TREX: A Proposed Search for T Violation in Polarized Neutron Optics

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IU Center for Spacetime Symmetries

Amplification of parity violation in compound nuclear resonances

Polarized neutron optics test of T invariance: the idea

New developments which now make this experiment attractive to consider

What is to be done? How can we make the polarized target?

Thanks for slides from: D. Bowman, V. Gudkov, Z. Tang, H. Shimizu,…

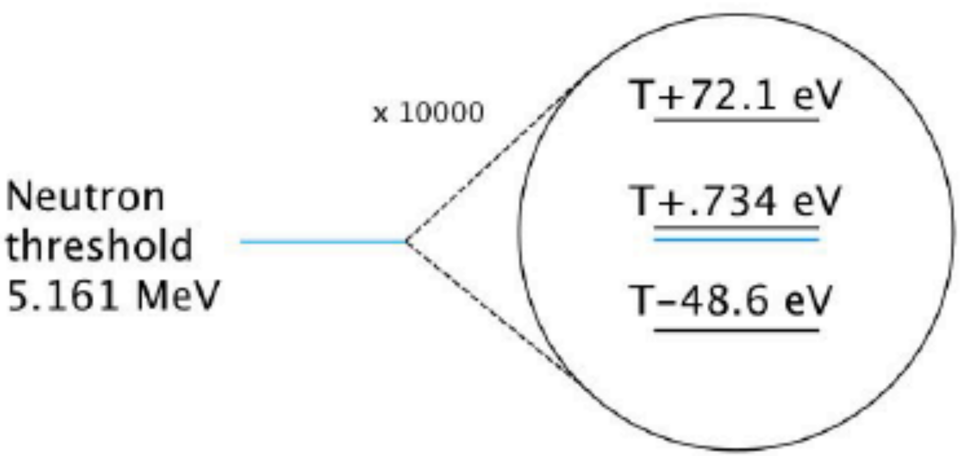
Time Reversal Experiment "TREX"
Neutron Optics for T Violation "NOP-T"
Proto-collaborations

M. Snow	Indiana U
S. Penttila	ORNL
D. Bowman	ORNL
T. Tong	ORNL
V. Gudkov	U South Carolina
C. Gould	North Carolina State U
C. Crawford	U Kentucky
B. Plaster	U Kentucky
N. Fomin	U Tennessee
Z. Tang	LANL

NOPTREX?

H Shimizu	Nagoya U
M. Kitaguchi	Nagoya U
K. Hirota	Nagoya U
G. Ichikawa	Nagoya U
T. Ino	KEK
T. Shima	Osaka
T. Iwata	Yamakata U
T. Yoshioka	Kyushu U
Y. Yamagata	RIKEN
M. Hino	Kyoto
T. Momose	UBC
K. Asahi	Tokyo I. Tech.
K. Sakai	JAEA
H. Harada	JAEA
A, Kimura	JAEA

139La+n System



Compound-Nuclear States in ^{139}La+n system

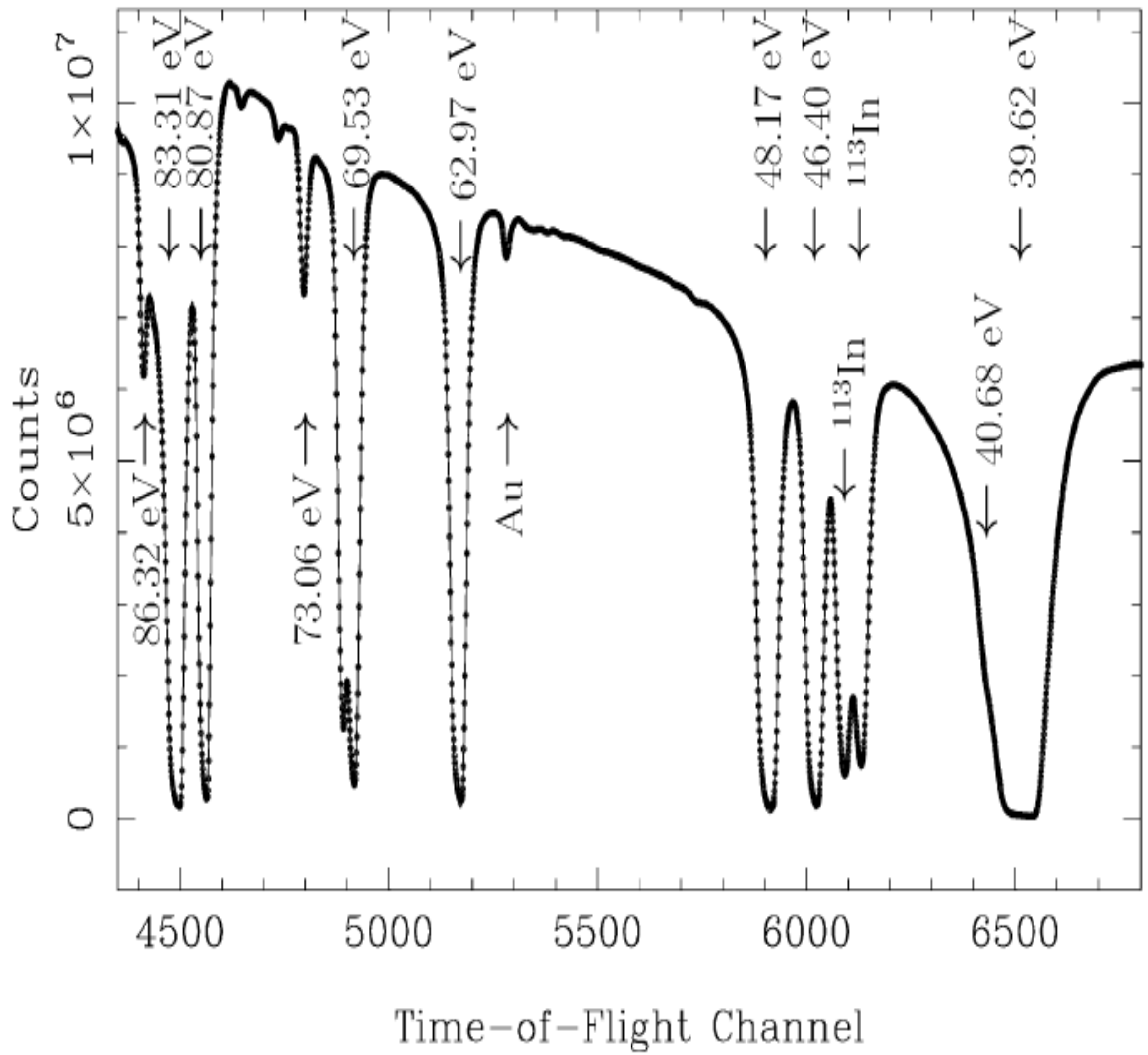
Low energy neutrons can access a dense forest of highly excited states in the compound nucleus.

Unique phenomena occur in this regime which are not widely known

One such phenomenon is the large amplification of discrete symmetry violation effects like P and T

140La G. S.

