Neutron Physics

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5 lectures:

1. Physics/Technology of Cold and Ultracold Neutrons
2. Electroweak Standard Model Tests [neutron beta decay]
3. Nuclear physics/QCD [weak interaction between nucleons]
4. Physics Beyond the Standard Model [EDM/T violation]
5. Other interesting stuff that neutrons can do [NNN interaction, searches for extra dimensions,…]

Nuclear Physics/QCD with Neutrons

1. The weak NN interaction
2. Nuclear and Atomic parity violation
3. Connection with QCD
4. NN weak interaction theoretical description
5. Examples of experiments

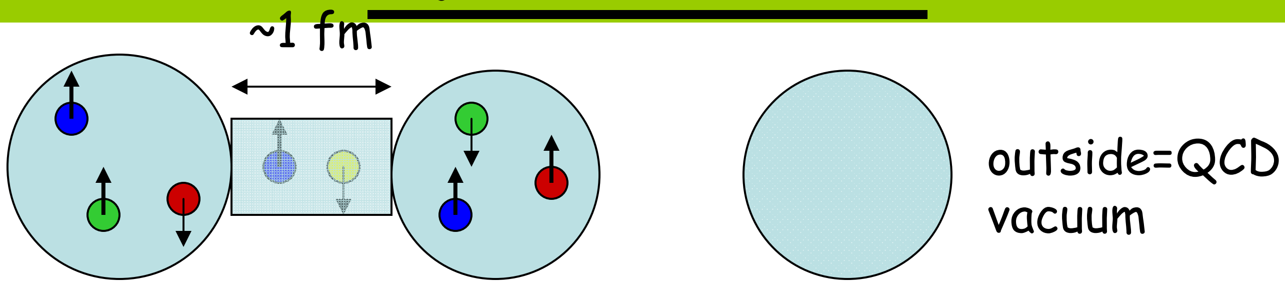
Thanks for slides to: Seppo Penttila (LANL), Shelley Page (Manitoba), Diane Markoff (TUNL)

The Weak NN Interaction

M. Snow, Indiana

- What is the weak NN interaction and how big is it?
- Why study the weak NN interaction? [describe weak interaction in nuclei and atoms, study qq correlations in strong limit of QCD]
- Status of knowledge of weak NN interaction [it certainly exists, but current data+theory is inconsistent]
- What can be done? [measure PV spin rotation in n+p and n+4He, PV gamma asymmetry in n+p and n+D, determine 4 of the NN weak couplings using only few-body systems]

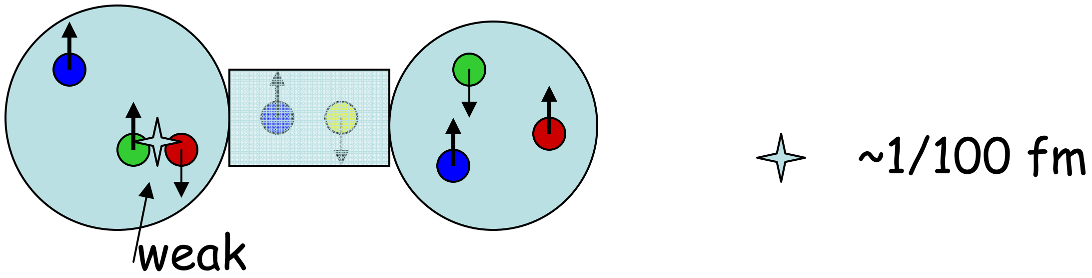
The Weak NN Interaction: What is it?



$|N\rangle = |qqq\rangle + |qqqqq\rangle + \ldots =$ "valence"+"sea" quarks+… interacts through strong NN force (residue of QCD)

Mediated in part by mesons $|m\rangle = |q\bar{q}\rangle + |qq\bar{q}\bar{q}\rangle + \ldots$

Both interactions have long range, conserve parity



If the quarks are close, they can also interact via the weak interaction, which violates parity.

Relative strong/weak amplitudes:
$[g^2/m_\pi^2]/[e^2/m_W^2] \sim 10^7$

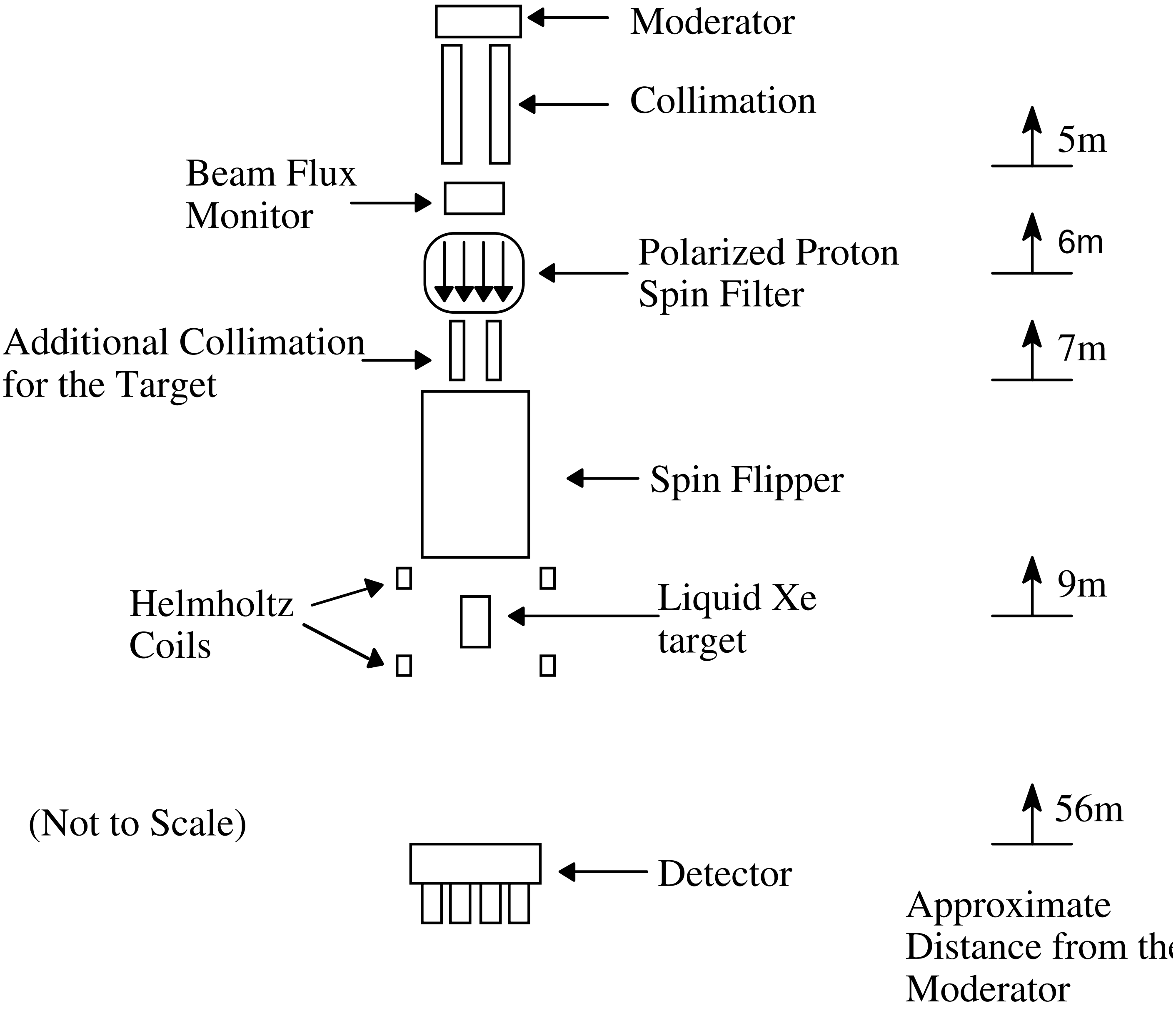
Who Needs the Weak NN Interaction?

- PV in atomic physics: effect of nuclear anapole moment on atomic structure [seen in 133Cs, searches in Tl, plans in Fr, Yb,…]

- PV in p-shell and light s-d shell nuclei with parity doublets [lots of good measurements (14N, 18F, 19F, 21Ne), but shell model calculations converge slowly for P-odd operators]

- PV in heavy nuclei [TRIPLE measurements +theoretical analysis with chaotic nuclear wavefunctions gives prediction for weak couplings]
- PV electron scattering [attempt to isolate strange sea quark effects in N using parity violation, but weak qq/anapole effects in N also present]
- Weak NN interaction needed to understand PV in atomic, nuclear, and hadronic systems

PV in Heavy Nuclei(TRIPLE)



Moderator

Collimation

Beam Flux
Monitor

Polarized Proton
Spin Filter

Additional Collimation
for the Target

Spin Flipper

Helmholtz
Coils

Liquid Xe
target

(Not to Scale)

Detector

5m

6m

7m

9m

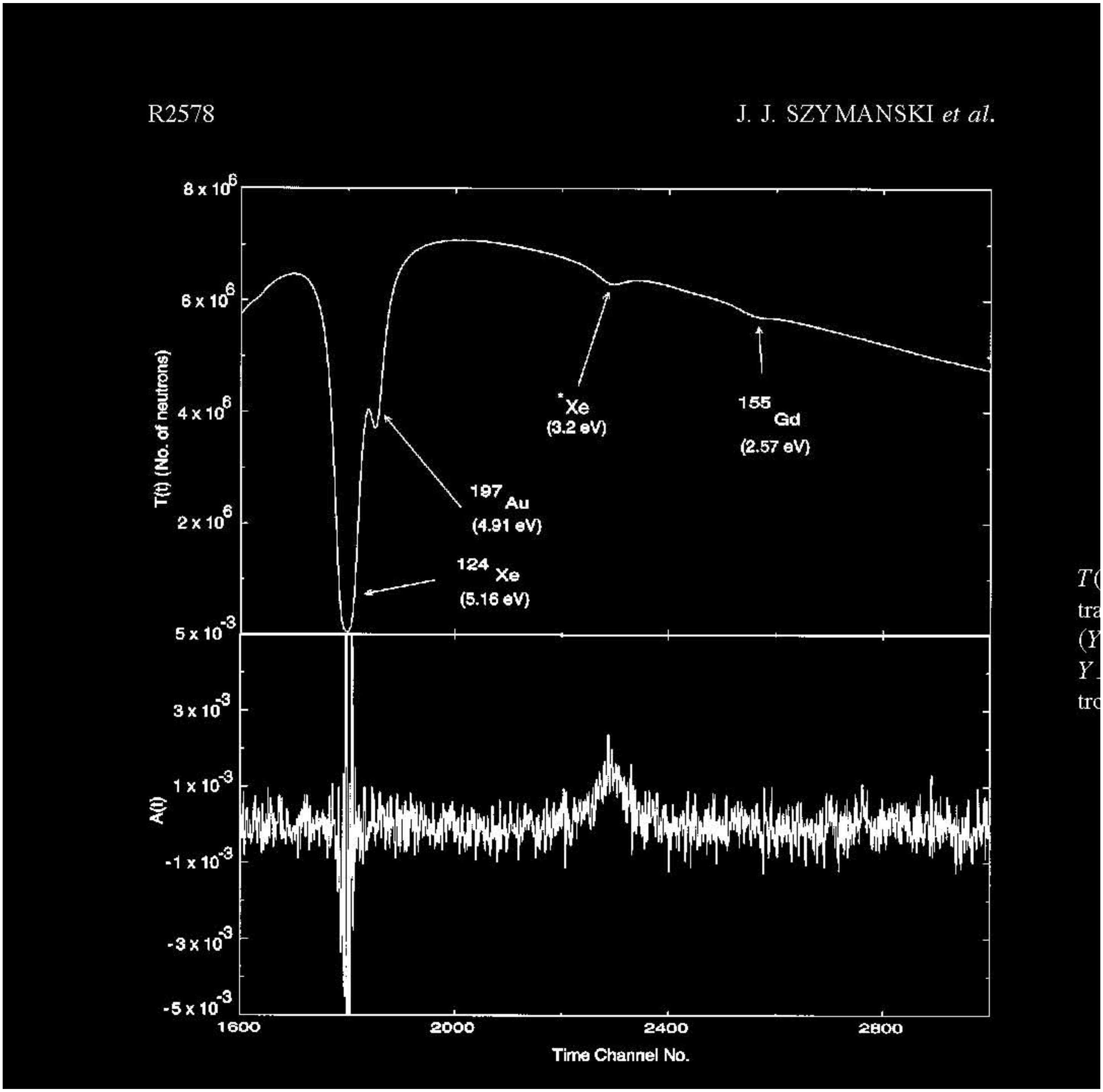
56m

Approximate
Distance from th
Moderator

Measure neutron helicity dependence of total cross section. $\sigma_{\pm}=\sigma\pm(s_n\bullet p_n)\sigma_p$. Violates P, picks out weak interaction amplitude

