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EXPERIMENTAL DETERMINATION OF THE η LIFETIME BY THE MEASUREMENT OF THE PRIMAKOFF EFFECT.-

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ABSTRACT

An experiment for determining the η lifetime has been performed at DESY. The cross section for η photoproduction has been measured between 0^o and 4^o, at 4.0 GeV and 5.5 GeV incident γ ray energies and on different target materials (lead, silver, zinc).

η's were detected through their γ-γ decays.

The production is dominated by the Primakoff effect from which a value of $\Gamma_{\gamma\gamma}$ = (1.21 $\pm$ 0.26) keV. is derived.

We have measured the width of the $\eta \to \gamma\gamma$ decay by studying photoproduction on nuclei. This method has been discussed by several authors(1, 2, 3,4, 13) and has been successfully applied to determine the π^o lifetime(5).

Mesons which decay into two gammas can be produced by the interaction of an incident photon with a virtual photon associated with the Coulomb field of the target nucleus. At the momentum transfer involved ($Q < 80$ MeV/c), this process (Primakoff effect) can be considered as the inverse of the meson decay into two photons and the resulting cross section is directly proportional to the $\Gamma_{\gamma\gamma}$ decay width.

$$\frac{d\sigma_P}{d\Omega} = 8\alpha \Gamma_{\gamma\gamma} Z^2 \frac{\beta^3 E^4}{\mu^3} \frac{|F_{em}(Q)|^2}{Q^4} \operatorname{sen}^2\Theta \qquad (1)$$

Here α is the fine structure constant, Z the charge number of the target nucleus, μ, β, Θ, the meson mass, velocity and angle respectively; E is the energy of the incident photon which equals the total energy of the produced eta since the recoil of the nucleus can be disregarded. Q is the momentum transfer and $F_{em}(Q)$ is the electromagnetic form factor of the nucleus. $F_{em}(Q)$ was corrected to take into account the reabsorption of η's in nuclear matter. The "absorbed" form factor was calculated by a method developed by Morpurgo(3) for π^o production, but using a better approximation as needed for the larger mass of the η meson. Due to the peripheral character of the Primakoff production this correction was not large, ranging from 17 % to 8 % in the energy and atomic number regions covered in our experiment. As an input parameter the total cross section for η -nucleon interaction was assumed to be $\sigma^{TOT}_{N} = 27$ mb; $\frac{d\sigma_P}{d\Omega}$ is only slightly sensitive to the choice of $\sigma^{TOT}_{\eta N}$ ($\pm$ 50 % variation in $\sigma^{TOT}_{\eta N}$ produces $\mp$ 5 % in $\frac{d\sigma_P}{d\Omega}$).(12)

The Primakoff cross section (1) has a peculiar behaviour with angle, energy and atomic number; it is 0 at 0^o due to angular momentum conservation, reaches a peak value proportional to $\sim(E/\mu)^4$ at an angle $\sim \mu^2/2E^2$ and then decreases as $1/\Theta^2$ (at E = 5.0 GeV, in zinc, $\Theta_{peak} = 0.3^o$ and for $\Gamma_{\gamma\gamma} = 1$ keV , $\frac{d\sigma_P}{d\Omega}_{peak} = 0.6$ mb/ster).

To take advantage of these properties in identifying the Primakoff effect, we measured the angular distribution for η photoproduction in the region from 0^o to 4^o, at 4.0 and 5.5 GeV incident gamma ray energies and on zinc, silver and lead nuclei.

The bremsstrahlung beam was generated on an internal rotating target, collimated twice and cleared from charged particles. The beam was incident on a $\sim 0.1\ L_{rad}$ target and was finally monitored by a Wilson type quantameter. To reduce charged particles background the target was placed in a sweeping magnet and the photon beam was passing through a Helium bag.

η's were detected by measuring the angles and energies of their two decay photons. Eight photon detectors were mounted symmetrically four above and four below the beam, at a distance of 380 cm from the target and were run in ten double coincidences according to the scheme shown in Fig. 1; ten independent counting channels were therefore obtained.

