Measuring the PNC Spin-Rotation of Polarized Neutrons Traversing Liquid Helium

C.Bass, D.Luo, H.Nann, M.Sarsour, W.Snow
Indiana University

P.Huffman
NIST

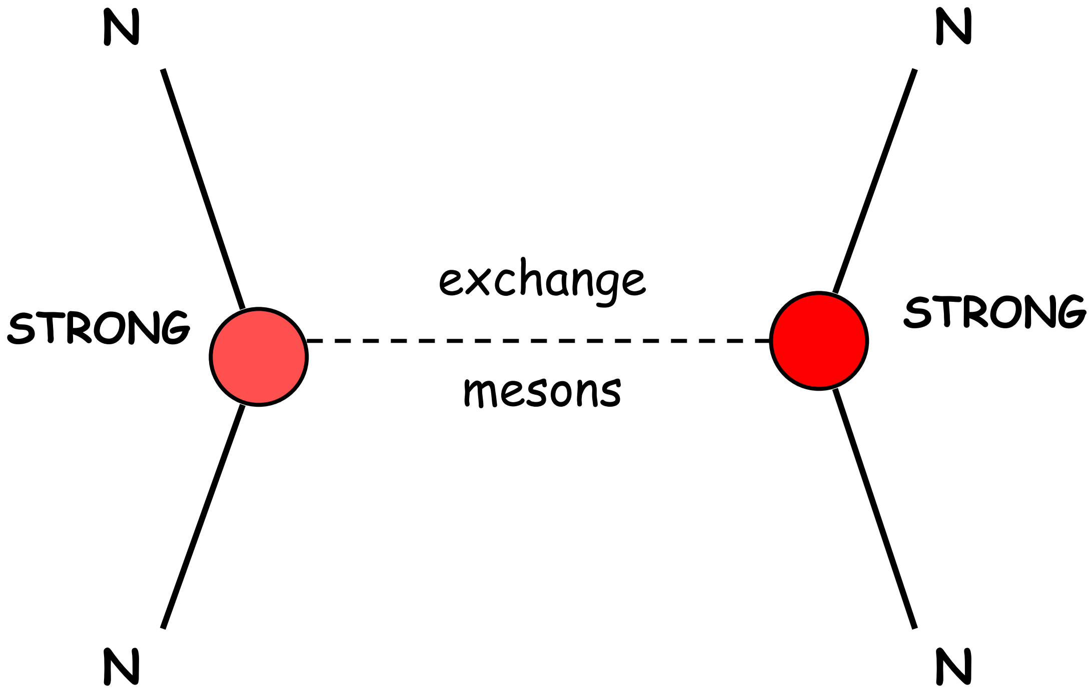
C.Gould, D.Haase, D.Markoff
North Carolina State University

E.Adelberger, B.Heckel, H.Swanson
University of Washington

Seminar Overview

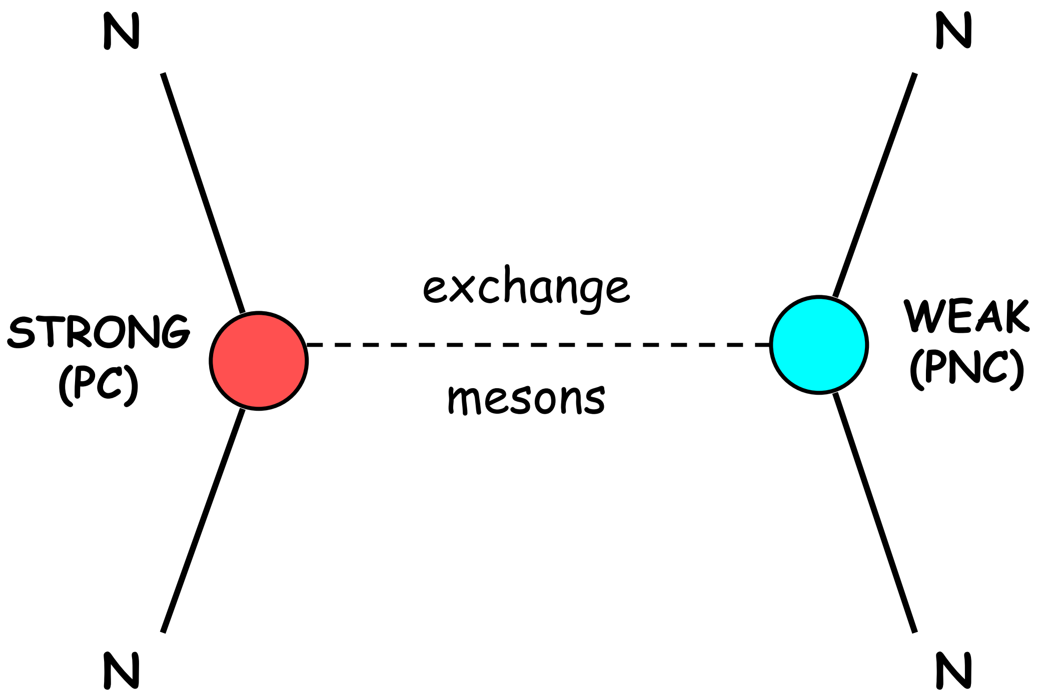
- Weak NN-Interaction and the Meson-Exchange Model
- Spin-Rotation Observable
- Experimental Apparatus
- Project Status

Nuclear Force: The Meson Exchange Model



- separation distance < 0.8 fm:
  - repulsive core best described by spin-spin interaction between constituent quarks
- separation distance > 2 fm:
  - one-meson exchange model yields excellent fit to data
- intermediate separation distances:
  - various parameters need to be fitted by hand to both types of models

Weak NN Interaction

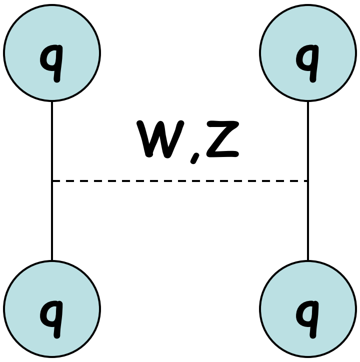


- Z, W are massive (effective range 10^{-3} fm)
  - the low energy weak interaction is essentially point-like

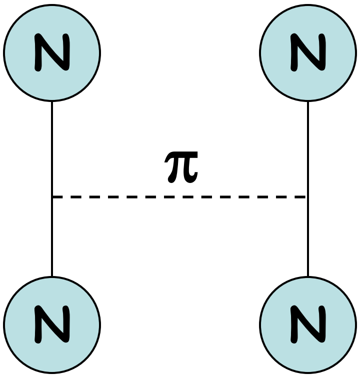
- NN-interaction is strongly repulsive at short distances:
  - essentially no direct weak interaction at low energies

- weak PNC potential characterized by weak meson exchange coupling constants
  - essentially all of the weak interaction physics is contained within the values of these coupling constants

How Big is the Effect?



$$a_W \approx \frac{e^2}{m_{W,Z}^2}$$



$$a_S \approx \frac{g_S^2}{m_\pi^2}$$

$$a_W \big/ a_S \approx \left(\frac{e^2}{m_{W,Z}^2}\right) \Big/ \left(\frac{g_S^2}{m_\pi^2}\right) \sim 10^{-7}$$

Which Mesons?

