Particle Physics Readout Electronics and Novel Detector Technologies for Neutron Science

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Content

- Neutron detection
- Detector requirements
- Technology for neutron detectors
  - Micro-Channel Plate
  - Time-Projection Chamber
  - Gas Electron Multiplier
Introduction: Neutron Detection

Neutron: Neutral particle, penetrate material easily → absorption imaging, similar to X-ray imaging
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Visible light                                    X-ray                                    Neutrons

*John R.D. Copley, Dynamics and Neutron Scattering, Summer school 2007*

*Lehmann, Eberhard H., Stefan Hartmann, and Markus O. Speidel. “Investigation of the content of ancient Tibetan metallic Buddha statues by means of neutron imaging methods.” Archaeometry 52.3 (2010): 416-428.*
Neutron: Neutral particle, penetrate material easily → absorption imaging, similar to X-ray imaging

Interaction with materials containing hydrogen e.g.
- Water
- Organic materials
- H-atoms at borders of molecules
Enabler for neutron detection: Conversion to charged particle

Most common neutron detector: $^3$He-filled Geiger-Müller tube

$^3$He + n → $^3$H + p

Adopted from: Anastasopoulos, Michail, et al. "Multi-Grid detector for neutron spectroscopy: results obtained on time-of-flight spectrometer CNCS." Journal of Instrumentation 12.04 (2017): P04030.
Requirements at ESS / He-3 crisis

Detectors for the European Spallation Source (ESS) currently built in Lund

From: R. Hall-Wilton, Detectors for Neutron Scattering Science at the European Spallation Source, Presentation given at the CERN detector seminar (2020)
Requirements at ESS / He-3 crisis

Detectors for the European Spallation Source (ESS) currently built in Lund

$^3$He: decay product from Tritium in thermonuclear weapon stockpile

From: R. Hall-Wilton, Detectors for Neutron Scattering Science at the European Spallation Source, Presentation given at the CERN detector seminar (2020)

Grossmann, Agnes & Gabrielli, Roland & Herdrich, Georg & Fasoulas, Stefanos & Schnauffer, Peter & Middendorf, Peter & Fateri, Miranda & Gebhardt, Andreas. (2015). Overview of the MultiRob 3D Lunar Industrial Development Project.
Solid converters: Detection with $^{10}$B and Gd

Requirements:

- High absorption cross section
- 1-2 charged particles in final state
- Easy to handle during construction

Candidates:

- $^{6}$Li: very difficult to handle
- $^{235}$U: difficult to get/handle
- $^{155/157}$Gd: very high cross-section, but final state looks like $\gamma$-conversion in gaseous detectors.
- $^{10}$B: high cross-section → our favourite choice

Beckurts, Karl-Heinrich, and Karl Wirtz. Neutron physics. Springer Science & Business Media, 2013.

Alvarez-Estrada, Ramón & Peña, Ignacio & Calvo, Maria. (2017). Focalizing slow neutron beams at and below micron scales: Discussion on BNCT. Phosphorus, Sulfur, and Silicon and the Related Elements. 193. 10.1080/10426507.2017.1417300.
Micro-Channel Plate (MCP) detector with Timepix3 readout
Neutron MCP detector: nMCP

Two-stage MCP: $^{10}\text{B}$ and Gd loaded first stage + traditional MCP second stage

_detector concept (with Timepix): S. Pinto et al., Neutron imaging and tomography with MCPs, JINST 12, C12006. 2017_
Experimental setup:

- n beam
- object
- detector
- Quartz entrance window
- $^{10}$B and Gd loaded MCP
- Readout with 4 Timepix3

Quartz entrance window:
- does not activate
- UV transparent for detector tests
- transparent for neutrons
- checking detector visually is possible
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Detector Requirements:

- Good vacuum ($10^{-6}$ mbar)
- Aluminium Vacuum chamber
- Timepix3 close to MPC
- Timepix3 cooling
Neutron MCP detector: Impressions

Major part of the setup: Vacuum system
Currently ongoing: vacuum and HV tests
Group of Anton S. Tremsin [1]: Similar detector with four Timepix ASICs → problem: Shutter based Timepix → dead time

Our design foresees four Timepix3 ASICs:

- Simultaneous Charge and time measurement
- Timing resolution: 1.56 ns
- Zero suppression on chip
- Self-triggered, continuous data-driven readout

Implementation of Timepix3 in Scalable Readout System (SRS) of RD51:

M. Gruber et al. "SRS-based Timepix3 readout system." Journal of Instrumentation 17.04 (2022) C04015

[1] Tremsin, Anton S., et al. "High Resolution Photon Counting With MCP-Timepix Quad Parallel Readout Operating at > 1 kHz Frame Rates." IEEE TNS 60.2 (2012): 578-585.
Particle Physics technology for Neutron Science

Time-Projection Chamber (TPC) detector with GridPix readout
Neutron TPC detector: Concept

- Neutron entering the detector
- Wavelength shifting fibres
- Glass:
  - Ionisation
  - Ions
- Scintillator 10 B / 10 B4C (0.9 μm)
- E-field
- Cathode
- GridPix Readout
- SiPM
- Anode
- Trigger board
- Trigger
- Scintillator (10-100 μm)
- Glass (1 mm)
- WLSF
- Silicon grease (refractive index 1.465)
- Reflectors
- SiPM
- E-field
- He2+
- Li3+
- Ar:CO2
- Neutron interactions
- Trigger board
- SiPM
Neutron TPC detector: Concept

- Neutron enters the detector and interacts with the Ar:CO$_2$ scintillator.
- Helium ions ($\text{He}^{2+}$) are produced through the interaction.
- Ionisation takes place in the gas volume.
- Ions are collected by the cathode and anode.
- E-field is used to separate electrons ($\text{e}^-$) from ions.
- Scintillator and wavelength shifting fibres guide the light for detection.
- Glass anode serves as a reflector for the WLSF.
- SiPMs detect the light signals.
- GridPix Readout is used for event readout.
- Trigger board controls the data acquisition.
- Reflector system helps in the direction of neutron and ion paths.
Neutron TPC detector: Concept

- Neutron interactions:
  - Ar:CO$_2$
  - $^4$He$^{2+}$ ions
  - $^3$Li$^3$

- Detectors and components:
  - Anode
  - Cathode
  - Wavelength shifting fibres
  - Scintillator
  - SiPM
  - GridPix Readout
  - Trigger board
  - Trigger board

- Reflector system
  - Silicone grease (n$\text{_grease} = 1.465$)
  - WLSF

- Ionisation and electron processes:
  - Ionisation of Ar:CO$_2$
  - Ionisation of $^4$He$^{2+}$

- E-field distribution

Michael Lupberger
Neutron TPC detector: Impressions
Neutron TPC detector: GridPix readout

Micromegas + bare Pixel ASIC = GridPix

Used in CAST, proposed for ILD TPC (ILC), ATHENA TPC (EIC) and IAXO with Timepix3

NIM A535 (2004) 506-510
NIM A845 (2017) 233-235
Particle Physics technology for Neutron Science

Gas Electron Multiplier (GEM) detector with VMM3a readout
Detector concept similar to the CASCADE detector used at MIEZE (FRM II)

Planned major improvement:

- Independent layers, each with own cathode, coating and readout
- Thin $^{10}$B coating $\implies$ Many layers needed

$\rightarrow$ Main challenge: large number of electronic channels ($\sim 70,000$).
Neutron GEM detector: Impressions

First test layer front-end electronics.

For comparison: COMPASS GEM detector

Detector

10×10 cm²
Neutron GEM detector: VMM3a readout

Update of SRS for the next decade of (MPGD) R&D and instrumentation: Implementation of VMM in Scalable Readout System (SRS) of RD51:

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Summary:

State-of-the-art neutron detector
  =
Particle Physics detection concept
  +
  Solid converter
  +
Recent electronics
Summary:

State-of-the-art neutron detector
= Particle Physics detection concept
  + Solid converter
  + Recent electronics
Summary:

State-of-the-art neutron detector

= Particle Physics detection concept

+ Solid converter

+ Recent electronics

→ Technology transfer from Particle Physics to Neutron Science
Summary:

State-of-the-art neutron detector = Particle Physics detection concept + Solid converter + Recent electronics

⟹ Technology transfer from Particle Physics to Neutron Science

Three novel neutron detectors with different properties developed in Bonn.
The Team

K. Desch,
J. Kaminski,
M. Lupberger
other stuff

THANKS FOR YOUR ATTENTION

Other Photos of the Team:
- Salim Gurbas
  - nMCP detector
- Markus Gruber
  - Timepix3 readout
- Thomas Block
  - Timepix3 readout
- Patrick Schwab
  - VMM readout

