The NPDGamma Experiment

Probing the Hadronic Weak Interaction

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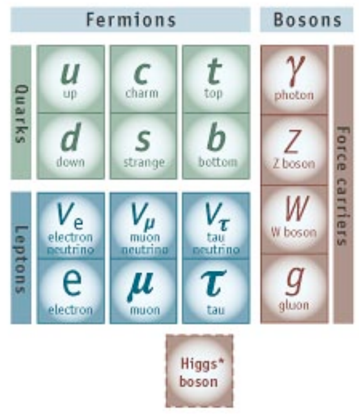
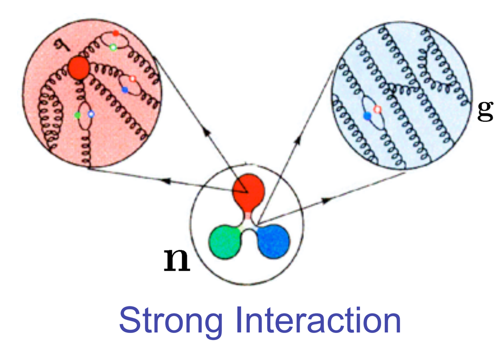
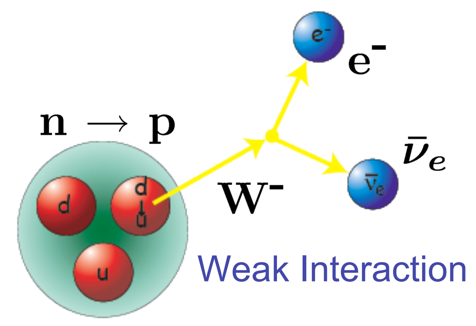
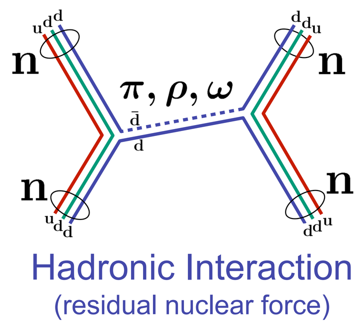
***Abstract**: Although QCD has had tremendous success in describing the strong interaction at high energy, the structure of nuclear matter remains elusive due to the difficulty of QCD calculations in the low energy frontier. Thus nuclear structure has typically been explored through electromagnetic interactions, like electron scattering. The hadronic weak interaction (HWI) is an attractive alternative because it involves only nucleons, but the weak component is short-range and precisely calculable at low energies. While the HWI is dominated by the strong force by a factor of 10^7, it can be isolated due to its unique property of parity violation (PV). NPDGamma is a precision experiment designed to measure the HWI coupling constant A_γ from the reaction* $n + p \rightarrow d + \gamma$.

The Standard Model





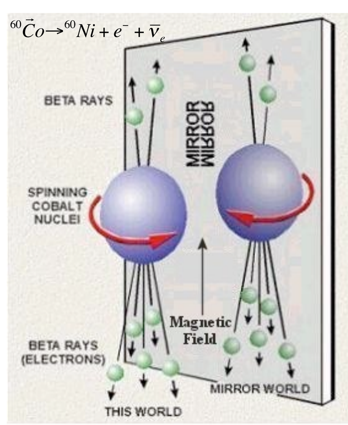




Matter is composed of quarks and leptons, which interact through the exchange of bosons (force carriers). The nuclear force (between neutrons and protons) is a residual effect of both the strong and weak interactions, and can be interpreted as the exchange of quark-antiquark pairs (π, ρ, ω-mesons).

