ski, Nuovo Cimento 20, 1182 (1961).

[8]Evidently this argument cannot justify treating the pion itself by conventional quantum theory.

[9]J. R. Taylor, Phys. Rev. 140, B187 (1965).

[10]The momentum transfer need not be so large that elastic scattering is negligible. See, for example, G. Placzek, Phys. Rev. 86, 377 (1952); G. C. Wick, Phys. Rev. 94, 1228 (1954).

[11]An seemingly equivalent physical suggestion involving more concrete models has been made by J. Bjorken, Stanford Linear Accelerator Center Report No. SLAC-PUB-338, 1967 (unpublished).

NEUTRAL DECAY BRANCHING RATIOS OF THE η^0 MESON*

C. Baltay,† P. Franzini, J. Kim, R. Newman, and N. Yeh
Columbia University, New York, New York, and Brookhaven National Laboratory, Upton, New York

and

L. Kirsch
Brandeis University, Waltham, Massachusetts

(Received 10 November 1967)

The branching ratios for the decay of the η^0 meson into $3\pi^0$, $\pi^0\gamma\gamma$, and $\gamma\gamma$ have been measured. Under the assumption that no other neutral decays are significant, the results are $(\eta^0\rightarrow 3\pi^0)/(\eta^0\rightarrow\gamma\gamma)=0.88\pm0.16$ and $(\eta^0\rightarrow\pi^0\gamma\gamma)/(\eta^0\rightarrow\gamma\gamma)\leq 0.28$ (95% confidence-level upper limit).

We have measured the branching ratios[1] of the decays of the η^0 meson into $3\pi^0$, $\pi^0\gamma\gamma$, and $\gamma\gamma$. Assuming that no other neutral decay modes are significant, we obtain

$$\frac{\eta^0\rightarrow 3\pi^0}{\eta^0\rightarrow\gamma\gamma}=0.88\pm0.16,$$

$$\frac{\eta^0\rightarrow\pi^0\gamma\gamma}{\eta^0\rightarrow\gamma\gamma}\leq 0.28 \text{ (95\% confidence level).}$$

The η^0 mesons studied in this experiment were produced in the reaction

$$\pi^+d\rightarrow pp\eta^0 \qquad (1)$$

in the Brookhaven National Laboratory–Columbia 30-in. bubble chamber filled with liquid deuterium, exposed to a separated π^+ beam of 820-MeV/c incident momentum at the Brookhaven alternating-gradient synchrotron. The entire exposure consisting of 435 000 photographs was scanned for examples of Reaction (1), in which the η^0 decayed into neutrals (i.e., no charged decay products were visible) and one of the γ rays resulting from the η^0 decay produced an e^+e^- pair in the visible region of the chamber. Events with internally converted (Dalitz) pairs were not used because of possible confusion with the numerous background events of the reaction $\pi^+d\rightarrow pp\pi^+\pi^-$. Events of Reaction (1) were accepted only if at least one of the two protons stopped in the chamber, and any nonstopping protons had a measurable length of 5 cm or more. After measurement, events were removed from the sample if the e^+e^- did not point back to the η^0 production vertex or if either the e^+ or e^- had a dip over 70° in the chamber.

A total of 2014 events were left with both the production vertex and the γ-conversion point occurring inside a clearly defined fiducial region of the chamber. No further cuts or kinematic fitting were imposed on these events. The distribution in the square of the mass of x^0 for these events, where x^0 is defined by $\pi^+d\rightarrow ppx^0$, is shown in Fig. 1. From this distribution we estimate that, of these events, 240 are $\pi^+d\rightarrow pp\eta^0$, ~400 are $\pi^+d\rightarrow pp\pi^0$, and the

