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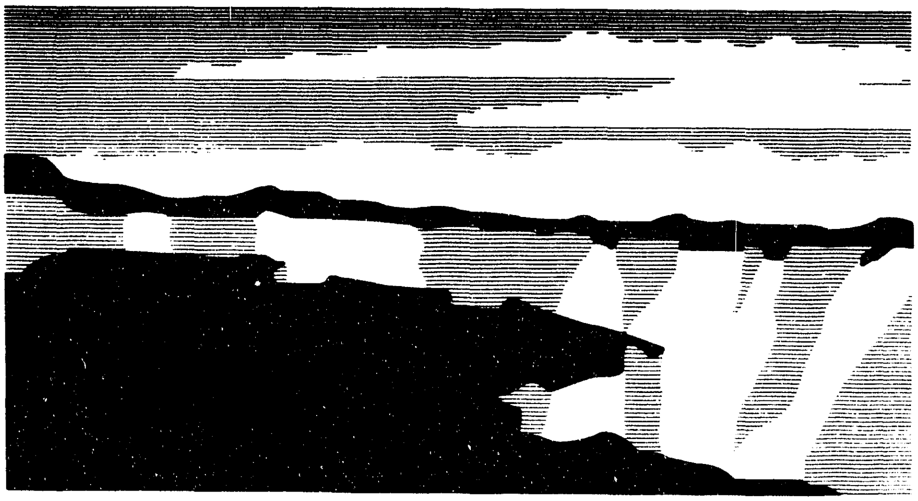

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A Measurement of the Michel Parameter ρ in Muon Decay*

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ABSTRACT

An improved measurement of the Michel parameter ρ in normal muon decay has been made using the MEGA positron spectrometer. Muons were stopped in the center of a large solenoid (1.5 T nominal field) and the momenta of positrons with energies over about 35 MeV were measured with a precision of about 0.6 MeV/c FWHM. There are over 15 million events in each spectrum taken for three operating configurations. The previous result has a precision of $\delta\rho/\rho = 0.003$ based on a sample of about 1 million events in the positron energy spectrum. The present experiment expects to improve the precision by a factor of three to six, depending on the level of systematic uncertainties. The improved result is a precise test of the standard model of electroweak interactions for a purely leptonic process. It also provides a better constraint on the mixing angle in a left-right symmetric extension to the standard model.

Normal muon decay, $\mu \rightarrow e\nu\bar{\nu}$, is an easily accessible, purely leptonic process, which makes it an important testing ground for models of the weak interaction. In recent years, sufficient information about muon decay has been accumulated to permit a model independent analysis of the interaction,[1] but improved precision is needed to distinguish between the currently accepted standard model of the weak interaction[2] and proposed extensions. In this experiment the positron arm of the MEGA detector[3,4] has been used to measure the Michel parameter[5] ρ in normal muon decay.

The muon decay rate is given by

$$\frac{d\Gamma}{x^2 dx d(\cos\theta)} \sim 3(1-x) + \frac{2\rho}{3}(4x-3) \mp P_\mu \xi \cos\theta \left[1 - x + \frac{2\delta}{3}(4x-3)\right],$$

where $x = E_e/E_{\max}$; θ is the angle between the positron direction and the muon spin; ρ, δ, and ξ are Michel parameters; and P_μ is the average muon polarization. The positron mass, the W mass, and the Michel parameter η have been neglected.

The best previous value[6,7] for ρ, based on a sample of about 1 million events is

$$\rho = 0.7518 \pm 0.0026\,.$$

A deviation of ρ from the standard model value of 0.75 would indicate new physics. An example of a candidate extension is the left-right symmetric model[8] based on the gauge group $SU(2)_R \otimes SU(2)_L \otimes U(1)$. In this model, the weak charged current is carried by right as well as left handed bosons (W_R,W_L). The mass eigenstates W_1 and W_2 of the quark interaction, with masses m_1 and m_2, could be a mixture of the chirality eigenstates with mixing angle ζ. The Michel parameter ρ becomes

$$\rho \simeq \frac{3}{4}(1 - 2\zeta^2)\,.$$

The constraint on the mixing angle provided by the precision of the previous measurement of ρ is shown in Fig. 1. This result complements other experiments that test the left-right symmetric model.

The experiment is performed by measuring the energy spectrum of positrons from Michel decay. Theoretical spectra for three values of ρ are shown in Fig. 2. The abscissa is the energy of the positron in units of x. These spectra are independent of the angle of the positron with respect to the muon spin even for a polarized muon beam if the solid angle for $\pm\cos\theta$ is matched.