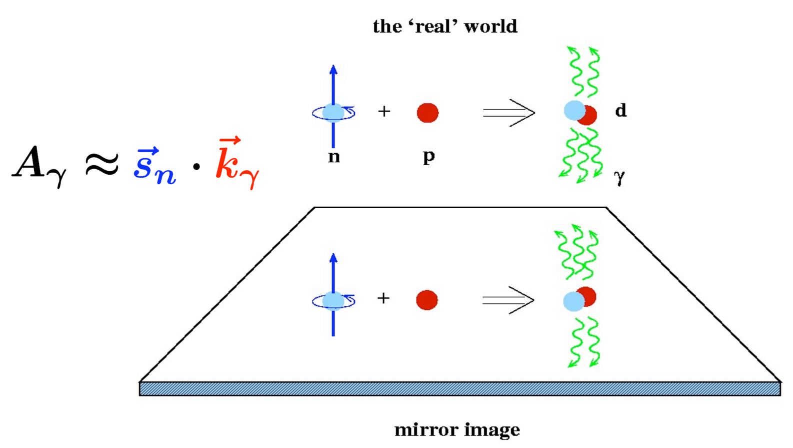
Parity Violation

The weak interaction is 10^7 times smaller than its strong counterpart. However, experiments can probe this small component of the hadronic interaction by observing a unique property of it, parity violation (PV). Weak interactions look different under spatial inversion (looking at them in a mirror.)



PV was discovered by C.S. Wu in 1957, by observing a correlation between the polarization of Co nuclei and the direction of beta emission.

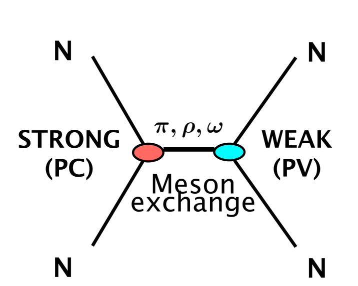
$$A_\gamma \approx \vec{s}_n \cdot \vec{k}_\gamma$$



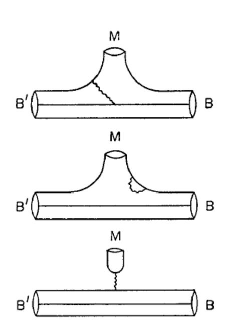
The goal of the NPDGamma experiment is to isolate the **hadronic weak interaction** (HWI) in neutron-proton capture, by observing a PV asymmetry in the emission of gamma rays. The gamma momentum is a vector, which changes direction under parity inversion. But spin is a pseudo-vector, and remains unchanged. Therefore, the correlation between these two quantities changes sign under parity inversion (violates parity).

Hadronic Weak Couplings

In the DDH meson exchange model, the strength of the HWI is specified by coupling constants at the vertex where (when) an exchange meson is emitted or absorbed. The fundamental weak interaction occurs at the vertex (shown by wavy lines in three vertices illustrated below). There are six unique couplings characterized by the type of meson exchanged and details of the vertex.



$$\frac{e^2}{M_W^2} \Big/ \frac{g^2}{m_\pi^2} \approx 10^{-7}$$



Cabibbo model	Reasonable range	"Best" value
f_π	$0 \rightarrow 1$	0.5
h_ρ^0	$15 \rightarrow -64$	−25
h_ρ^1	$0 \rightarrow -0.7$	−0.4
h_ρ^2	−58	−58
h_ω^0	$6 \rightarrow -22$	−6
h_ω^1	$0 \rightarrow -2$	−1

Amplitudes are in units of $g_\pi = 3.8 \times 10^{-8}$.

Different hadronic nuclear reactions have varying sensitivity to each coupling. The goal of the HWI program is to measure enough different reactions to solve for each of the coupling constants.

	np A_γ	nD A_γ	np ϕ	nα ϕ	pp A_z	pα A_z
f_π	-0.11	0.92	-3.12	-0.97		-0.34
h_ρ^0		-0.50	-0.23	-0.32	0.08	0.14
h_ρ^1	-0.001	0.10		0.11	0.08	0.05
h_ρ^2		0.05	-0.25		0.03	
h_ω^0		-0.16	-0.23	-0.22	0.07	0.06
h_ω^1	-0.003	-0.002		0.22	0.07	0.06

n-capture spin rotation elastic scattering

$n + p \rightarrow d + \gamma$

$$A_\gamma = -0.11\ f_\pi + -0.001\ h_\rho^1 + -0.003\ h_\omega^1$$

For example, the NPDGamma PV asymmetry is almost exclusively sensitive to f_π, the long range pion coupling constant.

