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Measurement of the Phase Difference Between η_{00} and η_{+-} to a Precision of 1°

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Abstract

We propose to add an additional regenerator to the E731 spectrometer in the MC beamline to enable us to measure the phase difference between the CP violation parameters η_{00} and η_{+-} to an accuracy of 1°. Very general considerations indicate that CPT conservation requires the phase difference, $\Delta\phi = Arg(\eta_{00}) - Arg(\eta_{+-})$, to be smaller than one degree. The current experimental value is $\Delta\phi = (9.4 \pm 5.1)^{\circ}$.

Introduction

CPT conservation requires the phase difference $\Delta\phi$ between η_{00} and η_{+-} to be at most a fraction of a degree.[1] The value listed by the Particle Data Group[2] is $(9.4 \pm 5.1)^{\circ}$. Based on our experience with E731, we believe we can measure $\Delta\phi$ to an accuracy of $\pm 1^{\circ}$ in a ten week run in the MC beam. The new experiment will use two closely spaced beams, one containing a 40cm thick carbon regenerator 57m from our lead glass array, and the other a 61cm thick carbon regenerator 14m further upstream. Information about the interference between K_L and regenerated K_S, and therefore about the phases of η_{00} and η_{+-}, can be obtained by comparing the decay rates into $\pi^0\pi^0$ and $\pi^+\pi^-$ downstream of the two regenerators.

Physics Motivation

The ratio of the amplitudes for K_L and K_S to decay into neutral pions is

$$\eta_{00} = \frac{Amp(K_L \rightarrow \pi^0\pi^0)}{Amp(K_S \rightarrow \pi^0\pi^0)};$$

η_{+-} is defined in similar fashion as

$$\eta_{+-} = \frac{Amp(K_L \to \pi^+\pi^-)}{Amp(K_S \to \pi^+\pi^-)}.$$

The kaon decay eigenstates K_L and K_S can be described as a mixture of the CP eigenstates K_1 and K_2: $|K_L >\sim |K_2 > +\epsilon|K_1 >$ while $|K_S >\sim |K_1 > +\epsilon|K_2 >$. Most, if not all, CP violation can be ascribed to the small CP impurity of K_L and K_S, indicated by the non-zero value of $\epsilon \approx 2.3 \times 10^{-3} e^{i44^\circ}$. An additional source may arise from the decay of the K_2, the CP -1 eigenstate, directly into two pions. Defining $A_2 \equiv Amp(K^0 \to 2\pi(I=2))$ and $A_0 \equiv Amp(K^0 \to 2\pi(I=0))$, this direct decay can only occur if

$$\epsilon' \equiv \frac{Im(A_2/A_0)}{\sqrt{2}} e^{i(90+\delta_2-\delta_0)^\circ}$$

is non-zero. δ_2 and δ_0 are the strong interaction phase shifts[3,4] due to final-state interactions of the I=2 and I=0 pion final states; $\delta_2 = (-7.2 \pm 1.3)^\circ$ while $\delta_0 = (46 \pm 5)^\circ$. Given δ_2 and δ_0, the phase of ϵ' is $(37 \pm 5)^\circ$, close to the phase of ϵ.

η_{00} and η_{+-} may be expressed in terms of ϵ and ϵ' as $\eta_{00} = \epsilon - 2\epsilon'$, $\eta_{+-} = \epsilon + \epsilon'$. E617 has measured[5] $|\eta_{00}/\eta_{+-}| = 1.014 \pm .017$, yielding a derived value for ϵ'/ϵ of -.0046 ± .0058. Given the size of ϵ'/ϵ and the similarities of the phases of ϵ and ϵ', the phase difference between η_{00} and η_{+-} should be less than a third of a degree. A larger value is forbidden unless CPT-violating amplitudes contribute to kaon decay.

Previous Measurements

The only measurement with a quoted error smaller than 18° came from an NYU group in 1979.[6] By studying K_L/K_S interference in the proper time spectrum of $\pi\pi$ decays between 4 and 11 K_S lifetimes downstream of a production target, the group measured a value for ϕ_{00}, the phase of η_{00}. Data taken at a different time with the same spectrometer yielded a value for ϕ_{+-}, the phase of η_{+-}. Significant acceptance corrections and background subtractions were applied to decay distributions to produce proper time distributions; the final results were $\phi_{00} = (55.7 \pm 5.8)^\circ$, $\phi_{+-} = (41.7 \pm 3.5)^\circ$, and $\Delta\phi = (12.6 \pm 6.2)^\circ$. The NYU experiment was performed in a single neutral beam at Brookhaven using kaons in the energy range 6-18 GeV. Since the experiment's fiducial decay volume was close to the production target, no regenerator was required to generate K_S.