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Backup slides
Introduction: Neutron detection

Neutron: Neutral particle, penetrate material easily → absorption imaging, similar to X-ray imaging

Neutron detection: Conversion to charged particle

| Element | Reaction | Reaction |
|---------|----------|----------|
|          |         | 3He + n → 3H + p + 764 keV |
|          | 6Li      | 6Li + n → 3H + α + 4.78 MeV |
| 10B      | 10B + n  | 7Li + α + 2.79 MeV (6%) |
|          | 10B + n  | 7Li* + α + 2.31 MeV (94%) |
| 113Cd    | 113Cd + n | 114Cd + γ + 9.04 MeV |
| 155Gd    | 155Gd + n | 156Gd + γ + e^- + (30−180) keV |
| 157Gd    | 157Gd + n | 158Gd + γ + e^- + (30−180) keV |
| 235U     | 235U + n | fission fragments + 160 MeV |
Different Neutron Energy Ranges

With higher energies:
Cross sections are lower
→ neutron penetrate further into material
→ contrast of pictures decrease as more material is needed to scatter/absorb ns

Usually good compromise:
Thermal neutrons (~50 meV)
Also cold neutrons are used sometimes

Source: Reactors + moderators

https://en.wikipedia.org/wiki/Neutron_cross_section
The GdGEM detector for NMX at ESS

Pfeiffer, Dorothea, et al. “First measurements with new high-resolution gadolinium-GEM neutron detectors.” Journal of Instrumentation 11.05 (2016): P05011.

Lupberger, Michael, et al. “SRS VMM readout for Gadolinium GEM-based detector prototypes for the NMX instrument at ESS.” Journal of Physics: Conference Series. Vol. 1498. No. 1. IOP Publishing, 2020.
Group of Anton S. Tremsin [1]: Similar detector with four Timepix ASICs → problem: Shutter based Timpix → dead time

⇒ Our design foresees four Timepix3 ASICs:

- Number of pixels: 256 × 256 pixels
- Pixel pitch: 55 × 55 µm²
- Charge (ToT) and time (ToA) simultaneously or hit counter
- Timing resolution: 1.56 ns
- Zero suppression on chip
- Self-triggered, continuous data-driven or sequential readout
- Output rate up to 5.12 Gbps

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[1] Tremsin, Anton S., et al. “High Resolution Photon Counting With MCP-Timepix Quad Parallel Readout Operating at > 1 kHz Frame Rates.” IEEE TNS 60.2 (2012): 578-585.
Micromegas + bare Pixel ASIC = GridPix

Motivation: Diffusion in amplification region:
Ar:CO$_2$ 80:20, Ar:iC$_4$H$_{10}$ 95:5, Ar:CF$_4$:iC$_4$H$_{10}$ 95:3:2 → $\sigma \approx 11$ µm
Smaller pads/pixels $\implies$ better resolution!

Used in CAST, proposed for ILD TPC (ILC), ATHENA TPC (EIC) and IAXO with Timepix3

NIM A535 (2004) 506-510
NIM A845 (2017) 233-235
Neutron TPC detector: TPC field cage

Current detector: 30 µm thick wires with a spacing of 2 mm soldered on PCB with resistor divider chain.

- Additional support structures
- PCB frame
- Copper strips near the endplates
- Wires soldered on the PCB frame
- Current detector: 30 µm thick wires with a spacing of 2 mm soldered on PCB with resistor divider chain.

Electric field inside the field cage

- Cathode (-5400 V)
- PCB with strips
- GridPix (-400 V)
Neutron TPC detector: Trigger

**Side wall:**
- ~1 µm thick $^10$B layer
- 20 µm thick scintillator
- Quartz light guide
- Wavelength shifting fibres
- SiPMs
- Reflector
Neutron TPC detector: Trigger

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- Reflector

- MPPC S13360-1375PE

Trigger board for 30 SiPMs / fibers
Neutron TPC detector: First tests

- 8 GridPixes based on Timepix used.
- Placed strip with $^{10}\text{B}_4\text{C}$ inclined across the GridPixes at a distance of 3.8 cm
- Neutron sources with non-directional beam
- Observed $\alpha$ and Li$^{3+}$ tracks
- Reconstruct head of track → point of conversion
- Spatial resolution < 100 µm

**Track of $\alpha$:**
- Charge
- $dE/dx$
- Time of arrival

**Ideal for directional WIMP search!**