Neutron Time-of-Flight spectrum in transmission through Indium

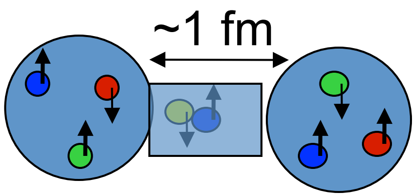


Excited state energies=~6 MeV +(eV->keV)

Narrow resonances (~100 meV)

High density of levels per unit energy

N- N Weak Interaction: Size and Mechanism

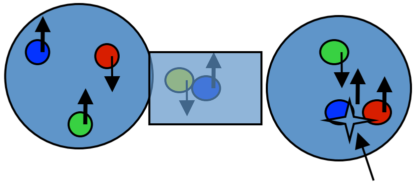


NN repulsive core → 1 fm range for NN strong force

$|N\rangle = |qqq\rangle + |qqqq\bar{q}\rangle + \cdots$ = valence + sea quarks + gluons + …

interacts through NN strong force, mediated by mesons $|m\rangle = |q\bar{q}\rangle + |q\bar{q}q\bar{q}\rangle + \cdots$

QCD possesses only vector quark-gluon couplings → *conserves parity*



Both W and Z exchange possess
much smaller range [~1/100 fm]

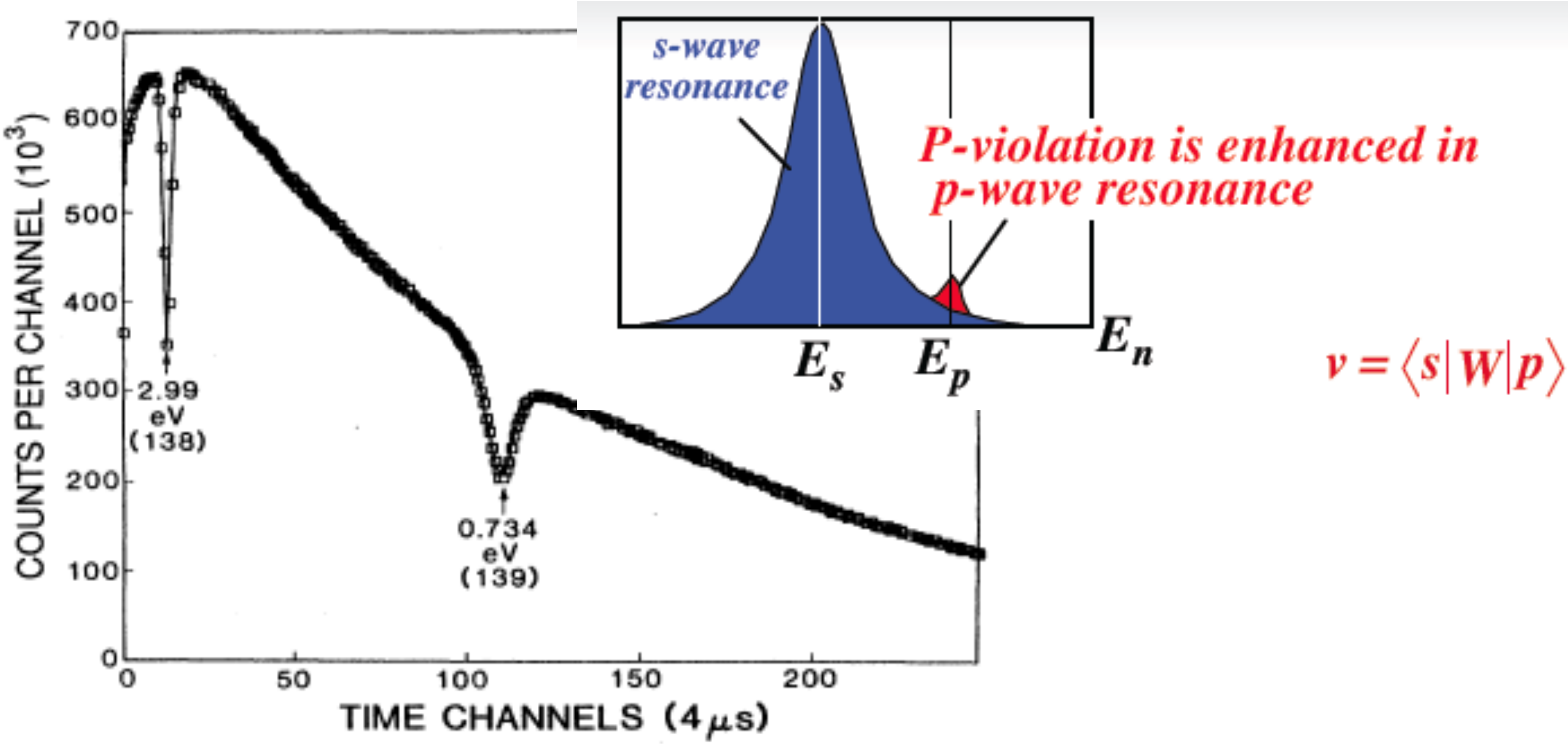
Relative strength of weak / strong amplitudes: $\left(\frac{e^2}{m_W{}^2}\right) / \left(\frac{g^2}{m_\pi{}^2}\right) \approx 10^{-6}$

Use parity violation to isolate the weak contribution to the NN interaction.

NN strong interaction at low energy largely dictated by QCD chiral symmetry.
Can be parametrized by effective field theory methods.

Parity Violation in ^{139}La .734 eV $\Delta\sigma/\sigma$ =0.097±.005.

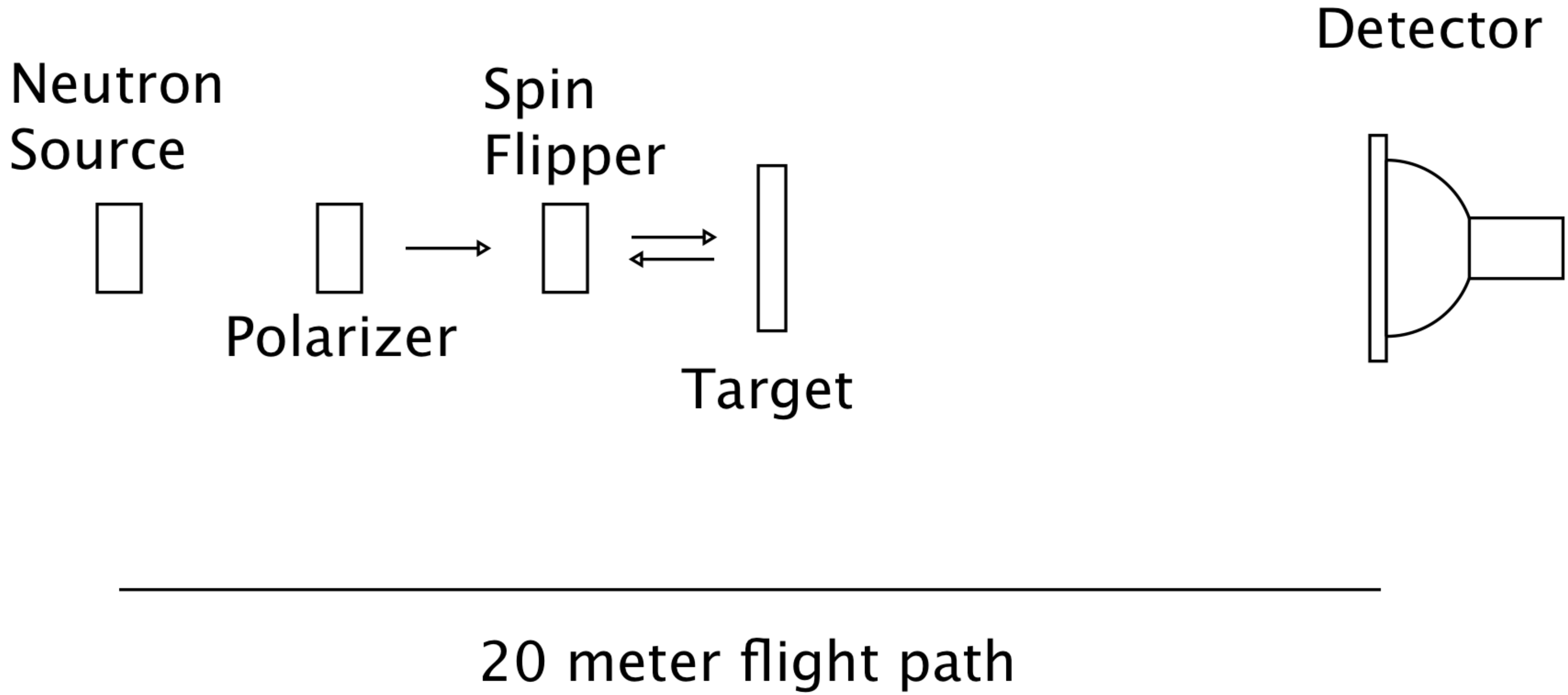
10^6 amplification!