K_S Regeneration

Far from a target, K_L/K_S interference may be effected through K_S regeneration. After passage through a block of material, an initially pure K_L beam becomes a mixture of K_L and K_S. The 2π decay rate[7] at a kaon proper time τ downstream of the regenerator is proportional to

$$|\rho|^2 e^{-\Gamma_S \tau} + |\eta|^2 e^{-\Gamma_L \tau} + 2|\rho\eta| e^{-(\Gamma_L + \Gamma_S)\tau/2} \cos(\Delta m \tau + \phi_\rho - \phi_\eta).$$

Γ_S, Γ_L are the K_S, K_L total decay rates, ρ is the K_S regeneration amplitude, and η is the ratio of the $K_L \to \pi\pi$ and $K_S \to \pi\pi$ decay amplitudes. Δm is the $K_L - K_S$ mass difference, ϕ_ρ is the phase of ρ, and ϕ_η is the phase of η. Γ_S is 1.12×10^{10} sec^{-1}, Γ_L is 1.93×10^{7} sec^{-1}, ϕ_ρ is typically -32° at Fermilab energies, and Δm is $30.6^\circ/10^{-10}$ sec. Values[8] for $|\rho|$ for different thickness carbon regenerators are shown in Figure 1. The last term in the above expression, the interference between K_L and K_S decay amplitudes, contains information about ϕ_{00} or ϕ_{+-}. Defining Γ_{+-} as the $K \to \pi^+\pi^-$ decay rate, Γ_{00} as the

$K \to \pi^0\pi^0$ decay rate, and $\Delta\phi$ as $\phi_{00} - \phi_{+-}$, one may write

$$\Gamma_{+-} \sim |\rho|^2 e^{-1.12\tau} + |\eta_{+-}|^2 + 2|\rho\eta_{+-}|e^{-.56\tau}\cos(30.6\tau - 76)^\circ$$

and

$$\Gamma_{00} \sim |\rho|^2 e^{-1.12\tau} + |\eta_{00}|^2 + 2|\rho\eta_{00}|e^{-.56\tau}\cos(30.6\tau - 76 - \Delta\phi)^\circ$$

when τ is in units of 10^{-10} seconds.The interference term in Γ_{00} is most sensitive to $\Delta\phi$ when the cosine's argument is near -90°, corresponding to $\tau \sim 0$. For $\tau \sim 2.5 \times 10^{-10}$ sec the argument of the cosine is near zero and the interference term in Γ_{00} is insensitive to small changes in $\Delta\phi$.

Experimental Considerations

If experimental acceptance and detection efficiency were known with sufficient accuracy, $\Delta\phi$ could be determined in a single beam experiment through a comparison of the proper time evolution of Γ_{00} and Γ_{+-}. The problems associated with reconstructing $\pi^0\pi^0$ final states are very different from those concerning $\pi^+\pi^-$ reconstruction, however. Resolution smearing, as well as loss of events at large τ due to merging of photon showers in the lead glass array, affect Γ_{00} more than Γ_{+-}.

To avoid these systematic problems we propose to measure Γ_{00} and Γ_{+-} using a double-beam technique similar to that employed by E731. One beam will pass through a thin regenerator at the start of the fiducial decay volume while the other beam will traverse a thick regenerator 14 meters further upstream. The separation is chosen to make the $\pi^0\pi^0$ decay rate inside the decay volume insensitive to $\Delta\phi$ for K_S from the upstream regenerator, and maximally sensitive to

$\Delta\phi$ for K_S from the downstream regenerator. Data will be recorded simultaneously for $\pi^0\pi^0$ decays in both beams; later $\pi^+\pi^-$ decays will be recorded. The regenerators will switch beams between machine pulses. The double ratio of decay rates, for a given value of kaon energy E and decay position z is

$$R \equiv \frac{\Gamma_{00}(up)}{\Gamma_{00}(down)} \bigg/ \frac{\Gamma_{+-}(up)}{\Gamma_{+-}(down)}.$$

"Up" and "down" refer to the beams containing regenerators in the upstream and downstream positions. Binned in E and z, R is insensitive to differences in $\pi^0\pi^0$ and $\pi^+\pi^-$ resolution, acceptance, and reconstruction efficiency. Figure 2 shows simulated decay distributions for $K \rightarrow \pi^0\pi^0$ events. Acceptance and resolution effects are modeled using the E731 spectrometer, but with the addition of a 61cm carbon regenerator in the " upstream" beam and a 40 cm regenerator in the "downstream" beam. Figure 3 shows $R-1$ vs. decay position, neglecting resolution effects, for an infinitely large $\pi\pi$ sample using various values of $\Delta\phi$. The deviation of R from unity is typically 1% per degree of phase difference between η_{00} and η_{+-}.

