Precise Measurement of the Neutral Branching Ratios of the η Meson*

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The neutral branching ratios of the η meson have been determined from the energy spectrum of single γ rays in the η center of mass. The sample of 7200 events after background subtraction yields $(\eta\to\gamma\gamma)/(\eta\to\text{neutrals})=(53.5\pm1.8)\%$, $(\eta\to\pi^0\gamma\gamma)/(\eta\to\text{neutrals})=(2.6\pm1.9)\%$, and $(\eta\to3\pi^0)/(\eta\to\text{neutrals})=(43.9\pm2.4)\%$ under the assumption that no other neutral decay modes contribute. The quoted errors include an estimate of possible systematic effects.

Of the allowed η neutral decay modes, $\eta\to\gamma\gamma$ and $\eta\to3\pi^0$ are well established, but the existence of the $\pi^0\gamma\gamma$ mode is less certain despite considerable experimental work. Before mid-1967 three results assigned more than 20 % of neutral decays to the $\pi^0\gamma\gamma$ mode[1-3] while another gave an upper limit 30 %.[4] Since then five experimental results have been consistent with zero,[5-9] but two others give ~12% for this mode.[10-11] The values of the branching ratios for the neutral decay modes also have suffered from large statistical uncertainties. This situation has emphasized the need for a precise measurement of the η neutral decays with careful attention to systematic errors.

We report a measurement of the η neutral branching ratios from the energy spectrum of single γ rays in the η center of mass. η production was detected by means of the time of flight (TOF) for forward-going neutrons in the reaction $\pi^-p\to\eta n$. The momentum of the γ rays was measured in an optical spark-chamber spectrometer. Assuming that no other neutral modes contribute and including an estimate of systematic errors, our results are

$$(\eta\to\gamma\gamma)/(\eta\to\text{neutrals})=(53.5\pm1.8)\%,$$

$$(\eta\to\pi^0\gamma\gamma)/(\eta\to\text{neutrals})=(2.6\pm1.9)\%,$$

$$(\eta\to3\pi^0)/(\eta\to\text{neutrals})=(43.9\pm2.4)\%.$$

These are based on a sample of 7200 events after background subtraction. A brief summary of the experiment follows and a more detailed account is in preparation.

The experiment was performed at the Princeton-Pennsylvania Accelerator with an (820 ± 8.2)-MeV/c π^- beam taken at an angle of 13° to the internal proton beam. The π^- beam was incident on a 40-in. liquid-hydrogen target surrounded by anti counters. The neutrons were detected in nine liquid scintillation counters placed 30 ft downstream from the target. Each counter was a 2-ft cube viewed by a single phototube. Together they formed a 6×6-ft array centered on the beam line. The neutron counter number, the TOF, and other information were recorded on magnetic tape for each event. Pions emerging from the target were swept clear of the counters by a large-aperture magnet located just downstream of the target.

γ rays were converted in 0.1 radiation length of Pb and momentum analyzed with an optical spark-chamber spectrometer placed beside the target and parallel to the beam. The entrance chamber was a wide-gap spark chamber with two cells each 60 in. long by 3 in. deep by 10 in. high. The magnet had an aperture $72\times18\times24$ in. and a field integral of 47.3 kG in. The exit chamber consisted of two pairs of gaps each $108\times0.5\times34$ in. separated by 6 in.

The spark chambers were triggered on the coincidence of a beam pion interacting in the target to produce a neutral final state, a neutron 30 to 60 nsec later, and a converted γ ray in the spectrometer. The converted γ ray was signaled by a pulse from one of five counters following the Pb converter and from two of eight counters following the exit chamber. Each γ ray was assumed to come from η production and, using the neutron direction as determined from the center of the neutron counter, was transformed into the η center of mass.

The neutron TOF spectrum from a typical neutron counter is presented in Fig. 1. There is clear evidence for η production and for a background of nonresonant multiple-pion production. Charge exchange $(\pi p\to\pi^0n)$ is not seen because the γ rays from the decay of the π^0 were outside the energy-angle acceptance of the spectrometer. A similar bias existed against low effective-mass multiple-pion states.

Branching ratios were calculated from the γ-ray energy spectra of events with neutron TOF within ±3 nsec of the η-production peak, the η

