Thermal and Fast Neutron Detection with two CLYC Scintillators

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Outline

✓ Introduction on Elpasolite scintillators;
✓ CLYC:Ce properties;
✓ CLYC:Ce neutron and gamma discrimination;
✓ Thermal neutron measurements with two CLYC with different concentration of $^7$Li and $^6$Li;
✓ Fast neutron measurement at neutron generator of ENEA, Frascati, Italy;
✓ Fast neutron measurement at the CN accelerator of Legnaro national laboratories, Italy;
   ✓ Energy signal and ToF techniques
   ✓ Thermal neutron background subtraction
✓ Fast neutron efficiency measurement at the LASA, Segrate, Italy.
Elpasolite scintillators: CLYC, CLLC and CLLB

- The elpasolite crystals were discovered approximately 10 years ago.
- Excellent performances in terms of gamma and neutron detection.
- CLYC:Ce (Cs$_2$LiYCl$_6$:Ce), CLLC:Ce (Cs$_2$LiLaCl$_6$:Ce) and CLLB:Ce (Cs$_2$LiLaBr$_6$:Ce)

### Gamma and Neutron detectors:
- High energy and time resolution
- Neutron-gamma pulse shape discrimination capability
- High linearity
- High efficiency for gamma and neutrons
- High light yield

<table>
<thead>
<tr>
<th></th>
<th>CLYC</th>
<th>CLLC</th>
<th>CLLB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density $[g/cm^2]$</td>
<td>3.3</td>
<td>3.5</td>
<td>4.2</td>
</tr>
<tr>
<td>Emission $[nm]$</td>
<td>290 CVL 390 Ce$^+$</td>
<td>290 CVL 400 Ce$^+$</td>
<td>410 Ce$^+$</td>
</tr>
<tr>
<td>Decay Time $[ns]$</td>
<td>1 CVL 50,~1000</td>
<td>1 CVL 60, ≤ 400</td>
<td>55, ≤ 270</td>
</tr>
<tr>
<td>Light yield $[ph/MeV]$</td>
<td>20000</td>
<td>35000</td>
<td>60000</td>
</tr>
<tr>
<td>Light yield $[n/MeV]$</td>
<td>70000</td>
<td>110000</td>
<td>18000</td>
</tr>
<tr>
<td>En. Res. at 662 keV $[%]$</td>
<td>4</td>
<td>3.4</td>
<td>2.9</td>
</tr>
<tr>
<td>PSD</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Possible</td>
</tr>
</tbody>
</table>
General Properties

**7Li Enriched CLYC scintillator**

Energy Resolution 4.5% at 662 keV

1 CLYC:Ce sample enriched with 99% of $^7\text{Li}$ to emphasize the fast neutron detection

**6Li Enriched CLYC scintillator**

Energy Resolution 4.8% at 662 keV

1 CLYC:Ce sample enriched with 95% of $^6\text{Li}$ to emphasize the thermal neutron detection
**CLYC: \(\gamma\) and neutron identification**

Different scintillation light decay response: CVL and Ce\(^{3+}\). The \(\gamma\)-ray signal contains the CVL component, neutron signal does not contain CVL.

PSD (pulse shape discrimination) is based on the differences in the scintillation decay response to gamma and neutrons.

**Width:**
- \(W_1 = 60\text{ns}\)
- \(W_2 = 250\text{ns}\)

**Range:**
- \(W_1 = 0\text{ns} - 60\text{ns}\)
- \(W_2 = 110\text{ns} - 360\text{ns}\)

**PSD ratio**
\[
PSD \text{ ratio } = \frac{W_2}{W_1 + W_2}
\]

**FOM**
\[
FOM = \frac{C_{\text{neutron}} - C_{\text{gamma}}}{FWHM_{\text{neutrons}} + FWHM_{\text{gamma}}} \approx 3.9
\]
Neutron identification

CLYC scintillators can detect both thermal and fast neutrons.

**Fast neutron detection**

The kinetic energy of the neutron can be measured:
- Via the time signal using **Time of Flight** (FWHM < 1 ns)
- Via the **energy signal**: Fast neutrons are detected using the reaction $^{35}\text{Cl} (n, p)^{35}\text{S}$ and $^{35}\text{Cl} (n, \alpha)^{32}\text{P}$ (proton or alpha energy is linearly related to neutron energy).

**CLYC is a neutron spectrometer**

**Thermal neutron detection**

The thermal detection capability arises from $^6\text{Li}$ ions, which have a 940 barns cross section for the reaction $^6\text{Li} (n, \alpha)t$.