Although the MEGA apparatus was not designed for this measurement, it is a very low mass apparatus with many independent, essentially digital parts. The large number of elements allows many checks for systematic errors. Another important feature is the high degree of symmetry for the upstream and downstream elements of the spectrometer. The MEGA apparatus has good acceptance for positrons with $0.75 < x < 1.0$ in a single setting of the magnetic field and a subset of the data has a reasonably flat acceptance over this range of x.

A schematic view of the MEGA apparatus is shown in Fig. 3. It is contained in a superconducting solenoid with a bore of 1.9 m and a length of 2.5 m and is operated at a field of 1.5 T. A beam of about 5 kHz of "surface" muons (29 MeV/c) enters along the axis of the solenoid and stops in a vertical 250 μm Mylar target. Positrons from $\mu \rightarrow e\nu\bar{\nu}$ are confined to the central region (30 cm radius) and are measured in a set of thin high rate MWPCs.[10] A Michel decay event is triggered by a hit in any scintillator contained in barrels of 87 scintillators each located at the upstream and downstream ends of the central region. The photon pair spectrometers outside the positron arm are not needed for the ρ measurement.

Data were taken in two short runs during 1992 and 1993. The 1993 data are of better quality and are being analyzed presently. Over 500 million triggers were recorded in a 5 day period. Figure 4 shows the reconstructed energy spectra for a sample of the data from each of the three data configurations. The nominal data set was taken with a surface beam tune and 1.5 T magnetic field. A second data set was taken with the magnetic field reduced to test our understanding of the acceptance. The increased acceptance for lower energy positrons in the case of the reduced magnetic field is evident in the spectrum. A third data set was taken with a decay tune that reversed the muon polarization. The spectra for the normal and reversed spin data are very similar, although a detailed analysis reveals small differences due primarily to differences in the beam phase space. For the range of x included with good acceptance, the expected statistical precision on ρ is $\sqrt{7.5/N}$ where N is the number of events. For the subset of the data with flat acceptance, the sum of the three data sets will yield a statistical precision on ρ of 0.00044.

In Fig. 5 the data spectrum for the decay tune is reproduced together with preliminary Monte Carlo spectra calculated for $\rho = 0.75$ and for the derivative of the theoretical spectrum with respect to ρ. A χ^2 minimization program is used to find a best fit of a linear combination of the two Monte Carlo spectra to the data. If the normalization coefficient of the derivative spectrum, (c), is nonzero, that would indicate that the preferred value of ρ deviates from the nominal value of 0.75.

To extract an accurate value for rho from the data requires that the Monte Carlo simulation accurately reproduces the experimental apparatus. The critical requirements include reproducing the geometry of the detectors and simulating the efficiencies of the chambers and scintillators. The detector geometry comes from physical measurements and analysis of the data. The chamber efficiencies are extracted from the data. In the case of the scintillators, because they were the trigger for the experiment, it was necessary to take auxillary data to determine their efficiencies. This was accomplished by using a signal from one of the chambers for a trigger.

The Monte Carlo simulation must include radiative corrections, which affect the shape of the spectrum mostly near the end point. The first order radiative corrections have been parameterized by Sachs and Sirlin[11] as two functions of x, one associated with ρ and one associated with δ. Until second order radiative corrections become available, the analysis procedure can be modified to reduce the sensitivity of ρ to radiative corrections at some cost in statistics.

The analysis of the experiment is dominated by understanding and minimizing sources of systematic error. Monte Carlo studies indicate that systematic errors will contribute at the level of $\delta\rho/\rho = 0.0003$, which is well below the level required. For some contributions, the required level of understanding has been reached; for the others more work is in progress. For example, the energy resolution from the data is about 600 keV (FWHM). Our knowledge of the match between the data and Monte Carlo resolution is currently limited by the Monte Carlo statistics to a precision of about 50 keV. We want to achieve a match at the level of 10 keV. As the Monte Carlo statistics are increased, some fine tuning of the Monte Carlo may be required.

Our understanding of the beam phase space and the magnetic field are at the required levels. At present the dominant systematic uncertainties come lack of knowledge of the chamber alignment, chamber efficiencies, and scintillator efficiencies. Adequate statistics exist to reach the required level of precision; the problems lie in developing algorithms to extract the necessary values and then implement sufficiently accurate representations of the physics in the Monte Carlo. We expect to reach the desired level for all known potential sources of systematic error.

