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Recent results and perspectives with KLOE–2

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Abstract

In this paper we summarize the recent experimental results from KLOE–2 on the dark photon search in the $e^+e^- \to U\gamma$, $U \to \pi^+\pi^-$, measurement of Branching Ratio and Transition Form Factor of $\phi \to \pi^0 e^+e^-$ decay, Dalitz plot analysis of $\eta \to \pi^+\pi^-\pi^0$ process and CPT symmetry and Lorentz invariance test with entangled K mesons. Additionally a discussion about ongoing test of CPT symmetry via measurement of K_S charge asymmetry is included together with description of the KLOE–2 detection system.

Keywords: dark matter, dark photon, Transition Form Factor, Dalitz plot, discrete symmetries, CPT, KLOE

1. Introduction

The multipurpose KLOE detector was used for data-taking campaigns in 2001-2002 and 2004-2005. After installation of new calorimeters and taggers as well as cylindrical GEM detector the system was upgraded to the KLOE–2 stage and at the end of 2014 the presently ongoing campaign wast started. The review of the selected recent result and ongoing analysis based on the 2004-2005 data is presented.

2. DAΦNE collider and KLOE detector

The DAΦNE electron-positron collider composed of two separate storage rings is located at the accelerator complex of the INFN National Laboratory of Frascati (LNF). The center-of-mass energy of the colliding beams is set to the mass of the ϕ meson. The KLOE detection system placed at one of the DAΦNE interaction points consists of the 4m diameter large cylindrical drift chamber [1] surrounded by an electromagnetic calorimeter [2] immersed in 0.5T magnetic field. High performance of drift chamber for momentum and vertex reconstruction ($\sigma_{p_\perp}/p_\perp < 0.4\%$ for $\theta > 45°$; ~150 μm in transverse plane) and excellent time and energy resolution of the calorimeter ($\sigma_t = 57ps/\sqrt{E(GeV)} \oplus 100ps$; $\sigma_E/E = 5.7\%/\sqrt{E(GeV)}$) ensure high quality of collected data.

3. U boson search in the $e^+e^- \to U\gamma, U \to \pi^+\pi^-$

Recently one of the possibilities of search for physics beyond the Standard Model (SM) are the investigations of the so called dark matter (DM), which can be account for about 24% of the total energy density of the Universe [3]. The Weakly Interacting Massive Particles are considered as possible dark matter candidates and their existence would imply a new interaction called the dark force. As a consequence, a new gauge vector boson — the U boson, also referred to as the dark photon or A', needs to be introduced. In that case the strength of the mixing U boson with the photon is parametrized by $\varepsilon^2 = \alpha'/\alpha$ as the ratio of the effective dark and SM photon couplings [4]. It's value is predicted to be in the range 10^{-8}–10^{-2}, therefore the effects of the U boson existence should be visible at O(1 GeV) collider experiments such as KLOE. The discovery of the dark photon could explain for example (I) the excess of positrons in cosmic rays observed by AMS and PAMELA [5, 6], (II) 511 keV gamma rays from the galactic center seen by INTEGRAL [7], (III) the annual modulation signal measured by DAMA/LIBRA [8]. No evidence of the U boson was found at KLOE in decays of the ϕ meson [9, 10], as well as in the dark Higgsstrahlunng process [11]. Search for radiative U boson in the $e^+e^- \to U\gamma, U \to e^+e^-$, $\mu^+\mu^-$ processes was also

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performed [12, 13]. However, the leptonic channels are affected by a decrease in sensitivity in the $\rho - \omega$ region due to the dominant branching fraction into hadrons. Therefore search for a short lived U boson decaying to $\pi^+\pi^-$ in a data sample corresponding to 1.93 fb^{-1} integrated luminosity was performed. Based on 28 million $e^+e^- \rightarrow \pi^+\pi^-\gamma$ events collected at KLOE we looked for a resonant peak in the dipion invariant mass spectrum with initial-state radiation (ISR) $\pi^+\pi^-\gamma$ events. Using the PHOKHARA event generator with the Gounaris-Sakhurai (GS) pion form factor parametrization [14] a very good description of the $\rho - \omega$ interference region was achieved. No signal has been observed and a limit at 90% CL has been set on the coupling factor ε^2 in the energy range between 527 and 987 MeV [15]. The limit is more stringent than other limits in the $\rho - \omega$ region and above. As the results reported here are presently limited by statistical uncertainty, KLOE-2 is expected to improve their sensitivity about twice.