- At low energies, light mesons should dominate the PNC potential because of their longer ranges

- possible scalar and pseudoscalar exchanges are limited by Barton's theorem:
  - CP invariance forbids coupling between J=0 neutral mesons and on-shell nucleons

- p^6, r^0, r^6, and v^0 exchanges dominate the low energy PNC potential

- the weak meson exchange coupling constants:

$$f_\pi, h_r^0, h_r^1, h_\rho^2, h_\rho^{19}, h_v^0, h_v^1$$

Meson Exchange Coupling Constants

- theoretical calculations of these coupling constants limited by uncertainties with quark model
- 6 independent coupling constants require 6 independent experiments
- the number of parameters can be reduced to 2 combinations of the couplings that dominate the observables:

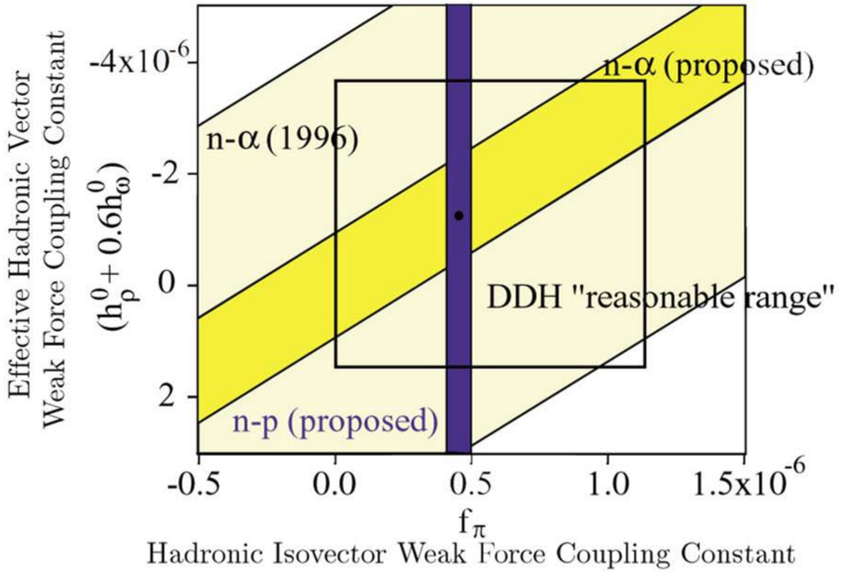
  f_π , and $(h_r^0 + 0.6\, h_v^0)$.
- experimental uncertainties are somewhat increased by allowing for variations of the four minor degrees of freedom:

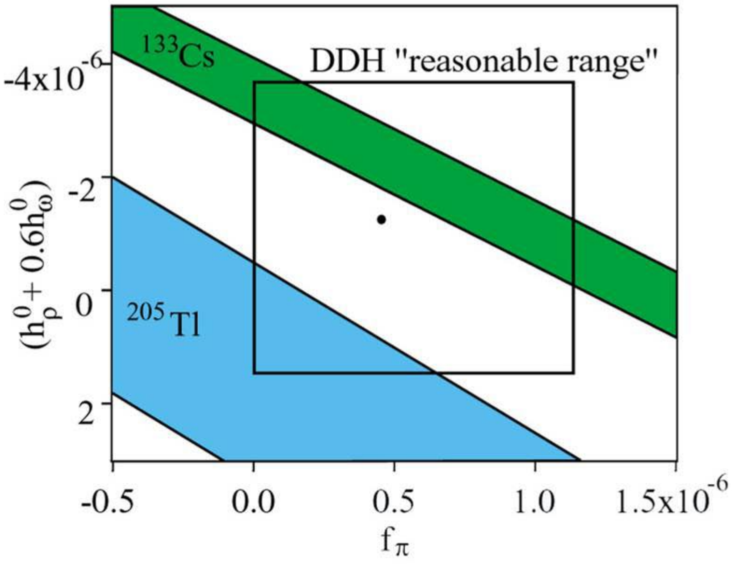
  h_r^1, h_ρ^2, h_v^1 and residual in h_v^0

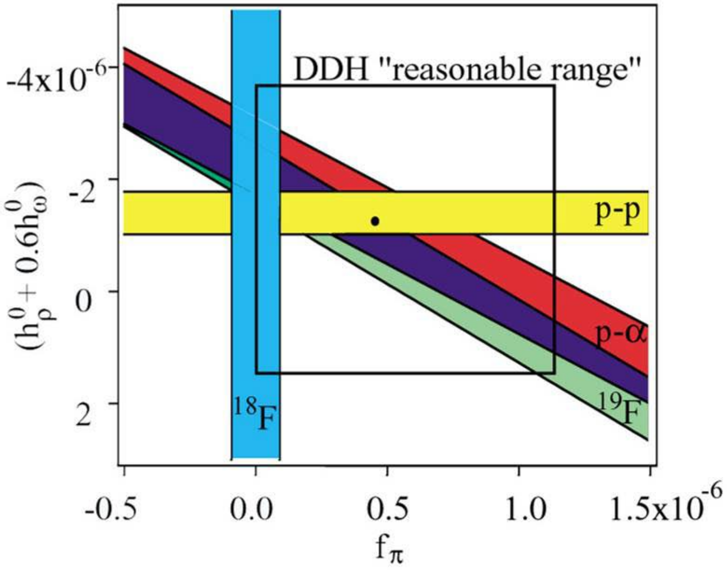
Weak meson-nucleon couplings constants

Coupling	Theoretical							Experimental	
	range **(DDH)**	“best value” **(DDH)**	value **(DZ)**	range **(FCDH)**	“best value” **(FCDH)**	value **(D)**	value **(KM)**	best fit	range
f_p	0 → 11.4	4.6	1.1	0 → 6.5	2.7	2.7	0.19	2.3	0 → 11
h_r^0	-31 → 11.4	-11.4	-8.4	-31 → 11	-3.8	-6.1	-1.9	-5.7	-31 → 11
h_r^1	-0.38 → 0	-0.19	0.38	-1.1 → 0.4	-0.4	-0.4	-0.02	-0.2	-0.4 → 0.0
h_r^2	-11.0 → -7.6	-9.5	-6.8	-9.5 → -6.1	-6.8	-6.8	-3.8	-7.6	-11 → -7.6
h_v^0	-10.3 → 5.7	-1.9	.308	-10.6 → 2.7	-4.9	-6.5	-3.8	-4.9	-10 → 5.7
h_v^1	-1.9 → 0.8	-1.1	.-2.2	-3.8 → -1.1	-2.3	-2.3	-1.0	-0.6	-1.9 → -0.8

