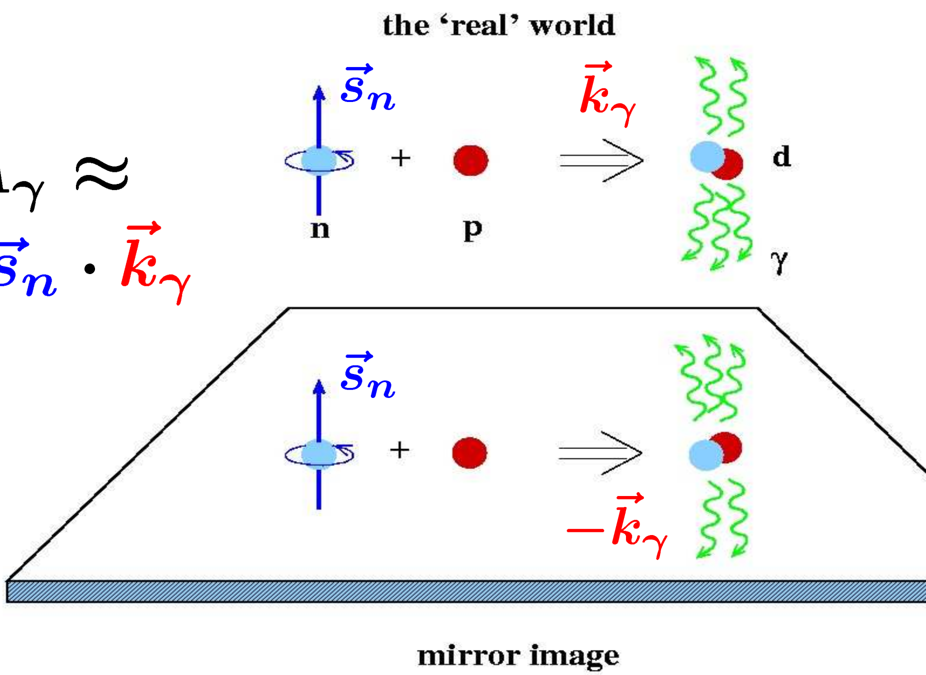
Parity Violation and the Neutron

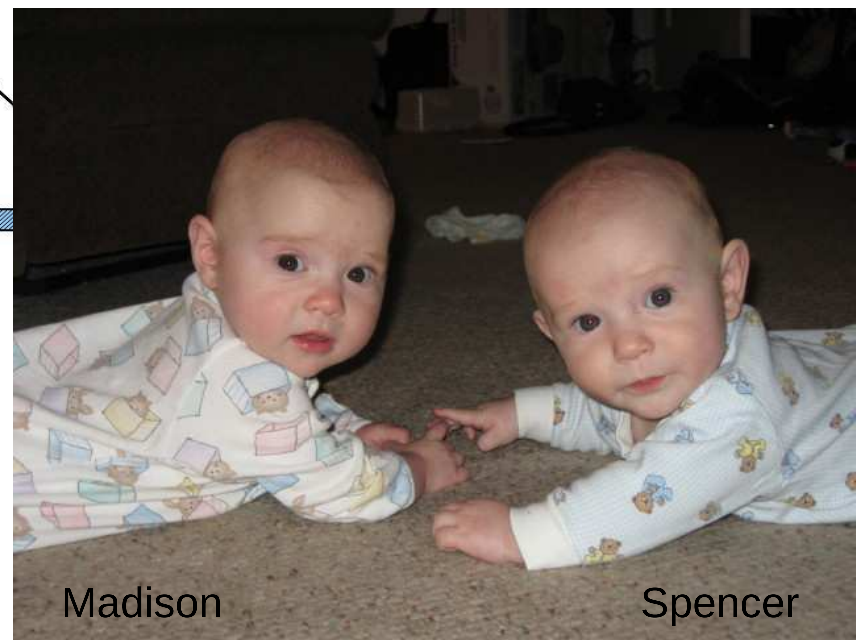
Christopher Crawford
University of Tennessee

2007-03-26

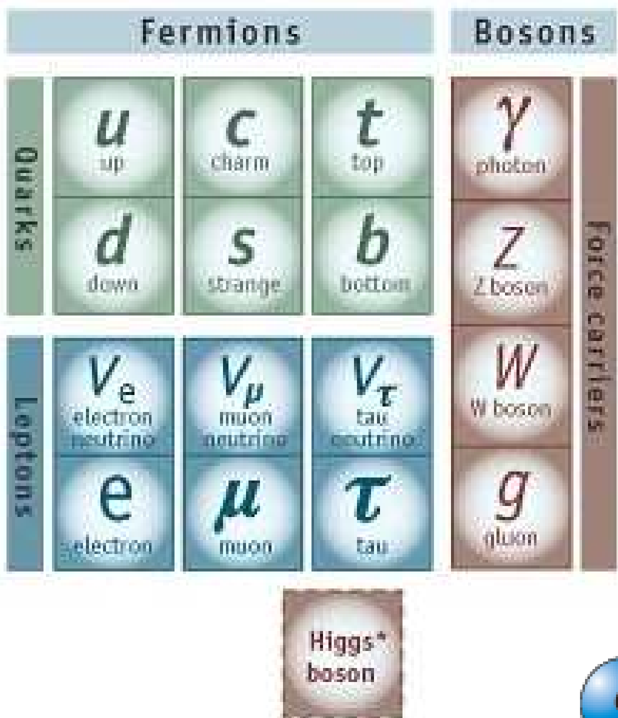
$$A_\gamma \approx \vec{s}_n \cdot \vec{k}_\gamma$$

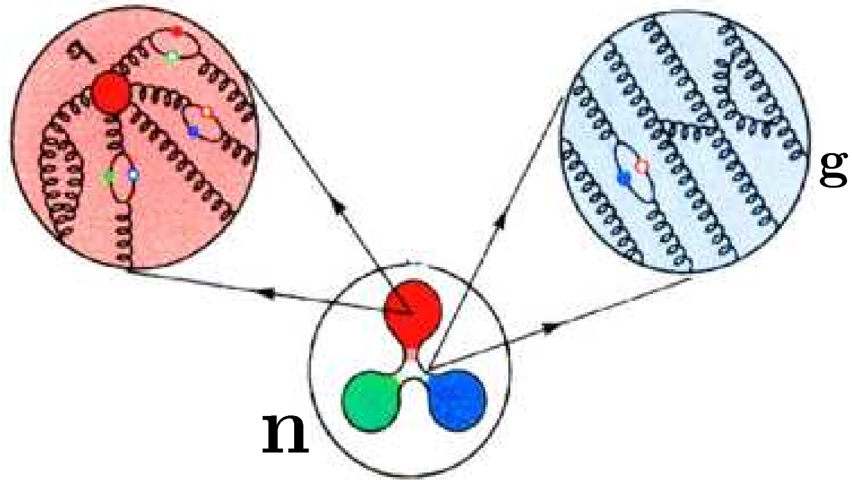


- symmetries and interactions
- properties of the neutron
- the NPDGamma experiment

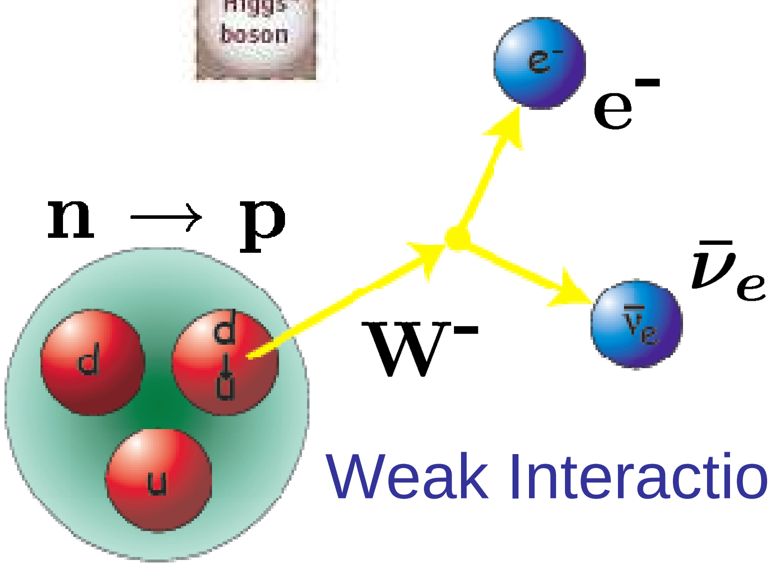


Standard Model of Particles

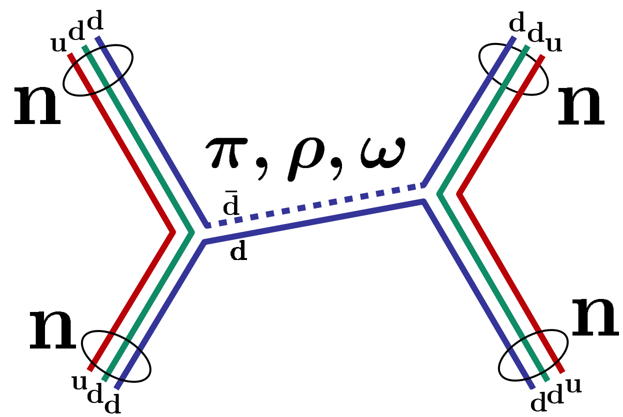




Strong Interaction



Weak Interaction



Hadronic Interaction
(residual nuclear force)

Standard Model of Automobiles

Degenerate Fermi Gas

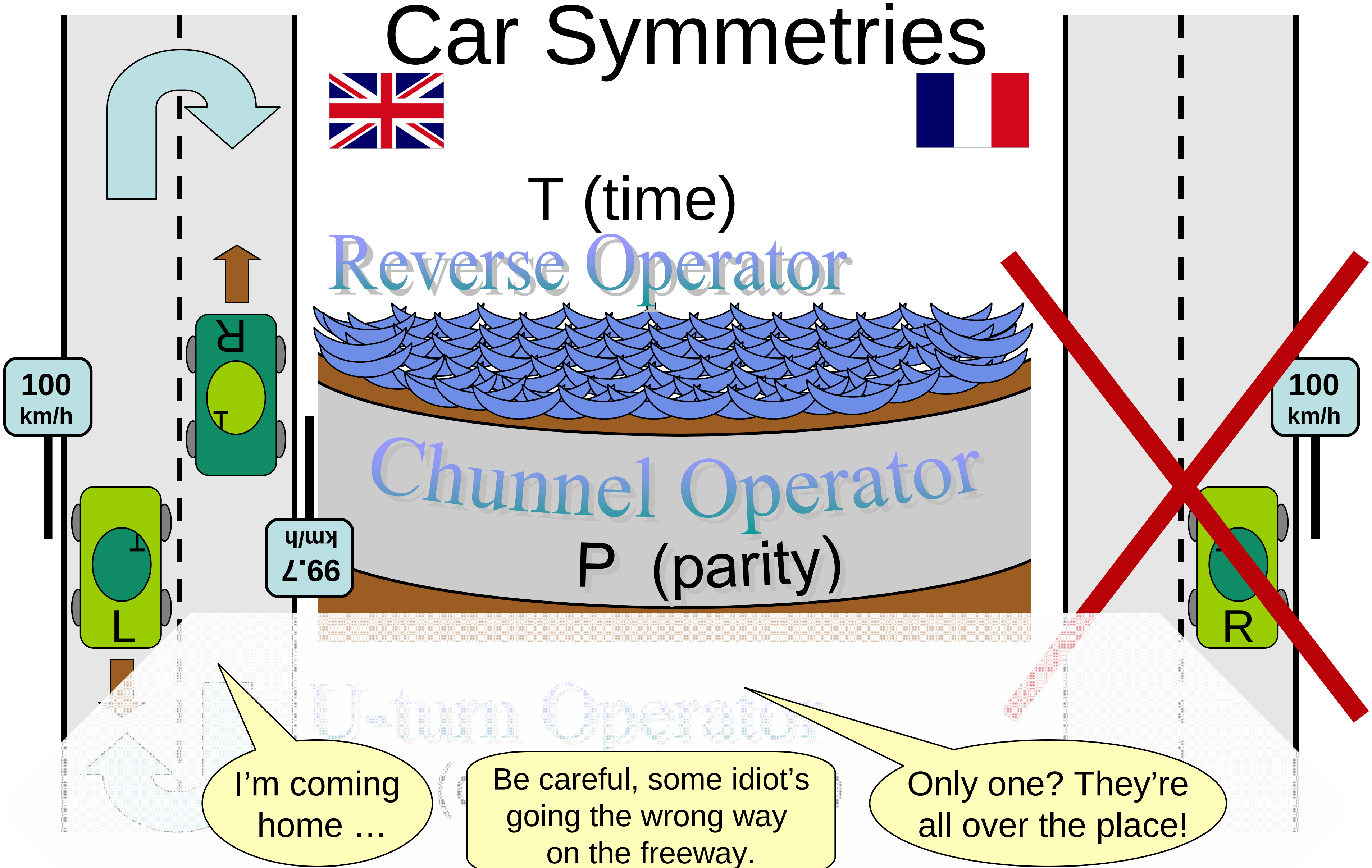
Annihilation

Higgs?

Particle Decay

QuickTime™ and a
decompressor
are needed to see this picture.

Car Symmetries



CPT theorem: ALL laws are invariant under CPT

Parity-violation in weak interaction (1956)

Parity-transformation (P) : $\vec{r} \rightarrow -\vec{r}$

T. D. Lee

C. N. Yang

October 1, 1956 issue of the Physical Review

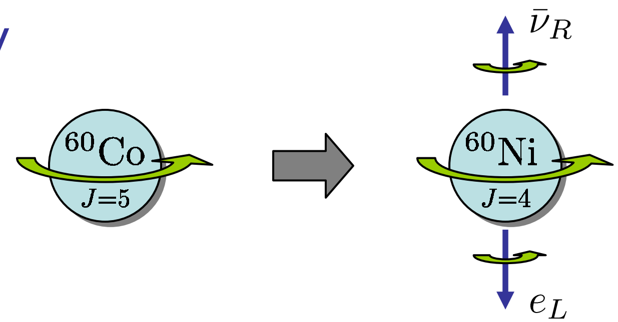
History of Parity Violation

- 1956: Lee & Yang postulated PV
  to explain τ-θ puzzle

$$|K_S^0\rangle = \frac{1}{\sqrt{2}}\left\{|K^0\rangle - |\bar{K}^0\rangle\right\}$$
$$|K_L^0\rangle = \frac{1}{\sqrt{2}}\left\{|K^0\rangle + |\bar{K}^0\rangle\right\}$$

- 1957: Wu *et al.* observed PV
  in pol. ^{60}Co beta decay

$$\vec{J} \cdot \vec{k}_e$$



- 1964: Cronin & Fitch *et al.* observed CPV
  in the K_L, K_S system

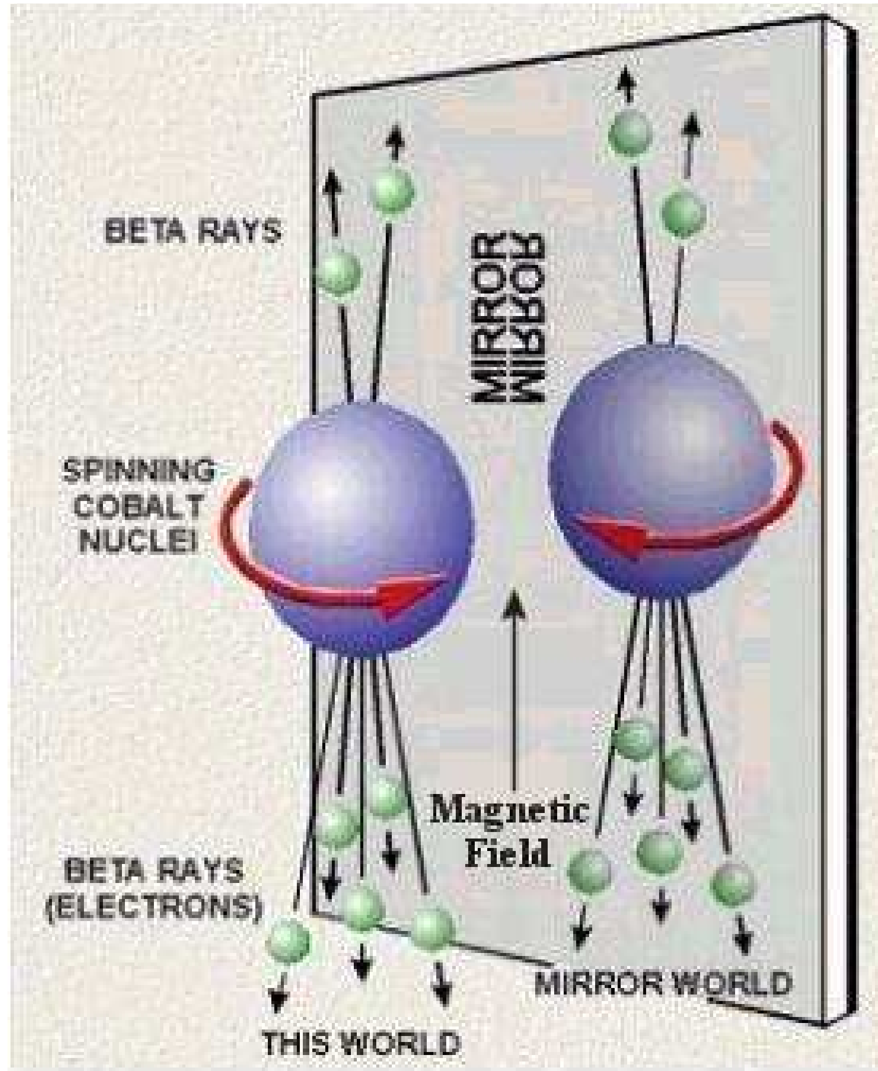
$$\text{B.R.}(\ K_L^0 \rightarrow \pi + \pi\ ) = 0.28\%$$

$$\frac{K_L^0 \rightarrow e^+ + \pi^- + \nu}{K_L^0 \rightarrow e^- + \pi^+ + \bar{\nu}} = 1.00668(28)$$

