Large volume LaBr₃:Ce detectors and HECTOR⁺

F. Camera
University of Milano – INFN sez. of Milano

Outline:

- Recent results in R&D with large volume 3.5”x8” LaBr₃:Ce
- Scientific Activity in Milano with large volume 3.5”x8” LaBr₃:Ce
- Conclusion and Perspectives
Characterization of Large Volume LaBr$_3$:Ce Detectors

- Rise time
- Pulse line-shape
- Count Rate
- Pulse distortion with $\gamma$-rays energy
- Linearity in energy
- Energy resolution and NON homogeneity
- High energy gamma rays
- Efficiency

- Properties of large volume LaBr$_3$:Ce cannot be scaled from small crystals

- Efficiency vs. high energy $\gamma$-rays
- High count rates
- Large dynamic range (0.1 – 30 MeV)
- Large PMT with more evident non idealities

-Work done with C.Boiano, S.Brambilla and S.Riboldi

NIM to be submitted Giaz, Riboldi, Camera et al
Characterization of Large Volume LaBr₃:Ce Detectors

Increasing the high voltage level leads to faster PMT output signals.

The minimum rise time practically obtainable with the five configurations of Table 1 ranges from 14 ns up to 23 ns, depending on the PMT and voltage divider models and the size of the detector.
Characterization of Large Volume LaBr$_3$ :Ce Detectors

The LaBr$_3$ :Ce signal pulse shapes obtained with the Hamamatsu H6533 PMT

Using the same (extremely fast) PMT on three different crystals (1”x1”, 3”x3” and 3.5”x 8”) we observe quite different pulses.

The difference in the pulse shapes is a direct consequence of the different spread in the collection time of the scintillation photons.

Simulations show that the median path length of the scintillation photons in case of

4x4x5 mm$^3$ LaBr$_3$ :Ce is 31 mm,
Ø 51 x 76 mm LaBr$_3$ :Ce is 390 mm,
Ø 76 x 76 mm LaBr$_3$ :Ce is 450 mm
Ø 90 x 200 mm LaBr$_3$ :Ce is 1200 mm

As energy resolution is the same in all these crystals (3-3.3% at 661 keV) self absorption inside the crystal is negligible
Characterization of Large Volume LaBr$_3$:Ce Detectors

<table>
<thead>
<tr>
<th>PMT Pulse Height</th>
<th>LABRVD</th>
<th>E1198-26</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 mV</td>
<td>790 V</td>
<td>600 V</td>
</tr>
<tr>
<td>60 mV</td>
<td>880 V</td>
<td>670 V</td>
</tr>
<tr>
<td>90 mV</td>
<td>970 V</td>
<td>740 V</td>
</tr>
</tbody>
</table>

Count Rate induced effects:

**Passive Voltage Divider**

The voltage unbalancing at the PMT dynodes induce a positive gain drift (over-linearity effect).

**Active Voltage Divider**

The gain drift is much smaller and induced by thermal effects.

Not only the PMT but also the subsequent electronics, e.g. shaping amplifier, analog to digital converter, etc. may easily impair the LaBr$_3$:Ce detector performances, especially in case of high count rate of events and with lack of pile-up rejection circuits.
Characterization of Large Volume LaBr$_3$:Ce Detectors

Pulse Line-shape parameters for different $\gamma$-ray energy

Pulse deformation indicate a NON properly working PMT
- NON Linearity in Energy
- Bad Time Resolution as optimal CFD delay changes with $\gamma$-ray energy
Characterization of Large Volume LaBr$_3$:Ce Detectors

Linearity in Energy

At 22.6 MeV the NON linearity is of the order of 3%

PMT Linear response fluctuates between ± 2% from tube to tube
Characterization of Large Volume LaBr$_3$:Ce Detectors

Energy Resolution

Digital electronic (Milano Laboratory)  Analog electronic (Debrecen)

\[
\text{FWHM} = \sqrt{a + bE + cE^2}
\]

- $a \Rightarrow$ Electronic noise
- $b \Rightarrow$ Poisson Statistics
- $c \Rightarrow$ Drift, Temperature, NON homogeneities
Characterization of Large Volume LaBr$_3$:Ce Detectors

Energy Resolution

NIM 608 (2009) 76–79

NIM 629 (2011) 157–169
Characterization of Large Volume LaBr$_3$:Ce Detectors

NON Homogeneity

Different crystals sections have different Light yield.

The relevance of the effects significantly changes with each crystal.

