3He Ionization Chambers as Neutron Beam Flux Monitors for the NPDGamma Experiment

Chad Gillis

Indiana University

NSERC Canada

APS DNP Meeting
Nashville, Tennessee
October 2006
The NPDGamma Experiment

A precision measurement of the coupling constant for weak pion exchange between nucleons

The NPDGamma Experiment

The Los Alamos Neutron Science Center

The NPDGamma + p + n + (2.2 MeV) γ (800 MeV Linac) reaction

Pulsed (20 Hz) proton beam strikes production target

Cold (meV) neutrons from LH₂ moderator

The NPDGamma Collaboration

Summary and Conclusion
The NPDGamma Apparatus

Helmholtz coils provide uniform vertical magnetic field.

20 Hz pulsed cold neutrons

neutron guide

beam monitor

beam monitor

beam monitor

beam monitor

M1

M2

spin flipper

LH$_2$
target

gamma detectors

M3

The NPDGamma Experiment
The NPDGamma Apparatus

Helmholtz coils provide uniform vertical magnetic field.

20 Hz pulsed cold neutrons

beam polarizer

beam monitor

beam monitor

M1

M2

spin flipper

LH$_2$ target

gamma detectors

beam monitor

M3

neutron guide

The Beam Monitors

What they are

How they work

A transmission measurement

Beam Monitor Analysis

Polarimetry

Polarizer Transmission Measurement

The NPDGamma Collaboration

Summary and Conclusion
The NPDGamma Apparatus
The beam monitors of the NPDGamma experiment

Chad Gillis

Background
The NPDGamma Experiment

Experimental Setup
A Gamma Asymmetry Measurement

The Beam Monitors
What they are
How they work
A transmission measurement

Beam Monitor Analysis
Polarimetry
Polarizer Transmission Measurement

The NPDGamma Collaboration

Summary and Conclusion

The NPDGamma Apparatus

Helmholtz coils provide uniform vertical magnetic field.

neutron guide

20 Hz pulsed cold neutrons

beam monitor

beam monitor

beam monitor

beam monitor

gamma detectors

spin flipper

LH$_2$ target

M1

M2

M3
The NPDGamma Apparatus

20 Hz pulsed cold neutrons

Helmholtz coils provide uniform vertical magnetic field.

The NPDGamma Apparatus

The NPDGamma Experiment

Chad Gillis

Background

The NPDGamma Experiment

Experimental Setup

A Gamma Asymmetry Measurement

The Beam Monitors

What they are

How they work

A transmission measurement

Beam Monitor Analysis

Polarimetry

Polarizer Transmission Measurement

The NPDGamma Collaboration

Summary and Conclusion
The NPDGamma Apparatus

- Beam Monitors of the NPDGamma Experiment
- Chad Gillis

Background
The NPDGamma Experiment

Experimental Setup
A Gamma Asymmetry Measurement

The Beam Monitors
What they are
How they work
A transmission measurement

Beam Monitor Analysis
Polarimetry
Polarizer Transmission Measurement

The NPDGamma Collaboration

Summary and Conclusion

Helmholtz coils provide uniform vertical magnetic field.

20 Hz pulsed cold neutrons

neutron guide

beam monitor

beam polarizer

spin flipper

LH₂ target

gamma detectors

M1

M2

M3

beam monitor

beam monitor

beam monitor
The NPDGamma Apparatus

Helmholtz coils provide uniform vertical magnetic field.