A one interaction length regenerator gives the largest amount of K_L/K_S interference, since ρ is proportional to regenerator length, while the fraction of beam surviving passage through the regenerator falls exponentially with length. Most of the coherent K_S flux in the "upstream" beam, proportional to ρ^2, will have decayed before reaching the decay volume. Consequently, the proper time distribution for decays in the upstream beam will fall roughly like $e^{-\Gamma_S\tau/2}$. A judicious choice for the thickness of the downstream regenerator will produce a decay distribution in this beam with about the same time dependence. By choosing regenerator lengths which give similar proper time spectra, the importance of systematic errors caused by resolution effects is reduced. A distribution which falls exponentially with decay position z will appear shifted towards larger z due to resolution smearing. Quantitatively, a z spectrum described by e^{-az} with z determined with resolution σ will misreconstruct as $e^{-a(z-a\sigma^2/2)}$. This misreconstruction grows worse with larger σ and with more steeply falling distributions. In the ratio $\Gamma(up)/\Gamma(down)$, the $e^{a^2\sigma^2/2}$ factors cancel if both decay spectra decrease with z at the same rate. Different rates of decrease for the "up" and "downstream" decay distributions would induce a resolution- dependent change in the ratio $\Gamma_{00}(up)/\Gamma_{00}(down)$. Since decay vertex resolution is much better for $\pi^+\pi^-$ than for $\pi^0\pi^0$ final states, this change would not be canceled by a similar shift in $\Gamma_{+-}(up)/\Gamma_{+-}(down)$. The optimum length for the downstream regenerator is about two-thirds of an interaction length. Figure 4 shows $R-1$, assuming a photon energy resolution of $(1+6/\sqrt{E})\%$. The smearing-induced spike at the left of the plot results from the lack of a sharp boundary in the upstream beam at the start of the decay volume.

Beam and Detector

The proposed detector is shown in Figure 5. It is similar to the E731 detector downstream of the regenerators. A one interaction length regenerator and mover assembly are placed 109.5 meters downstream of the MC production target. This far from the decay volume, the regenerator does not need to be in vacuum. Shielding and magnetic sweeping, however, will probably be necessary. A second regenerator, approximately two-thirds of an interaction length thick, is placed at z=123.5. Both regenerators will be instrumented with scintillator and will be required to move from beam to beam, or completely out of both beams. A lead sheet inside the vacuum tank which can be moved into the beams will serve as a calibration target to produce π^0's. A fixed thin scintillator just downstream of the lead sheet near z=123.5 meters will define the start of the decay volume in $\pi^+\pi^-$ mode, and aid in the generation of a calibration trigger when the lead sheet is in place. The movable absorber currently attenuating the beam hitting E731's regenerator will be used to reduce the beam flux striking the proposed experiment's downstream regenerator.

Running Time

Monte Carlo studies show that the $K \rightarrow 2\pi^0$ rate in the decay volume downstream of a 40 cm graphite regenerator shadowed by a 40 cm upstream absorber is 2.0 times greater than the $K_L \rightarrow 2\pi^0$ rate from an unobstructed beam. Neglecting deadtime, 1.5×10^{11} K_L in each beam during $\pi^0\pi^0$ data taking would provide a sample of 5×10^4 reconstructed decays from the beam containing the downstream regenerator and 3.5×10^4 from the other beam. 5×10^{10} K_L during $\pi^+\pi^-$ running would result in a considerably larger sample, yielding an accuracy of 1° in $\Delta\phi$. We expect to run E731 at an incident intensity of $10^7 K_L$ per pulse of 3×10^{12} protons on target. At this intensity, the proposed experiment would require about 250 hours of beam. E731 recorded roughly $10^4 K_L \rightarrow 2\pi^0$ running 1×10^{12} protons per spill during the closing weeks of its first run; the same exposure would allow the proposed experiment to measure $\Delta\phi$ to an accuracy of 1.6°. Improvements to the E731 data acquisition and trigger systems will allow the new experiment to run at an intensity of 3×10^{12} protons per spill with minimal deadtime.

Additional beam time for initial set up, and periodic calibration runs will be required.

Calibration, Systematic Effects, and Backgrounds

It is important that there be no systematic offset between decay positions or kaon energies determined using the drift chamber spectrometer for $\pi^+\pi^-$ decays and the lead glass array for $\pi^0\pi^0$ decays. A 1% shift in E, corresponding to a 50 cm. shift in $\pi\pi$ decay vertices would induce an error of $\sim 1^\circ$ in $\Delta\phi$.

A natural tool for monitoring spectrometer calibration during data taking is $K_L \to \pi^+\pi^-\pi^0$ decay. The positions and energies at the lead glass of the photons from the π^0 uniquely determine the distance between the π^0 decay vertex and the glass array. When proper glass and chamber calibration are maintained, no systematic difference between the π^0 decay point and the tracks' crossing point will be evident, and the reconstructed K_L mass will be correct. A prescaled $\pi^+\pi^-\pi^0$ trigger recorded during all data taking should provide a large sample useful for calibration. Straight-through muons, $K_L \to 3\pi^0$ decays, and the existing E731 calibration flasher will provide additional checks of lead glass performance. During special calibration runs, electrons produced upstream can be pitched vertically in a sweeping magnet near z=120 meters, bent horizontally in the separator magnet, and then momentum analyzed in the drift chamber spectrometer. π^0's produced when the calibration target is inserted into the beams also will provide a check of performance of the lead glass array.