$v = \langle s|W|p\rangle$

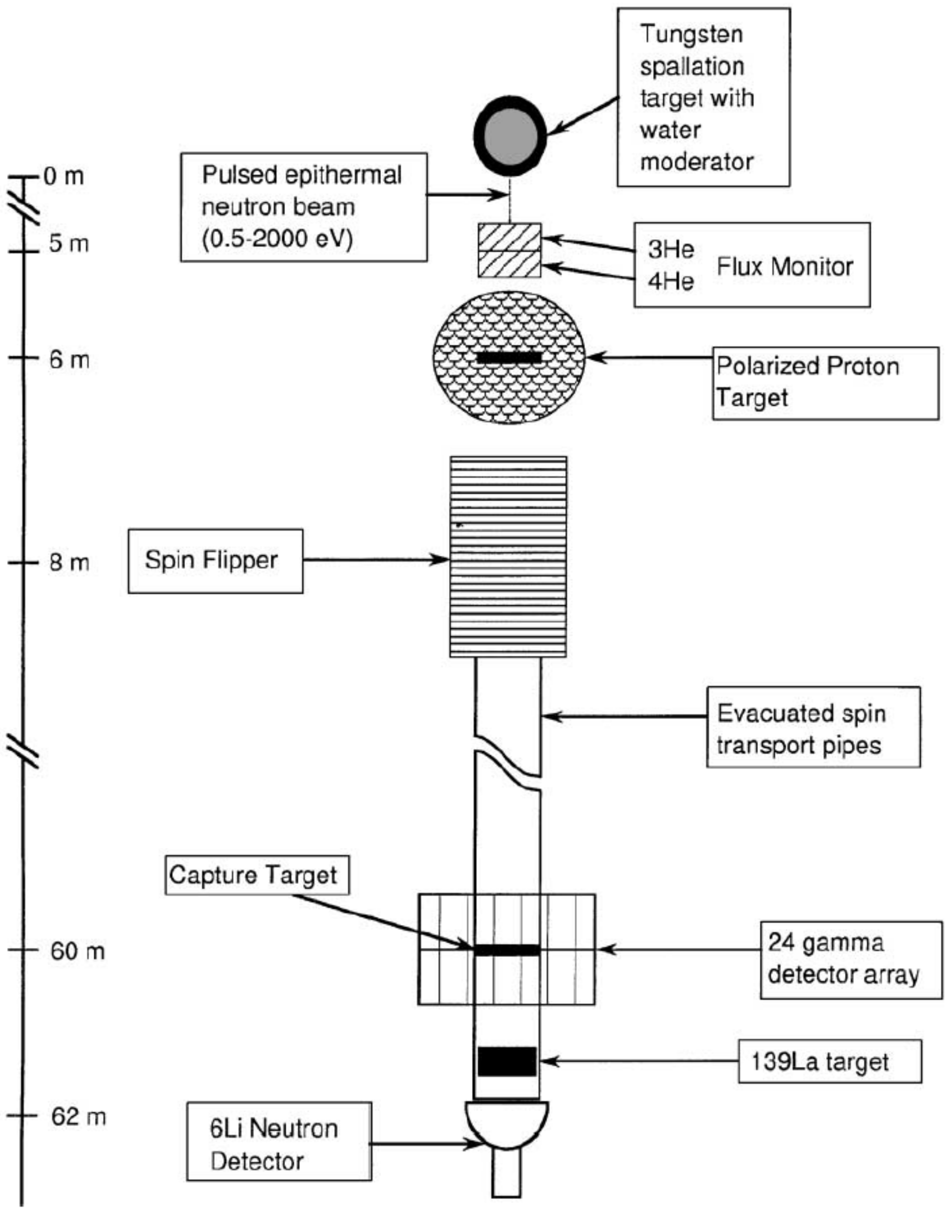
How? (1) Admixture of (large) s-wave amplitude into (small) p-wave ~1/kR~1000
(2) Weak amplitude dispersion for 10^6 Fock space components ~sqrt(10^6)=1000
Idea is to use the observed enhancement of PV to search for a TRIV asymmetry.

Apparatus to Measure $\sigma \cdot k$ Parity Violating Asymmetry



TRIPLE collaboration measured ~80 parity-odd asymmetries in p-wave resonances in heavy nuclei G. M. Mitchell, J. D. Bowman, S. I. Penttila, and E. I. Sharapov, Phys. Rep. 354, 157 (2001).

Quantitative analysis of distribution of parity-odd asymmetries conducted using nuclear statistical spectroscopy S. Tomsovic, M. B. Johnson, A. Hayes, and J. D. Bowman, Phys. Rev. C 62, 054607 (2000).



Apparatus for
PV at a spallation neutron source

Polarized proton target to make polarized neutrons (S. Penttila, using cryostat now at UVA!)

Look for σ.k dependence of total cross section

Study of Parity Violation in the Compound Nucleus
A Paradigm for Time Reversal

Parity violations observed by TRIPLE

Target	Reference	All	$p+$	$p-$
^{81}Br	[67]	1	1	0
^{93}Nb	[125]	0	0	0
^{103}Rh	[132]	4	3	1
^{107}Ag	[97]	8	5	3
^{109}Ag	[97]	4	2	2
^{104}Pd	[134]	1	0	1
^{105}Pd	[134]	3	3	0
^{106}Pd	[43,134]	2	0	2
^{108}Pd	[43,134]	0	0	0
^{113}Cd	[121]	2	2	0
^{115}In	[136]	9	5	4
^{117}Sn	[133]	4	2	2
^{121}Sb	[101]	5	3	2
^{123}Sb	[101]	1	0	1
^{127}I	[101]	7	5	2
^{131}Xe	[140]	1	0	1
^{133}Cs	[126]	1	1	0
^{139}La	[152]	1	1	0
^{232}Th below 250 eV	[135]	10	10	0
^{232}Th above 250 eV	[127]	6	2	4
^{238}U	[41]	5	3	2
Total		75	48	27
Total excluding Th		59	36	23

PHYSICAL REVIEW C, VOLUME 62, 054607

Statistical theory of parity nonconservation in compound nuclei

S. Tomsovic
Department of Physics, Washington State University, Pullman, Washington 99164

Mikkel B. Johnson, A. C. Hayes, and J. D. Bowman
Los Alamos National Laboratory, Los Alamos, New Mexico 87545
(Received 22 November 1999; published 10 October 2000)

Comparison of experimental CN matrix elements with Tomsovic theory using DDH "best" meson-nucleon couplings: agreement within a factor of 2

TABLE IV. Theoretical values of M for the effective parity-violating interaction. Contributions are shown separately for the standard (Std) and doorway (Dwy) pieces of the two-body interaction. A comparison of the experimental value of M given in Table III is also shown.