- 1951: Julian Schwinger: CPT theorem (based on Lorentz invariance)

$$^{60}\vec{Co} \rightarrow {}^{60}Ni + e^- + \overline{\nu}_e$$

Madame C.S. Wu



History of Parity Violation

- 1956: Lee & Yang postulated PV
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$$|K_S^0\rangle = \frac{1}{\sqrt{2}}\left\{|K^0\rangle - |\bar{K}^0\rangle\right\} \qquad \tau{=}K_S$$
$$|K_L^0\rangle = \frac{1}{\sqrt{2}}\left\{|K^0\rangle + |\bar{K}^0\rangle\right\} \qquad \theta{=}K_L$$

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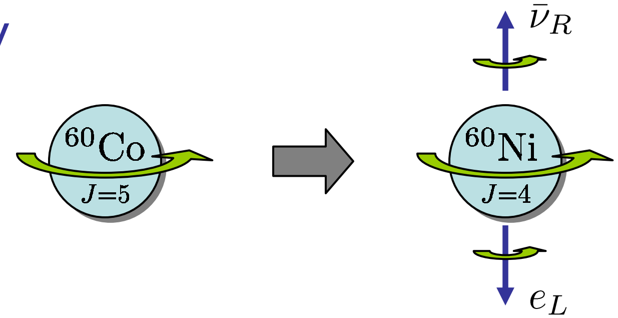
$$\vec{J} \cdot \vec{k}_e$$



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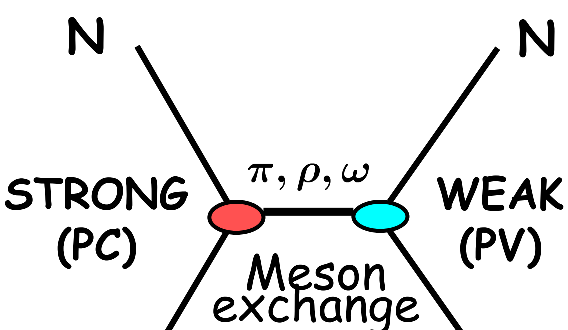
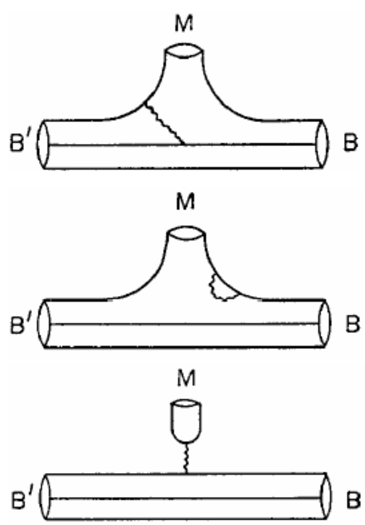
T violation

Hadronic Weak Interaction

- Desplanques, Donahue, & Holstein (DDH) formalism:
  - 6 meson-nucleon coupling constants: range + isospin structure
  - pion channel dominated by neutral current (Z^0)
  - PV effects: interference between strong and weak vertex
- other treatments:
  - partial waves, chiral perturbation theory, lattice QCD



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



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

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

Why Study Hadronic PV?

- probe of atomic, nuclear, and hadronic systems
  - map out coupling constants
  - resolve ^{18}F, ^{133}Cs discrepancy
  - probe nuclear structure effects
  - anapole and qq contributions to PV electron scattering
- probe of QCD in low energy non-perturbative regime
  - confinement, many-body problem
  - sensitive to qq correlations
  - measure QCD modification of qqZ coupling

	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

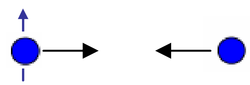
n-capture spin rotation elastic scattering

$$n + p \rightarrow d + \gamma$$

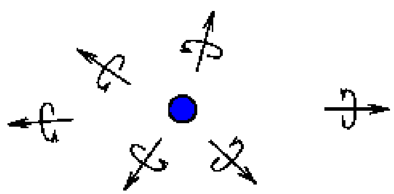
$$A_\gamma = -0.11\ f_\pi + -0.001\ h_\rho^1 + -0.003\ h_\omega^1$$

Existing Measurements

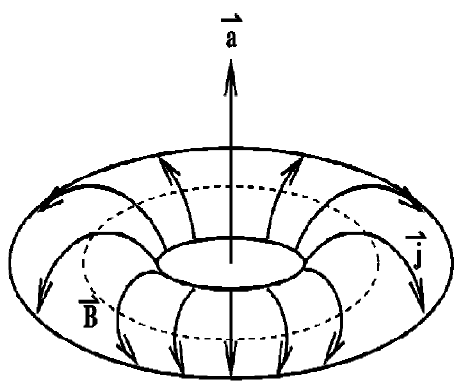
Polarized proton scattering asymmetries



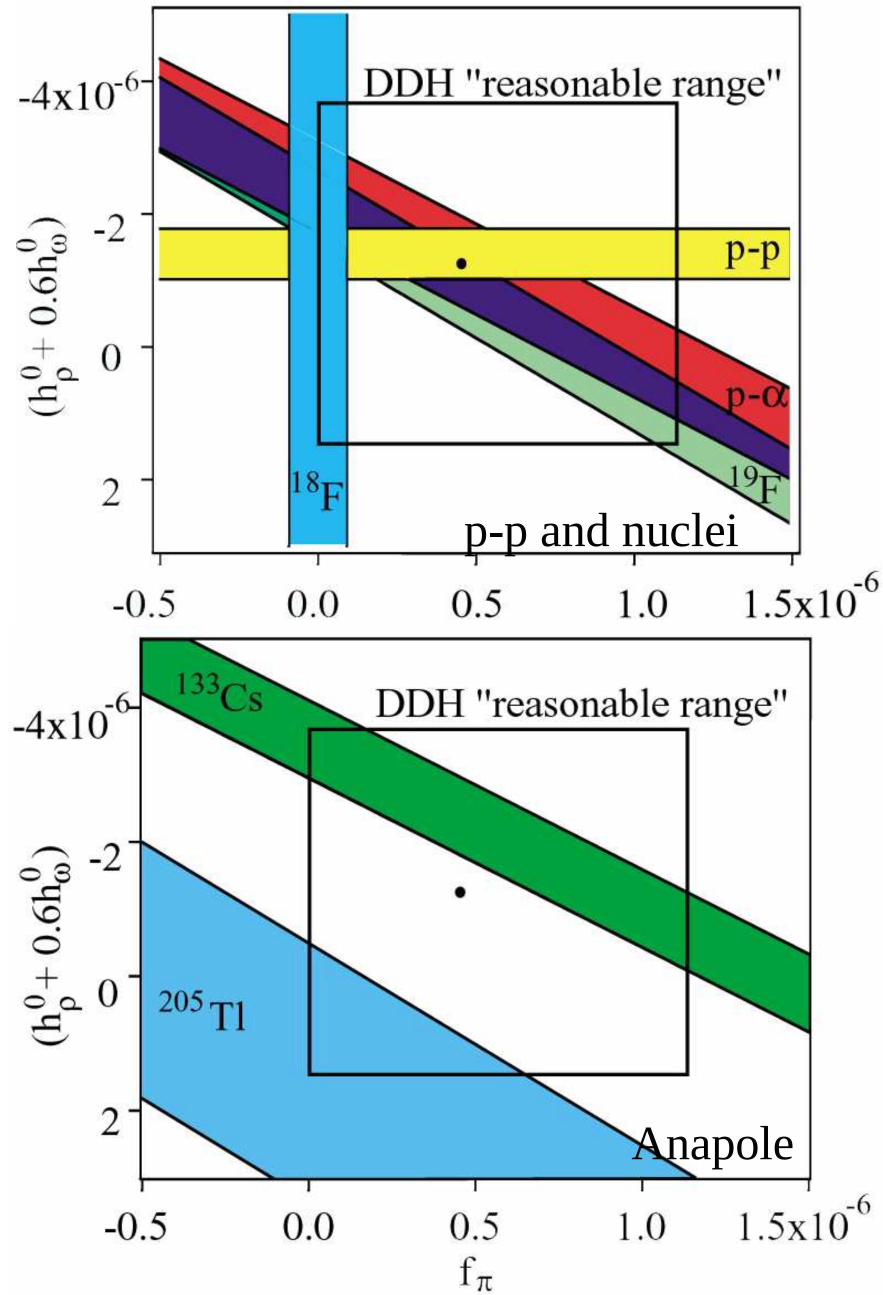
Light nuclei gamma transitions
(circular polarized gammas)



Nuclear anapole moment
(from laser spectroscopy)



$$\vec{a} = -\int d^3r\ r^2 \vec{j}(r)$$



Properties of the Neutron

$m_n = m_p + m_e + 782$ keV

$\tau_n = 885.7 \pm 0.8$ s

$q_n < 2 \times 10^{-21}$ e

$d_n < 3 \times 10^{-26}$ e cm

$\mu_n = -1.91 \ \mu_N$

$r_m = 0.889$ fm

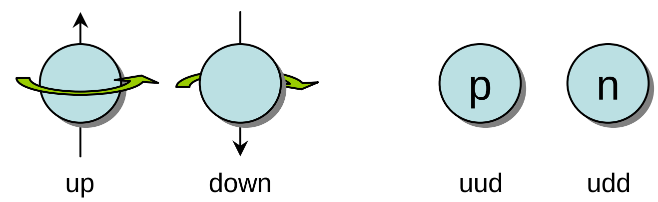
$r_e^2 = -0.116$ fm^2

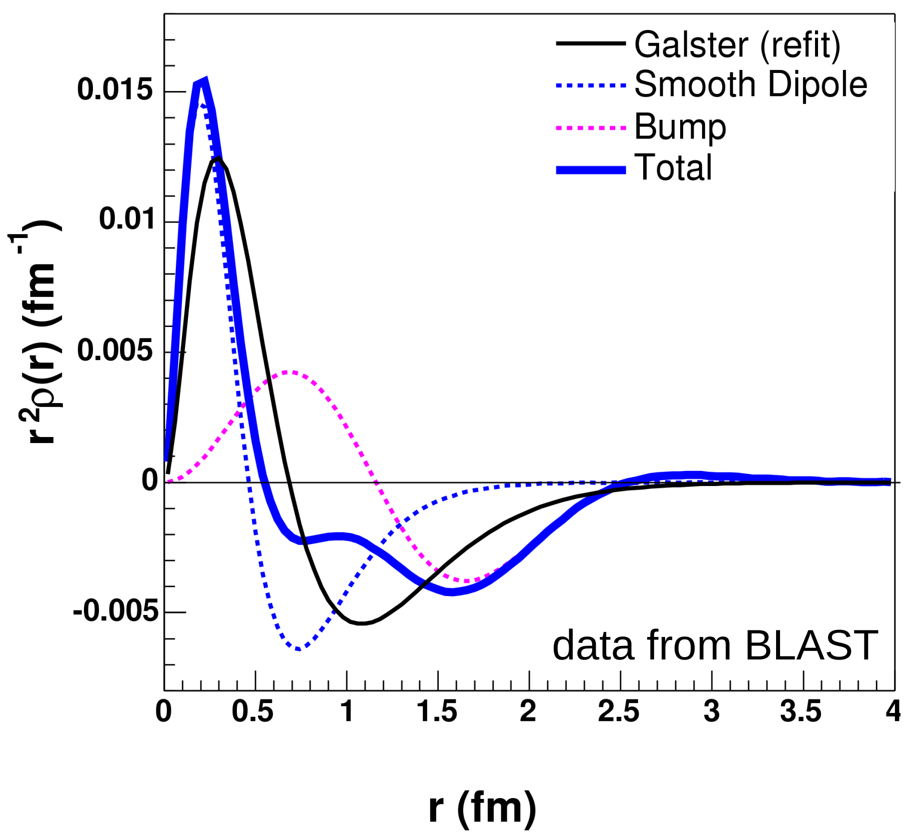
– 3 valence quarks + sea

– exponential magnetization distribution

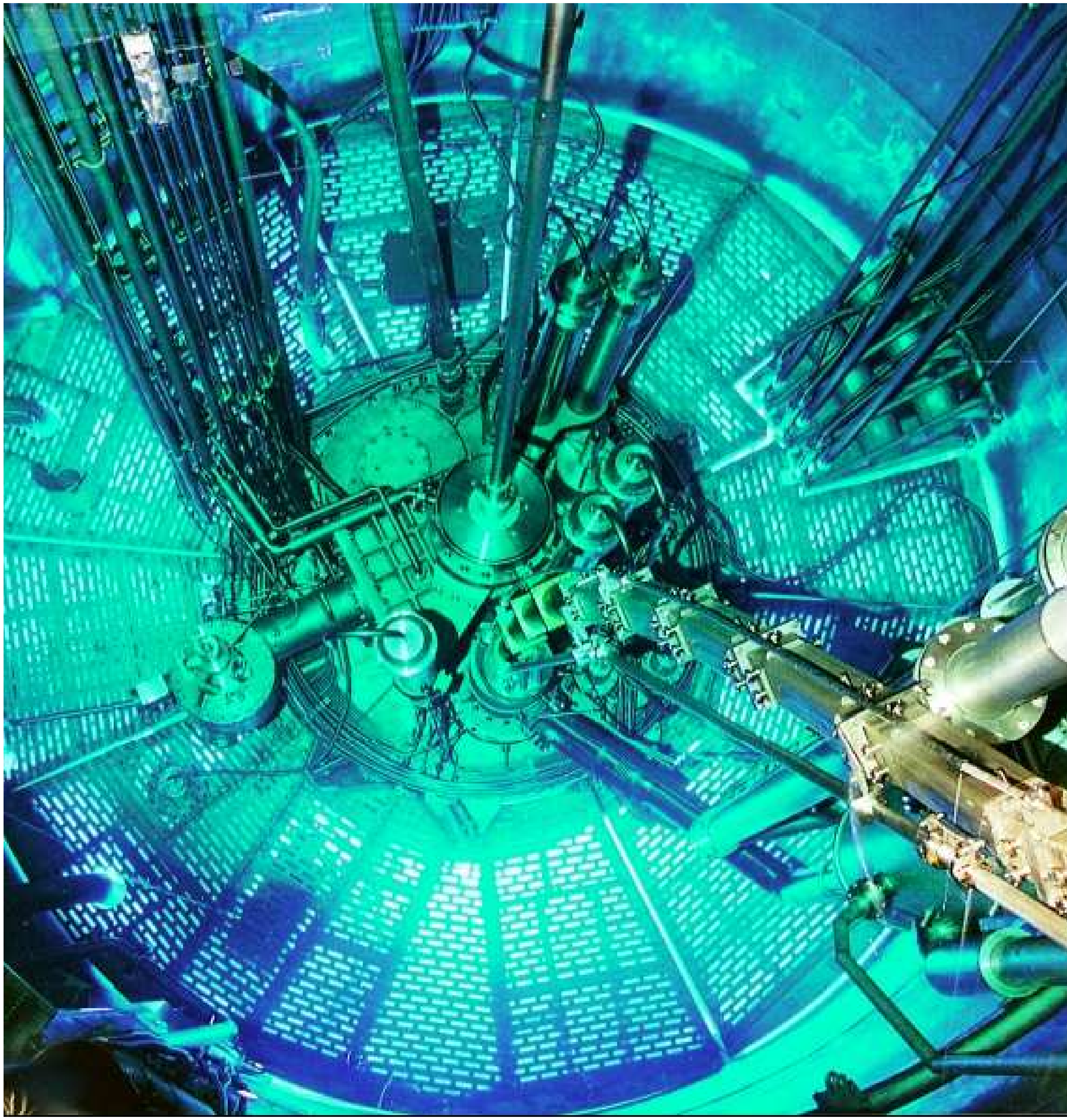
– pion cloud: $n \leftrightarrow p + \pi^-$