Source: Collimated Beam of 661 keV $\gamma$-rays

Now St. Gobain delivers NON homogeniety measurements
- Centroid changes between 0.5-1.5 %

Thanks to S.Ceruti
Characterization of Large Volume LaBr$_3$:Ce Detectors

NON Homogeneity
Low energy $\gamma$-rays spectrum from large volume 3.5” x 8” LaBr$_3$:Ce

Non linear region in LaBr$_3$:Ce scintillation light
Characterization of Large Volume LaBr$_3$:Ce Detectors

Energy Spectra 17.6 MeV

3.5” x 8” Large Volume LaBr$_3$:Ce  
2” x 2” LaBr$_3$:Ce

Ciemala et al. NIMA 608 (2009) 76–79
LaBr$_3$:Ce detectors provide, at the same time, clean spectroscopic information from a few tens of keV up to tens of MeV, being furthermore able to clearly separate the full energy peak from the first escape one. This is particularly true for large volume detectors which have FEP efficiency for high energy $\gamma$-rays.

Large volume LaBr$_3$:Ce detectors can perform spectroscopy of high energy $\gamma$-rays probably up to 30-40 MeV.

HpGe detectors have excellent energy resolution but the small size of the crystal, the low density and $Z_{\text{eff}}$ make them several time less efficient than large volume LaBr$_3$:Ce.
**HECTOR+**

**An array of 10 Large Volume 3.5” x 8” LaBr$_3$:Ce detectors**

- First detector delivered in 2008
- Last detector delivered in 2012

**Pre Hector+ experimental campaign (2-6 detectors) in 2011**

<table>
<thead>
<tr>
<th>Location</th>
<th>Electronic System</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGATA @LNL - Isomix</td>
<td>1$^{\text{st}}$ release LABRVD and BAFPRO adapted electronic</td>
</tr>
<tr>
<td>GSI (Land Setup)</td>
<td>1$^{\text{st}}$ release LABRVD and BAFPRO adapted electronic</td>
</tr>
<tr>
<td>OSLO</td>
<td>2$^{\text{nd}}$ release LABRVD and BAFPRO adapted electronic</td>
</tr>
<tr>
<td>Debrecen</td>
<td>2$^{\text{nd}}$ release LABRVD and BAFPRO adapted electronic</td>
</tr>
</tbody>
</table>

**Hector+ Experimental Campaign (8-10 detectors)**

- December 2011 - AGATA@LNL - Inelastic scattering of $^{17}$O
  - 2$^{\text{nd}}$ release LABRVD and 1$^{\text{st}}$ release LABPRO

- FALL 2012 - PRESPEC@GSI – All Campaign (PDR on $^{64}$Ni)
  - 2$^{\text{nd}}$ release LABRVD and 2$^{\text{nd}}$ release LABPRO

- R&D is not finished
Beam Time in Oslo

- 24 Large Volume collimated NaI (Cactus Arrays)
- 6 Large Volume collimated LaBr3:Ce (Pre-HECTOR+)

High lying structure of light isotopes ($^{13}$C)

Thanks to I. Morales
\( \gamma \)-ray spectrum of \(^{28}\text{Si}\), gated in silicon on the 1\(^{\text{st}}\) excited state at 8905 keV, (FWHM = 90-100 keV) with no time gate

“The difference between NaI and LaBr\(_3\) :Ce is really striking.”

Thanks to A.C. Larsen
Isospin Mixing in the N=Z Nucleus $^{80}$Zr at Medium Temperature

We use the GDR $\gamma$-decay selection rule to extract isospin mixing at $T > 0$.

We extract $\Gamma_c \approx \Gamma_{\text{IAS}}$ to extrapolate the mixing value at $T=0$.

AGATA@LNL Experiment - May 2011

6 large volume LaBr$_3$:Ce and 4 AGATA triple Cluster

Thank to S.Ceruti and A.Giaz

A.Corsi et al. PRC 84, 041304(R) (2011)
Neutron channel gives a negligible contribution in $^{40}\text{Ca} + ^{40}\text{Ca}$ while it is weak but present in the $^{40}\text{Cl} + ^{44}\text{Ca}$.

Statistical model calculation in progress
Isospin symmetry in nuclei is broken by Coulomb interaction $V_c$ which mixes states with $T$ and $T+1$ ($T+2, \ldots$).