$^7\text{Li}$ enriched CLYC:Ce has less sensitivity to thermal neutrons with respect to $^6\text{Li}$ enriched CLYC:Ce (less background between 3.0-3.5 MeV).
Thermal Neutron Detection

Thermal neutron measurements with CLYC scintillators.

- **$^7$Li enriched CLYC:Ce**
  - No Thermal Neutrons

- **$^6$Li enriched CLYC:Ce**
  - AmBe source to produce the thermal neutrons.
  - Same acquisition time $\sim 2h$

Thermal neutrons counts:
- **$^6$Li enriched CLYC:Ce** $\sim 10000$
- **$^7$Li enriched CLYC:Ce** $\sim 30$

$^7$Li enriched CLYC:Ce is $\sim 400$ time less sensitive to thermal neutron

The $^7$Li-enriched CLYC scintillators has an efficiency to thermal neutrons of 0.3% with respect to $^6$Li-enriched CLYC scintillators.

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Thermal and Fast Neutron Detection with two CLYC Scintillators
Fast Neutron Detection

On April 2014 measurement at the Neutron Generator at ENEA laboratories in Frascati (Italy): **monochromatic beam of 14.1 MeV and \(\approx 2.5\) MeV neutrons.** The two sample of CLYC:Ce (\(^6\)Li and \(^7\)Li enriched) were placed at 1.25 m from the neutron source due to the flux. The neutron generator is at 4.5 m from the floor and walls, to reduce the thermal neutron background.

Neutrons at 2.5 MeV were measured only with the \(^7\)Li enriched detector.

**2.5 MeV**

\[\text{2.5 MeV neutrons}\]

\[\text{\(^7\)Li enriched CLYC:Ce}\]

**14.1 MeV**

At 14.1 MeV 3 bodies channels are open e.g. cross section of \(^{133}\)Cs (n, 2n)\(^{132}\)Cs is \(\approx 1.5\) barns.

The cross sections of \(^{35}\)Cl (n, p)\(^{35}\)S and \(^{35}\)Cl (n, \(\alpha\))\(^{32}\)P at 14.1 MeV is \(\approx 0.15\) barns.
Fast Neutron Detection

An experiment at CN accelerator (LNL) was performed in April 2015. The aim was the study of the response to fast neutron (1.9 – 3.8 MeV) of two 1”x1” samples of a CLYC scintillator enriched with $^7$Li (> 99%) and $^6$Li (~ 95%), respectively.

The kinetic energy of neutrons:
1) Via the time signal using ToF technique (FWHM < 2 ns) exploiting the pulse beam.
2) Via the energy signal ($^{35}$Cl(n,p)$^{35}$S and $^{35}$Cl(n,$\alpha$)$^{32}$P)
**Fast Neutron Detection**

### Preliminary Results

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<tr>
<th>Proton Energy [MeV]</th>
<th>Detector Angle</th>
<th>Neutron Energy [MeV]</th>
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<tr>
<td>5.5</td>
<td>0°</td>
<td>3.83</td>
</tr>
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<tr>
<td>5.5</td>
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<td>2.68</td>
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<tr>
<td>5</td>
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<td>2.30</td>
</tr>
<tr>
<td>4.5</td>
<td>90°</td>
<td>1.93</td>
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**Distance:** 70 cm

**Proton Beam** ➔ **Target** ➔ **CLYC-6** ➔ **CLYC-7**

**Proton Energy [MeV]**

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**Gamma ToF**

**Neutron ToF**
Fast Neutron Detection

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Proton Beam

CLYC-7

Distance: 70 cm

Target

CLYC-6

Proton Beam

Preliminary Results

3.3 MeV neutrons

2.3 MeV neutrons

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Fast Neutron Detection

Proton Energy [MeV] | Detector Angle | Neutron Energy [MeV]
--- | --- | ---
5.5 | 0° | 3.83
5 | 0° | 3.33
4.5 | 0° | 2.83
5.5 | 90° | 2.68
5 | 90° | 2.30
4.5 | 90° | 1.93

Preliminary Results

CLYC-7

Distance: 70 cm

CLYC-6

Target

Proton Beam

Thermal neutrons
CLYC-7 Fast Neutron Detection

PSD Matrix - $E_{\text{beam}} = 5$ MeV

Energy Spectrum

Time vs Energy

Energy Spectrum

PSD Matrix - $E_{\text{beam}} = 5.5$ MeV

Time vs Energy

Energy Spectrum

Preliminary

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Thermal and Fast Neutron Detection with two CLYC Scintillators
CLYC-7 Fast Neutron Detection

PSD Matrix - \(E_{\text{beam}} = 5\) MeV

Time vs Energy

Energy Spectrum

PSD Matrix - \(E_{\text{beam}} = 5.5\) MeV

Time vs Energy

Energy Spectrum

Preliminary

Preliminary

Preliminary

Preliminary

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Thermal and Fast Neutron Detection with two CLYC Scintillators
The sum of the time vs energy matrix, gated on n, of 5 configurations measured. The time resolution is dominated by the beam. It is about 4-5 ns. The Time resolution of CLYC-7 is 2 ns.