Properties of the Neutron

The neutron has zero net charge, eluding common nuclear physics techniques such as particle acceleration, beam optics, tracking, and magnetic spectrometry. In addition, the 15 minute lifetime makes free neutron targets impractical. However, it has a magnetic dipole moment and internal charge distribution. Ultra cold neutrons can be confined by various potentials.

Physical Properties

m_n = 939.6 MeV/c^2
= $m_p + m_e$ + 782 keV
τ_n = 885.7 ± 0.8 s
r_m = 0.889 fm

$q_n < 2 \times 10^{-21}$ e
$d_n < 3 \times 10^{-26}$ e cm
μ_n = -1.91 μ_N

Neutron Energy Spectrum

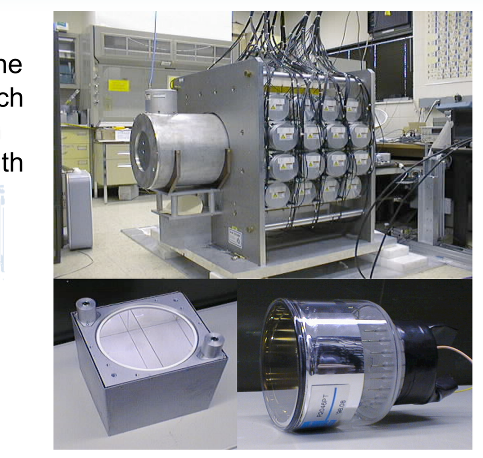
> .1 MeV	fast	produced in reactors
25 meV	thermal	moderated at room temp.
< 25 meV	cold	can be guided
<200 neV	ultracold	can be trapped

Ultracold Neutron Potentials

nuclear	335 neV	(^{58}Ni)
magnetic	60 neV	(1 Tesla)
gravitational	102 neV	(1 meter)