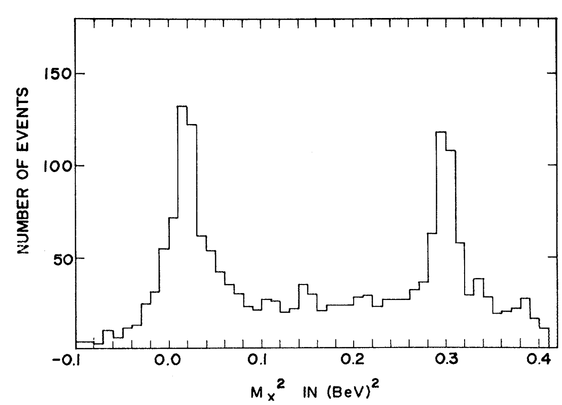

FIG. 1. Distribution in the mass squared (m_x^2) for the reaction $\pi^+d\rightarrow ppx^0$ with one associated γ ray observed.

remainder are presumably $\pi^+d \to pp + 2$ or 3 π^0's. The resolution in the mass of η^0 is sufficiently good to allow a reliable estimate of the amount of background under the η^0 peak.

For each event, the energy of the γ ray was calculated from the measured momenta of the e^+ and the e^-, and the γ energy was transformed into the x^0 center-of-mass frame. For the η^0 events, the distribution of $E_\gamma{}^*$, the γ-ray energy in the η^0 rest frame, allows us to distinguish between the various neutral η^0 decay modes. Figure 2(a) shows the expected $E_\gamma{}^*$ distributions, calculated by a Monte Carlo program. The dashed curves are the theoretical distributions; the solid curves show the distributions after the γ-detection efficiencies and measurement resolution of our experiment have been folded in. The normalization of the solid curves corresponds to equal branching ratios for $3\pi^0$, $\pi^0\gamma\gamma$, and $\gamma\gamma$. The curves for the $3\pi^0$ decay mode were generated using a constant matrix element (i.e., phase space). The curves for the $\pi^0\gamma\gamma$ decay mode are based on the simplest gauge-invariant matrix element,

$$M = (\epsilon_1 \circ \epsilon_2)(k_1 \cdot k_2) - (\epsilon_1 \cdot k_2)(\epsilon_2 \cdot k_1),$$

where ϵ and k are the polarization and momentum vectors of the photons. After summing over polarizations the square of this matrix element is proportional to $(m_{\gamma\gamma})^4$, where $m_{\gamma\gamma}$ is the effective mass of the two photons. The $E_\gamma{}^*$ distribution derived from a constant matrix element for the $\pi^0\gamma\gamma$ decay mode is similar to the distribution shown; the results of the following analysis are valid for both the constant and the simplest gauge-invariant matrix elements.

The effective γ-detection efficiency as a function of the γ laboratory energy was determined by comparing the energy spectrum of 387 observed gammas from the reaction $\pi^+d \to pp\pi^0$ with the spectrum predicted on the basis of a large independent sample of the same reaction selected regardless of γ conversion. The resulting detection efficiency includes the known probability of a γ converting into an e^+e^- pair in addition to such energy-dependent factors as scanning efficiency for e^+e^- pairs and event rejection due to poor measurement of the e^+ or e^- tracks, and agrees well with independent estimates of these effects.

The experimental distribution in $E_\gamma{}^*$ for the η^0 events is shown in Fig. 2(c). The η^0 events were selected by requiring $m_x{}^2$ to fall between

