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Institution: University of Virginia (U.Va.)
Advisor: Dr. Sergio Corneli
Keith N. Marshall

The Quadrupole Tile Calorimeter at KLOE
100X more abundant

backgrounds: $K_\ell^\nu_\ell^\nu_\ell \
\nu_\ell \nu_\ell \nu_\ell 
\nu_\ell \nu_\ell \nu_\ell

primary goal: CP violation in strange quark systems
wide range of physics
KLOE Experiment

KLOE
10

-- to an accuracy of

3

3

-- measure

Main Goal for KTOE:

-- not well-studied, until recently

-- known for many years

CP Violation:

KTOE
DAPHNE

Double-Annular PHI Factory for Nice Experiments

20 km southeast of Rome, Italy

collider $e^+ e^-$

optimized at 1020 MeV, phi-meson mass
ideal environment for $K$ physics

$\% (34.1 \div 0.6)$

$S_{Y+K} \leftarrow \phi$

$\% (49.1 \div 0.8)$

$S_{Y+K} \leftarrow \phi$


dince

DAPHNE
2 Coplanar Rings

Accumulator

LINAC

DAPHNE
| 10° ± 15 mrad | Half Crossing angle | 1300 ± 2200 mA | Current |
| 1.35° ± 3.40° | Luminosity | 8.9 · 10^10 | Particles/bunch |
| \( \omega = 3.0 \text{ cm} \) | Bunch Length | 1/10.8 ± 1/2.7 ns | Collision Frequency |
| \( \rho = 21 \text{ mm} \) | | 30 ± 120 | Number of bunches |
| \( \sigma = 2.1 \text{ mm} \) | Transverse dimension | 510 MeV | Beam energy |

Tab. 2.3: DAΦNE characteristic parameters.
KLOE Detector

- be self-calibrating
- accuracy
- reconstruct and measure $S, K, K^T$ and path lengths to required precision
- collect enough statistics

Requirements:
<table>
<thead>
<tr>
<th>Method</th>
<th>Process</th>
<th>Time Scale</th>
<th>Energy Scale</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous, Relative, $K_0$</td>
<td>$\mu_0^{+0_+} \rightarrow \mu_0^{+0_+} \rightarrow \mu_0^{+0_+}$</td>
<td>$V_0^{+0_+}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Photon Efficiency</td>
<td>Continuous, absolute, $e^+\rightarrow e^-\rightarrow \mu_0^{+0_+} \rightarrow \mu_0^{+0_+}$</td>
<td>$\mu_0^{+0_+}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tracking Efficiency</td>
<td>Continuous, absolute, $\gamma^{+0_+} \rightarrow e^+\rightarrow e^-\rightarrow \mu_0^{+0_+}$</td>
<td>$\mu_0^{+0_+}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5. Detector Calibration
<table>
<thead>
<tr>
<th>$\gamma_S$ = 0.59</th>
<th>$\gamma_T$ = 3.43</th>
<th>$\gamma_T$ = 95</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s &gt; 1.27$</td>
<td>$d = 1.10$</td>
<td>$d = 0.27$</td>
</tr>
<tr>
<td>$K^0 \rightarrow \nu_0 \nu_0 \eta$</td>
<td>$K^0 \rightarrow \nu \nu$</td>
<td>$K^0 \rightarrow \phi$</td>
</tr>
<tr>
<td>Decay Length (cm)</td>
<td>Momentum (MeV/c)</td>
<td>Decay</td>
</tr>
</tbody>
</table>
quadrupole calorimeter (QCAL)
wire drift chamber (DC)
electromagnetic calorimeter (EMC)
superconducting solenoidal magnet

Parts

KLOE Detector
...magnetic calorimeter, the superconducting coil, the iron yoke, the quadrupoles with the associated calorimeters (QCA), the drift chamber, the electron...
Fig. 2.7: Section of the KLOE detector along the $z - y$ coordinate.
$\mathcal{L} = 0.77$  

Field strength  

Solenoidal  

Superconducting  

KLOE Detector: Magnet
\[
\frac{\langle \Lambda e \rangle \sqrt{E}}{sd} = \sigma \quad \text{Time resolution}
\]
\[
\frac{\langle \Lambda e \rangle \sqrt{E}}{\%} = \sigma \quad \text{Energy resolution}
\]

0.5 mm thick Pb plates interspersed with plastic scintillating fibers

KLOE Detector: EMC
K

--- Enough decay length for

Why so big?

