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PRODUCTION OF RESONANCES IN PHOTON-PHOTON COLLISIONS*

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I. INTRODUCTION

In 1960 there appeared in the Physical Review a paper[1] by F. Low which showed how a measurement of the cross section for $ee \to ee\pi^0$ could yield a value for $\Gamma(\pi^0 \to \gamma\gamma)$, a quantity whose magnitude was otherwise rather uncertain experimentally at the time. All the essential elements of the subject of resonance production by the two photon processes in e^+e^- or $e^\pm e^\pm$ collisions, together with their derivation, are contained in that paper. It is the very model of a modern letter. What remains for this talk is just some commentary on the production of particular states in photon-photon collisions and why the results are of contemporary interest.

II. CROSS SECTIONS FOR RESONANCE PRODUCTION

The cross section for production by two photons of a particular resonance, R, with spin J_R in e^+e^- collisions is[1,2]

$$\sigma(e^\pm e \to e^+ e\, R) = [4\,\alpha \ln(E/m_e)]^2 \, f(m_R/2E) \frac{(2J_R+1)\Gamma(R\to\gamma\gamma)}{m_R^3} \quad , \qquad (1)$$

where E is the lepton beam energy,

$$f(x) = (2+x^2)^2 \ln(\frac{1}{x}) - (1-x^2)(3+x^2) \quad , \qquad (2)$$

and the only improvement on Ref. 1 is the factor of $2J_R+1$. For a given resonance $m_R/E \to 0$ as $E \to \infty$ and correspondingly $f(m_R/2E) \to 4\ln(2E/m_R) - 3$.

For purposes of discussion we shall factor the right hand side of Eq. (1) into two figures of merit. The quantity $(2J_R+1)\Gamma(R\to\gamma\gamma)/m_R^3$ is purely a characteristic of the particular resonance. The remaining factor, $[4\,\alpha\ln(E/m_e)]^2 f(m_R/2E)$, is mainly characteristic of the "colliding beams of photons" produced by the incident electrons and/or positrons. Of course, through $f(m_R/2E)$ the latter factor does have some dependence on the resonance, so our separation is somewhat arbitrary. However, for high enough beam energy ($E \gg m_R$), the value of $f(m_R/2E)$ is governed by the $\ln E$ in Eq. (2) and $f(m_R/2E)$ becomes less and less dependent on the value of m_R.

In Table 1 the cross sections for production of several resonances of interest are given for beam energies of 3 GeV, which are characteristic of

Table I

Cross Sections for Production of Various Resonances

in Two Photon Collisions for an Electron Beam Energy $E = 3$ GeV

Resonance	$\Gamma(R \to \gamma\gamma)$ (keV)	$(2J_R+1)\Gamma/m_R^3$ (nb)	$[4\alpha \ln(\frac{E}{m_e})]^2 f(\frac{m_R}{2E})$	$\sigma(ee \to eeR)$ (nb)
π°	7.95×10^{-3} [a]	1.26	0.78	1.0
η	0.324 [a]	0.76	0.43	0.2
η'	5.9 [b]	2.61	0.29	0.8
A_2	1.8 [c]	1.55	0.22	0.4
f	5 [c]	4.75	0.23	1.1
f'	0.4 [c]	0.22	0.19	0.04
η_c	6.4 [c]	9.2×10^{-2}	0.07	6×10^{-3}
χ_0	1 [c]	9.8×10^{-3}	0.05	5×10^{-4}
χ_2	4/15 [c]	2.3×10^{-3}	0.05	1×10^{-4}
η_b	0.4 [c]	1.9×10^{-4}	--	0

[a] Ref. 6.
[b] Ref. 7.
[c] Ref. 8.

the SPEAR or DORIS machines. The values of the decay widths into two photons for particular resonances are taken from experiment or are theoretical estimates whose basis is discussed in the next section. Note that the cross sections for production of the "old physics" particles such as pseudoscalar mesons (π°, η, η') or tensor mesons (A_2, f, f') are roughly one nanobarn. When we proceed to charmonium we lose two or more orders of magnitude in cross section, probably making experimental detection impossible.[5] With two photon decay widths of order a keV for both "old physics" and charmonium, this drop in cross section arises both from the m_R^{-3} in the figure of merit, $(2J_R+1)\Gamma/m_R^3$, characteristic of the resonance, and from the m_R dependence of $f(m_R/2E)$ in the figure of merit, $[4\alpha \ln(E/m_e)]^2 f(m_R/2E)$, of the beam when it has an energy of 3 GeV and we are interested in resonances with $m_R \sim 3$ GeV.