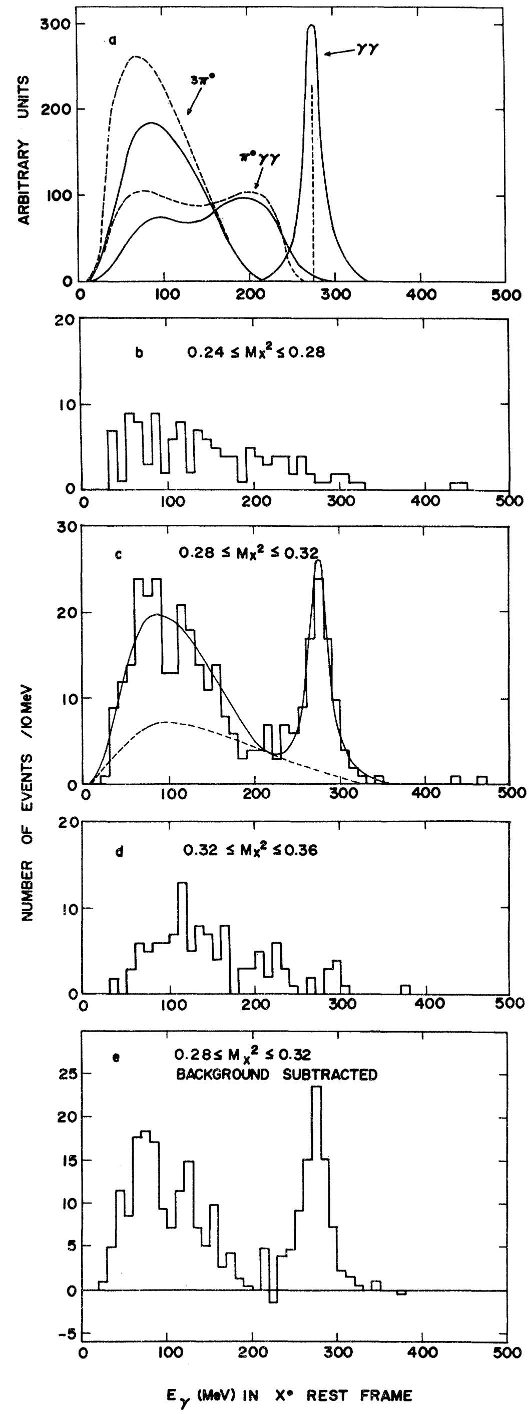

FIG. 2. Distributions of the γ energy in the missing-mass rest frame. (a) The dashed curves show the theoretical distributions for three decay modes of the η^0, and the solid curves represent the expected distributions modified by the experimental resolution and γ-detection efficiencies. (b), (c), (d) The experimental distributions for the η^0 and two control regions. The curves on (c) represent the fit described in the text. (e) The data after a bin-by-bin subtraction of the background.

0.28 and 0.32 BeV^2. The η^0 sample selected in this way contains some background of $\pi^+p \to pp+2$ or 3 π^0 events, as can be seen from Fig. 1. The E_γ^* distribution of the background events can be estimated from the control regions below and above the η^0. The E_γ^* distributions for these control regions are shown in Figs. 2(b) and 2(d). The background in the η^0 region is taken to be the average of the E_γ^* distributions of the two control regions. The total number of background events obtained in this way agrees with the amount of background expected under the η^0 peak from the m_x^2 distribution of Fig. 1. The E_γ^* distribution for the η^0 events after this background subtraction is shown in Fig. 2(e).

Comparison of the E_γ^* distribution after background subtraction [Fig. 2(e)] with the expected distributions [Fig. 2(a)] shows that we have no evidence in this experiment for the existence of the $\pi^0\gamma\gamma$ decay mode. This is particularly evident from the absence of events in the region from 180 to 240 MeV, which is where the $\pi^0\gamma\gamma$ mode can be most clearly distinguished from the $3\pi^0$ and $\gamma\gamma$ modes. To set an upper limit on the $\pi^0\gamma\gamma$ mode and to evaluate the ratio $(3\pi^0)/(\gamma\gamma)$, we did a simultaneous maximum-likelihood fit to the experimental E_γ^* distribution in the η^0 region without a background subtraction [Fig. 2(c)] and to the m_x^2 distribution (Fig. 1). The free parameters in the fit were the ratio $(\eta^0\to 3\pi^0)/(\eta\to\gamma\gamma)$, the ratio of $(\eta^0\to\pi^0\gamma\gamma)/(\eta^0\to\gamma\gamma)$, and the amount of non-$\eta^0$ background. The fit used the E_γ^* distributions from the Monte Carlo calculation [the solid curves on Fig. 2(a)] for the various η^0 decay modes, and the average of the experimental E_γ^* distributions in the control regions below and above the η^0 [Figs. 2(b) and 2(d)] for the shape of the background. The best fit is shown by the solid curve of Fig. 2(c); the dashed curve indicates the non-η^0 background in the fit. The mean probability of detecting an η^0 decay with a single γ ray in our experiment was calculated by the Monte Carlo program mentioned previously to be 1/29.9, 1/37.9, and 1/60.1 for the $3\pi^0$, $\pi^0\gamma\gamma$, and $\gamma\gamma$ decay modes, respectively.