Diameter: 4 m

Length: 3.5 m

-- Reduces regeneration and multiple scattering

Gas mixture: 90%H2 + 10%Isobutane

KLOE: Wire Drift Chamber
Fig. 2.12: Schematic view of the drift chamber supporting structure.
Figure 2.5: Pictorial volumes for $K_S$ and $K_L$ (shaded areas), also the chamber walls are drawn.
entering localization quadrupole magnets -- •

Non-negligible probability •

Why does this happen in the first place? •

\( \Lambda \text{ EMC misses } Z \) -- •

\( u \overset{\text{K}}{\leftarrow} Z \) -- •

Suppose •

KTOE: GCA
the interaction region and the two tracks are bent in the magnetic field.

and then in six photons. The $Y$ decays in two charged pions very close
then the two $QCD$ calorimeters. In the upper part the $K_L$ decays into three
around the beam pipe the two triplets of quadrupoles are shown and around
zontal cross section (as it appears from the detector Monte Carlo Program).

Figure 2: $K_L Y \nu_+ \nu_-$ event inside the KLOE detector (hor-

[4]
--- Quadrupole Calorimeter (QCAT) ---

Answer:

How do we detect these missing photons?

Question:

KTOE: QCAT
\[ \mathcal{L} \mathcal{V} (20-280) \text{ MeV} \]

- Good Time Resolution
- Highest efficiency for \( 20 \text{ - } 280 \text{ MeV} \)
- Maximize KLOE hermeticity, i.e. decrease leakage

KLOE: QCAT

Required performance:
KLOE: QCAT

Good resolution $\lesssim \mu \text{ns}$

--eventual time between bunch crossings $\gtrsim 2.7 \mu \text{s}$

Necessary for:

- neighboring bunch separation

$\sim 1 \mu \text{ns}$

Good Time Resolution
Three physical constraints:

1. lack of free space
   - has to fit between drift chamber and quadrupole magnets

2. mass
   - the QCALs are cantilevered
   - no more than 400 kg

3. ends close to interaction region
   - inaccessible

KLOE: QCAL Physical Constraints
shown together with the surrounding calorimeter (QCAL).

Figure 11: One side of the experiment interaction region. Two permanent quadrupoles (QVA1) are
KLOE qCAL: Rejected Proposals

- Better light output than the adopted solution
- Difficult to construct
- 3. Sashlik Calorimeter
- Hence no space to bring out the light
- Too many fibers
- 2. Spaghetti or SCI-FI Calorimeter
- Expensive
- Too slow in time response
- 1. BGO (crystal) Calorimeter
- Plastic scintillation fibers connecting non-adjacent sectors
- 16 azimuthal sectors
- Roughly coincident device w/
- Collaboration of Roméz and U. V.A

The Result:
- Easier to build
- Small number of fibers
- Tile calorimeter

Adopted solution:

KLOE qCAT: The Adopted Solution
Figure 1: Artist's view of upper half of one QGL calorimeter. Fibers between non-adjacent sectors are shown schematically.
collect the high of two non-adjacent sectors.

Figure 10: The same fibers are used to:

FIGURE 9: Before cutting and polishing, the 60 fibers of each gal sector are bundled together and glued.
Figure 8: A sector of the \( \text{CAL} \). It is possible to notice the lead plates and the \text{Scintillator tiles} and fibers are wrapped together in layers. The \text{WLS fibers} run along the tiles.
Overall efficiency about 98%.

Then use the drift chamber to track them.