Experimental Constraints on Weak Meson Exchange Constants

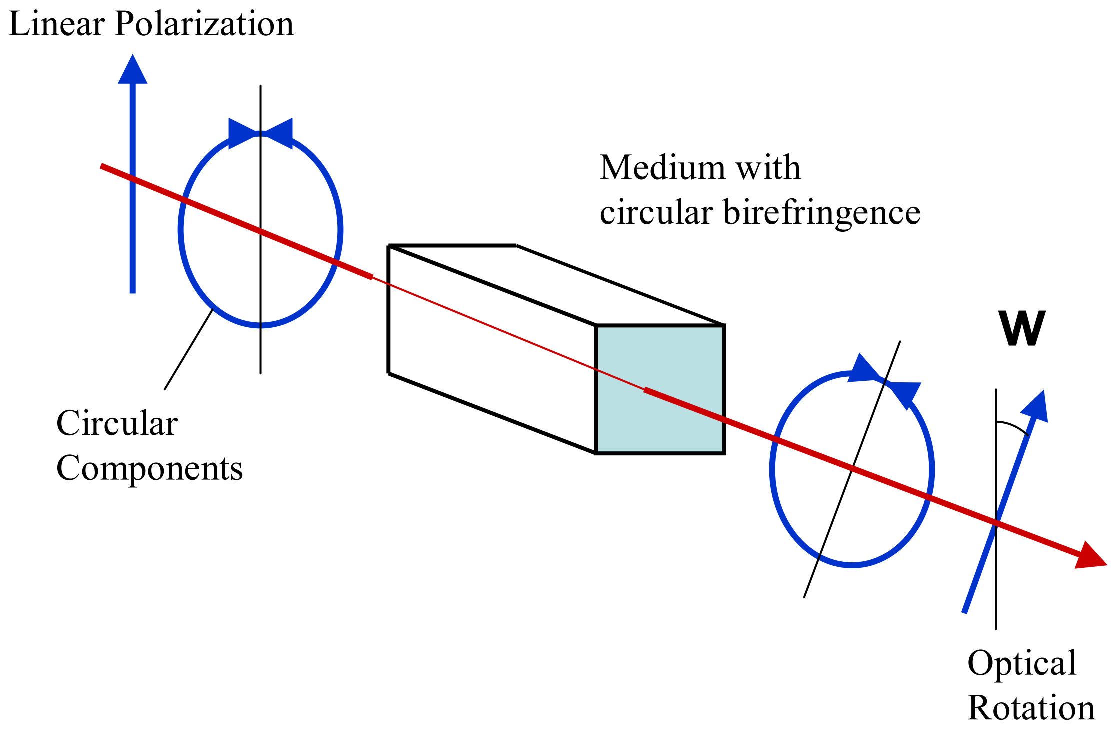






Optical Spin-Rotation

- polarized photons propagating through a "handed" medium undergo spin-rotation:



- cold neutrons propagating through spin-0 nuclei experience a similar rotation of the spin-polarization vector, but the "handedness" is the weak interaction

Neutron Optics

- long-wavelength neutron scattering is mostly s-wave and isotropic:

$$f(\theta) = f(0)$$

- coherent forward scattering amplitude for low-energy neutrons:

$$f(0) = A + B\vec{\sigma}_n \cdot \vec{S}_N + C\vec{\sigma}_n \cdot \vec{k}_n + D\vec{S}_N \cdot \vec{k}_n + E\vec{\sigma}_n \cdot (\vec{k}_n \times \vec{S}_N)$$

  - $\vec{\sigma}_n$ is the neutron spin
  - $\vec{k}_n$ is the neutron wave vector
  - $\vec{S}_N$ is the target nuclei spin

- index of refraction of a medium in terms of forward scattering amplitude:

$$\mathrm{n} = 1 + \left(\frac{2\pi}{k^2}\right)\rho f(0)$$

- the scattering potential contributes a phase to the neutron wave as it passes through a medium:

$$\begin{aligned}\phi &= \mathrm{Re(n)}k_0 z \quad \text{for} \quad \vec{k}_0 = k_0\hat{z} \\ &= \left(1 + \frac{2\pi}{k^2}\rho\, f(0)\right)k_n z\end{aligned}$$

Neutrons Traveling Through Helium

- ^{4}He is spin-0 $\Rightarrow \quad \langle \vec{S}_N \rangle = 0$

- so the coherent forward scattering amplitude becomes:

$$f(0) = A + C\vec{\sigma}_n \cdot \vec{k}_n = f_{PC} + f_{PNC}(\vec{\sigma}_n \cdot \vec{k}_n)$$

- the contributed phase for neutrons passing through ^{4}He:

$$\phi = \left(1 + \frac{2\pi}{k^2} \rho \left(f_{PC} + f_{PNC}(\vec{\sigma}_n \cdot \vec{k}_n) \right) \right) k_n z$$

$$\phi_{\pm} = \phi_{PC} \pm \phi_{PNC}$$

$$\phi_{PC} = \left(1 + \frac{2\pi\rho}{k^2} \rho \; f_{PC} \right) k_n z$$

$$\phi_{PNC} = 2\pi \, \rho \, z \, f_{PNC}$$

- so, the accumulated phase differs for opposite helicity states $\left(\pm \vec{k}_n \right)$

Spin Rotation Observable

- start with a transversely polarized neutron beam:

$$\langle \sigma_x \rangle = +1$$

- in the z-basis (beam direction) this is:

$$|x\rangle = \frac{1}{\sqrt{2}}|+\rangle + \frac{1}{\sqrt{2}}|-\rangle$$

- opposite helicity states accumulate <u>different</u> phases:

$$\frac{1}{\sqrt{2}}\left(e^{i\phi_{PC}} e^{i\phi_{PNC}}\right)|+\rangle + \frac{1}{\sqrt{2}}\left(e^{i\phi_{PC}} e^{-i\phi_{PNC}}\right)|-\rangle$$

- the Parity NonConserving rotation of the angle of transverse spin is the accumulated phase difference:

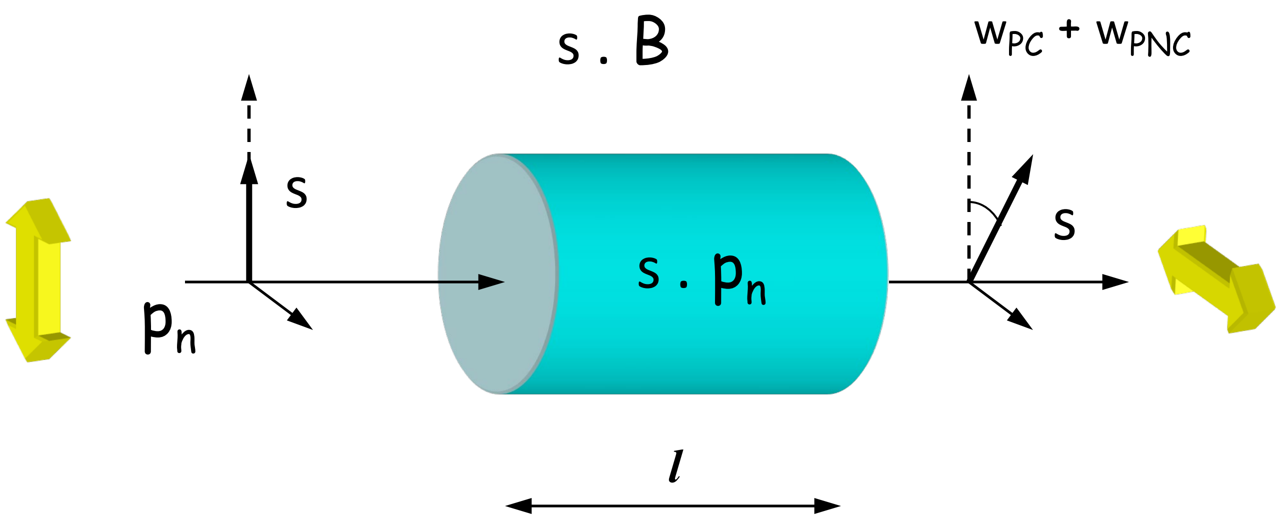
$$\varphi_{PNC} = \phi_+ - \phi_- = 2\phi_{PNC} = 4\pi\,\rho\,z\,f_{PNC}$$

- Dmitriev *et al.* calculated the spin rotation of (n+a) based on the meson coupling constants (DDH):

$$= -(0.97 f_\pi + 0.22 h_\omega^0 - 0.22 h_\omega^1 + 0.32 h_\rho^0 - 0.11 h_\rho^1 - 0.02 h_\rho'^1)$$

- using DDH best values, $\varphi_{PNC} = \left(-0.1 \pm 1.5\right) \times 10^{-6}\ \mathrm{rad/m}$

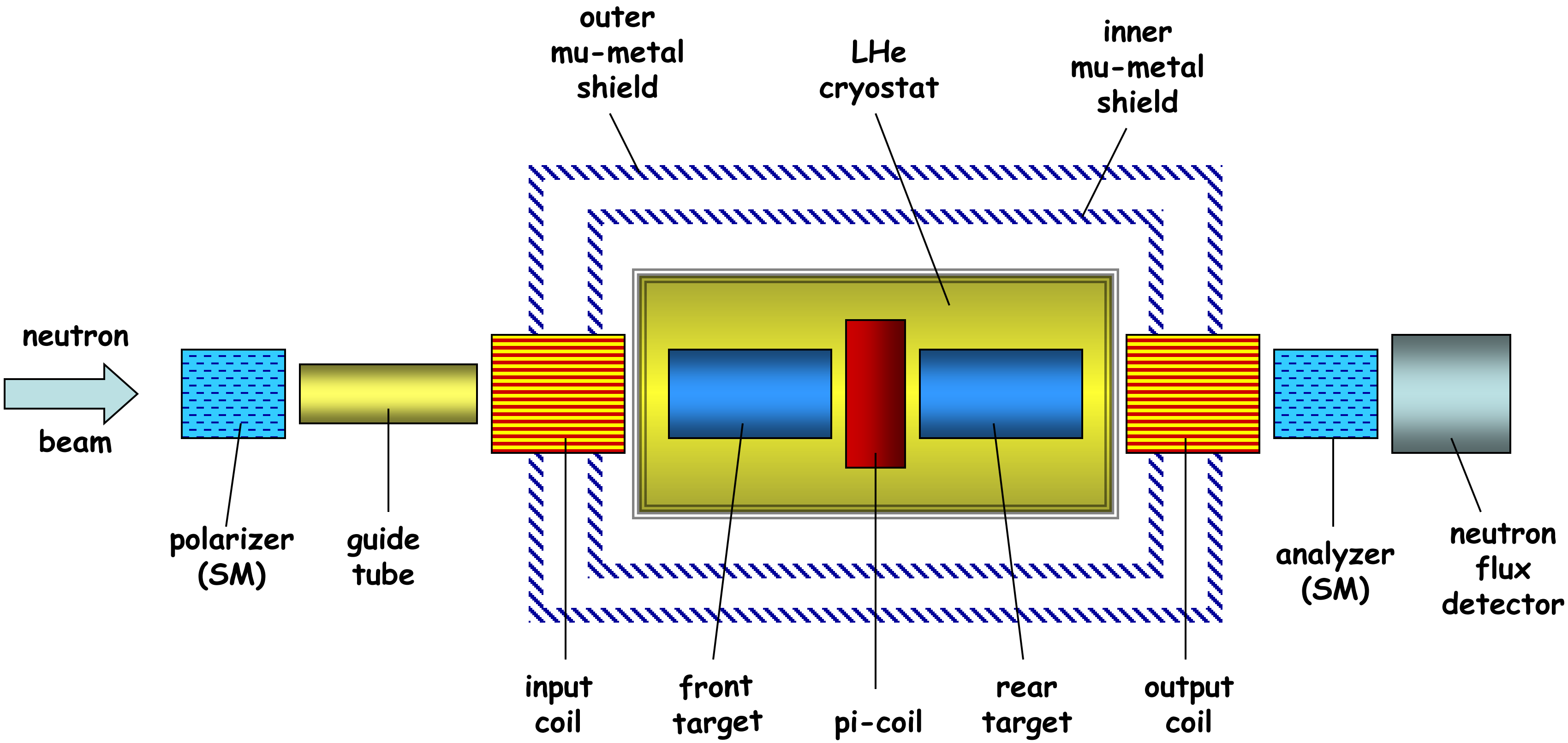
Experiment Concept



- cold neutrons are transversely polarized
- neutrons travel through a helium target
  - PNC spin-rotation
  - PC spin-rotation
    - background B-field in target region
- need to maximize PNC signal and minimize PC signal
  - B_{axial} = 0.5 Gauss ⇨ w_{MAG} ~ 10 rad/m,
  - magnetic shielding ⇨ B_{axial} < 100 mGauss
- neutrons enter the analyzer
  - transmitted neutron flux contains information about the PC and PNC spin-rotation
- goal of experiment:

