Scalar mesons and $\delta_0 - \delta_2$ at KLOE

The KLOE collaboration

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The KLOE measurements of $\phi$ radiative decays and of the ratio $\Gamma(K_S^0 \rightarrow \pi^+\pi^- (\gamma))/\Gamma(K_S^0 \rightarrow \pi^0\pi^0)$ are discussed. The first measurement aims at understanding the real nature of the scalar mesons $a_0$ and $f_0$, whose possible compositions are $q\bar{q}$, $q\bar{q}q\bar{q}$, or $KK$ molecule. The second measurement is related to the estimate of the phase shift difference $\delta_0 - \delta_2$. Previous measurements were affected by a large uncertainty due to the presence of radiative effects which are correctly included in our analysis.

1 The KLOE experiment

The KLOE experiment collects data at DAΦNE, an $e^+e^-$-collider with center of mass energy $\sim 1020$ MeV corresponding to the $\phi$ meson mass. The detector consists of a large drift chamber surrounded by an electromagnetic calorimeter, both embedded in a magnetic field of $\sim 0.5$ Tesla (Fig. 1).

The drift chamber [11] is a cylinder 4 m in diameter and 3.3 m in length, with a stereo write-geometry for the reconstruction of the longitudinal coordinate. The momentum resolution for particles with $p \geq 100$ MeV is $\sigma_p/p \leq 0.5\%$. The calorimeter [2] is a lead/scintillating-fiber sampling calorimeter, composed of a barrel and two end-caps. The energy resolution is $\sigma_E/E = 5.7\%/\sqrt{(E\text{ GeV})}$. The intrinsic time resolution is $\sigma_t = 54\text{ ps}/\sqrt{(E\text{ GeV})} \pm 50\text{ ps}$.

KLOE collected $\sim 500$ pb$^{-1}$ in three years of data taking. During the year 2002 DAΦNE reached a maximum luminosity of $\sim 8 \times 10^{31}$ cm$^{-2}$s$^{-1}$.

2 Scalar mesons

SU(3) flavor symmetry has been very useful in classifying mesons and baryons. Both the pseudoscalar ($J^{PC} = 0^{-+}$) and vector mesons ($J^{PC} = 1^{-+}$) clearly show the nonet structure expected for $q\bar{q}$ states, with masses following expectation. The same is not true for scalar mesons ($J^{PC} = 0^{++}$). In fact, instead of the expected 9 particles, 15 scalar mesons are observed below 2 GeV as listed by the Particle Data Group [3], with masses not in accord with the $q\bar{q}$ model. The excess of particles can be explained by introducing non-conventional mesons such as glue balls, multiquark states, or mesonic molecules.

Two possible non-conventional scalar mesons are the isoscalar $f_0$ and the isovector $a_0$. These particles can be studied in the $\phi$ radiative decays $\phi \rightarrow f_0\gamma$ and $\phi \rightarrow a_0\gamma$. The branching ratios for these processes strongly depend

Figure 1. Section of the KLOE detector.
on the meson compositions: \( BR \sim O(10^{-5}) \) for conventional \( q\bar{q} \) mesons; \( BR \sim O(10^{-3}) \) for \( qgq \) mesons; \( BR \approx O(10^{-5}) \) for \( K\bar{K} \) molecules. The decays \( f_{0} \to \pi^{0}\pi^{0} \) and \( a_{0} \to \eta\pi^{0} \) contribute to the radiative decays \( \phi \to \pi^{0}\pi^{0}\gamma \) and \( \phi \to \eta\pi^{0}\gamma \), respectively. However, other contributions to these decays come from \( \phi \to \rho\pi^{0} \) with the \( \rho \) decaying to \( \pi^{0}\gamma \) and \( \eta\gamma \), and from \( \phi \to \sigma(600)\gamma \to \pi^{0}\pi^{0}\gamma \). The \( f_{0} \) and \( a_{0} \) contributions are therefore extracted by fitting the \( \pi\pi \) and \( \eta\pi \) mass spectra.