In summary, if the systematic errors can be reduced below the level of the statistical errors, the improvement in the precision of ρ will be about a factor of six. The schedule for completing the analysis is to have a preliminary value, based on about 25% of the data by early July 1994, and the full analysis by the end of this summer.

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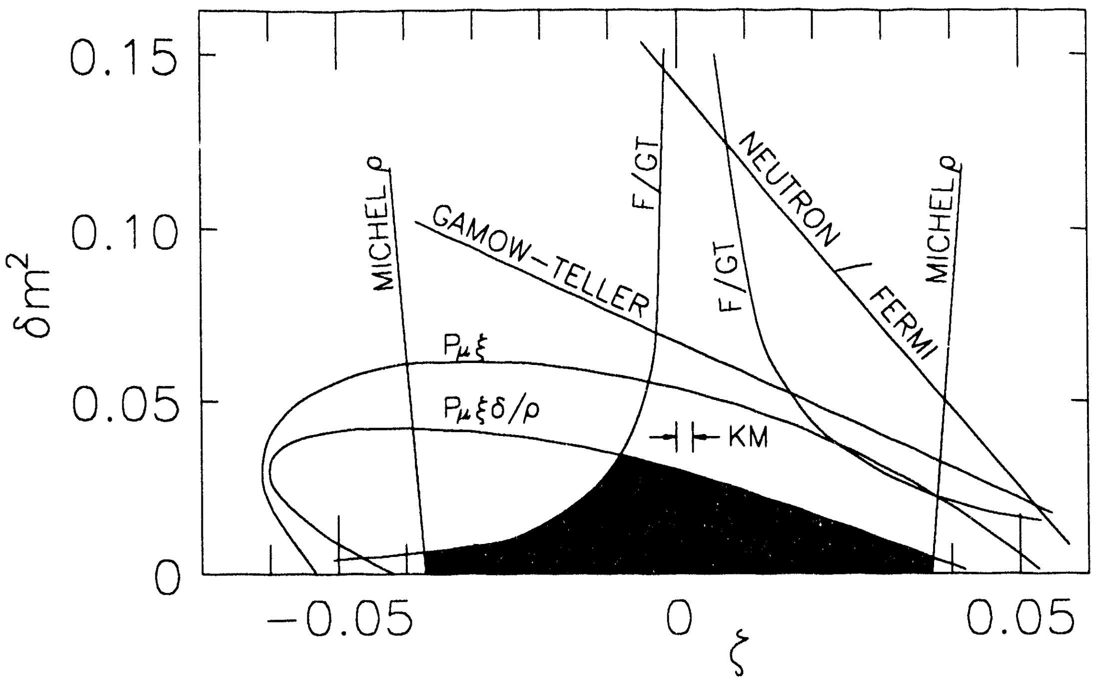
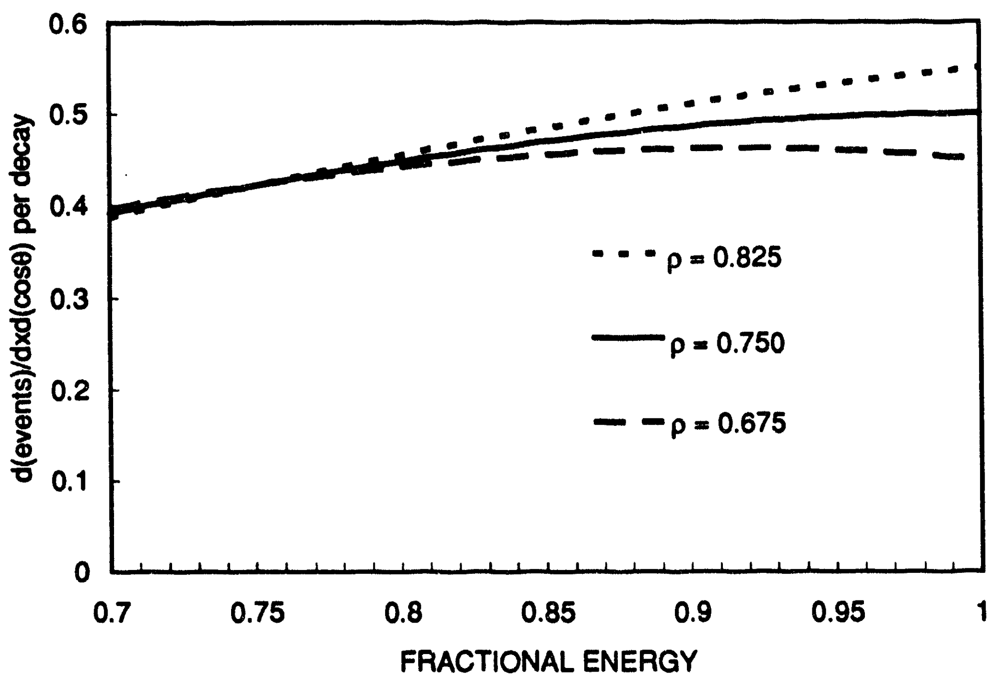
FIGURE CAPTIONS