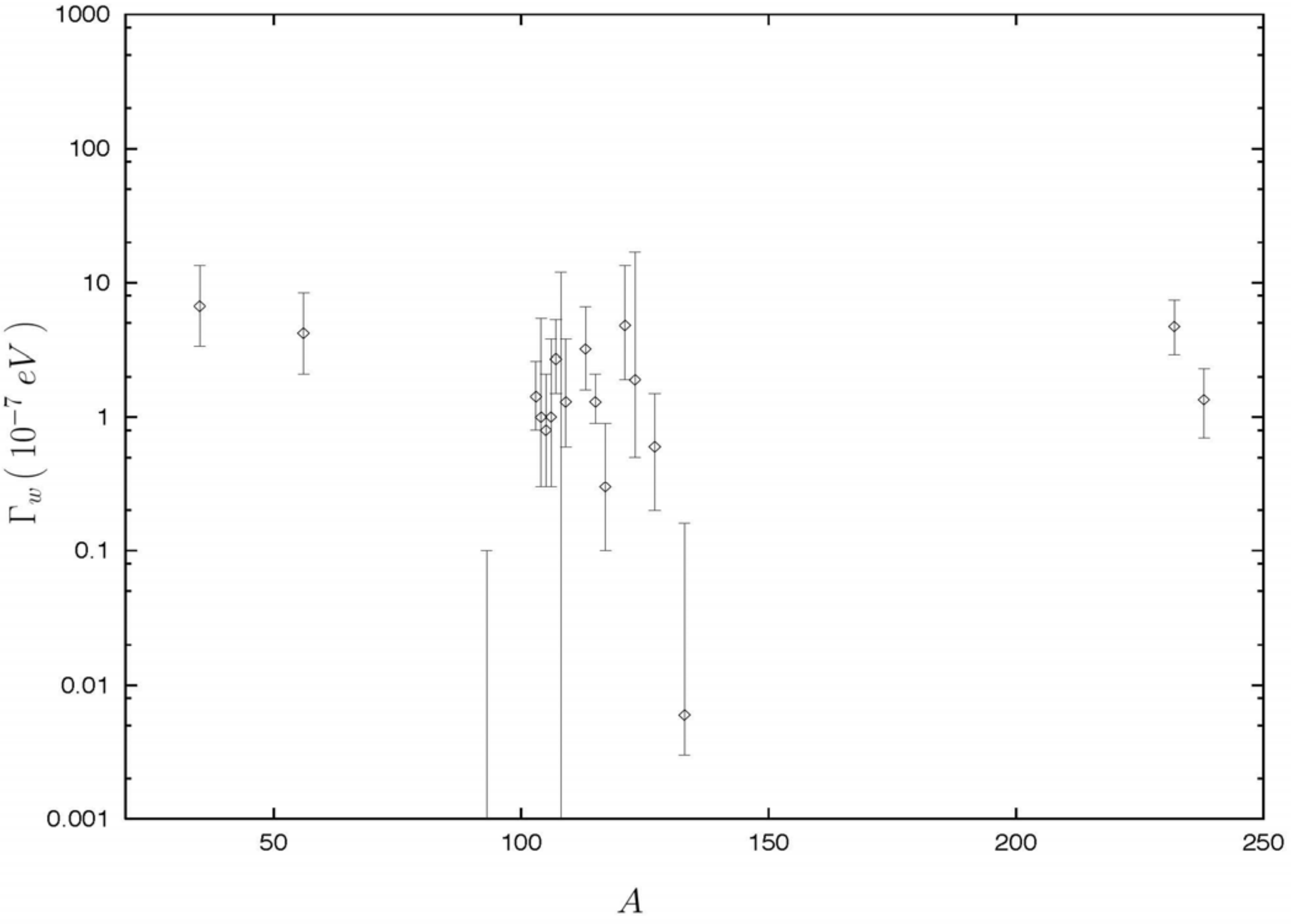
Ex: PV Asymmetry in 131Xe

PV analyzing power=4% at 3.2 eV resonance!
Huge amplification of expected 10-7 effect….



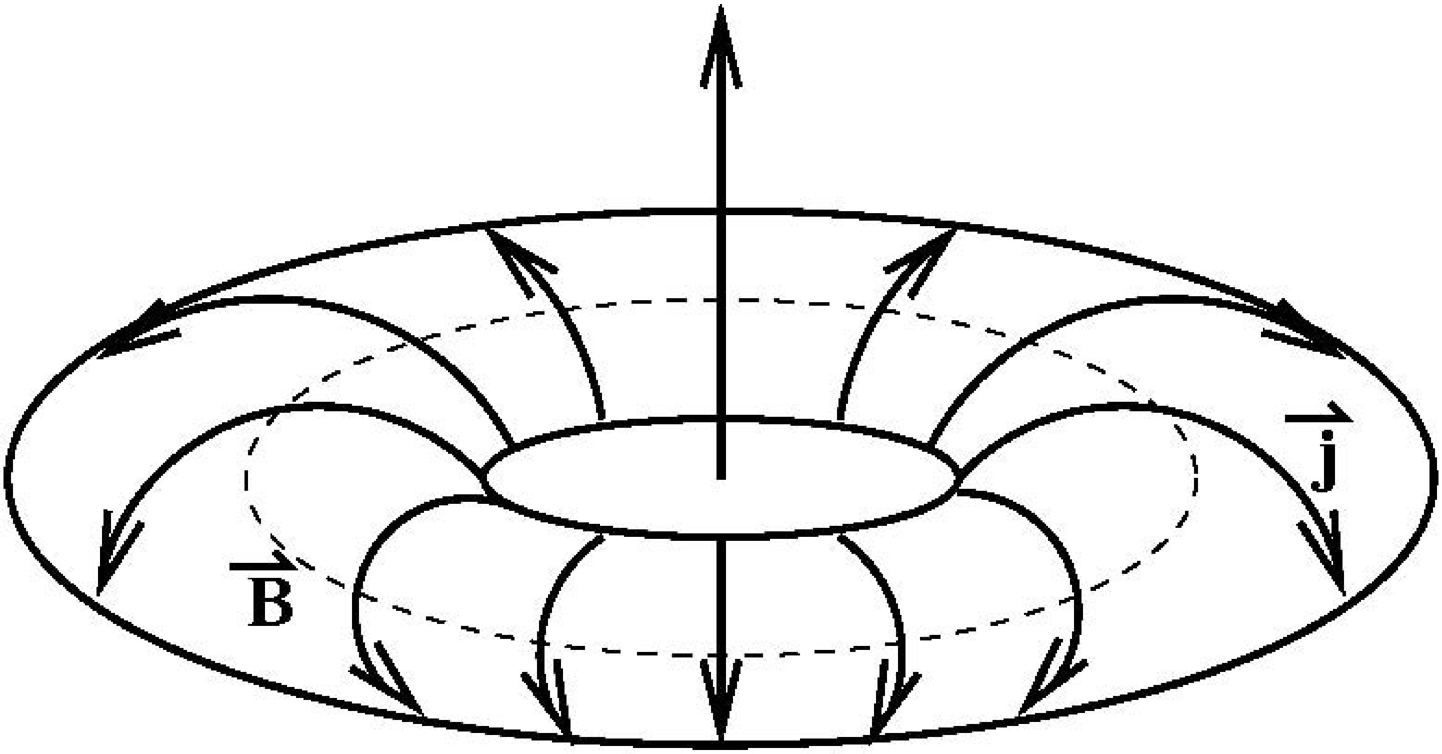
R2578 J. J. SZYMANSKI *et al.*

Weak Matrix Elements in Heavy Nuclei



Measure at many resonances in many nuclei
Apply statistical spectroscopy techniques to determine mean square PV matrix elements in isoscalar and isovector channels
Get a result consistent with rough estimates

Nuclear Anapole Moment



Parity-odd coupling to virtual photon(=αG_F)
due to weak NN
Dominantcontribution to P-odd radiative corrections
in heavy nuclei (=$A^{2/3}$)
Classical analog: toroidal current distribution
$\vec{A}(r) \to \vec{a}\delta(r) \sim \int dV\, r^2\, \vec{J}(r)$
Doesn't make long-range fields (and therefore does not appear in Jackson!)
Helicity of current windings~parity-odd
Measured for 133Cs

Connection with NN PV

$|\psi\rangle=|s\rangle|\uparrow\rangle+[|p\rangle\langle p|H_W|s\rangle\ /\Delta E]\ |\uparrow\rangle$, $H_W=Gs\bullet p$
$=[1-iGs\bullet r]|s\rangle|\uparrow\rangle$

=spin rotation about r, tilts spin to give a helical current, violating parity and generating an anapole moment (Haxton and Wieman)

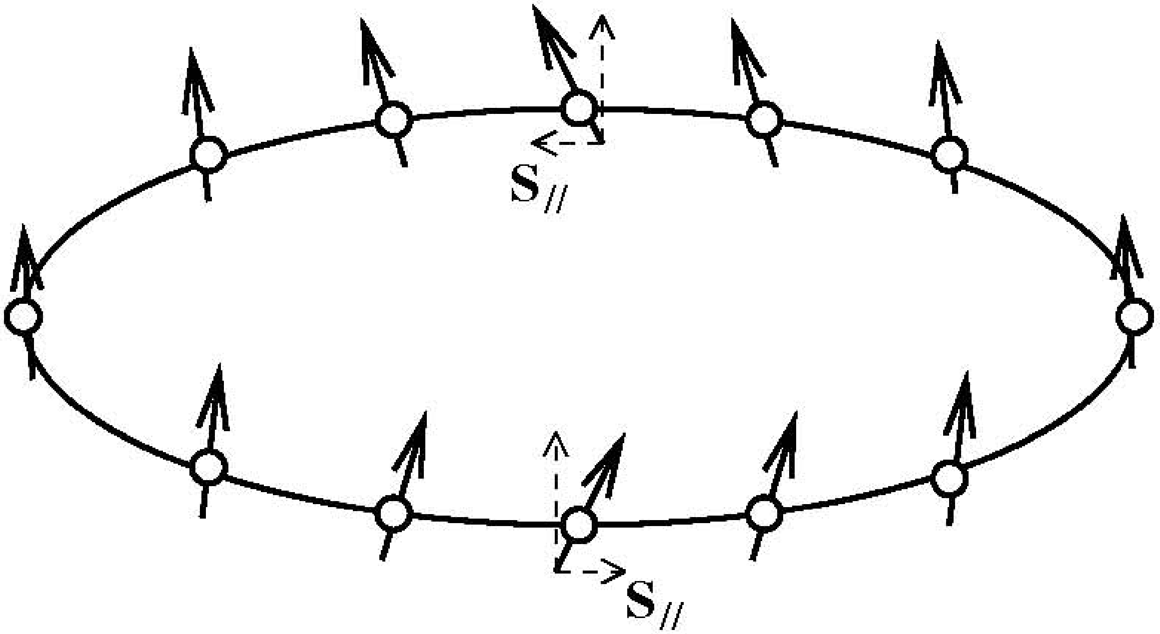
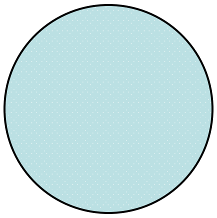
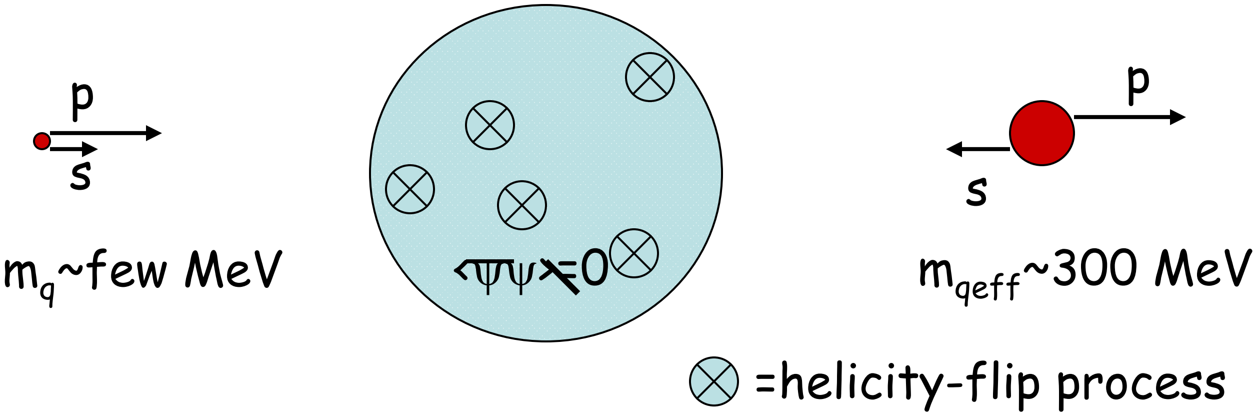


FIG. 2. Spin helix structure due to the parity mixing.