  6 2 3 10^{-7} rad/m sensitivity

Experiment Overview



neutron beam

polarizer (SM)

guide tube

outer mu-metal shield

input coil

front target

LHe cryostat

pi-coil

rear target

inner mu-metal shield

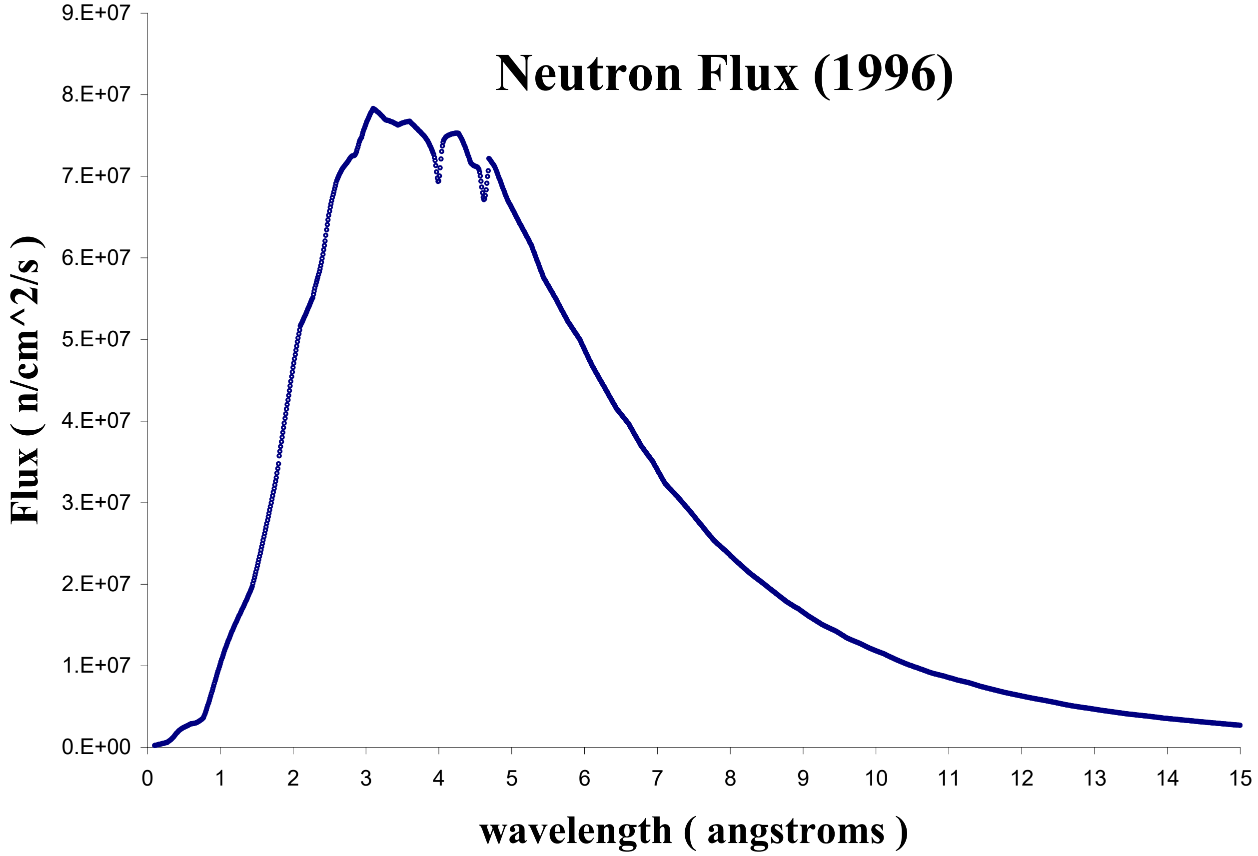
output coil

analyzer (SM)

neutron flux detector

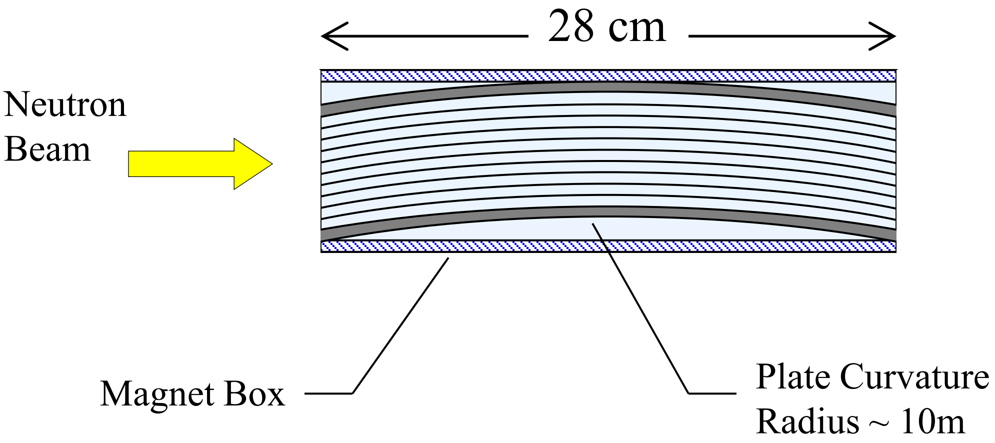
Neutron Beam

- NG-6 beamline at NIST (Gaithersburg, MD)
- energies in the 10^{-3} eV range (l ~ 5A)
- beryllium filters provide high-energy cut-off
  - essentially 0% transmission below 3.4A
  - approx. 4% between 3.4A and 3.9A
  - about 90% above 3.9A



