WNPPC 2021

SIMULATING DAEMON (DETECTOR ARRAY FOR ENERGY MEASUREMENTS OF NEUTRONS): A NEW COMPLEMENTARY NEUTRON DETECTOR FOR GRIFFIN

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TRIUMF

UNIVERSITY OF GUELPH
Studying neutron rich nuclei is at the forefront of nuclear physics research.

As the ratio of neutrons (N) to protons (Z) increases, the valence neutrons become less bound which can give rise to beta delayed neutron emission.

\[ A_X \rightarrow \beta^- + A_Y + n + \gamma \]

\[ Q_{\beta} > S_n \]


- Studying neutron rich nuclei is at the forefront of nuclear physics research.
- As the ratio of neutrons (N) to protons (Z) increases, the valence neutrons become less bound which can give rise to beta delayed neutron emission.
Astrophysical Processes
Many r-process nuclei are beta delayed neutron emitters
Canada’s particle accelerator centre

• Strong campaign studying neutron rich nuclei at TRIUMF

• Via beta decay and beta delayed neutron spectroscopy
Canada’s particle accelerator centre

- Strong campaign studying neutron rich nuclei at TRIUMF
- Via beta decay and beta delayed neutron spectroscopy
 Experimental Setup

- GRIFFIN (Gamma-Ray Infrastructure For Fundamental Investigation of Nuclei)

- DESCANT (DEuterated SCintillator Array for Neutron Tagging)

- In addition there are beta particle detectors and positions for other ancillary devices are available
DESCANT has good neutron detection efficiency, but at the expense of precision on the neutron kinetic energy - an important quantity for beta delayed neutron emitters!

Want to create a neutron detector array that can measure neutron energy with high precision that would be compatible with GRIFFIN and DESCANT
Experimental Setup

- Good neutron energy resolution could be obtained through the addition of an array of plastic scintillators potentially placed in front of DESCANT

  - DAEMON (Detector Array for Energy Measurements Of Neutrons)

  - Plastic scintillators have good timing resolution, are inexpensive, and can be customized into nearly any shape

  - Energy can be determined via Time-of-Flight technique
**TIME OF FLIGHT TECHNIQUE**

\[ E = \frac{1}{2}mv^2 = \frac{1}{2}m \frac{L^2}{TOF^2} \]

- Get TOF from 2 separate detectors that act as a stopwatch
- Good TOF energy resolution requires thin detectors
- Good efficiency requires thick detectors
- Detector geometry must be optimized

\[ \left( \frac{\Delta E}{E} \right)^2 = \left( \frac{2\Delta L}{L} \right)^2 + \left( \frac{2\Delta TOF}{TOF} \right)^2 \]

Decaying Nucleus (stationary)

Detector A

Detector B

\[ TOF = t_2 - t_1 \]
TIME OF FLIGHT TECHNIQUE

\[
\left( \frac{\Delta E}{E} \right)^2 = \left( \frac{2\Delta L}{L} \right)^2 + \left( \frac{2\Delta \text{TOF}}{\text{TOF}} \right)^2
\]

- DESCANT TOF energy resolution dominated by detector thickness

\[ \frac{\Delta E}{E} \propto \frac{\Delta L}{L} = \frac{15 \text{ cm}}{50 \text{ cm}} = 30\% \]

- DAEMON energy resolution simulated to be 6.5% at 1 MeV with a the 1.5 cm thick scintillator

\[ \text{TOF} = t_2 - t_1 \]

Decaying Nucleus (stationary)

Detector A

Detector B

t_1

t_2
GEANT4 SIMULATIONS

Detector Geometry

• GEANT4 is a toolkit for simulating particles passing through matter
  • Monte-Carlo technique
  • Ideal for designing and optimizing new detector concepts
GEANT4 SIMULATIONS

Detector geometry optimized to fit on the inside of DESCANT. Optical physics is incorporated into simulation. TOF is then determined by collecting optical photons in both SiPM’s.

Path of optical photons generated by neutron scattering

Scattered neutron

Each detector has a top and bottom light collector, likely a SiPM

Hole for beam line
Making more realistic SiPM configurations and adding to the front face.

