Pulsed Cold Neutron Beam Polarimetry for the NPDGamma Experiment

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U of Manitoba Subatomic Physics Club November 2004

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The meson exchange model of the weak interaction between nucleons:

\[ (\pi, \rho, \omega) \]

\[ \text{parity-violating weak vertex} \]

\[ \text{parity-conserving strong vertex} \]

A full quantitative description of this model has not been completed.

**NPDGamma**: Measure the **parity-violating asymmetry** \( A_\gamma \) in order to determine the **pion-nucleon weak coupling constant** \( f_\pi \):

\[ A_\gamma \approx -0.11 f_\pi \] \[ [1] \]

The NPDGamma apparatus is tested and delivers the accuracy required to measure the cleanly interpretable but small \( (A_\gamma \approx -5 \times 10^{-8} \) expected) effect from a two-body system.

The parity transformation (P):
\[ x \rightarrow -x \ ; \ y \rightarrow -y \ ; \ z \rightarrow -z \]

For experimental purposes, a parity reversal is equivalent to a reversal of left and right, which includes a reversal of angular momentum.

The weak interaction is the only interaction known to violate parity.

To isolate the weak force use a polarized beam.
The NPDGamma reaction
\[ \bar{n} + p \rightarrow d + \gamma \ (2.2 \text{ MeV}) \]

\[ \gamma \text{ DETECTORS} \]

\[ A_{\gamma} = \frac{1}{P_n} \frac{N_{\text{up}} - N_{\text{down}}}{N_{\text{up}} + N_{\text{down}}} \]

\[ P_n = \text{neutron polarization} = \frac{n_{\text{up}} - n_{\text{down}}}{n_{\text{up}} + n_{\text{down}}} \]

\( N = \text{number of gammas} \)

\( n = \text{number of neutrons} \)
- LH$_2$ moderator slows neutrons (peak at 9 meV = 3 Å)
- Frame overlap chopper prevents pulse overlap
- Pulsed source provides correspondence between neutron energy and time of flight.
$^3\text{He}$ has a strong affinity for neutrons.

\[ \text{n} + ^3\text{He} \rightarrow \text{p} + ^3\text{H} + 764 \text{ keV of KE} \]

Cross Section

\[
\sigma \propto \frac{1}{\sqrt{E}} \propto \text{tof}
\]

energy range of interest
The NPDGamma Beam Monitors

Primary function: To provide a signal proportional to the rate of neutrons passing through.

Gas mixture:
- $\frac{1}{2}$ Atm ($^3$He + $^4$He)
- $\frac{1}{2}$ Atm $N_2$

Amount of $^3$He depends on monitor’s purpose
Uses of the NPDGamma Beam Monitors

Until present:

• Monitor neutron flux.
• Measurement of beam polarization:

In the future:

• Measurement of the ortho-para ratio of the LH$_2$ target:
Beam Intensity Measurement

N neutrons

\[ I = NP(E)Q \]

\( P(E) \): known neutron capture probability increases with neutron tof

\( Q \): charge liberated in the gas per neutron

\[ \approx 10^4 \text{ e} \]

independent of neutron tof
voltage signal from upstream monitor preamp

\[ I = N P(E) Q \]

Calibration of the monitors is a determination of \( Q \).

flux calculation normalized to monte carlo

Monitor efficiency increases with tof \((\sigma \propto \text{tof})\)

Calibration of the monitors is a determination of \( Q \).
**Beam Polarizer Diagnostics**

The probability of interaction for a neutron with $^3\text{He}$ is highly spin-dependent:

\[
\begin{align*}
&\text{n} + ^3\text{He} \quad \sigma_p \sim 3 \text{ barns} \\
&\text{n} + ^3\text{He} \quad \sigma_a \sim 17,000 \text{ barns} @ 10 \text{ meV} \\
&\quad \quad \quad \sigma_a \propto \frac{1}{v} \quad (v = \text{neutron speed})
\end{align*}
\]

A cell of polarized $^3\text{He}$ filters out neutrons of one spin state.

Beam monitors are used to measure that effect.
Relative transmission through the cell polarized and unpolarized is an **absolute measure** of **neutron polarization** $P_n$:

$$P_n = \sqrt{1 - \left(\frac{T_0}{T}\right)^2}$$

$T_0$ = transmission of unpolarized cell  
$T$ = transmission of polarized cell

Knowing $P_n$ and the amount of $^3$He in the cell, it’s possible to calculate the $^3$He polarization:

$$P_n = \tanh(n_3\sigma l P_3)$$

$P_3$ = $^3$He polarization  
$n_3$ = $^3$He number density  
$l$ = width of cell
M2 Signal With Cell Polarized and Unpolarized

Polarized +
Unpolarized ×

Preamp output (Volts)

Neutron time of flight at 21.4 meters

$P_n$ from transmission measurements
Fit to $\tanh(n_3\sigma I P_3)$

Fit yields $n_3\sigma I P_3 = 0.0328 \text{ ms}^{-1} \text{ tof}$
\[ T_0 = e^{-n\sigma l} \]

\[ \ln(T_0) = -n\sigma l \propto \text{tof} \]

Unpolarized $^3$He Transmission
(corrected for glass cell wall transmission)

\[ \ln(T_0) = -n\sigma l \]

best fit: \( n\sigma l = 0.0714 \text{ ms}^{-1} \text{ tof} \)

\[ P_3 = \frac{n_3\sigma l P_3}{n_3\sigma l} = \frac{0.0328 \text{ ms}^{-1} \text{ tof}}{0.0714 \text{ ms}^{-1} \text{ tof}} = 0.46 \]
Spin Flipper Commissioning

Spin-dependent transmission of the analyzer cell can be seen in the third monitor:

Spin flipper performs an imperfect flip:

\[ P_n \rightarrow -RP_n \quad ; \quad R < 1 \]

The ratio between spin flipper on and spin flipper off signals is dependent on polarizer and analyzer properties and \( R \).
**Liquid $\text{H}_2$ target diagnostics**

Two nuclear spin states of the $\text{H}_2$ molecule:

- ortho-hydrogen
- para-hydrogen

$\Delta E = 15 \text{ meV}$

Cross-section as a function of neutron KE$^{[1]}$

- $\text{ortho-H}_2$ has a high spin-incoherent cross-section for neutron scattering.
- $\text{para-H}_2$ below 15 meV does not.

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Concluding Remarks

- Neutron polarization for the NPDGamma experiment is provided by a polarized $^3\text{He}$ spin filter.

- Pulse-by-pulse spin flips are performed by an RF neutron spin rotator.

- $^3\text{He}$ ion chambers provide the ability to perform neutron flux and neutron transmission measurements.

- Knowledge of neutron polarization and spin flip efficiency is provided by performing neutron transmission measurements of polarized $^3\text{He}$.

- The polarization of the $^3\text{He}$ in the polarizer and analyzer cells can similarly be determined.

- Beam monitors will also be used to monitor the ortho-para ratio of our liquid hydrogen target during the $\bar{n} + p \rightarrow d + \gamma$ asymmetry measurement.