spin 1/2 isospin 1/2



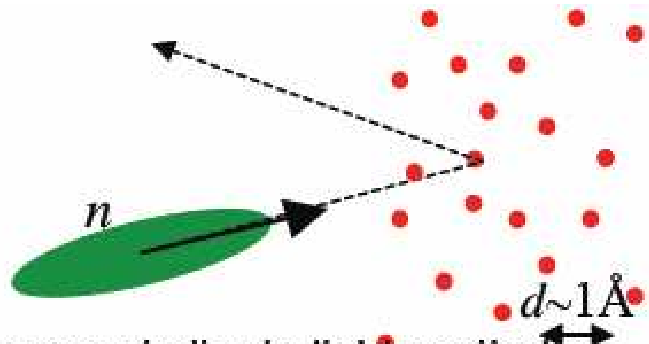


Neutron sources - Reactors



ILL, Grenoble, France

Guides - neutron optical potential

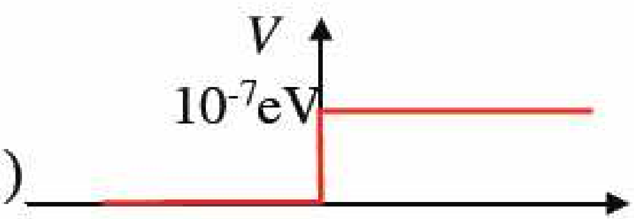


Fermi pseudopotential

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

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

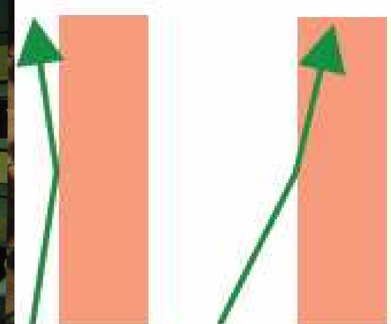
⇒Potential of wall



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

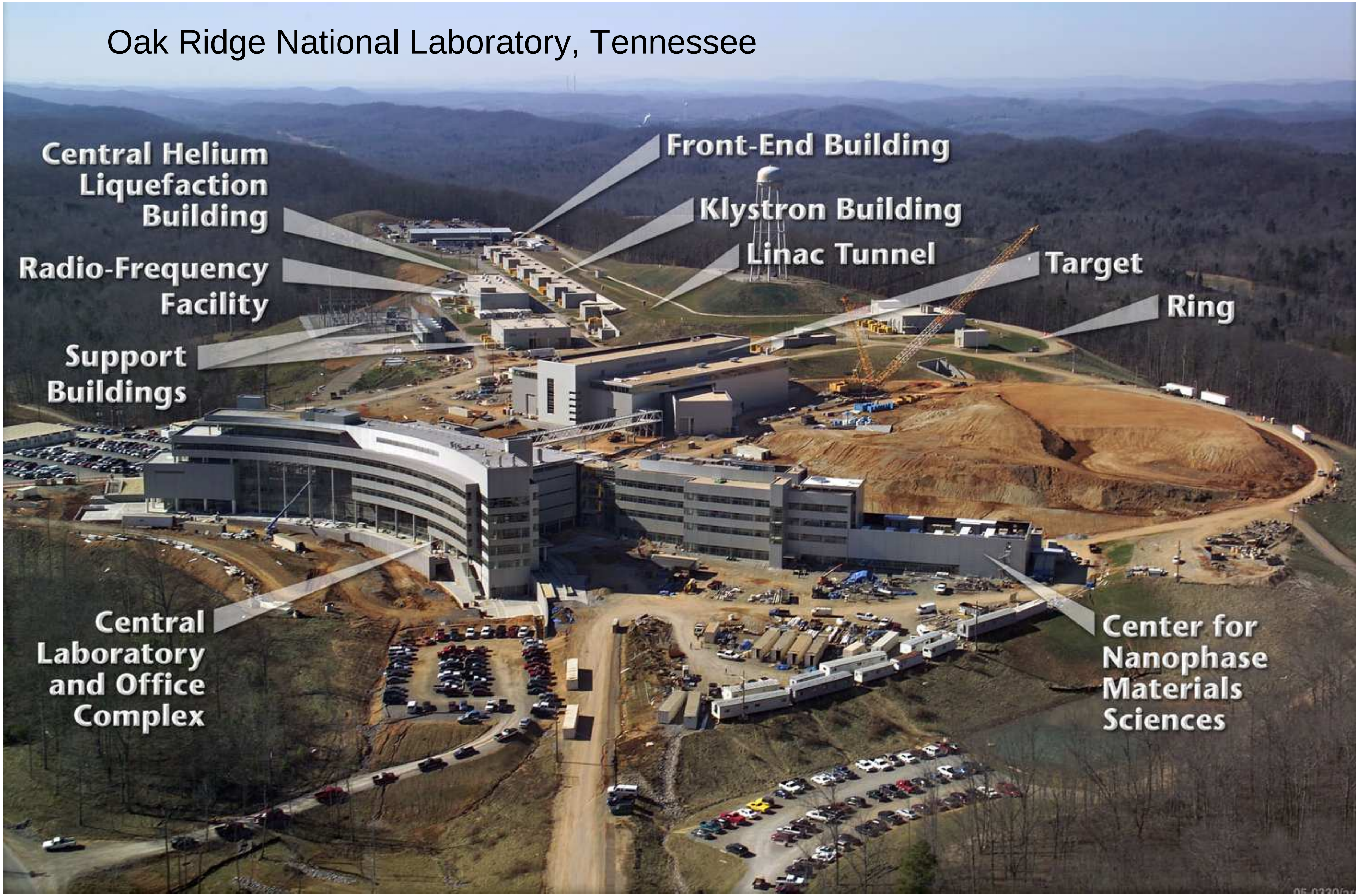
Index of refraction

$$n \approx 1 - \frac{\lambda^2 b\rho}{2\pi}$$

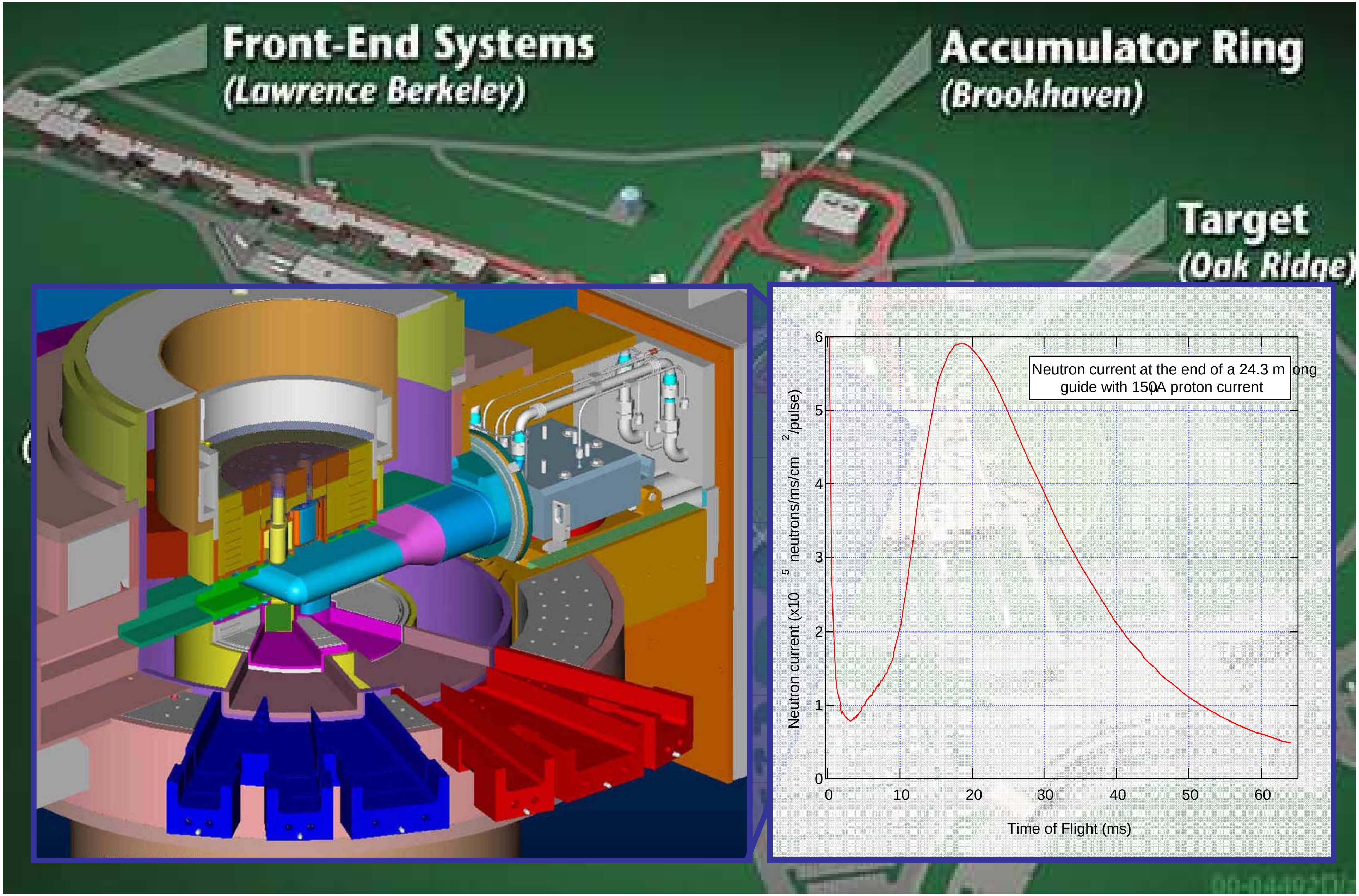


slide courtesy A. Young

Spallation Neutron Source (SNS)

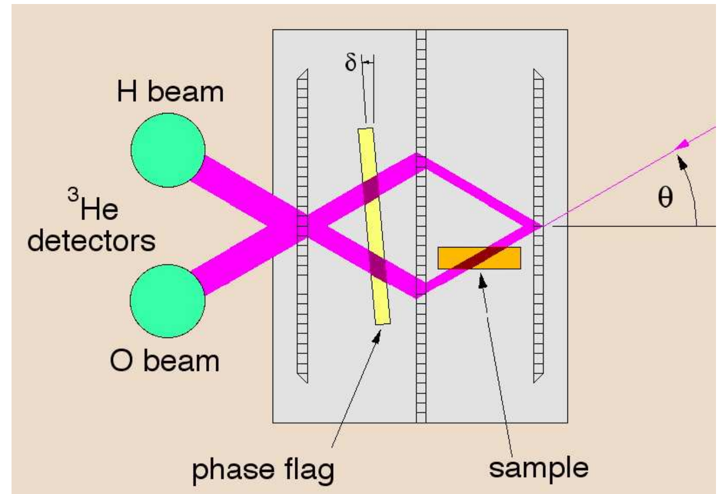


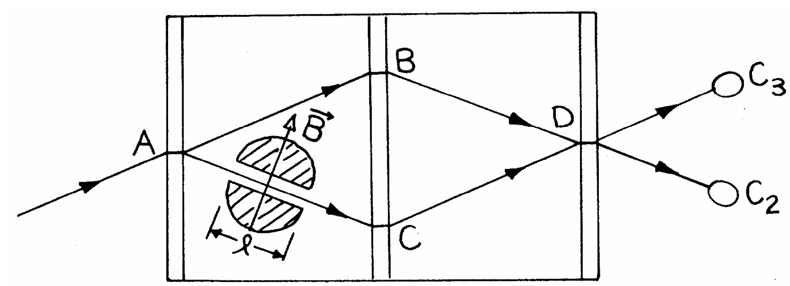
Spallation Neutron Source (SNS)

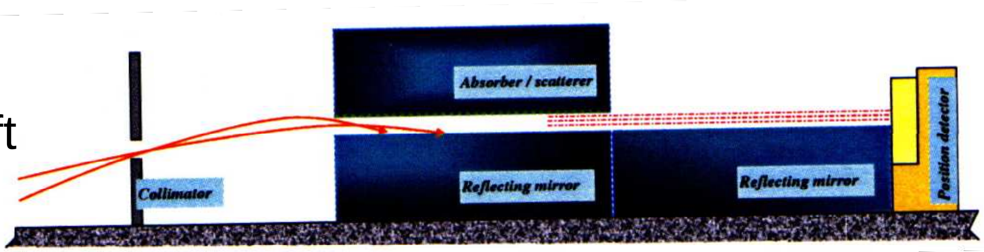


What can we do with neutrons?

- scattering / diffraction
  - complementary to
    X-ray Bragg diffraction
  - large penetration
  - large H,D cross section
    - life sciences
    - fuel cell research
    - oil exploration
- fundamental tests of quantum mechanics
  - neutron interferometry
    - scattering lengths
    - neutron charge radius
    - spinor 4π periodicity
    - gravitational phase shift
  - quantum states in a
    gravitational potential

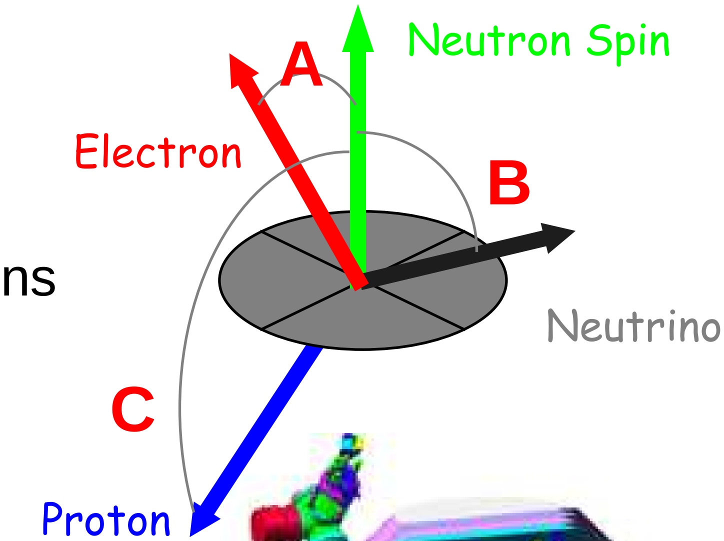


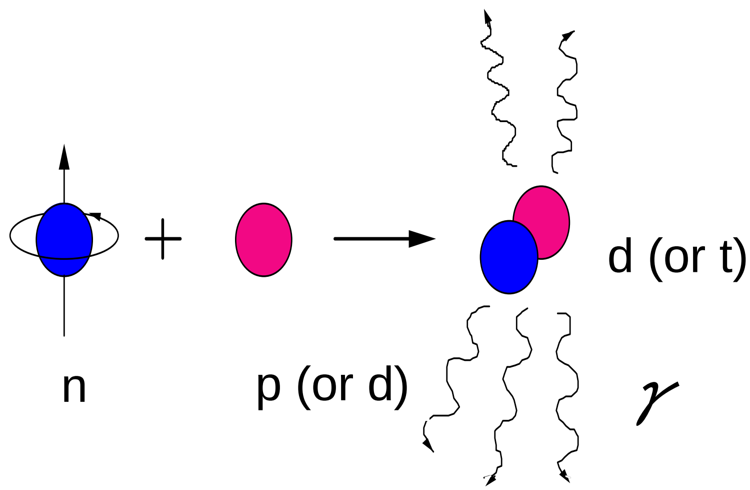


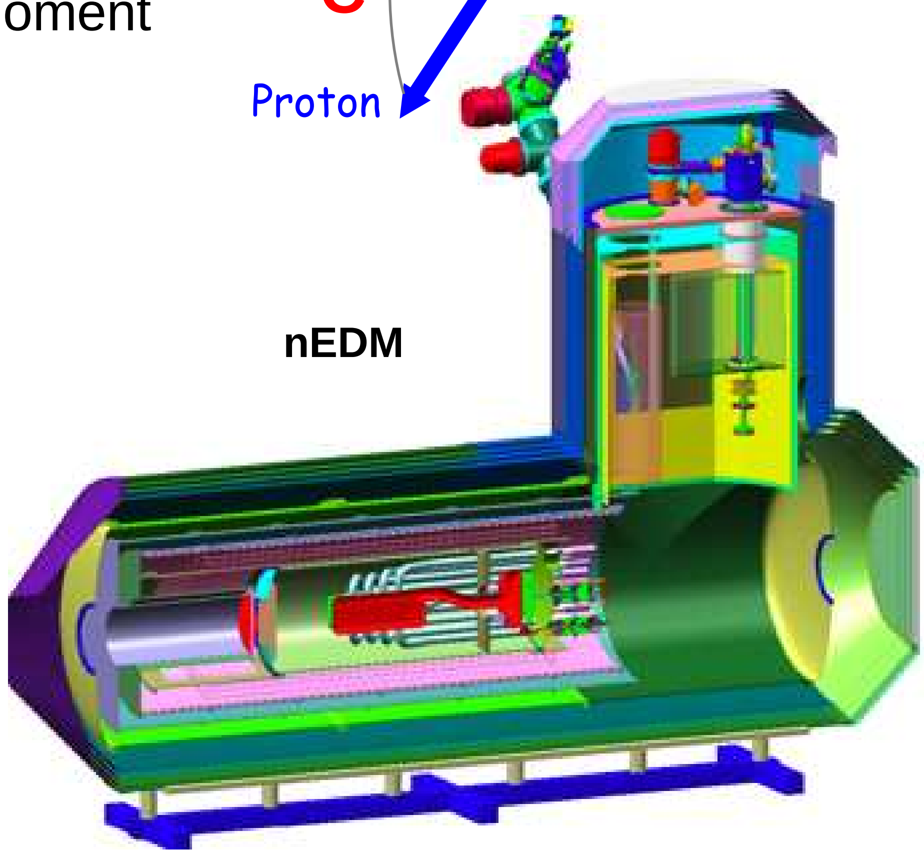


What can we do with neutrons?