Each photon detector consisted of a lead glass total absorption Cerenkov counter with a veto scintillation counter in front. The solid angles (typically 0.15 mster) were defined for each detector by circular lead collimators, resulting in an angular resolution of $\pm 0.4^{\circ}$.

The ten counting channels simultaneously collected data over the angular region between 0° and 3° in steps of 1°. By two placements of the apparatus it was possible to measure the cross section in steps of 0.5°.

Events generating coincidences in each of the ten channels (within 14 ns resolving time) were recorded; the pulses from the Cerenkov counters and, if present, from the anticoincidence counters were displayed on a fast scope and photographed together with a lamp selecting the channel involved.

Data reduction was made for each channel separately. Good events are defined as the uncharged ones within a resolving time of 3.5 ns. These events are represented by points in a two dimensional logaritmic plot whose coordinates are the two Cerenkov pulse heights (Fig. 2); the η's are clearly separated from the background.

Accidental $\gamma\gamma$ events in the η loci were typically 5 % of the η yield; η events randomly vetoed were also about 5 % and nearly compensated the previous correction.

A measurement of the "without target" background showed this to be less than 2.5 %.

Time correlated $\gamma\gamma$ events can be generated by other processes. In our experimental conditions, kinematical constraints forbid events, coming from $\pi^{0} + \gamma$ decays of vector mesons, to approach the η region.

$\gamma\gamma$ events arising from multiple π^{0} production or electromagnetic processes are not expected to shows any strong correlation