Backgrounds under $K \to 2\pi^0$ mass peaks from misidentified $K_L \to 3\pi^0$ decays are expected to be less than 1% for either beam. Another source of background arises from inelastic K_S regeneration. The E731 regenerator is instrumented with four planes of scintillator to tag inelastic events; the level of inelastic contamination in the coherently regenerated K_S sample is less than 2% and is currently well understood. The new regenerators will also be instrumented to permit rejection of incoherently regenerated K_S. As a result, it will be possible to determine the level of background from inelastic regeneration with sufficient accuracy to avoid biasing the value of $\Delta\phi$.

Equipment and Schedule

New hardware, not already in use in E731, consists of an upstream regenerator and sweeping magnet, a movable lead calibration target near the downstream regenerator, and a small amount of new scintillator. We would rely on Fermilab's assistance in carrying out the beamline modifications required to install the new regenerator and calibration target. Upon approval, we would expect to begin the construction of new hardware. Tests of prototypes will be possible during the second E731 run in 1987; the phase experiment will be able to take data during the first fixed target run following the Spring, 1987 run.The beam time we will need to measure $\Delta\phi$ to 1° is listed below.

Task	**Duration**	**Beam requirements**
Initial tuneup	4 weeks	Usually low intensity, some high intensity rate studies
Initial calibration	1 day	Low intensity
Charged mode	5 weeks	3×10^{12} protons/spill
Neutral mode		
Calibration		
Special runs (eg $K_{\mu 3}$)	1 week	High and low intensity

Conclusions

The proposed experiment, an outgrowth of our experience with E731, should be able to measure the phase difference $\Delta\phi$ between η_{00} and η_{+-} to an accuracy of 1°. Appropriate choice of regenerator thickness and placement eliminates most of the sources of systematic error unavoidable in single beam experiments, or in double beam experiments using one regenerator.

The current world average for $\Delta\phi$ is two standard deviations away from the limit imposed by CPT invariance. A more precise measurement in agreement with the central value of the previous result would have major consequences.

References

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Figure Captions

1. Regeneration amplitude vs. energy for different length graphite regenerators. We plan to use a 61 cm regenerator in the "upstream" beam and a 40 cm regenerator in the "downstream" beam. The value of η_{+-} is shown for comparison.

2. Simulated decay position spectra of $K \rightarrow \pi^0\pi^0$ in the "upstream" and "downstream" beams. The regenerators are at $z = 109.5$ meters and z=123.5 meters. The decay volume ends at $z = 137.5$ meters; the lead glass array is at $z = 180$ meters. Acceptance is modeled using the E731 spectrometer and assuming photon energy resolution is $(1 + 6/\sqrt{E})\%$. A 250 hour run will yield 5×10^4 reconstructed events in the "downstream" beam and 3.5×10^4 events in the "upstream" beam. Statistical errors are not included in the curves.

3. $R - 1$ for various kaon energies and several values of the phase difference $\Delta\phi$ between η_{00} and η_{+-}. R is the double ratio of the decay rates in the two beams for $\pi^0\pi^0$ and $\pi^+\pi^-$ final states. Resolution effects are not included; individual curves are labeled with values of $\Delta\phi$, expressed in degrees. Statistical errors are not included.

4. $R - 1$ for various kaon energies and several values of the phase difference $\Delta\phi$ between η_{00} and η_{+-}. Unlike Figure 3, resolution effects are included in the decay spectra. Photon energy is taken to be $(1 + 6/\sqrt{E})\%$. Resolution smearing of $\pi^0\pi^0$ decays into the region upstream of the decay volume causes the narrow spike near z=123.5 meters, the position of the downstream regenerator. Statistical errors are not included.