- fundamental symmetry tests of the standard model
  - neutron decay lifetime and correlations
  - PV: NPDGamma, ^{4}He spin rotation
  - T reversal: electric dipole moment

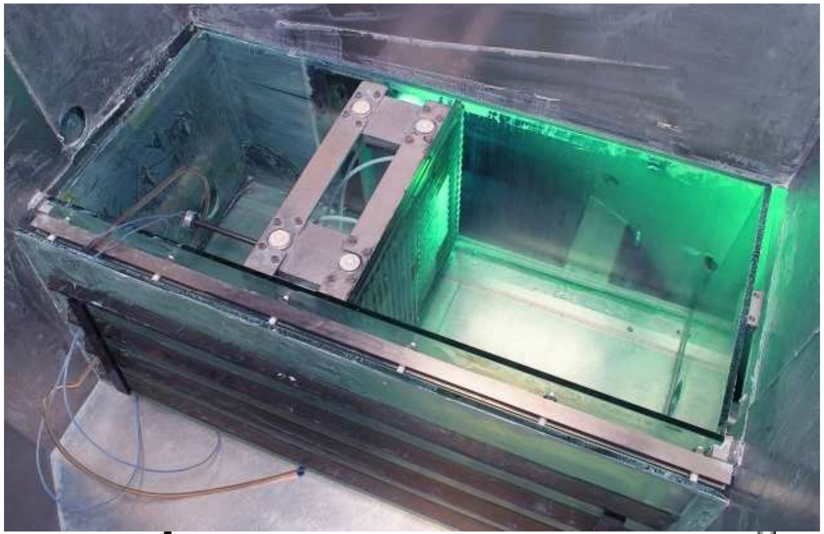






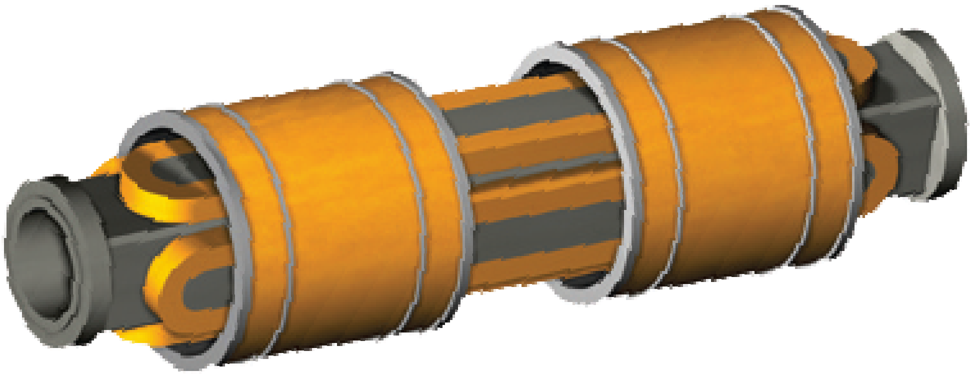
Neutron Traps

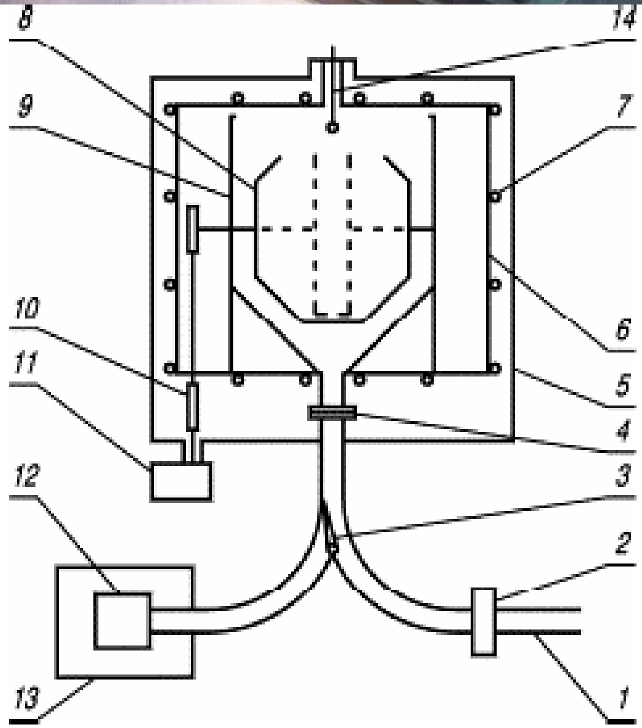
ultra cold neutrons:
slow enough to be completely
reflected by ^{58}Ni optical potential



kinetic: 8 m/s
thermal: 4 mK
wavelength: 50 nm

nuclear: 335 neV (^{58}Ni)
magnetic: 60 neV (1 T)
gravity: 102 neV (1 m)





Car Traps

Measurement of the Parity - Violating Gamma Asymmetry A_γ in the Capture of Polarized Cold Neutrons by Para-Hydrogen

NPDGamma Collaboration

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Los Alamos National Laboratory

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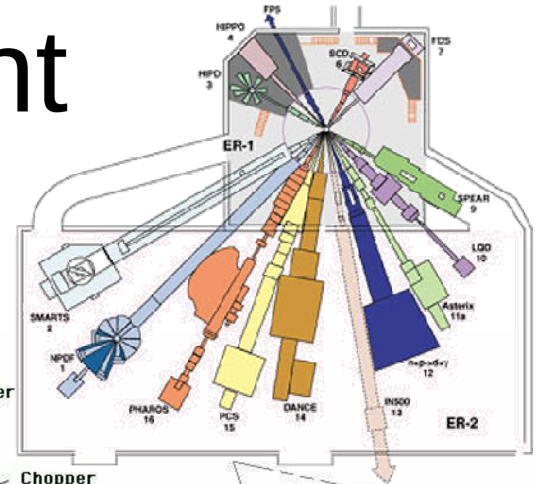
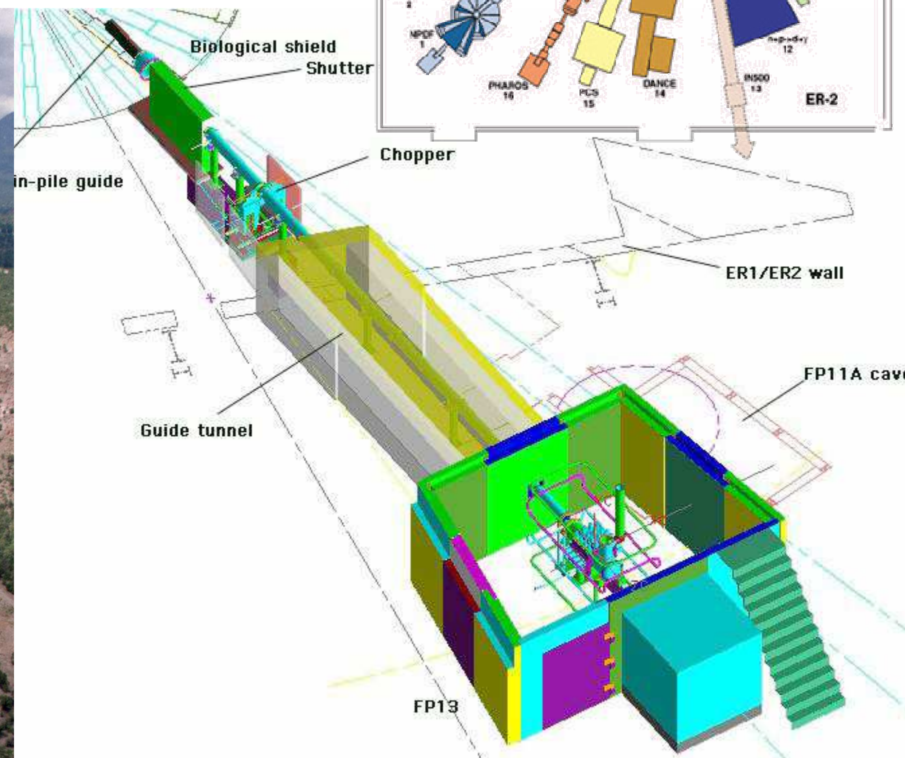
Bhabbha Atomic Research Center

P.N. Seo
North Carolina State University

E. Sharapov
Joint Institute of Nuclear Research

NPDGamma Experiment

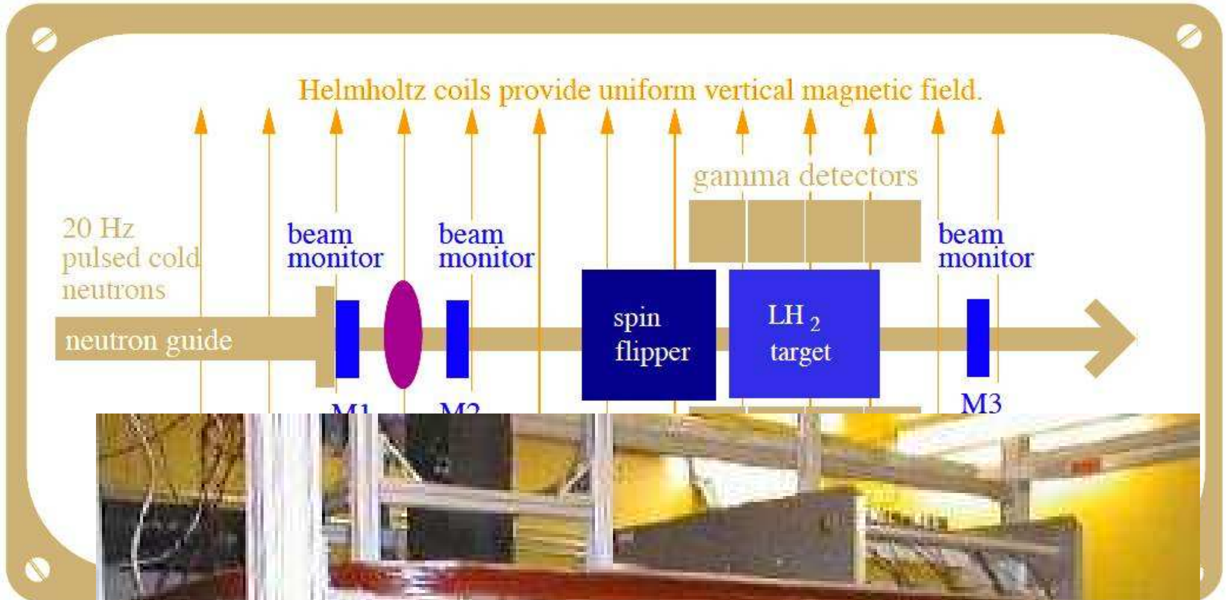


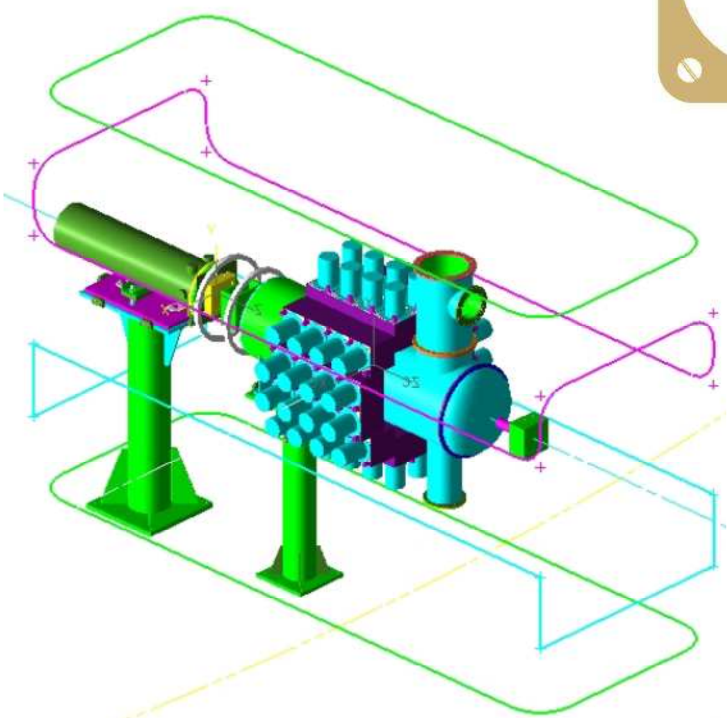


~$6x10^8$ cold neutrons per 20 Hz pulse at the end of the 20 m supermirror guide (largest pulsed neutron flux)

Overview of NPDG experiment

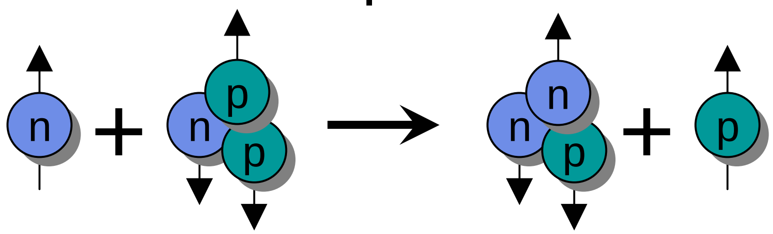
- ^3He polarizer
- beam monitors
- RF spin flipper
- LH_2 target
- CsI detectors





^{3}He neutron polarizer

- n + ^{3}He $\rightarrow$ ^{3}H + p cross section is highly spin-dependent



$\sigma_{J=0}$ = 5333 b λ/λ_0

$\sigma_{J=1}$ ¼ 0

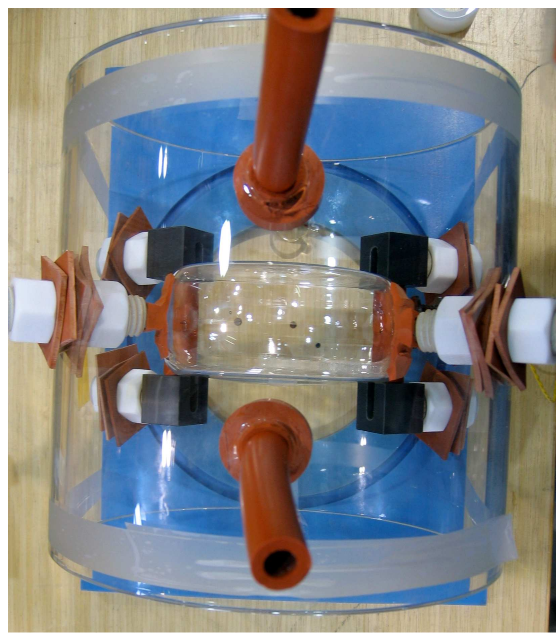
- 10 G holding field determines the polarization angle

  rG < 1 mG/cm to avoid Stern-Gerlach steering

P_3 = 57 %

Steps to polarize neutrons:

1. Optically pump Rb vapor with circular polarized laser
2. Polarize ^{3}He atoms via spin-exchange collisions
3. Polarize ^{3}He nuclei via the hyperfine interaction
4. Polarize neutrons by spin-dependent transmission



Neutron Beam Monitors

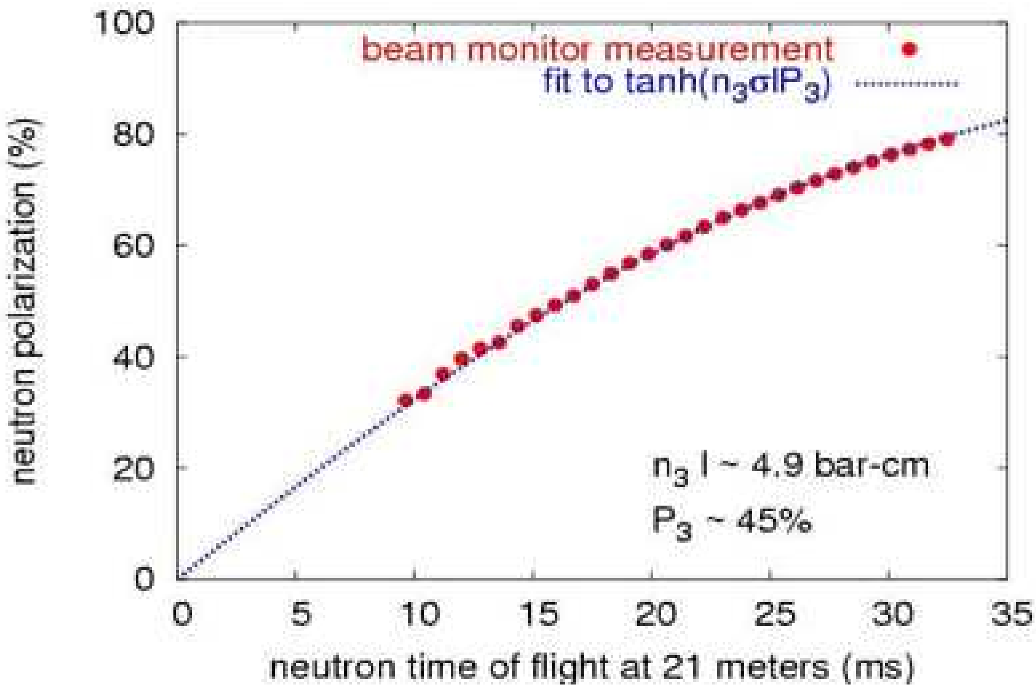
- ^{3}He ion chambers
- measure transmission through ^{3}He polarizer

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

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

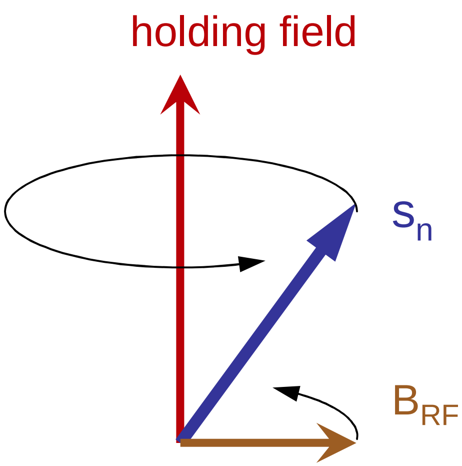
$$\boldsymbol{P} \equiv \frac{(T_+ - T_-)}{(T_+ + T_-)} = \tanh(nl\sigma P_3)$$

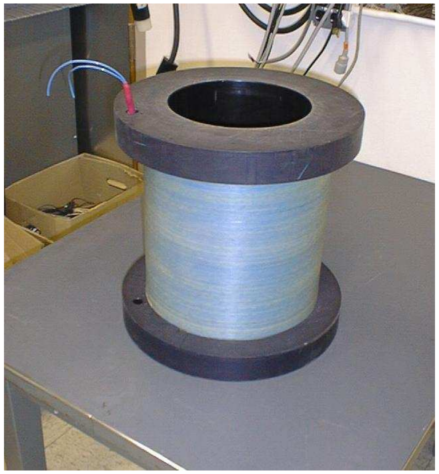
$$= \sqrt{1 - T_0^2/T^2}$$



RF Spin Rotator

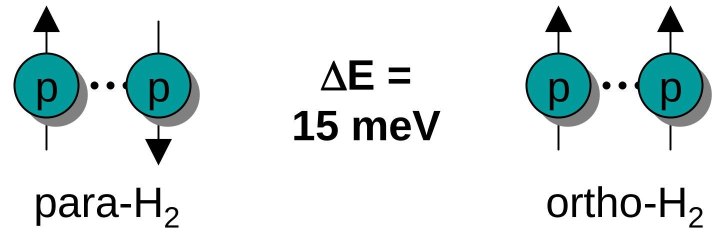
– essential to reduce instrumental systematics
  - spin sequence: ↑↓↓↑ ↓↑↑↓ cancels drift to 2nd order
  - danger: must isolate fields from detector
  - false asymmetries: additive & multiplicave
– works by the same principle as NMR
  - RF field resonant with Larmor frequency rotates spin
  - time dependent amplitude tuned to all energies
  - compact, no static field gradients

