Neutron Detector development at the ILL
Based on $^3$He and alternative convertors

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outline

• Basic principles of $^3$He neutron gas detectors

• The golden age of $^3$He detectors (~2000→2010) shown with examples
  ✓ MultiTube for SANS (FP5), Reflectometers, and chopper spectrometers
  ✓ Curved detectors for powder diffraction and single crystal diffraction
  ✓ High gas pressure MWPC (MILAND/FP6)
  ✓ Active Gas Scintillation Proportional Chamber(NMI3/FP7_1)
  ✓ Charge division MSGC

• $^3$He alternative techniques
  ✓ $^{10}$B thin film convertors (CRISP and NMI3/FP7_2)
  ✓ $^{10}$BF$_3$ gas
  ✓ Scintillators not discussed here
Common nuclear reactions for neutron detectors

- \( n + {}^3\text{He} \rightarrow {}^3\text{H} + {}^1\text{H} + 0.764 \text{ MeV} \) \( (\sigma_c = 5330 \text{ barns @1.8 Å}) \)
- \( n + {}^6\text{Li} \rightarrow {}^4\text{He} + {}^3\text{H} + 4.79 \text{ MeV} \) \( (\sigma_c = 937 \text{ barns @1.8 Å}) \)
- \( n + {}^{10}\text{B} \rightarrow {}^7\text{Li}^* + {}^4\text{He} \rightarrow {}^7\text{Li} + {}^4\text{He} + 2.31 \text{ MeV} + \text{gamma (0.48 MeV)} \) (93%)
  \( \rightarrow {}^7\text{Li} + {}^4\text{He} + 2.79 \text{ MeV} \) (7%)
  \( (\sigma_c = 3840 \text{ barns @1.8 Å}) \)
- \( n + {}^{14}\text{N} \rightarrow {}^{14}\text{C} + {}^1\text{H} + 0.626 \text{ MeV} \) \( (\sigma_c = 1.8 \text{ barns @1.8 Å}) \)
- \( n + {}^{157}\text{Gd} \rightarrow \text{Gd*} \rightarrow \text{gamma-ray spectrum + conversion electron spectrum (~70 keV)} \)
- \( n + {}^{235}\text{U} \rightarrow \text{xn + fission fragments + ~160 MeV (<x> ~ 2.5)} \) \( (\sigma_c = 698 \text{ barns @1.8 Å}) \)

For thermal neutrons, \( \sigma_c \) increases linearly with \( \lambda \)

Natural isotopical fraction

\({}^{10}\text{B}: 19.8\% \quad {}^6\text{Li}: 7.6\% \quad {}^{157}\text{Gd}: 15.7\% \)
Good gamma \( \gamma \) discrimination

Energy (arbitrary units)

Number of counts

Pulse height spectrum obtained with a single counter and a low noise FET pre-amplifier

\[ E = 764 \text{ keV} \]

Tritium (1/4E)

Proton (3/4E)

Capture in 3 cm of \( ^3\text{He} \)

\[ \epsilon = 14\% @ 1 \text{ cm. bar} \]

Efficiency requires high \( ^3\text{He}_\text{Pressure}*\text{gap} \)

\( \Rightarrow \) parallax error
Stopping gas

Particle Range
(for 2 bars of CF4)

Energy loss
Ionization Centroid

0 (neutron capture point)

Distance between the neutron interaction point and the ionization centroid = 35% of the proton range (in CF4).

CF4 is added to the convertor gas to reduce the range of the ionizing particles.

Graph:
- 1 bar CF4: 2.5 mm FWHM
- 2 bars CF4: 1.4 mm FWHM

Graph parameters:
- Amplification Gain
- FWHM (mm)
3He Detectors, example 1: SANS

From standard MWPC …
XY measured by coincidence of 2 orthogonal wire frames (max count rate 200 KHz)

… to Multi-PSD
Running on D22 since 2004

128 PSD covering 1 m² of sensitive area.
Position measurement by charge division
Tube diam.: 8 mm. Pressure: 15 bars
Efficiency: 75 % @ 5 Angstroms
No deviation from linearity at 3 MHz

- Counting rate capability of D22 increased by 50.
- Better time resolution and lower background.
- Lower parallax error.