5. Elevation view of the proposed spectrometer.

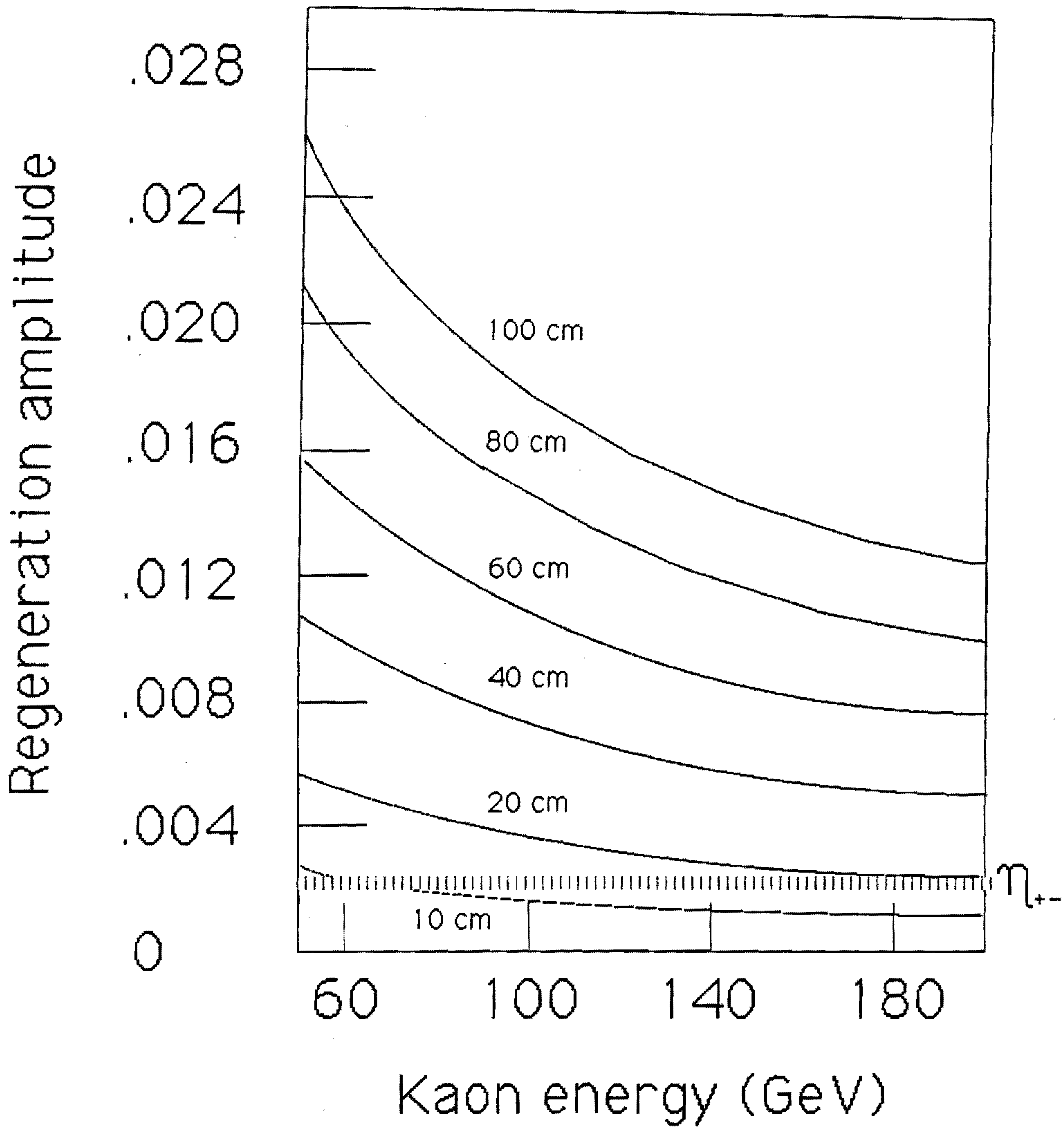

Figure 1. Regeneration amplitude vs. energy for different length graphite regenerators.

