Measurement of the neutron detection efficiency of the KLOE calorimeter

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Why neutrons at KLOE?

- Detection of neutrons of $10^1$–$10^2$ MeV traditionally performed with organic scintillators: efficiency scales with thickness $\Rightarrow$ 1%/cm
- Use of high-Z material improves neutron efficiency
  
  \[(\text{C.Birattari et al., NIM A297 (1990) and NIM A338 (1994)}\]
  \[(\text{T.Baumann et al., NIM B192 (2002)}\]

- Preliminary estimate with KLOE data ($n$ produced by $K^-$ interactions in the apparatus) showed high efficiency ($\sim$40%) for neutrons with $E_n<$ 20 MeV, confirmed by the KLOE MC

- $n$ detection is relevant for the DAΦNE-2 program at LNF; two proposals:
  - search for deeply bounded kaonic nuclei (AMADEUS)
  - measurement of the neutron time-like form factors (DANTE)

Tests have been performed with the neutron beam of the The Svedberg Laboratory in Uppsala

(October 2006 and June 2007)
The neutron beam @ TSL

- Neutrons produced in the reaction $^7\text{Li}(p,n)^7\text{Be}$
- Proton beam energy from 180 MeV to ~20 MeV
- Neutron energy spectrum peaked at max energy (at 180 MeV $\Rightarrow f_p=42\%$ of n in the peak)
- Tail down to thermal neutrons
Experimental setup

1. **KLOE EMC prototype:**
   - total length $\sim 60$ cm, $3 \times 5$ cells
   - $(4.2 \text{ cm} \times 4.2 \text{ cm})$ read out at both ends by Hamamatsu/Burle PMT’s

2. Beam Position Monitor:
   - array of 7 scintillating counters
   - 1 cm thick (removed in June ’07)

3. Reference counter:
   - NE110; 5 cm thick; $10 \times 20$ cm$^2$ area
   - (June 2007 $\Rightarrow$ two other NE110 counters 2.5 cm thick)

Everything is mounted on a rotating frame allowing for vertical (data taking with $n$ beam) and horizontal (for calibration with cosmic rays) positions
**Trigger & DAQ**

**Trigger:**
- No neutron tagging available: self-triggering required
- **Scintillator trigger:** Side 1 - Side 2 overlap coincidence
- **Calorimeter trigger:** analog sum of the signals of the cells (4 or 5 planes out of 5) ⇒ \( \Sigma_A \cdot \Sigma_B \) overlap coincidence
- **Trigger signal is phase-locked with the RF signal** (45 - 54 ns)

**Acquired Data:**
- For each configuration/energy: **scans with different trigger thresholds**
- Three data-sets:
  - \( E_{\text{peak}} = 174 \text{ MeV} \) -- October 2006 - two weeks
  - \( E_{\text{peak}} = 46.5 \text{ MeV} \) -- June 2007
  - \( E_{\text{peak}} = 21.8 \text{ MeV} \) -- "
- Typical run: \( 10^6 \) events - Max DAQ rate: 1.7 kHz (Simplified version of the KLOE experiment DAQ system (VME standard))
Efficiency measurement

Global efficiency measurement: integrated over all the energy spectrum

\[
e = \frac{\text{Rate(trigger)}}{\text{Rate}(n) \cdot f_{\text{live}} \cdot \alpha}
\]

\( flive = \text{fraction of DAQ live time} \)
\( \alpha = \text{acceptance (assuming beam fully contained in the calorimeter surface} \Rightarrow \alpha \approx 1^*) \)

*At low energies: presence of Beam halo!
Evaluated through TSL off-beam counters

Absolute flux of neutrons measured after the collimator

  - Ionization Chamber Monitor (7 cm \( \varnothing \)): online monitor, not position sensitive
  - Thin-Film Breakdown Counter (1 cm \( \varnothing \)): offline monitor; used to calibrate the ICM by measuring the neutron flux at the collimator exit

- \( \text{Rate}(n) = \text{Rate(ICM)} \cdot K \cdot \pi r^2 / f_p \)
  - \( r = \text{collimator radius (1 cm)} \)
  - \( K = \text{calibration factor (TFBC to ICM)} \)
  - \( f_p = \text{fraction of neutrons in the peak} \)

\( \Rightarrow \text{accuracy: 10\% at higher peak energy (174 MeV)} \)
\( 20\% \text{ at lower peak energy} \quad (22 - 46 \text{ MeV}) \)
Scintillator calibration

- Trigger threshold calibration in equivalent electron energy (MeV):

  - ADC counts
  - β source to set the energy scale in MeV:
    - $^{90}\text{Sr}$ β$^{-}$ endpoint = 0.56 MeV
    - $^{90}\text{Y}$ β$^{-}$ endpoint = 2.28 MeV
    - 25 keV/ADC count

<table>
<thead>
<tr>
<th>Thr. [mV]</th>
<th>20 → 100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thr. [MeV]</td>
<td>2.5 → 15</td>
</tr>
</tbody>
</table>
Scintillator efficiency

- Agrees with the “thumb rule” (1%/cm) at thresholds above 2.5 MeV el.eq.en.

\[ \varepsilon(\%) = \text{scint.} \]

\[ \varepsilon(\%) = \frac{(\%)}{\text{cm of scintillator}} \]