The latter effect can be largely alleviated by raising the beam energy, as can be seen in Table II where cross sections are given for E = 15 GeV, characteristic of PETRA and PEP. Now the figures of merit of the beam for both "old physics" and charmonium are within a factor of two or so, as we are out of the "threshold region" of $f(m_R/2E)$ in both cases. In particular the charmonium cross sections are up by an order of magnitude, perhaps making experimental measurements possible. Going to LEP energies, with cross sections as shown in Table III, does not help that much for charmonium. It still leaves the detection of η_b production hopeless, even though the figure of merit of the beam is within about a factor of two of that for η'.

Table II

Cross Sections for Production of Various Resonances

in Two Photon Collisions for an Electron Beam Energy E = 15 GeV

Resonance	$\Gamma(R\to\gamma\gamma)$ (keV)	$(2J_R+1)\Gamma/m_R^3$ (nb)	$[4\alpha \ln(\frac{E}{m_e})]^2 f(\frac{m_R}{2E})$	$\sigma(ee\to eeR)$ (nb)
π°	7.95×10^{-3} [a]	1.26	1.68	2.1
η	0.324 [a]	0.76	1.17	0.9
η'	5.9 [b]	2.61	0.97	2.6
A_2	1.8 [c]	1.55	0.86	1.3
f	5.0 [c]	4.75	0.87	4.2
f'	0.4 [c]	0.22	0.81	0.18
η_c	6.4 [c]	9.2×10^{-2}	0.57	5×10^{-2}
χ_0	1 [c]	9.8×10^{-3}	0.53	5×10^{-3}
χ_2	4/15 [c]	2.3×10^{-3}	0.51	1×10^{-3}
η_b	0.4 [c]	1.9×10^{-4}	0.21	4×10^{-5}

[a] Ref. 6.
[b] Ref. 7.
[c] Ref. 8.

Table III

Cross Sections for Production of Various Resonances

in Two Photon Collisions for an Electron Beam Energy E = 70 GeV

Resonance	$\Gamma(R\to\gamma\gamma)$ (keV)	$(2J_R+1)\Gamma/m_R^3$ (nb)	$[4\alpha\ln(\frac{E}{m_e})]^2 f(\frac{m_R}{2E})$	$\sigma(ee\to eeR)$ (nb)
π°	7.95×10^{-3} [a]	1.26	2.95	3.7
η	0.324 [a]	0.76	2.29	1.7
η'	5.9 [b]	2.61	2.02	5.3
A_2	1.8 [c]	1.55	1.87	2.9
f	5.0 [c]	4.75	1.89	8.9
f'	0.4 [c]	0.22	1.80	0.40
η_c	6.4 [c]	9.2×10^{-2}	1.48	0.14
χ_0	1 [c]	9.8×10^{-3}	1.41	1.4×10^{-2}
χ_2	4/15	2.3×10^{-3}	1.40	3.2×10^{-3}
η_b	0.4 [c]	1.9×10^{-4}	0.94	1.8×10^{-4}

[a] Ref. 6.
[b] Ref. 7.
[c] Ref. 8.

III. PHOTON-PHOTON COUPLINGS OF VARIOUS RESONANCES

We consider mesons to be composed of a quark and antiquark. Restricting our attention to begin with to those mesons composed of u, d, and s quarks, photon-photon couplings are possible to the neutral, nonstrange states $(\bar{u}u - \bar{d}d)/\sqrt{2}$, $(\bar{u}u + \bar{d}d - 2\,\bar{s}s)/\sqrt{6}$, and $(\bar{u}u + \bar{d}d + \bar{s}s)/\sqrt{3}$, which transform as the third component of an octet, eighth component of an octet, and singlet, respectively, under SU(3).