The branching ratios and mass spectra (Figs. 2 and 3) for the decays \( \phi \to \pi^{0}\pi^{0}\gamma \) \([14]\) and \( \phi \to \eta\pi^{0}\gamma \) \([5]\) have been measured by the KLOE collaboration using data collected in the year 2000 corresponding to an integrated luminosity of \( \sim 16 \text{ pb}^{-1} \) \( (\sim 5 \times 10^{7} \phi \text{ mesons}) \). The mass spectra have been fitted using a theoretical framework mainly due to Achasov and co-workers \([6][7][8]\). However, there is no general agreement on the fit method. Several other authors have analyzed the KLOE data using alternative fits \([2][10][11]\).

![Figure 2](image_url)

**Figure 2.** Mass spectra for \( \phi \to \pi^{0}\pi^{0}\gamma \) decays. The fit is superimposed together with individual contributions.

### 2.1 Event selection

\( \phi \to \pi^{0}\pi^{0} \to 5\gamma \) events are selected first of all by looking for five photons with total energy close to the \( \phi \) mass and total momentum close to zero. Specifically, we require 5 clusters in the calorimeter with a time compatible with the photon hypothesis, with total energy \( E_{T\text{OT}} > 800 \text{ MeV} \) and total momentum \( |\vec{p}_{T\text{OT}}| < 200 \text{ MeV}/c \). Sources of background for this decay are \( e^{+}e^{-} \to \omega\pi^{0} \to \pi^{0}\pi^{0}\gamma \), \( \phi \to \eta\pi^{0}\gamma \to 5\gamma \), and \( \phi \to \eta\gamma \to 3\pi^{0}\gamma \) decays with signal-to-background ratios of 0.8, 3.52, and 0.027, respectively. Energy and momentum conservation for the five photons are imposed in a kinematic fit in which photons coming from a \( \pi^{0} \) are paired. The correct pairing is obtained in \( \sim 90\% \) of the time. Events with a \( \pi\gamma \) invariant mass consistent with the \( \omega \) mass are identified as \( \omega\pi \) events and rejected. Data and Monte Carlo (MC) distributions are compared and good agreement is found. The background contribution, which is obtained from MC simulation, is then subtracted from the 3102 selected events. \( 2438 \pm 61 \phi \to \pi^{0}\pi^{0}\gamma \) events remain. The signal acceptance \( \epsilon_{\gamma\gamma} \) \( \sim 40\% \) is obtained using MC simulation and data control samples such as \( \phi \to \eta\gamma \to 3\pi^{0}\gamma \) events. A systematic uncertainty of 2\% has been estimated. The measured branching ratio is:

\[
BR(\phi \to \pi^{0}\pi^{0}\gamma) = (1.09 \pm 0.03_{\text{stat}} \pm 0.05_{\text{syst}}) \times 10^{-4}
\]

The \( \pi^{0}\pi^{0} \) mass spectrum is fitted by combining experimental effects, such as mass resolution and wrong pairing, with the theoretical function. The ratio between the function

![Figure 3](image_url)

**Figure 3.** Mass spectra for \( \phi \to \eta\pi^{0}\gamma \) decays: comparison of data (points) and fit (histogram) for (a) 5\( \gamma \) final state and (b) \( \pi^{+}\pi^{-}5\gamma \) final state. In (c) is shown the theoretical contribution of the \( a_{0} \) as extracted from the fit.
with and without experimental effects folded in is used to correct the mass spectrum. The purely theoretical spectrum is shown in Fig. 2. Two different final states are selected for $\phi \rightarrow \eta \pi^0 \gamma$ decays: $\phi \rightarrow 5\gamma$ and $\phi \rightarrow \pi^+ \pi^- 5\gamma$. The main background processes for the $5\gamma$ final state are $e^+ e^- \rightarrow \omega \pi^0 \rightarrow \pi^0 \pi^0 \gamma$, $\phi \rightarrow \pi^0 \pi^0 \gamma$, and $\phi \rightarrow \eta \gamma$ with $\eta \rightarrow \gamma \gamma$ and $\eta \rightarrow 3\pi^0$. For $\phi \rightarrow \pi^+ \pi^- 5\gamma$ decays there is no background with the same final state, so only decays with similar topologies but larger branching ratio contribute. These are $\phi \rightarrow \eta \gamma \rightarrow \pi^+ \pi^- 3\gamma$, $e^+ e^- \rightarrow \omega \pi^0 \rightarrow \pi^+ \pi^- 4\gamma$, and $K_S K_L$ decays with kaons decaying into both charged and neutral pions close to the interaction point (IP).

