Search for CPT and Lorentz invariance violation with neutral kaons at KLOE.

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Abstract. The neutral kaon system offers a unique possibility to perform fundamental tests of fundamental symmetry such as CP and CP T invariance. In this contribution the KLOE search for CP T symmetry and Lorentz Invariance breaking in the Standard Model Extension framework is reported. Preliminary results are:

\[
\Delta a_0 = (-6.2 \pm 8.2_{\text{stat}} \pm 3.3_{\text{syst}}) \times 10^{-18} \text{GeV}^{-1}
\]

\[
\Delta a_x = (3.3 \pm 1.6_{\text{stat}} \pm 1.5_{\text{syst}}) \times 10^{-18} \text{GeV}^{-1}
\]

\[
\Delta a_y = (-0.7 \pm 1.3_{\text{stat}} \pm 1.5_{\text{syst}}) \times 10^{-18} \text{GeV}^{-1}
\]

\[
\Delta a_z = (-0.7 \pm 1.0_{\text{stat}} \pm 0.3_{\text{syst}}) \times 10^{-18} \text{GeV}^{-1}
\]

1. The KLOE experiment

The KLOE experiment operates at DAΦNE, the Frascati φ–factory. DAΦNE is an e+e− collider running at a center of mass energy of \(\sim 1020\) MeV, the mass of the φ meson. Positron and electron beams collide at an angle of \(\pi-25\) mrad, producing φ mesons with small momentum in the orbit plane \(p_x(\phi) \sim -15\) MeV.

The KLOE detector consists of a large cylindrical drift chamber (DC) surrounded by a lead-scintillating fiber electromagnetic calorimeter (EMC). A super-conducting coil around the EMC provides a 0.52 T axial field.

The DC[1] is 4 m in diameter and 3.3 m long and has 12,582 all-stereo tungsten sense wires. The chamber shell is made of carbon fiber-epoxy composite and the gas used is a 90% helium, 10% isobutane mixture. These features maximize transparency to photons and reduce \(K_L \rightarrow K_S\) regeneration and multiple scattering. The position resolutions for single hits are \(\sigma_{r,\phi} \sim 150\) µm and \(\sigma_z \sim 2\) mm almost omogeneus in the active area. Those performances results in a decay

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vertex position resolution ranging between 3–6 mm in the instrumented decay volume. The moment resolution is \( \sigma(p) / p \sim 0.4\% \).

The calorimeter is divided into a barrel and two end-caps, and covers 98\% of the solid angle. The modules are read-out at both ends by photo-multipliers, both in amplitude and time for a total of 2440 cells per side arranged in five layers. Cells close in time and space are grouped into calorimeter clusters. The cluster energy \( E \) is the sum of the cell energies. The cluster time \( T \) and position \( \vec{R} \) are energy-weighed averages. Energy and time resolutions are \( \sigma_E / E = 5.7\% / \sqrt{E} (\text{GeV}) \) and \( \sigma_t = 57\text{ps} / \sqrt{E} (\text{GeV}) \oplus 100 \text{ ps, respectively.} \)

During KLOE data taking DAΦNE beam conditions and detectors calibrations are constantly monitored in order to guarantee the highest quality of the collected data. Presently KLOE has acquired 2.5 fb\(^{-1}\) of data and a new extensive campaign of data taking is starting under the project KLOE-2[3].

2. Neutral kaons at KLOE
At DAΦNE the \( \phi \)-meson is produced almost at rest in the center of the KLOE sdetector and decays mostly in kaon pairs: 34\% of decays are in neutral kaons. The initial state of the kaon pair is produced with quantum numbers \( J^{PC} = 1^{--} \):

\[
|i| = \frac{|K_0||\overline{K}_0| - |\overline{K}_0||K_0|}{\sqrt{2}} = \mathcal{N}(|K_S(\overline{p})||K_L(\overline{\rho})| - |K_S(\overline{\rho})||K_L(\overline{p})|),
\]

where \( |K_S/K_L| \) are the kaon mass eigenstate and \( \mathcal{N} \) is a normalization factor. The last expression holds because of the Bose-Einstein principle and is independent from the \( \phi \)-meson decay mechanism.