Development supported by TECHNI_FP5 (2000-2004)
3He Detectors, example 2: TOF chopper spectrometer

Multi-Tube (introduced on IN5 in 2008)

3 m long Multitubes, 32 tubes each
- 3000 liters of 3He
- Area 30 m²
- Reduced gap between detectors
- Reduced fabrication cost
- Mechanical simplicity
3He Detectors, example 3: neutron reflectometers

Monoblock Multi-Tube

Square tubes in Aluminium are machined by spark-erosion.
0.5 mm wall between the tubes
Resolution: 8 mm x 1.5 mm

\[ \varepsilon = 50\% \text{ @ } 2\text{ A} \]
\[ 72\% \text{ @ } 5\text{ A} \]
3He Detectors, example 4: the D20 Powder diffractometer

48 MSGC plates (8 cm x 15 cm)
160° x 5,8°. resol: 2.57 mm (0,1°)
2.8 bars 3He + 1.2 bar CF4
ε = 60% @ 0.8 Å

3He Detectors, example 5: the D19 Single Crystal diffractometer

40 MWPC modules
120° x 29°. resol: 2.5 mm (0.2°)
5 bars of 3He + 1 bar CF4
ε = 80% @ 2.5 Å
3He Detectors, example 6: the MILAND MWPC

- 32 cm x 32 cm sensitive area
- 1 mm readout pitch (640 ind. ch.)
- 5 mm conversion gap (+ 20 mm optional)
- 15 bars gas pressure (13.5 $^3$He + 1.5 CF4)
- TOT (Time-Over-Threshold) processing

Detection efficiency 70% @ 2.5 Angstroms
Position resolution: 1.2 mm cathodes; 1.5 mm Anodes
Global counting rate t : 0.7 MHz @ 10% neutron lost

Image obtained on the D16 instrument with a lysozyme crystal, (data accumulated for acquisitions at different angles)
The detector was mounted at 35 cm from the sample. The neutron flux on the sample was $4 \times 10^4$ n/sec, and the total acquisition time 16 hours.

Development in NMI3_FP6 (2004-2008)
ILL in collaboration with BNC, LLB, TU, ISIS, ESRF, GKSS, SNS, FRM-II, LIP)
3He Detectors, example 7: Measuring the light produced by avalanche in a MSGC

Scintillation light decay time
primary light: 15 ns
Second. light : 30 ns
Typically 100 ns total dead time taking into account the track charge collection time
→ 1 MHz counting rate @ 10% dead time correction

Conditions to reach 0.5 mm FWHM position resolution ?
→ 6 bars of CF4
→ amplification gain =1000 (estimated by simulation)
Gas amplification: MSGC is the only gas detector that can be operated with 6 bars of CF4

Development in FP7-1 (2008-2012) with LIP, ISIS, FRM-II, JCNS, TU

10B thin films and BF₃ detector workshop 13-14 March 2012
3He Detectors, example 8: Charge division MSGC

Each anode is readout individually on both ends for position measurement

Al coating on Cr strips for adequate resistance

Possible applications
- Resolution of 0.5 mm needed in one direction
- Very high counting rate
- Limited sensitive area (20 cm x 20 cm)

Status
Al coating degrades rapidly with CF4 under irradiation → use other gases like Ar-CO2
Pb: requires 2 times more pressure
3He Alternatives techniques to be considered in priority
(Neutron scattering facility meeting March 2010)

$^6$LiF-ZnS(Ag) scintillators with coded clear fibers readout and WLS Fibers
Efficiency, count rate, gamma sensitivity worse than $^3$He but acceptable in the context
Development at ISIS, NIST, SNS and J-PARC

**Solid convertor layer (Boron) in gas detector**
Short range of products limit efficiency
  Multi-Blades (1 film oriented at $\alpha \leq 5^\circ$)
  Multi-Grids ($\geq 30$ films oriented at $\alpha = 90^\circ$)
Development at ILL, ESS, FRM-II, HZB

**BF$_3$ gas** : widely used in the 80s
Less efficient than 3He (high bias voltage limits pressure)
Toxicity
Development at HZB, ILL
2nd International workshop on 10B and 10BF3 detectors (March 2012)

21 lectures and 60 participants from 19 different institutes.
Sponsored by 7 companies involved in detectors for scientific instrum. and homeland security.