After correcting for the detection efficiency, we obtain $(\eta^0\to 3\pi^0)/(\eta^0\to\gamma\gamma)=0.88\pm0.16$ and $(\eta^0\to\pi^0\gamma\gamma)/(\eta^0\to\gamma\gamma)=-0.06\pm0.14$. The errors on these ratios include the statistical errors as well as our estimate of the systematic uncertainties in these measurements. The last ratio is consistent with zero; we prefer to quote this result as a 95% confidence-level (2-standard-deviation) upper limit $(\eta^0\to\pi^0\gamma\gamma)/(\eta^0\to\gamma\gamma) \le 0.28$. This upper limit is in good agreement with the results of recent experiments.[2,3]

A consistency check on the validity of these results is provided by the m_x^2 distributions for the three regions $0\le E_\gamma^*\le 180$ MeV, $180 \le E_\gamma^* \le 240$ MeV, and $240\le E_\gamma^*\le 300$ MeV, shown in Figs. 3(a), 3(b), and 3(c), respectively. An unambiguous η^0 signal is seen in the distributions of both Figs. 3(a) and 3(c), corresponding to the $3\pi^0$ and the $\gamma\gamma$ decay modes; the numbers of events in these peaks are in excellent agreement with the numbers obtained from the maximum likelihood fit. We expect six η^0 events due to the tails of the $3\pi^0$ and $\gamma\gamma$ events, and approximately 30% of the $\pi^0\gamma\gamma$ decays in the region between 180 and 240 MeV [Fig. 3(b)]. After removing these six events around 0.3 BeV^2 in Fig. 3(b), no η^0 peak is apparent, in agreement with our conclusion that we see no evidence for $\eta^0\to\pi^0\gamma\gamma$.

We can also express our results as fractions of all neutral decays (in percent):

$$\frac{\eta^0\to\gamma\gamma}{\eta^0\to\text{neutrals}}=53.3\pm4.6,$$

$$\frac{\eta^0\to 3\pi^0}{\eta^0\to\text{neutrals}}=46.7\pm6.7,$$

$$\frac{\eta^0\to\pi^0\gamma\gamma}{\eta^0\to\text{neutrals}}\le 15.0.$$

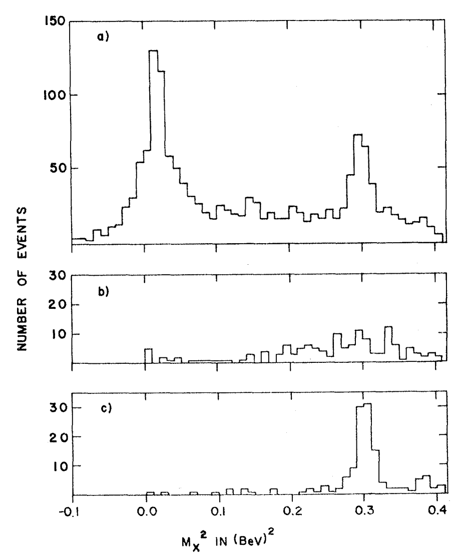

FIG. 3. Distribution in m_x^2 for events with E_γ^* (a) below 180 MeV, (b) 180 to 240 MeV, and (c) to 300 MeV.

We would like to thank the operating crews of Brookhaven National Laboratory alternating-gradient synchrotron and the 30-in. bubble chamber, as well as the scanning and measuring staffs at Nevis Laboratories and Brandeis University. We would also like to thank the Stony Brook Bubble Chamber Group for processing the π^0 events used for calibration of the γ-ray detection efficiency.