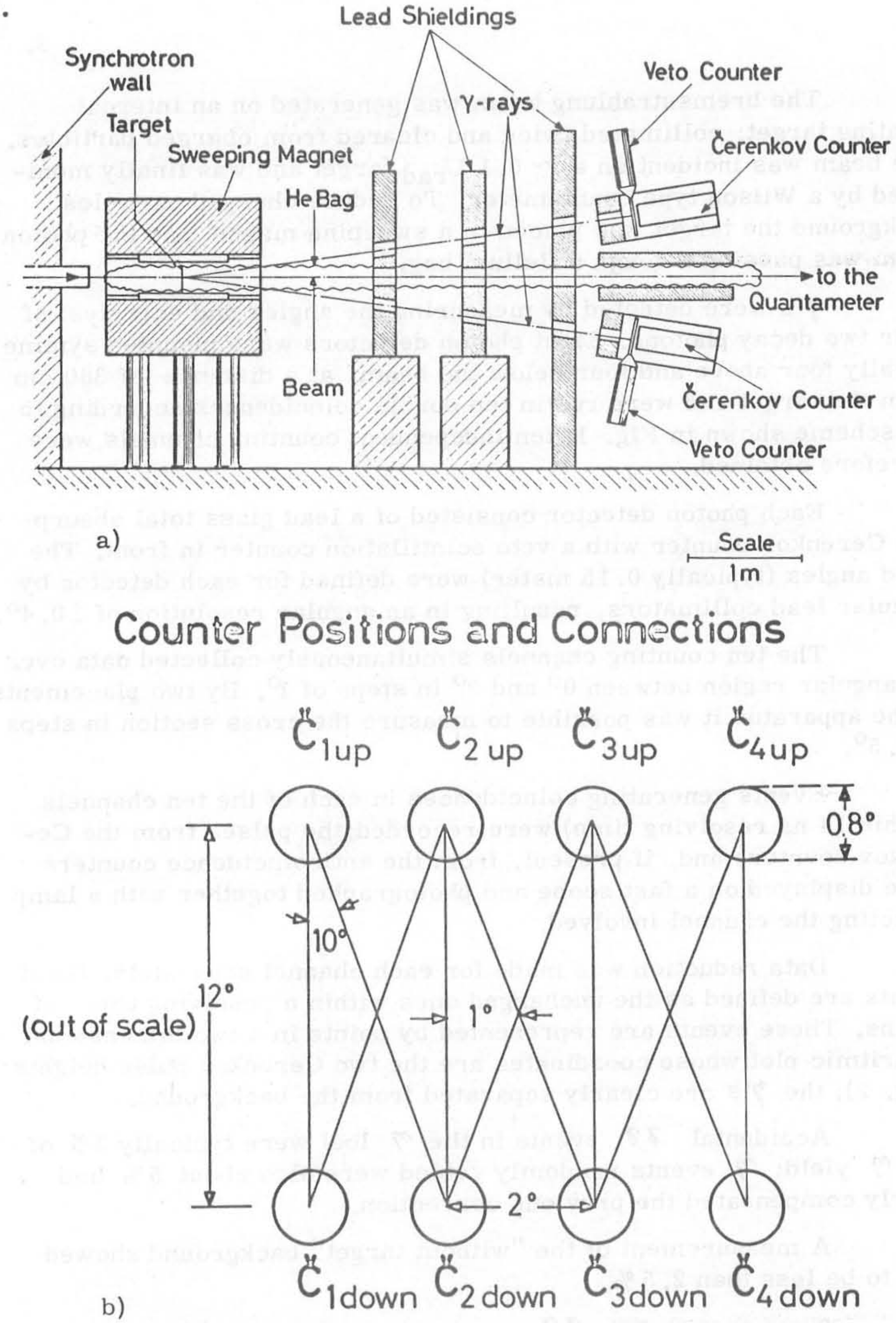

FIG. 1 - Side view of the experimental layout. The schematic front view of the counter system and of the ten associated counting channels illustrates the situation for the 5.0 GeV measurements. In the 4.0 GeV measurements collimators of total angular aperture 1.05° were used.

between the energies of the two detected photons. If such a contamination had been important, the E_1 vs. E_2 plots (Fig. 2) would have shown no clear separation between background and η's. To give an upper limit for this contamination the experimental conditions were slightly changed in order to make the detection of η's kinematically impossible. The counting rate in the η region was found to be smaller than 5 % of that obtained under normal conditions.

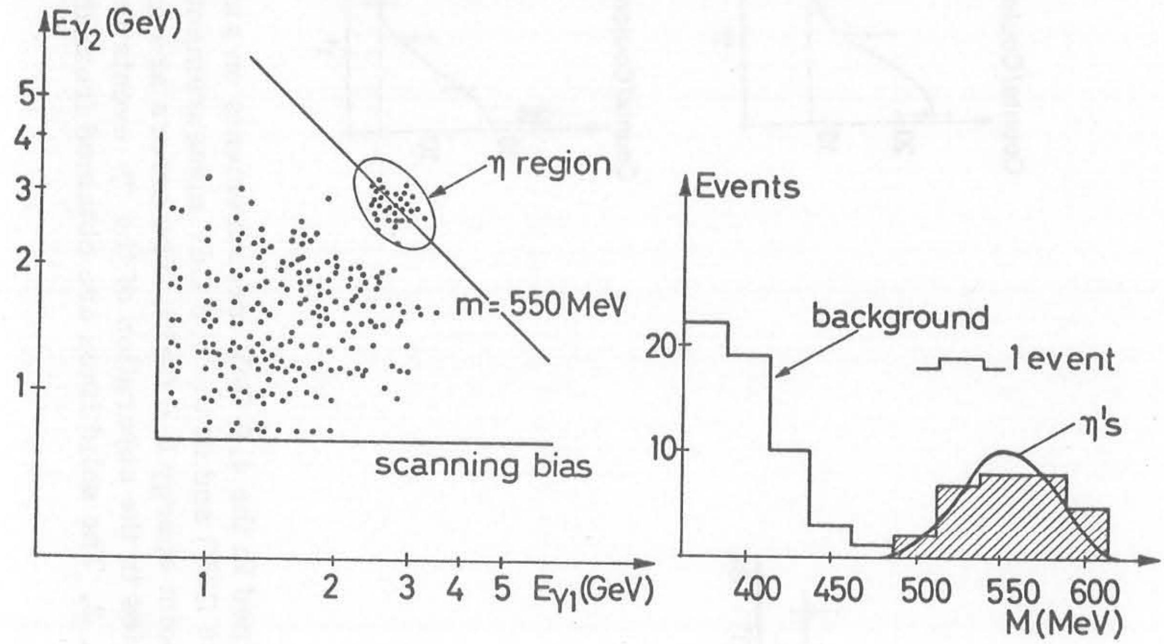

FIG. 2 - Typical plot of the pulse height correlation for good $\gamma\gamma$ events. The m = 550 MeV line is the predicted locus of the η events in the hypothesis of point counters; the elliptic locus is that predicted by the Monte Carlo calculation taking into account the finite dimensions of the Cerenkov apertures. The mass histogram on the right is derived from the $E\gamma_1$ vs. $E\gamma_2$ plot. The solid line represents the mass distribution as calculated by the Monte Carlo program.