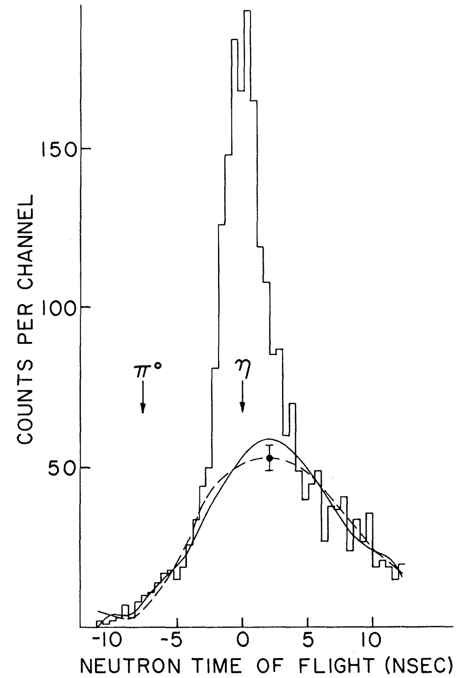

FIG. 1. Neutron time-of-flight spectrum for a typical counter. The neutron times of flight corresponding to $\pi^- p \rightarrow \pi^0 n$ and $\pi^- p \rightarrow \eta n$ are indicated. The time of flight shown is relative to the center of the η peak. The background fits are shown for a fourth-order polynomial (dashed curve) and a sixth-order polynomial (solid curve). The error bar indicates the statistical uncertainty in the background fit for one choice of polynomial.

timing window. For each neutron counter the background amplitude in this region was determined by fitting the TOF spectrum with a Gaussian shape for the η peak and a modified polynomial for the background. The width of the Gaussian was fixed by fitting the TOF spectrum cut to include only events with γ-ray energies near the $\gamma\gamma$ peak to enhance the amplitude of the η peak; typical standard deviations were 1.5 nsec.

The background shape was approximated by a polynomial since no theoretical model for the background could be found which fitted the data. The polynomial was multiplied by an efficiency function to account for the effect of the spectrometer requirement on the shape of the TOF spectrum. This function was relatively flat for TOF for η production and longer, but decreased rapidly for short TOF, and was determined by dividing the spectrum taken with a γ required by the spectrum taken without the spectrometer included.

The quality of the fits was judged by the χ^2 probability and by the requirement that the background shape be smooth and show no evidence of distortion in the region directly under the η Gaussian. Acceptable fits for all counters were obtained from a fourth-order polynomial, but for some counters, up to sixth-order polynomials could not be ruled out. Figure 1 shows the background fits for a fourth-order polynomial (dashed curve) and a sixth-order polynomial (solid curve) for a typical counter. The statistical uncertainty on the background fit (indicated by the error bar) was included with other statistical errors. The indeterminacy in the order of background polynomial is discussed later as a source of possible systematic error.

The shape of the background γ-ray energy spectrum for the data from each neutron counter was obtained in two ways. The first method used the shape of the γ-ray energy spectrum of those events with neutron TOF more than 4 nsec above the center of the η peak. The second background shape was calculated by dividing the data into 25-MeV γ energy bins and fitting the TOF spectrum in each bin with a fourth-order polynomial background plus a Gaussian η signal. The TOF background amplitude as a function of energy bin obtained in this manner gave a rough γ-ray energy background shape. Bin sizes smaller than 25 MeV could not be used because of limited statistics.

The spectra from these two methods were compared and found to be equivalent at the limit of experimental resolution for those neutron counters centered vertically on the beam line and for those on the side of the beam line opposite the spectrometer. For counters on the spectrometer side, however, a difference could be seen at low γ-ray energies. This was a result of the general asymmetry introduced into the experiment by the spectrometer through its energy-angle acceptance function which gave a particularly strong bias against the soft γ rays from the decay of pion systems moving away from the spectrometer.

For counters where the two background spectra agreed, the high-statistics above-η spectra were used. For the remaining three counters, the 25-MeV spectra were used. Figure 2(a) presents the γ-ray energy spectrum summed over all counters for events with neutron TOF in the η timing window. The solid curve is the estimated background from fourth-order timing fits summed over all counters.

A Monte Carlo program was used to predict the center-of-mass single-γ-ray energy spec-

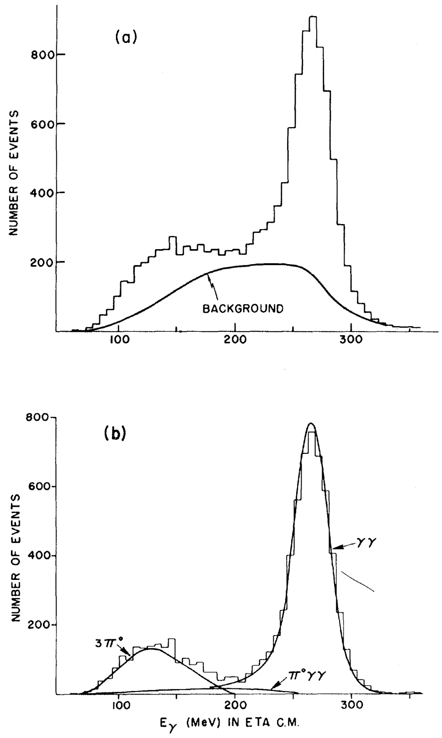

FIG. 2. (a) Single γ-ray energy spectrum summed over all counters for events with neutron times of flight within ±3 nsec of the center of the η peak. The solid curve is the estimated background subtraction. (b) The subtracted γ energy spectrum and the best fits of the Monte Carlo spectra.