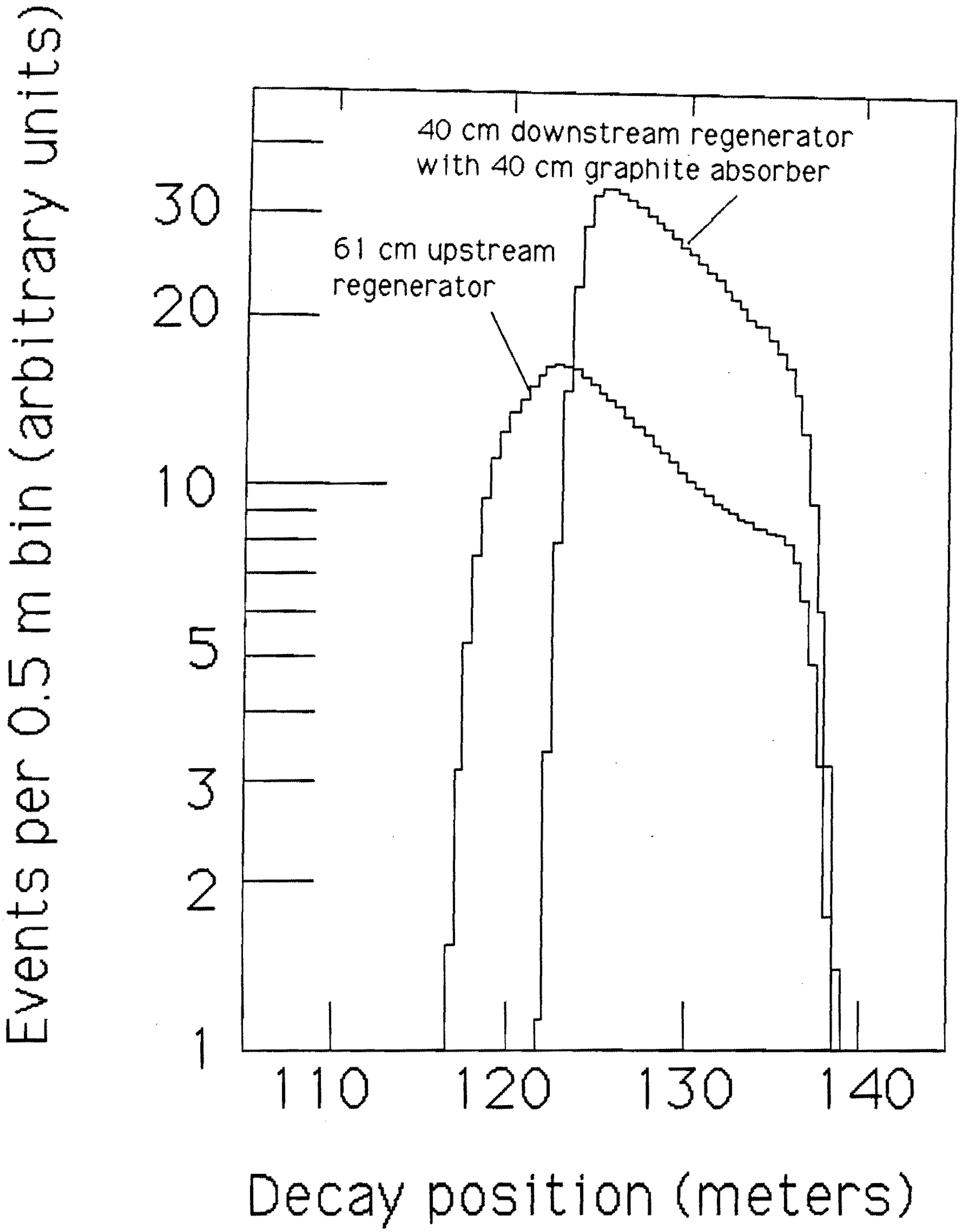

Figure 2. Decay rate vs. position for $K \rightarrow \pi^0\pi^0$ decays; upstream regenerator is at z=109.5 meters. Downstream regenerator is at z=123.5 meters, lead glass is at z=180. meters. Decay volume ends at z=137.5 meters.