The yields were corrected for η losses due to the conversion of the decay photons in the target, in the air and in the scintillators in front of the Cerenkov counters; this correction was about 10 %. A correction was also applied for the beam intensity as measured by the Wilson quantameter to account for the loss of the energy of the electron pairs produced in the target and swept by the cleaning magnet; this correction amounted to about - 9 %.

The angular distributions obtained at an average energy of 5.5 GeV from lead, silver and zinc, and at an average energy of 4.0 GeV from lead and zinc are shown in Fig. 3.

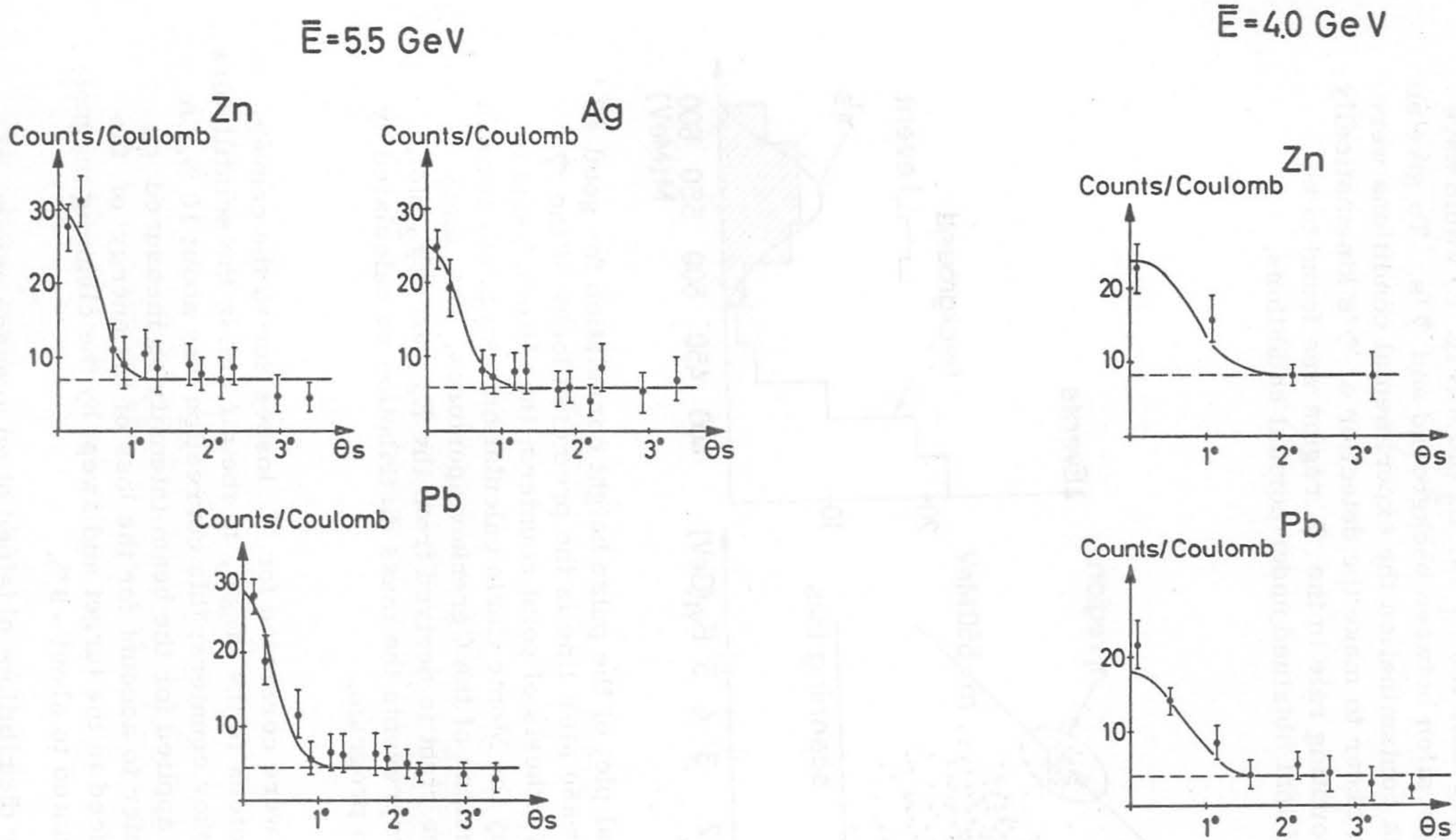

FIG. 3 - Experimental yields as obtained in the 4.0 GeV measurements on zinc and lead (bremsstrahlung end point energy 4.35 GeV) and in the 5.5 GeV measurements on zinc, silver and lead (bremsstrahlung end point energy 6.0 GeV). The errors are mainly statistical but include also the uncertainties in the separation of the η events from the background in plots like the one of fig. 2. The solid lines are obtained from the fits of Table 1.

The experimental yields show evidence for a large peak in the very forward direction followed by a rather constant production at larger angles.

Since the Primakoff cross section is a rapidly varying function of E and Θ, it is not possible to deduce the cross section directly from the experimental counting rates. A folding procedure had to be adopted by calculating a theoretical yield :

$$N(\Theta_S) = N_t \int_0^{4\pi} d\Omega \int_0^{E_{End\ point}} dE\, N(E)\, B\mathcal{E}(E\Theta\phi, \Theta_S) \frac{d\sigma(E\Theta)}{d\Omega} \quad (2)$$