Larger errors at low energies due to:
- big uncertainty in the beam halo evaluation
- worse accuracy of the beam monitors

Correction factor for beam halo \( \approx 0.9 \pm 0.1 \)

- Agrees with previous measurements in the same energy range after rescaling for the thickness

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**Calorimeter calibration**

- **Cell response equalization**: MIP peak at \( \sim 550 \text{ ADC counts} \)
- **Trigger threshold calibration**

\[ \begin{array}{|c|c|}
\hline
\text{Thr. [mV]} & 15 \rightarrow 75 \\
\text{Thr. [MeV]} & 1.5 \rightarrow 23 \\
\hline
\end{array} \]

Energy scale calibration with the MIP/MeV conversion factor from KLOE (1 MIP in one calorimeter cell \( \approx 35 \text{ MeV eq. en.} \))

(KLOE Collaboration, NIM A354 (1995),352)
Calorimeter efficiency (174 MeV)

- Very high efficiency
  w.r.t. the naive expectation
  (~ 10% @ 2 MeV thr.)

- Stable for different run conditions

\[
\frac{\varepsilon(\text{calor.}) \cdot \text{th.(scint.)}}{\varepsilon(\text{scint.}) \cdot \text{th.(calor.)}}
\]

Comparison with our scintillator
normalized to the same active
material thickness
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Calorimeter efficiency (21-46 MeV)

- Very high efficiency
- Agreement with the high energy measurements
- Correct. factor for beam halo ≈ 0.8 ± 0.1

The ratio is almost independent from the halo  
(Ratio normalized to the same active material thickness)
Events’ anatomy

Energy deposited by neutrons for the three beam energies

- 22 MeV
- 46 MeV
- 174 MeV

Number of cells per neutron cluster increases with beam energy

Position of neutron clusters in the calorimeter along the forward direction
Efficiency vs energy

Fast MC to test the sensitivity of the time distribution to the shape of the efficiency curve shows better agreement with an efficiency decreasing with energy.

Energy spectrum can be related to Time Of Flight.
A detailed simulation of the calorimeter structure and of the beamline (source, collimator and concrete shielding) has been carried out with the FLUKA Code.
Preliminary results of MC

Some discrepancy in the low energy part of the spectrum

- No cut in released energy
- No trigger simulation
  ⇒ Upper limit on $\varepsilon$

Efficiency enhancement appears to be due to the large inelastic production of secondary neutrons in Pb.
Conclusions

• The first measurement of the detection efficiency for neutrons of 20 - 180 MeV of a high sampling Pb-sci.fi. calorimeter has been performed at the The Svedberg Laboratory in Uppsala.

• Measurement of the \( n \) efficiency of a NE110 scintillator agrees with published results in the same energy range.

• The KLOE calorimeter efficiency, integrated over the whole neutron energy spectrum, ranges between 30-50 % at the lowest trigger threshold.

• Estimate of beam halo, the main source of uncertainty at low energies, is being carried on, also with further tests at TSL which are foreseen to better understand the halo.
Spares
Preliminary results of MC

• Simulated neutron beam: $E_{\text{kin}} = 180$ MeV
• Each primary neutron has a high probability to have elastic/inelastic scattering in Pb

• On average 5.4 secondaries per primary neutron are generated, counting only neutrons above 19.6 MeV.

• Secondaries created in interactions of low energy neutrons (below 19.6 MeV) are - on average - 97.7 particles per primary neutron.

<table>
<thead>
<tr>
<th>target</th>
<th>$P_{\text{el}}(%)$</th>
<th>$P_{\text{inel}}(%)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb</td>
<td>32.6</td>
<td>31.4</td>
</tr>
<tr>
<td>fibers</td>
<td>10.4</td>
<td>7.0</td>
</tr>
<tr>
<td>glue</td>
<td>2.3</td>
<td>2.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Neutrons above 19.6 MeV</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>photons</td>
<td>26.9%</td>
</tr>
<tr>
<td>protons</td>
<td>6.8%</td>
</tr>
<tr>
<td>He-4</td>
<td>3.2%</td>
</tr>
<tr>
<td>deuteron</td>
<td>0.4%</td>
</tr>
<tr>
<td>triton</td>
<td>0.2%</td>
</tr>
<tr>
<td>He-3</td>
<td>0.2%</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>neutrons</td>
<td>94.2%</td>
</tr>
<tr>
<td>protons</td>
<td>4.7%</td>
</tr>
<tr>
<td>photons</td>
<td>1.1%</td>
</tr>
</tbody>
</table>
• The enhancement of the efficiency appears to be due to the large inelastic production of neutrons in Pb. These secondary neutrons:
  • are produced isotropically;
  • are associated with a non negligible fraction of e.m. energy and of protons, which can be detected in the nearby fibers;
  • have low energy and then have a large probability to do new interactions in the calorimeter with neutron/proton/γ production.
Beam halo

- TSL beam experts measured a sizeable beam halo at low peak energy (21.8 and 46.5 MeV):
  - TFBC scan of the area near the collimator
  - integrated flux over the ICM area ~ 5% of the “core” flux (with large uncertainty)
  - halo shape also measured
- Confirmed by our background counters
- Our calorimeter is larger than the projection of ICM area
- By integrating over the calorimeter we obtain an estimate of the halo contribution to the trigger rate of (20 ± 10)%
- Only 10% on the reference scintillator due to the smaller area