The NPDGamma Apparatus

20 Hz pulsed cold neutrons

Beam Monitors
What they are
How they work
A transmission measurement

Analysis
Polarimetry
Polarizer Transmission Measurement

The NPDGamma Collaboration

Summary and Conclusion
A Gamma Asymmetry Measurement

\[ A_\gamma P_n = \frac{1}{\cos(\theta)} \frac{[N(\theta) - N(\pi + \theta)]}{[N(\theta) + N(\pi + \theta)]} \]

\( A_\gamma \) = gamma asymmetry

\( P_n \) = beam polarization

The Beam Monitors of the NPDGamma Experiment
Chad Gillis

Background
The NPDGamma Experiment
Experimental Setup
A Gamma Asymmetry Measurement

The Beam Monitors
What they are
How they work
A transmission measurement

Beam Monitor Analysis
Polarimetry
Polarizer Transmission Measurement

The NPDGamma Collaboration
Summary and Conclusion
A Gamma Asymmetry Measurement

\[
A_\gamma P_n = \frac{1}{\cos(\theta)} \left[ N(\pi + \theta) - N(\theta) \right]
\]

\[
\left[ N(\pi + \theta) + N(\theta) \right]
\]

\[
A_\gamma = \text{gamma asymmetry}
\]

\[
P_n = \text{beam polarization}
\]
A Gamma Asymmetry Measurement

\[ A_\gamma P_n = \frac{1}{\cos(\theta)} \frac{N(\pi + \theta) - N(\theta)}{N(\pi + \theta) + N(\theta)} \]

\( A_\gamma \) = gamma asymmetry
\( P_n \) = beam polarization
The Beam Monitors

- Ionization chambers containing $^3\text{He}$, $^4\text{He}$, $\text{N}_2$. 

---

**Background**

The NPDGamma Experiment
Experimental Setup
A Gamma Asymmetry Measurement

**The Beam Monitors**

What they are
How they work
A transmission measurement

**Beam Monitor Analysis**

Polarimetry
Polarizer Transmission Measurement

**The NPDGamma Collaboration**

Summary and Conclusion
The Beam Monitors

- Ionization chambers containing $^3\text{He}$, $^4\text{He}$, $\text{N}_2$.
- Function by application of a high voltage.

Background
The NPDGamma Experiment
Experimental Setup
A Gamma Asymmetry Measurement
The Beam Monitors
What they are
How they work
A transmission measurement
Beam Monitor Analysis
Polarimetry
Polarizer Transmission Measurement
The NPDGamma Collaboration
Summary and Conclusion
The Beam Monitors

- Ionization chambers containing $^3\text{He}$, $^4\text{He}$, $\text{N}_2$.
- Function by application of a high voltage.
- Placed directly in the beam.

Ionization chambers containing $^3\text{He}$, $^4\text{He}$, $\text{N}_2$. Function by application of a high voltage. Placed directly in the beam.
The Beam Monitors

- Ionization chambers containing $^3\text{He}$, $^4\text{He}$, $\text{N}_2$.
- Function by application of a high voltage.
- Placed directly in the beam.
- Run in current mode.

Ionization chambers containing $^3\text{He}$, $^4\text{He}$, $\text{N}_2$. Function by application of a high voltage. Placed directly in the beam. Run in current mode.
The Beam Monitors

- Ionization chambers containing $^3$He, $^4$He, N$_2$.
- Function by application of a high voltage.
- Placed directly in the beam.
- Run in current mode.
- Output current signal depends only on neutron energy and incident neutron rate.
The Beam Monitors

- Ionization chambers containing $^3$He, $^4$He, N$_2$.
- Function by application of a high voltage.
- Placed directly in the beam.
- Run in current mode.
- Output current signal depends only on neutron energy and incident neutron rate.
- Very low noise
The Beam Monitors

Background
The NPDGamma Experiment
Experimental Setup
A Gamma Asymmetry Measurement

The Beam Monitors
What they are
How they work
A transmission measurement

Beam Monitor Analysis
Polarimetry
Polarizer Transmission Measurement

The NPDGamma Collaboration

Summary and Conclusion
To detect low energy neutrons, use an exothermic reaction that produces charged particles.

\[ n + ^3\text{He} \rightarrow p + t + 764 \text{ keV} \]

- Energy: 20.6 MeV
- Ground state: 0 MeV
- Differential cross section: 0.5 MeV wide
- Total cross section: 20.2 MeV
The $n + ^3\text{He}$ reaction