Supermirror Polarizer and Analyzer

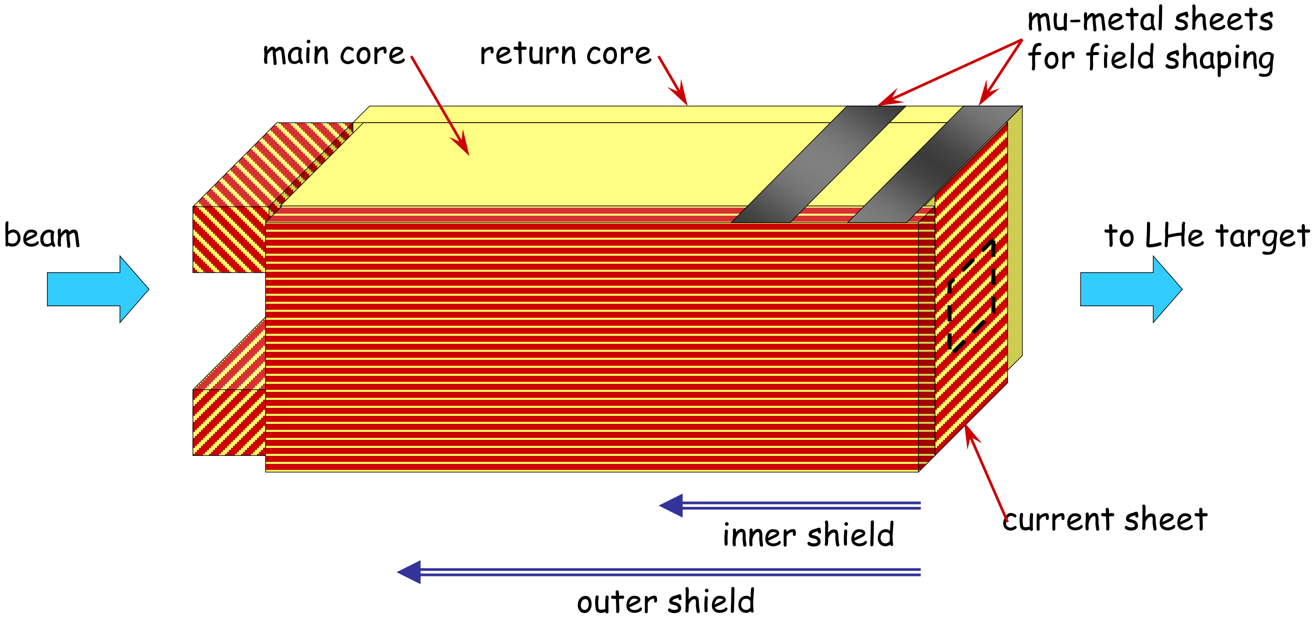
- neutrons are polarized through spin-dependent scattering from magnetized mirrors
- one spin-state is preferentially reflected by the mirror surface while the other state is transmitted and absorbed
- designed to pass neutrons with the “up” spin state in the vertical direction
- typical polarization: 98%



Input Coil

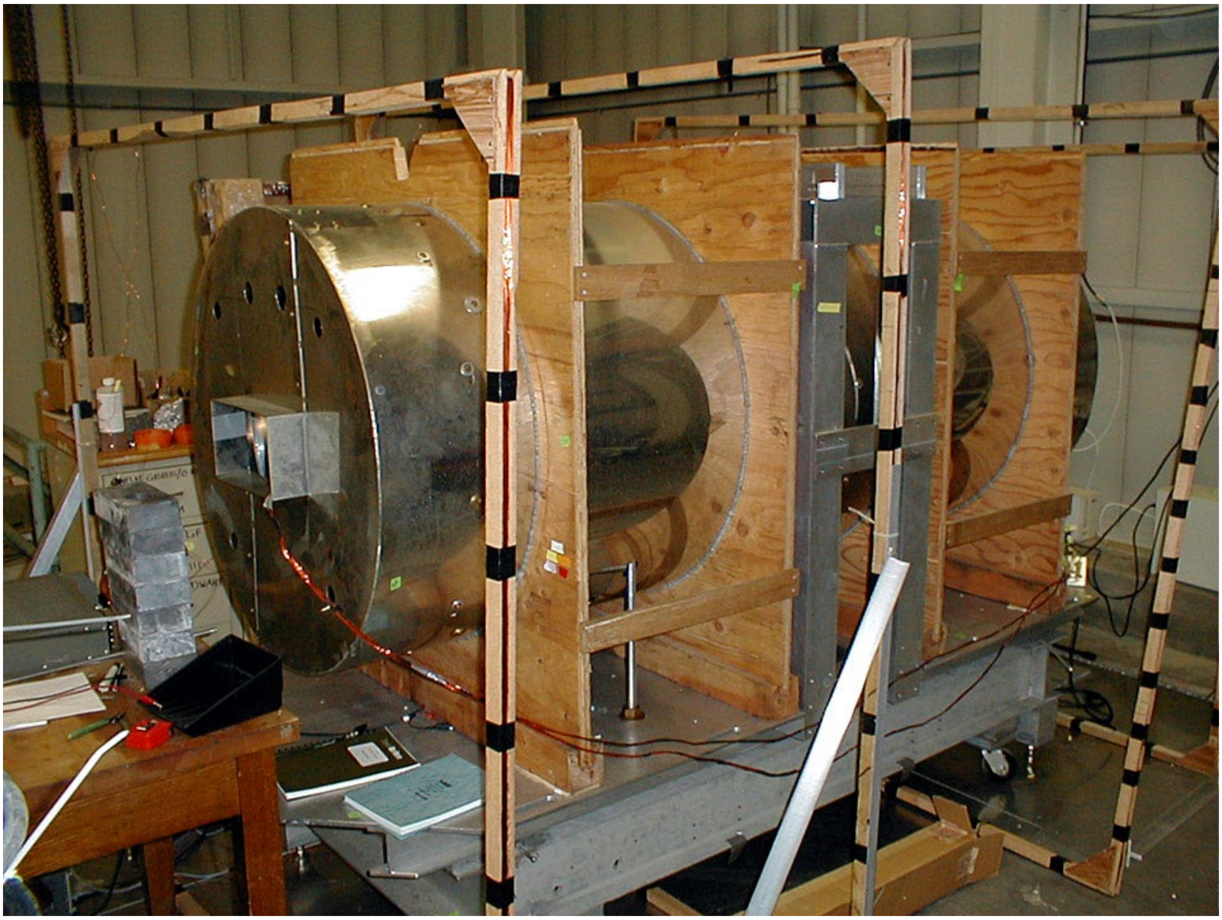
- spins precess about aligned vertical fields as the neutrons pass adiabatically through the input coil

- neutrons reach a current sheet at the back of the coil and pass non-adiabatically into the field-free region

