Radiative decays with scalar mesons $a_0(980)$ and $f_0(980)$ in Resonance Chiral Theory

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Motivations

- Poorly known structure of scalar mesons ($J^{PC} = 0^{++},\ I = 0, 1$)
- Radiative decays featured by scalars $f_0(980)$ and $a_0(980)$:

$$\begin{array}{rl} a_0 \to \gamma\gamma, & f_0 \to \gamma\gamma \\ \phi(1020) \to \gamma a_0, & \phi(1020) \to \gamma f_0 \\ f_0/a_0 \to \gamma\rho(770) & f_0/a_0 \to \gamma\omega(782) \end{array}$$

  Interest to $\phi \to \gamma f_0/a_0$ was initiated by Achasov and Ivanchenko, NP B315, 465 (1989).
- A unified description based on Resonance Chiral Theory (RχT)
- Decay widths and invariant mass spectra of $\pi^0\pi^0$ (or $\pi^0\eta$) in $e^+e^- \to \gamma^* \to \gamma f_0\ (a_0) \to \pi^0\pi^0\gamma\ (\pi^0\eta\gamma)$
- Comparison with data from KLOE, SND, CMD; predictions for decay widths of $f_0/a_0 \to \gamma\rho/\omega$ (DAΦNE or its upgrade, COSY in Jülich)

Lagrangian of RχT [Ecker, Gasser, Pich, de Rafael 1989]

$$\mathcal{L}_{\chi-sym.} = \frac{f_\pi^2}{4}\left\langle D_\mu U D^\mu U^\dagger \right\rangle + \frac{eF_V}{2\sqrt{2}} F^{\mu\nu}\left\langle V_{\mu\nu}(uQu^\dagger + u^\dagger Q u)\right\rangle$$
$$+\frac{iG_V}{\sqrt{2}}\langle V_{\mu\nu}u^\mu u^\nu\rangle + \mathcal{L}_{kin.\ terms\ +\ axial-vector\ mesons},$$

$$U \equiv \exp(i\sqrt{2}P/f_\pi), \qquad u = U^{1/2}, \qquad u^\mu = iu^\dagger(D^\mu U)u^\dagger,$$

$f_\pi = 93.2$ MeV, F_V and G_V are coupling constants, P is octet of pseudoscalar mesons ($J^P = 0^-$),

$$D_\mu U \equiv \partial_\mu U + \imath e B_\mu [U, Q]$$

$F^{\mu\nu} = \partial^\mu B^\nu - \partial^\nu B^\mu$, B^μ is EM field, $Q \equiv \mathrm{diag}(\frac{2}{3}, -\frac{1}{3}, -\frac{1}{3})$ is quark charge matrix and $V_{\mu\nu}$ is nonet of vector mesons.

Chiral symmetry breaking part is

$$\mathcal{L}_{\chi-sym.break} = \frac{f_\pi^2}{4}\left\langle \chi U^\dagger + \chi^\dagger U \right\rangle$$

$$\chi = -\frac{2}{3f_\pi^2}\mathrm{diag}(m_u, m_d, m_s)\langle 0|\bar{q}q|0\rangle \stackrel{SU(2)_f}{=} \mathrm{diag}(m_\pi^2, m_\pi^2, 2m_K^2 - m_\pi^2).$$

We add pseudoscalar singlet η_0, combine $P + \eta_0/\sqrt{3}$ into nonet, and use for η - η' a two-parameter mixing scheme [Beisert, 2001]

$$\begin{aligned} \eta &= \cos\theta_8\,\eta_8 - \sin\theta_0\,\eta_0, \\ \eta' &= \sin\theta_8\,\eta_8 + \cos\theta_0\,\eta_0 \end{aligned}$$

with $\theta_0 = -9.2^\circ$ and $\theta_8 = -21.2^\circ$ from experiment [Feldmann et al., PR D58, 114006 (1998)].