where N_t is the number of nuclei per cm^2 in the target, N(E)dE is the number of photons with energy between E and E + dE in the bremsstrahlung spectrum and B is the branching ratio $\frac{\eta \to \gamma\gamma}{\eta \to TOT}$ = 31.4 %[6]. The efficiency $B\mathcal{E}(\Theta\phi E, \Theta_S)$ represents the probability for an η of energy E, emitted in the direction Θ, ϕ with respect to the beam, to be detected by a counting channel positioned at an angle Θ_S. These efficiencies were calculated between 0^o and 3.5^o by a Monte Carlo program whose statistical accuracy was $\pm$ 3 %. Due to this averaging over angle and energy the angular behaviour of the Primakoff yield is different from that of the Primakoff cross section and is peaked at $\Theta_S = 0^o$.

To interpret the experimental data three assumptions were made for the cross section to be used in (2). First we performed a two parameter fit using the sum of the Primakoff cross section, with $\Gamma_{\gamma\gamma}$ as a first parameter, and a constant non-interfering cross section as the second one. In Table 1 and Fig. 3 the results of these fits are presented. The best fit lines and the experimental points

TABLE 1

E_{pos} (GeV)	Element	$\Gamma_{\gamma\gamma}$ (keV)	Constant prod. $\frac{d\sigma}{d\Omega}/A$ (μb/ster · nucleon)	deg. of freedom	χ^2	Level of confidence (%)
5.5	Zn	1.38±0.15	1.14±0.12	10	6.3	~ 80
5.5	Ag	1.15±0.15	1.54±0.15	10	5.8	~ 85
5.5	Pb	1.10±0.10	1.03±0.10	10	6.1	~ 80
4.0	Zn	1.61±0.24	0.77±0.18	2	1.1	~ 60
4.0	Pb	1.21±0.20	0.43±0.10	6	5.0	~ 60

are in very good agreement for all five angular distributions; the five $\Gamma_{\gamma\gamma}$ values agree within the statistical errors.