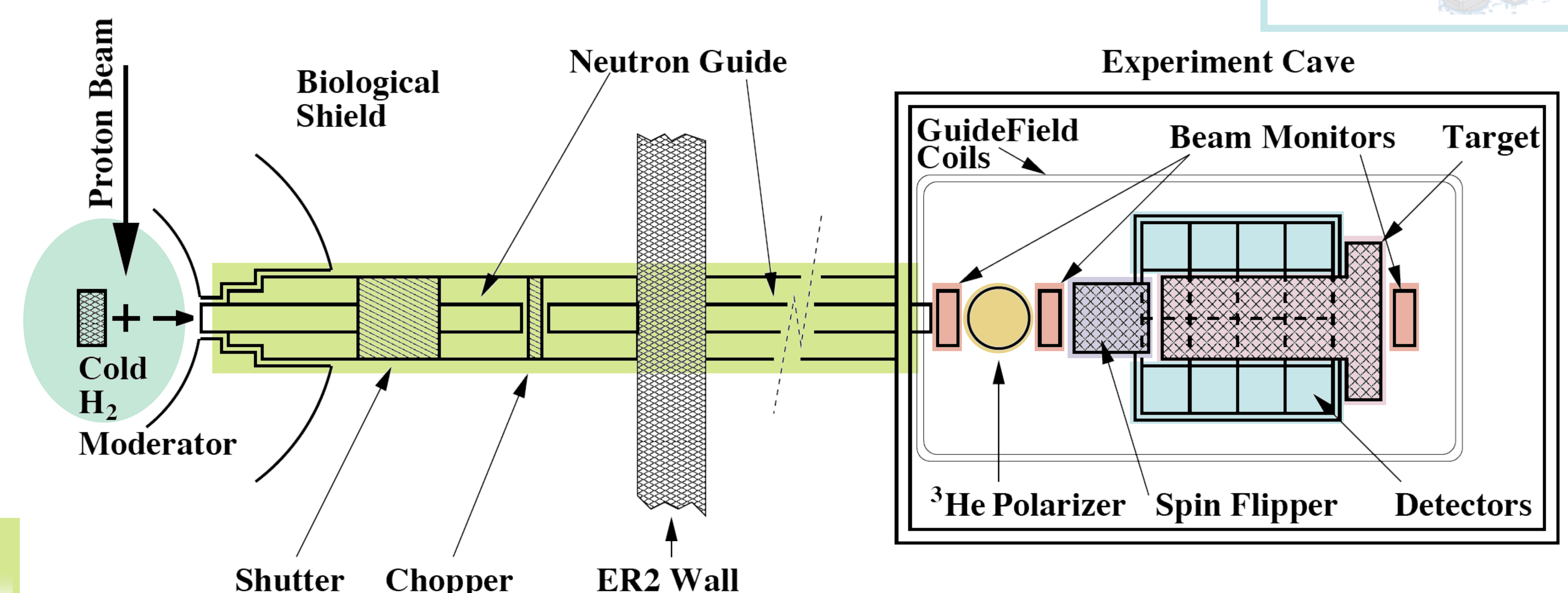
CsI Gamma Detectors

48 CsI scintillators, grouped in 4 rings around the target, detect 72% of the γ's produced. The light is collected in vacuum photo-diodes, which are insensitive to stray RF fields from the spin flipper. They are read out in current mode (with counting statistics sensitivity) to handle high count rate of 50 MHz.



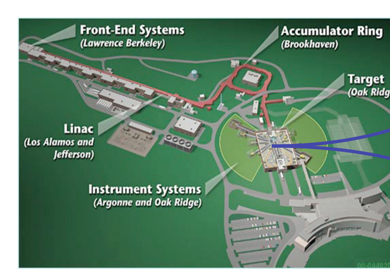
Experimental Setup

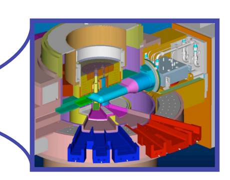
To measure the correlation between the neutron spin and the direction of emitted gammas, three components are needed: a) an intense source of polarized neutrons (~10^{17} neutrons), b) a liquid hydrogen target; and c) gamma detectors capable of measuring $\delta A \sim 10^{-8}$.



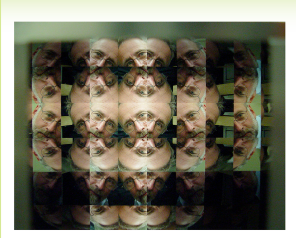
Spallation Neutron Source

An intense neutron beam is produced by pulsing a high energy proton beam on a mercury target. The 60 Hz pulse structure gives timing information to determine the neutron energy. The neutrons are moderated in liquid hydrogen before being guided to the NPDGamma experiment and other neutron instruments at the SNS.





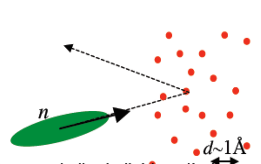
Neutron Guide



A rectangular guide preserves the intensity, reflecting neutrons by the repulsive nuclear potential. Neutrons with small transverse velocity (8 m/s) have a large enough wave packet to feel the effective repulsion of many nuclei near the point of reflection.

Fermi pseudopotential

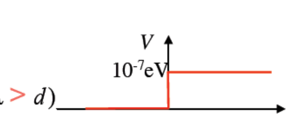
$$V(\mathbf{r}) = \frac{2\pi\hbar^2}{m_n} b\delta(\mathbf{r}-\mathbf{r}_0) \qquad b = b_{coh} + ib_{abs}$$



When $\lambda_n > d$, neutron scatters from many atoms/nuclei at once: similar to light scattering from transparent or metallic surfaces: reflection & refraction

