Search for the C-Noninvariant Decay $\pi^0 \to 3\gamma$

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A search for the three-photon decay of the neutral pion has been conducted using fast counter techniques. Such a decay would indicate a violation of charge-conjugation invariance. No excess of signal over background was observed, providing an upper limit to the branching ratio of 1.5×10^{-6} at 90% confidence level.

The decay of the π^0 meson into three photons is forbidden only by invariance of the interaction under charge conjugation. A search for this decay consitiues a check on the fundamental principle of C incariance in the electromagnetic interaction of strongly interacting particles.[1,2] The two most sensitive searches[3,4] for this decay have both set upper limits to the branching ratio of 5×10^{-6} (90% confidence level). Unfortunately the expected extra factor of α and the phase-space ratio ($\frac{1}{315}$) predict a maximum branching ratio of 23×10^{-6}. Thus current experiments only begin to test C invariance in this fundamental reaction.

We report here the first results of a new search for the decay $\pi^0 \to 3\gamma$. Neutral pions were produced by π^- charge exchange on protons in the stopping pion beam (LEP) at the Clinton P. Anderson Meson Physics Facility. The apparatus is shown schematically in Figs. 1 and 2. The 70-MeV pion beam was defined by a counter telescope and brought to rest in a liquid hydrogen target. The position of a remotely adjustable graphite degrader was optimized by observing the yield of $\pi^0 \to 2\gamma$ decays. The 7.5-cm-diam target cup was surrounded by a cylindrical veto counter 6.4 mm thick; the end of the cylinder

was capped by a disk of scintillator. The cylindrical walls of the target vacuum jacket were 1.8-mm-thick aluminum. The telescope included a Lucite threshold Cherenkov counter to help identify the 30% of the beam particles which were electrons. Electrons turned out not to contribute to the trigger and so the information from the counter finally proved unnecessary.

The γ detector was an octagonal array of lead-glass Cherenkov counters (C) and anticoincidence counters (A) surrounding the target in the plane perpendicular to the beam. Each C counter consisted of type-F2 lead glass 31.2 cm wide $\times$15.6 cm high $\times$25.6 cm deep, viewed by two Amperex 58-DVP phototubes. The front face of each counter was 61 cm from the target center. At this distance a single 2γ decay cannot register in a pair of noncollinear counters despite the effects of target and counter size and the minimum π^0 opening angle of 157° caused by the π^0 recoil. The effective distance to the detector for the solid-angle calculation is the distance to the face
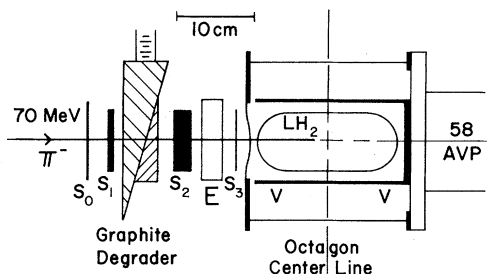

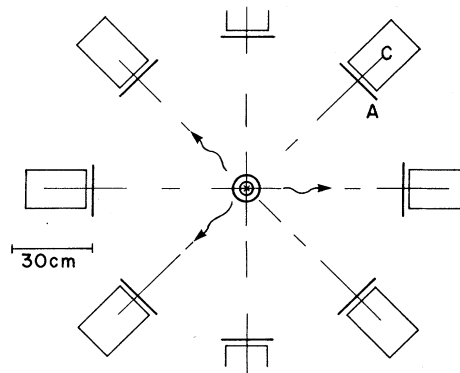FIG. 1. Plan view of the beam telescope and liquid hydrogen target.

FIG. 2. Front view of the array of γ-ray detectors. At the center is the hydrogen target, on which the pion beam is incident normal to the page. The beam telescope is omitted for clarity.

plus the photon mean free path (5.8 cm). A signal from either phototube equivalent to an energy of 10 MeV was sufficient to cause a C count. During off-line analysis the threshold for the sum signal was set at 12 MeV and a minimum of 10% signal sharing between tubes was insisted upon, in order to suppress tube noise.