Nucleus	M_{Std} (meV)	M_{Dwy} (meV)	$M_{Std+Dwy}$ (meV)	M_{expt} (meV)
^{239}U	0.116	0.177	0.218	$0.67^{+0.24}_{-0.16}$
^{105}Pd	0.70	0.79	1.03	$2.2^{+2.4}_{-0.9}$
^{106}Pd	0.304	0.357	0.44	$0.20^{+0.10}_{-0.07}$
^{107}Pd	0.698	0.728	0.968	$0.79^{+0.88}_{-0.36}$
^{109}Pd	0.73	0.72	0.97	$1.6^{+2.0}_{-0.7}$

Matter/Antimatter Asymmetry in the Universe in Big Bang, starting from zero

Sakharov Criteria to generate matter/antimatter asymmetry from the laws of physics

- Baryon Number Violation (not yet seen)
- C and CP Violation (seen but too small by $\sim 10^{10}$)
- Departure from Thermal Equilibrium (no problem?)

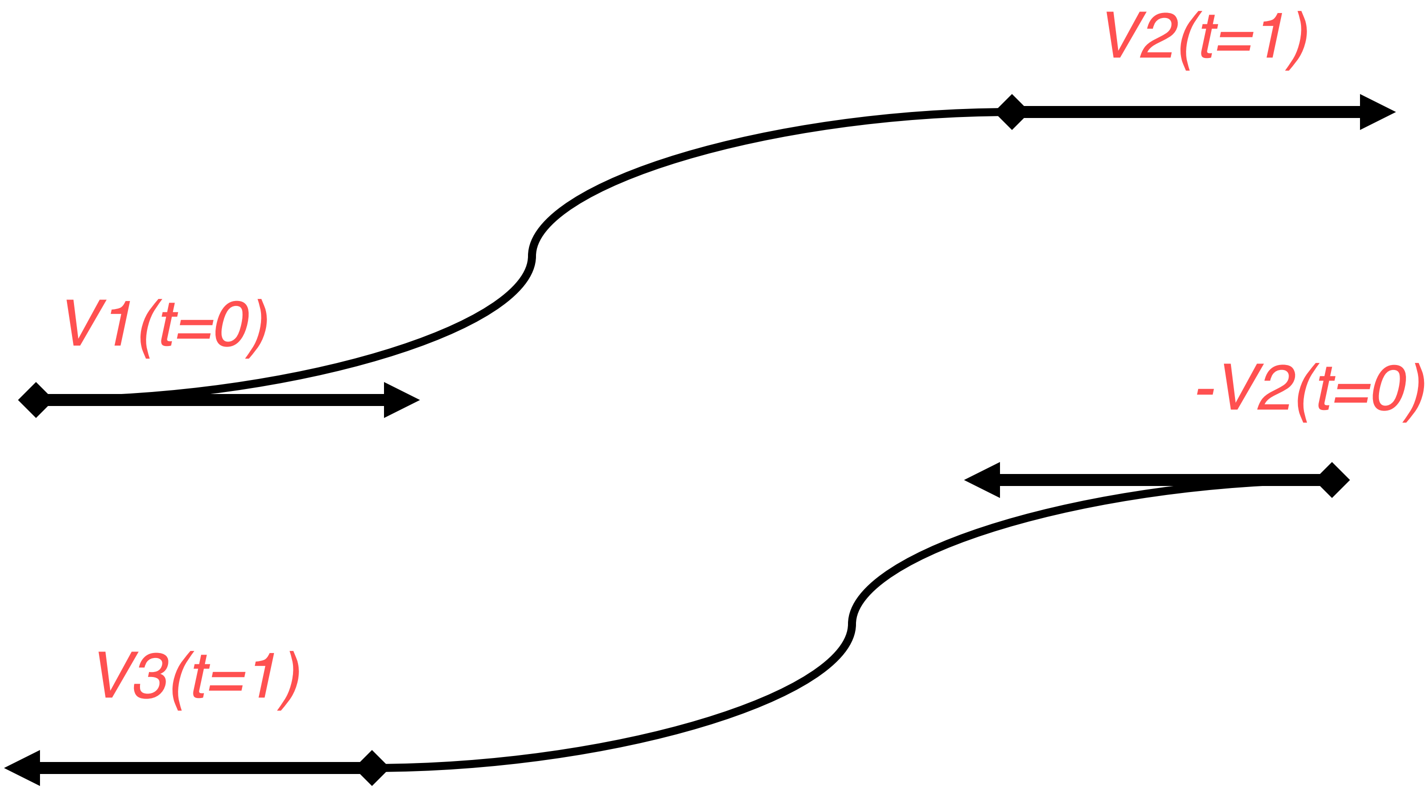
A.D. Sakharov, JETP Lett. 5, 24-27, 1967

Relevant neutron experimental efforts

Neutron-antineutron oscillations (B)
Electric Dipole Moment searches (T=CP)

T Violation in Polarized Neutron Optics (T=CP)

“Time Reversal” -> Motion Reversal



Is the final state of the motion with time-reversed final conditions V3(t=1) the same as the time-reversed initial condition -V1(t=0)?