We picture the decay of mesons as occuring through the annihilation of the quark and antiquark into two photons. Hence the amplitude is proportional to the square of the charges of the quarks contained in a given meson. Assuming that the spatial wave functions for all nine states of a given J^P are the same (so-called "nonet symmetry"), the ratio of two photon decay amplitudes in the usual fractionally charged quark model[9] for the states enumerated above is

$$A_3 : A_8 : A_1 = \frac{1}{\sqrt{2}}\left(\frac{4}{9} - \frac{1}{9}\right) : \frac{1}{\sqrt{6}}\left(\frac{4}{9} + \frac{1}{9} - \frac{2}{9}\right) : \frac{1}{\sqrt{3}}\left(\frac{4}{9} + \frac{1}{9} + \frac{1}{9}\right) \quad . \tag{3}$$

The corresponding reduced widths behave as the square of these amplitudes, i.e.,

$$\bar{\Gamma}_3 : \bar{\Gamma}_8 : \bar{\Gamma}_1 = 3 : 1 : 8 \quad . \tag{4}$$

The opposite extreme to meson eigenstates consisting of an SU(3) octet and singlet is that of ideal mixing. In terms of the quark model, the states are $(\bar{u}u - \bar{d}d)/\sqrt{2}$, $(\bar{u}u + \bar{d}d/\sqrt{2}$ and $\bar{s}s$. Again assuming "nonet symmetry" a simple computation like that above establishes that

$$\bar{\Gamma}_{(\bar{u}u-\bar{d}d)/\sqrt{2}} : \bar{\Gamma}_{(\bar{u}u+\bar{d}d)/\sqrt{2}} : \bar{\Gamma}_{\bar{s}s} = 9 : 25 : 2. \tag{5}$$

As we discuss various mesons composed of u, d, and s quarks we will be viewing the ratio of two photon decay widths as a reflection of singlet-octet mixing or vice versa, and will be referring back to Eqs. (4) and (5) as extreme cases.

We begin our consideration of specific mesons with the pseudoscalars π°, η, and η'. First we shall do a calculation of their relative decay widths into two photons as it might have been carried out in 1964. Using one decay width, say $\Gamma(\pi^\circ \to \gamma\gamma)$, as input, plus the assumption of nonet symmetry, allows us to calculate the other two widths. Actually, the situation is a little more complicated in that the η and η' do not appear to be exactly in an SU(3) octet and singlet, respectively. From a quadratic Gell-Mann-Okubo mass formula one obtains a mixing angle $\theta_{ps} \approx -11°$. Using this mixing angle and the central value for $\Gamma(\pi^\circ \to \gamma\gamma) = 7.95$ eV together with a p^3 phase space factor yields the predictions $\Gamma(\eta \to \gamma\gamma) = 414$ eV and $\Gamma(\eta' \to \gamma\gamma) = 6.3$ keV. These are to be compared with the experimental values of 324 ± 46 eV and $5.9 \pm 1.6 \pm 1.2$ keV, respectively.

This rather satisfactory agreement may be put another way. Let us input the central values of $\Gamma(\pi^\circ \to \gamma\gamma)$, $\Gamma(\eta \to \gamma\gamma)$, and $\Gamma(\eta' \to \gamma\gamma)$ and fit the singlet and octet amplitudes for decay into two photons, A_1 and A_8, and pseudoscalar mixing angle θ_{ps}. One finds in addition to a strength for A_8, that

$$A_1/A_8 = 0.92\ (2\sqrt{2})$$

and

$$\theta_{ps} = -7.7° .$$

A value of $2\sqrt{2}$ for A_1/A_8 corresponds to nonet symmetry. We are fairly close to the situation in Eq. (4). It seems very likely that if we had the presently available data on pseudoscalar decays to two photons 15 years ago, the above comparison of theory and experiment would have been hailed as an outstanding success of the SU(3) classification of the pseudoscalars and of nonet symmetry.

But it is 1979 and we know some additional theoretical information which is very germane to this problem. Most importantly, there is an anomaly[10] in the Ward identities for the axial-vector-photon-photon vertex which when combined with the PCAC hypothesis leads to an absolute prediction for $\Gamma(\pi^\circ \rightarrow \gamma\gamma)$. With the inclusion of color the theoretical prediction is $\Gamma(\pi^\circ \rightarrow \gamma\gamma) \approx 7.6$ eV. to be compared to the experimental[6] 7.95 ± 0.55 eV. This is a real success of the theory and an improvement over the earlier situation.

But what about η and η'? For fractionally charged quarks as long as we keep the conventional assignment of the η and η' everything goes through essentially as above in relating the η and η' widths to that of the π°. For integrally charged Han-Nambu[11] quarks, however, things change.