1. Parameter space limits for the Minimal Left-Right Symmetric Model taken from Ref. 9. The present constraint on the mixing angle comes from Ref. 8; the limits implied by the statistical precision of this experiment are indicated by the dashed lines.
2. Theoretical Michel spectra of unpolarized muon decay with three ρ values for the fractional energy $x \geq 0.7$.
3. Schematic side view of the MEGA apparatus.
4. Reconstructed energy spectra for each of the three data configurations. There are about 2.5 million events in each plot, representing about 15% of the data.
5. (a) Energy spectrum of positrons from the decay tune data. (b) Monte Carlo spectrum with $\rho = 0.75$ for the experimental conditions of the decay tune data. (c) Monte Carlo spectrum for the same experimental conditions as (b), but using the derivative of the theoretical spectrum with respect to ρ.



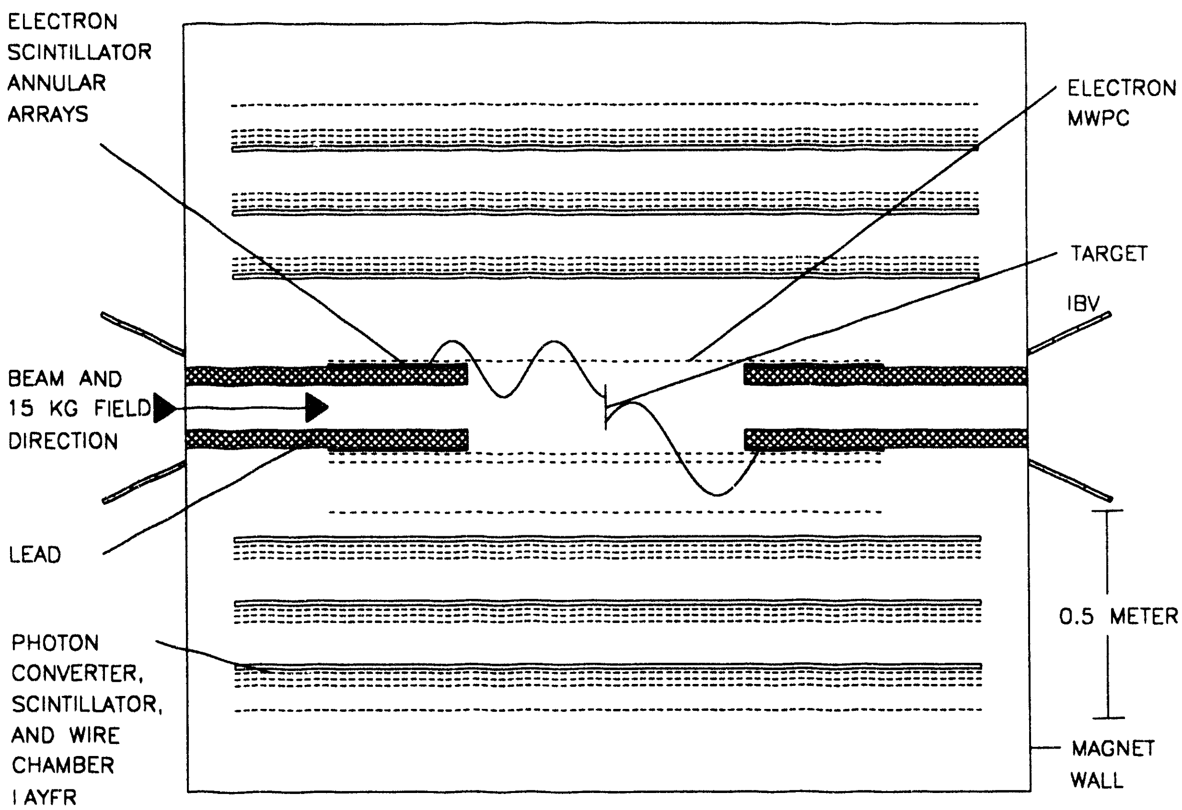
0.15
0.10
0.05
0
δm²
MICHEL ρ
GAMOW-TELLER
F/GT
F/GT
NEUTRON
FERMI
MICHEL ρ
Pμξ
Pμξδ/ρ
KM
−0.05
0
0.05
ζ

Fig 1.