Interaction of scalars with pseudoscalars

$$\mathcal{L}_S = c_d \left\langle S^{oct} u_\mu u^\mu \right\rangle + c_m \left\langle S^{oct} \chi_+ \right\rangle + \tilde{c}_d S^{sing} \langle u_\mu u^\mu \rangle + \tilde{c}_m S^{sing} \langle \chi_+ \rangle ,$$

$\chi_+ = u^+ \chi u^+ + u \chi u$. The lightest scalar nonet

$$S = \begin{pmatrix} a_0^0/\sqrt{2} + S_8/\sqrt{6} & a_0^+ & \kappa^+ \\ a_0^- & -a_0^0/\sqrt{2} + S_8/\sqrt{6} & \kappa^0 \\ \kappa^- & \bar{\kappa}^0 & -2S_8/\sqrt{6} \end{pmatrix} + \frac{1}{\sqrt{3}} S^{sing},$$

c_d, c_m and $\tilde{c}_d, \tilde{c}_m$ are octet and singlet couplings.
Multiplet decomposition of isoscalar mesons $f_0(980)$ and $\sigma \equiv f_0(600)$

$$\begin{cases} f_0 = S^{sing} \cos\theta - S_8 \sin\theta \\ \sigma = S^{sing} \sin\theta + S_8 \cos\theta \end{cases}$$

with octet-singlet mixing angle θ.

General features, decay channels

- RχPT = χPT $+$ resonances V, A, S
- reliable below and near 1 GeV
- no direct coupling of scalars to $\gamma\gamma$ and γV $\Longrightarrow$ in lowest order one-loop mechanism

Calculated decay widths:

- tree level: dominant channels $a_0 \to \pi\eta$ and $f_0 \to \pi\pi$
- one-loop level:
  two-photon decays $a_0 \to \gamma\gamma$ and $f_0 \to \gamma\gamma$
  ϕ(1020) decays $\phi \to \gamma a_0$ and $\phi \to \gamma f_0$
  decays of scalars $a_0 \to \gamma\rho$, $a_0 \to \gamma\omega$, $f_0 \to \gamma\rho$, $f_0 \to \gamma\omega$

General features, decay channels

- interaction vertices are momentum-dependent (also pointed out to in [Black, Harada, Schechter, PR D73, 054017 (2006)])
- 5 fitting parameters: $c_d, c_m, \tilde{c}_d, \tilde{c}_m, \theta$. If $N_c \to \infty$ then

$$\tilde{c}_m = c_m/\sqrt{3}, \qquad \tilde{c}_d = c_d/\sqrt{3}$$

  and the number is reduced to 3.
- Divergent part of $\phi \to \gamma f_0/a_0$ is proportional to difference $F_V - 2\ G_V$; therefore to have the amplitude finite we choose

$$F_V = 2\ G_V$$

General features, decay channels

In practice the coupling constants G_V and F_V are determined from decay widths

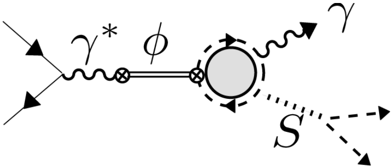
$$\Gamma_{\rho\to\pi\pi} = 146.4 \pm 1.5 \; MeV$$

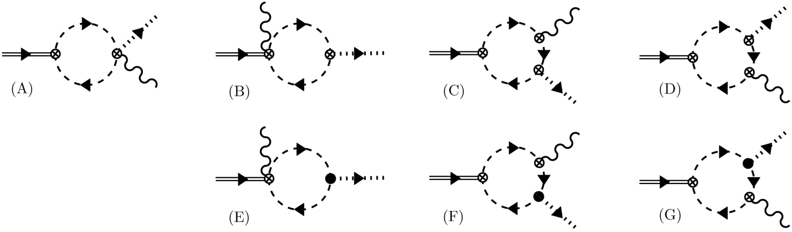
$$\Gamma_{\rho\to e^+e^-} = 7.02 \pm 0.11 \; keV$$

In fact $G_V = 65.2$ MeV and $F_V = 156.16$ MeV.

This relation naturally arises in Hidden Local Gauge Symmetry Model [Bando et al. 1988] and massive Yang-Mills models [Meissner 1988]; it also follows from high-energy constraints [Ecker, Gasser, Pich, de Rafael 1989].