To understand the change in predictions when integrally charged quarks are involved, it is perhaps clearest to note[12] that in these models the electromagnetic current,

$$J_\mu^{em}(x) = J_\mu^1(x) + J_\mu^8(x), \tag{6}$$

where the superscripts refer to the transformation properties of these currents under the SU(3) of color. The color singlet current $J_\mu^1(x)$ is just the usual electromagnetic current. The color octet current J_μ^8 is absent in in the fractionally charged quark model. Even when present:

$$\langle h |\ J_\mu^8(x)\ | h' \rangle \equiv 0, \tag{7}$$

where h and h' are color singlet hadrons, as have only been observed up to now. However.

$$< h \,|\, J_\mu^{8}(x)\, J_\mu^{8}(0) \,|\, h^1 >$$

is not necessarily zero. In particular it turns out that

$$< \eta_1 \,|\, J_\mu^{8}(x)\; J_\mu^{8}(0) \,|\, 0> \;=\; < \eta_1 \,|\, J_\mu^{1}(x)\; J_\mu^{1}(0) \,|\, 0> \;, \qquad (8)$$

so that the amplitude for the singlet pseudoscalar, η_1, to decay into two photons, which is proportional to $< \eta_1 \,|\, J_\mu^{em}(x)\, J_\nu^{em}(0) \,|\, 0>$ is twice as big in the integrally charged quark model as its value (proportional to $< \eta_1 \,|\, J_\mu^{1}(x)\, J_\nu^{1}(0) \,|\, 0>$) in the fractionally charged quark model. As a result the prediction for $\Gamma(\eta' \to \gamma\gamma)$ goes up by about a factor of four[13] ("about" because the η' is mostly, but not entirely, η_1), when compared to the fractionally charged model with the same assumptions about nonet symmetry and mixing angles. It is important to note that these conclusions rest implicitly on the fact that the amplitudes for $\pi^\circ \to \gamma\gamma$, $\eta_8 \to \gamma\gamma$ and $\eta_1 \to \gamma\gamma$ all originate in the anomaly in the axial-vector-photon-photon vertex, which is a short distance effect. Otherwise, $< \eta_1 \,|\, J_\mu^{8}(x)\; J_\mu^{8}(0) \,|\, 0>$ would not be unambiguously calculable. Moreover, looked at in terms of the insertion of a complete set of intermediate states between the currents, if longer distances and hence lower masses (known to be characterized as being color singlets) dominate, the color octet currents (which cannot connect the vacuum or η_1 to such color singlet states) will give a vanishing contribution. Only a truly short distance effect gets contributions from colored states at arbitrarily high masses.

Thus, the ratios $\Gamma(\pi^\circ \to \gamma\gamma)$: $\Gamma(\eta \to \gamma\gamma)$: $\Gamma(\eta' \to \gamma\gamma)$ are a test for fractionally versus integrally charged quarks provided nonet symmetry is assumed. It is certainly possible to object to this latter assumption (equivalent to taking $A^1/A^8 = 2\sqrt{2}$ in our "1964 analysis"). In fact, if the wave function of η_1 is changed so as to reduce the amplitude for $\eta_1 \to \gamma\gamma$ through the color singlet currents from its nonet symmetry value by a factor of two, it would exactly compensate for the factor of two in going from fractional to integral charge quarks.

Chanowitz[14] tried to get around this by using current algebra low energy theorems for the amplitudes for $\eta \to \pi\gamma\gamma$ and $\eta' \to \pi\gamma\gamma$ in addition to those for the two photon decays. The former are affected somewhat differently than the latter in going from fractional to integral charge quarks. However, one may object to this because experimentally the $\pi\pi$ system for the η' decay is mostly in the ρ resonance, calling into doubt the usefullness of low energy theorems for the pions in describing the actual decay amplitude.

Recently Chanowitz[15] has also tried to avoid these objections by examining $\Gamma(\eta_1 \to \rho\gamma)/\Gamma(\eta_1 \to \gamma\gamma)$ and using the vector dominance model. Aside from the vector dominance model, there is still an extrapolation to be made (this time in $\langle\eta_1|J_\mu^8 J_\mu^8|0\rangle / \langle\eta_1|J_\mu^1 J_\nu^1|0\rangle$ from zero mass^2 to $m_{\eta'}^2$).