What can the Weak NN Interaction do for QCD?



QCD |vacuum>: 2 (distinct?) phenomena:Chiral symmetry breaking +quark confinement



- Physical nature of the ground state of QCD is not understood (instantons? diquarks?)
- Single-particle models (quark model, bag model) are wrong.
- Chiral symmetry breaking seems to dominate dynamics of light hadrons such as protons and neutrons
- Strong QCD is really many body physics.
- Lesson from condensed matter physics: understand the correlations!
- *weak qq interaction range~1/100 size of nucleon-> sensitive to short-range q-q correlations+vacuum modifications, an "inside-out" probe*

QCD vs Electroweak: which is more "fundamental" ?

$L_{QCD}=-1/4\, F^{\mu\nu} F_{\mu\nu}+q(i\not{D}-m)q\ (\theta_{QCD}=0)$

$L_{EW}= L_V + L_F+ L_{Higgs}+ L_{int}$

$L_V = =-1/4\, F^{\mu\nu} F_{\mu\nu}+m_W^2(W_+^2+ W_-^2)/2$

$+m_Z^2 Z^2/2$

$L_F= q(i\not{D}-m)q$

$L_{higgs}= \partial_\mu \phi\, \partial^\mu \phi\ -m_H^2\phi^2$

$L_{int}= L_{VF} + L_{HV}+ L_{HF}+ L_{HH}$

$L_{VF} =g/2(W_+^\mu J_{+\mu} +W_-^\mu J_{-\mu})$

$+e A^\mu J_{\mu,EM}+g/\cos\theta_W Z^\mu J_{\mu,neut}$

$L_{HV}=[m_W^2(W_+^2+ W_-^2)/2+m_Z^2 Z^2/2]\ \phi/\rho(1+$

$\phi/2\rho)$

$L_{HF}= qMq\ \phi/\rho$

$L_{HH}=- \rho\lambda\phi^3/6 - \lambda\phi^4/24$

Standard Model Structure of Low-Energy qq Weak Interaction

- At low energies H_{weak} takes a current-current form with charged and neutral weak currents

$H_{weak} \sim G_F(J^{c\dagger} J^c + J^{n\dagger} J^n)$, where

$J^c_\mu = u\gamma_\mu(1+\gamma_5)d'$; $J^n_\mu = u\gamma_\mu(1+\gamma_5)u - d\gamma_\mu(1+\gamma_5)d - s\gamma_\mu(1+\gamma_5)u - 4\sin^2\theta_W J^{EM}_\mu$

- Isospin structure: $\Delta I = 0, 1, 2$
- $H_{weak}^{\Delta I=2} \sim J_c^{I=1} J_c^{I=1}$, charged currents
- $H_{weak}^{\Delta I=1} \sim J_c^{I=1/2} J_c^{I=1/2} + J_n^{I=0} J_n^{I=1}$

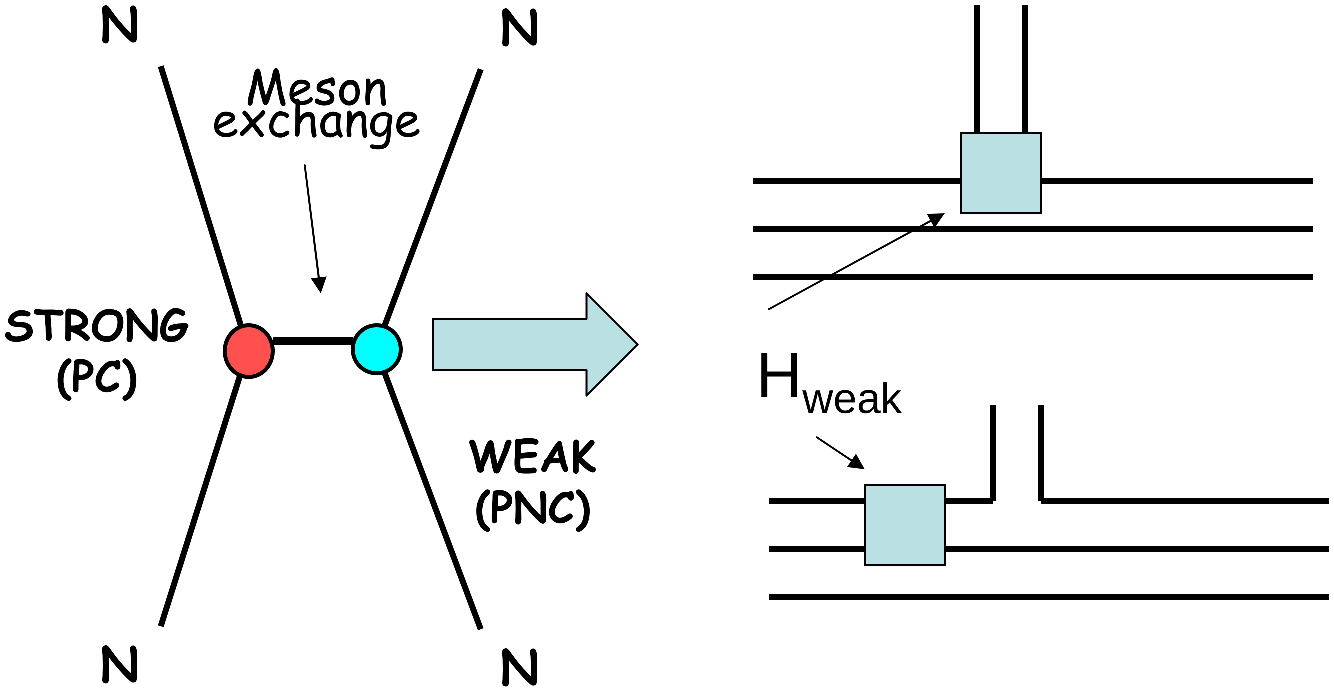
neutral current will dominate the $\Delta I = 1$ channel [unless strange sea quarks contribute].

- $H_{weak}^{\Delta I=0} \sim J_c^{I=0} J_c^{I=0} + J_n^{I=0} J_n^{I=0}$

$+ J_n^{I=1} J_n^{I=1}$, both charged and neutral currents

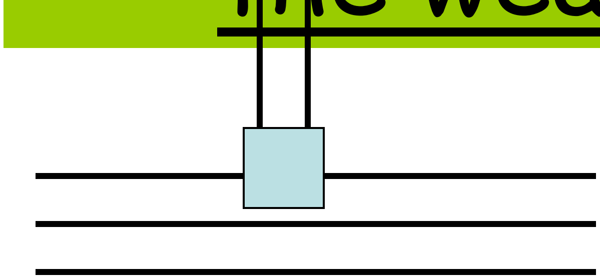
➲ H_{weak} is known,can be used to probe QCD

Weak NN Interaction



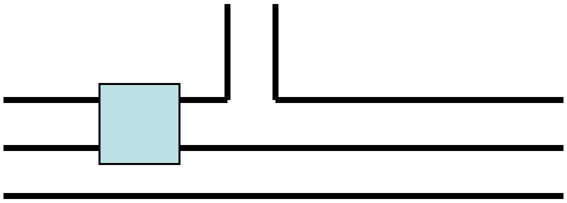
- P-odd partial waves [5 S->P transition amplitudes]
- Meson exchange model for weak NN [effect of qq weak interactions parametrized by ~6 couplings]
- χ perturbation theory [Musolf&Holstein, under construction, incorporates chiral symmetry of QCD]
- Physical description starting from Standard Model [need QCD in strong interaction regime, lattice+EFT extrapolation (Beane&Savage)]

qq weak processes hidden in the weak NN vertex



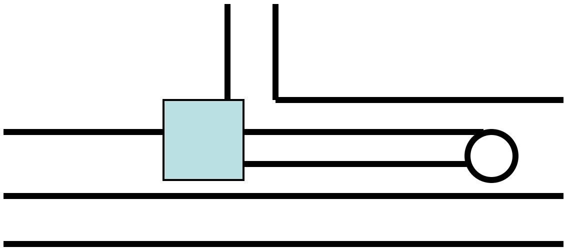
"factorization" amplitude
$[\langle N| H_{weak}|Nm\rangle$
$\sim\langle 0|qq|m\rangle\langle N|q\,\gamma_5 q|N\rangle]$

Valence quarks

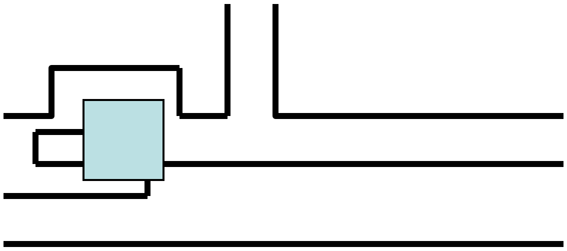


P-odd admixture into N

DDH



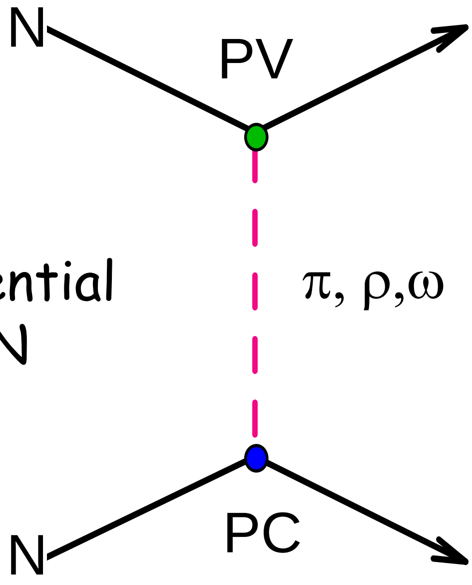
sea quarks



"disconnected" sea quarks from χ corrections [Zhu et al]

- Non-negligible amplitudes from u,d,s sea quarks
- Sign cancellations among different contributions

Meson Exchange Model (DDH)



assumes π, ρ, and ω exchange dominate the low energy PNC NN potential as they do for strong NN

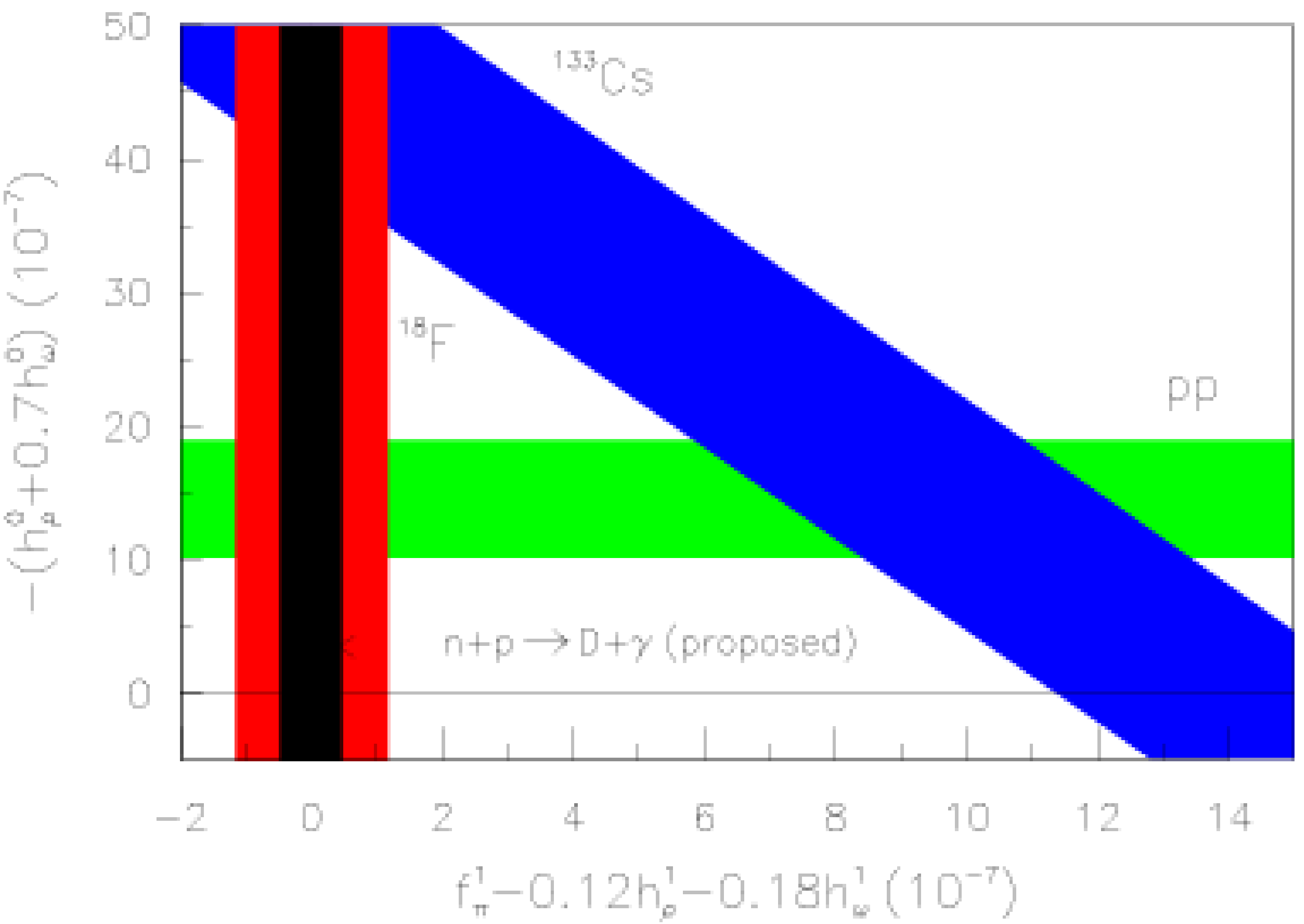
Barton's theorem [CP invariance forbids coupling between S=0 neutral mesons and on-shell nucleons] restricts possible couplings