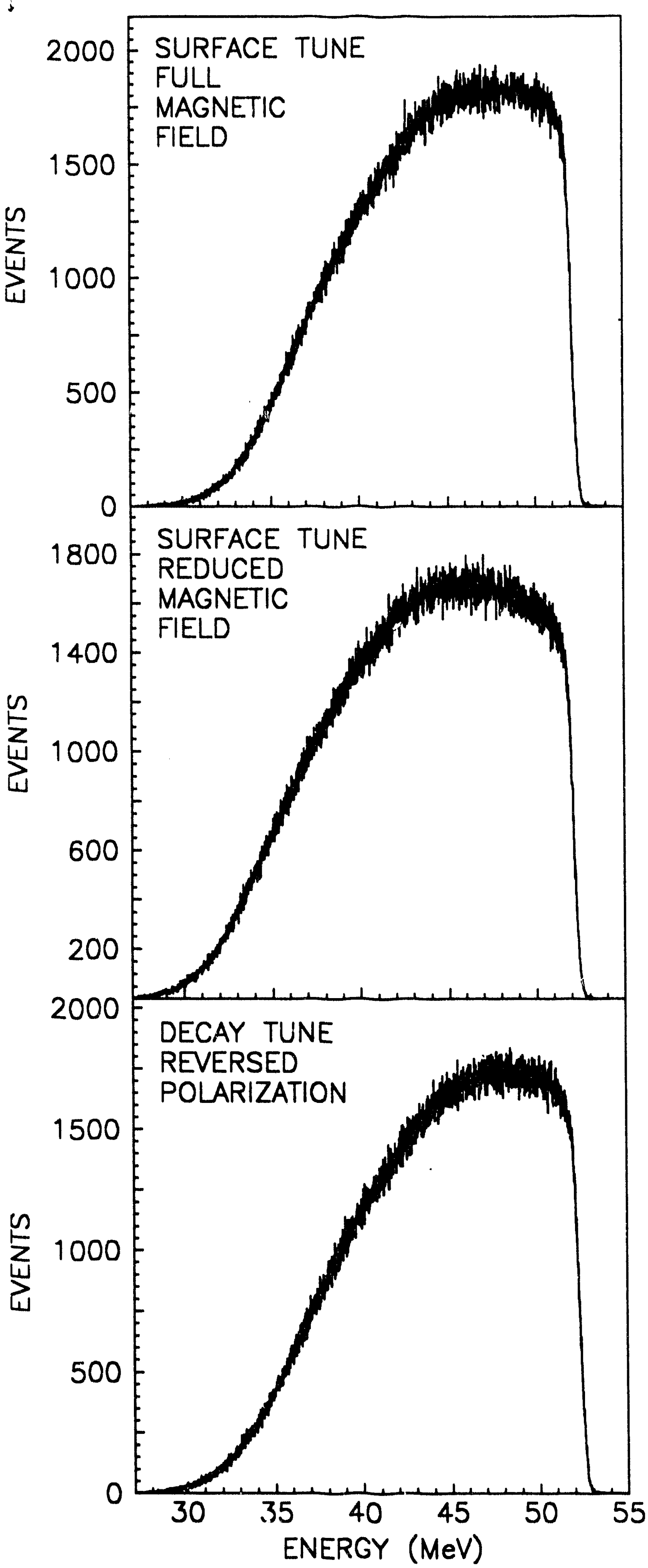
0.6
0.5
0.4
0.3
0.2
0.1
0
d(events)/dxd(cosθ) per decay
ρ = 0.825
ρ = 0.750
ρ = 0.675
0.7
0.75
0.8
0.85
0.9
0.95
1
FRACTIONAL ENERGY