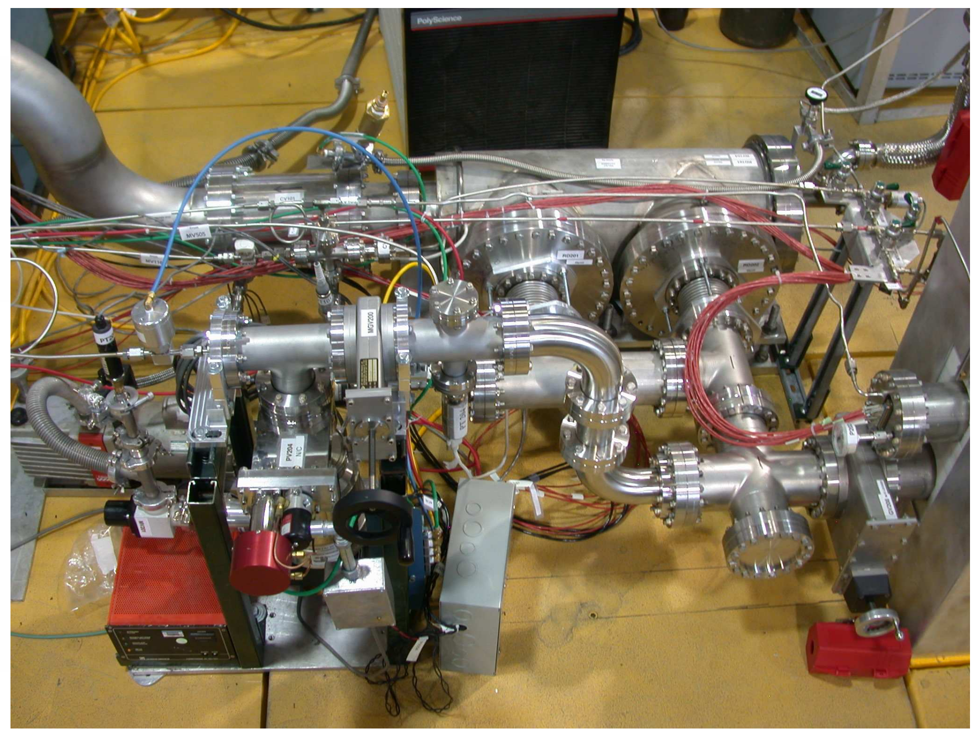




16L liquid para-hydrogen target

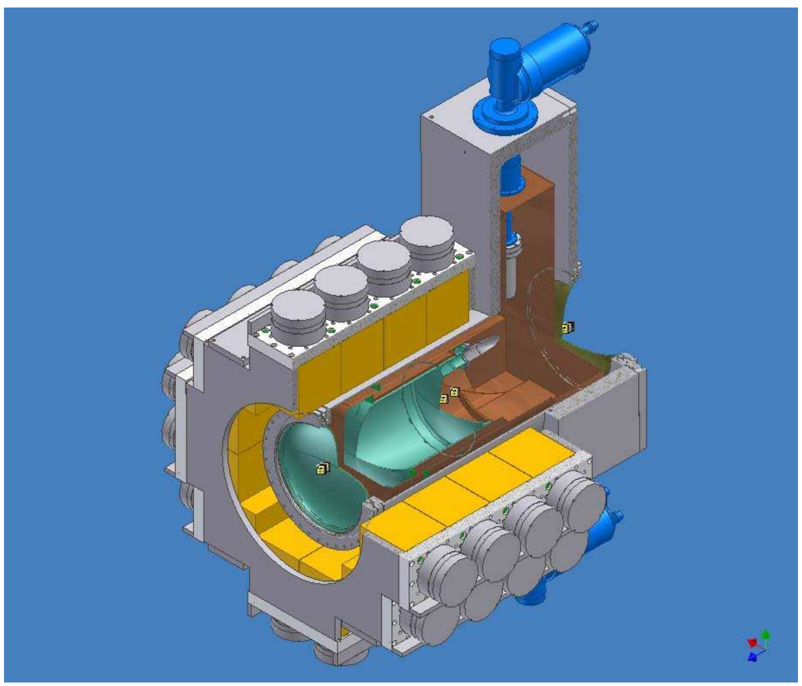
- 30 cm long → 1 interaction length
- 99.97% para → 1% depolarization
- super-cooled to reduce bubbles
- SAFETY !!

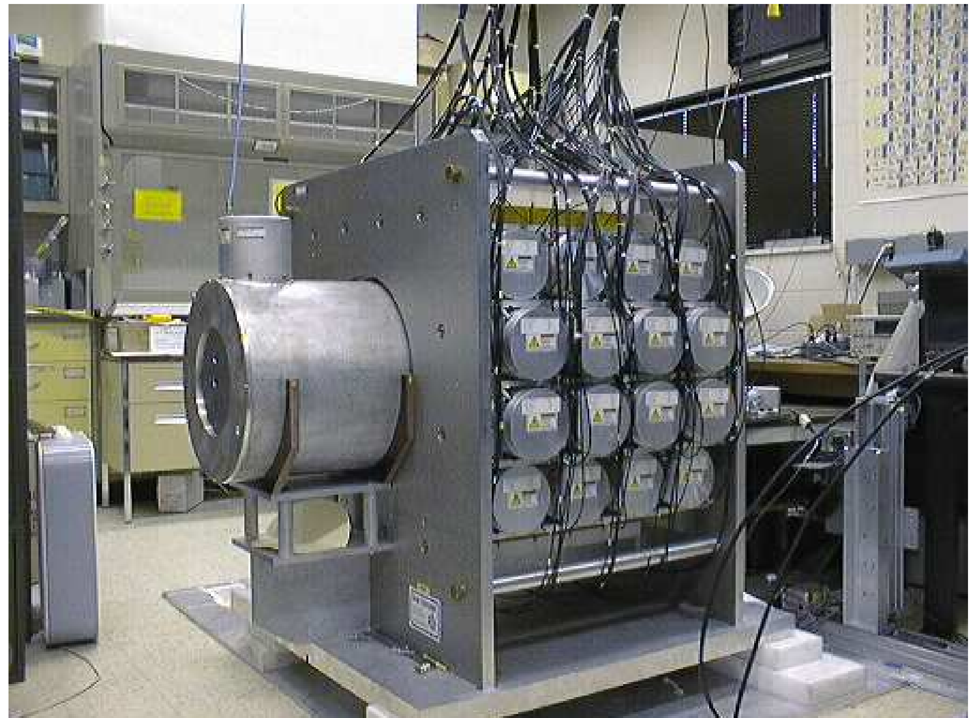




CsI(Tl) Detector Array

- 4 rings of 12 detectors each
  - 15 x 15 x 15 cm^3 each
- VPD's insensitive to B field
- detection efficiency: 95%
- current-mode operation
  - 5 x 10^7 gammas/pulse
  - counting statistics limited





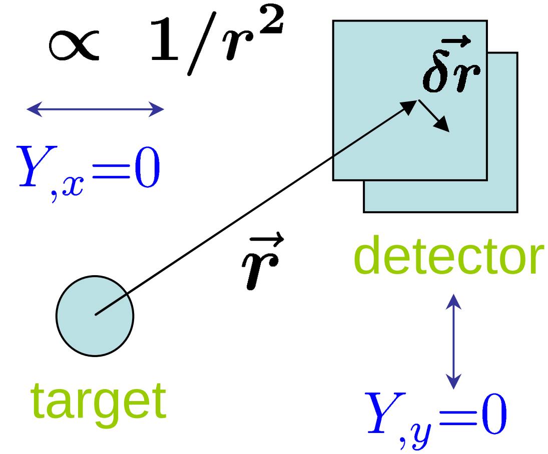
Detector position scans

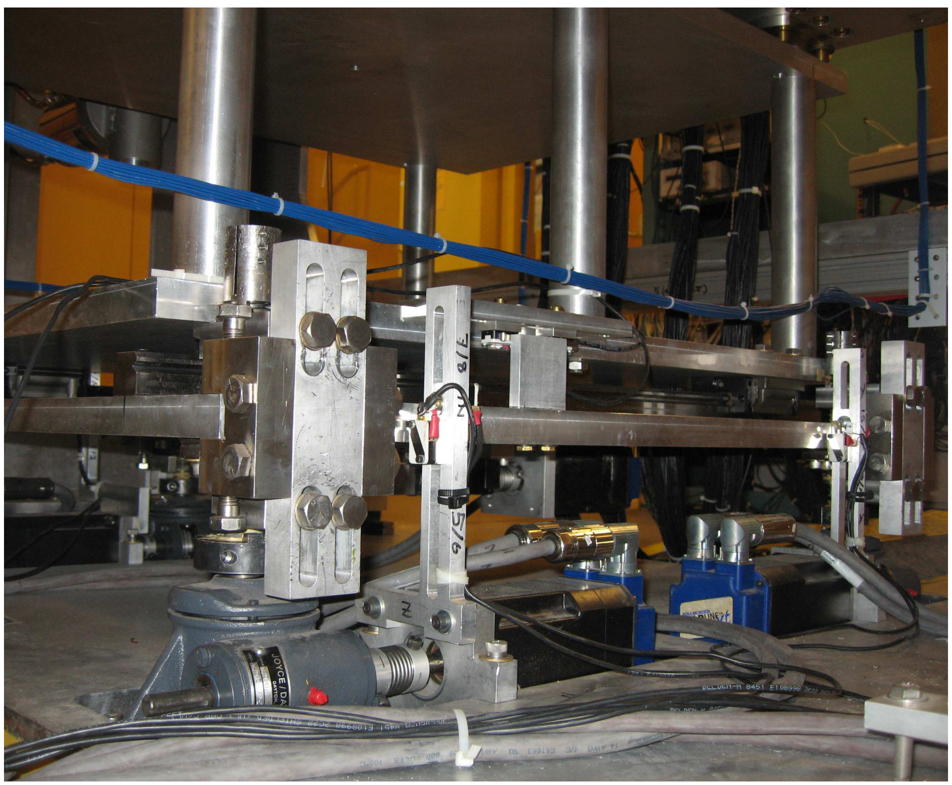
$$Y \propto 1 + A_{\gamma}^{PV} \cos\theta + A_{\gamma}^{PC} \sin\theta$$

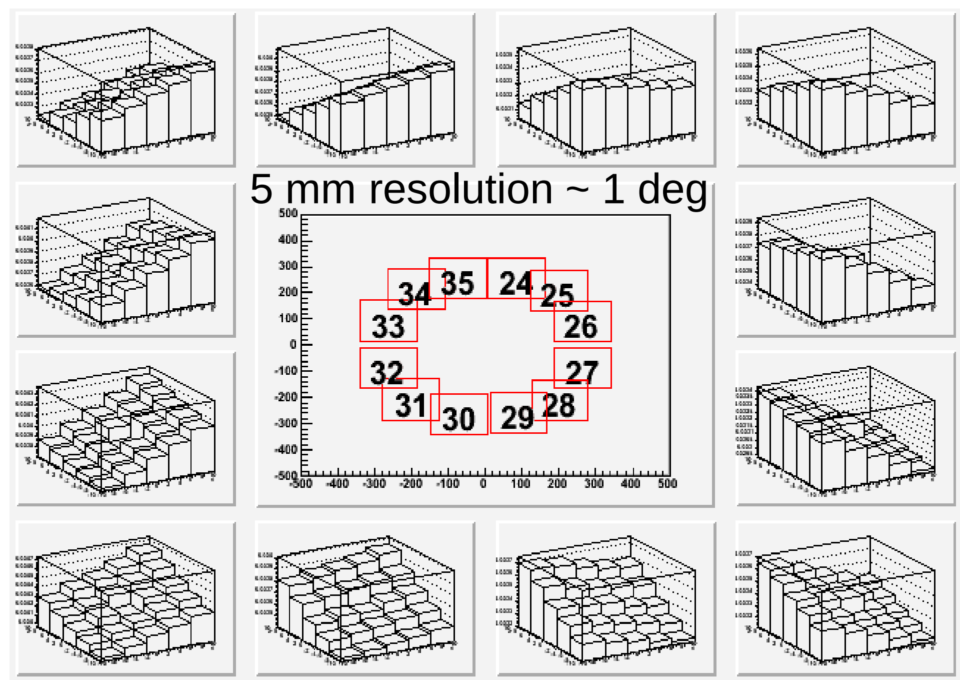
UP-DOWN $\quad$ LEFT-RIGHT

$$\boldsymbol{s_n \cdot k_\gamma} \qquad \boldsymbol{s_n \cdot k_n \times k_\gamma}$$

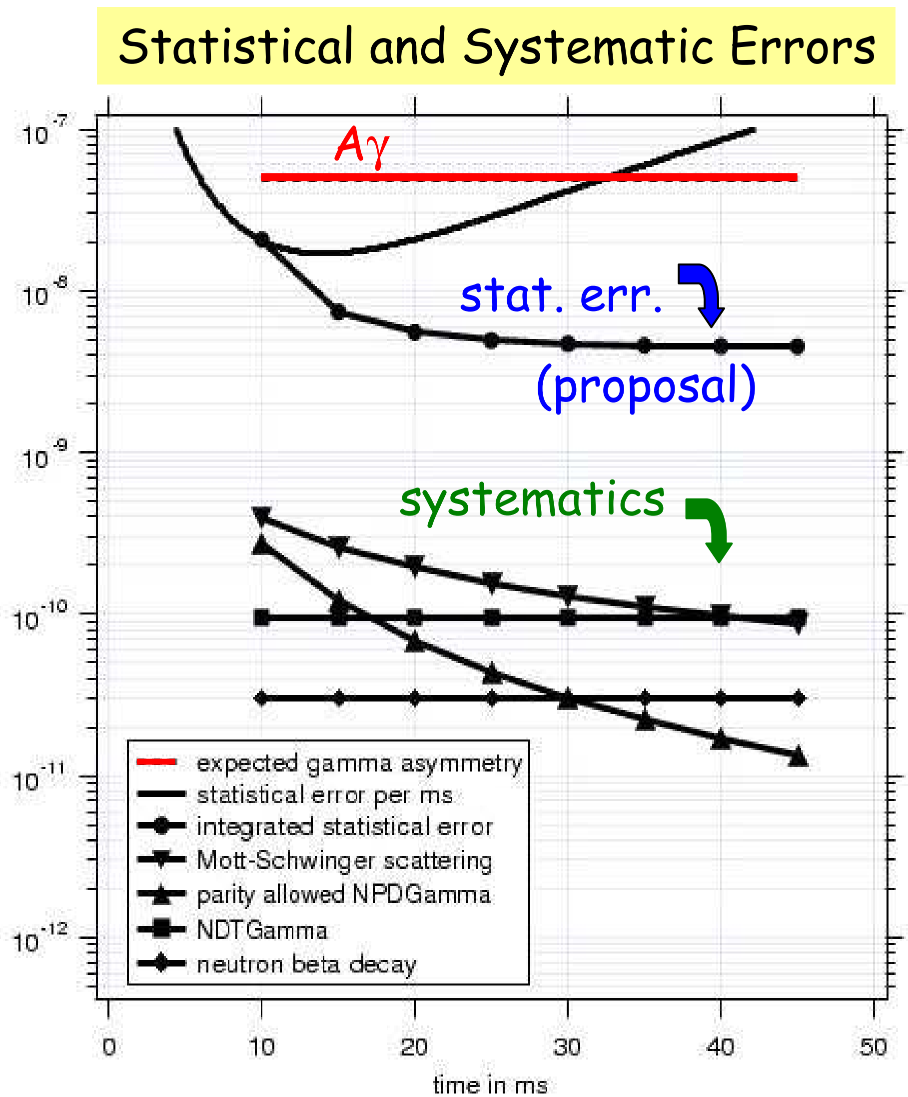
$$Y \propto 1/r^2$$







Systematic Uncertainties



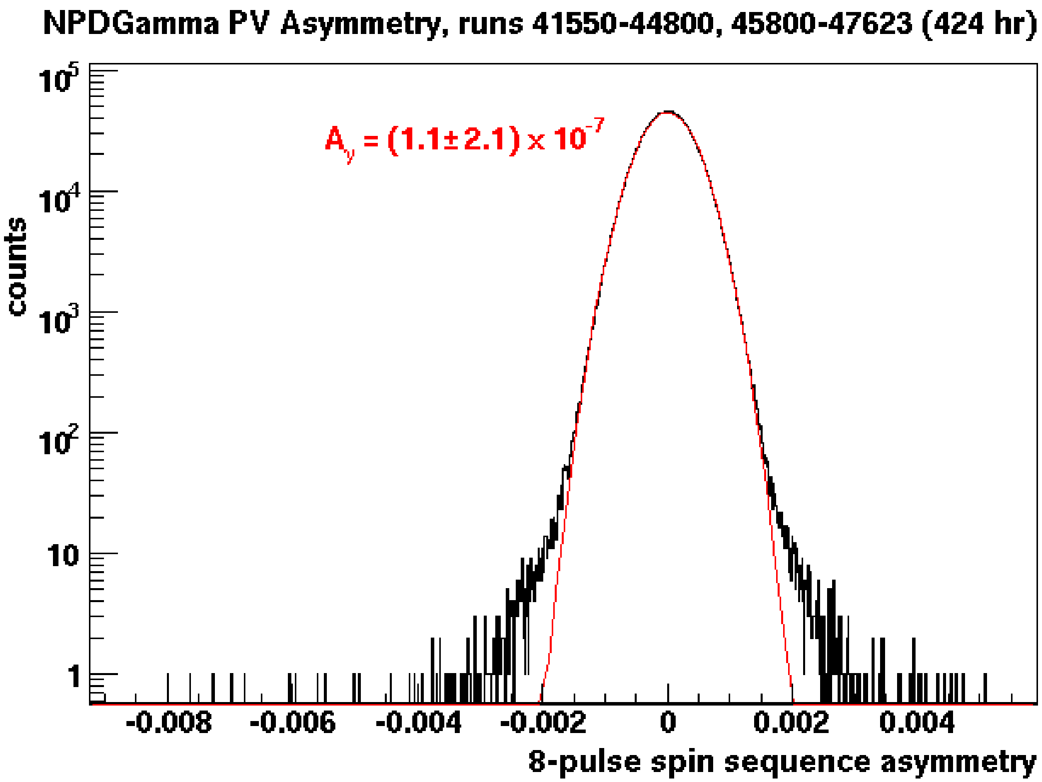
Systematics, e.g:

- activation of materials,
  e.g. cryostat windows
- Stern-Gerlach steering
  in magnetic field gradients
- L-R asymmetries leaking into
  U-D angular distribution
  (np elastic, Mott-Schwinger...)
- scattering of circularly polarized
  gammas from magnetized iron
  (cave walls, floor...)

