in the type of process we consider here.

The state generated by the degenerate parametric amplifier, $|z(t), \alpha(t)\rangle$, is not a state of minimum uncertainty product in general. But the uncertainty product does take on its minimum value periodically every time $z(t)$ becomes real. This happens at a rate equal to the pump frequency. It does not appear that minimality is in any way crucial to the ACE especially since there are density matrices displaying the ACE but, as I have shown in a recent paper,[10] there are no minimum-uncertainty density matrices.

I have suggested here a possible specific way to detect the photon anticorrelation effect and also provided some ideas which might lead to other ways. The effect is of interest in several contexts and it seems worthwhile to pursue its detection.

The author would like to thank his colleagues, Professor M. Menes and Professor E. Cassedy, for helpful discussions regarding some experimental aspects of the measurements proposed here.

Note added.—The principal ideas contained in this paper were discussed by the author at the February 1973, New York Meeting of the American Physical Society.[11]

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Decay Width of the Neutral π Meson*

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(Received 8 July 1974)

The cross section for the photoproduction of π^0 mesons from complex nuclei at small angles has been measured at incident bremsstrahlung energies of 4.4 and 6.6 GeV. The data are fitted by a cross section calculated from a sum of Primakoff and nuclear-production amplitudes. A total decay width for the π^0 meson of 8.02 ± 0.42 eV is obtained from the magnitude of the Primakoff amplitude.

The $Y=0$, neutral pseudoscalar mesons decay into photon pairs. The partial width of this decay mode can be determined by measuring the cross section for the photoproduction of the meson in the Coulomb field.[1] Recently we reported the width of the η^0 meson measured in this way.[2] In this paper, the results of a similar experiment carried out for the π^0 meson are given.

A measurement of the π^0 photoproduction cross section at small angles was made for photon energies near 4.4 and 6.6 GeV. Data were recorded for targets of beryllium, aluminum, copper, silver, and uranium. At each machine energy a set of runs on the five targets was taken with photon hodoscope counters located directly above and below the beam line. At the lower photon energy an extra set of runs was made with the counters displaced by 15 mrad from the beam line in or-

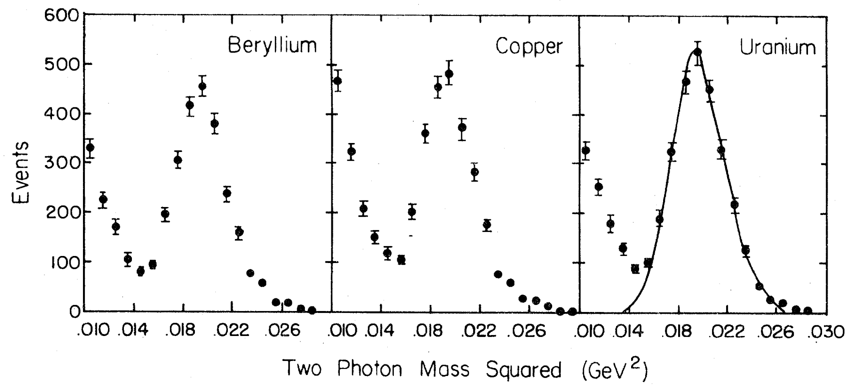

FIG. 1. Two-photon mass-squared spectra. The machine energy was 6.6 GeV. The solid curve shown on the uranium spectrum was calculated by using the measured energy and spatial resolution of the counters.

der to see the maximum in the coherent-nuclear-production signal. The equipment used for this experiment was the same as in the η^0 measurement. The counter hodoscopes were pulled back to 1140 cm from the target to accomodate the smaller photon opening angles of the π^0 decay. The distance between the hodoscope centers was 77.2 cm and 51.4 cm for the respective photon energies. The active aperture of each counter was 27.4 cm vertically by 36.6 cm horizontally. The data taking was arranged to minimize systematic errors associated with counter drifts by limiting the data runs to approximately 1 h duration and alternating the targets.[3]

The data were treated in a manner analogous to that in the η^0 experiment. Events were selected on the measured opening angle between the photons. The maximum allowed opening angle was 0.075 (0.050) rad for the data at a machine energy of 4.4 (6.6) GeV. These correspond to minimum π^0 energies of 3.6 and 5.4 GeV. A minimum-opening-angle cut of 0.058 (0.039) rad was also imposed. Several mass-squared spectra of the events that survive these cuts are shown in Fig. 1. The angular distributions of all events above a mass squared of 0.014 GeV^2 were used for comparing with the theoretical angular distributions.