$\phi \rightarrow 5\gamma$ events are selected as in the previous analysis by requiring 5 photon clusters and constraining energy-momentum conservation with a kinematic fit. Events with a $\gamma \gamma$ invariant mass close to the $\eta$ mass are retained. Events with a photon with energy greater than 340 MeV are identified as $\phi \rightarrow \eta \gamma$ and rejected. $\gamma \gamma$ invariant masses are used to pair photons from $\eta^0$'s and $\eta$'s. $\omega \pi$ and $\pi \eta \gamma$ events are rejected using the $\pi \gamma$ and $\pi \pi \gamma$ invariant masses obtained by pairing the photons in the two different hypotheses. The final sample consists of 916 events. The average acceptance is $\sim 32\%$. The number of background events as estimated from MC simulation is 309 ± 20.

$\phi \rightarrow \pi^+ \pi^- 5\gamma$ events are selected by requiring two tracks of opposite charge connected to a vertex at the IP and 5 photon clusters. A kinematic fit is then performed imposing energy-momentum conservation and the $\eta$ and $\pi^0$ mass constraints. 197 events are found with about 10 background events. The acceptance ($\sim 20\%$) obtained from MC has been corrected using $K_S \rightarrow \pi^+ \pi^-$ data sample to obtain tracking efficiency, and a $e^+ e^- \gamma$ sample to obtain cluster efficiency.

For the $\phi \rightarrow \eta \pi^0 \gamma$ branching ratio, we obtain from the $5\gamma$ final state:

$$BR(\phi \rightarrow \eta \pi^0 \gamma) = (8.51 \pm 0.51_{stat} \pm 0.57_{syst}) \times 10^{-5}$$

(2)

and from the $\pi^+ \pi^- 5\gamma$ final state

$$BR(\phi \rightarrow \eta \pi^0 \gamma) = (7.96 \pm 0.60_{stat} \pm 0.40_{syst}) \times 10^{-5}$$

(3)

The mass spectra and the fit are shown in Fig. 5.

According to the results of the fits to the $\eta \pi^0 \gamma$ and $\eta \pi^0 \gamma$ events, the $f_0$ and the $a_0$ give the dominant contributions to these decays, and the branching ratios are $(4.47 \pm 0.21) \times 10^{-4}$ and $(7.4 \pm 0.7) \times 10^{-5}$ for $f_0 \rightarrow \gamma \gamma$ and $\phi \rightarrow a_0 \gamma$ decays, respectively. According to the predictions given in the previous section for various meson compositions, the $f_0$ is likely to be a $qq\bar{q}\bar{q}$ state, while the value obtained for the $a_0$ doesn’t distinguish between 2- and 4-quark states.

3. $\Gamma(K_S \rightarrow \pi^+ \pi^-(\gamma))/\Gamma(K_S \rightarrow \pi^0 \pi^0)$ and $\delta_0 - \delta_2$

Assuming that electromagnetic interactions can be neglected, the amplitudes for $K \rightarrow \pi \pi$ decays can be written as:

$$A(K_1 \rightarrow \pi^+ \pi^-) = \sqrt{2/3} A_0 e^{i\delta_0} + \sqrt{1/3} A_2 e^{i\delta_2}$$