The neutral kaon mass eigenstate could be expressed as:

\[
\begin{cases}
|K_S| = (1 + \epsilon_S)|K_0| + (1 - \epsilon_S)|\overline{K}_0| \\
|K_L| = (1 + \epsilon_L)|K_0| - (1 - \epsilon_L)|\overline{K}_0|
\end{cases}
\]

where \( \epsilon_{S/L} = \epsilon_K \pm \delta_K \). The parameter \( \epsilon_K \) represents \( CP \) violation in the neutral kaon system (both direct and indirect) while \( \delta_K \) stands for possible \( CPT \) violation. Assuming no \( CPT \) violation \( \epsilon_S = \epsilon_L \).

Equation 1 implies that the detection of one of the two kaons (on one side) reveals the presence of the other kaon with known momentum and direction on the opposite side. In the KLOE data reconstruction this feature, the tagging, is used to select pure \( K_S \) or \( K_L \) beams identifying \( K_L \) interactions in the EMC or \( K_S \to \pi^+\pi^- \) decays respectively.

A different approach can be exploited at KLOE since the two kaons are produced in an antisymmetric correlated state. Labeling \( f_1 \) and \( f_2 \) the decay channels for the two kaons, the time evolution of the initial state decaying into \( |f_1, f_2\rangle \) final state is expressed as a function of the difference of proper decay times \( \Delta \tau = \tau_2 - \tau_1 \) as:

\[
I_{f_1f_2}(\Delta \tau) \propto e^{-\Gamma|\Delta \tau|} \left[ |\eta_{f_1}|^2 e^{\frac{\Delta \tau}{\tau} \Delta \tau} + |\eta_{f_2}|^2 e^{\frac{\Delta \tau}{\tau^2} \Delta \tau} - 2\Re\left( \eta_{f_1} \eta_{f_2}^* e^{-i\Delta m \Delta \tau} \right) \right]
\]

where \( \eta_{f_i} = \langle f_i|K_L \rangle / \langle f_i|K_S \rangle \), \( \Gamma = \Gamma_S + \Gamma_L \) and \( \Delta \Gamma = \Gamma_S - \Gamma_L \).

Equation 3 shows a time interference term characteristic of the type of correlation firstly pointed out by Einstein, Podolsky and Rosen [4].

If the final states considered are the same for the two kaons \( f_1 = f_2 = f \) it becomes impossible to distinguish between them (e.g. decay times are not ordered). In the standard Quantum Mechanics description of the time evolution of the system, a fully destructive
interference is expected for equal decay times ($|\Delta \tau| = 0$). In this case the resulting ratio of amplitudes ($\eta_j$) becomes:

$$\eta_j = \eta_{n^+n^-} = \frac{\langle K_L|\pi^+\pi^- \rangle}{\langle K_S|\pi^+\pi^- \rangle} = \varepsilon_K - \delta_K$$  \hspace{1cm} (4)

for both kaons decay and the only possibility to distinguish between them is to label the final state according to some fixed direction in the space (e.g. $|\mathbf{f}_1\rangle \equiv |\pi^+\pi^- (\hat{P}_K^1)\rangle$). This choice is well suited to observe violation of the fundamental symmetry $CPT$ in the framework of the Standard Model Extension (SME) developed by A. Kostelecky [5].

According to SME, $CPT$ violating parameter $\delta_K$ has to be expressed as:

$$\delta_K \approx i \sin \phi_{SW} e^{i \phi_{SW}} \gamma_K (\Delta a_0 - \tilde{\beta}_K \cdot \Delta \tilde{a}) / \Delta m,$$  \hspace{1cm} (5)

where $\gamma_K$ and $\beta_K$ are the usual Lorentz factors, $\phi_{SW}$ is the superweak phase and $\Delta a_\mu$ are the SME parameters for the kaon system.

Equation 5 shows that $\delta_K$ is modulated by the kaon momentum modulus ($\gamma_K$ and $|\tilde{\beta}_K|$) and by its spatial direction ($\tilde{\beta}_K$). At KLOE kaons are produced back-to-back in the $\phi$-meson decay and therefore they will evolve with two different $\delta_K$ values. The effect produced by $\delta_K$ parameter different from zero will be observed in the distribution of equation 3.