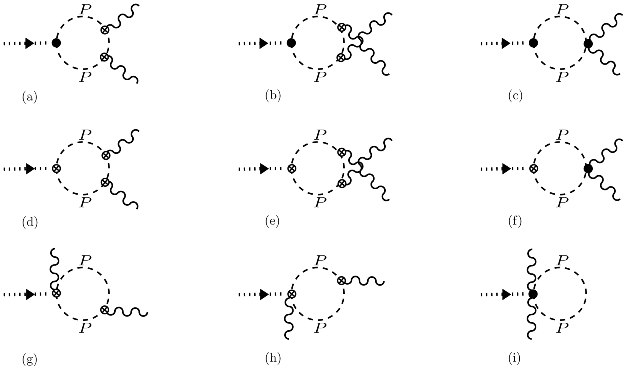
One-loop mechanism for ϕ-meson decays to $f_0(a_0)$





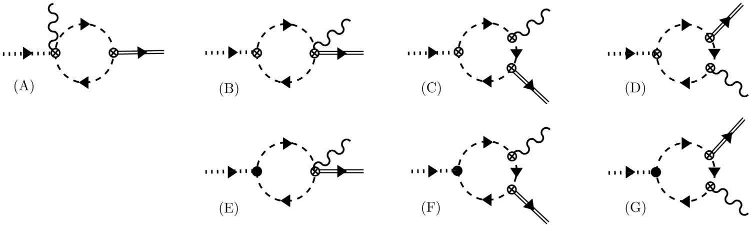
(momentum-dependent $\otimes$ and momentum-independent $\bullet$ vertices for interactions with scalar meson)

Two-photon decay amplitude for scalar meson



(momentum-dependent $\otimes$ and momentum-independent ● vertices)

Scalar-meson radiative decay amplitude



(momentum-dependent ⊗ and momentum-independent ● vertices)

Crucial quantity is three-point loop integral $\Psi(m_P^2, M_S^2, M_V^2)$ for scalar-vector-photon transition

Calculations [Ivashyn, Korchin, EPJ C54, 89 (2008)] vs. PDG values

widths	our fit	[Kalashnikova et al. (2006)]	PDG average
$\frac{\Gamma_{\phi\to\gamma a_0}}{\Gamma_\phi}$	1.7×10^{-4}	1.4×10^{-4}	$(7.6\pm0.6)\times10^{-5}$
$\frac{\Gamma_{\phi\to\gamma f_0}}{\Gamma_\phi}$	$4.4\times10^{-4*}$	1.4×10^{-4}	$(4.40\pm0.21)\times10^{-4}$
$\frac{\Gamma_{\phi\to\gamma f_0}}{\Gamma_{\phi\to\gamma a_0}}$	2.6	1	6.1 ± 0.6
$\Gamma_{a_0\to\pi\eta}$	14.2 **MeV**	—	—
$\Gamma_{f_0\to\pi\pi}$	41.8 **MeV**	—	$34.2^{+22.7}_{-14.3}$ MeV
$\Gamma_{a_0,\,total}$	17.8 **MeV**	—	$50-100$ MeV
$\Gamma_{a_0\to\gamma\gamma}$	0.30 keV*	0.24 keV	0.30 ± 0.10 keV
$\Gamma_{f_0\to\gamma\gamma}$	0.31 keV*	0.24 keV	$0.31^{+0.08}_{-0.11}$ keV
$\Gamma_{a_0\to\gamma\rho}$	9.1 **keV**	3.4 keV	—
$\Gamma_{f_0\to\gamma\rho}$	9.6 **keV**	3.4 keV	—
$\Gamma_{a_0\to\gamma\omega}$	8.7 **keV**	3.4 keV	—
$\Gamma_{f_0\to\gamma\omega}$	15.0 **keV**	3.4 keV	—

(* marks input values)

Parameter-independent predictions

- Ratio

$$\frac{\Gamma_{a_0\to\gamma\gamma}}{\Gamma_{\phi\to\gamma a_0}} = \frac{3e^2 f_\pi^4 M_\phi}{G_V^2 M_{a_0}(M_\phi^2 - M_{a_0}^2)} \left| \frac{\Psi(m_K^2; M_{a_0}^2; 0)}{\Psi(m_K^2; M_{a_0}^2; M_\phi^2)} \right|^2 = 0.42.$$

  Experiment (PDG average) gives 0.93.

