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A PRECISE COMPARISON OF π^+ AND π^- LIFETIMES*

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A second and more precise experiment has been performed at the Lawrence Radiation Laboratory's 184-inch cyclotron to look for any difference in the total lifetimes of π^+ and its antiparticle, π^-. Any observed difference would be direct evidence for a violation of CPT invariance in the weak decay of the charged pion. We find $\tau_+/\tau_- = 1.00064 \pm 0.00069$, and thus no evidence for a CPT violation.

The existence of a CP-violating decay of the neutral kaon requires that either T or CPT be violated in that weak interaction. Despite numerous attempts, no evidence has been found for T noninvariance in other systems. Thus it becomes increasingly relevant to look for other weak interactions that might not be invariant under CPT. To do this one can make use of the fact that CPT invariance is a sufficient, but not necessary, condition for the equality of the lifetimes of a particle and its antiparticle. Because any such lifetime difference is expected, on the basis of the magnitude of the CP violation, to be very small, we have compared to high precision the π^+ and π^- total lifetimes.

The method employed was an improved version of that used in an earlier, less precise measurement,[1] which was also performed at the Lawrence Radiation Laboratory's 184-inch cyclotron. The most significant improvements in the present experiment were a 100-fold increase in the beam rate and the use of liquid deuterium (instead of liquid hydrogen) as the radiating medium in the movable differential Cerenkov counter, which detected pions along the decay path. The equipment for this experiment was completely redesigned to eliminate many of the difficulties encountered in the earlier one.

Figure 1 shows the experimental setup and describes the beam. Beam particles, defined by counters M_1, M_2, M_3, M_4, and anti-counter A_1, were brought to a dispersionless image at M_4. Electrons were rejected by the 3-atm CO_2 threshold Cerenkov counter AE. Positive identification of pions was achieved by the differential Cerenkov counter CM (similar to the counter shown in Fig. 2),[2] which could be filled with either liquid hydrogen or liquid deuterium. Since the Cerenkov counter has a momentum acceptance five times as large as the $\pm 0.5\%$ beam momentum spread, the counter efficiency was independent of the pion momentum. The counter was equipped with an anticoincidence ring, CMA, to improve the rejection of unwanted particles. To eliminate scattering, the beam was in vacuum after M_4, while further definition of beam size was provided by the round holes in the anti-counters A_2 to A_6. Particles accompanied by coincident pulses in M_1, M_2, M_3, M_4, and CM and no signal in any of the anti-counters were scaled as the intensity monitor, M. This monitor coincidence contained less than 0.01% electrons, 0.04% muons, and no protons (protons being stopped by the radiator in CM).

The experiment was performed by measuring the number of surviving pions at each of seven positions along the 35-ft decay path, using the movable Cerenkov counter CP (Fig. 2). The coincidence $MCP\overline{CPA} \equiv D$ indicated the arrival of a pion at CP, so the fraction of surviving pions was given by the ratio of the D coincidences to the M coincidences, D/M. The beam polarity was alternated between π^+ and π^- many times at each position, and the ratio $(D/M)_-/(D/M)_+$ was determined for each π^+-π^- group. This ratio would be the same for all CP positions unless the lifetimes were different.

An important aid in elimination of systematic errors was use of pulse-height analysis to observe the distribution of pulses from CP (Fig. 3). In an ideal counter, all the pulses from pions should be above some minimum height so that definition of a pion by the CP discriminator would be unambiguous. Because of the interactions of pions in the deuterium, however (our momentum being near the peak of the 3/2 -3/2 πp resonance), some pions ceased to make Cerenkov light at the correct angle after penetrating only a short distance into CP. This effect produced a continuous distribution of small pulses, and made the efficiency dependent on such factors as CP discrimination level, drifts in tube gain, and variation of light-collection efficiency across the face of the counter. If the pulse-height distributions are the same for π^+ and π^-, however, measurement of the lifetime ratio is not affected by such troubles, provided only that the π^+ and π^- beams are sufficiently alike spatially, and that the time variations of efficiency are slow relative to the period of polarity reversals during data taking. This is true because measurement of the lifetime ratio requires only that the ratio of π^+ efficiency to π^- efficiency be constant during the data taking.[1] When liquid deuterium was the radiating medium, we found that the pulse-height distributions for π^+ and π^- were indistinguishable because of charge independence. However, the distributions were remarkably different when liquid hydrogen was used (Fig. 3), since the nuclear cross section for π^+p is three times that for π^-p.