1.5 cm thick and approximately 5.5 cm wide.
Detector geometry is being optimized to fit on the inside of DESCANT with GRIFFIN. Run Simulations with $1\times 10^6$ mono-energetic neutrons with bars 1.5 cm thick and 5.5 cm wide.
GEANT4 SIMULATIONS

1 optical photon threshold and 2 different arrays of SiPMs are required to fire to register event

At 1 MeV and 1.5 cm thick:
- 8.1% absolute peak efficiency
- 65 keV FWHM
- 6.5% energy resolution

Detector Configuration

DAEMON +
GRIFFIN
DAEMON +
GRIFFIN +
DESCANT

Counts per 1 keV

Neutron Energy (keV)
GEANT4 SIMULATIONS

DAEMON + GRIFFIN + DESCANT with condition of 2 different arrays of SiPMs required to fire to register event

Threshold of optical photons collected

- 10 photons
- 5 photons
- 1 photon

Counts per 1 keV vs. Neutron Energy (keV)
Beta Delayed Neutron Emission

\[ AX \xrightarrow{\beta^-} \] (Parent)

\( Q_\beta > S_n \) (Mass energy differences between reactants and products)

\( S_n \)

\[ \beta^- : n \rightarrow p + e^- + \bar{\nu}_e \]

\[ AY \] (Emitter)

\[ A-1Y \] (Daughter)
Simplified Decay

\[ Q_\beta = 5 \text{ MeV} \]
\[ t_{1/2} = 0.085 \text{ s} \]
\[ E_\gamma = 247 \text{ keV} \]
\[ E_n = 1 \text{ MeV} \]
GEANT4 SIMULATIONS

1 optical photon threshold and 2 different arrays of SiPMs are required to fire to register event.
1 optical photon threshold and 2 different arrays of SiPMs are required to fire to register event.

- Neutron Only
- Decay, Beta corrected
- Decay, Beta corrected and gamma gate

Maintain 65 keV FWHM
• DAEMON is able to increase precision to the neutron kinetic energy in the presence of GRIFFIN and DESCANT compared to the pre-existing setup

• Detector geometry has been designed to maximize performance and minimize cost

• Prototype construction and comparing results to simulation
THANK YOU

Collaborators
University of Guelph
Paul Garrett
Carl Svensson
Vinzenz Bildstein
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Allison Radich
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Fred Sarazin
Steven Shadrick

GRIFFIN + DESCANT Collaborations

UNIVERSITY OF GUELPH

TRIUMF
Time determined to be 35.3 ns in this case. This is done for both SiPM arrays

\[ t_{scatter} = t_{avg} - \frac{t_{Max}}{2^3} \]
TOF DETERMINATION

Optical Photons collected in 1 SiPM for 2 MeV neutron

Time (ns)  | Number Photons Collected per 0.1 ns
---|---
20 | 5
22 | 10
24 | 20
26 | 30
28 | 35
30 | 30
32 | 30
34 | 25
36 | 20
38 | 15
40 | 10

CFD algorithm Monitor Output

Zero Crossing: ~25.6 ns

After linear interpolation and bin randomization

Time determined to be 35.3 ns in this case. This is done for both SiPM arrays

\[ t_{scatter} = t_{avg} - \frac{t_{Max}}{2} \]
DETECTOR THICKNESS
With front SiPMs, 2 SiPM firing condition, 1 optical photon threshold
WIDTH OF BARS
NUMBER OF DETECTORS

10 Detectors
Across

20 Detectors
Across
NUMBER OF DETECTORS

Detector Thickness
- 2 cm
- 1 cm

Absolute Peak Efficiency (%)

Number of Detectors Across

Preliminary
NUMBER OF DETECTORS

Number of Detectors Across

Energy FWHM (keV)

Detector Thickness
- 2 cm
- 1 cm

Detector Thickness
- 10 cm Wide
- 4 cm Wide

Preliminary
POSITION RESOLUTION

Arc Length ($S$) Between Calculated and Actual Scatter Position Within Bars

- $X$ is assumed to be centre of detector.
- $Y$ is calculated via SiPM time when both fire.
- Radial distance ($r$) is assumed to be middle of detector.
- $Z$ is calculated using $x$, $y$, and $r$.

Calculated scatter position
Actual scatter position
Arc Length (S) Between Calculated and Actual Scatter Position Within Bars

Number of Detectors Across

Detector Thickness
- 2 cm
- 1 cm

Arc Length Average (cm)
ENERGY SPECTRA
GEANT4 SIMULATIONS

1 optical photon threshold and 2 different arrays of SiPMs are required to fire to register event.