- $$\frac{\Gamma_{a_0\to\gamma\rho}}{\Gamma_{a_0\to\gamma\omega}} = \frac{(M_{a_0}^2 - M_\rho^2)M_\rho^2}{(M_{a_0}^2 - M_\omega^2)M_\omega^2} \left| \frac{\Psi(m_K^2; M_{a_0}^2; M_\rho^2)}{\Psi(m_K^2; M_{a_0}^2; M_\omega^2)} \right|^2 = 1.04$$

  has not been measured.
  Theoretical prediction [Kalashnikova et al., PR C73, 045203 (2006)]: $q\bar{q}$ model via quark loop gives 1/9, $qq\bar{q}\bar{q}$ structure predicts ≈ 0, $K\bar{K}$-loop gives ≈ 1.

Parameter-independent predictions

- Ratio

$$\frac{\Gamma_{a_0 \to \gamma\, \rho(\omega)}}{\Gamma_{\phi \to \gamma\, a_0}} = \frac{3M_\phi^3}{M_{a_0}^3} \frac{M_{a_0}^2 - M_\rho^2}{M_\phi^2 - M_{a_0}^2} \left(\frac{M_\rho^2}{2M_\phi^2}\right) \left|\frac{\Psi(m_K^2, M_{a_0}^2, M_\rho^2)}{\Psi(m_K^2, M_{a_0}^2, M_\phi^2)}\right|^2 \approx 12$$

has not been measured so far. The model [Dobado, Pelaez, PR D56, 3057 (1997)] predicts about 5.6.

Invariant-mass distributions

- Charged-meson final states in $e^+e^- \to \pi^+\pi^-\gamma$ are used to scan cross section via radiative return method – is relied on dominance of initial-state radiation.
- Neutral-meson final states in

$$e^+e^- \to f_0\gamma \to \pi^0\pi^0\gamma, \qquad e^+e^- \to a_0\gamma \to \pi^0\eta\gamma$$

  are particularly suitable for studying dynamics: no initial-state radiation.
- Decomposition of tensor for $\gamma^*(Q) \to \gamma(k)P_1P_2$ transition

$$\mathcal{M}^{\mu\nu} = f_1\tau_1^{\mu\nu} + f_2\tau_2^{\mu\nu} + f_3\tau_3^{\mu\nu}$$

  with functions $f_{1,2,3}(Q^2, m^2)$, $Q^2 = s$, m is $\pi^0\pi^0$ invariant mass,

$$\tau_1^{\mu\nu} = k^\mu Q^\nu / k \cdot Q - g^{\mu\nu}, \ \ldots$$

Invariant-mass distributions

- for $e^+e^- \to \pi^0\pi^0\gamma$ reaction, $f_0(980)$ contribution

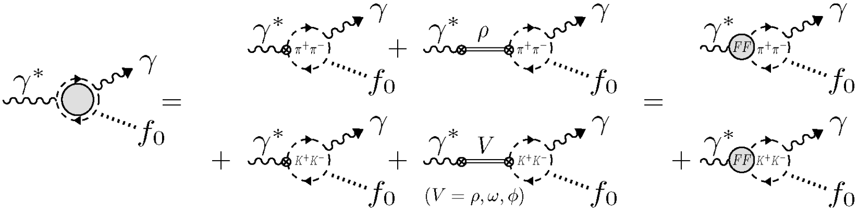
$$\begin{aligned} f_1 &= [G^{(\pi)}_{f_0\gamma\gamma}(m^2, Q^2)F^{\pi}_{em}(Q^2) + G^{(K)}_{f_0\gamma\gamma}(m^2, Q^2)F^{K}_{em}(Q^2)] \\ &\quad \times D_{f_0}(m^2)G_{f_0\pi\pi}(m^2), \end{aligned}$$