Most of our running time was spent investigating, measuring, and eliminating a number of systematic errors, as discussed briefly below.

1. Possible π^+ - π^- Momentum Difference

Great care was taken in reversing magnets to insure that the π^+ and π^- beams were identical in every respect. Magnetic shielding reduced the non-reversing cyclotron fringe field to less than 0.2 gauss along the beam line, and nuclear magnetic resonance was used to monitor the central fields of the two bending magnets. Moreover any difference between π^+ and π^- momenta would have been detected by a very sensitive method peculiar to our apparatus. This involved measuring the CP efficiency as a function of momentum. The resulting momentum-response curve had a short flat-top near the central momentum and fell off sharply (30% drop in efficiency for 1% momentum change) at higher and lower momenta. By comparing the steeply sloping sides of the π^+ and π^- response curves, we could have detected a momentum difference as small as 0.03%, but found no difference.

Several weeks at the end of the running were spent making a time-of-flight measurement of the pion velocity in order to determine the absolute lifetime precisely. These measurements also showed any difference in the momenta of the π^+ and π^- beams to be less than 0.02%.

2. Systematic Changes in CP Efficiency With Distance

One such effect involved the fact that as CP was moved downstream, cable delay had to be removed from the CP phototube signals in order to maintain proper timing in the D = MCP$\overline{\text{CPA}}$ coincidence. At first this variable delay was placed before the discriminator, thus providing an attenuation of the photomultiplier pulses which decreased as the counter was moved farther downstream. Since the pulse-height distribution was less than ideal, this gave rise to an increase in efficiency with distance downstream. Furthermore, when the radiating medium was liquid hydrogen the difference in the π^+p and π^-p cross sections makes the effect three times as large on π^+ as on π^-. This effect was responsible for the apparent lifetime difference and the anomalously long π^+ lifetime reported in Ref. 1. In the experiment reported here this difficulty was overcome by placing the variable delay after the discriminator, and by using liquid deuterium as a radiating medium.

The second (much smaller) effect was due to a rate-dependent gain in the CP phototube, which caused a gradual decrease in the amplitude of the CP pulses as the counter was moved downstream. Again, with liquid hydrogen as the radiating medium, the change in the π^+ efficiency was greater than for π^-, making the π^- appear to have a longer lifetime. This effect was of no consequence when liquid deuterium was used in the counter.

3. Spatial Nonuniformity of Response in CP

Since the beam size changed along the decay path, it was important that the CP efficiency be constant over its entrance aperture. In fact, we detected a roughly linear variation in efficiency of as much as 0.2%/inch as CP was moved laterally across the beam. Also, the remaining cyclotron fringe field caused a 0.15-in. separation of the π^+ and π^- beams at the end of the decay path. Coupled with the lateral nonuniformity of response, this effect could cause an apparent lifetime difference as large as 0.03% for some runs (depending on the phototube in use at the time), and appropriate corrections have been applied.

4. CP Efficiency for Counting Particles That Were Not Pions

Muons and electrons were counted in CP with efficiencies of about 1% and 7% respectively, due to scattering of the wide-angle Cerenkov light. Since CM defined beam pions, the only muons or electrons which could make a D coincidence were pion decay products, and only a small fraction of these had suitable directions through CP. The very small number of decay products counted, resulting from this product of geometric and counter efficiencies, were plus-minus symmetric and could not contribute to a lifetime difference.

5. Errors Inherent in CP

In order to check on any systematic errors inherent in the complicated movable Cerenkov counter, we replaced CP during part of the running with a movable pion detector which selected pions by their strong interactions rather than by their velocity. The device consisted of an 8-in.-square scintillation counter to identify all particles entering a 2.8-in.-thick aluminum block, and a 14-in.-square counter to veto those particles which emerged. About 20% of the beam pions stopped in the aluminum, while electrons and muons continued on through and were vetoed. Unfortunately the device exhibited small edge effects, making the veto counter most effective near the middle of the decay path where the beam was smallest. Although this shortcoming made it unsuitable for an absolute lifetime determination, the ratio of π^+ to π^- efficiencies was constant along the decay path, and the lifetime difference measurement was valid. The result of this measurement was $\tau_+/\tau_- = 1.0006 \pm 0.0011$, where the uncertainty is purely statistical.