one consequence: pp parity violation blind to weak pion exchange [need np system to probe $H_{weak}^{\Delta I=1}$]

weak meson exchange coupling constants

$f_\pi, h_\rho^0, h_\rho^1, h_\rho^2, h_\omega^0, h_\omega^1$

"should" suffice [but are chiral corrections large?]



data from p-p, 133Cs anapole moment, and 18F are inconsistent, adding p-4He and 19F does not help [Haxton et al]

odds are low for great progress in theory for PV in medium/heavy nuclei

What can be learned with Low Energy Neutrons?

For elastic scattering, A_z->0 as p ->0

Hard to flip spin quickly for large polarized targets

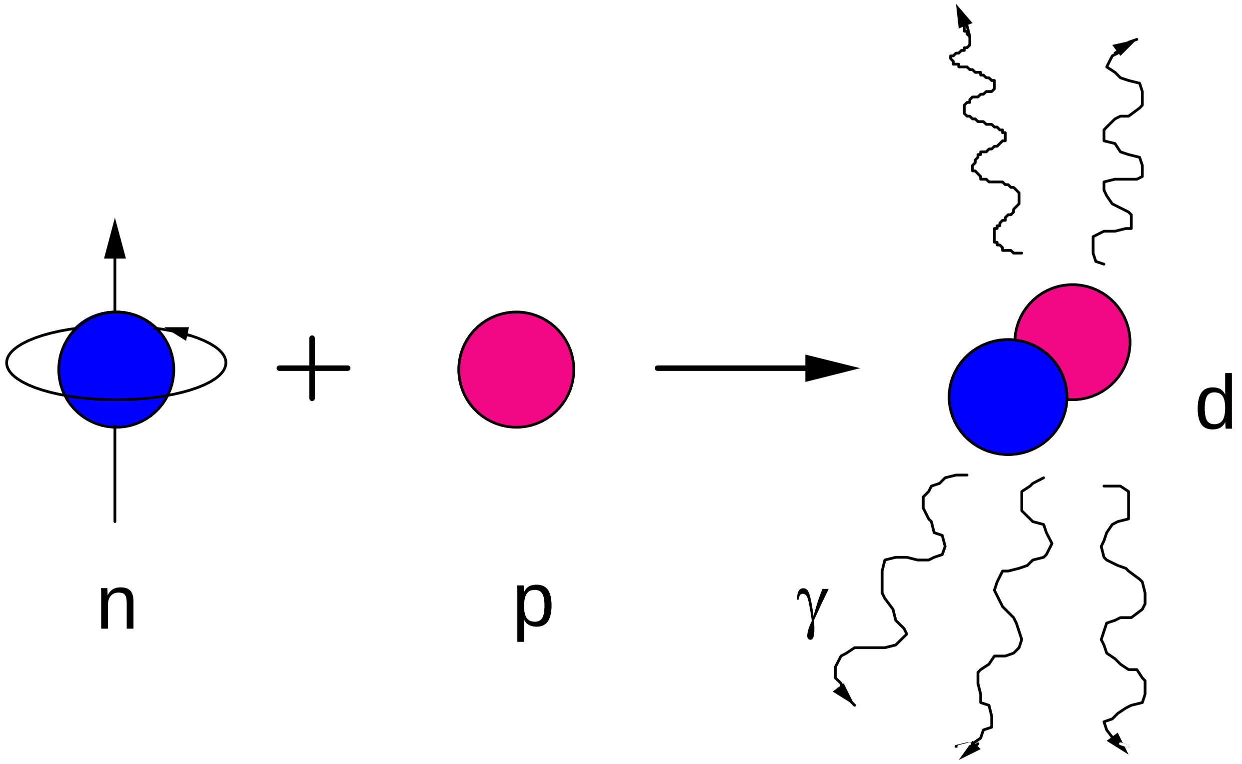
MeV gamma polarimeters are inefficient

Easy to flip neutron spin

-> 2 classes of experiments: PV spin rotation [~Re(f)] and reactions with inelastic channels [gamma capture]

Possible experiments: PV spin rotation in n-p and n-4He, PV gamma asymmetry in n-p and n-D

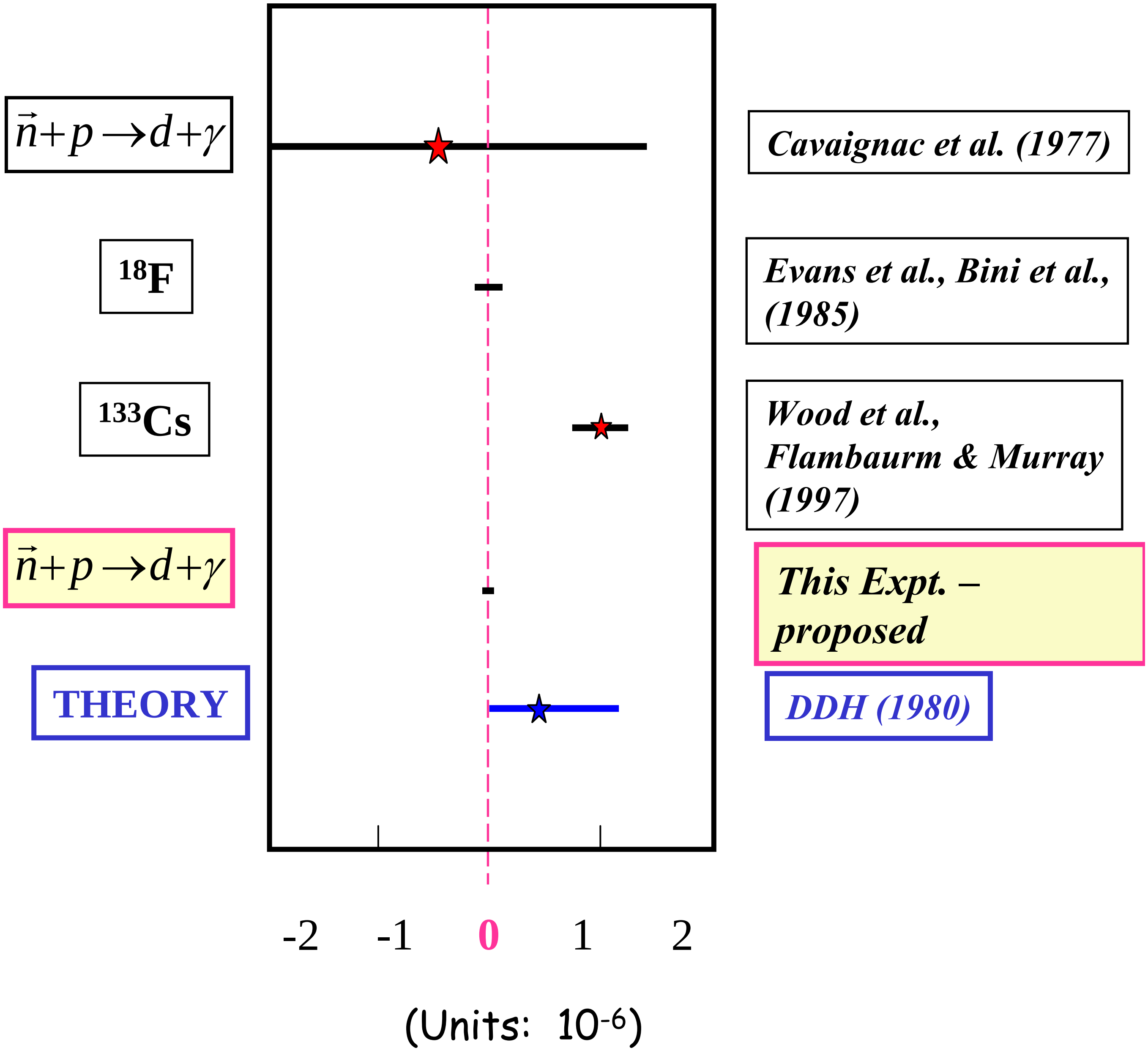
PV Gamma Asymmetry in Polarized Neutron Capture



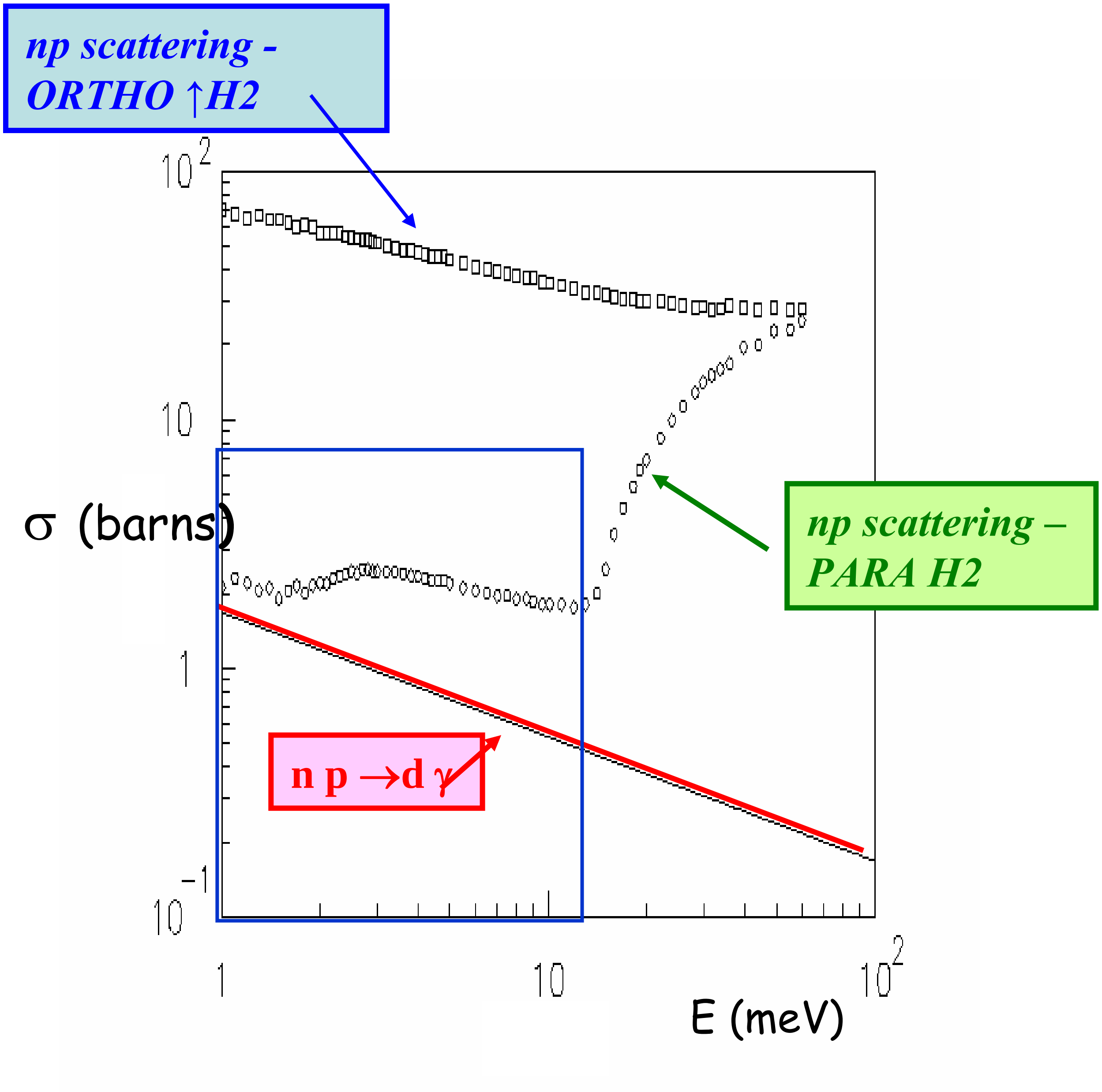
- Asymmetry A_γ of gamma angular distribution upon polarized neutron capture due to weak NN interaction [from $s_n \bullet p_\gamma$]
- A_γ independent of neutron energy away from resonances
- H has low A and negligible neutron spin-flip scattering (parahydrogen)
- Determines weak pion coupling