Finite lifetime (compound nucleus) does not allow to achieve full mixing: restoration of isospin symmetry

### Isospin mixing induced by Coulomb interaction

- **almost good quantum number**
- **Symmetry “breaks”**
- **Symmetry is restored**

- nuclear reactions which involve low-lying states
- Moderate excitation energy
- fusion-evaporation reactions ($E^* > 20$ MeV)

The CN might decay before isospin mixes

### PHYSICS CASE

From two or more measurements of isospin mixing in the same system but at different temperature it could be possible to extract the value of isospin mixing at $T=0$

\[
(\alpha_{I_{0}+1})^2 = \frac{1}{l_0 + 1} \left( \frac{\widetilde{I}_{IAS}(E^*)}{\widetilde{I}_c(E^*)} + \widetilde{I}_M(E^*) \right)
\]

References:

A LaBr$_3$:Ce/scintillators array can increase the efficiency and makes more powerful the physics program of an HPGe Array

Scintillators not only for
- Anticompton shields
- Multiplicity filter
- Ancillary

Scintillators as spectroscopic detectors
New studies of high lying nuclear states with AGATA and LaBr$_3$:Ce detectors

AGATA@LNL Experiment

December 2011

AGATA Demonstrator

Scintillator array (Large volume LaBr$_3$:Ce)

ΔE-E Telescopes from the TRACE project

Thanks to L. Pellegri
PRESPEC Campaign at GSI: Search for PDR on $^{64}$Fe

AGATA@GSI Experiment

October 2012

AGATA Triple and Double Clusters
10 large volume LaBr$_3$:Ce
8 Large Volume BaF2

LYCCA Calorimeter
Target Detectors

FRS Beam Tracking system

Beam time started September 1$^{st}$, 2012
PDR run ⇒ 4 days in october
4 weeks of beam time allotted to PRESPEC

Thanks to O.Wieland
PuC Calibration for High Energy Gamma Rays

GSI - S430

Agata (Core)

BaF$_2$

LaBr$_3$:Ce

Thanks to O. Wieland
In beam Time spectra and background

LaBr₃:Ce γ background (No Dop. Corr.)

- 511 and 546 KeV
- 844 keV 1014 keV from ²⁷Al
- Nat Rad

LaBr₃:Ce TOF
- 64Fe incoming
- FWHM < 2ns

AGATA TOF
- 64Fe incoming
- FWHM ~ tenths of ns

CoreTime

Time [ns]
Conclusions

• LaBr₃:Ce detectors are a breakthrough in detector technology
  • However ⇒ they are not “simple” detectors to handle
    • Crystal non idealities
      Non Homogeneities
    • PMT non idealities
      Temperature
      Earth Magnetic Field
      Linearity
      Count Rate
      Pulse Distortion
      Rise/Fall time
    • Electronics non idealities
      Dynamic range
HECTOR+ is probably the first array of large volume LaBr₃:Ce

A LaBr₃:Ce array can face several physics cases and can increase the efficiency and makes more powerful the physics program of an HPGe Array or other γ-array

HECTOR+ measured since 2011

- Isospin mixing in $^{90}$Zr using GDR probe
  from the value of $T \neq 0$ to the $T=0$ value
- Structure of $^{13}$C
- Structure of $^{12}$C
- Antianalog GDR (GDR build on the IAS)
- Inelastic scattering of $^{170}$ on $^{90}$Zr, $^{124}$Sn, $^{140}$Ce, $^{208}$Pb
- PDR on $^{64}$Fe

In all cases data analysis is in progress
Future Perspective

CLYC scintillators

One 1” x 1” CLYC crystal arrived in Milano at the end of december
Test in 2013
Thank you for the attention
PSA in LaBr₃:Ce and LaCl₃:Ce

Digital Board 2 GHz 12 Bits

PSA Algorithm

90% of particles identified

F.C.L. Crespi et al  NIMA 602 (2009) 520–524
BaFPro (for BaF$_2$ and … also for LaBr$_3$::Ce)

Main functions

- NIM standard module
- 16 channels
- Fast output = 2µS Time to peak
- Energy output = 2µS Time to peak
- CFD resolution < 100pS
- CFD OR output
- Multiplicity Output
- RS485 dedicated software control
- Coarse & Fine Gain, CFD thresholds

BaFPro offers flexibility in size:

- 1”x1”
- 2”x2”
- 3”x3”

C. Boiano, IEEE CR 2009
Doppler Broadening Correction

- Large Crystals give large efficiency for high energy $\gamma$-rays (16% at 10 MeV) but they substand a large solid angle and this will affect energy resolution.

The $\gamma$-rays, even though monocromatic in the CM, enter with an energy spread due to the emission angle.

LaBr$_3$:Ce 4’x 8’ placed at 20 cm from target
1 MeV $\gamma$-rays source $v/c = 0.1$

1 MeV $\gamma$-rays source $v/c = 0.5$
FWHM ($60^\circ$) = 160 keV
GEANT4 Simulations
Scintillation light transport

Fully black lateral and front surfaces

Diffusive surfaces

IEEE-CR -2010 Knoxville
Measurement in Milano using a collimated source of $^{137}$Cs and a cylindrical LaBr$_3$:Ce 3”x3” and a PSPMT.
Measurement in Milano using a collimated source of $^{137}$Cs and a square 5cm x 5cm 1 cm thick CsI + pads of SDD.
2 cm thick CsI detector (diffusive surfaces)
Mu-metal shield for magnetic field