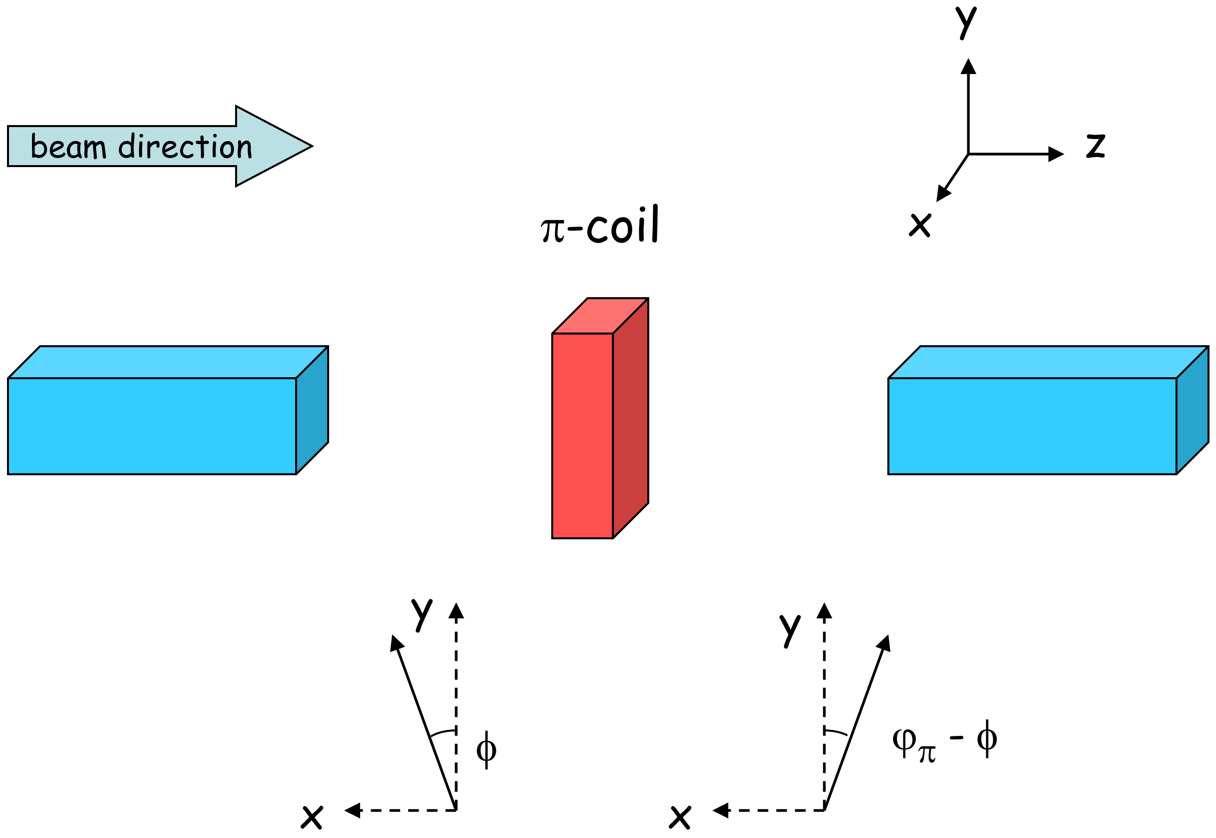


Magnetic Shielding

- mu-metal shielding surrounds the target region (including cryostat)
- solenoidal coils inside shielding further reduces any residual axial B-fields



π-coil

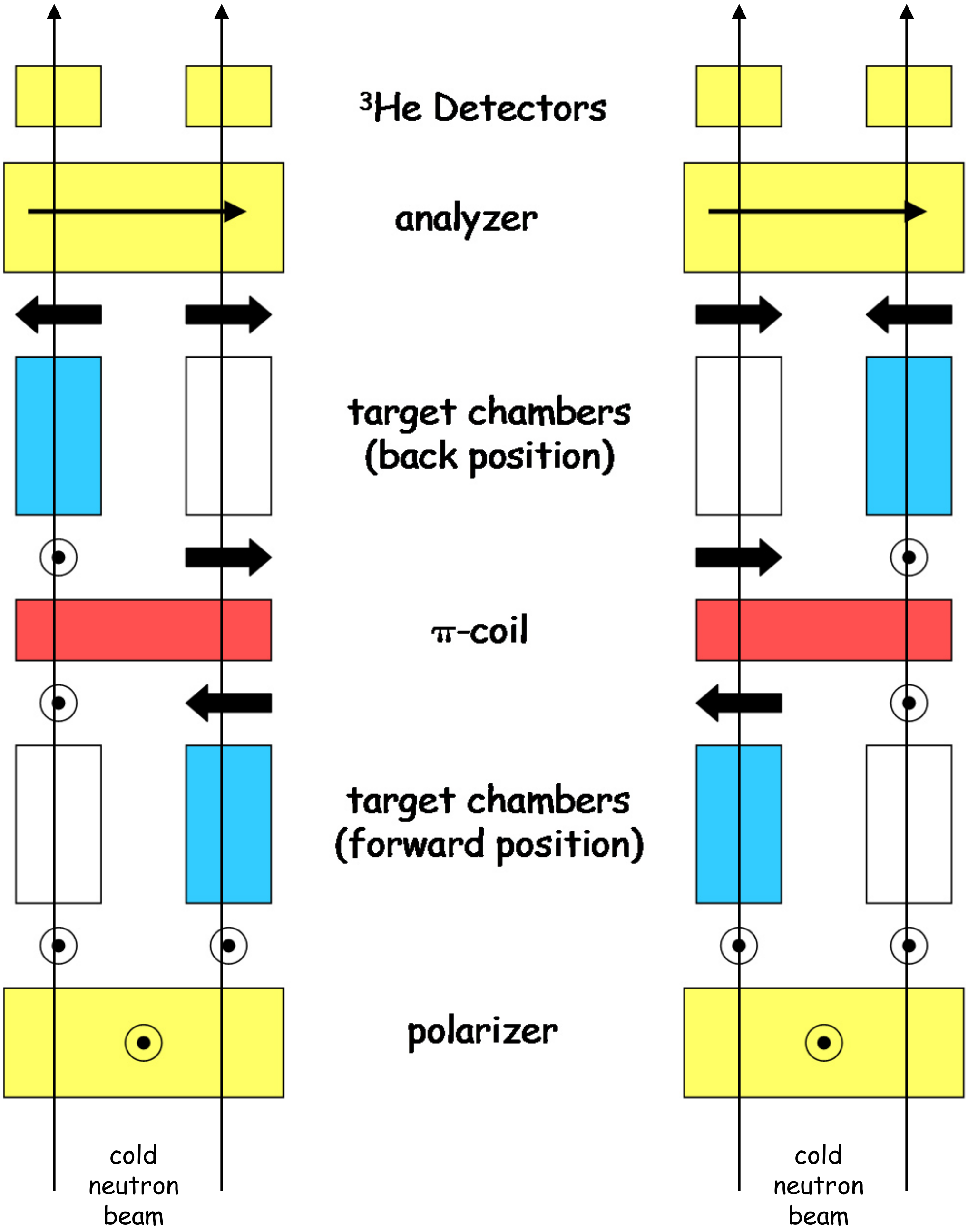


- a rectangular coil that produces a vertical magnetic field in the path of the beam