$G_{f_0\pi\pi}(m^2)$ is $f_0\pi\pi$ vertex (momentum-dependent),
$D_{f_0}(m^2)$ – scalar-meson propagator and

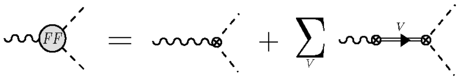
$$G^{(\pi,K)}_{f_0\gamma\gamma}(m^2, Q^2) = \frac{1}{4\pi^2} G_{f_0\pi\pi,\ f_0KK}(m^2)\Psi(m^2_{\pi,K}, m^2, Q^2)$$

Invariant-mass distributions

Schematically transition $\gamma^* \to \gamma f_0$

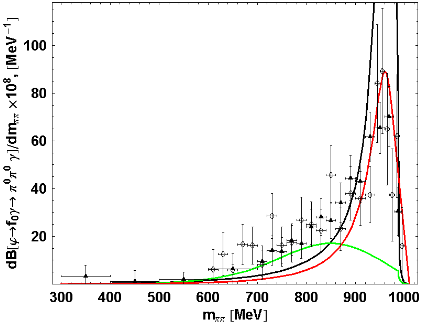


in terms of pion and kaon EM form factors $F^{\pi}_{em}(Q^2)$ and $F^{K}_{em}(Q^2)$

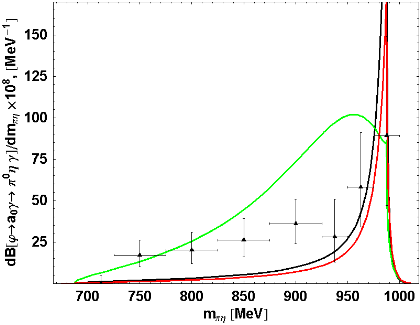


Similarly for $\gamma^* \to \gamma a_0$ transition.

$\phi \to \pi^o\pi^o\gamma$ inv. mass distribution $\phi \to \pi^o\eta\gamma$



data: [PL B440 (1998) 442; PL B485 (2000) 349] (Novosibirsk)



data: [PL B479 (2000) 53] (Novosibirsk)

— $c_m = -58.83$ MeV, $c_d = -6.38$ MeV, $\theta = -7.33^o$ (from PDG data)

— $c_m =$ 42 MeV, $c_d =$ 32 MeV, $\theta = -35.26^o$ (“standard”)

— $c_m = -38.32$ MeV, $c_d = -9.47$ MeV, $\theta = -11.62^o$ (new fit)

Calculations vs. PDG values

widths	from widhts (—)	from distributions (—)	PDG average
$\frac{\Gamma_{\phi\to\gamma a_0}}{\Gamma_\phi}$	1.7×10^{-4}	6.3×10^{-5}	$(7.6\pm0.6)\times10^{-5}$
$\frac{\Gamma_{\phi\to\gamma f_0}}{\Gamma_\phi}$	$4.4\times10^{-4*}$	3.16×10^{-4}	$(4.40\pm0.21)\times10^{-4}$
$\frac{\Gamma_{\phi\to\gamma f_0}}{\Gamma_{\phi\to\gamma a_0}}$	2.6	4.99	6.1 ± 0.6
$\Gamma_{a_0\to\pi\eta}$	14.2 **MeV**	21.11 MeV	—
$\Gamma_{f_0\to\pi\pi}$	41.8 **MeV**	54.56 MeV	$34.2^{+22.7}_{-14.3}$ MeV
$\Gamma_{a_0,\ total}$	17.8 **MeV**	26.39 MeV	$50-100$ MeV
$\Gamma_{a_0\to\gamma\gamma}$	0.30 keV*	0.16 keV	0.30 ± 0.10 keV
$\Gamma_{f_0\to\gamma\gamma}$	0.31 keV*	0.13 keV	$0.31^{+0.08}_{-0.11}$ keV
$\Gamma_{a_0\to\gamma\rho}$	9.1 **keV**	5 keV	—
$\Gamma_{f_0\to\gamma\rho}$	9.6 **keV**	4.1 keV	—
$\Gamma_{a_0\to\gamma\omega}$	8.7 **keV**	4.8 keV	—
$\Gamma_{f_0\to\gamma\omega}$	15.0 **keV**	8.4 keV	—