Lower statistics of neutron only runs instead of scaling.
Scintillator in vacuum, neutrons shot at a 1cm thick, 8 cm wide detector, using a threshold of 1 optical photons detected in each SiPM
DETECTOR CONFIGURATION COMPARISONS
TILE CONFIGURATIONS

1.5 cm thick

With SiPMs on the front of detector

With no SiPMs on the front of detector
DIFFERENT SIPM CONFIGURATIONS

With SiPMs on the front of detector

With no SiPMs on the front of detector

1.5 cm thick
CONFIGURATION COMPARISON

Counts per 1 keV

Neutron Energy (keV)

Detector Configuration
- Bars with Front
- Bars no Front
- Tiles Unseg
- Tiles Seg

Preliminary
CONFIGURATION COMPARISON

Detector Configuration
- Red: Unsegmented Tiles
- Black: Segmented Tiles
- Blue: Bars: With front SiPM
- Green: Bars: No front SiPM

Absolute Peak Efficiency (%) vs. Neutron Energy (MeV)

Energy Resolution (%) vs. Neutron Energy (MeV)
TOF SPECTRA
1 optical photon threshold and 2 different arrays of SiPMs are required to fire to register event
With front SiPMs, 1.5 cm thick, 2 SiPM firing condition, 1 optical photon threshold
GEANT4 SIMULATIONS

Counts per 0.1 ns

TOF (ns)

Decay, Beta tagged
Decay, Beta tagged and gamma gate

Preliminary
Full setup, 1 optical photon threshold and 2 different arrays of SiPMs are required to fire to register event.
Full setup, 1 optical photon threshold and 2 different arrays of SiPMs are required to fire to

**GEANT4 SIMULATIONS**

Counts per 0.2 ns

At 2 MeV: 150 keV FWHM
At 1 MeV: 65 keV FWHM
At 5 MeV: 505 keV FWHM
At 500 keV: 32 keV FWHM

Neutron Energy:
- 500 keV
- 1 MeV
- 2 MeV
- 5 MeV

Preliminary
OPTICAL PHYSICS AND MATERIALS
Time determined to be 35.3 ns in this case. This is done for both SiPM arrays

\[ t_{scatter} = t_{avg} - \frac{t_{Max}}{2} \]
TOF DETERMINATION

Optical Photons collected in 1 SiPM for 2 MeV neutron

CFD algorithm Monitor Output

Time (ns)

Number Photons Collected per 0.1 ns

Time determined to be 35.3 ns in this case. This is done for both SiPM arrays

\[ t_{scatter} = t_{avg} - \frac{t_{Max}}{49} \]

A 600 ps FWHM coincidence timing uncertainty is then applied

Time Obtained: 25.65 ns

After linear interpolation and bin randomization

Zero Crossing: \(~25.6\) ns
EMISSION SPEC

Saint Gobain data sheets: https://www.crystals.saint-gobain.com/products/bc400-bc404
EMISSION SPEC

BC408

Peak at 430 nm

Relative Light Output

Wavelength (nm)

BC404

Peak at 405 nm

Relative Light Output

Wavelength (nm)

Saint Gobain data sheets: https://www.crystals.saint-gobain.com/products/bc400-bc404
DECAY TIME

Photons generated in plastic scintillator as a function of time

BC408
2.1 ns decay time from data sheets
2.14 ns obtained from fit

BC404
1.8 ns decay time from data sheets
1.77 ns obtained from fit
PUT IN BC404 VS 408 COMPARISON

Bars with Front SiPM Configuration, 1.5 cm thick, 5.5 cm wide
Bars with Front SiPM Configuration, 1.5 cm thick, 5.5cm wide
PARTICLE BASED LIGHT OUTPUT

Taken from Saint-Gobain plastic scintillator data sheet
DETERMINING SCATTER TIME AND POSITION
Want to extract $t_{scatter}$ from $t'_1$ and $t'_2$

Assume Bottom SiPM fires before Top.
Assume scatter is closer to Bottom

Define
\[ \Delta t = t_{scatter} - t_{TransitToMiddle} \]

And
\[ t'_1 = t_{scatter} + t_{transitTop} \]
\[ t'_2 = t_{scatter} + t_{transitBottom} \]

Therefore
\[ t'_1 = t_{scatter} + t_{transitMid} + \Delta t \]
\[ t'_2 = t_{scatter} + t_{transitMid} - \Delta t \]

$\star$ Scatter Location at time $t_{scatter}$
Want to extract \( t_{\text{scatter}} \) from \( t'_1 \) and \( t'_2 \)