Fig. 2

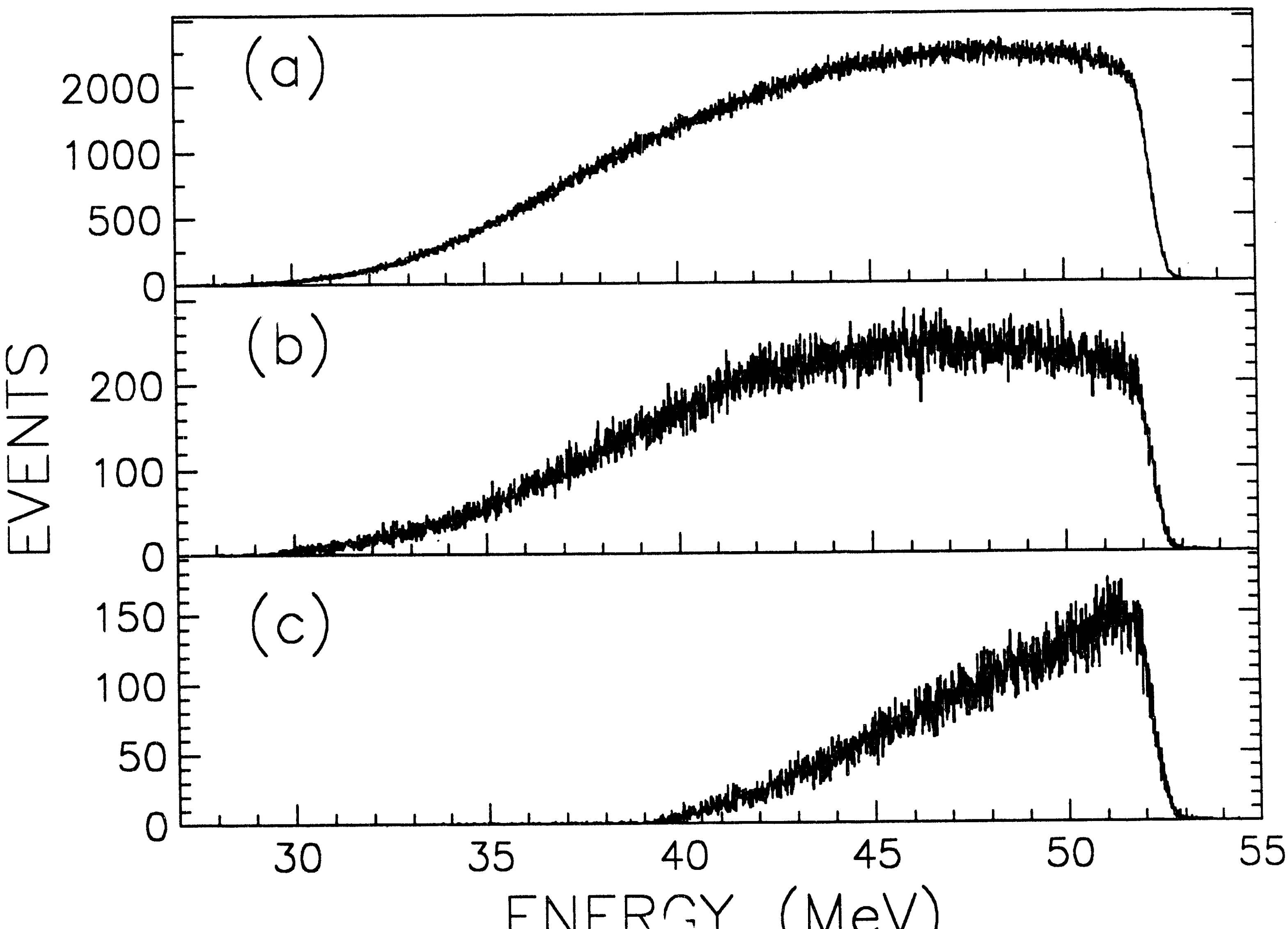


ELECTRON SCINTILLATOR ANNULAR ARRAYS
ELECTRON MWPC
TARGET
IBV
BEAM AND 15 KG FIELD DIRECTION
LEAD
0.5 METER
PHOTON CONVERTER, SCINTILLATOR, AND WIRE CHAMBER LAYER
MAGNET WALL

Fig. 3



SURFACE TUNE
FULL
MAGNETIC
FIELD
EVENTS
2000
1500
1000
500
0
SURFACE TUNE
REDUCED
MAGNETIC
FIELD
EVENTS
1800
1400
1000
600
200
DECAY TUNE
REVERSED
POLARIZATION
EVENTS
2000
1500
1000
500
0
30
35
40
45
50
55
ENERGY (MeV)



(a)
(b)
(c)
2000
1000
500
0
200
100
0
150
100
50
0
30
35
40
45
50
55
EVENTS
ENERGY (MeV)

DATE

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END