- Dominated by: $n + ^3\text{He} \rightarrow p + t + 764 \text{ keV KE}$

![Graph showing cross section vs neutron energy]

**Cross Section**

- $\sigma \propto \frac{1}{\sqrt{E}} \propto t_{of}$

Energy range of interest:

- $10^{-4}$ to $10^{2}$ eV

Barns vs Neutron energy $E$ (eV)
The $n + ^3\text{He}$ reaction

- Dominated by: $n + ^3\text{He} \rightarrow p + t + 764$ keV KE
- Cross section is huge and has a very clean energy dependence.
The n + $^3$He reaction

- Dominated by: $n + ^3He \rightarrow p + t + 764$ keV KE
- Cross section is huge and has a very clean energy dependence.
- Products do not leave the chamber.

![Graph showing cross section vs neutron energy](image)
The n + $^3$He reaction

- Dominated by: $n + ^3He \rightarrow p + t + 764$ keV KE
- Cross section is huge and has a very clean energy dependence.
- Products do not leave the chamber.
- Gas can be mixed to produce required attenuation and response.
The n + $^3$He reaction

- Dominated by: $n + ^3He \rightarrow p + t + 764$ keV KE
- Cross section is huge and has a very clean energy dependence.
- Products do not leave the chamber.
- Gas can be mixed to produce required attenuation and response.
- Response to gamma background is negligible.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{cross_section_plot}
\caption{Cross Section}
\end{figure}

\begin{align*}
    \sigma &\propto \frac{1}{\sqrt{E}} \propto tof \\
    \text{energy range of interest}
\end{align*}
Workings of the Beam Monitors

The Beam Monitors
What they are
How they work
A transmission measurement

Beam Monitor Analysis
Polarimetry
Polarizer Transmission Measurement

The NPDGamma Collaboration
Summary and Conclusion
Beam Monitors of the NPDGamma Experiment

Chad Gillis

Background
The NPDGamma Experiment
Experimental Setup
A Gamma Asymmetry Measurement

The Beam Monitors
What they are
How they work
A transmission measurement

Beam Monitor Analysis
Polarimetry
Polarizer Transmission Measurement

The NPDGamma Collaboration

Summary and Conclusion

Frame overlap chopper prevents overlap of neighboring pulses. Time-dependent signal allows time of flight analysis.

E = \frac{1}{2} \cos^2(t)

Beam Monitor Signal

Source is pulsed at 20 Hz.
Beam Monitor Signal

Source is pulsed at 20 Hz.
Frame overlap chopper prevents overlap of neighbouring pulses.
Beam Monitors of the NPDGamma Experiment

Chad Gillis

Background
The NPDGamma Experiment
Experimental Setup
A Gamma Asymmetry Measurement

The Beam Monitors
What they are
How they work
A transmission measurement

Beam Monitor Analysis
Polarimetry
Polarizer Transmission Measurement

The NPDGamma Collaboration

Summary and Conclusion

Source is pulsed at 20 Hz.
Frame overlap chopper prevents overlap of neighbouring pulses.
Time-dependent signal allows time of flight analysis.

\[ E = \frac{1}{2} m \left( \frac{1}{t} \right)^2 \]
Beam Monitors of the NPDGamma Experiment
Chad Gillis

Background
The NPDGamma Experiment
Experimental Setup
A Gamma Asymmetry Measurement

The Beam Monitors
What they are
How they work
A transmission measurement

Beam Monitor Analysis
Polarimetry
Polarizer Transmission Measurement

The NPDGamma Collaboration
Summary and Conclusion

Beam Monitor Signal

\[ V = NPQR \]

Constant time of flight:
\[ V \propto N \]

Beam Monitor Signal

output voltage
neutron rate
capture probability
charge per neutron
amplifier gain
Beam Monitor Signal

\[ V = N P Q R \]

Constant time of flight:
\[ V \propto N \]

Output voltage
Neutron rate
Capture probability
Charge per neutron
Amplifier gain