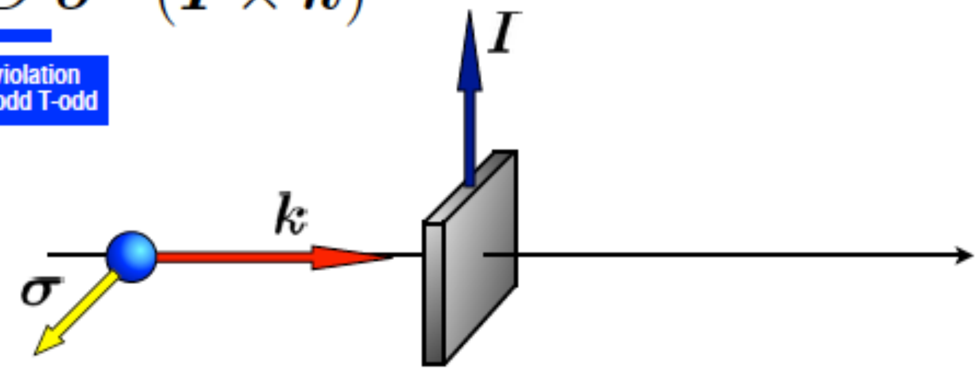
This is an experimental question

Gotta reverse the spins too

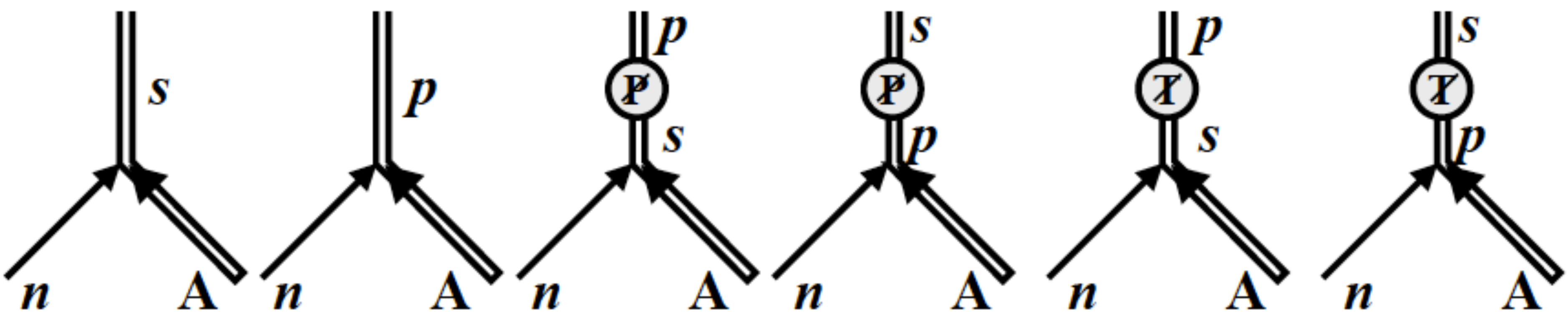
Forward Scattering Amplitude

$$f = A' + B'\boldsymbol{\sigma}\cdot\hat{\boldsymbol{I}} + C'\boldsymbol{\sigma}\cdot\hat{\boldsymbol{k}} + D'\boldsymbol{\sigma}\cdot(\hat{\boldsymbol{I}}\times\hat{\boldsymbol{k}})$$

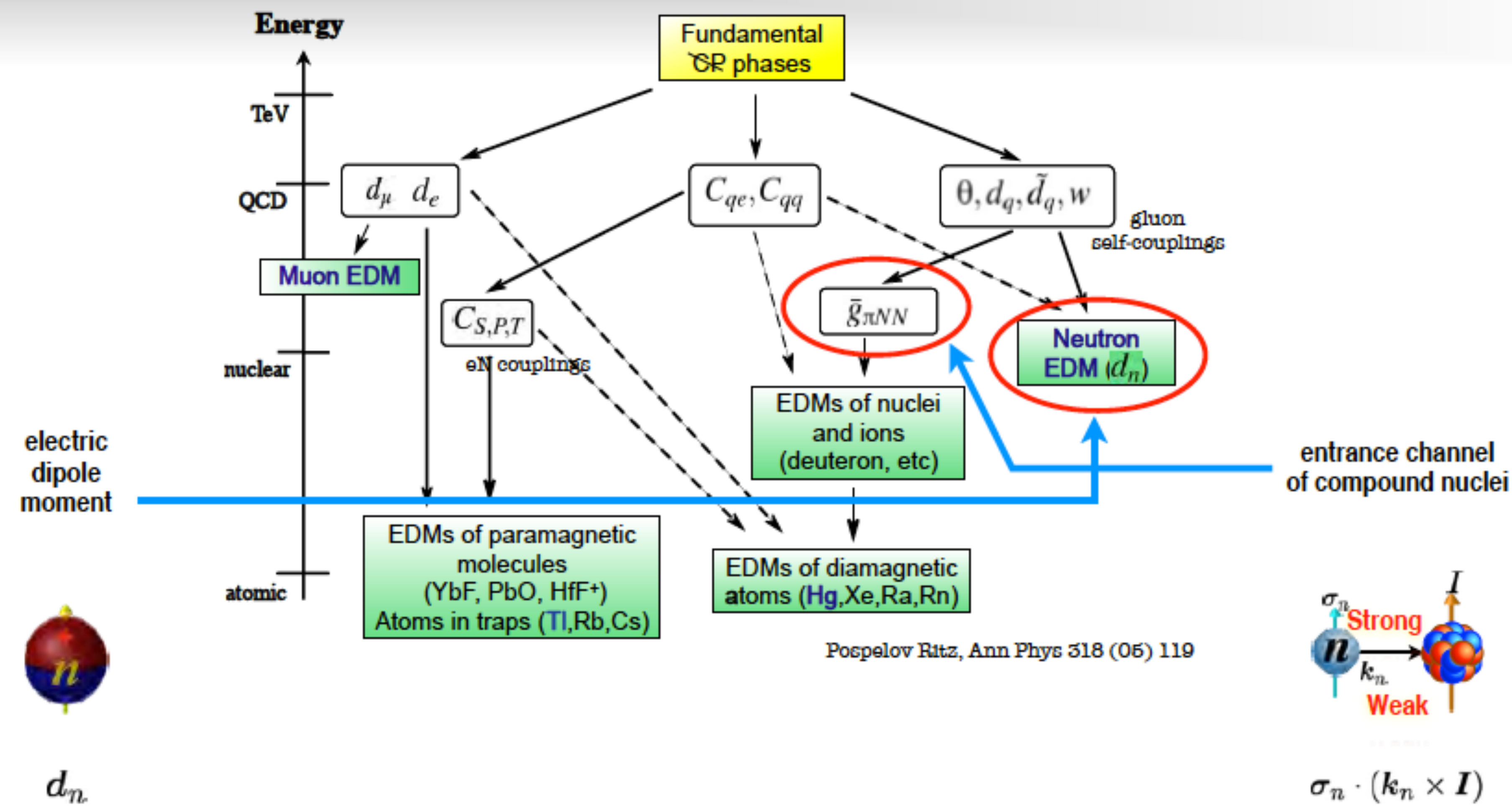
- A': Spin Independent, P-even T-even
- B': Spin Dependent, P-even T-even
- C': P-violation, P-odd T-even
- D': T-violation, P-odd T-odd



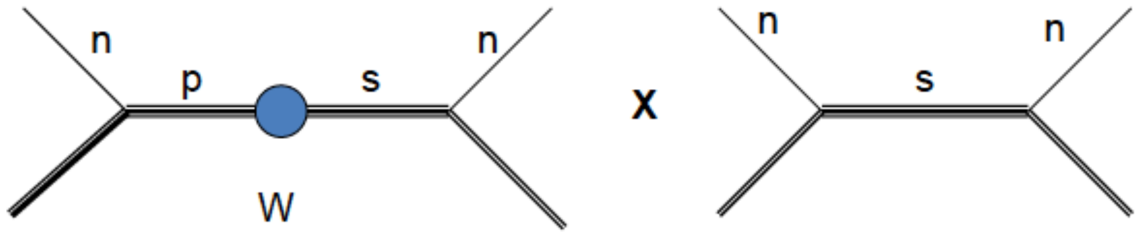
$\lvert s\rangle$	$\lvert p\rangle$	$\lvert p_{1/2}\rangle$	$\lvert p_{3/2}\rangle$	
$J_s\,E_s\Gamma_s\Gamma_s^n$	$J_p\,E_p\Gamma_p\Gamma_p^n$	$\Gamma^n_{p,1/2}$	$\Gamma^n_{p,3/2}$	$\langle W\rangle$



T violation Searches with EDMs and Compound Nuclei



P- and T-violation in Neutron transmission



$$\Delta\sigma_T \sim \vec{\sigma}_n \cdot [\vec{k} \times \vec{I}] \sim \frac{W\sqrt{\Gamma_s^n \Gamma_p^n(s)}}{(E - E_s + i\Gamma_s/2)(E - E_p + i\Gamma_p/2)} [(E - E_s)\Gamma_p + (E - E_p)\Gamma_s]$$

$$\Delta\sigma_T / \Delta\sigma_P \sim \lambda = \frac{g_T}{g_P} \qquad [\sim \; - \; ?]$$

The enhancement of PVTR (σ.[*K* X *I*]) is (almost) the same as for PV (σ.*K*).
Sensitivity expressed as a ratio of P-odd/T-odd to P-odd amplitudes $\lambda_{PT} = \dfrac{\delta\sigma_{PT}}{\delta\sigma_P}$

λ can be measured with a statistical uncertainty of ~1 10^{-5} in 10^7 sec at MW-class spallation neutron source like SNS/JSNS.

sensitivity ~ 100 times better than present n EDM limit, completely different system.