The simple expression of equation 5 holds in a special frame, the sidereal reference frame, with axes fixed with respect to the fixed stars. Taking into account the Earth motion with respect to the fixed stars and the laboratory frame, the $CPT$ violation parameter becomes:

$$\delta_K(\tilde{\beta}_K, T_{sid}) = \frac{i \sin \phi_{SW} e^{i \phi_{SW}} \gamma_K}{\Delta m} \left[ \Delta a_0 + \beta_K \Delta a_Z (\cos \vartheta \cos \chi - \sin \vartheta \cos \varphi \sin \chi) - \beta_K \Delta a_X \sin \vartheta \sin \varphi \sin \omega_E T_{sid} + \beta_K \Delta a_X (\cos \vartheta \sin \chi + \sin \vartheta \cos \varphi \cos \chi) \cos \omega_E T_{sid} + \beta_K \Delta a_Y (\cos \vartheta \sin \chi + \sin \vartheta \cos \varphi \cos \chi) \sin \omega_E T_{sid} + \beta_K \Delta a_Y \sin \vartheta \sin \varphi \cos \omega_E T_{sid} \right].$$  \hspace{1cm} (6)

where $\omega_E$ is the angular velocity of the Earth, $T_{sid}$ is the sidereal time, $\chi$ is the 3D angle between the $\hat{z}_{LAB}$ axis of the laboratory frame and the Earth rotation axis, and $\vartheta$ and $\varphi$ are the polar and azimuthal angle in the laboratory, respectively.

The equation 6 shows that the sidereal time dependence of $\delta_K$ could be observed only associated with $\Delta a_X$ and $\Delta a_Y$ parameters different from zero. $\Delta a_0$ parameter, being coupled only with the $\gamma_K$, will be the most difficult to observe\(^2\).

The introduction of equation 6 in the time evolution of the kaon system implies the angular dependence of equation 3:

$$I(\Delta t, T_{sid}, \vartheta, \varphi) \propto e^{-|\Delta \tau|} \left[ |\eta_{K_1}(T_{sid}, \vartheta, \varphi; \Delta a_\mu)|^2 e^{\frac{i \Delta m T_{sid}}{2}} + |\eta_{K_2}(T_{sid}, \vartheta, \varphi; \Delta a_\mu)|^2 e^{-\frac{i \Delta m T_{sid}}{2}} \right] - 2 \Re(\eta_{K_1}(T_{sid}, \vartheta, \varphi; \Delta a_\mu) \eta_{K_2}(T_{sid}, \vartheta, \varphi; \Delta a_\mu) e^{-i \Delta m T_{sid}}).$$  \hspace{1cm} (7)

Since at KLOE the $\phi$-meson is not produced exactly at rest the kaons are not perfectly back-to-back in the lab frame. This has two implications: the Lorentz factors in equation 6 ($\gamma_K$ and $\beta_K$) have their own angular dependence and the two kaons momenta are not equal in modulus.

\(^2\) The excursion of $\gamma_K$ at KLOE is of the order of 2-3%.
To study all the components of $\Delta a_{K}$, we analyzed the KLOE data-set as a function of sidereal time and kaon angle. Ordering kaon according to the momentum component along $z$ transfers the polar angle dependence into $\Delta \tau$ sign. To enhance possible effects the azimuthal angle dependence will be considered by splitting the sample according to kaon direction with respect to $\phi$-meson momentum (e.g. $P_{x}^{K} > 0$ or $P_{x}^{K} < 0$). The observable will be defined as:

$$S(\Delta \tau, \Delta T_{sidj}, \Delta \Omega_{h}) = \int_{\Delta \tau} d\Delta \tau \int_{\Delta T_{sidj}} dT_{sidj} \int_{\Delta \Omega_{h}} d\Omega_{K} \rho(\vartheta, \varphi, T_{sid}) I(\Delta \tau, T_{sid}, \vartheta, \varphi)$$

(8)

where $\rho(\vartheta, \varphi, T_{sid})$ is the angular and sidereal density distribution of the produced kaon in the positive direction of the $z$ axis. This density has a $\sin^{2} \vartheta d\vartheta$ for the polar angle dependence and an unespected dependence as a function of $T_{sid}$. This behavior is due to inhomogeneity of data taking during data taking period. This part of the density function has been taken directly from data in a independent sample. The integration ranges are defined as:

$\Delta \tau$ Proper decay time difference. Should be in the range 0.5 – 1.5 $\tau_{s}$;

$\Delta T_{sidj}$ Sidereal time interval. The default number of divisions of a sidereal day will be four, 8 sidereal hour each;

$\Delta \Omega_{h}$ Angular interval. The polar angle range will be $\vartheta \in [0, \pi/2]$ and the azimuthal range will be $\varphi \in [-\pi/2, \pi/2]$ or $\varphi \in [\pi/2, 3\pi/2]$, sel. “A” and sel. “B”, respectively.