6% peak shift obtained by turning the detector by 30 degrees
(gamma source energy is 661 keV, peak resolution is 20.5 keV FWHM and absolute peak shift is 40 keV)

Re-cycled mu-metal shield (for testing purpose only)

Dedicated mu-metal shields that fits the Aluminum enclosure from the inside are being manufactured by a private company and will be readily available. Mu-metal shields have already proved to be useful for experiments at GSI.
Lucido Sergio

![Graph showing energy and amplitude](image)

- **Energy (a.u.)**
- **Amplitude (a.u.)**
- **Fast (a.u.)**
- **Slow (a.u.)**
- **Gamma**
- **Alpha**

- γ-rays, electrons
- Alpha
- Gamma
LaBr$_3$:Ce Scintillation light

LaBr$_3$:Ce linearity in scintillation light emission is much better than that of NaI and any other scintillator (this is critical for high energy $\gamma$-rays measurements)

- NaI has a NON-linearity yield of 15% in 100 keV – 3 MeV energy interval
- LaBr$_3$:Ce has a non linearity yield of 3% in 100 keV – 3 MeV energy interval

This makes the energy resolution of LaBr$_3$:Ce to scale as $1/\sqrt{E}$ …. at least up to some MeV
LaBr$_3$:Ce and NaI comparison (linearity)

**Figure 3**
Comparison of 3"x3" spectra for the Thorium decay chain. 
BriLLanCe 380 detector (red) and NaI(Tl) (blue)

Note: NaI non linearity P/B ratio
# LaBr₃:Ce Scintillator properties

<table>
<thead>
<tr>
<th>Scintillator</th>
<th>Light Yield (ph/MeV)</th>
<th>Wavelength of maximum emission</th>
<th>Density (g/cm³)</th>
<th>Attenuation length at 511 keV (cm)</th>
<th>Initial photon intensity (photons/ns keV)</th>
<th>Principal decay time (ns)</th>
<th>Melting point °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaF₂ (fast/Slow)</td>
<td>1800/10000</td>
<td>220/310</td>
<td>4.88</td>
<td>1.1</td>
<td>1800</td>
<td>0.7/630</td>
<td>1354</td>
</tr>
<tr>
<td>NaI:Tl</td>
<td>38000</td>
<td>415</td>
<td>3.67</td>
<td>3.3</td>
<td>165</td>
<td>230</td>
<td>660</td>
</tr>
<tr>
<td>LSO</td>
<td>24000</td>
<td>420</td>
<td>7.4</td>
<td>1.2</td>
<td>600</td>
<td>40</td>
<td>1050</td>
</tr>
<tr>
<td>BGO</td>
<td>8200</td>
<td>505</td>
<td>7.13</td>
<td>1.1</td>
<td>30</td>
<td>300</td>
<td>1050</td>
</tr>
<tr>
<td>CsI(Na)</td>
<td>39000</td>
<td>420</td>
<td>4.51</td>
<td>2.3</td>
<td>62</td>
<td>630</td>
<td>621</td>
</tr>
<tr>
<td>GSO</td>
<td>7600</td>
<td>430</td>
<td>6.7</td>
<td>1.5</td>
<td>125</td>
<td>30-60</td>
<td>1900</td>
</tr>
<tr>
<td>YAP</td>
<td>20000</td>
<td>370</td>
<td>5.37</td>
<td>2.1</td>
<td>570</td>
<td>26</td>
<td>1875</td>
</tr>
<tr>
<td>LaBr₃:Ce</td>
<td>63000</td>
<td>360</td>
<td><strong>5.08</strong></td>
<td><strong>2.1</strong></td>
<td><strong>4000</strong></td>
<td>&lt; 30</td>
<td><strong>783</strong></td>
</tr>
<tr>
<td>LaCl₃:C3</td>
<td>46000</td>
<td>350</td>
<td>3.67</td>
<td>2.8</td>
<td>2000</td>
<td>&lt; 30</td>
<td>859</td>
</tr>
</tbody>
</table>

It is well known that:

- LaBr₃:Ce has a ‘strong’ internal activity from $^{138}$La and Actinides
- $\alpha$-particles and $\gamma$-rays produce slightly different pulses which can be identified and separated, hints are present for protons, no high bandwidth measurements with neutrons yet
- Scintillation light wavelength matches SBA Hamamatsu PMT
- There is a 2.36 factor between the scintillation light produced by $\gamma$ relative to $\alpha$
Characterization of Large Volume LaBr$_3$:Ce Detectors

Energy Spectrum of the AmBeNi Composite Source

![Graphs showing energy spectrum for LaBr$_3$:Ce and HPGe detectors.](image)