Beam Monitor Signal

![Beam Monitor Signal Graph](image)
Beam Monitor Signal

\[ V = N P Q R \]

Constant time of flight:

\[ V \propto N \]

Beam Monitor Signal

output voltage
neutron rate
capture probability
charge per neutron
amplifier gain

Beam Monitor Signal

Beam Monitor Signal

beam monitor preamplifier output (volts)
time (ms)
Beam Monitor Signal

\[ V = N \rho P Q R \]

Constant time of flight:
\[ V \propto N \]

Beam Monitor Signal
Beam Monitors of the NPDGamma Experiment

Chad Gillis

Background
The NPDGamma Experiment
Experimental Setup
A Gamma Asymmetry Measurement

The Beam Monitors
What they are
How they work
A transmission measurement

Beam Monitor Analysis
Polarimetry
Polarizer Transmission Measurement

The NPDGamma Collaboration

Summary and Conclusion

Beam Monitor Signal

\[ V = N P Q R \]

Constant time of flight:
\[ V \propto N \]

Beam Monitor Signal

output voltage
neutron rate
capture probability
charge per neutron
amplifier gain

Beam Monitor Signal
Beam Monitor Signal

\[ V = NPQR \]

Constant time of flight:
\[ V \propto N \]

The diagram shows the beam monitor signal over time. The horizontal axis represents time in milliseconds (ms), ranging from 0 to 130 ms, and the vertical axis represents the beam monitor preamplifier output in volts, ranging from 0 to 4 volts. The signal peaks at regular intervals, indicating the arrival of neutron beams at the monitor. The equation \( V = NPQR \) gives the output voltage in terms of neutron rate, capture probability, charge per neutron, and amplifier gain.
Beam Monitors of the NPDGamma Experiment

Chad Gillis

Background
The NPDGamma Experiment
Experimental Setup
A Gamma Asymmetry Measurement

The Beam Monitors
What they are
How they work
A transmission measurement

Beam Monitor Analysis
Polarimetry
Polarizer Transmission Measurement

The NPDGamma Collaboration

Summary and Conclusion

\[ V = NPQR \]

\[ Q, R \text{ constant} \]

\[ P \text{ increases with tof } (\sigma \propto \text{tof}) \]
A Transmission Measurement

\[ \alpha N \]

\[ V_1 = N f_1(E_1) \]

\[ V_2 = \alpha N f_2(E_2) \]
A Transmission Measurement

\[ \tilde{V}_1 = \tilde{N} f_1(E_1) \]

\[ \tilde{V}_2 = \alpha \tilde{N} f_2(E_2) \]
A Transmission Measurement

\[ V_1 = N f_1(E_1) \]
\[ V_2 = \alpha N f_2(E_2) \]

\[ \tilde{V}_1 = \tilde{N} f_1(E_1) \]
\[ \tilde{V}_2 = T \alpha \tilde{N} f_2(E_2) \]
**A Transmission Measurement**

\[ T = \frac{\tilde{V}_2}{\tilde{V}_1} \]

**Beam Monitors of the NPDGamma Experiment**

**Chad Gillis**

**Background**

The NPDGamma Experiment

Experimental Setup

A Gamma Asymmetry Measurement

**The Beam Monitors**

What they are

How they work

A transmission measurement

**Beam Monitor Analysis**

Polarimetry

Polarizer Transmission Measurement

**The NPDGamma Collaboration**

Summary and Conclusion
**3He As a Spin Filter**

- Resonance requires $J^\pi = 0^+$

![Diagram showing the reaction $n + ^3\text{He} \rightarrow p + t + 764 \text{ keV}$ with energy levels and spin states.](image)
**3He As a Spin Filter**

- Resonance requires $J^\pi = 0^+$
- Polarized $^3\text{He}$ preferentially attenuates neutrons of one spin direction

![Diagram showing the resonance and energy levels for $^4\text{He}$ and $^3\text{He}$](image)

- $^4\text{He}$ ground state is $0^+$ with a width of 0 MeV.
- Polarization in $^3\text{He}$ is denoted by $J^\pi = 1^+_2$ and $J^\pi = 1^+_2$.
- Neutrons from $n + ^3\text{He}$ at 20.6 MeV are transmitted through $^4\text{He}$ and result in $p + t + 764 \text{ keV}$.