Table I. η neutral branching ratios and error estimates.

Neutron Counter	$\gamma\gamma$/neutrals (%)	$\pi^0\pi^0\pi^0$/neutrals (%)	$\pi^0\gamma\gamma$/neutrals (%)
1	48.2 ± 4.5	55.3 ± 7.2	-3.5 ± 4.2
2	55.0 ± 4.7	41.0 ± 6.2	4.0 ± 3.7
3	51.1 ± 5.7	48.0 ± 8.0	0.9 ± 4.8
4	54.6 ± 4.4	42.1 ± 6.1	3.3 ± 3.4
5	58.8 ± 4.5	34.7 ± 5.3	6.5 ± 3.5
6	59.7 ± 6.2	44.0 ± 7.7	-3.7 ± 4.5
7	45.9 ± 5.5	44.4 ± 8.9	9.7 ± 5.3
8	54.2 ± 6.2	51.8 ± 9.0	-6.0 ± 5.2
9	51.4 ± 3.5	43.7 ± 4.8	4.9 ± 3.2
Weighted Average (Statistical Errors)	(53.5 ± 1.7)%	(43.8 % 2.1)%	(2.6 ± 1.4)%
χ^2 Probability that all counters are consistent	65%	70%	40%
Maximum Estimated Error from Background Amplitude	0.4%	0.5%	0.9%
Maximum Estimated Error from Background Shape	0.3%	1.0%	1.3%

trum for each η decay mode. It included the momentum acceptance of the spectrometer and the effects of bremsstrahlung, multiple scattering, energy loss, measurement error, and the energy dependence of the γ-conversion probability.

Several checks were made on the Monte Carlo predictions by comparison with features of the data. Two factors were found that needed adjustment to make the Monte Carlo spectra agree with the data. It was necessary to use an experimentally observed angular dependence of the efficiency of the wide-gap spark chamber. Also the Monte Carlo predicted a $\gamma\gamma$ peak at 265 MeV with a full width of 30 MeV while the data had a full width of 31 MeV. The Monte Carlo spectra were broadened to remove this slight difference. The branching ratios were not sensitive to either correction.

To calculate branching ratios, the Monte Carlo γ-ray energy spectra plus background were fitted to the unsubtracted data spectrum of each neutron counter with a maximum-likelihood program. Table I lists the results for each counter and the weighted-average branching ratios. Also given is the χ^2 probability that all nine counters give consistent results for each mode. The data with the background subtracted and the best fits of the Monte Carlo spectra (summed over all counters) are presented in Fig. 2(b).

The uncertainty in the background amplitude was estimated by calculating the results for the lowest and highest acceptable orders of background polynomial. The branching ratios quoted in Table I are the central values between these extremes shown with their statistical errors. Half the difference between extremes is used as an estimate of this contribution to the probable systematic error. Similarly the probable systematic error due to uncertainty in the background energy shape was estimated by considering the difference between the results using the two methods of determining the shape. Other estimated systematic errors (e.g., the effect of the form of the $\pi^0\gamma\gamma$ matrix element) were small. The final error estimates are a quadrature sum of the statistical error with the two systematic error estimates given in Table I.

Note that uncertainties in the background subtraction are a major contribution to the final error assignments to the branching ratios. In particular, consider the $\pi^0\gamma\gamma$ mode for which our result is $2.6 \pm 1.9\,\%$. The statistical uncertainty in the background amplitude in each counter was 3 to 5 % of the magnitude of the background. Typically a change of 3 % of the magnitude of the background in a counter resulted in a change in the value of the $\pi^0\gamma\gamma$ branching ratio of 1 %. As shown in Table I, the total statistical uncertainty in the value of the $\pi^0\gamma\gamma$ branching ratio is $\pm 3\,\%$ to $\pm 5\,\%$ for each counter. When all nine counters are combined the statistical uncertainty on the weighted average is $\pm 1.4\,\%$. Additional contributions to the final error due to possible systematic errors in the choice of background shape and background amplitude are 1.3 and 0.9 %, respectively. When these are added in quadrature with the statistical error, we obtain our error assignment of $\pm 1.9\,\%$.

Our result is strong evidence that $\eta \to \pi^0\gamma\gamma$ represents a small fraction of the η neutral decays. In addition, our values for the neutral decay modes are consistent with a constrained fit to other data.[12] The results of this experiment may be added to the data used in Ref. 12 to recompute the experimental value for $R = (\eta \to 3\pi^0)/(\eta \to \pi^+\pi^-\pi^0)$. The result is $R = 1.38 \pm 0.09$ which is more than 2 standard deviations below the value of 1.58 ± 0.03 predicted theoretically assuming a totally symmetric $I = 1$ three-pion final state and a linear matrix element.[13]

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