Cosmic rays - energy deposition equivalent to 25 MeV photons.

Cosmic Ray Detection Efficiency

Finish Modules: Measured Performance.
Figure 13: Cosmic rays efficiency versus GCal tower. Towers I-16 refer to GCal A, I7-32 refer to GCal B.
especially at $\phi = 0^\circ$ and $\phi = 180^\circ$. The angular separation of $\phi$ and $\theta$ is evident. The loss of efficiency for the interval $\phi$ indicates that the peak at 96 cm in the small peak is due to a $\phi$.

Figure 1.4: Cosmic ray efficiency as a function of $\phi$.

Figure 1.5: Cosmic ray efficiency as a function of $\phi$. Probable due to Cerenkov.
Cross section on the left, scintillator tile was used as trigger, tile and the two fibers are shown in.

Figure 3: Experimental setup for the light output measurement. On the right.

WLS fiber

\[ \text{1 mm} \]

\[ \text{2 cm} \]
\((1 - \varepsilon) \frac{\mathcal{J}}{\lambda} - T = z\)

use the following expression

compare with the results in the drift chamber

\(\mathcal{J} \sigma = z \sigma\)

proportional to spatial resolution

large amount of cosmics is needed

very important for discriminating \(K^+\) decays from background

Cosmic Ray Time Resolution

Final Modules: Measured Performance
Figure 2: Experimental setup used to measure the time resolution of a tile calorimeter.

- Cosmic Ray
- Scintillator
- PM 1
- PM 2
- WLS Fibers
- Tracker
\[
\frac{\int \mathcal{E} \mathcal{G}}{\int \mathcal{P}} = \phi
\]

Photon

Obtained time resolution (w/ cosmic ray equivalence to 75 MeV)

\[ su(\tau \div 88 = 0, 0) = \phi \]

Obtained time resolution

\[ mu(\tau \div 0, 0 = 3, 0) = z \phi \]

Obtained z-resolution

Cosmic Ray Time Resolution

Final Modules: Measured Performance
Figure 7: Time resolution $\rho(t_2 - t_1)$ as a function of the signal.

$20 \rho(t_2) \sigma(t_1 - t_2) = \left( \frac{t_2}{t_1} \right)$

Figure 6: $t_2 - t_1$ distribution.

$\rho(t_2 - t_1) = \frac{\sigma(t_2 - t_1)}{\sigma(t_2)}$

$su(t_2 - t_1) = 2.96 \, 909 \, 6 \, ns = \Omega$
• Check the difference between measured and expected times

• Check for proper expected time

• GCAL

• Consider only those events in which the missing photon points to the
kinematically reconstructed photon's direction

• Select \( K \rightarrow 3\nu \) and \( K \rightarrow l\nu \) with \( I \nu - \nu + \nu \)

Final Modules: Measured Performance

Detection Efficiency
FIGURE 17: Cluster times for photons.

FIGURE 16: Cluster times for photons.
Figure 19: $z_{DC}$ distribution for the GCD $z_{res}$. Since the drift chamber resolution has a resolution of about 3 mm, this is the GCD $z_{res}$.

Cosmic ray events located with the drift chamber track for GCD information versus the $z$ caliper.

Figure 18: $z$ coordinate measured with...
<table>
<thead>
<tr>
<th>Charged Events</th>
<th>Neutral Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(70 \pm 5%)$</td>
<td>$(74 \pm 2%)$</td>
</tr>
<tr>
<td>$(63 \pm 3%)$</td>
<td>$(66 \pm 2%)$</td>
</tr>
</tbody>
</table>

Experimental Monte Carlo

Detection Efficiency $K \rightarrow 3\nu$
Resolution

QCAT: Will detect photons w/ required efficiency and time/space

Preliminary tests

Cosmic ray data: excellent agreement between simulations and performances

Good agreement between design parameters and measured

Detection efficiency of $\approx 92\%$ for protons in $20 - 250 M e V$

Conclusion