*Work supported in part by the U. S. Atomic Energy Commission.

†Alfred P. Sloan Foundation Fellow 1967-1969.

[1]For a summary of previous experimental results and a list of references, see A. H. Rosenfeld, A. Barbaro-Galtieri, W. J. Podolsky, L. R. Price, P. Soding, C. G. Wohl, M. Roos, and W. J. Willis, Rev. Mod. Phys. 39, 1 (1967).

[2]P. Bonamy and P. Sonderegger, in Proceedings of the International Conference on Elementary Particles, Heidelberg, Germany, 1967 (to be published).

[3]S. Buniatov, E. Zavattini, W. Deinet, H. Muller, D. Schmitt, and H. Staudenmaier, in Proceedings of the International Conference on Elementary Particles, Heidelberg, Germany, 1967 (to be published).

PARTIAL DECAY RATES OF THE η^0 MESON*

C. Baltay,† P. Franzini, J. Kim, L. Kirsch,‡ R. Newman, and N. Yeh
Columbia University, New York, New York, and Brookhaven National Laboratory, Upton, New York

and

J. A. Cole, J. Lee-Franzini, and H. Yarger
State University of New York at Stony Brook, Stony Brook, New York, and Brookhaven National Laboratory, Upton, New York

(Received 10 November 1967)

We have measured the ratios ($\eta^0\to$neutral decay modes)/($\eta^0\to$ charged decay modes) and $(\eta^0\to\pi^+\pi^-\gamma)/(\eta\to\pi^+\pi^-\pi^0)$ to be, respectively, 2.64 ± 0.23 and 0.28 ± 0.04. By combining these ratios with the results of the preceding Letter for the neutral modes, we obtain partial decay rates for the various η^0 decays. In particular, we obtain $(\eta^0\to3\pi^0)/(\eta^0\to\pi^+\pi^-\pi^0)=1.58\pm0.25$, in good agreement with the assumption that the three-pion final state has $I=1$.

We have measured the branching ratios of the decays of the η^0 meson which involve charged particles in the final state.[1] Our results are

$$\frac{\eta^0\to\text{all neutral modes}}{\eta^0\to\text{all charged modes}}=2.64\pm0.23,$$

$$\frac{\eta^0\to\pi^+\pi^-\gamma}{\eta^0\to\pi^+\pi^-\pi^0}=0.28\pm0.04,$$

$$\frac{\eta^0\to\pi^+\pi^-\pi^0\gamma}{\eta^0\to\pi^+\pi^-\pi^0}\leq0.016,$$

$$\frac{\eta^0\to\pi^+\pi^-\gamma\gamma}{\eta^0\to\pi^+\pi^-\pi^0}\leq0.016.$$

A large sample of η^0 mesons has been produced in the Columbia-Brookhaven National Laboratory 30-in. bubble chamber filled with liquid deuterium and exposed to 820-MeV/c π^+ mesons from the low-energy separated beam at the Brookhaven National Laboratory alternating-gradient synchrotron. The production reaction was $\pi^+d\to pp\eta^0$. The η^0 mesons decaying neutrally were observed in the chamber as interactions producing two charged prongs, both of which are protons, while charged decays were observed as interactions producing four charged prongs, two protons and two charged pions. At this beam energy the protons are always produced with sufficiently low momenta to allow their identification at the scanning table. The entire exposure consisting of 435 000 photographs was scanned twice for four-prong interactions, producing a sample of 65 000 events. Approximately 120 000 photographs were scanned twice for two-prong interactions, producing a sample of 42 000 events. In both samples we only used events in which at least one of the protons stopped in the chamber.

(1) Ratio of neutral to charged decays.—For both the two- and the four-prong events the invariant mass, m_x, recoiling against the two protons was computed, using only the measured variables of the incident π^+ and the two protons. The distributions in m_x^2 for the two samples