The differential cross section for the photoproduction of π^0 mesons at small angles is assumed to be given by[4,5]

$$d\sigma/d\Omega = |\sqrt{b_C}\,T_C + \sqrt{b_n}\,e^{i\varphi}T_n|^2 + b_b|T_b|^2,$$

where T_C and T_n are the amplitudes[5] for the coherent production in the Coulomb field and the nuclear field, and T_b is an amplitude describing incoherent production. Following the notation of Ref. 2,

$$T_C = [8\alpha Z^2\Gamma(\pi\to 2\gamma)]^{1/2}(\beta/\mu)^{3/2} \times [K\sin\theta/\Delta^2]F_C(K,\theta),$$

where $\alpha = 1/137$; K is the photon energy; μ, β, and θ, are the mass, velocity, and direction of the meson; Δ^2 is the square of the four-momentum transfer; and $F_C(K,\theta)$ is the Coulomb form factor.[4] Similarly,

$$T_n = AL\sin\theta\, F_n(K,\theta),$$

where A is the atomic number; $L\sin\theta$ is the forward spin-nonflip nucleon amplitude; and $F_n(K,\theta)$ is the nuclear form factor. The incoherent amplitude T_b was assumed isotropic and proportional to $A^{3/8}$:

$$|T_b|^2 = 1.0A^{0.75}\,\mu\mathrm{b/sr}.$$

The parameters b_C, b_n, φ, and b_b are varied in order to fit the data. For numerical convenience, we take $\Gamma(\pi^0\to 2\gamma) = 1$ eV in the expression for T_C so that the fitted value of b_C is the partial decay width in eV. We take $L^2 = 100K^2$ μb (K in GeV) so that the fitted value of b_n should be of order unity.

We have also considered the possibility that a substantial fraction of the detected π^0's come from the coherent production of ω^0 mesons followed by their subsequent decay into $\pi^0\gamma$. The contribution of this source was calculated from measured nuclear cross sections[6] and a parameter, b_0, was introduced to permit the data to fix the normalization.

The expected event rate in each angular bin was calculated by folding in the bremsstrahlung spectrum[7] and the angular resolution of the detector.

TABLE I. Fitted values of the b_i's for each data set. The errors given in this table are those derived in the fitting procedure (diagonal elements of the error matrix).

Data set	b_C	b_n	$\lvert\varphi\rvert$ (rad)	b_b	b_0	χ^2/d.f.
4.4 Gev on axis	7.66 ± 0.14	1.41 ± 0.29	1.09 ± 0.16	3.2 ± 0.5	0.5 [a]	205/191
4.4 GeV off axis	8.02 ± 0.36	1.47 ± 0.06	1.18 ± 0.08	4.1 ± 0.4	0.5 [a]	239/215
6.6 GeV	8.08 ± 0.11	1.36 ± 0.15	0.84 ± 0.14	8.2 ± 0.8	0.5 [a]	220/210
All combined	7.92 ± 0.08	1.48 ± 0.05	1.18 ± 0.04 [b] 0.86 ± 0.07 [c]	4.1 ± 0.6 [b] 8.5 ± 1.6 [c]	0.42 ± 0.20	675/623

[a]Coefficient b_0 held fixed at 0.5. [b]Value for 4.4 GeV. [c]Value for 6.6 GeV.

This rate may be expressed as

$$N(\theta)=b_C N_C(\theta)+b_n N_n(\theta)+(b_C b_n)^{1/2}N_{Cn}(\theta,\varphi)+b_b N_b(\theta)+b_0 N_0(\theta),$$

where the $N_i(\theta)$'s are the number[5] of events in each bin computed for each component of the cross section.

The five free parameters were determined by fitting data from all targets, simultaneously. A separate fit was made for each data set—4.4 GeV on axis, 4.4 GeV off axis, and 6.6 GeV. The results are tabulated in Table I. The value of $\lvert\varphi\rvert$ is given since an equally good fit is obtained for positive and negative values of φ. This can be traced to the fact that F_C and F_n have very small imaginary parts at these energies. The last entry in Table I is the result of simultaneously fitting all three data sets and allowing only the phase, φ, and the amount of incoherent background, b_b, to vary between 4.4 and 6.6 GeV. Using the result of this fit, 7.92 eV, as the best estimate to the partial width, we computed the rms deviation of the value obtained for this number in the three data sets. We use this deviation, 0.2 eV, as a measure of the consistency of the data in computing an overall error. Some of the measured angular distributions together with the fitted curves are shown in Fig. 2.