A second two parameter fit was attempted using as $d\sigma/d\Omega$ in (2) the sum of a coherent nuclear cross section and a constant cross section as before. The form of the coherent nuclear cross section was assumed to be[3, 4]

$$\frac{d\sigma_{co}}{d\Omega} = C_{co} A^2 \operatorname{sen}^2\Theta \left| F_n(Q) \right|^2 \tag{3}$$

where C_{co} is a free parameter which can still contain an energy dependence and a small angular dependence. A and $F_n(Q)$ are respectively the mass number and the nuclear form factor. The coherent nuclear cross section is 0 at 0^o and has a shape determined by the rising $\operatorname{sen}^2\Theta$ factor and the decreasing $|F_n(Q)|^2$ factor. The peak is at an angle quite larger than that of the Primakoff cross section (for zinc at 5.0 GeV $d\sigma_{co}/d\Omega$ peaks at $\Theta_{peak} = 0.9^o$). The coherent nuclear cross section was corrected for η reabsorption in nuclear matter; this correction is very large (a factor between 2 and 5) but does not affect the shape and the peak position. No appreciable difference in shape can be obtained assuming different photoproduction models like vector meson exchange, reggeized vector meson exchange[7, 8] or simply an angle independent C_{co}. All reasonable models fail to reproduce the rapid angular variation of the Primakoff cross section. The results of the two parameter fits are given in Table 2 under the assumption of an angle independent C_{co}. The hypothesis of coherent cross section and constant background is strongly rejected by the quoted χ^2 values.

TABLE 2

E_{pos} (GeV)	Element	C_{co} (μb/ster)	Constant prod. $\frac{d\sigma}{d\Omega}/A$ (μb/ster · nucleon)	deg. of freedom	χ^2	Level of confidence (%)
5.5	Zn	400±52	0.63±0.07	10	23.9	~ 1
5.5	Ag	400±48	0.79±0.08	10	23.0	~ 1
5.5	Pb	820±83	0.29±0.03	10	18.0	~ 5
4.0	Zn	100±15	0.035±0.008	2	2.6	~ 25
4.0	Pb	160±26	0.095±0.002	6	7.3	~ 50

We checked if a coherent nuclear production is present together with the Primakoff effect; a third fit to all the data was performed after subtracting the constant background from the angular distributions. The assumed form for $d\sigma/d\Omega$ in (2) was the sum of the Primakoff cross section, the coherent nuclear cross section, the interference between the two and the constant contribution. The results of this four parameter fit is reported in Table 3. The coherent nuclear cross section as well as the constant contribution are consistent with 0. For the partial width of the η decay into two photons we get a best fit value

$$\Gamma_{\gamma\gamma} = (1.21 \pm 0.065)\ \text{keV}\ .$$

TABLE 3

$\Gamma_{\gamma\gamma}$ (keV)	C_{co} (μb/ster)	Interference phase	Constant prod. $\frac{d\sigma}{d\Omega}/A$ (μb/ster· nucleon)	deg. of freedom	χ^2	Level of confidence (%)
1.21±0.065	0.0±30	--	0.0±0.04	44	25.6	~98

Some considerations should be added on the mechanism of η production generating the almost angle independent contribution in the measured angular distributions. This contribution can only be an additive non interfering background since it is not depressed at large angles by the form factor as would be the case for a coherent η photoproduction.

Two hypotheses were considered: an incoherent nuclear production[(4)] and a two step process due to diffractive vector meson production and subsequent $V \rightarrow \eta + \gamma$ decays and η detection. These hypotheses produce η angular distribution whose shapes contrast sharply with our experimental yields. The understanding of this production is relevant to the determination of the $\Gamma_{\gamma\gamma}$ decay width because it introduces an uncertainty in the subtraction of the non-Primakoff contribution in the region of the Primakoff peak. For this reason there is an estimated error in $\Gamma_{\gamma\gamma}$ of $\pm$ 20 %.

Combining this error with the statistical error of the fit in Table 3 ($\pm$ 5 %), the estimated uncertainties due to the choice of $\sigma^{TOT}_{\eta N}$ ($\pm$ 5 %), the error in the quantameter calibration ($\pm$ 3 %), the error in the target thickness ($\pm$ 1 %), we quote as final result

$$\Gamma_{\gamma\gamma} = (1.21 \pm 0.26)\ \text{keV}.$$

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