As you surely would suspect, all these different tests of the hypothesis of fractionally versus integrally charged quarks support fractional charges if one is willing to swallow the extra assumptions necessary to make a prediction in each case. I would summarize the situation as strongly favoring fractionally charged quarks. But if integrally charged quarks were found tomorrow, all the objections needed to wiggle out of every test are already in place, ready for use.

Before leaving the subject of anomalies and low energy theorems we note one other possible connection to two photon physics. It was realized a number of years ago that there is also an anomaly in the vertex for the stress energy tensor $\theta_{\mu\nu}$, and two photons.[16] If a scalar meson, σ, dominates the trace of the stress energy tensor (much as the pion dominates the divergence of the axial-vector current), then the anomaly translates[16] into a coupling strength for $\sigma \to \gamma\gamma$. In the time period since this idea was first suggested the proofs of the existence of an anomaly (to all orders in QCD) have improved dramatically.[17] However, the theoretical desire for a scalar meson dominating the trace of $\theta_{\mu\nu}$ has lost its impetus, and which, if any, scalar meson corresponds to the σ has become increasingly obscure experimentally.

Another somewhat elusive type of meson which is producible in two photon collisions is a "glueball"--a set of quarkless states expected to exist in pure QCD. Rather strong arguments[18] have been made that the lowest lying such states with $J^{PC} = 0^{++}$, 2^{++} should have masses of 1 to 2 GeV. Both here and elsewhere, arguments[19] have been made suggesting widths for "glueball" $\to \gamma\gamma$ of the order of keV's. As such they should be observable with the sensitivity level of two photon experiments now envisioned. A search for such states in these experiments is certainly worthwhile, although I would guess $\psi \to \gamma +$ "glueball" is better, especially in light of the direct photon signal at the ψ which has been recently found.[20]

The $q\bar{q}$ mesons with one unit of internal angular momentum can have $J^{PC} = 0^{++}$, 1^{++}, 2^{++}, and 1^{+-}. Those states with $J = 1$ are forbidden to couple to two real photons by a well known theorem.[21] The scalar mesons δ, S^*, ϵ?, ϵ',... are candidates for the $J^{PC} = 0^{++}$ states composed of u, d, and s quarks, but the proper identification of the experimentally observed particles with the quark model states is obscure, to say the least. Observing their two photon decay widths may help sort things out.

The situation for $J^{PC} = 2^{++}$ is much clearer, and has been for a long time. The A_2, f, and f' appear to be close to the ideally mixed states $(\bar{u}u - \bar{d}d)/\sqrt{2}$, $(\bar{u}u + \bar{d}d)/\sqrt{2}$ and $\bar{s}s$, respectively, both from their masses and decay modes. Hence, as calculated earlier, we expected two photon decay widths (corrected for phase space) in the approximate ratios 9:25:2. Absolute predictions for $\Gamma(f \to \gamma\gamma)$ in the literature[22] range from about 4 to 20 keV, with my own prejudice favoring the lower end (as reflected in the tables). Hints of the f, with a width into $\gamma\gamma$ in this range, are found in talks at this conference.[23,24,25]

An additional handle for separating the different models enters for the tensor mesons since the net angular momentum, λ, along either photon's momentum is 0 or $\pm$ 2. The total width for decay into two photons can then be decomposed as

$$\Gamma = \Gamma_{\lambda=o} + \Gamma_{\lambda=2} \tag{9}$$

The division of the width between $\Gamma_{\lambda=0}$ and $\Gamma_{\lambda=2}$ can be studied in two photon collisions by examination of the angular distribution of the tensor meson decays into hadrons. For example, in $\gamma\gamma \to f \to \pi\pi$ the angular distribution of a final pion with respect to an initial photon is

$$\frac{d\Gamma}{d\cos\theta} \propto \left(\frac{3\cos\theta - 1}{2}\right)^2 \Gamma_{\lambda=0} + \left(\sqrt{\frac{3}{8}}\sin^2\theta\right)^2 \Gamma_{\lambda=2} \quad . \tag{10}$$

To extend these considerations to heavier quarks we must take into account the charges of the heavier quarks and the wave function of the bound state "-onia." For two photon decay the amplitude goes as the square of the charge of the quark involved, so the former effect is straightforward to take into account. The latter is not so trivial, even though our assumption of nonet symmetry (same wave functions) seemed to work well for the π°. η, and η'. This is because these states, composed of light u, d, and s quarks, have a relativistic bound state character, while those composed of c, b,... quarks have an increasingly nonrelativistic nature. I feel that naively extending nonet symmetry to include the wave functions for charmonium, bottomonium,... is unlikely to be correct.

