A new scintillator detector for nuclear physics experiments: the CLYC scintillator

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Outline

✔ Characterization measurements on new scintillators (SrI₂, CeBr₃, CLYC)
✔ CLYC
  • Enrichment with ⁶Li (Thermal and fast neutrons)
  • Enrichment with ⁷Li (fast neutrons)
  • Measurements with monochromatic fast neutrons
  • Neutron energy resolution from PSD
  • Continuous neutron spectra
✔ Co Doped LaBr₃:Ce, CLLB and CLLBC crystals
✔ LaBr3:Ce with SIPM
✔ Summary
Scintillators in nuclear physics experiments

Detector requirements:

- Measurement of low and high energy gamma rays (0.1 - 15 MeV) → Good efficiency
- Good Time resolution
  - background rejection
  - TOF measurements
- Imaging properties to reduce Doppler Broadening
- Energy resolution is not mandatory but very useful for:
  - calibration
  - measurement and studies of discrete structures
- Possibility to discriminate between gamma rays and neutrons using TOF and PSD

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<th>Material</th>
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<th>Emission $\lambda_{\text{max}}$ [nm]</th>
<th>En. Res. at 662 keV [%]</th>
<th>Density [g/cm$^2$]</th>
<th>Principal decay time [ns]</th>
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<tbody>
<tr>
<td>NaI:Tl</td>
<td>38000</td>
<td>415</td>
<td>6-7</td>
<td>3.7</td>
<td>230</td>
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<tr>
<td>CsI:Tl</td>
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<td>6-7</td>
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<td>1000</td>
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<td>CeBr$_3$</td>
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<td>$\sim$4</td>
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<td>17</td>
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<tr>
<td>GYGAG</td>
<td>40000</td>
<td>540</td>
<td>$&lt;5$</td>
<td>5.8</td>
<td>250</td>
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<tr>
<td>CLYC:Ce</td>
<td>20000</td>
<td>390</td>
<td>4</td>
<td>3.3</td>
<td>1 CVL 50, $\sim$1000</td>
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The SrI$_2$:Eu scintillator (2” x 2”)

Characterization measurements:
- Energy resolution up to 9 MeV
- Crystal scan along the three axes
- Study of the signal shape

- Energy resolution of ~ 3.2% at 662 keV
- Slow detector (fall time ~ 7 μs)
- Large volume crystals (2” x 2”)
- Self absorption

Presence of self-absorption

Energy resolution up to 9 MeV

Crystal scan along the three axes

Study of the signal shape

4.0% at 662 keV

100 ± 20 keV @ 9 MeV

 Rise: 24 ns
Fall: 7 μs
The CeBr$_3$ scintillator (2” x 3”)

Characterization measurements:
- Energy resolution up to 9 MeV
- Crystal scan along the three axes
- Study of the signal shape

- Energy resolution of ~ 3.5% at 662 keV
- Very similar to Labr$_3$:Ce
- Large volume crystals (3” x 3”) available
- No internal activity

Energy resolution up to 9 MeV

The 9 MeV is at 8.6 MeV (4% non linearity).
The CeBr$_3$ scintillator (3” x 3”)

A. Giaz

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CeBr$_3$

LaBr$_3$:Ce

NaI
The CLYC scintillator \((\text{Cs}_2\text{LiYCl}_6:\text{Ce}^{3+})\)

The CLYC crystals were developed approximately 10 years ago.

- Density of 3.3 g/cm³,
- Light yield of 20 ph/keV
- High linearity, especially at low energy.
- Energy resolution at 622 keV < 5%
- Time resolution of 1.5 ns.
- Excellent neutron gamma discrimination.

\[
FOM = \frac{C_{\text{neutron}} - C_{\text{gamma}}}{FWMH_{\text{neutrons}} + FWMH_{\text{gamma}}} \approx 3.9
\]

\[
PSD \text{ ratio} = \frac{W2}{W1 + W2}
\]
Neutron detection

**Fast neutrons:**
- $^{35}\text{Cl}(n,p)^{35}\text{S} \rightarrow Q\text{-value} = 0.6 \text{ MeV} \sigma \approx 0.2 \text{ barns at } E_n = 3 \text{ MeV}$
- $^{35}\text{Cl}(n,\alpha)^{32}\text{P} \rightarrow Q\text{-value} = 0.9 \text{ MeV} \sigma \approx 0.01 \text{ barns at } E_n = 3 \text{ MeV}$

$$E_{p/\alpha} = (E_n + Q) q_{p/\alpha} \rightarrow p \text{ or } \alpha \text{ energy is linearly related to } n \text{ energy} \rightarrow \text{CLYC is a neutron spectrometer}$$

$$E_n > 6 \text{ MeV} \text{ other reaction channels on detectors isotopes } \rightarrow \text{not easy neutron spectroscopy}$$

**Thermal neutrons:**
- $^6\text{Li}(n,\alpha)t \rightarrow Q\text{-value} = 4.78 \text{ MeV} \sigma = 940 \text{ barns at } E_n = 0.025 \text{ eV}$.