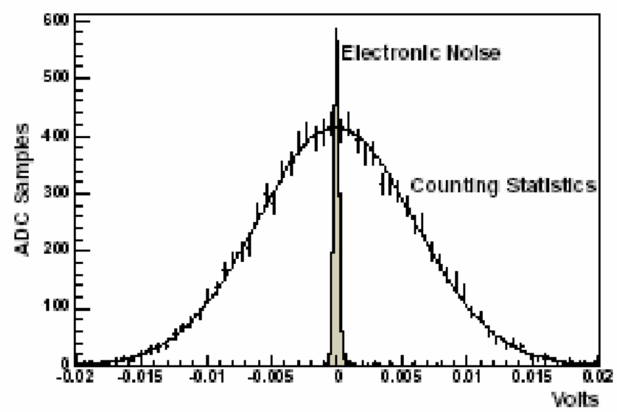
→ estimated and expected to be negligible (expt. design)

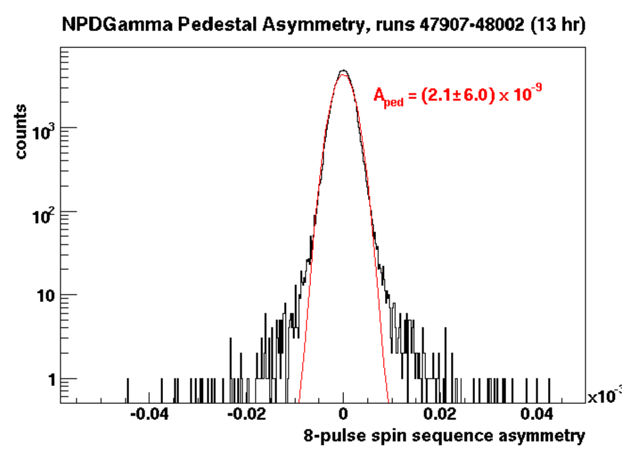
slide courtesy Mike Snow

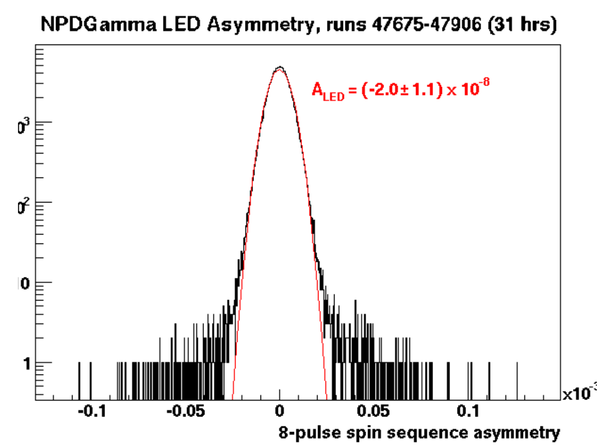
Preliminary raw results



Material	# runs	A_γ $(\times 10^{-6})$	
Engineering:			
Cl	53	−21.	± 1.6
Cu	17	−1.	± 3.
B_4C	11	−1.	± 2.
Al	1057	−0.00	± 0.30
In	716	−0.68	± 0.30
LEDs	2864	−0.0477	± 0.0603
Noise		∼ 0.001	
Physics:			
Mn	529	0.53	± 0.78
V	2313	0.24	± 0.45
Ti	2864	0.41	± 0.36
Co	744	0.61	± 0.31
Sc	2179	−1.04	± 0.25







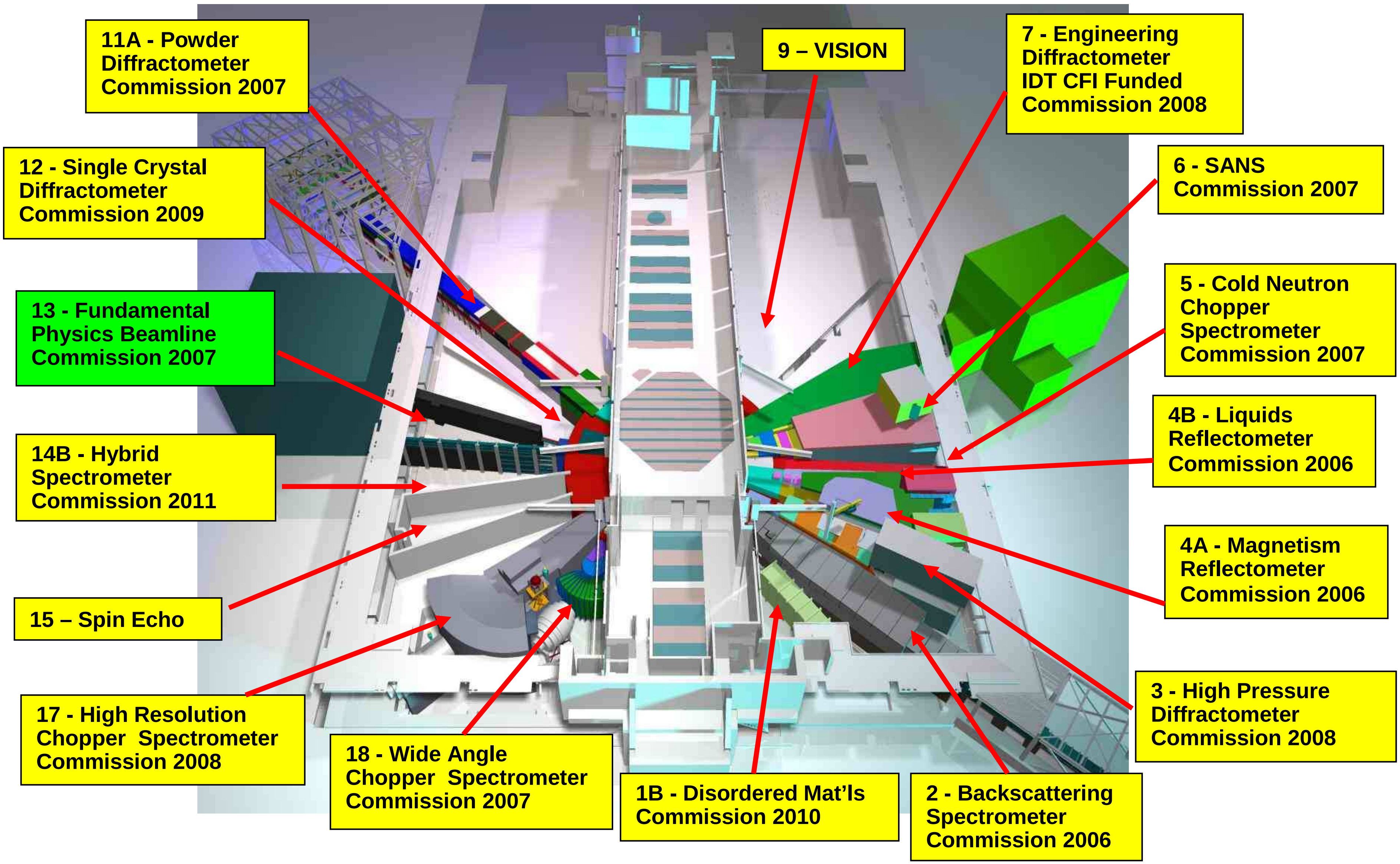
Conclusion

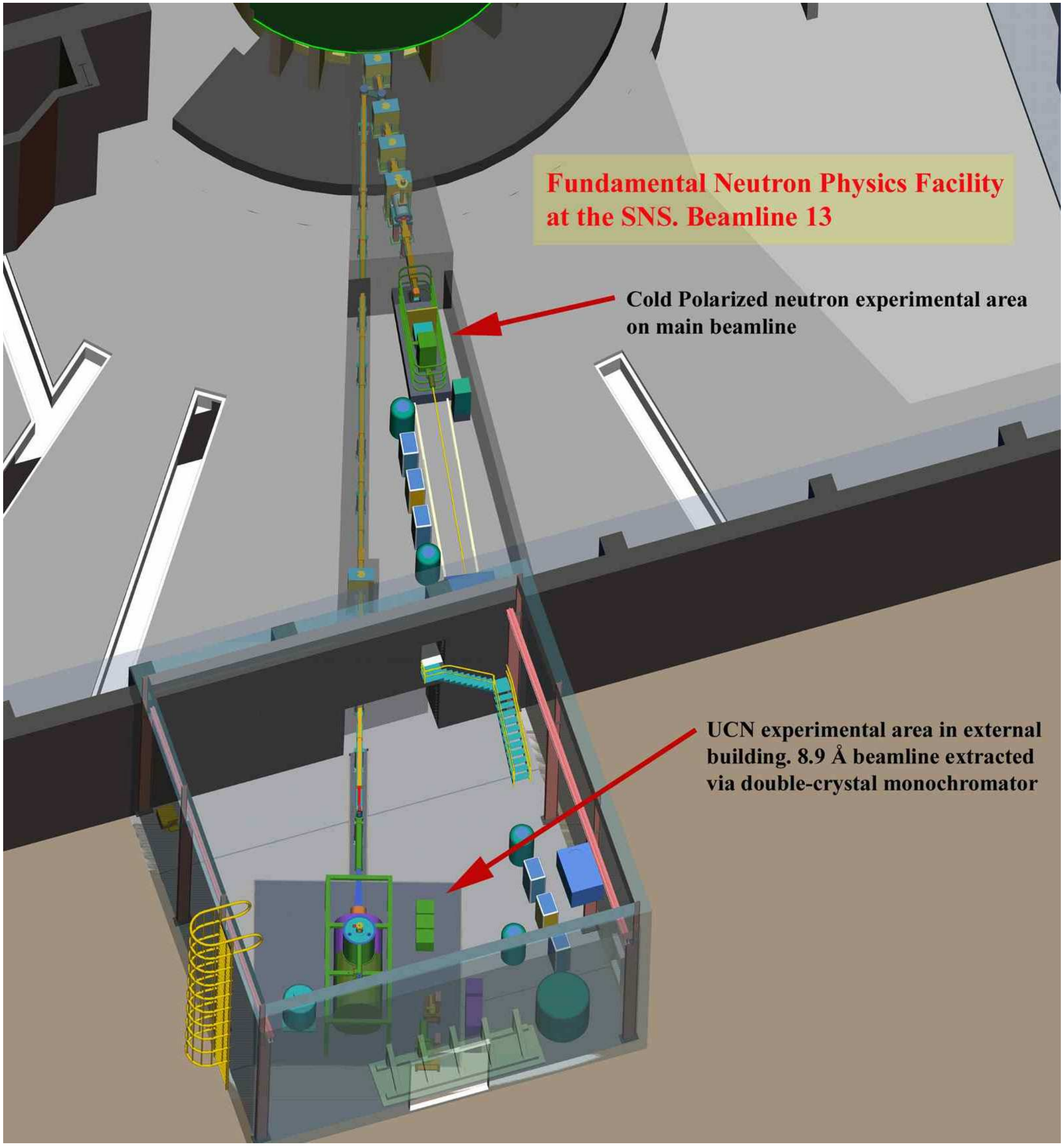
- the NPDG experiment had a successful first phase at LANSCE
  - already most precise value of A_γ
- it will determine f_π to 10% of it's predicted value at the SNS
  - next: $n + d \rightarrow t + \gamma$
- hadronic parity violation is a unique probe of short-distance nuclear interactions and QCD
  - neutron capture is an important key to mapping the structure of the hadronic weak interaction

END of Presentation

SNS Beamlines

Beamline 13 Has Been Allocated for Nuclear Physics

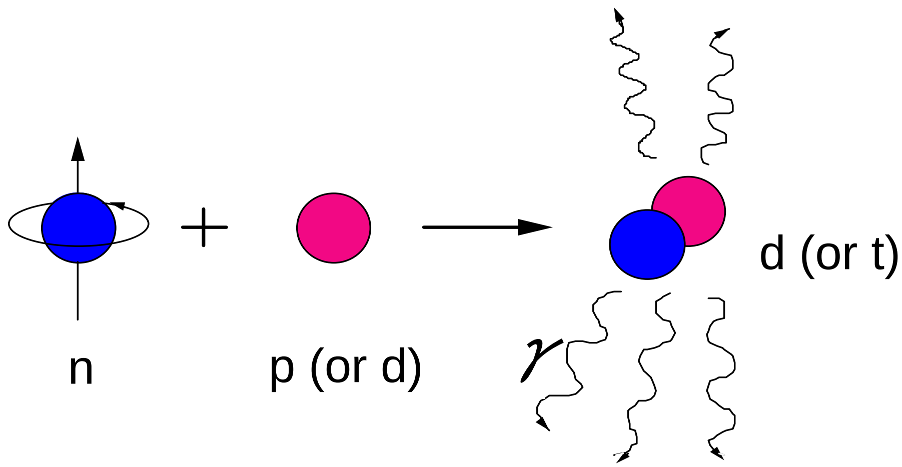




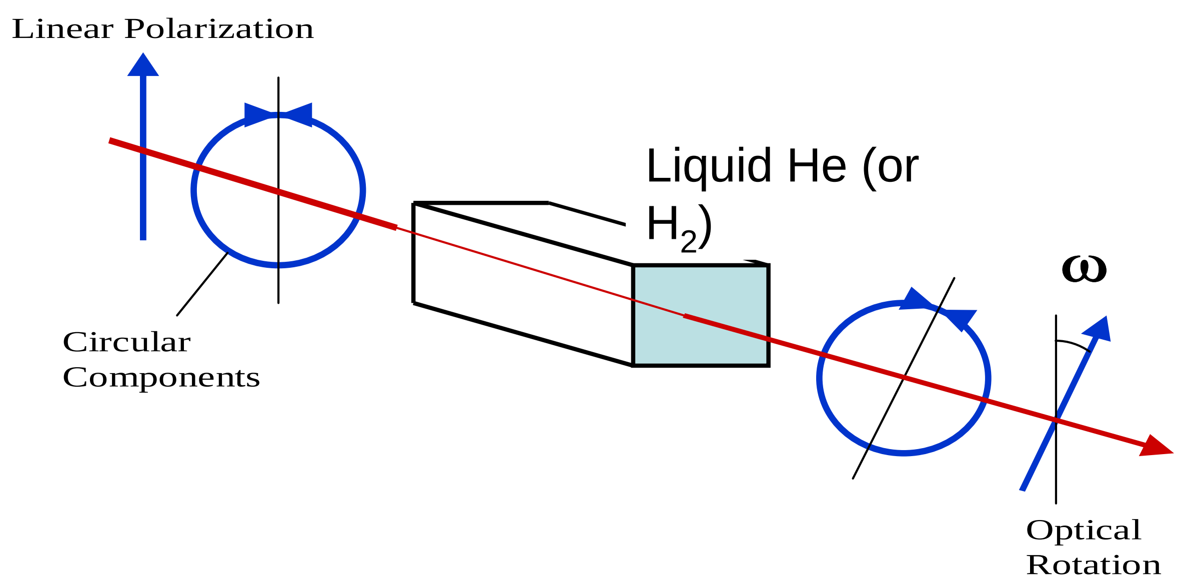
Fundamental Neutron Physics Facility
at the SNS. Beamline 13
Cold Polarized neutron experimental area
on main beamline
UCN experimental area in external
building. 8.9 Å beamline extracted
via double-crystal monochromator

HPV in “Simple” Systems
n+p, n+d, n+α

PNC Capture Gam



Weak Nuclear PN



Slide courtesy of Mike Snow

Correlations in Neutron Decay

Parity violation implies a rich phenomenology in neutron decay.