T violation in Neutron Optics

- T – odd term in FORWARD scattering amplitude (a null test, like EDMs) with polarized n beam and polarized nuclear target
- P-odd/T-odd (most interesting) $\vec{\sigma_n} \cdot (\vec{k_n} \times \vec{I})$
- Amplified on select P-wave epithermal neutron resonances by ~5-6 orders of magnitude
- Estimates of stat sensitivity at SNS/JSNS look very interesting:

Existing technology/sources->$\Delta\sigma_{PT}/\Delta\sigma_P$~1E-5

- The nuclei of interest, resonance energies, and P-odd asymmetry amplifications are measured

Nucleus	Resonance Energy	PV asymmetry
^{131}Xe	3.2 eV	0.043
^{139}La	0.748 eV	0.096
^{81}Br	0.88 eV	0.02

So why has this experiment never been done?

How to design experiment that can realize a “null test”?

How to get enough polarized eV neutrons on resonance?

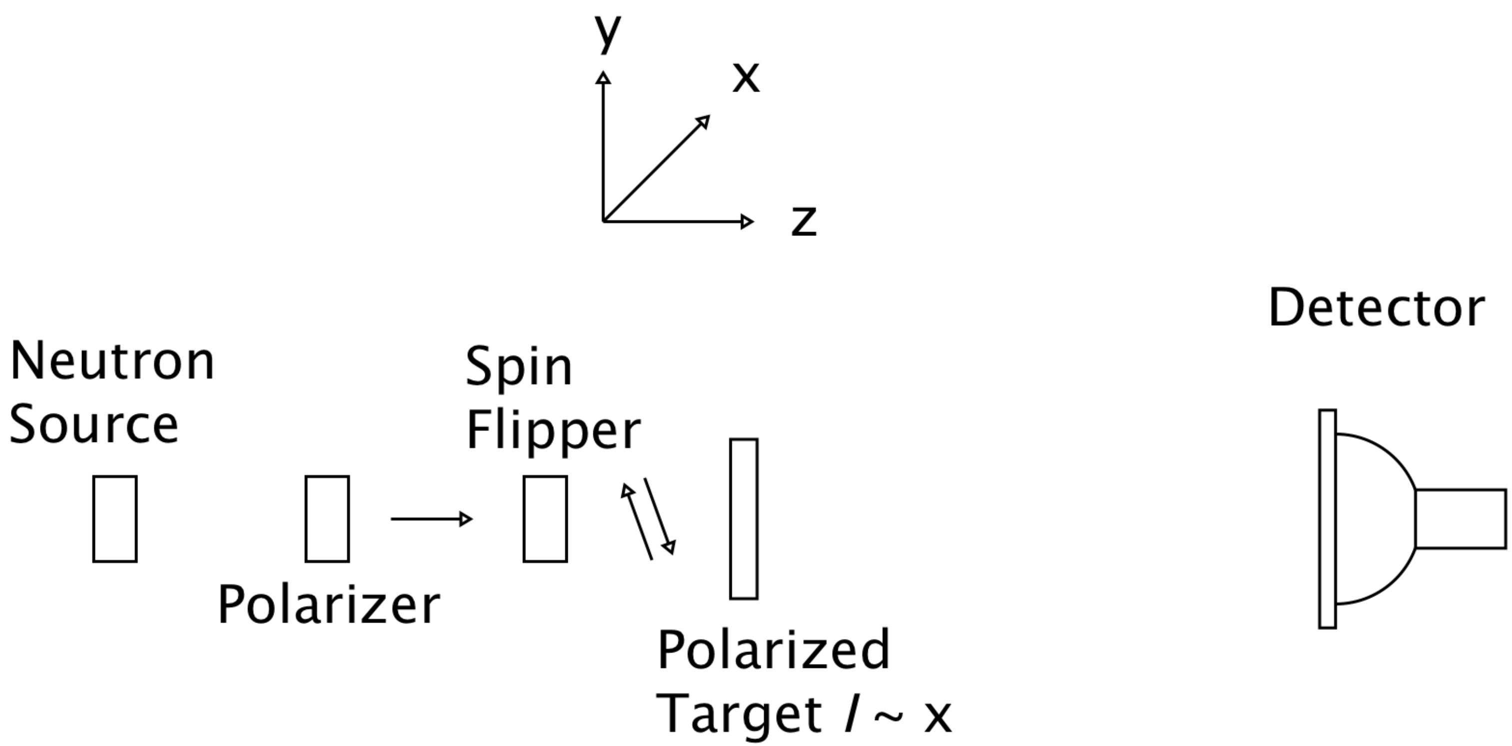
How best to characterize/eliminate “non-optical” systematic effects?

Russian/Japanese/US groups looked into it in ~1990s:
“death by a thousand cuts”

Now the situation is greatly improved

Last remaining difficulty: POLARIZED TARGET

False TR asymmetries caused by TRI interactions



Ideally, the spin is along y such that $\sigma.I$xk is maximal and $\sigma.k$ is zero. σ is shown making a small angle, +/−θ, in the y−z plane. Because $\sigma.k$ is non−zero there is a PV asymmetry ~ Sin(θ).

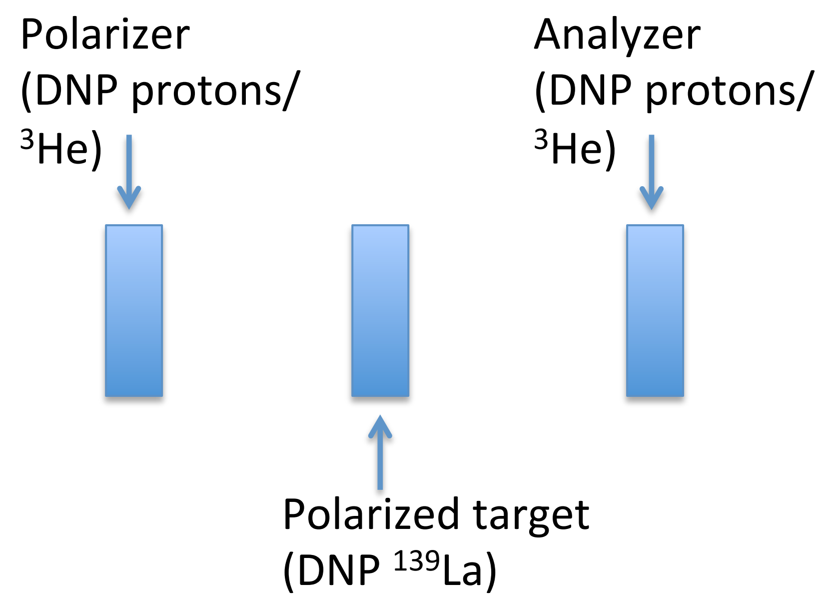
Thinking of the 90s: Make the apparatus "symmetric" by having both a neutron polarizer and a neutron polarization analyzer.