- Goal: 5×10^{-9} for A_γ in $n+p \to D+\gamma$

Current Knowledge of f_π



How to capture neutrons - low energy cross sections:



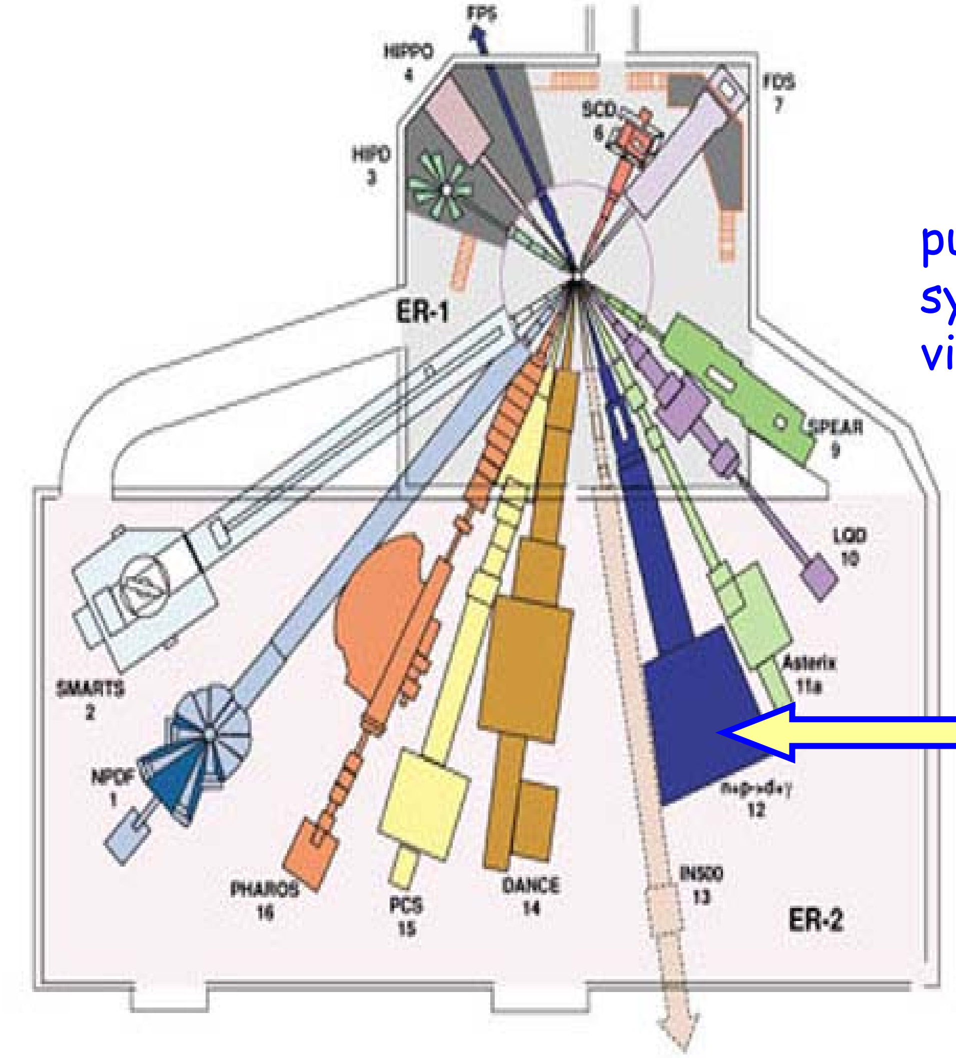
np scattering - ORTHO ↑H2

np scattering – PARA H2

n p →d γ

- useful energy range is ~ 1 – 15 meV
- PARA – H_2 target is essential

Where to capture neutrons new beamline at LANSCE

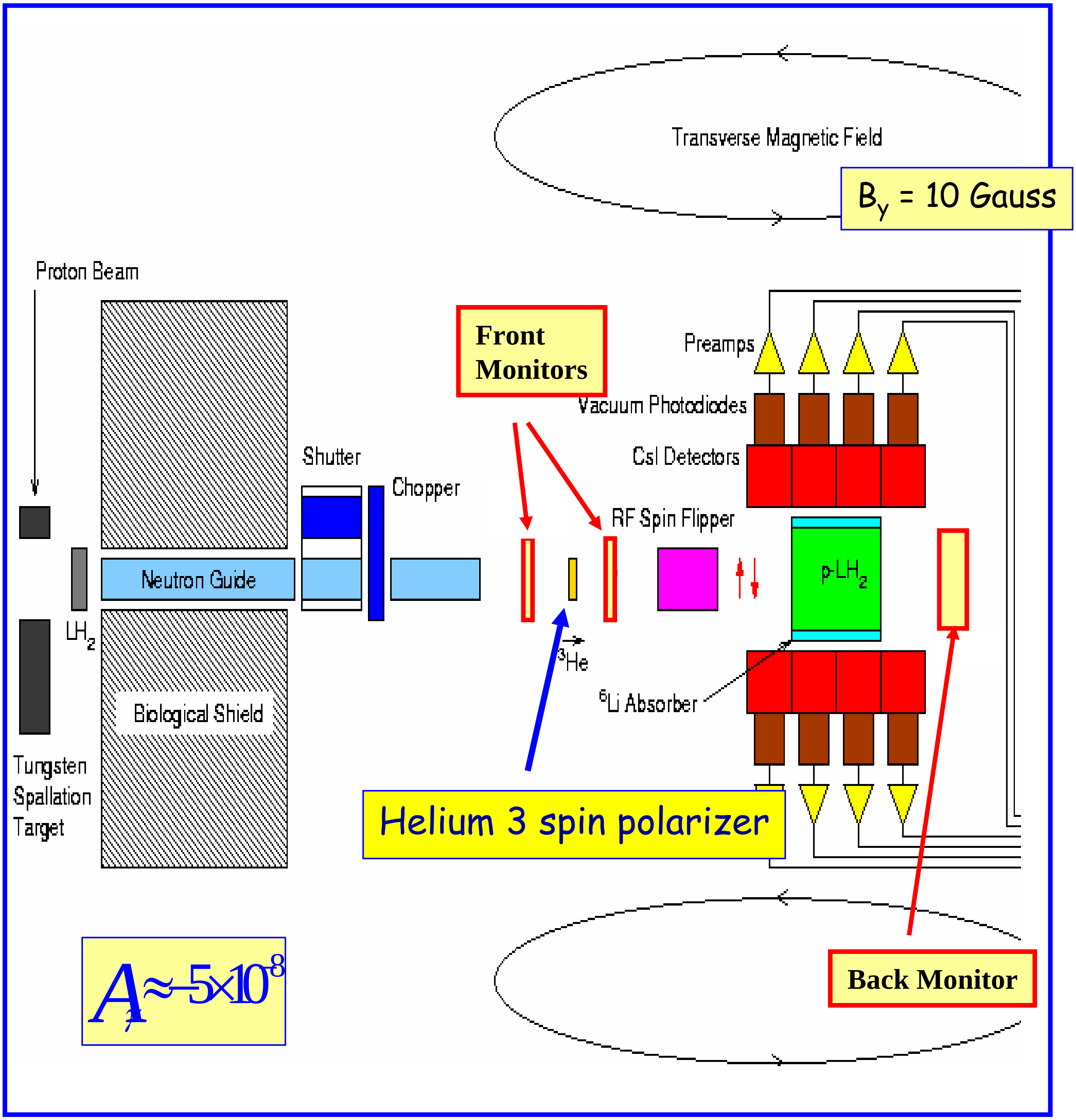


pulsed beam allows systematic checks via time of flight.

FP 12,
NPDGamma

Los Alamos
NATIONAL LABORATORY

Experimental Apparatus



B_y = 10 Gauss

Front Monitors

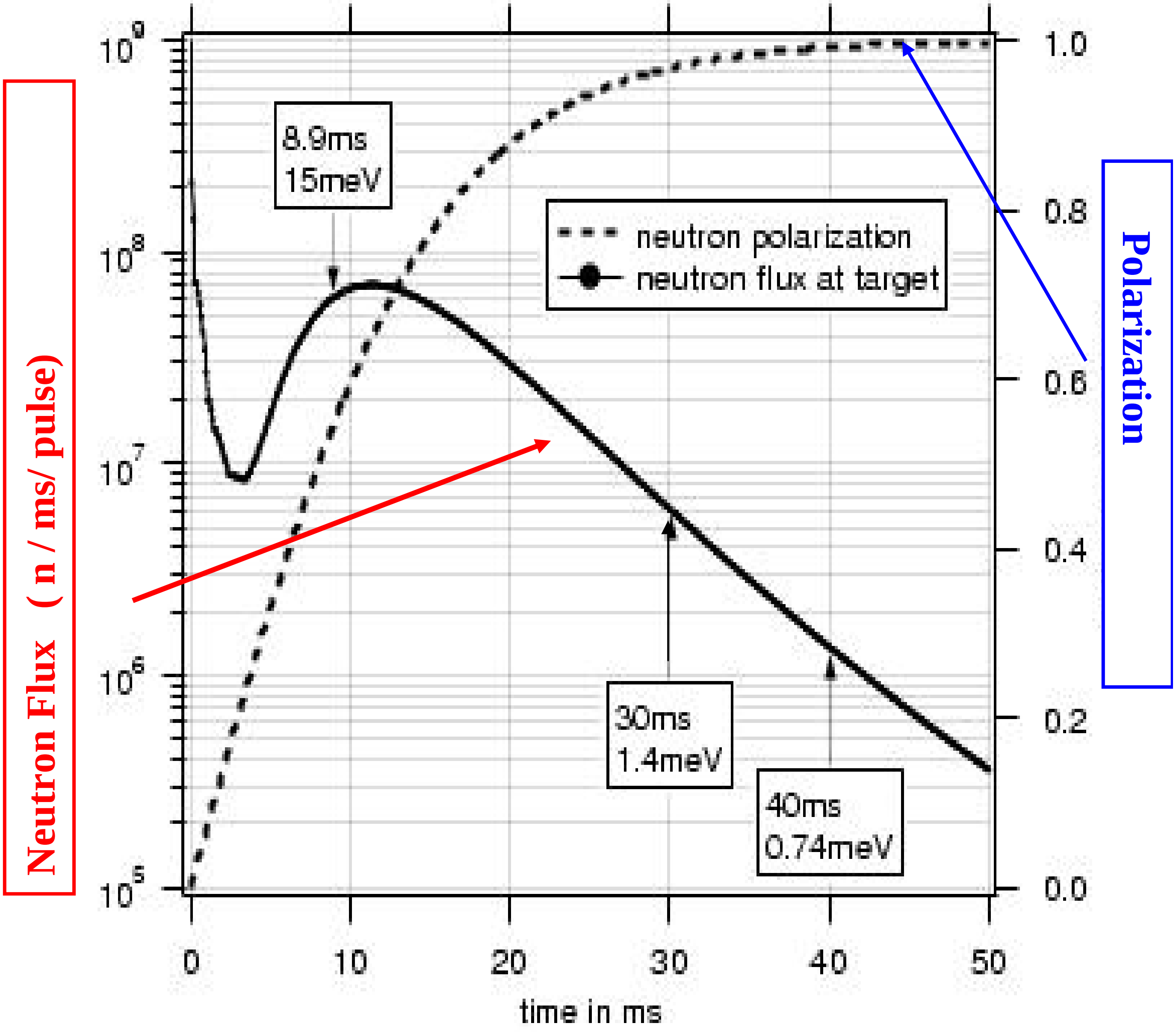
Helium 3 spin polarizer

Back Monitor

$A_\gamma \approx -5\times10^{-8}$

Experimental Apparatus

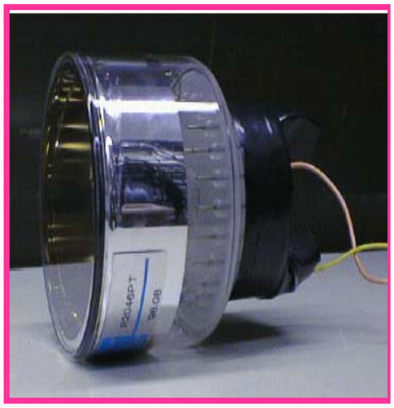
Pulsed Cold Neutron Beam (Monte Carlo)