The form factors were calculated by using a Woods-Saxon potential with the same nuclear radii and skin thickness as given in Ref. 2. A pion absorption cross section of 30 mb was used. The sensitivity of our value for the π^0 width to small changes in these parameters was tested by varying them one at a time and refitting the data. The results are summarized in Table II. We have assigned an overall error of 1.2% to account for uncertainties in the form factors. The derived value of the width is inversely proportional to the number of photons that are able to contribute to the detected event rate. In this analysis the maximum photon energy is set by the machine energy which has been calibrated several times and is believed to be known to $\pm0.5\%$.[8] The lower edge of the accepted-photon spectrum is set by the maximum-opening-angle cut. Surveys made before and after the experiment reproduced the ge-

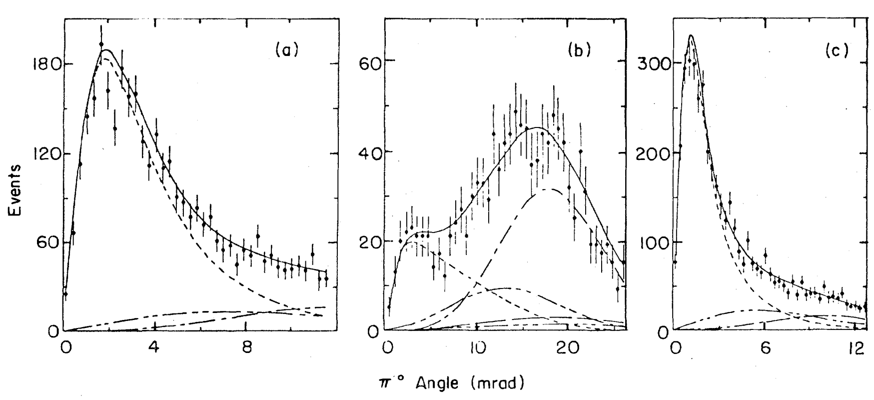

FIG. 2. π^0 angular distribution for silver. (a) 4.4 GeV on axis; (b) 4.4 GeV off axis; (c) 6.6 GeV. The various curves are short-dashed, $b_C N_C(\theta)$; dash-dotted, $b_n N_n(\theta)$; dash-double-dotted, $b_{Cn} N_{Cn}(\theta,\varphi)$; long-dashed, $b_b N_b(\theta)$; dash-triple-dotted, $b_0 N_0(\theta)$; solid, $N(\theta)$. The b_i's and φ are those given in the last entry of Table I.

TABLE II. Changes induced in the b_i's by variations in the values of experimental parameters.

Parameter	Amount changed	δb_C	δb_n	$\lvert\delta\varphi\rvert$ (rad)
Nuclear radii	$\pm 10\%$	± 0.07	± 0.23	0.09
Nuclear skin thickness	$\pm 10\%$	± 0.02	± 0.07	0.03
π^0 absorption cross section	± 10 mb	± 0.01	± 0.31	0.06
Synchrotron energy	$\pm 0.5\%$	∓ 0.25	∓ 0.05	<0.02
Max-opening-angle cut	± 0.27 mrad	∓ 0.16	∓ 0.05	<0.02

ometry to better than ± 3 mm. This translates into an opening-angle uncertainty of ± 0.27 mrad. The effect of the experimental uncertainties in each of these quantities was also tested by refitting the final data sample (see the last two entries in Table II). An error of $\pm 4\%$ was assigned for these. The photon beam was monitored with a differential secondary-emission quantameter whose calibration is known to $\pm 2\%$. Corrections for the loss of beam photons in the target (about 5%) are canceled almost exactly by the correction for the loss of π^0-decay photons.

Our final value for the partial width into photons is 7.92 ± 0.42 eV. The quoted error is obtained by combining each of the above contributions in quadrature. Using the branching ratio 0.988 for this decay mode,[9] we find that the full width is 8.02 ± 0.43 eV. Previously reported experimental values of the π^0 width[9] have a weighted average of 7.9 eV and a rms spread of 1.6 eV. Although our experiment does not change the best value, it reduces the large uncertainty.

Theoretical calculations of the $\pi^0 \to 2\gamma$ rate have been advanced by several authors. Ambiguities and unresolved questions in these calculations have been estimated to be 20 to 30%, in which case the present experimental situation is adequate. However, another measurement of the π^0 width of comparable accuracy but employing a technique other than the Primakoff effect would be assuring.

The ratio of partial radiative widths for the η^0 and π^0 mesons, derived from this experiment and from Ref. 2, is $\Gamma(\eta^0 \to 2\gamma)/\Gamma(\pi^0 \to 2\gamma) = 40.9 \pm 6.2$. This ratio can be accommodated by SU(3) models that mix η and η'. Recent theoretical calculations which are consistent with this ratio have been reported by Matsuda and Oneda[10] and by Bramon and Greco.[11] A measurement of the $X^0(960) \to 2\gamma$ width would now constitute a critical test of these mixing models. It would check the equivalence of the η-η' mixing angle derivable from the particle masses with that obtained from the decay rates.

We wish to acknowledge the assistance of the technical staff of the R. R. Wilson Laboratory in the execution and analysis of this experiment.

*Work supported in part by the National Science Foundation.

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