The number of different $\Delta \tau$ distributions considered in the present analysis will be: 4 sidereal time bins $\times$ 2 angular bins. The kaon regeneration on the beam pipe walls is taken into account in the integration of equation 8 as a multiplicative correction of $I(\Delta \tau, T_{sid}, \vartheta, \varphi)$.

3. Data analysis

In this analysis the entire KLOE data-set acquired during 2004-05 has been used. The total integrated luminosity is about 1.7 fb$^{-1}$. The Monte-Carlo (MC) samples used are two having equivalent integrated luminosity of 3.4 fb$^{-1}$ and 17 fb$^{-1}$, respectively. The former, containing all the $\phi$-meson decay channel, has been used for analysis optimization, while the latter, containing only signal events has been used for efficiency and resolution determination.

The data reduction starts with the topological identification of the candidate signal events: two vertices with two tracks each. For each vertex the same list of selection criteria is applied:

- $|m_{trk} - m_{K}| < 5$ MeV
  where $m_{trk}$ is the invariant mass of the kaon reconstructed from the tracks assuming charged pion mass hypothesis;

- $\sqrt{E_{miss}^{2} + |P_{miss}^{x}|^{2}} < 10$ MeV
  where $P_{miss} = P_{K}(tag) - P_{K}(trk)$ with $P_{K}(tag) = P_{\phi} - P_{K}(opposite)$ the kaon tagged momentum from the opposite decay vertex information and $P_{K}(trk) = \vec{p}_{\pi^{+}} + \vec{p}_{\pi^{-}}$ the reconstructed kaon momentum from the tracks, $E_{miss} = E_{K}(tag) - E_{K}(trk)$ with $E_{K}(tag) = E_{\phi} - E_{K}(opposite)$ the kaon tagged energy from the opposite decay vertex informations and $E_{K}(trk) = \sqrt{|\vec{p}_{\pi^{+}}|^{2} + m_{\pi}^{2} + \sqrt{|\vec{p}_{\pi^{-}}|^{2} + m_{\pi}^{2}}$ is the energy of the kaon reconstructed from tracks;

- $-50$ MeV$^{2} < M_{miss}^{2} < 10$ MeV$^{2}$
  where $M_{miss}^{2} = E_{miss}^{2} - |P_{miss}^{y}|^{2}$

- $|P^{*}_{K}(trk) - \sqrt{x}P^{*}_{0}(kinematics)| < 10$ MeV
  where $P^{*}_{K}(trk)$ is the momentum of the kaon, as derived from tracks, in the $\phi$-meson reference frame, while $P^{*}_{0}(kinematics) = \sqrt{\frac{x^{2}}{4} - m_{K_{0}}^{2}}$ represents the expected value from two body kinematics in the $\phi$-meson decay.

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The background contamination after those selections is 1.5%, as estimated from MC. The background events are mainly due to kaon regeneration. This background is irreducible because it is made of regenerated kaons moving in the forward direction (in the limit of the angular resolution).

A global fit is performed in order to improve the resolution on the decay time difference. In this global fit the free parameters are the φ-meson decay point coordinates ($\vec{V}_{\phi}$) and the decay length for the two kaons ($\lambda_1, \lambda_2$). A global Likelihood function is built in order to take into account all the information for each event. The outputs of the fit are then used to compute the proper decay times and $\chi^2$ and pulls of the fit are used to reject badly reconstructed events.