(* marks input values)

Comparison with other predictions

Γ, keV	[1] (a)	[1] (b)	[2] (a)	[2] (b)	[3]	present
$f_0 \to \rho\gamma$	125	3	19 ± 5	3.3 ± 2	4.2 ± 1.1	$4.1 - 9.6$
$f_0 \to \omega\gamma$	14	3	126 ± 20	88 ± 17	4.3 ± 1.3	$8.4 - 15$
$a_0 \to \rho\gamma$	14	3	3 ± 1	3 ± 1	11 ± 4	$5 - 9.1$
$a_0 \to \omega\gamma$	125	3	641 ± 87	641 ± 87	31 ± 13	$4.8 - 8.7$

[1] Yu. Kalashnikova et al., PR C73, 045203 (2006)

a) $\bar{q}q$-loop and $f_0 = (u\bar{u} + d\bar{d})/\sqrt{2}$

b) $K\bar{K}$-loop

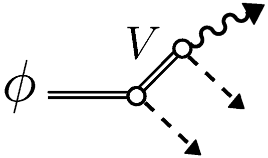
[2] D. Black, M. Harada, J. Schechter, PRL 88, 181603 (2002):

vector-meson dominance + chiral model of Schechter et al.

[3] H. Nagahiro, L. Roca, E. Oset, arXiv: 0802.0455 [hep-ph]:

contribution from vector mesons inside loops

Background contributions



Channels with intermediate vector mesons may be important:

- $\phi \to \rho^0\pi^0 \to \pi^0\pi^0\gamma$,
- $\phi \to \omega\eta \to \eta\pi^0\gamma$,
- $\phi \to \rho^0\pi^0 \to \eta\pi^0\gamma$,
- others, if one stays aside of ϕ-meson pole.

Account for
– background for $\pi^0\pi^0$ and $\pi^0\eta$,
– mixing between $f_0(980)$ and $\sigma \equiv f_0(600)$ and their self-energy corrections
is in progress [Ivashyn, Korchin, Shekhovtsova].

Conclusions

- The widths of decays
  $a_0 \to \gamma\gamma$, $f_0 \to \gamma\gamma$, $a_0 \to \gamma\rho\,(\omega)$, $f_0 \to \gamma\rho\,(\omega)$, $\phi \to \gamma a_0$, $\phi \to \gamma f_0$
  are calculated in approach based on RχT at one-loop level.

  – both derivative and non-derivative couplings *SPP* are included
  – in $f_0 \to \gamma\rho$ and $f_0 \to \gamma\gamma$, the loops with $\pi^+\pi^-$ and K^+K^- are comparable
  – a few model parameters (though under assumption $N_c \to \infty$)

- Invariant mass distributions for $\pi^0\pi^0$ and $\pi^0\eta$ are sensitive to model ingredients. The most appropriate comparison with experiment would be to apply a Monte Carlo event generator (*e.g.* like MC in [Pancheri, Shekhovtsova, Venanzoni, PL B642, 342 (2006); EPJ A31, 458 (2007)])

Conclusions

- Octet-singlet mixing angle θ is the crucial parameter. Mixing has been studied $\pi\pi$, $\pi\eta$, $K\bar{K}$ and $K\eta$ scattering [e.g., Oller, NP A727 353 (2003)].
  Scalar resonances may show up in different ways in elastic scattering experiments and in radiative decays $\Longrightarrow$ it is a challenge to build unified description.
- Accurate data on invariant mass distributions for $\pi^0\pi^0$ and $\pi^0\eta$ are very desirable.

Acknowledgments

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- Thanks to Organizers of the Workshop!
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