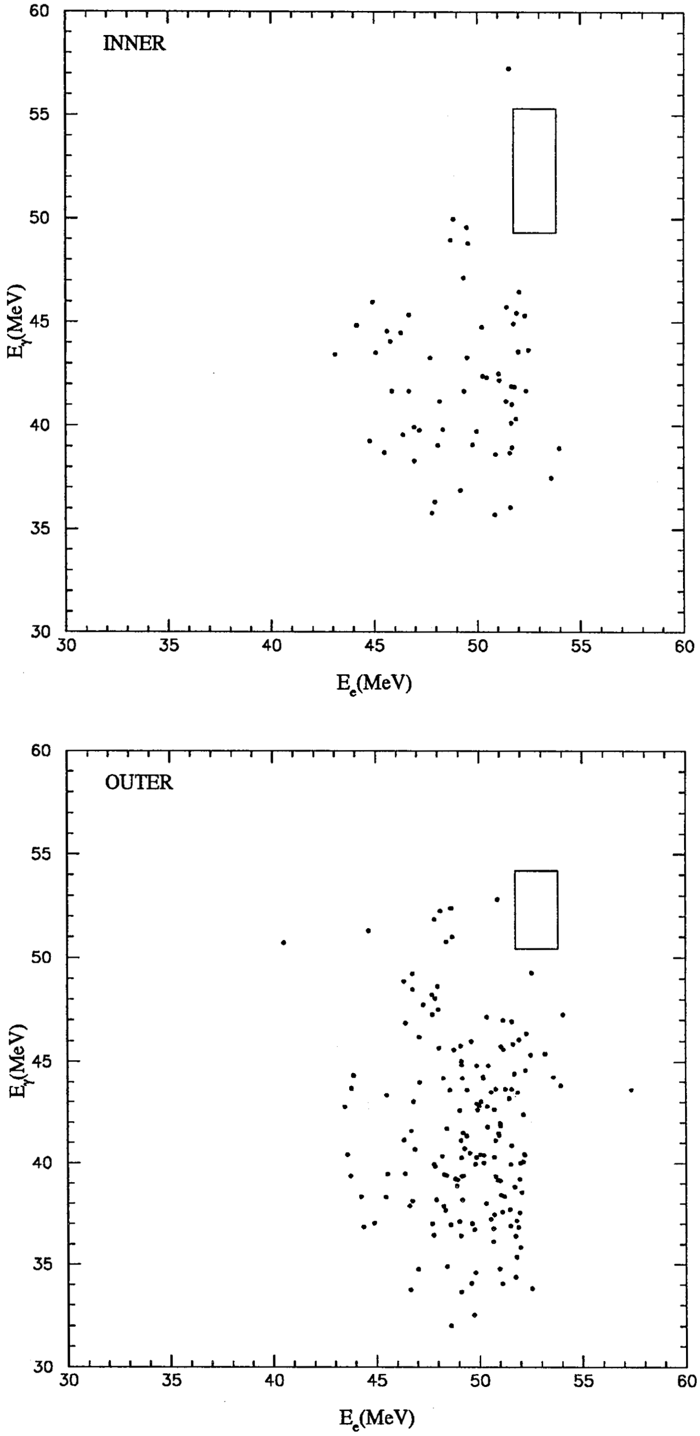


Figure 5. The 1992 MEGA data set is plotted, after timing and angular cuts. The top spectrum contains events in which the photon conversion took place in the inner Pb layer and the bottom spectrum is for photon conversions that took place in the outer Pb layer. The two types of conversion events are separated because the photon energy cut is different in the two cases. No $\mu \to e\gamma$ candidate events are found in either of the two boxes.

the box shown in Fig. 5. Because no events are in the box, we can extract an upper limit on the branching ratio to $\mu \to e\gamma$ of 6.5×10^{-10}. This result is less sensitive than the current limit of 4.9×10^{-11}, which is not surprising given the limited detector acceptance, muon stopping rate and data acquisition time for the 1992 run.

1. The MEGA Collaboration consists of the following member institutions: UCLA, University of Chicago, Fermilab, Hampton University, University of Houston, Indiana University, Los Alamos National Laboratory, Queens University, Stanford University, Texas A&M University, University of Virginia, Virginia Polytechnical Inst. and State University, University of Wyoming, and Yale University.
2. J.J. Szymanski, *et al.*, in *Proc. of the 5th Conf. on the Intersections of Particle and Nuclear Physics,* St. Petersburg, Florida, June 1994.
3. Y.K. Chen, M.D. Cooper, P.S. Cooper, M. Dzemidzic, C.A. Gagliardi, G.E. Hogan, E.V. Hungerford, G.J. Kim, J.E. Knott, K.J. Lan, F. Liu, B.W. Mayes, R.E. Mischke, R. Phelps, L.S. Pinsky, K.M. Stantz, J.J. Szymanski, L.G. Tang, R.E. Tribble, X.L. Tu, L.A. Van Ausdeln, W. Von Witsch and C.S. Wright, submitted to Nucl. Instrum. & Methods, 1995.

A SEARCH FOR THE H PARTICLE (BNL EXPTS. E813/836)

J.J. Szymanski
Indiana University Cyclotron Facility, Bloomington, Indiana 47408

The goal of this experiment is to search for a strangeness −2 dibaryon called the H particle. This state was predicted by Jaffe to have a mass 80 MeV less than the $\Lambda\Lambda$ mass of 2232 MeV.[1] The experimental observation of this state would provide much needed data to help understand the confinement mechanism of quarks. The apparatus and experimental technique were presented in a previous progress report[2] and will not be repeated here.

The main IUCF contribution to this project was originally the second-level trigger system, which separates protons from K^+ particles using time-of-flight. The second-level trigger has since been moved to a VME-based 68030 processor for the 1993 data-taking run, and IUCF is no longer responsible for maintaining this system.

For the 1993 data-taking run, IUCF contributed detectors and second-level trigger electronics to the experiment. For the 1994 and 1995 runs, IUCF contributed to the setup and monitoring of the experiment for data-taking.

The 1992 and 1993 data sets have been reduced and neutron energy spectra have been produced. In this experiment, the reactions $K^-p \to K^+\Xi^-$ and $\Xi^-d \to H\ n$ are used to produce and tag the H particle. If the H particle exists, there will be a peak in the neutron energy spectrum. We now have an integrated flux of 8×10^{12} K^- particles on target, which was our original goal. The experiment is now sensitive to H particles with a relatively large branching ratio from the Ξ^-d atom. Data analysis is complete for the 1993 data, and a publication is in preparation.

The experiment received more beam time during May, June and July, 1994, which was used primarily for a complementary version of the H search that involves a ^{3}He target and the reaction $K^-\ {}^3He \to K^+H\ n$.