The $\Delta\tau$ resolution is strongly correlated, as expected, with the opening angle of the pion tracks ($\theta_{\pm}$), and deteriorates at large values of $\theta_{\pm}$. A cut to eliminate large opening angles has been applied and events with $\cos(\theta_{\pm}) < -0.975$ have been rejected. The result is shown in figure 1. Since the two kaons are ordered according to the longitudinal momentum (z component) it is possible to mis-order them with respect to the true ordering. This effect has been suppressed by rejecting events with the “first” kaon having: $P_z(K_1) < 2$ MeV.

The shape of the efficiency as a function of true value of $\Delta\tau$ is shown in figure 1. The mean value is 25% for $\Delta\tau$ ranging in $[-12; 12]\tau_S$ with a consistent drop for $\Delta\tau \sim 0$. This is due to two concurrent effects: increasing extrapolation length for tracks coming from the interaction point and the wrong association of tracks with the kaon decay vertex $^3$ ("vertex interference").

![Figure 1: Left: resolution on $\Delta\tau$. The effect of the cut on opening angle between tracks is shown. Right: MC efficiency as a function of true $\Delta\tau$. Colors represents the different analysis stage: blue for global fit, green for opening angle cuts and red for the final efficiency.](image)

The total selection efficiency can be parametrized as follow:

$$\varepsilon_{tot} = \varepsilon_{trig} \varepsilon_{reco} \varepsilon_{cuts}$$

where the first two terms take into account trigger and standard reconstruction procedure effects while the last is the effect of the selection criteria. In this analysis the efficiencies are derived

$^3$ When the two vertex are so close in space ($\Delta\tau = 1\tau_S \Rightarrow \Delta x_V \sim 6$mm) it is possible to wrongly associate tracks to vertex by exchanging two of them.
from MC. For trigger and reconstruction efficiencies corrections obtained from data, using an independent control sample of $K_L \rightarrow \pi \mu \nu$, are applied. The control sample will be selected so to have the best purity and to cover the tracks momentum distribution of the signal.

The selection of the control sample requires the presence of a $K_S \rightarrow \pi^+ \pi^-$ tagging decay and a semileptonic decay on the opposite side. After the topological request (two tracks connected to a vertex), the selection of the semileptonic decay is mainly based on the following variable:

$$m_l^2(\pm) = E_{l}^2 - p^2_{\pm} = (E_{K}^{tag} - E_{\pi}(\mp) - |\vec{p}_{miss}|)^2 - p^2_{\pm}$$  \hspace{1cm} (9)

representing the reconstructed mass of the lepton of a given charge in the hypothesis that the other charged track is a pion. In figure 2 the distribution of the squared charged lepton mass is shown. The structures corresponding to $K_\mu 3$, $K_\pi 3$ and $\pi^+ \pi^-$ decay are clearly visible. The control sample is required to fulfill:

$$m_l^2(+) - m_l^2(-) \geq 15000 \text{ MeV}^2$$  
$$m_l^2(+) - m_l^2(-) \leq 30000 \text{ MeV}^2$$

After this simple selection the purity of $K_\mu 3$ sample is at the level of 93%. To further improve the purity the following cuts are applied:

- $\sqrt{E_{miss}^2 + P_{miss}^2} > 10 \text{ MeV}$ to remove the residual $K_L \rightarrow \pi^+ \pi^-$ events ensuring the statistical independence between signal and control sample;
- $|p^+_{\pm}| + |p^-_{\pm}| < 400 \text{ MeV}$;
- $\cos(\theta_{\pm}) < -0.6$ to ensure the same angular range for the opening angle between tracks.

This last cut is applied also on the tagging side.

The final purity of the control sample is 95% and the remaining background is fully dominated by $K_e 3$ decay.

**Figure 2:** Left: squared charged lepton mass, the highlighted region represent the cuts applied. Right: Efficiency correction as a function of $\Delta \tau$ in the sidereal time interval 18-24 hours. Plot refers to the angular selection: sel. “B”. Boxes represents statistical error. The fit with a constant function shows that on average the global correction is very small (0.2-0.5%).