Assume Bottom SiPM fires before Top.
Assume scatter is closer to Bottom

\[
\Delta t = t_{\text{scatter}} - t_{\text{TransitToMiddle}}
\]

\[
t'_1 = t_{\text{scatter}} + t_{\text{transitMid}} + \Delta t
\]

\[
t'_2 = t_{\text{scatter}} + t_{\text{transitMid}} - \Delta t
\]

Define

\[
t_{\text{avg}} = \frac{t'_1 + t'_2}{2}
\]

Therefore

\[
t_{\text{avg}} = t_{\text{scatter}} + t_{\text{transitMid}}
\]

☆ Scatter Location at time \( t_{\text{scatter}} \)
Want to extract $t_{scatter}$ from $t_1'$ and $t_2'$

Assume Bottom SiPM fires before Top.
Assume scatter is closer to Bottom

Define $t_{avg} = \frac{t_1' + t_2'}{2}$

Need the effective speed of light in the plastic

$t_{scatter} = t_{avg} - \frac{t_{Max}}{2}$
CFD Monitor output. Cross over is the point at which time is taken at signal time
Time determined to be 35.3 ns in this case. This is done for both SiPM arrays

\[ t_{scatter} = t_{avg} - \frac{t_{Max}}{2} \]
TOF DETERMINATION

Optical Photons collected in 1 SiPM for 2 MeV neutron

CFD algorithm Monitor Output

Zero Crossing: ~25.6 ns

20% Max height at ~25.6 ns

Time determined to be 35.3 ns in this case. This is done for both SiPM arrays

$$t_{scatter} = t_{avg} - \frac{t_{Max}}{2}$$
Calculated $E_{\text{numCollectedPhotonsTop} > 2 \land \text{numCollectedPhotonsBottom} > 2}$

ENERGY SPECTRA

Scintillator in vacuum, neutrons shot at a 1 cm thick, 8 cm wide detector, using a threshold of 1 optical photons detected in each SiPM
To make our extracted times from the CFD algorithms and the ZDS more realistic, we apply coincidence uncertainties. Timing uncertainties are approximated to 600 ps fwhm. Applying a 200 ps fwhm for the ZDS, we can work out the uncertainties in the CFD algorithms, depending if 1 or 2 SiPMs are involved. Then the times obtained are convoluted with a gaussian with the corresponding FWHM.

\[ \delta t^2 = \delta t_{ZDS}^2 + \delta_{DAEMON}^2 \]

\[ 600^2 = 200^2 + \delta_{DAEMON}^2 \]

\[ \delta_{DAEMON} = 565 \text{ps} \]

\[ \delta_{DAEMON}^2 = \delta_{CFD1}^2 + \delta_{CFD2}^2 \]

\[ 565^2 = (2\delta_{CFD})^2 \]

\[ \delta_{CFD} = 400 \text{ps} \]
Assume Top SiPM fires before Bottom.
Assume scatter is closer to Top

\[ t_{\text{avg}} = \frac{t_1' + t_2'}{2} \]

\[ t_{\text{avg}} = t_{\text{scatter}} + t_{\text{transitMid}} \]

\[ t_{\text{scatter}} = t_{\text{avg}} - \frac{t_{\text{Max}}}{2} \]

\[ S = (t_1' - t_{\text{scatter}}) \times c_{\text{eff}} \]

\[ S = (t_1' - t_{\text{avg}} + \frac{t_{\text{Max}}}{2}) \times c_{\text{eff}} \]

\[ S = (\frac{t_1' - t_2'}{2} + \frac{t_{\text{Max}}}{2}) \times c_{\text{eff}} \]
Assume Top SiPM fires before Bottom. Assume scatter is closer to Top

$$S = \left(\frac{t'_{1} - t'_{2}}{2} + \frac{t_{Max}}{2}\right) \times c_{eff}$$

Want $S'$$$

$$Arclength \frac{2}{2} = S + S'$$

$$S' = \frac{t_{Max}}{2} \times c_{eff} - \left(\frac{t'_{1} - t'_{2}}{2} + \frac{t_{Max}}{2}\right) \times c_{eff}$$

$$S' = \left(\frac{t'_{2} - t'_{1}}{2}\right) \times c_{eff}$$
Assume Top SiPM fires before Bottom.
Assume scatter is closer to Top

\[ S' = \left( \frac{t_2' - t_1'}{2} \right) * \text{c}_{\text{eff}} \quad \text{For} \quad t_1' < t_2' \]

If \( S' \) is negative, then \( t_1' > t_2' \).
Therefore \( S' \) has a negative y component

Shift to Center of Detectors YZ Planes

\[ r = \sqrt{(R^2 - X_{\text{MidDet}}^2)} \]

\[ Y_{\text{Scatter}} = r \sin \left( \frac{S'}{r} \right) \]
Arc Length (S) Between Calculated and Actual Scatter Position Within Bars

- X is assumed to be centre of detector.
- Y is calculated via SiPM time when both fire.
- Radial distance (r) is assumed to be middle of detector.
- Z is calculated using x, y, and r.