6. Errors Due to CM

The pion monitor was checked by measuring the lifetime difference with CM moved out of the beam, to test whether the absorption and scattering of pions in the liquid deuterium in CM was biasing the result. We obtained $\tau_+/\tau_- = 0.99961 \pm 0.00071$ (uncertainty purely statistical).

Having discussed the major sources of systematic error, we turn now to the final data selection. Six data runs were made, each using CM for more positive identification of pions, and each giving a statistical uncertainty of about 0.1%. During this data taking the proton beam intensity was adjusted to give equal π^+ and π^- rates within 10%. The order of CP positions was random and each position was repeated several times. For each run, the quantities $\ell n[(D/M)_-/(D/M)_+]$ obtained at various distances x were fitted by the method of least squares to a straight line A + Bx. The slope B is directly proportional to the lifetime difference and the χ^2 distribution for the fit gives a measure of reliability.[1]

Three of the runs were taken with liquid hydrogen in CM and CP and were not useful for the lifetime comparison because of the coupling of the rate effect with the difference in the π^+ and π^- interactions in hydrogen (see 2 above). The other three runs were made with liquid deuterium in CM and CP and had no important systematic errors. They included a total of 228 magnet reversals, giving the same number of π^+-π^- groups. Each run had a χ^2 per degree of freedom of about 1.1, and none of them indicated a lifetime difference.

The final weighted average from the three liquid deuterium runs is

$$\tau_+/\tau_- = 1.00064 \pm 0.00069.$$

This result has been corrected for the effects of the π^+-π^- beam separation discussed above. The quoted standard deviation is due to statistical error (0.059%), to uncertainties in the equality of the π^+ and π^- momenta (0.030%), and in the π^+-π^- beam separation correction (0.020%).

Our result agrees with other recent determinations, but has a considerable reduction in the error. The most accurate recent measurements of τ_+/τ_- are:

Columbia,[3]	1.004 ± 0.007;
Rochester-Brookhaven,[4]	1.0040 ± 0.0018 or 1.0023 ± 0.0040;
LRL-UCSB,[1]	1.0056 ± 0.0028;
LRL-UCSB, present result,	1.00064 ± 0.00069.

Due to the small π^-p nuclear cross section, the CP efficiency was very constant for much of the π^- data with hydrogen, and it should be possible to obtain a precise measurement of the π^- absolute lifetime. This measurement depends on determining the pion momentum accurately. This analysis is not yet complete, but preliminary results give the π^- lifetime as $\tau_- = 26.0 \pm 0.1$ nsec. We intend to publish later a more complete account of the experiment and analysis, including a final value for the absolute lifetime.

We thank James Vale and the cyclotron staff for help with the setup of our beam and counters, and for trouble-free cyclotron operation; Dr. R. J. Kurz for his many suggestions in the early stages of design; and Professors A. C. Helmholz and B. J. Moyer for support and encouragement. We also thank all those who helped with the liquid deuterium Cerenkov counters, particularly E. F. McLaughlin and R. V. Schafer for the cryogenic design and aid in making the counters function properly, A. H. Kleid for the flask assembly, and R. Bollaert and the Hydrogen Target Group for assistance with assembly and cryogenic operation.

Footnotes and References

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†On leave from Physics Department, Tufts University, Medford, Mass.

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Figure Captions

Fig. 1. Beam layout. 285-MeV/c pions produced at the beryllium target by the proton beam (EPB) were momentum analyzed and focused at the 2-in.-thick Pb collimator, where $\Delta p/p$ was defined as $\pm 0.5\%$. The second H

magnet produced a dispersion match at M_4. Nuclear magnetic resonance (NMR) probes in the two H magnets insured long-term stability and equality of the central fields on π^+ and π^- to 0.005%. M_1, M_2, M_3, M_4 were 1/16-in.-thick scintillation counters, A_1 to A_6 were scintillation anticoincidence counters, 8 in. square, with the beam passing through a central hole. AE was a 36-in.-long 3-atm CO_2 threshold Cerenkov counter to veto electrons; CM and CP were focusing differential liquid deuterium Cerenkov counters with 4-in. and 7-in. diameters, respectively. The beam was under vacuum except in the vicinity of the M counters and AE; in particular there was continuous vacuum between M_4 and CP.