(4)

$$A(K_1 \rightarrow \pi^0 \pi^0) = -\sqrt{1/3} A_0 e^{i\delta_0} + \sqrt{2/3} A_2 e^{i\delta_2}$$

$$A(K^+ \rightarrow \pi^+ \pi^0) = \sqrt{3/2} A_2 e^{i\delta_2}$$

where $A_{0,2}$ are the amplitudes to $\pi \pi$ states with isospin $0$ and $2$ respectively. Unitarity and CPT-invariance requires inclusion of the S-wave $\pi \pi$ scattering phases [12] in Eq. (4). However, the value extracted from the previously measured branching ratios of kaon decays (56.7 ± 3.8)$^o$ does not agree with the values obtained from $\pi \pi$ scattering. For instance, the most recent evaluations are (47.7 ± 1.5)$^o$ [13] and (48.4 ± 2.1)$^o$ [14]. This disagreement is ascribed to two effects [15] [16]. The first is the presence of isospin breaking effects such as electromagnetic interactions. In presence of these effects the isospin amplitudes become [16]:

$$A_I \Rightarrow (A_I + \delta A_I) e^{-i(\delta_0 + \gamma_I)}$$

(5)

Hence, the phase shift measured from kaon decays using Eq. (4), $(\delta_0 - \delta_2)_K$, differs from the $\pi \pi$ phase shift difference by a factor $\delta_{em}$:

$$(\delta_0 - \delta_2)_K = (\delta_0 - \delta_2)_{\pi \pi} + \delta_{em}$$

(6)

An estimate of this difference is 3.2$^o$ [16]. The second is the uncertainty on what portion of the $\pi \pi \gamma$ decay is included in the $\pi^+ \pi^-$ branching ratio. The last measurement of $\Gamma(K_S \rightarrow \pi^+ \pi^-(\gamma))/\Gamma(K_S \rightarrow \pi^0 \pi^0)$ ratio was performed in 1976 with a 4.3% accuracy [17] and there is no information on the procedure used to handle the radiated photon. This uncertainty lead to a large error on the estimate of $\delta_0 - \delta_2$.

The KLOE collaboration measured this ratio using an integrated luminosity of 17 pb$^{-1}$ collected during the year 2000. The KLOE measurement fully includes $\pi \pi \gamma$ radiative decays [18].

3.1 Event selection

The $\phi$ decays $\sim 34\%$ of the time into $K^0 \bar{K}^0$. The decay occurs nearly at rest and the two kaons are collinear. Since the initial state is $J^{PC} = 1^{--}$, the final state is always $K_S K_L$. This peculiarity allows us to select a pure $K_S$ beam by identifying a $K_S$ inside the detector ($K_S$-tagging). While the $K_S$...
K_{S} \rightarrow \pi^{0}\pi^{0} events are selected by requiring at least 3 photons defined as clusters not associated to any track with \( |r_{cl}-r_{cl}| < 5\sigma_{r} \). The background is rejected by cutting on energy and polar angle: \( E_{\gamma} > 20 \text{ MeV} \) and \( \cos \theta_{cl} < 0.9 \). The distribution of the number of clusters in \( \pi^{0}\pi^{0} \) is shown in Tab. 1. Almost 90% of the events are retained. The effects of cluster splitting and accidental clusters are reduced by an order of magnitude by these cuts. The photon detection efficiency is measured from \( \phi \rightarrow \pi^{+}\pi^{-}\pi^{0} \) samples and used to correct the MC simulation.

Table 1. Distribution of the number of clusters in \( \pi^{0}\pi^{0} \) events.

| N. clusters | % |
|-------------|---|
| < 2         | 1.3 |
| 2           | 8.6 |
| 3           | 33.2 |
| 4           | 56.6 |
| > 4         | 0.3 |