4. Branching Ratio and Transition Form Factor of $\phi \rightarrow \pi^0 e^+ e^-$

Stringent tests for theoretical models of the nature of mesons are the conversion decays of a light vector resonance (V) into a pseudoscalar meson (P) and a lepton pair, $V \rightarrow P\gamma^* \rightarrow P\ell^+\ell^-$. The squared dilepton invariant mass, $m^2_{\ell\ell}$, corresponds to the virtual photon 4-momentum transfer squared, q^2 in these processes and the q^2 distribution depends on the underlying electromagnetic dynamical structure of the transition $V \rightarrow P\gamma^*$. The fundamental quantity, so-called Transition Form Factor (TFF), $F_{VP}(q^2)$ is typically used to parametrize the description of the coupling of the mesons to virtual photons. The TFFs play an important role in many fields of particle physics, such as the calculation of the hadronic Light-by-Light contribution to the Standard Model prediction of the muon anomalous magnetic moment [16]. The discrepancy between the experimental data from NA60 [17] and Lepton G [18], and the Vector Meson Dominance (VMD) prediction for the $\omega \rightarrow \pi^0\mu^+\mu^-$ TFF $F_{\omega\pi^0}(q^2)$ increased an interest in conversion decays recently. The attempt to explain this discrepancy was performed in the several theoretical models over the last years [19–22]. The $\phi \rightarrow \pi^0 e^+ e^-$ process, due to its kinematics, is a good candidate to investigate the observed steep rise in NA60 data at q^2 close to the ρ resonance mass and a measurement of the $F_{\phi\pi^0}(q^2)$ TFF allows to check the consistency of the above-mentioned models.

Based on the data set of 1.7 fb^{-1} KLOE performed a measurement of the vector to pseudoscalar conversion decay $\phi \rightarrow \pi^0 e^+ e^-$. The overall efficiency estimated by the MonteCarlo simulation is 15.4%. At lower e^+e^- invariant masses the efficiency is 19.5% and decrease to a few percent at the highest values of momentum transfer, therefore the selected 14670 events with a residual background contamination of $\sim$ 35% are limited up to $\sqrt{q^2} = 700$ MeV. Applying an efficiency correction evaluated bin by bin to the background-subtracted e^+e^- mass spectrum allowed us to obtain the branching ratio of the $\phi \rightarrow \pi^0 e^+ e^-$ decay. The final result is $\mathrm{BR}\,(\phi \rightarrow \pi^0 e^+e^-;\ \sqrt{q^2} < 700\ \mathrm{MeV}) = (1.19 \pm 0.05\ ^{+0.05}_{-0.10}) \times 10^{-5}$. The result extended to the full $\sqrt{q^2}$ range achieved by an extrapolation based on the theoretical model gives $\mathrm{BR}\,(\phi \rightarrow \pi^0 e^+e^-) = (1.35 \pm 0.05\ ^{+0.05}_{-0.10}) \times 10^{-5}$.

The selected events were also used to perform the first measurement of the modulus square of the $F_{\phi\pi^0}$ Transition Form Factor in a function of the 4-momentum modulus $\sqrt{q^2}$ below 700 MeV [23]. Our results show the best agreement with the Unconstrained Resonant Chiral Theory (UChT), with parameters extracted from a fit of the NA60 data [21]. Based on the simple VMD-inspired one-pole parametrization the TFF can be represented as: $F(q^2) = (1 - q^2/\Lambda^2)^{-1}$, from which the form factor slope parameter is obtained:

$$b = \left.\frac{\mathrm{d}F(q^2)}{\mathrm{d}q^2}\right|_{q^2=0} = \Lambda^{-2}. \qquad (1)$$

Combining the above equation with KLOE data one get $b_{\phi\pi^0} = (2.02 \pm 0.11)\ \mathrm{GeV}^{-2}$, to be compared with the one-pole approximation expectation, $b_{\phi\pi^0} = M_\phi^{-2}$, and the prediction of the dispersive analysis, $b_{\phi\pi^0} = (2.52 \cdots 2.68)\ \mathrm{GeV}^{-2}$, of Ref. [20].