Fig. 2. Movable LD_2 Cerenkov counter (CP). Light from 285-MeV/c pions produced a ring image at the ring aperture viewed by the CP central phototube. Decay muons and other particles with the wrong velocity produced little light in the ring aperture, and in addition were vetoed by the anticoincidence ring CPA. Typically, CPA vetoed less than 1% of the particles counted by CP. The LH_2 shield surrounding the quartz lenses cryopumped impurities onto itself and kept the flask quartz window free of condensation. In order to keep the index of refraction constant, the temperature of the LD_2 in the flask was monitored by platinum resistance thermometers and kept constant to ± 0.02°K. This corresponded to a change in Cerenkov angle of ± 0.02 deg, which is to be compared with the aperture width of ± 3 deg.

Fig. 3. Typical pulse-height distributions from CP. A is the distribution obtained with liquid deuterium as the radiating medium and is identical for π^+ and π^-. B and C were obtained with liquid hydrogen in the counter for π^+ and π^- respectively.

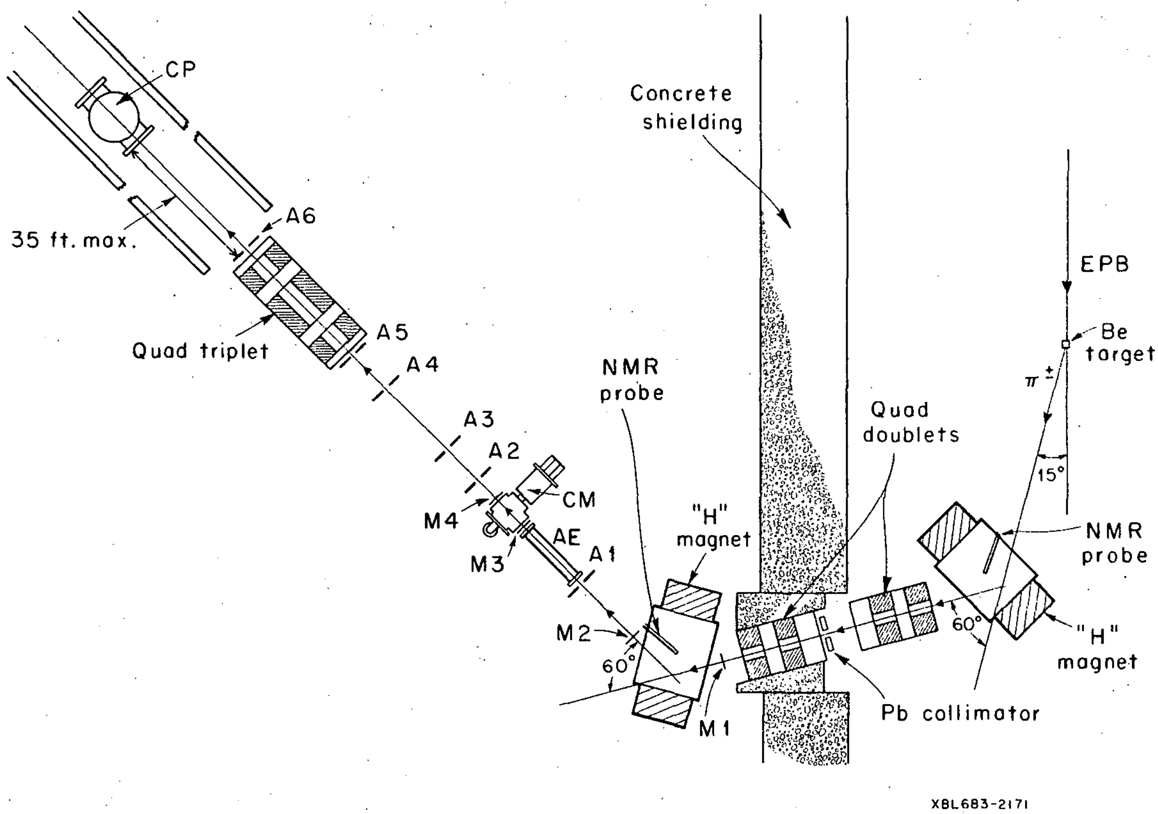
CP
35 ft. max.
A6
Quad triplet
A5
A4
A3
A2
CM
M4
AE
M3
A1
M2
60°
NMR
probe
"H"
magnet
M1
Concrete
shielding
Quad
doublets
Pb collimator
EPB
Be
target
$\pi^{\pm}$
15°
NMR
probe
60°
"H"
magnet
XBL683-2171