\( K_{S} \rightarrow \pi^{+}\pi^{-}(\gamma) \) events are selected by requiring the presence of two tracks of opposite charge coming from the IP that reach the calorimeter. The momentum distribution for charged tracks in tagged events is shown in Fig. 5. A peak due to charged kaons is visible at 100 MeV in the data (dots) as well as a long tail at higher momentum due to residual background. These events are rejected by requiring 120 < \( p < 300 \text{ MeV}/c \). The efficiency for reconstructing a track is measured from a control sample of \( K_{S} \rightarrow \pi^{+}\pi^{-} \) decays and then combined with the MC simulation. The overall acceptance is obtained from MC taking the radiated photon into account. The acceptance is shown in Fig. 5 as a function of the photon energy. The value for \( E_{\gamma} = 0 \) is obtained from \( \pi^{+}\pi^{-} \) simulation, and for \( E_{\gamma} > 20 \text{ MeV} \) from \( \pi^{+}\pi^{-}\gamma \) simulation. The acceptance in the region 0 < \( E_{\gamma} < 20 \text{ MeV} \) is obtained by linear interpolation. The decrease in acceptance is due to the requirement that both pions reach the calorimeter. For high values
of the photon energy the probability for both pions to reach the calorimeter is low. The overall acceptance is obtained by folding this efficiency with the photon spectrum from [16]. The inclusion of the radiated photon leads to a correction of \( \sim 0.3\% \).

![Figure 6](image.png)

**Figure 6.** Acceptance for \( K_S \to \pi^+\pi^-\gamma \) events as a function of the energy of the radiated photon, obtained from MC \( \pi^+\pi^- \) simulation \( (E_\gamma = 0) \) and from MC \( \pi^+\pi^-\gamma \) simulation \( (E_\gamma > 20 \text{ MeV}) \).

In the data collected during the year 2000 we identify 1,060,821 \( K_S \to \pi^+\pi^- \) and 766,308 \( K_S \to \pi^0\pi^0 \) events. The ratio of the branching ratios is obtained by correcting the ratio of these numbers with the acceptance and the tagging efficiencies. The result is:

\[
\frac{BR(K_S \to \pi^+\pi^-\gamma)}{BR(K_S \to \pi^0\pi^0)} = \left(2.236 \pm 0.003_{\text{stat}} \pm 0.015_{\text{syst}}\right) \quad (7)
\]

This value is higher than the world average, 2.197 \( \pm 0.026 \), as we expect due to the inclusion of all the radiative decays. The error, 0.7\%, is dominated by systematics. The statistical error is already at the 0.1\% level. The main contribution to the systematic error comes from the correction for the different tagging efficiencies. The cut on \( \beta^\prime \) was loosened in the year 2001 in order to reduce the contribution from this correction.

Using this new value, the phase shift is found to be:

\[
(\delta_0 - \delta_2)_K = (47.8 \pm 2.8)^\circ \quad (8)
\]

which is now in agreement with the values extracted from \( \pi\pi \) scattering. The contribution of the electromagnetic interactions can be estimated from the difference between \((\delta_0 - \delta_2)_{\pi\pi}\) and \((\delta_0 - \delta_2)_{\pi\pi}\). For instance, using the value in [13]:

\[
(\delta_0 - \delta_2)_{\pi\pi} - (\delta_0 - \delta_2)_{\pi\pi} = (-0.1 \pm 3.2)^\circ \quad (9)
\]

4 Conclusion and perspectives

With the data collected during the year 2000, the KLOE collaboration has improved the previous existing measurements of branching ratios and mass spectra for \( \phi \) radiative decays and the ratio \( BR(K_S \to \pi^+\pi^-\gamma)/BR(K_S \to \pi^0\pi^0) \). After two more years of data taking, the total integrated luminosity has increased by a factor of \( \sim 20 \), allowing new and more precise measurements. Preliminary results on radiative decays are in agreement with the previous ones. New analyses are also underway in order to study the Dalitz plot for \( \phi \to \pi^+\pi^-\gamma \) decays and the branching ratio and mass spectrum for \( \phi \to \pi^+\pi^-\gamma \) decays in order to look for the \( f_0\gamma \) intermediate state.

The ratio \( BR(K_S \to \pi^+\pi^-\gamma)/BR(K_S \to \pi^0\pi^0) \) has a statistical error which is already at per-mil level while the systematic error is \( \sim 0.7\% \). However, the higher statistics, together with the looser cut on the \( \beta^\prime \) distribution should allow us to reduce the systematic error. With the expected \( \sim 0.1\% \) fractional error, we can measure \((\delta_0 - \delta_2)_{\pi\pi}\) with an error of \( \sim 0.5\% \). Finally we are also planning to measure the energy distribution of the radiated photon.

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