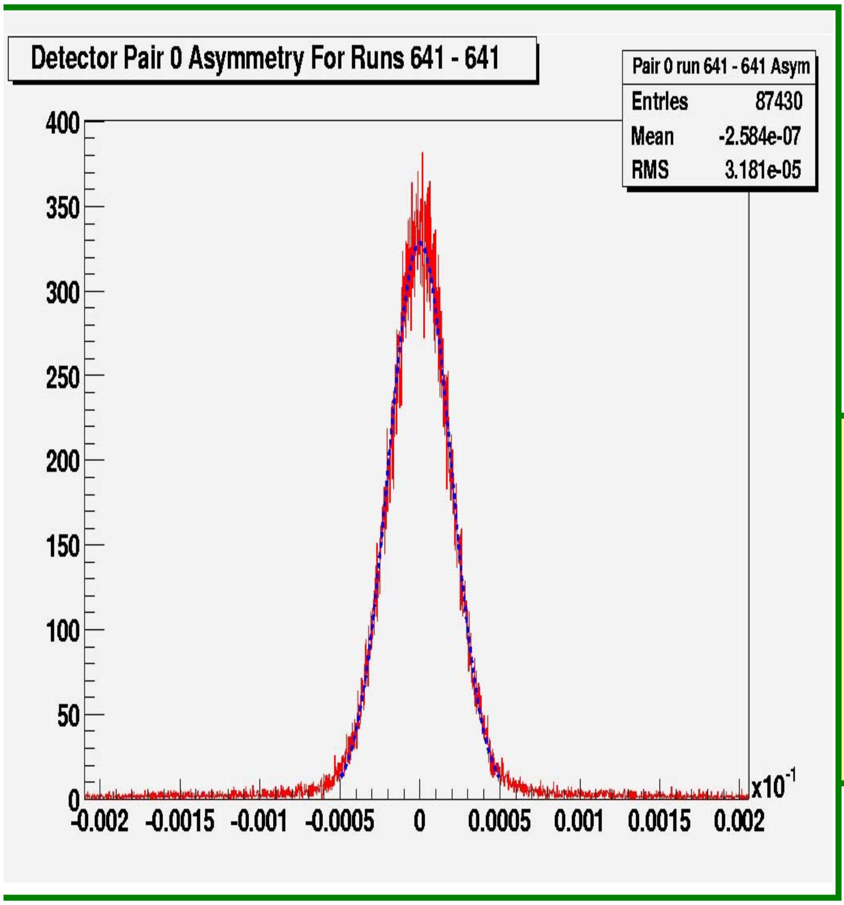


20 Hz pulse rate; all readouts in current mode ...

CsI Detector Array

- 48, (15 x 15 x 15) cm^3 CsI (Tl) crystals surrounding the LH_2 target
- coupled to 3" vacuum photodiodes (KEK)
- current mode readout via low noise I-V amplifiers

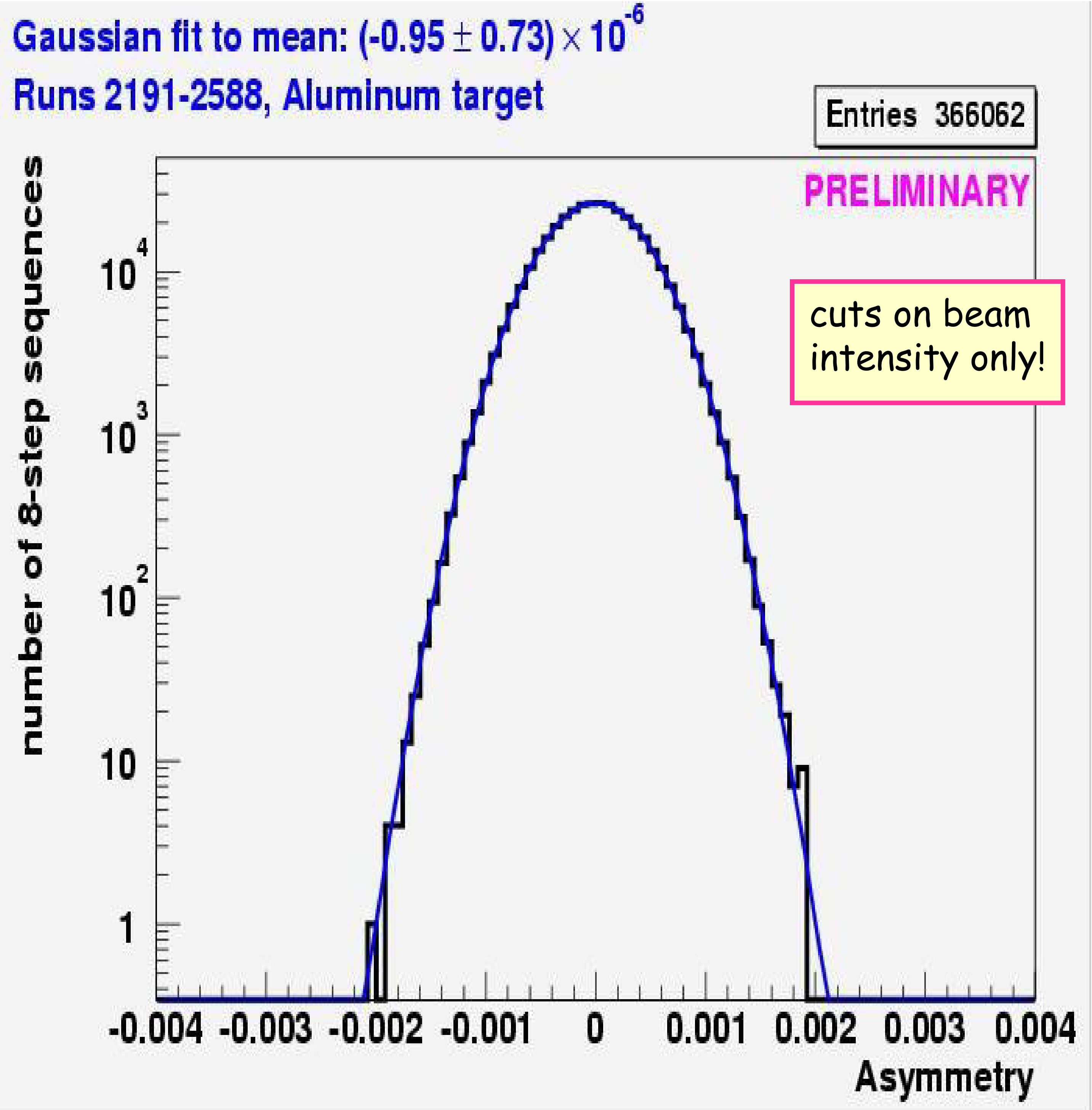




Electronic Asymmetry Test

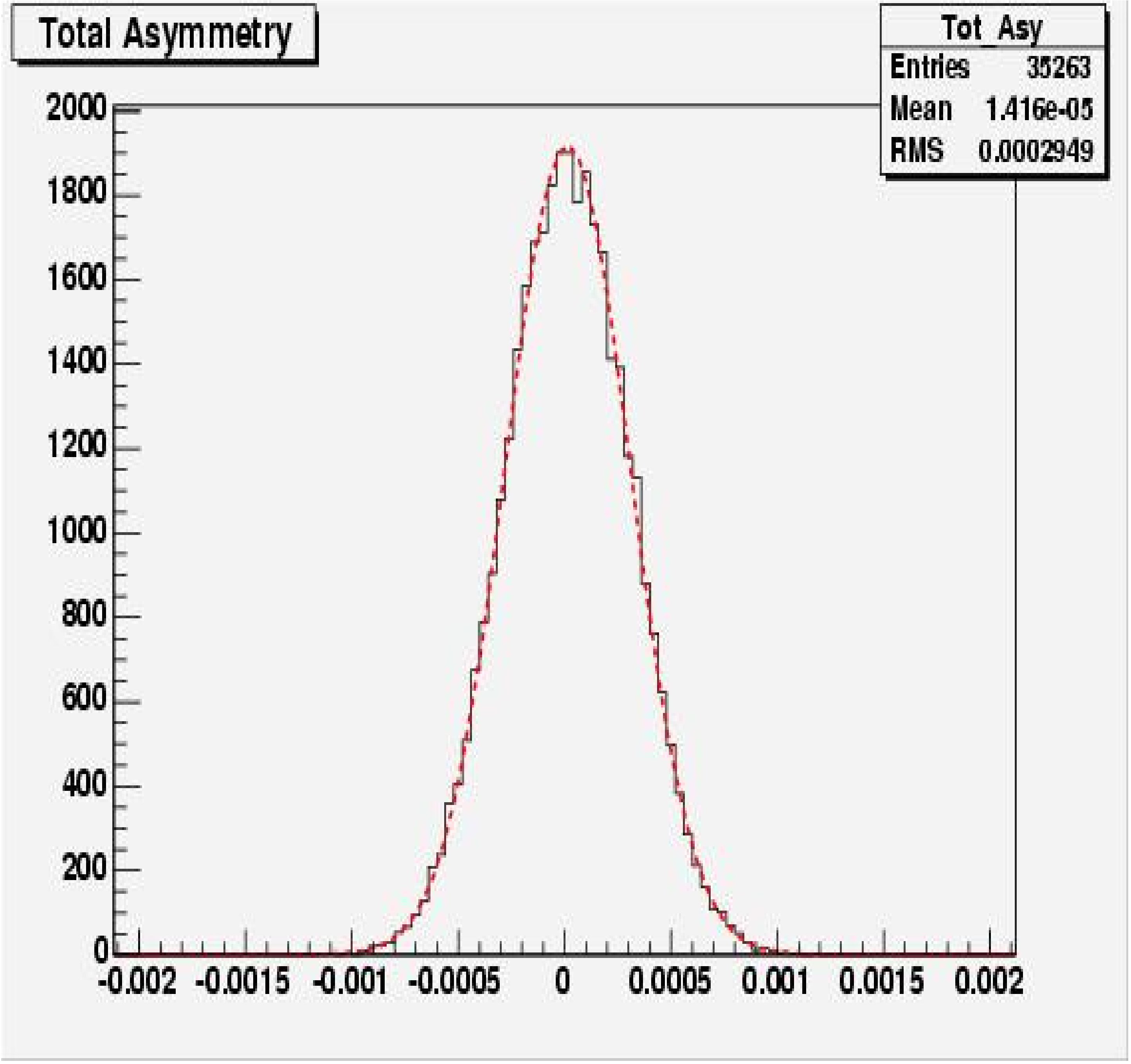
- RFSF pulsed as in expt.
- zero false asymmetry
- $5x10^{-9}$ sensitivity in 2 hr
- non-Gaussian tails: cosmic rays!