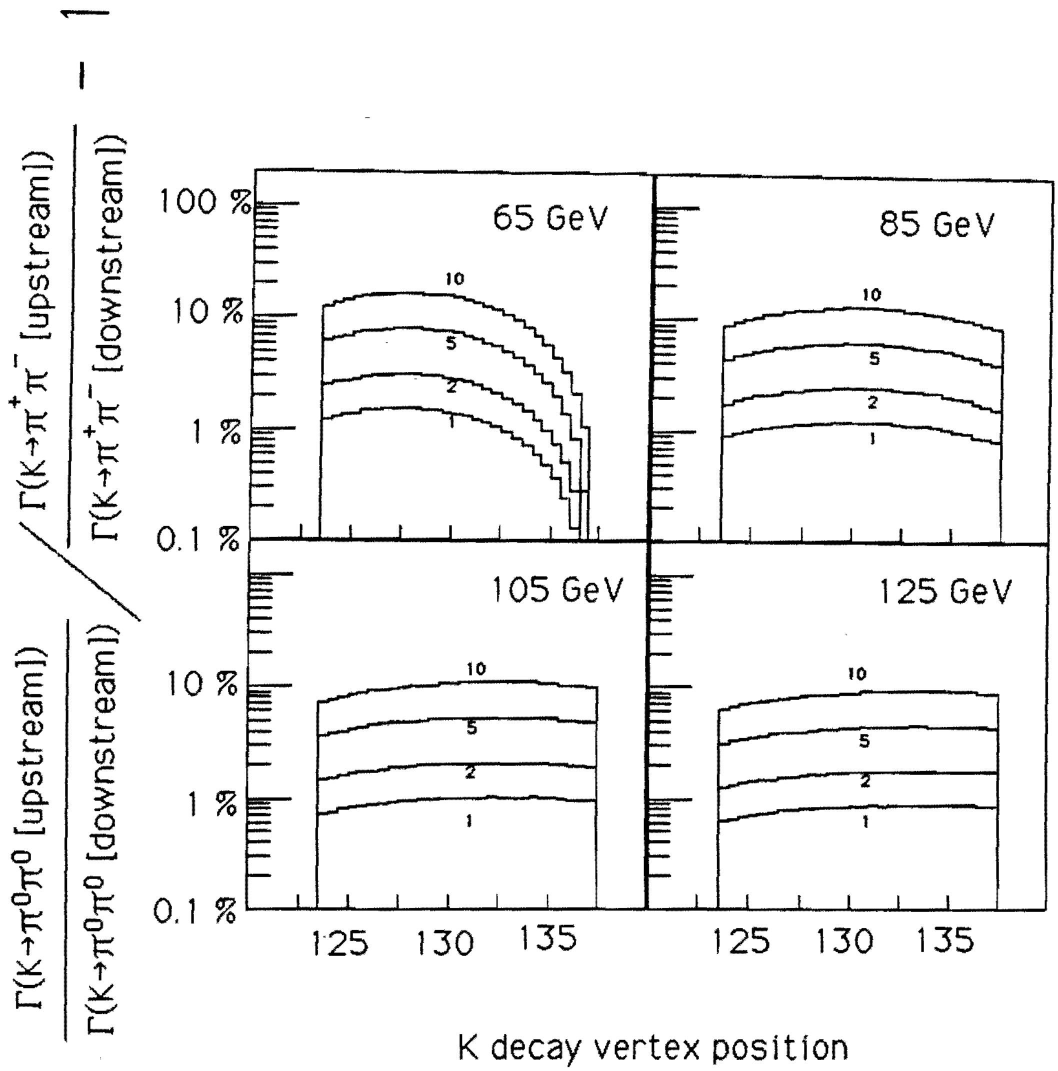

Figure 3.

$$\frac{\Gamma(K\to\pi^0\pi^0\ [\text{upstream}])}{\Gamma(K\to\pi^0\pi^0\ [\text{downstream}])}\Bigg/\frac{\Gamma(K\to\pi^+\pi^-\ [\text{upstream}])}{\Gamma(K\to\pi^+\pi^-\ [\text{downstream}])} - 1$$

vs. decay position for several different kaon energies and several different values of $\Delta\varphi \equiv \varphi_{00} - \varphi_{+-}$. Curves are labeled with values of $\Delta\varphi$, expressed in degrees. Energy resolution is not included.

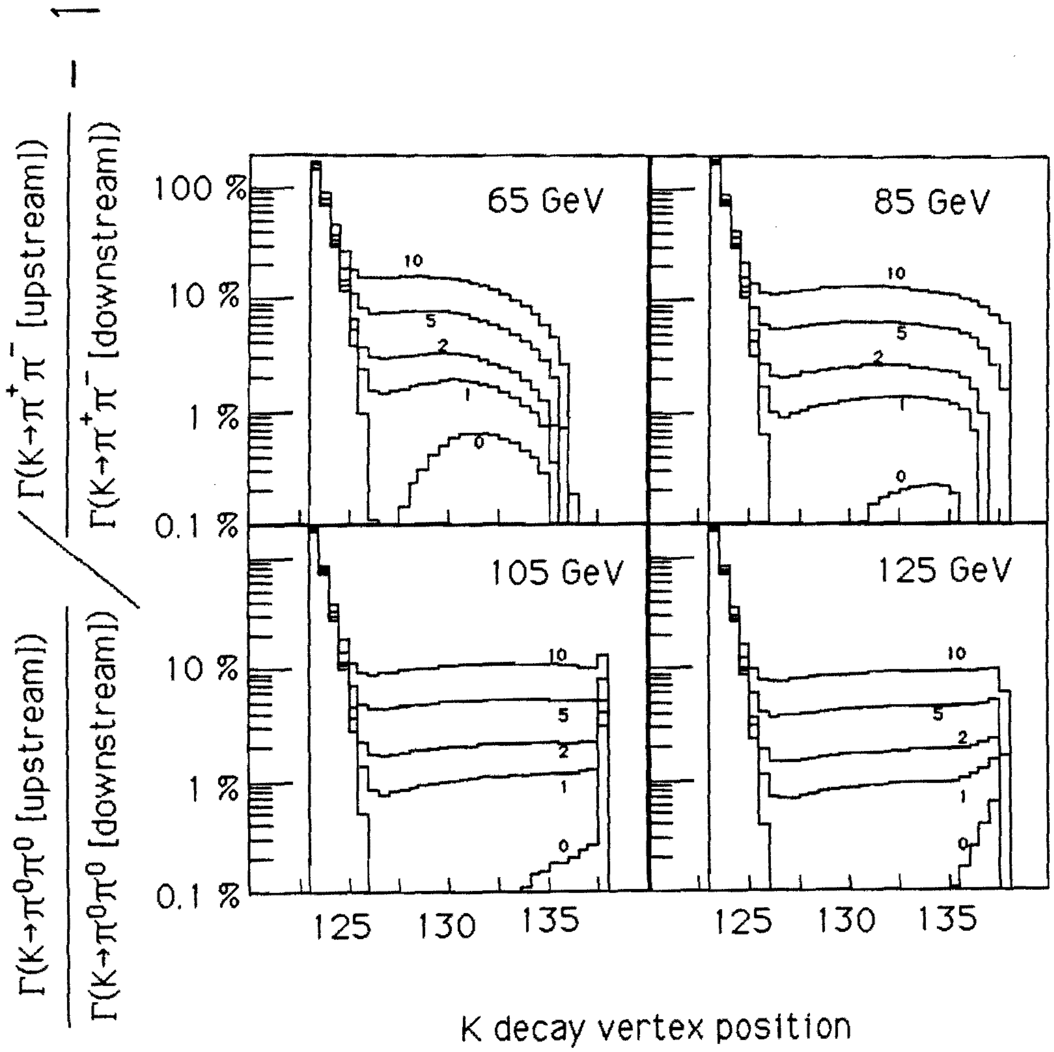

Figure 4.