A more accurate estimate of the 2γ decay width of η_c, η_b,... follows from considering them as nonrelativistic bound states, where to lowest order in strong interactions

$$\Gamma(\eta_q \to \gamma\gamma) \propto e_q^4 \frac{|f(o)|^2}{m_q^2} , \tag{11a}$$

$$\Gamma(V_q \to e^+e^-) \propto e^2 e_q^2 \frac{|f(o)|^2}{m_q^2} . \tag{11b}$$

Here q is a heavy quark species with mass m_q and charge e_q, η_q and V_q are the pseudoscalar and vector s-wave bound states with (assumed) common (for a particular quark, q) wave function at the origin, f(o). Taking the ratio of these widths, the wave function and mass cancel out leaving a dependence only on e_q^2. In particular, for the c and b quarks,

$$\begin{aligned} \Gamma(\eta_c \to \gamma\gamma)/\,\Gamma(\psi \to e^+e^-) &= \frac{4}{3} , \\ \Gamma(\eta_b \to \gamma\gamma)/\,\Gamma(T \to e^+e^-) &= \frac{1}{3} , \end{aligned} \tag{12}$$

leading to

$$\begin{aligned} \Gamma(\eta_c \to \gamma\gamma) &\approx 6.4 \text{ keV} \\ \Gamma(\eta_b \to \gamma\gamma) &\approx 0.4 \text{ keV} , \end{aligned} \tag{13}$$

as used in the Tables in Section II.[26] These numbers are orders of magnitude smaller than the widths one would obtain by naively extending nonet symmetry and using the 2γ widths of π°, η, and η'.

For the p-wave states of charmonium,[26] a related estimate of two photon decay widths can be made by noting that $\Gamma(\chi \to \gamma\gamma)/\Gamma(\chi \to gg)$, where the decay width into two gluons $\Gamma(\chi \to gg)$ is identified with the hadronic width, should be of order $(\alpha/\alpha_s)^2$. With $\Gamma(\chi_o \to \text{hadrons})$ probably of order several MeV's one obtains $\Gamma(\chi_o \to \gamma\gamma)$ of order a keV. Similar estimates hold for $\chi_2(3550)$. An interesting and more clearcut test here is of the ratio of two photon widths, rather than the crude estimates of their absolute values. The related quark spin structure of the $^3P_o(\chi_o)$ and $^3P_2(\chi_2)$ systems yields $\Gamma(\chi_o \to \gamma\gamma)/\Gamma(\chi_2 \to \gamma\gamma) = 15/4$. This prediction for two photon decay widths should be more reliable than that for two gluons (hadrons?), which is in experimental difficulty[27] and theoretically suspect because of higher order QCD corrections.[28] Further theoretical work to see if the ratio 15/4 of $\gamma\gamma$ widths holds up under QCD corrections is needed.

IV. CONCLUSIONS

The subject of production of resonances via two photons in e^+e^- colliding beams has finally come into its own. In particular, the η' is already changing from "this year's sensation" to "next year's normalization."

As for the other "old physics" mesons with even charge conjugation it seems likely that measurements of the scalar and tensor mesons coupling to two photons are quite doable and will be forthcoming. These will yield some interesting information on the quark content of these states and/or the dynamics of their two photon decays.

As for the charmonium states, a measurement of some of the two photon decay widths would be quite interesting in terms of the information it gives on the dynamics of this system. However, even at LEP energies the cross sections for production of any particular state are rather small and one must be lucky to have a detectable decay mode or modes with substantial branching fraction. It is certainly worth trying--maybe we'll be lucky. For the η_b the situation looks hopeless.

Finally, there is the π° which started the whole subject. A measurement of this coupling is much easier using the complementary technique for determining two photon widths-the Primakoff effect.[29] $\Gamma(\pi^\circ \to \gamma\gamma)$ has long since been measured[6] with high accuracy in this way.

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