Background studies: Al asymmetry (target walls)



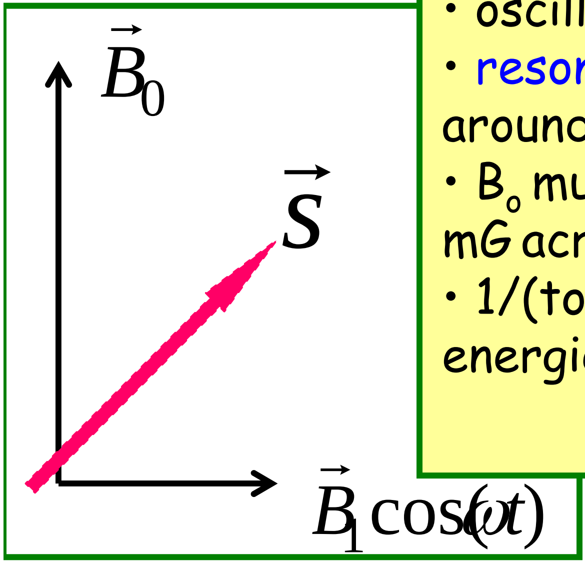
(asymmetry is small enough to proceed to hydrogen target)

Chlorine PV asymmetry (calibration!) -- 4 hrs data

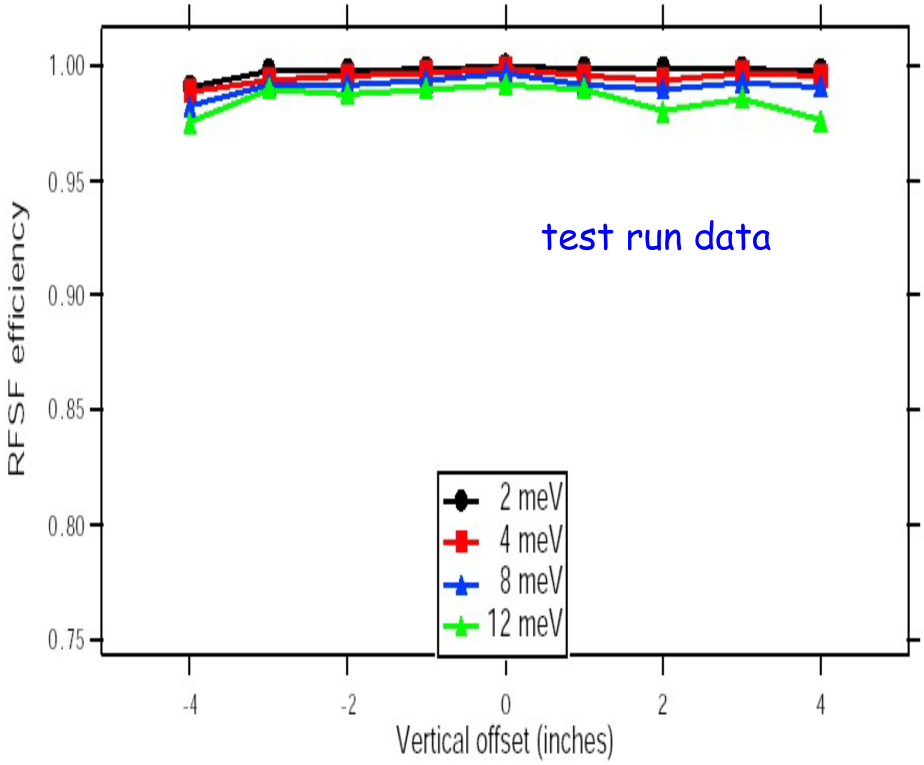


A(Cl) = (15 ± 1.6) $\times 10^{-6}$

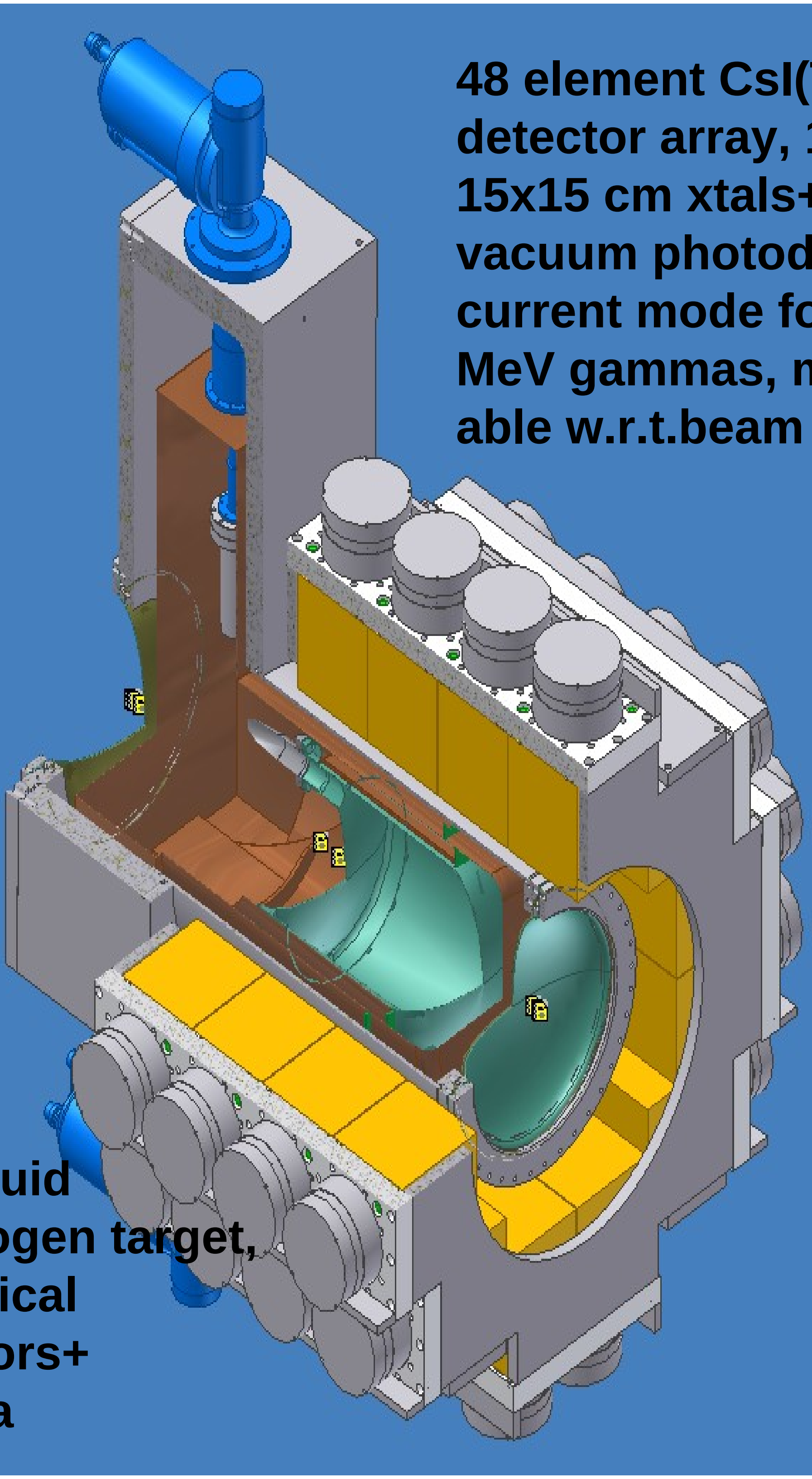
RF spin flipper (LANL)



- uniform vertical guide field B_o = 10 G
- oscillating RF solenoidal field B_1
- resonant condition: spins precess around RF field if $\omega = \gamma\ B_o$
- B_o must be uniform and stable to 6 mG across the spin flipper volume
- 1/(tof) RF amplitude flips spin for all energies



LH2 Target and CsI Array

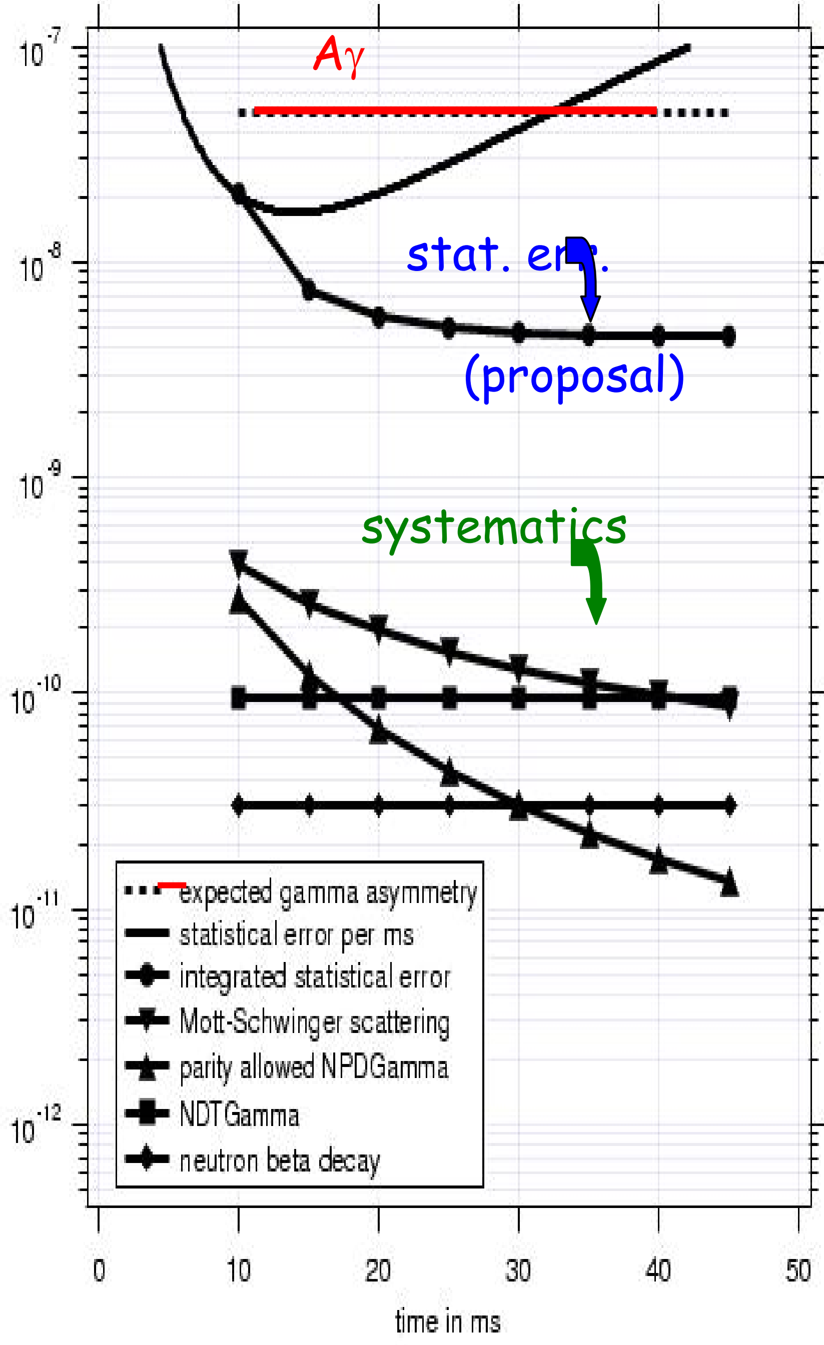


48 element CsI(Tl) detector array, 15x 15x15 cm xtals+ vacuum photodiodes, current mode for 2.2 MeV gammas, move-able w.r.t.beam

20 liter liquid parahydrogen target, 2 mechanical refrigerators+ ortho/para converter

Next step: hydrogen target

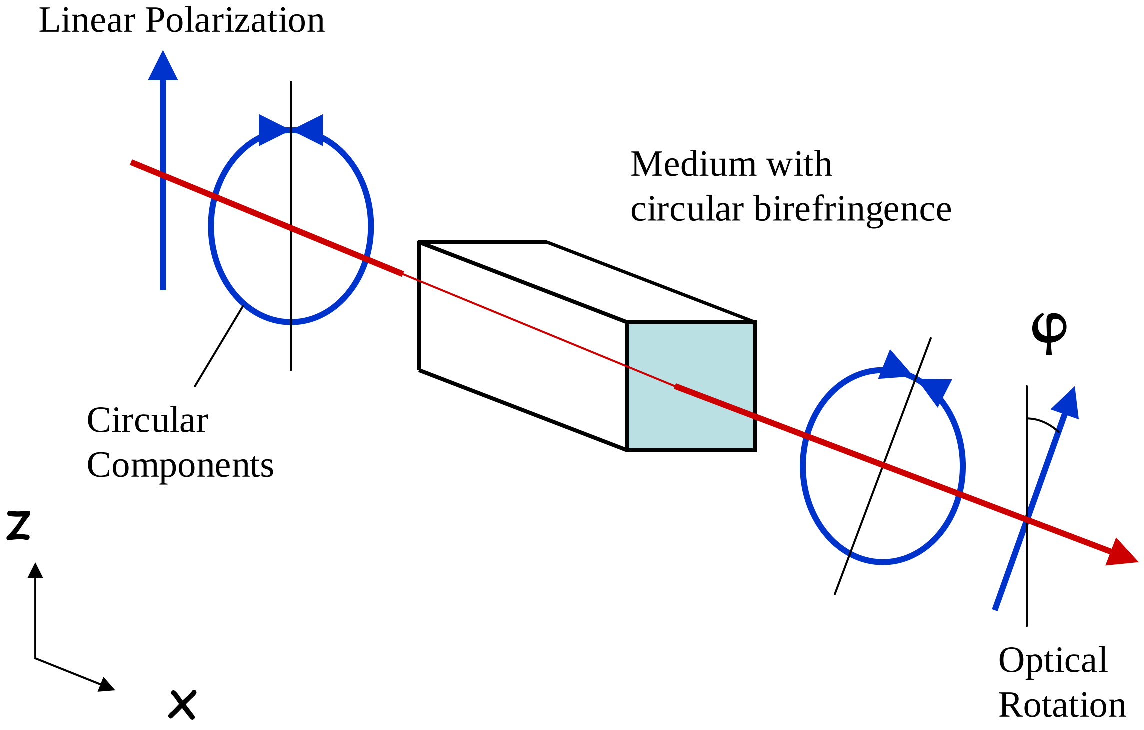
Statistical and Systematic Errors



- 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)