$$\frac{\Gamma(K\to\pi^0\pi^0\ \text{[upstream]})}{\Gamma(K\to\pi^0\pi^0\ \text{[downstream]})} \Bigg/ \frac{\Gamma(K\to\pi^+\pi^-\ \text{[upstream]})}{\Gamma(K\to\pi^+\pi^-\ \text{[downstream]})} - 1$$

vs. decay position for several different kaon energies and several different values of $\Delta\varphi \equiv \varphi_{00} - \varphi_{+-}$. Curves are labeled with values of $\Delta\varphi$, expressed in degrees. Energy resolution is $(1+6/\sqrt{E})$%.

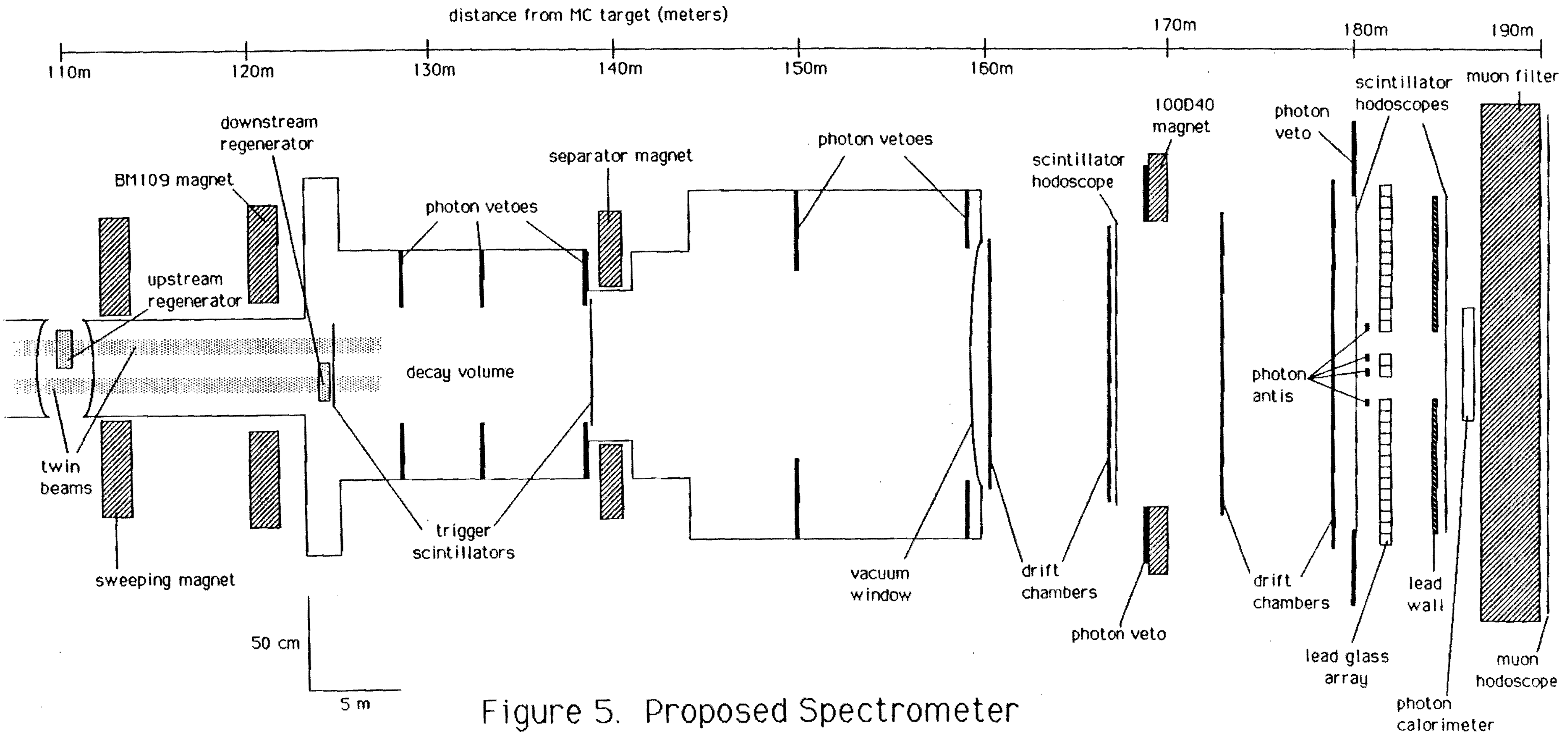

Figure 5. Proposed Spectrometer