Presentations available at www.ill.eu/10bbf3
Principle of detectors based on solid neutron convertor in gas detectors

1/ Normal incidence

Gas

\[ n + ^{10}\text{B} \rightarrow ^{7}\text{Li}^* + ^4\text{He} \]
\[ \rightarrow ^7\text{Li} + ^4\text{He} + 2.31 \text{ MeV} + \text{gamma (0.48 MeV)} \quad (93\%) \]
\[ \rightarrow ^7\text{Li} + ^4\text{He} + 2.79 \text{ MeV} \quad (7\%) \]

\( \sigma_c = 3840 \text{ barns @} 1.8 \text{ Å} \)

\( \alpha \) and Li ions emitted in opposite direction

\( ^{10}\text{B} \) thin films and BF\(_3\) detector workshop 13-14 March 2012
non detected event

Gas

n converter

substrate

$^{10}\text{B}$ thin films and BF$_3$ detector workshop  13-14 March 2012
Detection probability (emission cone) decreases @ deeper depth of interaction
No detection for neutron captured at depth > $\alpha$ particle range (3.6 $\mu$m in $\text{B}_4\text{C}$)
For a single convertor layer, the maximum of the detection efficiency is reached at thickness = $\alpha$ range
Stacking of several converters with optimal film thickness
Double coating
Multi layers optimisation by MC simulation

Detection efficiency vs thickness (30 layers)

Detection efficiency vs number of layer (1 μm thick)
**Multi-Grids detector**

Stacking of 96 grids of 2 cm height electrically insulated from each other
60 anode wires (gold plated W 20 μm)

The column of grids is inserted in a tube
Individual readout electronics (60 anodes and 96 grids)
$^{10}$B$_4$C depositions by DC magnetron sputtering

ERDA analysis → 79.3 at% $^{10}$B  
2.4 at% $^{11}$B  
17.1 at% C  
1.2 at% contaminants (N, O, H)

X-ray reflectivity → density = ~2.25-2.30 g/cm$^3$

18542-sided blades (1440 mounted)  
264 1-sided blades (not mounted)  
Total surface coated = 6.3 m$^2$
Study for a 10B-film Large Area detector

The IN5 instrument is taken as a model

Main deliverable in CRISP:
Development of a large area 10B demonstrator (2014)
Prototype test on CT2 (ILL) monochromatic @ 2.5 Å

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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<tbody>
<tr>
<td>Sensitive area</td>
<td>200 cm x 8 cm</td>
</tr>
<tr>
<td>Number of Grids</td>
<td>96</td>
</tr>
<tr>
<td>Number of anode wires</td>
<td>60 = 4 columns of 15 wires</td>
</tr>
<tr>
<td>Detection cell</td>
<td>X: 2 cm, Y: 2 cm, Z (ToF): 1 cm</td>
</tr>
<tr>
<td>Electronics readout</td>
<td>156 Individual charge amplifiers/discri</td>
</tr>
<tr>
<td>Number of Al blades for each Grid</td>
<td>14 double coated (+2 single coated non mounted)</td>
</tr>
<tr>
<td>Convertor film</td>
<td>$^{10}$B enriched B$_4$C, 1 micrometer thick</td>
</tr>
</tbody>
</table>
Reducing the gas pressure helps to reduce the operating voltage + gamma sensitivity and the mechanical constraints on the gas vessel.

Operating voltage is \(~1100\) V with 0.25 bars of CF4.
**Detection efficiency Measurement**

- Efficiency of each tube (%)
  - Tube number

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**Gamma sensitivity**

- Gamma-rays sensitivity
  - Neutron efficiency

<table>
<thead>
<tr>
<th></th>
<th>2.5 [Å]</th>
<th>4.5 [Å]</th>
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<tbody>
<tr>
<td>MC Simulation</td>
<td>52.6</td>
<td>63.3</td>
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<tr>
<td>Measurement</td>
<td>46.8</td>
<td>-</td>
</tr>
<tr>
<td>IN5-PSD</td>
<td>~ 73</td>
<td>~ 80</td>
</tr>
</tbody>
</table>

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10B thin films and BF$_3$ detector workshop  13-14 March 2012
Efficiency versus film thickness