PV Neutron Spin Rotation

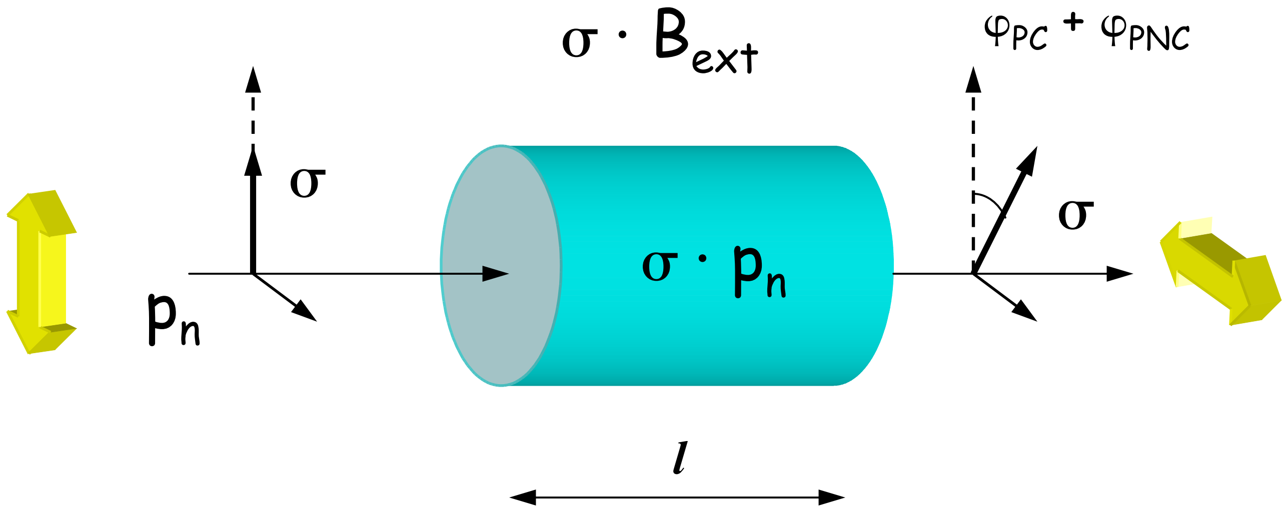


- transversely polarized neutrons corkscrew due to weak NN interaction [opposite helicity components of $|\uparrow>_z=1/\sqrt{2}(|\uparrow>_x+|\downarrow>_x)$ accumulate different phases from $s_n \bullet p_n$ term in forward scattering amplitude]

- PV rotation angle per unit length $d\phi/dx$ approaches a finite limit for zero neutron energy [$\phi=(n-1)px$, $n-1=2\pi f/p^2$, $f_{weak}=gp$ ->$d\phi/dx\sim g$]

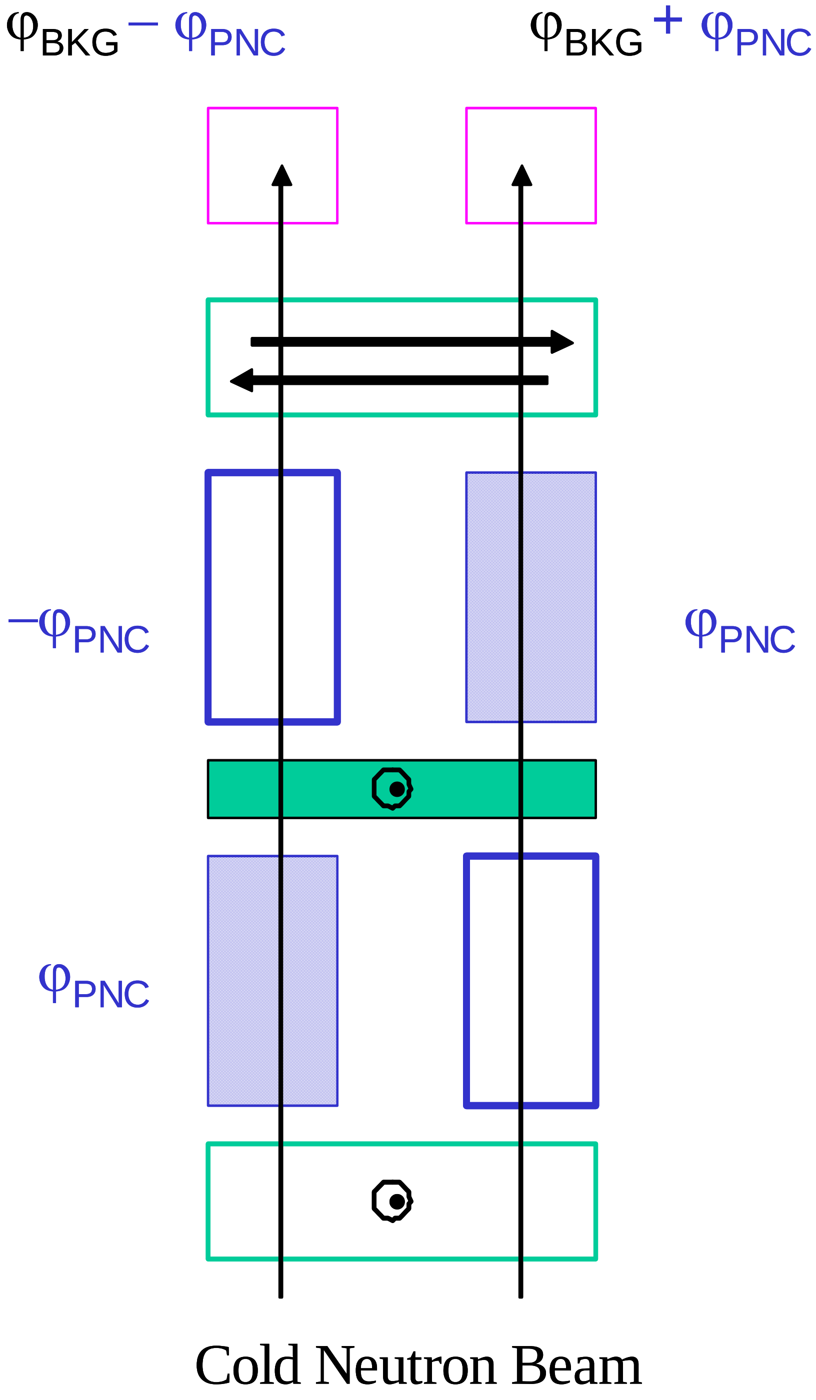
- $d\phi/dx$ is constant for low energy neutrons away from resonances

PV Neutron Spin Rotation in 4He and H



- only 4He and H have low A and negligible neutron spin-flip scattering (D difficult)
- precision goals for $d\phi/dx$:
- 1×10^{-7} rad/m for n-4He
- 1×10^{-7} rad/m for n-H

Signal Modulation



^{3}He *n*-detectors

Analyzer

Target Chamber
Back Position

π - Coil

Target Chamber
Front Position

Polarizer

Impact on NN Weak Meson Couplings (Bowman)

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

Column gives relation between PV observable and weak couplings (ex. A_γ ~-0.11 f_π)

If we know A_γ =5x10^{-9} in n+p->D+γ, 1x10^{-7} in n+D >T+γ

$d\phi/dx$ = 1x10^{-7} rad/m in n-4He, 1x10^{-7} rad/m in n-H

how well do we determine weak couplings?

f_π=4% h_ρ^0=7% h_ρ^2=34% h_ω^0=26%

Assumes calculations of PV in few body systems are reliable

Weak NN Interaction: Scientific Impact

Parts of the weak NN interaction needed for nuclear and atomic systems will essentially be determined (h_ρ^2 missed)

New probe of nuclear structure using existing PV measurements in medium and heavy nuclei

Resolve present inconsistencies

Test internal consistency of meson exchange model and/or χPT

Ambitious but foreseeable goal for lattice gauge theory+chiral extrapolation

Sensitivity to aspects of QCD dynamics (qq correlations) where vacuum structure matters

$\vec{n}+p\rightarrow d+\gamma$ is primarily sensitive to the ΔI = 1 component of the NN weak interaction->weak pion exchange

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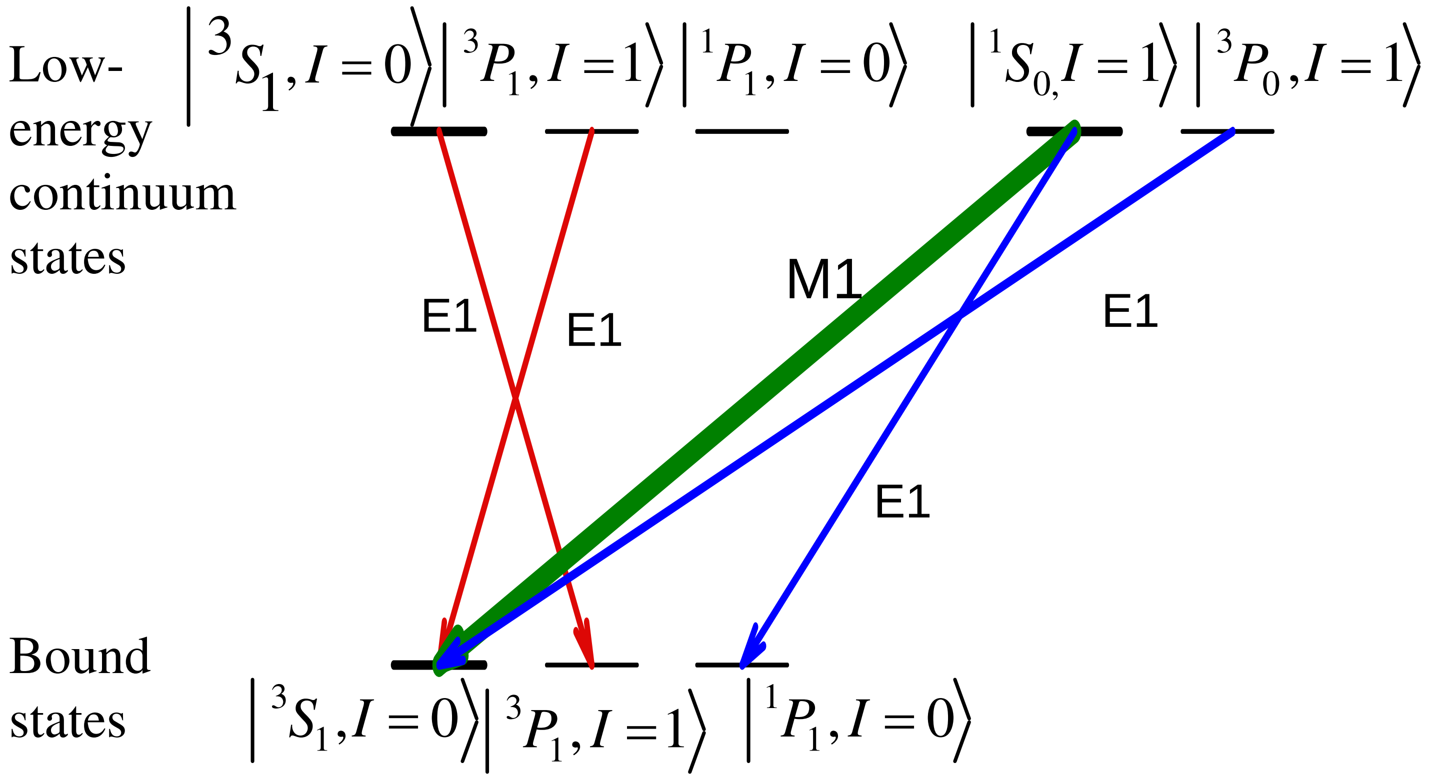
Simple Level Diagram of *n-p* System



- 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.

Mixing amplitudes:

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

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

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