The efficiency correction has been evaluated as the ratio between data and MC distribution of $\Delta \tau$, as shown in figure 2.
4. Fit results
Starting from the theoretical expression of equation 8 the fitting function ($\tilde{S}(\Delta \tau_i, \Delta T_{sidj}, \Delta \Omega_h)$)
has to include efficiency and resolution effects:

$$\tilde{S}(\Delta \tau_i, \Delta T_{sidj}, \Delta \Omega_h) = \rho_{K_{\mu}}(\Delta \tau_i) \sum_k \varepsilon_{MC}^{k} P_{ik}^{MC} S(\Delta \tau_{k}^{MC}, \Delta T_{sidj}, \Delta \Omega_h)$$

(10)

where $\rho_{K_{\mu}}(\Delta \tau_i)$ is the efficiency correction from the semileptonic control sample, $\varepsilon_{MC}^{k}$ is the
total efficiency corresponding to the MC bin ($\Delta \tau_{k}^{MC}$) and $P_{ik}^{MC}$ are the smearing matrix elements
connecting the true value $\Delta \tau_{k}$ with the observed one $\Delta \tau_i$.

The results obtained from the fit are show in figure 3 and are listed in table 1. The $\Delta \tau$ range is:
$\Delta \tau \in [-12 : 12] \tau_S$. This choice limits the effects from the regeneration on the spherical
beam pipe. The number of sidereal time bins used is four and the angular selection are two:
$\cos \vartheta_{K_1} \cos \varphi_{K_1} > 0$ (sel. “A”) and $\cos \vartheta_{K_1} \cos \varphi_{K_1} < 0$ (sel. “B”). All the distributions are
fitted at the same time (184 bins).

The systematic uncertainty sources taken into account are results variations as a function of: $\Delta \tau$ fit range, $\Delta \tau$ bin width, regeneration on beam pipe, subtraction of four pion direct production.

![Figure 3: Fit results: upper(lower) plots are for the angular selection “A” (“B”). Black points are for data while colored bands are the fit output. The errors on data are purely statistical, while the width of the fit result band represent the contribution to the uncertainty coming from MC statistics and efficiency correction.](image)

5. Conclusions and future plans
The continuation of the KLOE physics program with KLOE-2 [3] at an improved DAΦNE machine is starting with a new beam interaction scheme [6] and with the inclusion of two pairs of electron-positron taggers for the study of the gamma-gamma physics: Low Energy Tagger [7] inside KLOE apparatus and High Energy Tagger [8] along the beam lines outside the KLOE detector. Several other upgrades for the detector are going to be installed in the next months:

- a pair of crystal calorimeters (CCALT [9]) near the interaction region to improve the angular acceptance for low-$\theta$ particles;
Table 1: Fit results. Systematical uncertainties are still preliminary. The statistical errors are in the expected range. The fit $\chi^2/\text{NDoF}$ is 216/184 corresponding to a p-value of 5%.

| Parameter | Value |
|-----------|-------|
| $\Delta a_0$ | $(-6.2 \pm 8.2^{\text{stat}} \pm 3.3^{\text{sys}}) \times 10^{-18}$ GeV$^{-1}$ |
| $\Delta a_X$ | $(3.3 \pm 1.6^{\text{stat}} \pm 1.5^{\text{sys}}) \times 10^{-18}$ GeV$^{-1}$ |
| $\Delta a_Y$ | $(-0.7 \pm 1.3^{\text{stat}} \pm 1.5^{\text{sys}}) \times 10^{-18}$ GeV$^{-1}$ |
| $\Delta a_Z$ | $(-0.7 \pm 1.0^{\text{stat}} \pm 0.3^{\text{sys}}) \times 10^{-18}$ GeV$^{-1}$ |

- a pair of tile calorimeters (QCALT [10]) covering the quadrupoles along the beam pipe made of tungsten foil and singly read-out scintillator tiles to improve the angular coverage for particles coming from the active volume of the DC;
- a small and light tracker (IT [11]) made of four planes of cylindrical GEM to improve the resolution of the vertex reconstruction around the interaction point and to increase the low-$\theta$ acceptance for charged particles.

The results presented in table 1 are expected to be improved with the KLOE-2 data taking campaign. The sensitivity of $\text{CPT}$ and Lorentz invariance tests will improve either by the increased statistics either by the new interaction region (IR) with IT. The IT will improve the resolution on the vertex position and the acceptance for low-$\theta$ tracks, the IR will imply a larger beam crossing angle (from 25 to 60 mrad) that will enhance the effect of asymmetry between the two kaons. The expected sensitivity should increase up to $10^{-19}$ GeV for all the $\Delta a_\mu$ parameters.

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