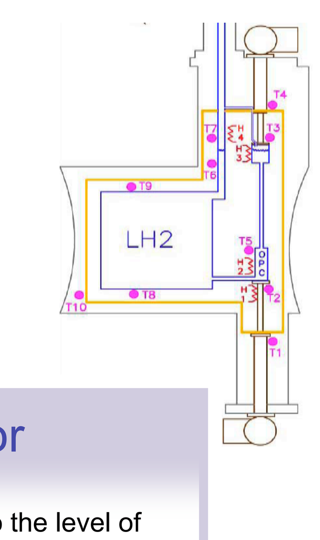
⇒Potential of wall

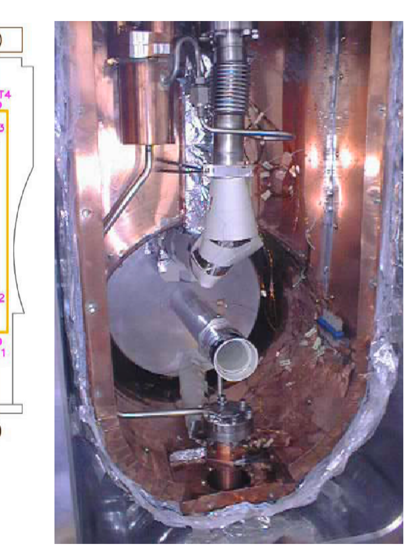
$$V(\mathbf{r}) = \frac{2\pi\hbar^2}{m_n} \sum_j b_j \delta(\mathbf{r}-\mathbf{r}_j) = u_0\theta(x) \quad (\lambda > d)$$



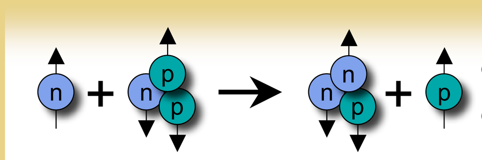
LH$_2$ Target

The proton target is 16 liters of LH_2 cooled to 17 K. The liquid hydrogen is circulated through a catalyst which converts ortho-H_2 to para-H_2. Para-hydrogen preserves the polarization of cold neutrons (E_n < 15 meV).



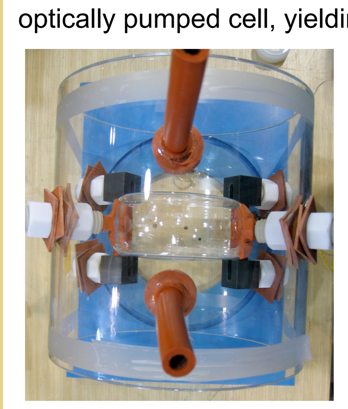


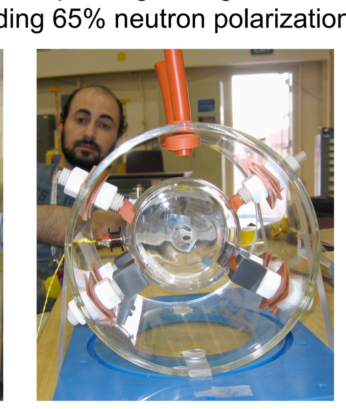
^{3}He Neutron Polarizer



$\sigma_{J=0}$ = 5333 b λ/λ_0
$\sigma_{J=1}$ = 0

Neutrons with spin anti-parallel to the polarization of the ^{3}He nuclei are absorbed when passing through an optically pumped cell, yielding 65% neutron polarization.





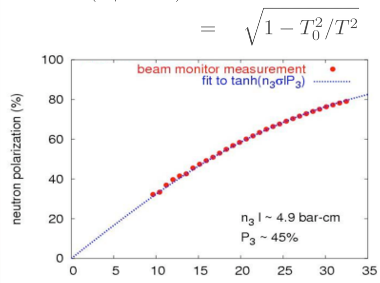
Neutron Beam Monitors

The polarization is monitored as a function of neutron energy by measuring transmission through the ^{3}He cell via ^{3}He ion chambers before and after the cell.

$$T_\pm = e^{-nl\sigma(1\mp P_3)} \qquad T_0 = e^{-nl\sigma}$$

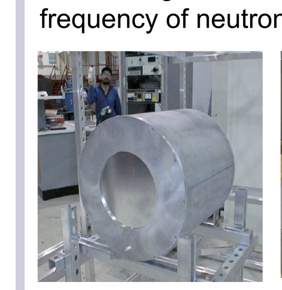
$$T \equiv \tfrac{1}{2}(T_+ + T_-) = T_0 \cosh(nl\sigma P_3)$$

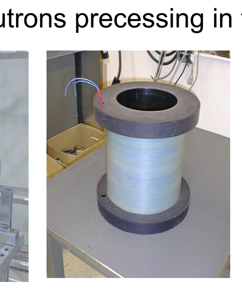
$$P \equiv \frac{(T_+ - T_-)}{(T_+ + T_-)} = \tanh(nl\sigma P_3) = \sqrt{1 - T_0^2/T^2}$$