Fig. 1

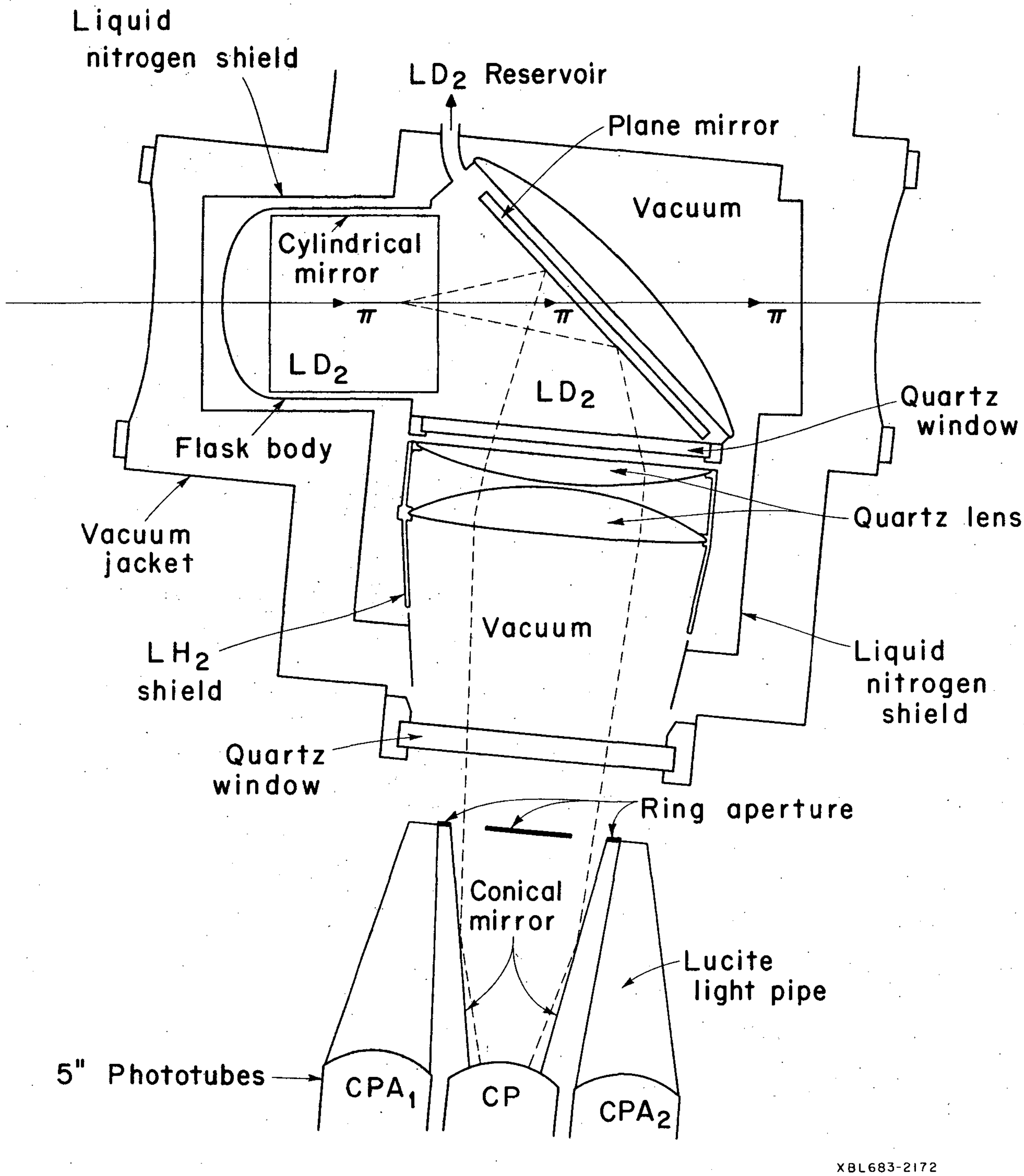
Liquid nitrogen shield
LD2 Reservoir
Plane mirror
Vacuum
Cylindrical mirror
π
LD2
Flask body
Vacuum jacket
Quartz window
Quartz lens
LH2 shield
Liquid nitrogen shield
Quartz window
Ring aperture
Conical mirror
Lucite light pipe
5" Phototubes
CPA1
CP
CPA2
XBL683-2172