V-A implies that All experimental Quantities can be related to the axial and vector coupling constants g_A and g_V.

$$dW \propto \frac{1}{\tau_n} F(E_e)\left[1 + a\frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{E_e \cdot E_\nu} + b\frac{m_e}{E_e} + A\frac{\sigma_n \cdot \mathbf{p}_e}{E_e} + B\frac{\sigma_n \cdot \mathbf{p}_\nu}{E_\nu}\right]$$

$$\tau_n \propto 1/(g_A^2 + 3g_V^2)$$

$$a = \frac{1 - \left(\frac{g_A}{g_V}\right)^2}{1 - 3\left(\frac{g_A}{g_V}\right)}$$

$$b = 0$$

$$A = -2\frac{\left(\frac{g_A}{g_V}\right)^2 + \left(\frac{g_A}{g_V}\right)}{1 - 3\left(\frac{g_A}{g_V}\right)^2}$$

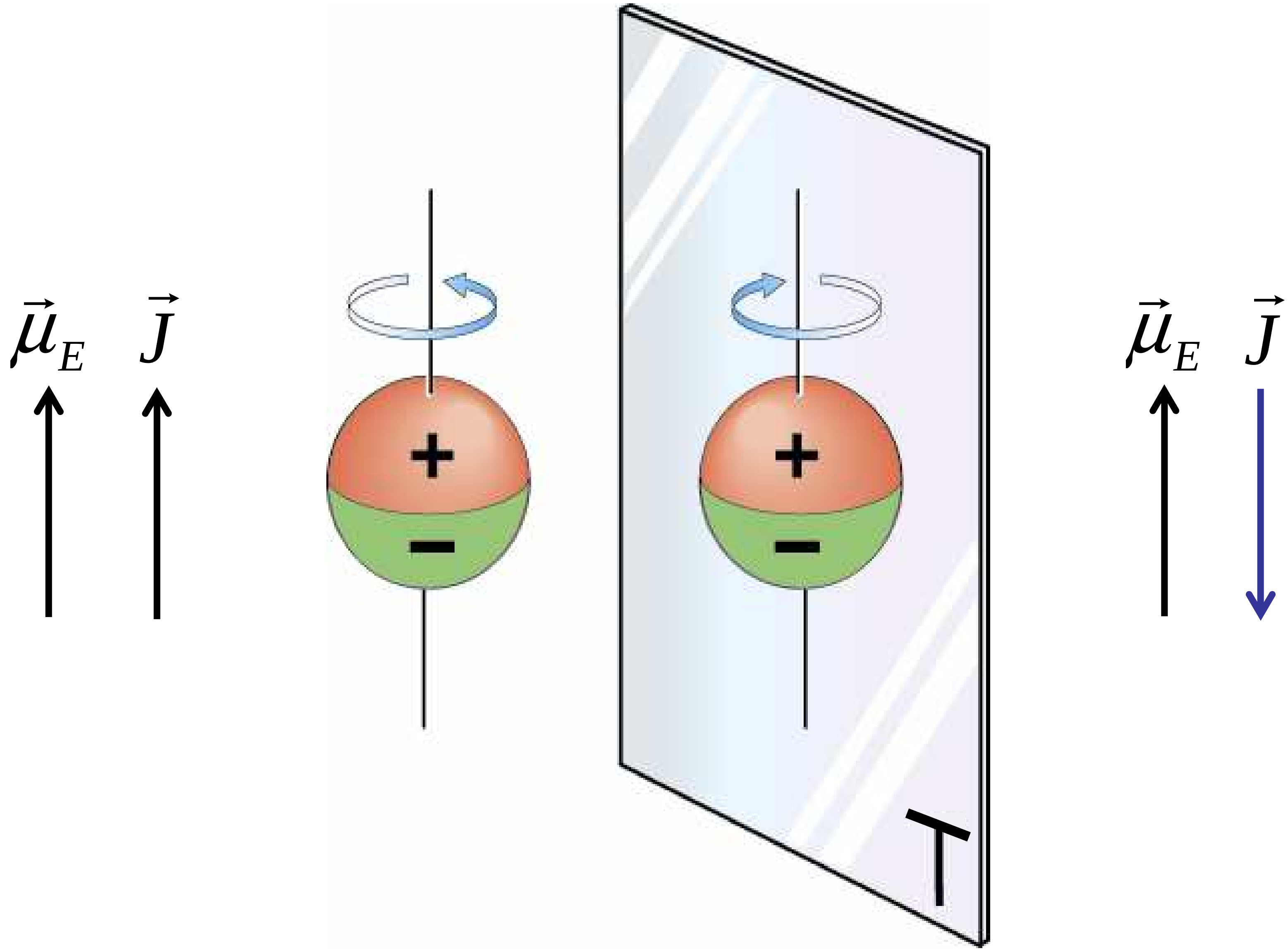
$$B = 2\frac{\left(\frac{g_A}{g_V}\right)^2 - \left(\frac{g_A}{g_V}\right)}{1 - \left(\frac{g_A}{g_V}\right)^2}$$

Neutron beta decay measurements give:

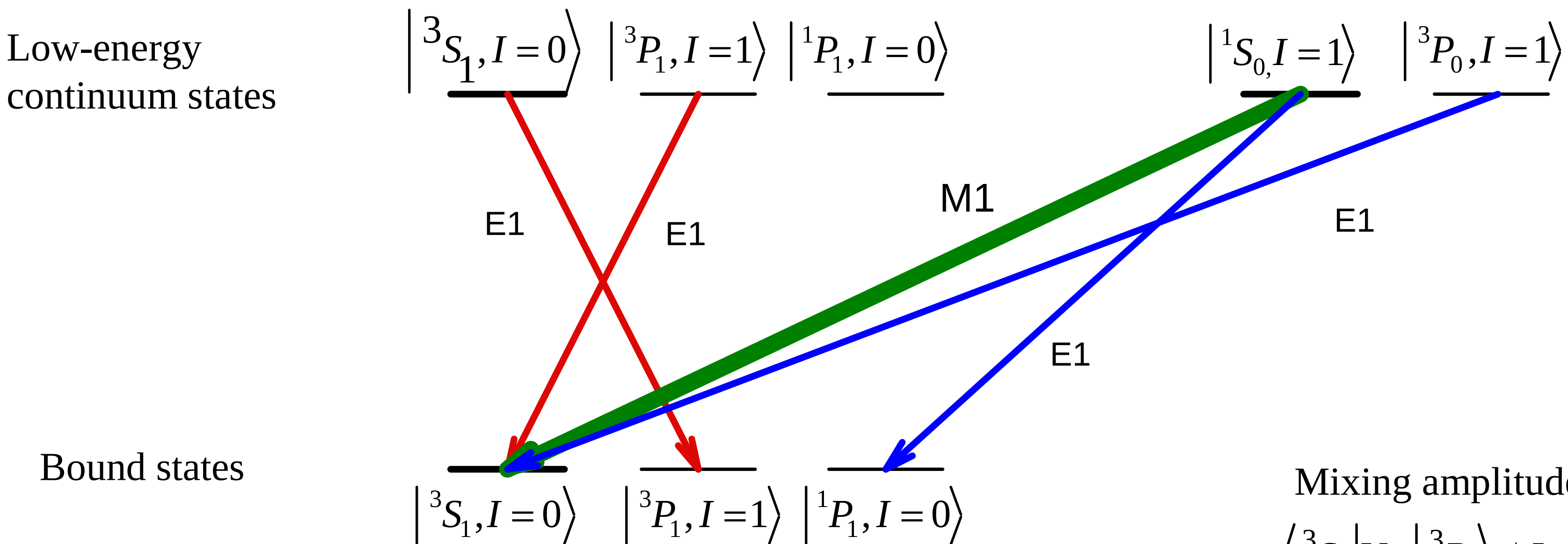
$$(g_V^2 + 3g_A^2)$$

$$g_A / g_V$$

An Electric Dipole Moment Violates T - Invariance



Simple Level Diagram of *n-p* System: $\vec{n}+p \to d+\gamma$ is primarily sensitive to the ΔI = 1 component of the weak interaction



Mixing amplitudes:

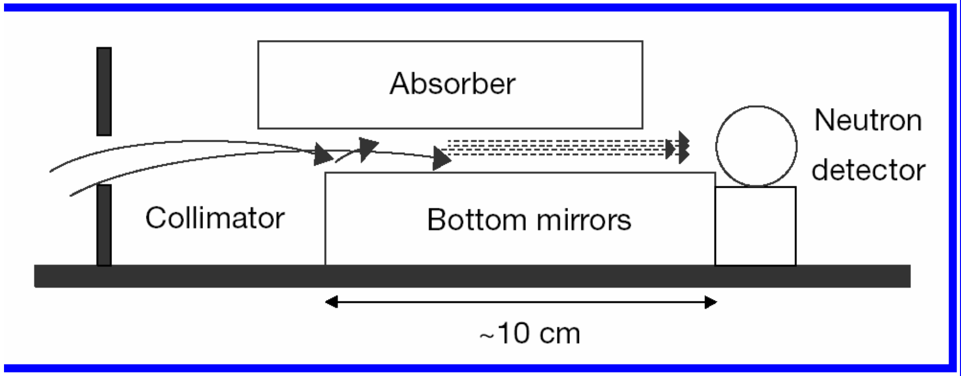
$\langle {}^3S_1 | V_W | {}^3P_1 \rangle; \Delta I = 1$

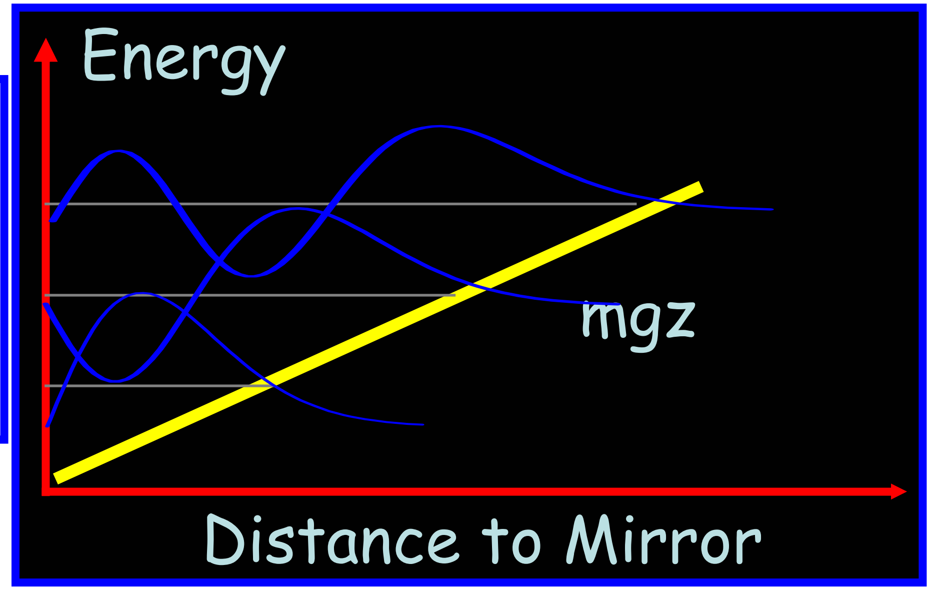
$\langle {}^3S_1 | V_W | {}^1P_1 \rangle; \Delta I = 0$

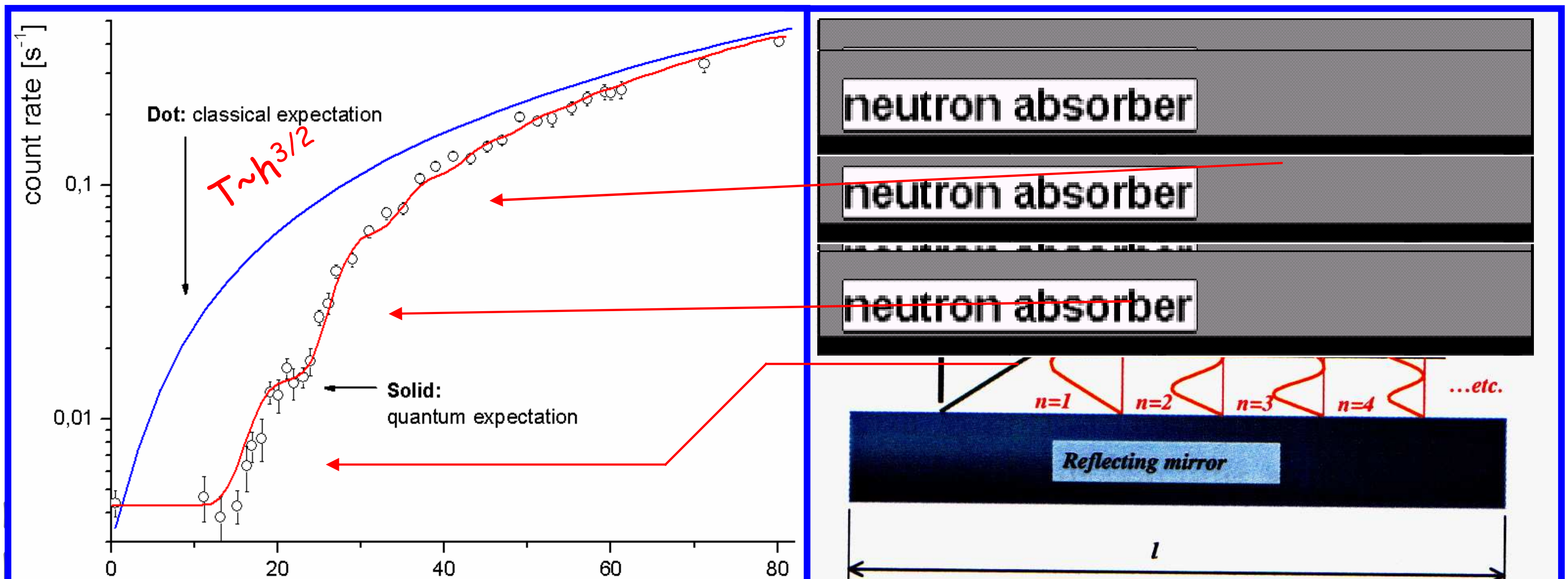
$\langle {}^1S_0 | V_W | {}^3P_0 \rangle; \Delta I = 2$

- Weak interaction mixes in *P* waves to the singlet and triplet *S*-waves in initial and final states.
- Parity conserving transition is *M*1.
- Parity violation arises from mixing in *P* states and interference of the *E*1 transitions.
- A_γ is coming from ${}^3S_1$ - ${}^3P_1$ mixing and interference of *E*1-*M*1 transitions - ΔI = 1 channel.

Observation of Bound Quantum States

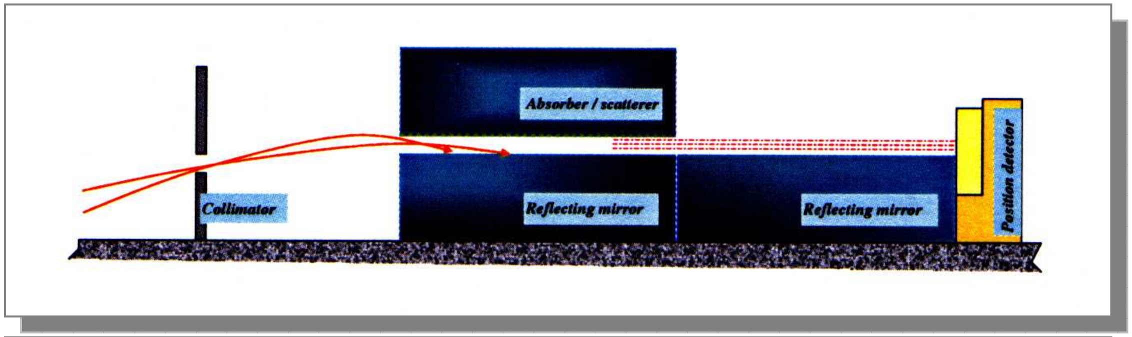


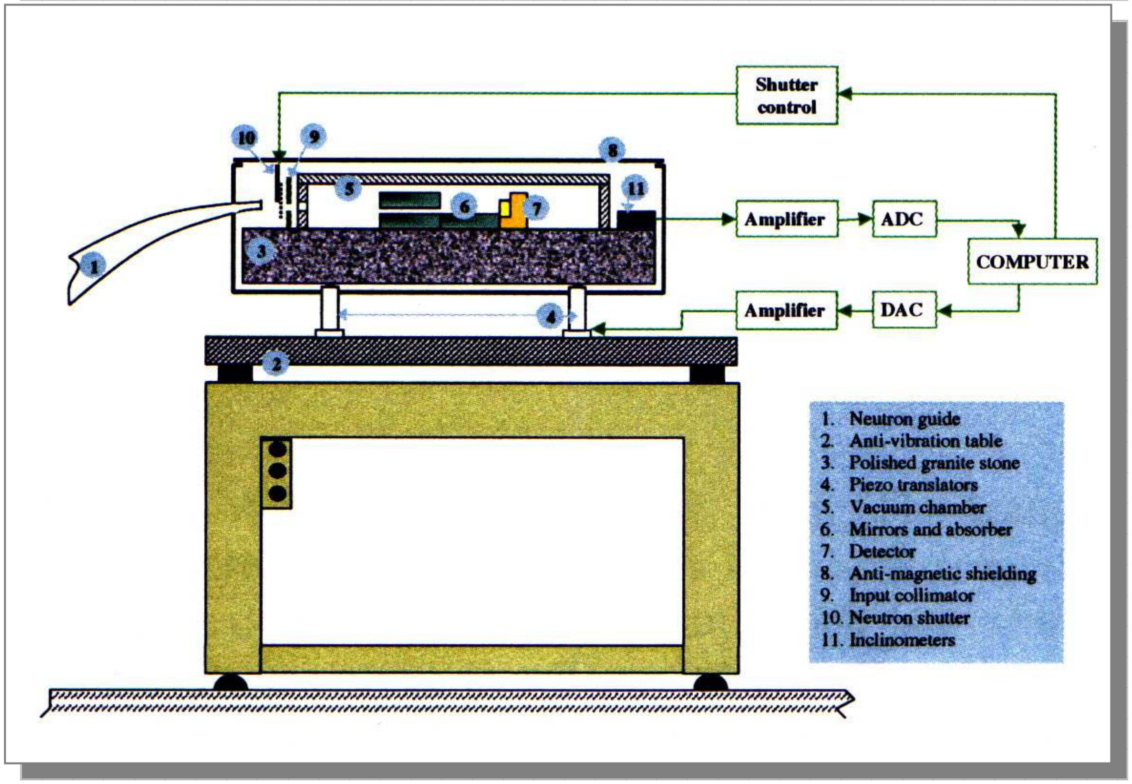




Nature 415 299 (2002), Phys. Rev. D 67 102002 (2003).