The trigger for an event to be recorded on magnetic tape was an incident beam particle in loose coincidence with three or more neutral counts ($\overline{A}C$) in the octagon. The target veto counter was not included in the logic; its pulse height was recorded and veto decisions were made off line. Events with a pair of collinear γ detectors were vetoed, since 2γ decay together with any random count would generate large numbers of triggers. The three-counter "Y" configuration with spacing of 135°, 135°, and 90° between counters is the only one that conserves momentum and hence is the only candidate for $\pi^0 \to 3\gamma$ decay. There are eight such valid patterns in the octagon. The remaining 24 invalid three-counter patterns serve as an estimate of the background.

Data were taken at three average beam rates: 0.6, 1.0, and 1.5 MHz, all at 6% duty factor. Using the loosely defined trigger described above, we collected 350 000 events on tape. Data runs on 2γ decays were alternated with the 3γ runs. The 2γ data served to determine the energy calibration and resolution and, more vitally, the relative timing and time resolution of the γ detectors. Lead-glass counters have excellent fast-timing properties but poor energy resolution at the energies of the expected γ rays (40, 40, and 60 MeV). In a test beam the energy resolution was measured as $4.5/\sqrt{E}$ [FWHM (full width at half-maximum), E in MeV] but because of the Doppler shift and edge effects the effective single-γ resolution in use was $6.8/\sqrt{E}$. The standard deviation of the time distribution of a γ counter relative to a signal derived from the 201-MHz accelerating voltage was typically 600 psec. Using the calibration runs and internal calibrations, long-term and short-term drifts were compensated to maintain the timing accuracy to 200 psec. An empirical correction was made for timing shifts as a function of pulse height.

An important background comes from two π^-'s in the same beam bunch or adjacent beam bunches (5 nsec apart). Multipion events were strongly enhanced by the trigger, but are easily rejected on the basis of pulse-height information from the beam counters. S_2 was treated especially carefully; it consisted of 0.75-in. Pilot-U scintillator

on a fast C31024 five-stage phototube.[5] The pulse height was sampled by 5-nsec gates for each of four consecutive beam bunches. This information allows us to identify events with a single pion in S_2 clearly, isolating the effects of simultaneous pions, adjacent pions, and dc-level shifts. Some double-pion events remain in which one π^- underwent charge exchange in flight in the first part of the telescope and the other continued to the target. A joint pulse-height cut on S_0 and S_1 removes most of these events. Backgrounds caused by scattering among the octagon counters are suppressed by the excellent time resolution, and Dalitz decay is eliminated by the veto counters V and A. Finally there are accidental coincidences of two γ counters with a prompt γ from a real π^0.

Selecting only events with a single pion in the beam telescope, reasonable timing (± 3 nsec) in exactly three γ counters, and at least 10% signal sharing in each counter reduce the data to 1800 events. Further timing selection is made by calculating χ_T^2 for each event on the hypothesis that the three photons were in prompt coincidence with the beam. Likewise a χ_E^2 was calculated on the hypothesis that the three energies came from a $\pi^0 \to 3\gamma$ decay. To calculate χ_E^2 for the invalid patterns, the observed energies are reassigned to a momentum-conserving pattern in an arbitrary way. Restricting each χ^2 (three degrees of freedom each) to be less than 12 and cutting on the veto-counter pulse height, together with some minor cuts rejecting events if there are other
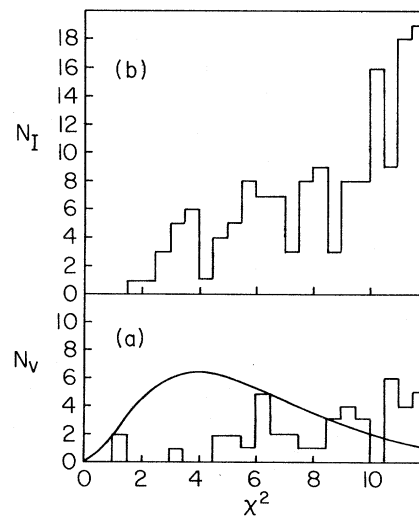

FIG. 3. Histogram of χ^2 for (a) the eight momentum-conserving ("valid") decay patterns and (b) the 24 momentum-nonconserving ("invalid") patterns. The curve is the χ^2 function for six degrees of freedom.