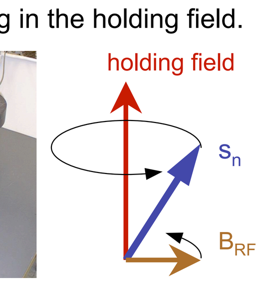


RF Spin Rotator

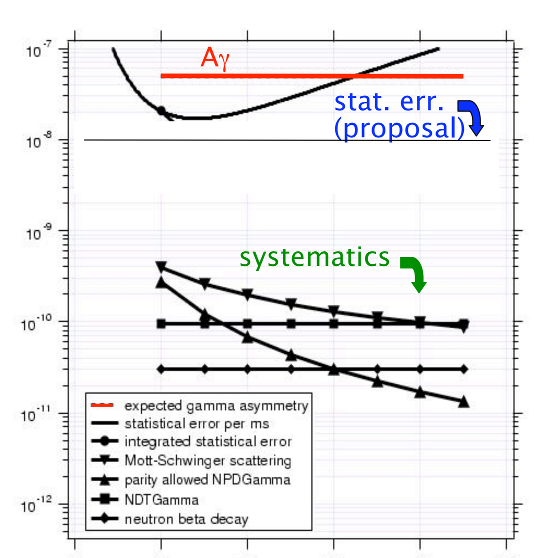
Instrumental drifts must be controlled to the level of $\delta A_\gamma \sim 10^{-8}$. This is accomplished by alternating the neutron spin on a pulse by pulse basis. The spin is flipped using an NMR technique: it precesses around the rotating B-field of an RF coil, tuned to the Larmor frequency of neutrons precessing in the holding field.







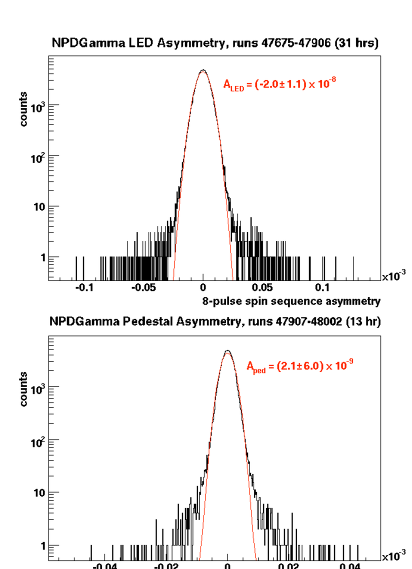
Systematic Uncertainties



Although the weak interaction is the only physical process which violates parity, there are other physically allowed processes which may mimic PV effects in the detector, for example:

- activation of materials (cryostat windows)
- Stern-Gerlach steering in B-field gradients
- PC asymmetries mixed in PV angular distribution (Mott-Schwinger, np elastic scattering, PC np→dγ)
- Compton scattering of circularly polarized gammas

Each of these effects were calculated and shown to be small compared to the projected statistical accuracy. Both background and multiplicace instrumental false asymmetries are monitored by taking asymmetries from background noise and from simulated signals.



Results

The NPDGamma apparatus was commissioned during 2004-2005 at LANSCE (Los Alamos National Lab). A series of engineering runs tested PV backgrounds from beamline materials and in other physically interesting nuclei. In 2006, the $n + p \rightarrow d + \gamma$ asymmetry A_γ was measured at a level comparable with previous world limit. Data analysis is in progress. The experiment is currently being installed at a ten times more intense beamline at the SNS, (Oak Ridge National Lab), where we project to measure A_γ with an uncertainty of $dA_\gamma = 10^{-8}$. At this level we expect to observe a statistically significant nonzero result.

Material	A_γ ($\times 10^{-6}$)	
Engineering:		
Cl	−21.	± 1.6
Cu	−1.	± 3.
B_4C	−1.	± 2.
Al	−0.00	± 0.30
In	−0.68	± 0.30
LEDs	−0.0477	± 0.0603
Noise	~ 0.001	
Physics:		
Mn	0.53	± 0.78
V	0.24	± 0.45
Ti	0.41	± 0.36
Co	0.61	± 0.31
Sc	−1.04	± 0.25