Masuda's analysis of systematic uncertainties from alignment

$$A = (R_+ - R_-)/(R_+ + R_-),$$
$$R_+ = R_{++} + R_{+-} = \mathrm{Tr}(t\rho(P_o, \varepsilon_x, \varepsilon_y)t^\dagger),$$
$$R_- = R_{-+} + R_{--} = \mathrm{Tr}(t\rho(-P_o, \varepsilon_x, \varepsilon_y)t^\dagger),$$
$$R_+ - R_- = \exp(-2\mathrm{Im}(\phi_0))$$
$$\{[2\varepsilon_x P_o + 2\varepsilon_y P_o\delta_y + 2P_o\delta_z]P_I\,\mathrm{Im}[\cos b\ (\sin b/b\ )^*\ \phi_1{}^*]$$
$$+\ 2P_o\ \ \mathrm{Im}[\cos b\ (\sin b/b\ )^*\ \phi_3{}^*]$$
$$+\ [2\varepsilon_x P_o\delta_y - 2\varepsilon_y P_o]P_I\ \mathrm{Im}[(\sin b/b)(\sin b/b)^*\ \phi_1\phi_3{}^*]$$
$$+\ 2P_o\ P_I{}^2\ \mathrm{Im}[(\sin b/b)(\sin b/b)^*\ \phi_1\phi_2{}^*]\ \},$$
$$P = (R_{0+} - R_{0-})/(R_{0+} + R_{0-}),$$
$$R_{0+} = R_{++} + R_{-+} = \mathrm{Tr}(P(P_a, \xi_x, \xi_y)tt^\dagger),$$
$$R_{0-} = R_{+-} + R_{--} = \mathrm{Tr}(P(-P_a, \xi_x, \xi_y)tt^\dagger),$$
$$R_{0+} - R_{0-} = \exp(-2\mathrm{Im}(\phi_0))$$
$$\{[2\xi_x P_a + 2\xi_y P_a\delta_y + 2P_a\delta_z]P_I\,\mathrm{Im}[\cos b\ (\sin b/b\ )^*\ \phi_1{}^*]$$
$$+\ 2P_a\ \ \mathrm{Im}[\cos b\ (\sin b/b\ )^*\ \phi_3{}^*]$$
$$+\ [-2\xi_x P_a\delta_y + 2\xi_y P_a]P_I\ \mathrm{Im}[(\sin b/b)(\sin b/b)^*\ \phi_1\phi_3{}^*]$$
$$-\ 2P_a\ P_I{}^2\ \mathrm{Im}[(\sin b/b)(\sin b/b)^*\ \phi_1\phi_2{}^*]\ \},$$

The ratio X is

$$X \cong P_o/P_a\ [\ 1\ +$$
$$\{[2(\varepsilon_x - \xi_x) + 2(\varepsilon_y - \xi_y)\delta_y\ ]P_I\ \mathrm{Im}[\cos b\ (\sin b/b\ )^*\ \phi_1{}^*]$$
$$+[2(\varepsilon_x + \xi_x P)\delta_y - 2(\varepsilon_y + \xi_y)]P_I\ \mathrm{Im}[(\sin b/b)(\sin b/b)^*\ \phi_1\phi_3{}^*]$$
$$4P_I{}^2\ \ \mathrm{Im}[(\sin b/b)(\sin b/b)^*\ \phi_1\phi_2{}^*]$$

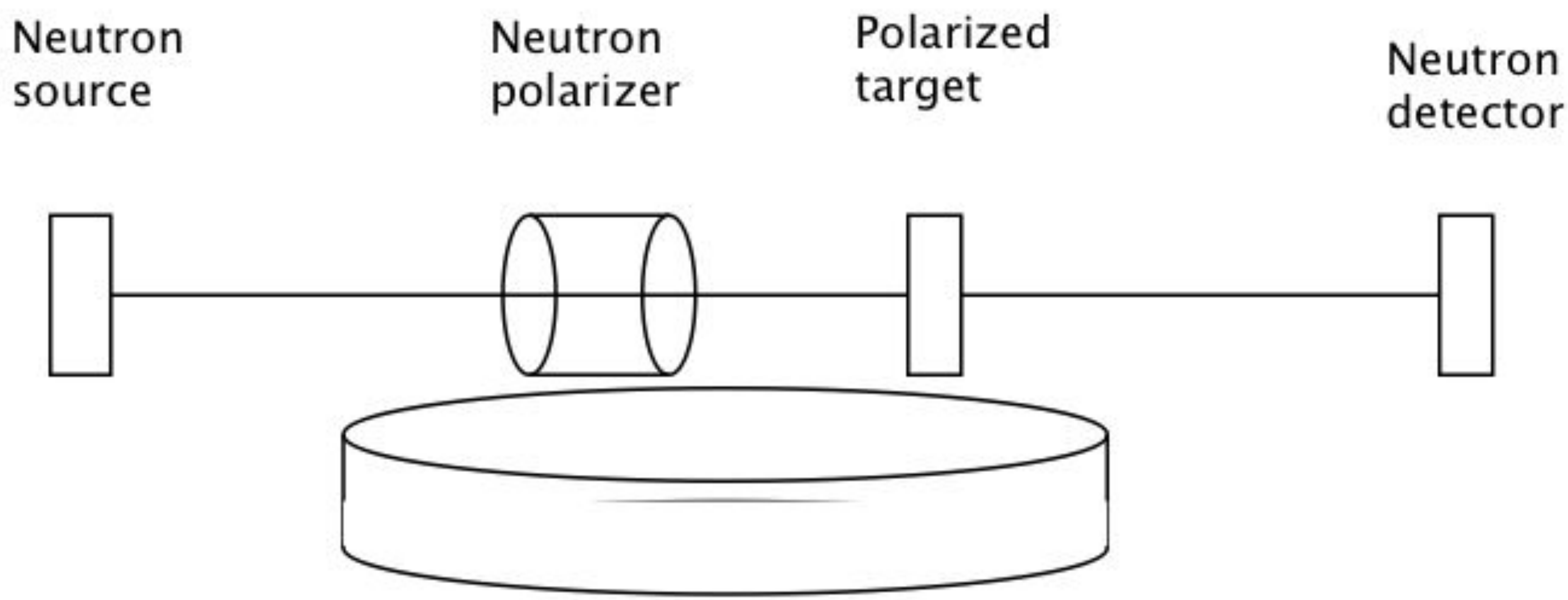


The 13 Greek letters are alignment errors

Criticism of alignment schemes formalized by Lamoreaux and Golub PRD50,5632(1994)

over 1 mm. Any experimental investigation must include evidence that the systematic effects discussed here do not mimic or mask a true P, T-violating interaction. It is unlikely that such evidence could be obtained directly from the neutron transmission.