Fig. 2

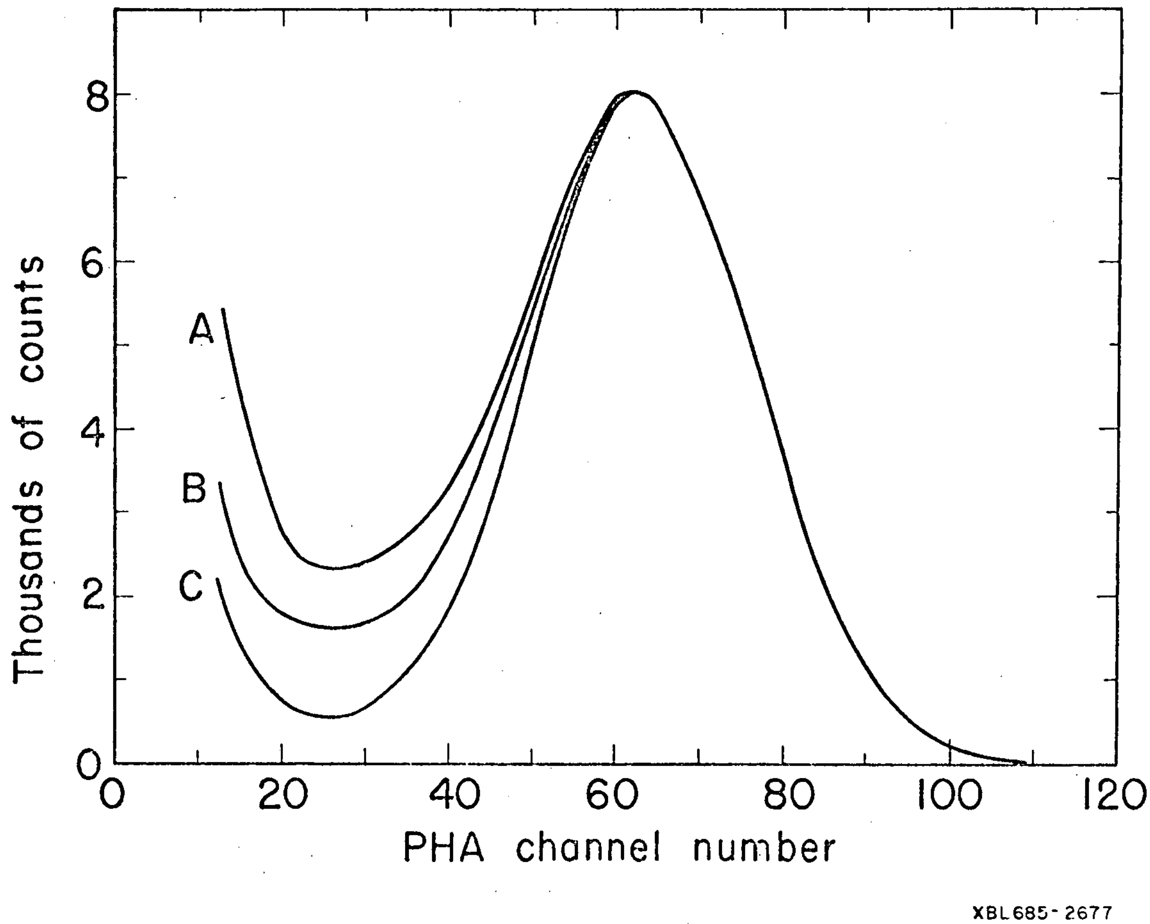
8
6
4
2
0
A
B
C
Thousands of counts
0
20
40
60
80
100
120
PHA channel number
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Fig. 3