5. Dalitz plot analysis of $\eta \rightarrow \pi^+\pi^-\pi^0$

Due to the difference between the masses of u and d quarks the isospin violating $\eta \rightarrow \pi^+\pi^-\pi^0$ decay can proceed via strong or electromagnetic interactions. The decay amplitude is dominated by the isospin violating part of the strong interaction as shown in the recent calculations performed at next-to-leading order (NLO) of the chiral perturbation theory (ChPT) [24, 25], while the electromagnetic part is known to be suppressed [26, 27].

Defining the quark mass ratio, Q, as $Q^2 \equiv (m_s^2 - \hat{m}^2)/(m_d^2 - m_u^2)$ with $\hat{m} = (m_d + m_u)/2$, the decay width at up to NLO ChPT is proportional to Q^{-4} [28]. Therefore determination of Q puts a stringent constraint on the light quark masses. In order to account for the electromagnetic effects, Q can be determined at the lowest order from a combination of kaon and pion masses using Dashen's theorem [29]. Having $Q = 24.2$, the

ChPT results for the $\eta \to \pi^+\pi^-\pi^0$ decay width at LO, $\Gamma_{LO} = 66$ eV, and NLO, $\Gamma_{NLO} = 160 \pm 50$ eV [30], are far from the experimental value $\Gamma_{exp} = 300 \pm 11$ eV [3]. This discrepancy could be explained by higher order contributions to the decay amplitude or by the corrections to the Q value.

At the KLOE system the η meson is produced in the radiative ϕ decay associated with a mono-energetic photon with energy E ∼ 363 MeV with the main background originating from the $e^+e^- \to \omega\pi^0$ reaction and the Bhabha scattering. From the 1.6 fb^{-1} of $e^+e^- \to \phi \to \eta\gamma$ data collected the Dalitz plot distribution for the $\eta \to \pi^+\pi^-\pi^0$ decay is studied with the world's largest sample of $\sim 4.7 \cdot 10^6$ events. The resulting $\eta \to \pi^+\pi^-\pi^0$ Dalitz plot was bin-by-bin background subtracted and fitted with the decay squared amplitude $|A|^2$ parametrized with a polynomial expansion:

$$|A(X,Y)|^2 \simeq N(1 + aY + bY^2 + cX + dX^2 + eXY + fY^3 + gX^2Y + \ldots), \quad (2)$$

where X and Y are the normalized Dalitz plot variables expressed by the kinetic energies of all the particles in the final state [31]. The bin widths of the Dalitz plot correspond to approximately three standard deviations and the minimum bin content is $3.3 \cdot 10^3$ events. The final results for the Dalitz plot parameters are:

$$\begin{aligned}
a &= -1.095 \pm 0.003^{+0.003}_{-0.002}\ (a = -1.104 \pm 0.003 \pm 0.002)\\
b &= +0.145 \pm 0.003 \pm 0.005\ (b == +0.142 \pm 0.003^{+0.005}_{-0.004})\\
d &= +0.081 \pm 0.003^{+0.006}_{-0.005}\ (d = +0.073 \pm 0.003^{+0.004}_{-0.003})\\
f &= +0.141 \pm 0.007^{+0.007}_{-0.008}\ (f = +0.154 \pm 0.006^{+0.004}_{-0.005})\\
g &= -0.044 \pm 0.009^{+0.012}_{-0.013}\ (g = 0).
\end{aligned}$$

Values in brackets are obtained with the g parameter set to zero. The obtained results are the most precise estimations of the Dalitz parameters, for the first time including also the g parameter. The statistical uncertainty of all parameters is improved by a factor two with respect to earlier measurements. These results confirm the tension with the theoretical calculations on the b parameter, and also the need for the f parameter. While the extracted Dalitz plot parameters are consistent with charge conjugation symmetry, the unbinned integrated charge asymmetries provide a more sensitive test. The left-right (A_{LR}), quadrant (A_Q) and sextant (A_S) asymmetries are defined in Ref. [32]. The final values of the charge asymmetries are:

$$\begin{aligned}
A_{LR} &= (-5.0 \pm 4.5^{+5.0}_{-11}) \cdot 10^{-4}\\
A_Q &= (+1.8 \pm 4.5^{+4.8}_{-2.3}) \cdot 10^{-4}\\
A_S &= (-0.4 \pm 4.5^{+3.1}_{-3.5}) \cdot 10^{-4}.
\end{aligned}$$

They are all consistent with zero and were obtained with the best sensitivity in the world [31].