TABLE I. Calculation of upper limit on the branching ratio b as a function of χ^2 cut. N_V and N_I are the number of valid and invalid events, N is the 90%-confidence-level (c.l.) upper limit on the net signal, and η is the efficiency of the χ^2 cut.

χ^2	N_V	N_I	$N_V - N_I/3$	N	η	b (90% c.l.)
10	29	92	-1.67 ± 6.26	8.01	0.875 ± 0.04	1.70×10^{-6}
8	18	59	-1.67 ± 4.95	6.34	0.762 ± 0.05	1.55×10^{-6}
6	8	34	-3.33 ± 3.43	4.39	0.577 ± 0.06	1.42×10^{-6}

significant signals in the octagon, leaves 381 events.

Histograms of the remaining events with a total $\chi^2 < 12$ are shown in Fig. 3; the 44 valid and 141 invalid pattern events are shown separately. Also shown is the χ^2 function for six degrees of freedom. The distributions of events appear similar and no accumulation near small χ^2 is observed. (A small amount of data taken in a special Dalitz-decay run gives valid events distributed like the χ^2 curve, as expected for real three-body π^0 decays.) No significant differences in these or other distributions are observed between the 8 valid and the 24 invalid decay patterns. The surviving backgrounds are expected to be randomly distributed among all the patterns, and so we take the number of invalid events (divided by three) as a measure of the backgrounds.

The number of observed three-γ events N is related to the branching ratio b by

$$N = b\,\epsilon\eta fkI,$$

where ϵ is the 3γ geometrical detection efficiency, η is the efficiency of the χ^2 cut, f is the efficiency of the other cuts on the octagon data, I is the number of incident beam particles, and kI is the effective number of π^0's produced per particle. The value of k is determined from the number of 2γ events:

$$N' = b'\,\epsilon' f' kI',$$

where the primed symbols have the same significance for 2γ data as above. Thus the final result depends only on the ratios of the various efficiencies. The value of k varies with beam rate. The yield N' was also checked against an absolute calculation of $\epsilon' = 7.65 \times 10^{-3}$; agreement is within 5%. Using the matrix element of Berends[6] to generate the 3γ events, a Monte Carlo calculation

gives $\epsilon = 1.68 \times 10^{-4}$.

The effective number of π^0 decays in the experiment was $fkI = 3.2 \times 10^{10}$. In Table I is shown the number of valid and invalid events as a function of the final χ^2 cut. Also shown is the 90%-confidence-level upper limit on the net signal, the χ^2 efficiency, and the result for the branching ratio. As the result of this experiment for the upper limit of the $\pi^0 \to 3\gamma$ branching ratio, we adopt the value 1.5×10^{-6} (90% c.l.). The systematic error is estimated to be 15%. The result implies that the ratio of the C-noninvariant to the C-invariant amplitude is less than 0.26.

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[2]J. Prentki and M. Veltman, Phys. Lett. 15, 88 (1965).

[3]J. Duclos, D. Freytag, K. Schlüpmann, V. Soergel, J. Heintze, and H. Rieseberg, Phys. Lett. 19, 253 (1965).

[4]V. M. Kutin, V. I. Petrukhin, and Yu. D. Prokoshkin, Pis'ma Zh. Eksp. Teor. Fiz. 2, 387 (1965) [JETP Lett. 2, 243 (1965)].

[5]Radio Corporation of America, Lancaster, Pa. A complete account of the use of this tube will be published.

[6]F. A. Berends, Phys. Lett. 16, 178 (1965).