The fast-neutron energy resolution is between 7.1% and 10.7%.
CLYC-6 Fast Neutron Detection

PSD Matrix - $E_{\text{beam}} = 5$ MeV

Time vs Energy

Energy Spectrum

Preliminary

PSD Matrix - $E_{\text{beam}} = 5.5$ MeV

Time vs Energy

Energy Spectrum

Preliminary

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Thermal and Fast Neutron Detection with two CLYC Scintillators
CLYC-6 Fast Neutron Detection

PSD Matrix - $E_{\text{beam}} = 5$ MeV

Time vs Energy

Energy Spectrum

PSD Matrix - $E_{\text{beam}} = 5.5$ MeV

Time vs Energy

Energy Spectrum

Thermal Neutrons Preliminary

Time vs Energy

Energy Spectrum

Thermal Neutrons Preliminary

A. Giaz Thermal and Fast Neutron Detection with two CLYC Scintillators
CLYC-6 Fast Neutron Detection

PSD Matrix - $E_{\text{beam}} = 5$ MeV

Time vs Energy

Energy Spectrum

PSD Matrix - $E_{\text{beam}} = 5.5$ MeV

Time vs Energy

Energy Spectrum

Preliminary

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Thermal and Fast Neutron Detection with two CLYC Scintillators
The sum of the time vs energy matrix, gated on n, of 5 configurations measured. The **time resolution is dominated by the beam**. It is about 4-5 ns.

The **fast-neutron energy resolution** is between **7.4% and 13.7%**, it is impaired by the thermal neutron background.
**CLYC-6 Thermal Neutron Subtraction**

- $E_{\text{beam}} = 4.5$ MeV
- Det angle = 0°
- $E_{\text{neutrons}} = 2.8$ MeV
- $E_{\text{neutrons mes}} = 3.2$ MeV (Q value)
- $E_{\text{thermal neutrons}} \sim 3.3$ MeV

Thermal neutrons have almost the same energy of the fast neutrons. Thermal neutrons were subtracted using a gate on the T vs E matrix. The used gate has the same time width.

Time information is fundamental to eliminate the thermal neutron background. The fast neutron energy resolution is improved by the subtraction of the thermal neutrons.
Fast Neutron efficiency

Measured fast neutron efficiency: 0.06%, expected fast neutron efficiency: 0.5%. These values are from J. Glodo et al. SORMA 12 proceeding.

A measurement of fast neutron efficiency was performed in March 2015 at LASA (Milan).

Detected

- CLYC-6
- CLYC-7
- BC501A
  - BC501A was from the RIPEN array.
  - It was used as a cross check.
  - Its efficiency was known.

Dead time measurement

Source

- Source activity: 1μCu
- Emitted neutrons: 2.4 $10^6$
- Neutrons expected per second on the detector at 1 m: ~ 97

Data are under analysis.
Conclusions

✓ The response of two CLYC scintillators (enriched with $^6\text{Li}$ and $^7\text{Li}$) to thermal and fast neutrons (from 1.9 up to 3.8 MeV and at 14.1 MeV) was measured, with both detectors.
✓ The $^7\text{Li}$-enriched CLYC scintillators has an efficiency to thermal neutrons of 0.3% with respect to $^6\text{Li}$-enriched CLYC scintillators.
✓ The kinetic energy of fast neutrons was measured via the energy signal (LNL and ENEA) and both via ToF (LNL).
✓ Combining the two techniques (energy signal and ToF) it is possible to have the energy of the neutrons from a continuous spectrum.
✓ Exploiting ToF it is possible to subtract the thermal neutron contribution (background for fast neutron measurement).
✓ The fast neutron efficiency was measured with a calibrated neutron source.
Acknowledgments

CLYC experiment collaboration:
and A. Pietropaolo, M. Pillon, for the measurement at the ENEA laboratories, Frascati Italy.

Thank you for the attention