6. CPT symmetry and Lorentz invariance test

The violation of the CPT symmetry (as a simultaneous composition of charged conjugation, parity and time reversal) might appear in conjunction with Lorentz symmetry breaking [33]. In view of an effective field theory (Standard Model Extension) [34–36] for neutral kaons the CPT violation is introduced in the mixing parameter δ_K, with an additional dependence on the four-momentum of kaon:

$$\delta_K \approx i\, \sin\phi_{SW} e^{i\phi_{SW}} \gamma_K (\Delta a_0 - \vec{\beta}_K \cdot \Delta\vec{a})/\Delta m, \quad (3)$$

where γ_K and $\vec{\beta}_K$ are the boost factor and velocity of the kaon in the observer rest frame, respectively, $\phi_{SW} = \arctan(2\Delta m/\Delta\Gamma)$ is the superweak phase with Δm and $\Delta\Gamma$ the differences of mass and width between K_S and K_L, respectively, and Δa_μ are four CPT and Lorentz violating coefficients [34–36]. For the determination of these parameters the reference frame of fixed stars is natural.

The ϕ meson produced at DAΦNE is almost at rest therefore $\vec{p}_1 \sim -\vec{p}_2$ and $\delta_K(\vec{p}_1) \neq \delta_K(\vec{p}_2)$, where momentum of each kaon is denoted as $\vec{p}_i$. The initial, coherent quantum state ($J^{PC} = 1^{--}$) of the K mesons produced in ϕ meson decays can be presented as:

$$|i\rangle = \frac{N}{\sqrt{2}} \Big[\big|K_S(\vec{p}_1)\big\rangle \big|K_L(\vec{p}_2)\big\rangle - \big|K_L(\vec{p}_1)\big\rangle \big|K_S(\vec{p}_2)\big\rangle \Big], \quad (4)$$

where $N = \sqrt{(1+|\epsilon_S|^2)(1+|\epsilon_L|^2)}/(1-\epsilon_S\epsilon_L) \approx 1$ is a normalization factor, and $\epsilon_{S,L} = \epsilon_K \pm \delta_K$ with ϵ_K as the known contribution from CP symmetry violation. The experimental observable is therefore [37]:

$$I_{f_1 f_2}(\Delta\tau) \propto e^{-\Gamma|\Delta\tau|} \Big[|\eta_1|^2 e^{\frac{1}{2}\Delta\Gamma\Delta\tau} + |\eta_2|^2 e^{\frac{1}{2}\Delta\Gamma\Delta\tau} - 2\mathrm{Re}\left(\eta_1\eta_2^* e^{-i\Delta m\Delta\tau}\right) \Big] \quad (5)$$

where $\Delta\tau = \tau_1 - \tau_2$ is the difference of proper decay times, $\eta_j = \langle f_j | T | K_L\rangle / \langle f_j | T | K_S\rangle \simeq \epsilon_K - \delta_K(\vec{p}_j, t_s)$, f_1 and f_2 denote kaon final states, $\Gamma = \Gamma_S + \Gamma_L$.

At KLOE the measurement of $\phi \to K_S K_L \to \pi^+\pi^-\pi^+\pi^-$ reaction has been performed based on the data sample of 1.7 $fb^{-1}$of integrated luminosity in order to obtain the Δa_μ parameters from the fit of equation (5) to the experimental data with 1.5% sample impurity and the average signal efficiency ~25%. In the reported measurement $f_1 = f_2 = \pi^+\pi^-$ and due to the fully destructive quantum interference at $\Delta\tau = 0$ the distribution (5) is sensitive to changes of η_1/η_2 ratio. The following values were obtained [38]:

$$\Delta a_0 = (-6.0 \pm 7.7_{stat} \pm 3.1_{syst}) \times 10^{-18}\ \text{GeV},$$
$$\Delta a_x = (\ 0.9 \pm 1.5_{stat} \pm 0.6_{syst}) \times 10^{-18}\ \text{GeV},$$
$$\Delta a_y = (-2.0 \pm 1.5_{stat} \pm 0.5_{syst}) \times 10^{-18}\ \text{GeV},$$
$$\Delta a_z = (\ 3.1 \pm 1.7_{stat} \pm 0.5_{syst}) \times 10^{-18}\ \text{GeV}.$$