- wound to prevent field leakage beyond the coil

- designed so that the spin of a typical cold neutron will precess a total of π radians over the path of the coil

Helium Target and Operation



^{3}He Detectors

analyzer

target chambers
(back position)

π-coil

target chambers
(forward position)

polarizer

TOP VIEW

Output Coil

- neutron spins pass non-adiabatically through front of output coil
- transverse component of spin adiabatically rotated into a horizontal B-field (y-axis)
- the orientation of this (y-axis) B-field is flipped at a rate of ~ 1 Hz
- spins then adiabatically rotated into the vertical (x-axis) direction of the analyzer
- neutrons spins are now either parallel or antiparallel to the analyzer (depending on the target state and the orientation of the y-axis B-field)

^{3}He Neutron Detector

- neutrons detected through the following reaction:

$$n\ \mathbf{1}\ {}^{3}\mathrm{He} \rightarrow {}^{3}\mathrm{H}\ \mathbf{1}\ {}^{1}\mathrm{H}$$

- charged reaction-products ionize the gas mixture
- high voltage and grounded charge-collecting plates produce a current proportional to the neutron flux

Previous Version of Experiment (1996)

- reached a sensitivity of ~2.6×10^{-6} rad/day of accumulated data
- limited by statistics
- systematic limits of the apparatus not reached

$w_{PNC}(n,a)$ 5 (8.0 6 14[stat] 6 2.2[syst]) 3 10^{-7} rad/m

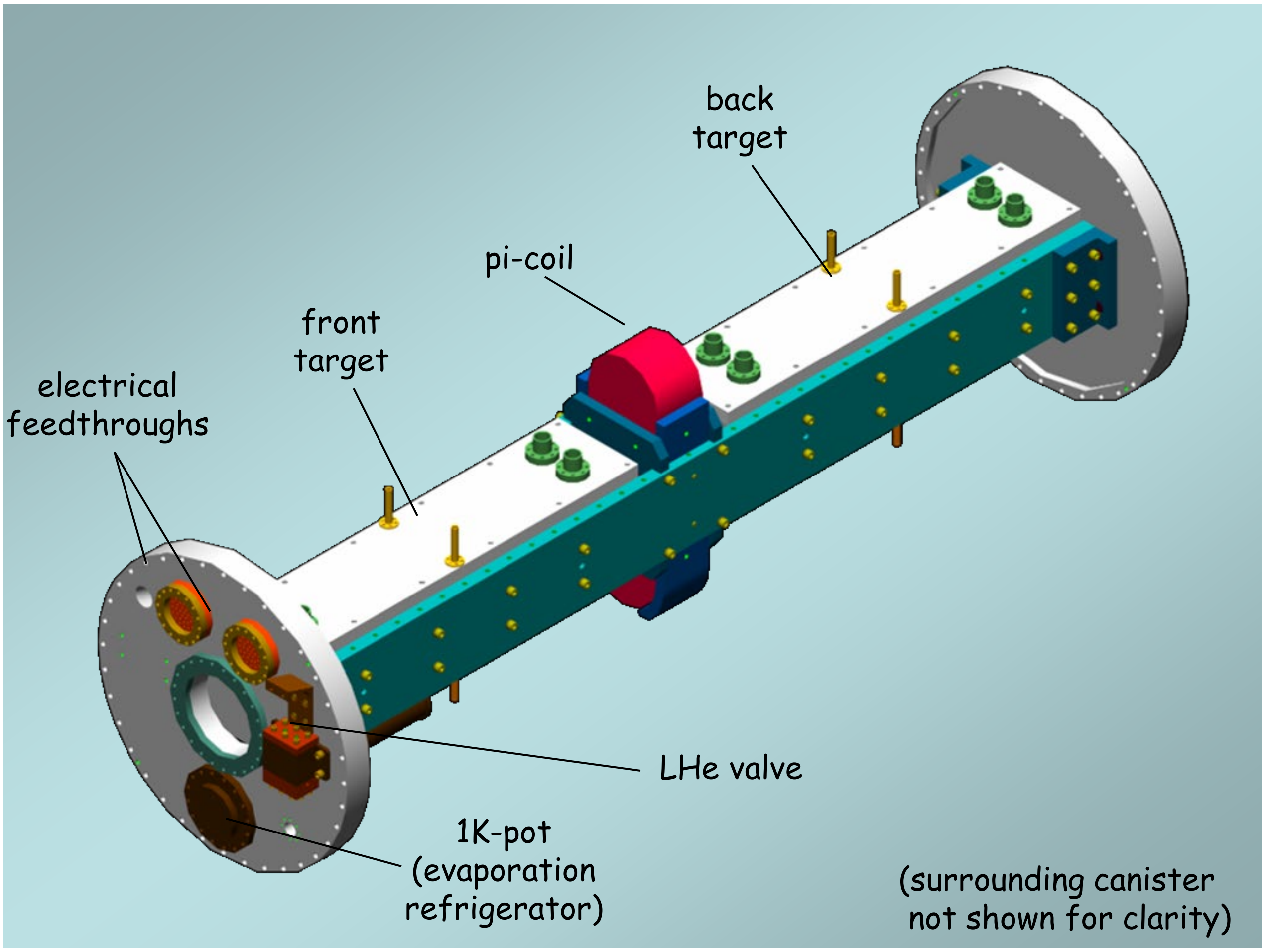
Redesign of Experiment

- increase available statistics by improving reliability and decreasing downtime
- increase the detected beam flux
  (NIST reactor upgrade: factor ~1.5)
- use of superfluid helium
- additional layer of mu-metal shielding
- want a factor of x10 higher sensitivity in order to obtain a non-zero / null result:
  ~ 0.6310^{-6} rad / day of accumulated data

estimate ~30 days of data for desired sensitivity

New Target

- use of superfluid helium (~1.7K)
  - lower temp requires additional refrigeration: 1K-Pot
  - superfluid leaktight
- non-magnetic and non-superconducting materials
  - stainless steel won't work
- new electrical feedthroughs (epoxy resin based)
- liquid helium valve



(surrounding canister not shown for clarity)

More Shielding

- installation of 3rd layer of magnetic shielding: Cryoperm-10
- preliminary B-field mapping inside all three nested shields:
  - measured ~50 mGauss in target region without solenoidal coils
  - previous version designed for 100 mGauss background
- want to further reduce this by 1/2 with trim coils

Current Status

- field mapping of in/output coils and magnetic shielding
- analysis of systematic effects
- computer simulations
- new target ready for machining
- machining of target components

- run at NIST in fall 2003