**To fast neutron detection:**
- $^7\text{Li} (^7\text{Li} > 99\%)$ enriched CLYC $\rightarrow$ CLYC-7

The kinetic energy of the neutrons can be measured via:
1) Time of Flight (TOF) techniques.
2) The energy signal

**To Thermal neutron detection:**
- $^6\text{Li} (^6\text{Li} = 95\%)$ enriched CLYC $\rightarrow$ CLYC-6

**Two measurements:**
- Monochromatic neutrons
- Continuous neutron spectrum of an $^{241}\text{Am}/^{9}\text{Be}$ source
Fast Neutron Detection with CLYC

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<tr>
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<td>0°</td>
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</tr>
<tr>
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<td>0°</td>
<td>2.83</td>
</tr>
<tr>
<td>5.5</td>
<td>90°</td>
<td>2.68</td>
</tr>
<tr>
<td>5</td>
<td>90°</td>
<td>2.30</td>
</tr>
<tr>
<td>4.5</td>
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A. Giaz et al., NIM A 825, (2016), 51
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Fast Neutron detection with CLYC

The energy of the outgoing proton is linearly related to the energy of the incoming neutron.

\[ E_n = \frac{E_{\text{mis}}}{q} - Q \]
Continuous neutron spectra

A continuous neutron spectra can be measured using the time vs energy matrices (gated on PSD).

The blue region includes contribution of $^{35}$Cl(n,p)$^{35}$S reaction only

Note:
PDS identify an incoming neutron but not its energy
TOF identify a neutron or a delayed $\gamma$-ray

Using both information it is possible to identify a neutron and to measure its energy
**241Am/9Be Source**

**241Am/9Be source:**

\[ ^{241}\text{Am} \rightarrow ^{237}\text{Np} + \alpha \ (E_\alpha \sim 5.5 \ \text{MeV}) \]

\[ \alpha + ^9\text{Be} \rightarrow ^{13}\text{C} \ (Q = 5.7 \ \text{MeV}) \]

\[ ^{13}\text{C} \rightarrow n + ^{12}\text{C} \ (E_n < 11.2 \ \text{MeV}) \]

\(^{12}\text{C}\) can be in different states:

- **Ground state**: \( Q = 5.7 \ \text{MeV} \)
- **1st excited state**: \( Q = 1.3 \ \text{MeV}, \ E_\gamma = 4.439 \ \text{MeV} \)
- **2nd excited state**: \( E_{th} = 2.8 \ \text{MeV}, \ E_\gamma = 7.654 \ \text{MeV} \)
- **3rd excited state**: \( E_{th} = 5.7 \ \text{MeV}, \ E_\gamma = 9.641 \ \text{MeV} \)

Neutron spectra measured in coincidence with a 4.439 MeV \( \gamma \) ray using the TOF technique.


Measurement of the $^{241}\text{Am}/^9\text{Be}$ spectrum

PDS to separate neutrons from gammas.

$E_n = E_{\text{mis}}/q - Q$

$E_n < 7$ MeV: dominant reaction is $^{35}\text{Cl}(n,p)^{35}\text{S}$

till $E_n < 4$ MeV, for higher energies it is necessary to separate different contributions. $\Rightarrow$ using TOF techniques.
New Scintillators

New scintillator materials are available in small size (ENSAR2-PASPAG Project)

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<td>45000</td>
<td>410</td>
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<tr>
<td>CLLB:Ce</td>
<td>55000</td>
<td>410</td>
<td>$&lt; 3$</td>
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CLYC $\Rightarrow$ Cs$_2$LiYCl$_6$  
CLLB $\Rightarrow$ Cs$_2$LiLaBr$_6$

CLLBC $\Rightarrow$ Cs$_2$LiLa(Br,Cl)$_6$

These new crystals are available since few months

CLYC 3”x3” is available since 2016 only

Co-doped LaBr$_3$:Ce
- Co-doping should improve the linearity at low energy
- Co doping should improve energy resolution
- No large volume detectors available (maybe first in 2017)

A. Giaz

New sensors- Large Area SiPM

Individual SiPM properties:

- Technology: NUV-HD produced by FBK
- Active area: 6 x 6 mm² (39600 mcells)
- Microcells size: 30 x 30 mm²
- Cell density: 1100 mcells/mm²
- FF (Fill Factor): 77%
- PDE (Particle Detection Efficiency (con FF)) (@380 nm, Vov = 6V): 43.5%
- DCR (Dark Count Rate) (Vov = 6V): 68 kcps/mm²
- ENF (Excess Noise Factor): 1.19

Modular Structure

- 1"
- 2"
- 3"
LaBr$_3$:Ce (2'' x 2'') coupled to SiPM

Results can be improved:
There were 4 cells (6 mm x 6 mm) not working LaBr$_3$ not in the center to cover the least possible of these 4 cells.
New arrays in production at FBK
Conclusions

Several new scintillators are or will be soon on the market

- CLLB, CLLBC CoDoped LaBr$_3$:Ce, CLYC, CeBr$_3$, SrI$_2$, ...
- Their detailed performances are not fully known
- Several studies on CLYC were done and will be done
  - Energy Resolution and PSD
  - Neutron spectroscopy
  - Continuous neutron spectra

R&D on light sensor (SiPM) for spectroscopy is starting

THANK YOU FOR THE ATTENTION