![Graph showing efficiency versus film thickness](image-url)
Increasing the capture probability with a small incidence angle
10° single-layer versus 90° multi-layer

PH spectra for 2.5 Å neutrons and different angles

The shape of the PH is independant from the angle

eff X 5 at 10° → 23% (measured)

PH spectra for 2.5 Å neutrons and $^{10}$B$_4$C film thickness of 445, 665, 895 μm

The average energy decreases when the converter thickness increases

Efficiency measured with 28 layers of 1 μm = 46%

$^{10}$B thin films and BF$_3$ detector workshop 13-14 March 2012
Multi-Grids detector next development

**IN6 prototype**
The 96 grids of the previous prototype will be assembled in 6 columns of 16 grids each.
Can BF$_3$ be considered as an alternative?

Risk analysis to define safety rules for fabrication, shipping, and operation

Be inspired by regulation in the industry …. knowing that we are in a more complex world (passive safety must be high)

Consider the TOF vacuum chamber as a protection barrier

\[ \sigma_{\text{Abs}}^{(10\text{B})} = 72\% \quad \sigma_{\text{Abs}}^{(3\text{He})} \rightarrow 4.25 \text{ bars } ^3\text{He (IN5)} = 6 \text{ bars BF}_3 \]

Detection Efficiency

High pressure \rightarrow Electron attachment

*only very few BF$_3$ detectors are filled with more than 1 bar*

High quenching gas \rightarrow High operational voltage
Solution 1: IN5 concept with several layers of tubes

IN5 → 6 bars BF$_3$ equivalent

Number of tube layers = 6 bars / Max BF$_3$ pressure

→ Determine the maximum BF$_3$ pressure in an IN5 module compatible with the Voltage limit
→ Check background induced by neutron scattering in the tube walls

2 layers configuration currently under study at HZB for the NEAT instrument
Test with an IN5 Multi-Tube prototype

Still good at 2 bars

At 2 bars, the “efficiency plateau” is reached at 3.6 kV

$^{10}$B thin films and BF$_3$ detector workshop  13-14 March 2012
Gain required to achieve 2 cm resolution FWHM

Interpolation at 6 bars: 8 kV!

Gain vs HV at various BF3 pressures

Spectrum Peak Position (arbitrary unit)

HV

Gain vs HV at various BF3 pressures

0.5 bar, 1 bar, 1.5 bar, 2 bar

HV limit of the electronics

3 layers of tubes @ 2 bars are needed to reach the detection efficiency of IN5

Image of Am-Be source
2 bars of BF3
HV = 3600 V

82 cm

2 m

10B thin films and BF3 detector workshop 13-14 March 2012
Solution 2: increasing the depth of the tube

Tween-Tube Prototype
Section of the tubes: 25 mm x 50 mm

Scan of one tube

Pulse Height Spectra vs Beam Distance to Anode Wire
Solution 3: Multi-Grid

The 2 tubes of the tween-tube prototype are filled with grids → smaller tubes → high electric field + short drift distance

Direction of neutrons

2 cm x 1 cm
Measured absorption profile on the BARC beam line
Minimal deviation from an exponential fit is for 4.88 Å
Detection efficiency is 94% for 10 tubes at 1 bar of BF3
CONCLUSION (1)

SANS inst, reflectometers, and Energy Spectro, have strongly benefit of the $^3$He Multi-Tube design.
$\rightarrow$ fast count rate (10 MHz/m²), modular, cost effective; further improved with the Aluminum Monoblock

The Miland detector is close to the limit one can reach with MWPC technique
MSGC still offer good prospects for detector improvement.

The detector landscape started to change dramatically
in 2008 with the arising of the $^3$He shortage crisis

$^3$He is still needed for detectors < 1m².
Technical development must continue in this field

$^3$He alternatives techniques are urgently needed for large area detectors
Solutions are not going to be cheap except BF3
Measurements with the $^{10}$B$_4$C Multi-Grid show that it is a serious candidate. We fabricated a 2 m long prototype and measured 50% detection efficiency at 2.5 Å.

The Multigrid technique is an attractive solution for BF3, but this technique should be considered as a spare or urgent solution.

European projects (FP5, FP6, FP7) enabled to create a European network in detector development. This support is very beneficial to support risky developments.

http://www.icnd.org/