the Experiment





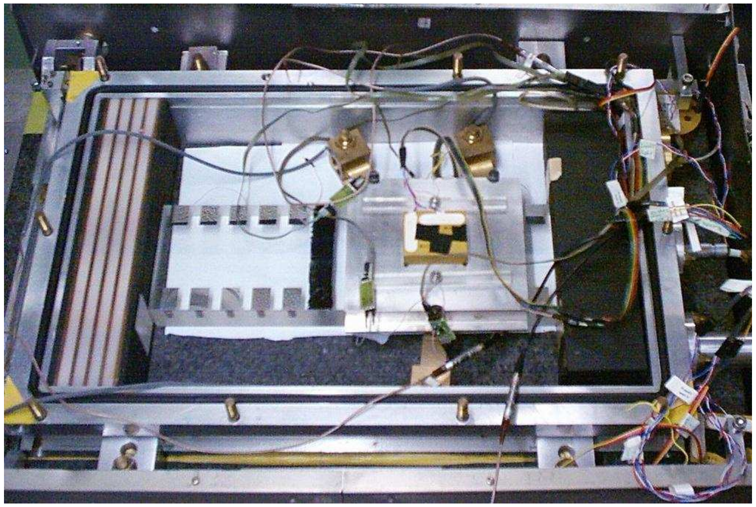
Neutron detection:

a) He – detector

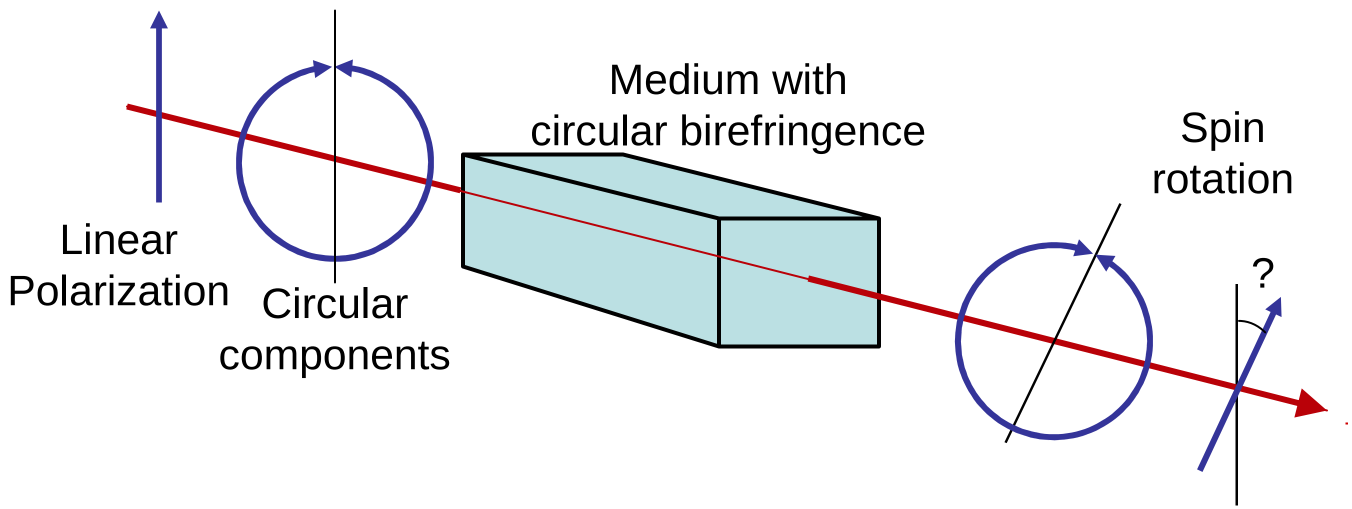
$n + {}^{3}He \rightarrow t + p$
(no spatial resolution)

b) Track detector

$n + {}^{235}U \rightarrow \text{fission}$
$n + {}^{10}B \rightarrow Li + \alpha$

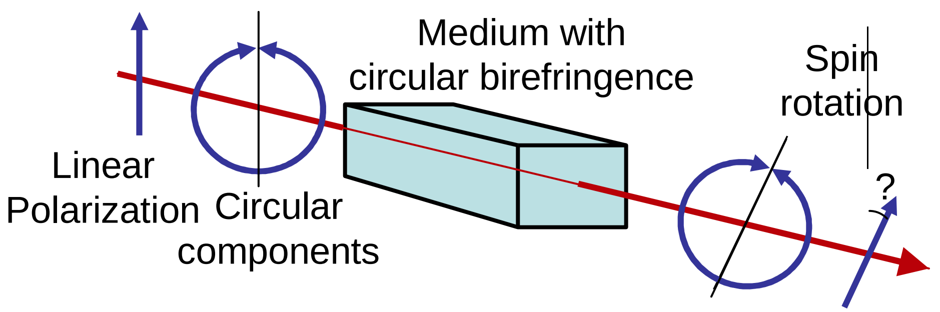


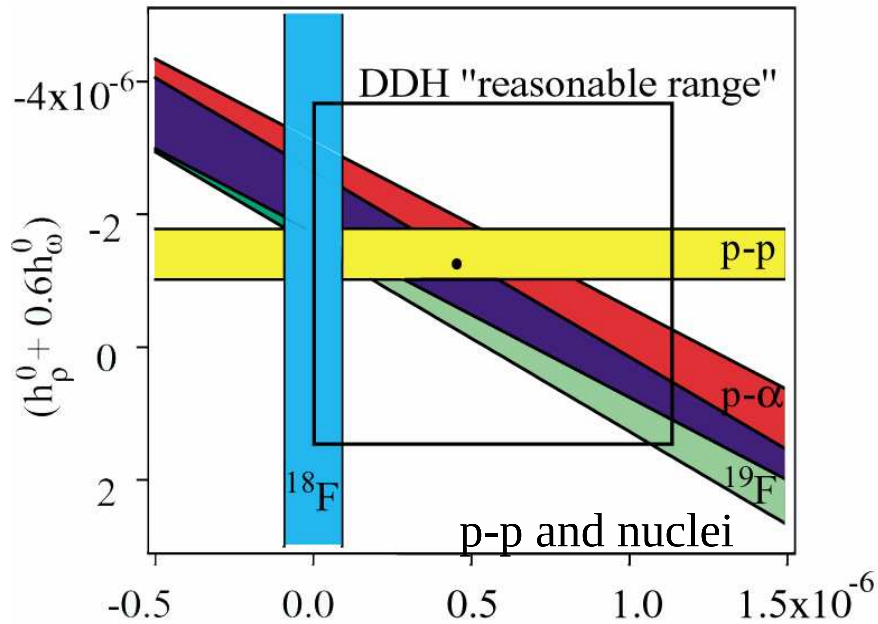
Neutron spin rotation

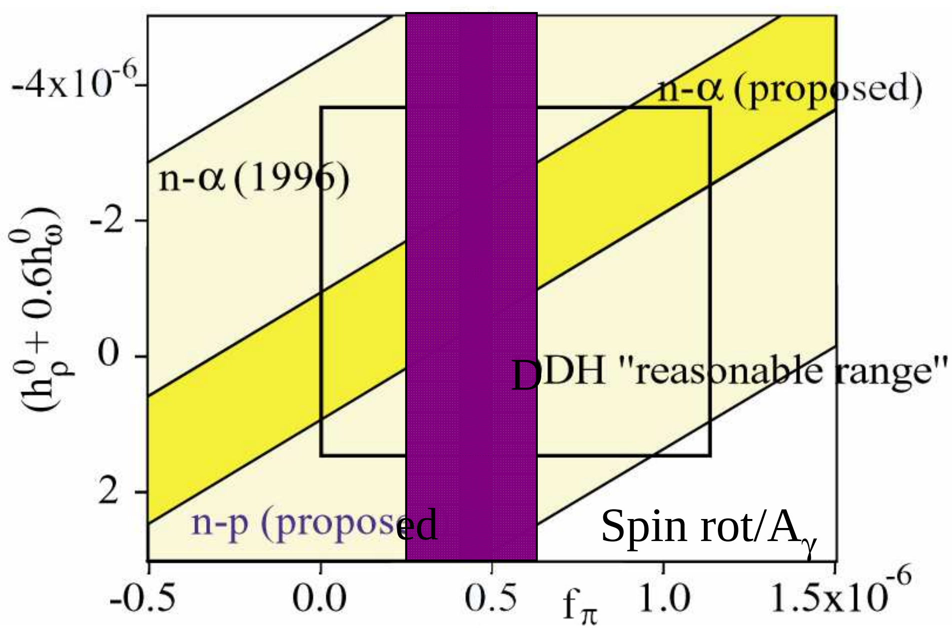


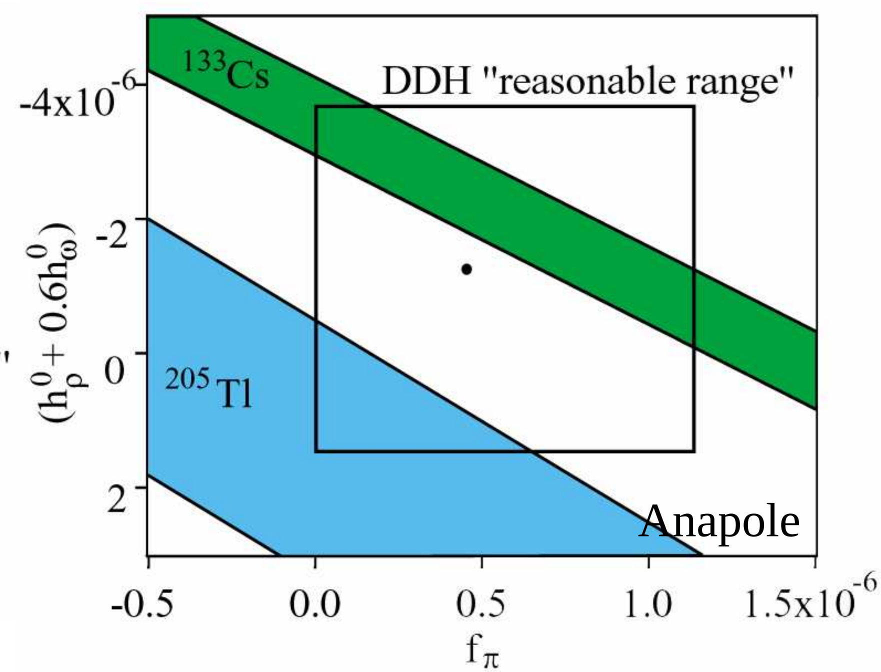
Existing Measurements

Neutron spin rotation

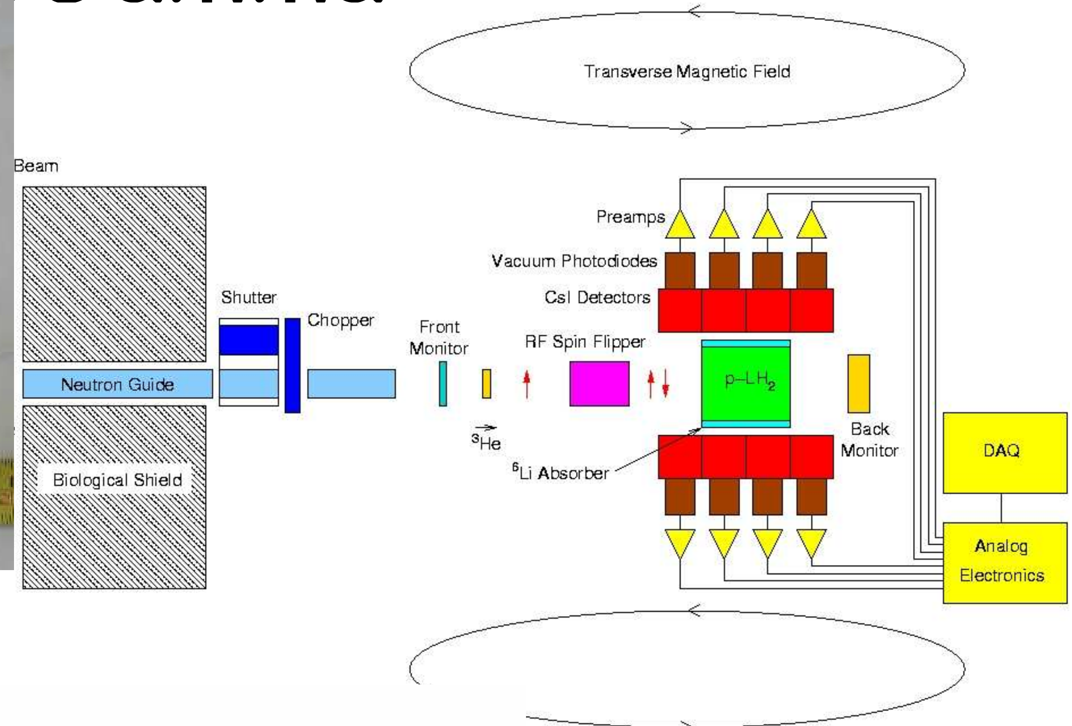


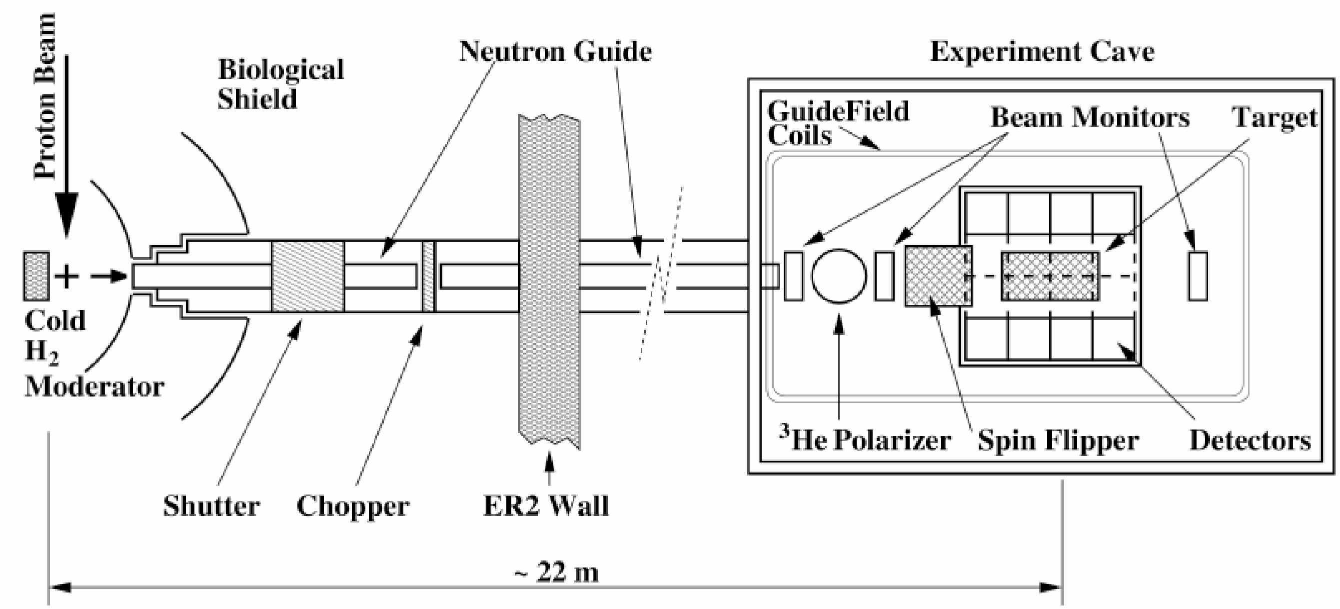




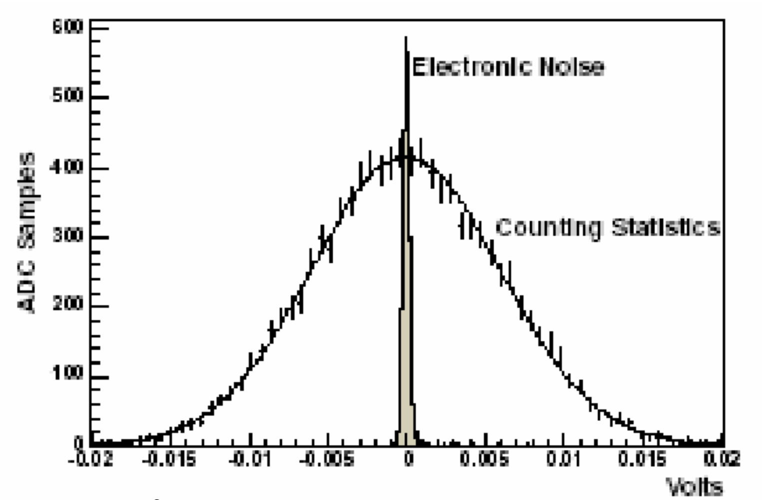


NPDGamma 1

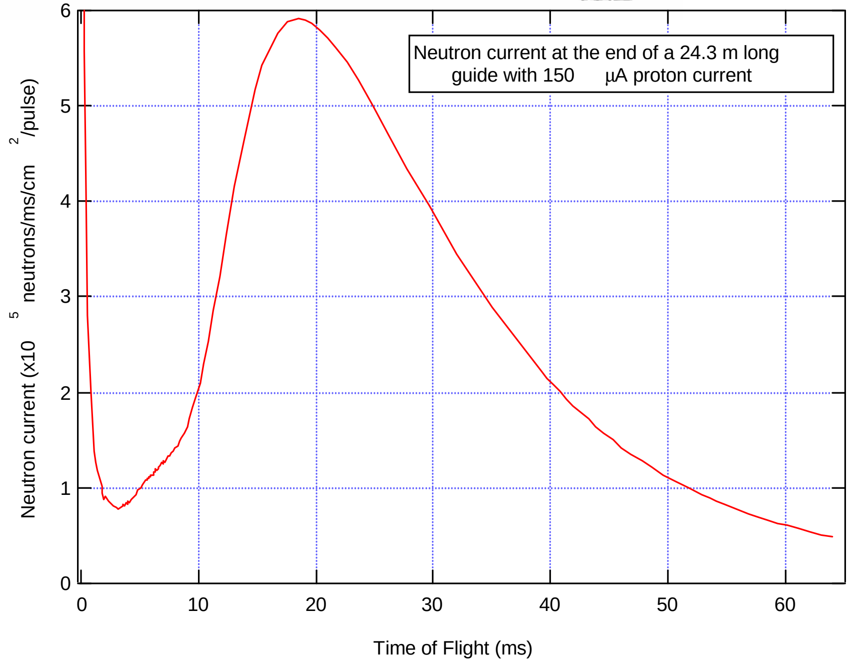

Transverse Magnetic Field
Beam
Neutron Guide
Biological Shield
Shutter
Chopper
Front Monitor
$\vec{^3He}$
^{6}Li Absorber
RF Spin Flipper
Preamps
Vacuum Photodiodes
CsI Detectors
p–LH$_2$
Back Monitor
DAQ
Analog Electronics


Proton Beam
Biological Shield
Neutron Guide
Experiment Cave
GuideField Coils
Beam Monitors
Target
Cold H$_2$ Moderator
Shutter
Chopper
ER2 Wall
^{3}He Polarizer
Spin Flipper
Detectors
~ 22 m

NPDGamma 2



Electronic Noise
Counting Statistics
ADC Samples
Volts



Neutron current at the end of a 24.3 m long guide with 150 µA proton current
Neutron current (x10 5 neutrons/ms/cm 2 /pulse)
Time of Flight (ms)

CsI Detector Array
IU, LANL, KEK

What's next?

- move NPDG to the SNS to achieve goal of $\delta A_\gamma = 5 \times 10^{-9}$
- follow-up experiment: $n + d \rightarrow t + \gamma$