Presently the reported values are the most precise measurement of these parameters in the quark sector of Standard Model Extension and the first independent measurement of all four parameters in the kaon sector.

7. Ongoing discrete symmetries tests

Another test of the CPT symmetry violation is the ongoing determination of the charge asymmetry defined for semileptonic decays of K_S and K_L mesons in the following way:

$$A_{S,L} = \frac{\Gamma(K_{S,L} \to \pi^- e^+ \nu) - \Gamma(K_{S,L} \to \pi^+ e^- \bar{\nu})}{\Gamma(K_{S,L} \to \pi^- e^+ \nu) + \Gamma(K_{S,L} \to \pi^+ e^- \bar{\nu})}. \quad (6)$$

which can be rewritten as:

$$A_{S,L} = 2\left[Re\,(\epsilon_K) \pm Re\,(\delta_K) - Re(y) \pm Re(x_-)\right]. \quad (7)$$

where y parametrizes CPT violation assuming $\Delta S = \Delta Q$ rule and x_- is a small term describing a possible violation of this rule, while the rule itself can be rephrased as: change of strangeness (ΔS) implies the corresponding change of electric charge (ΔQ) for the decay of K^0 (or $\bar{K^0}$) state associated with the transition of the $\bar{s}$ quark into $\bar{u}$ quark (or s into u) and emission of the charged boson. In that case, sum and difference of the A_S and A_L allow to search for the $\mathcal{CPT}$ symmetry violation, either in the decay amplitudes through the parameter y or in the mass matrix through the parameter δ_K:

$$\begin{aligned} A_S + A_L &= 4Re(\epsilon) - 4Re\,(y)\,, \\ A_S - A_L &= 4Re(\delta_K) + 4Re\,(x_-)\,. \end{aligned} \quad (8)$$

The most precise results of the A_S and A_L are

$$A_L = (3.322 \pm 0.058_{stat} \pm 0.047_{syst}) \times 10^{-3}$$

obtained by KTeV Collaboration [43] and

$$A_S = (1.5 \pm 9.6_{stat} \pm 2.9_{syst}) \times 10^{-3}$$

from the KLOE experiment [44]. Although the obtained charge asymmetries are consistent within error limits, the inaccuracy for A_S is more than two orders of magnitude bigger and dominated by a statistical uncertainty. The ongoing refined analysis of the four times bigger data sample from the KLOE experiment (1.7fb^{-1} integrated luminosity) shows a potential of reaching a two times better statistical error determination and reduced systematic uncertainty.

8. The KLOE–2 project

The KLOE detection system is operating now with the following subdetectors: the Inner Tracker [39], which improves resolution on the vertex position and acceptance for tracks with low transverse momentum; two pairs of small angle tagging devices to detect low (Low Energy Tagger - LET [40]) and high (High Energy Tagger - HET [41]) energy e^+e^- originated from $e^+e^- \to e^+e^-X$ reactions; new crystal calorimeters (CCALT) to cover the low polar angle region to increase acceptance for very forward electrons and photons down to 8° [45]; and a tile calorimeter (QCALT) used for the detection of photons coming from K_L decays in the drift chamber [46].

9. Summary

The KLOE–2 system updated with new detector components is currently during data taking campaign at the enhanced in luminosity DAΦNE collider aiming to collect at least 5 fb^{-1} of data. The Collaboration searched for the new physics around 1 GeV, tested CPT and Lorentz invariance and performed precision measurements in hadronic low-energy physics. The ongoing analyses and newly collected data promises significant progress to be made in the field of discrete symmetries and quantum mechanics test as well as low-energy structure of mesons [42].

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