Top SiPM

Bottom SiPM

Calculated scatter position
Actual scatter position
VALIDATING GEANT4 PHYSICS PACKAGES QGSP_BERT_HP
PHYSICS VALIDATION OF GEANT4

- Hydrogen

![Graph showing cross section vs. excitation energy. The x-axis represents excitation energy (MeV) ranging from 0 to 10, and the y-axis represents cross section (barns) ranging from 0 to 22. The graph includes lines for simulated total, simulated elastic, simulated inelastic, ENDF total, ENDF elastic, and ENDF inelastic.]
PHYSICS VALIDATION

- Deuterium
PHYSICS VALIDATION

- Carbon-12

![Graph showing cross-sections versus excitation energy for Carbon-12 with comparisons to simulated total, elastic, and inelastic, as well as ENDF total, elastic, and inelastic data.]
Resonance peaks from excited states in compound nucleus

- Carbon-12

\(^{13}\text{C}^*\) formed in scattering reaction

**PHYSICS VALIDATION**
PHYSICS VALIDATION

- Carbon-12

![Graph showing cross section versus excitation energy for Carbon-12. The graph compares simulated total, elastic, and inelastic cross sections with ENDF total, elastic, and inelastic cross sections.](image-url)
PHYSICS VALIDATION

- Carbon-12: Not HP physics package
GEANT4 SIMULATIONS
PHYSICS VALIDATION

- Carbon-12: HP physics package

![Graph showing scattering angle vs. differential cross section for 10MeV neutron on $^{12}$C target. The graph compares simulated data with ENDF predictions.](image)
GEANT4 SIMULATIONS
MEAN FREE PATH OF NEUTRONS IN BC408

15 cm thick detector

Mean Free Path
- 100 keV $\mu = 11.4$ mm
- 500 keV $\mu = 20.9$ mm
- 1 MeV $\mu = 29.0$ mm
- 3 MeV $\mu = 56.9$ mm
- 5 MeV $\mu = 70.1$ mm
BACKGROUND
Many of the nuclei found in the astrophysical rapid neutron capture process are beta delayed neutron emitters.
START WITH ENERGY CONSERVATION

\[ m_{\text{Emitter}}c^2 + E_{\text{Emitter}} = m_{\text{Daughter}}c^2 + E_{\text{Daughter}} + m_n c^2 + T_n + T_R \]

Use

\[ S_n = m_{\text{Daughter}}c^2 + m_n c^2 - m_{\text{Emitter}}c^2 \]

To get:

\[ E_{\text{Emitter}} = E_{\text{Daughter}} + T_n + T_R + S_n \]
• Beta delayed neutron spectroscopy

• If the following values are measured precisely, information on excited states can be extracted, which has nuclear structure implications.

$$E_{Emitter} = E_{Daughter} + T_n + T_R + S_n$$

- (Excited) State of Emitter
- (Excited) State of Daughter
- Kinetic Energy Neutron
- Nucleus Recoil Energy
- Neutron Separation Energy

• Our goal is to measure neutron energy with good resolution!
DEUTERATED SCINTILLATORS

\[ E = \frac{1}{2} m \nu^2 \]

\[ E_n (\text{MeV}) \]

\[ 10^4 \]

\[ 1 \]

\[ 13\text{CH}_2 \text{Target} \]
DEUTERATED SCINTILLATORS

Ideal for lighter nuclei close to closed shells with low level density

NEUTRON DETECTION
SCINTILLATORS

- Extracting neutron energies is slightly more complicated than other radiation due to their lack of charge.

- Need special detectors - like scintillators - which can convert kinetic energy of particles into photons for particle detection.

Singlet

\[ S_0 \]

\[ S_1 \]

\[ S_2 \]

Triplet

\[ T_1 \]

\[ T_2 \]

Absorption

Fluorescence

Phosphorescence

Inter-system crossing
It is possible to determine the type of radiation incident on a scintillator.

This can be based on the timing profile of the scintillation light emission.

Knoll, G. Radiation and Detection Measurement.