The diagram illustrates the energy levels and transitions relevant to the NPDGamma experiment, focusing on the use of $^3\text{He}$ as a spin filter.
Beams of the NPDGamma Experiment
Chad Gillis

3He As a Spin Filter

- Resonance requires $J^\pi = 0^+$
- Polarized $^3$He preferentially attenuates neutrons of one spin direction
- The attenuation is observed using the beam monitors
Beam Polarization measurement

- The polarization-dependent transmission of the $^3$He cell can be seen by observing the flux-normalized signal of the second monitor.

![Signal of downstream monitor](image)

- The polarization-dependent transmission of the $^3$He cell can be seen by observing the flux-normalized signal of the second monitor.
Beam Monitors of the NPDGamma Experiment

Chad Gillis

Background
The NPDGamma Experiment
Experimental Setup
A Gamma Asymmetry Measurement

The Beam Monitors
What they are
How they work
A transmission measurement

Beam Monitor Analysis
Polarimetry
Polarizer Transmission Measurement

The NPDGamma Collaboration

Summary and Conclusion

\[ T = \exp(-n\sigma) \]
\[ \log(T) = -n\sigma \]

\[ \sigma \propto \text{time of flight} \]
Beam Monitors of the NPDGamma Experiment

Chad Gillis

Background
The NPDGamma Experiment
Experimental Setup
A Gamma Asymmetry Measurement

The Beam
Monitors
What they are
How they work
A transmission measurement

Beam Monitor
Analysis
Polarimetry
Polarizer Transmission Measurement

The NPDGamma
Collaboration

Summary and
Conclusion

J.D. Bowman (Spokesperson), G.S. Mitchell, S.I. Penttilä, A. Salas-Bacci, W.S. Wilburn and V.W. Yuan Los Alamos National Laboratory
S.J. Freedman and B. Lauss University of California, Berkeley
G.L. Jones Hamilton College
P.-N. Seo North Carolina State University
T. Ino, Y. Masuda and S. Muto High Energy Accelerator Research Organization, Japan
M. Gericke, S.A. Page and W.D. Ramsay University of Manitoba and TRIUMF
E.I. Sharapov Joint Institute for Nuclear Research, Dubna
T.E. Chupp, K. Coulter, M. Kandes and M. Sharma University of Michigan
S. Covrig, M. Dabaghyan, F.W. Hersman, T.-U. Lee and H. Zhu University of New Hampshire
W. Chen and T.R. Gentile National Institute of Standards and Technology
C. Crawford, D. Desai, G.L. Greene, T. Ito, R. Mahurin and A. Yue University of Tennessee and ORNL
R. Alarcon, L. Barrón Palos Arizona State University
R.D. Carlini Thomas Jefferson National Accelerator Facility
T.B. Smith University of Dayton
Beam Monitors of the NPDGamma Experiment

Chad Gillis

Background

The NPDGamma Experiment
Experimental Setup
A Gamma Asymmetry Measurement

The Beam Monitors
What they are
How they work
A transmission measurement

Beam Monitor Analysis
Polarimetry
Polarimeter Transmission Measurement

The NPDGamma Collaboration

Summary and Conclusion

- NPDGamma: to provide a precise measurement of $h^1_\pi$, the coupling constant for weak meson exchange.
- To perform this measurement, the neutron beam polarization must be known.
- The beam monitors: ionization chambers that provide a signal proportional to incident beam flux.
- Beam monitors are reliable, low noise and low background.
- Beam monitors have been used to measure the beam transmission through components of the apparatus.
- Beam monitors allow for a continuous measurement of beam polarization.
- Beam monitors will be useful for similar measurements in the future.