How to eliminate the zoo of alignment angles: Think of the experiment to find a σ.Jxk interaction as comparing the transmission in two different configurations of the apparatus



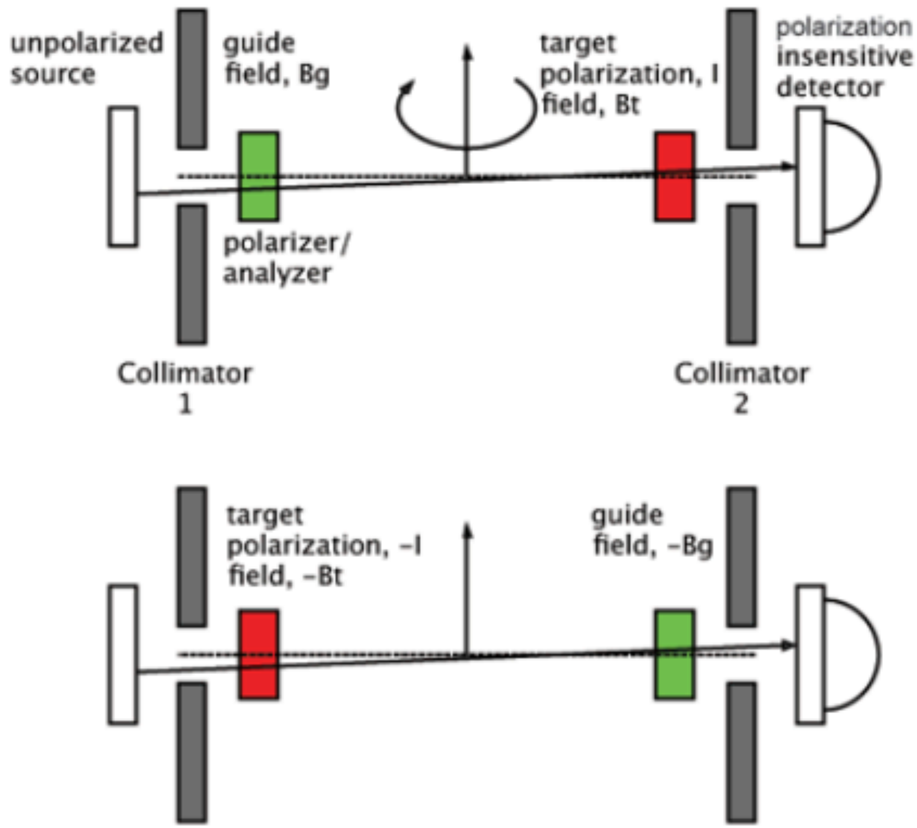
Rotate table that supports apparatus by 180 degrees and change the sign of all classical fields, B and J.

The misalignments are no longer relevant. The collimation system must accept the same set of trajectories through the target in both rotation states. The earth’s field must be compensated or shielded in order that σ, *B*, and *J* reverse.

EDITORS' SUGGESTION Phys. Rev. C (2015)

Search for time reversal invariance violation in neutron transmission

J. David Bowman and Vladimir Gudkov

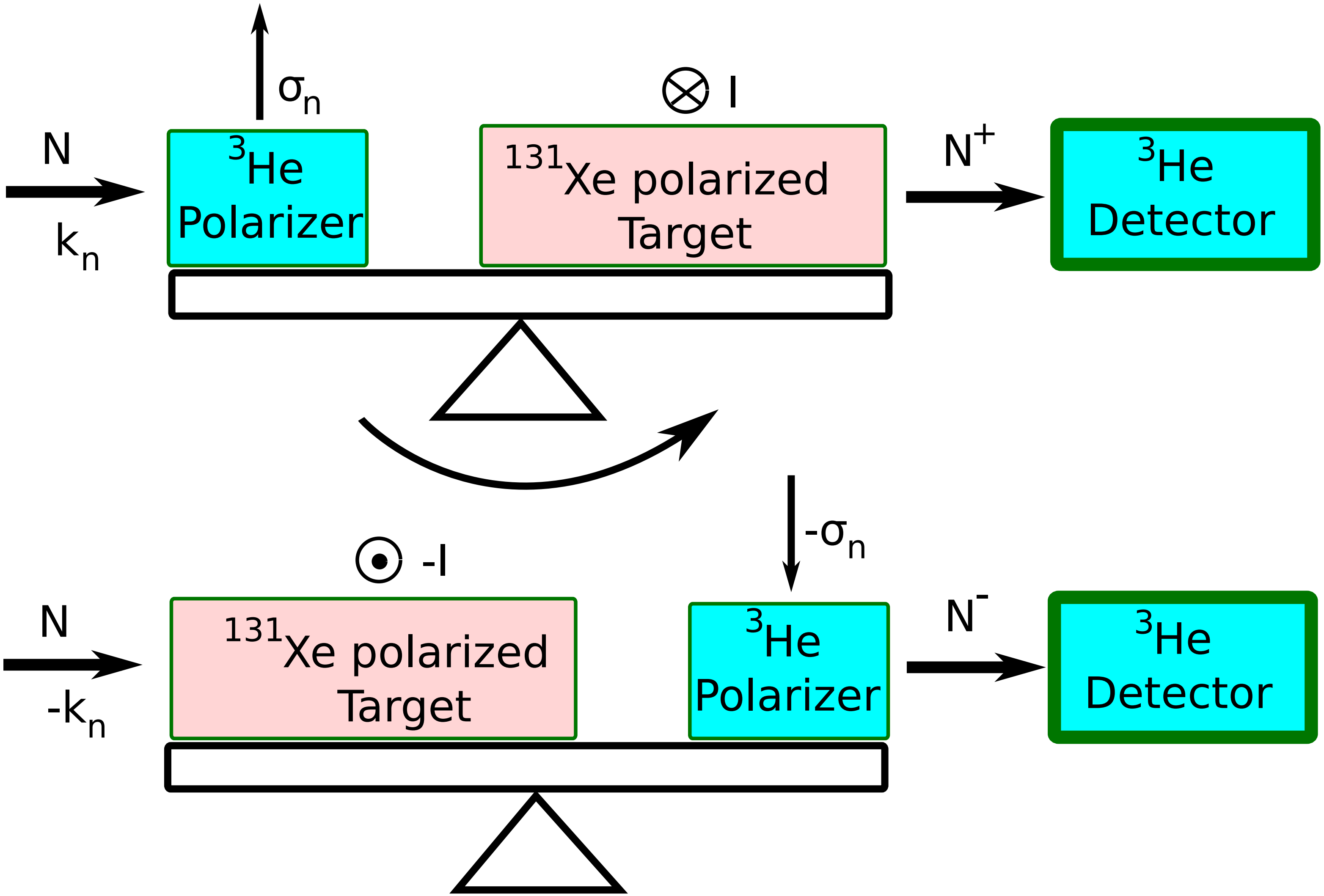


The authors analyze a novel null test to search for time reversal invariance in a model neutron transmission experiment. The proposed experimental procedure involves nuclear reactions and is sensitive to the neutron-nucleus interactions. The approach could significantly increase the discovery potential compared to the limits of present experiments.

“Motion-Reversed” Experiment (sys error free in the n optics limit)

$$f = f_0 + f_1 \vec{\sigma_n} \cdot \vec{I} + f_2 \vec{\sigma_n} \cdot k_n + f_3 \vec{\sigma_n} \cdot (\vec{k_n} \times \vec{I})$$

$f_3 << f_1, f_2$

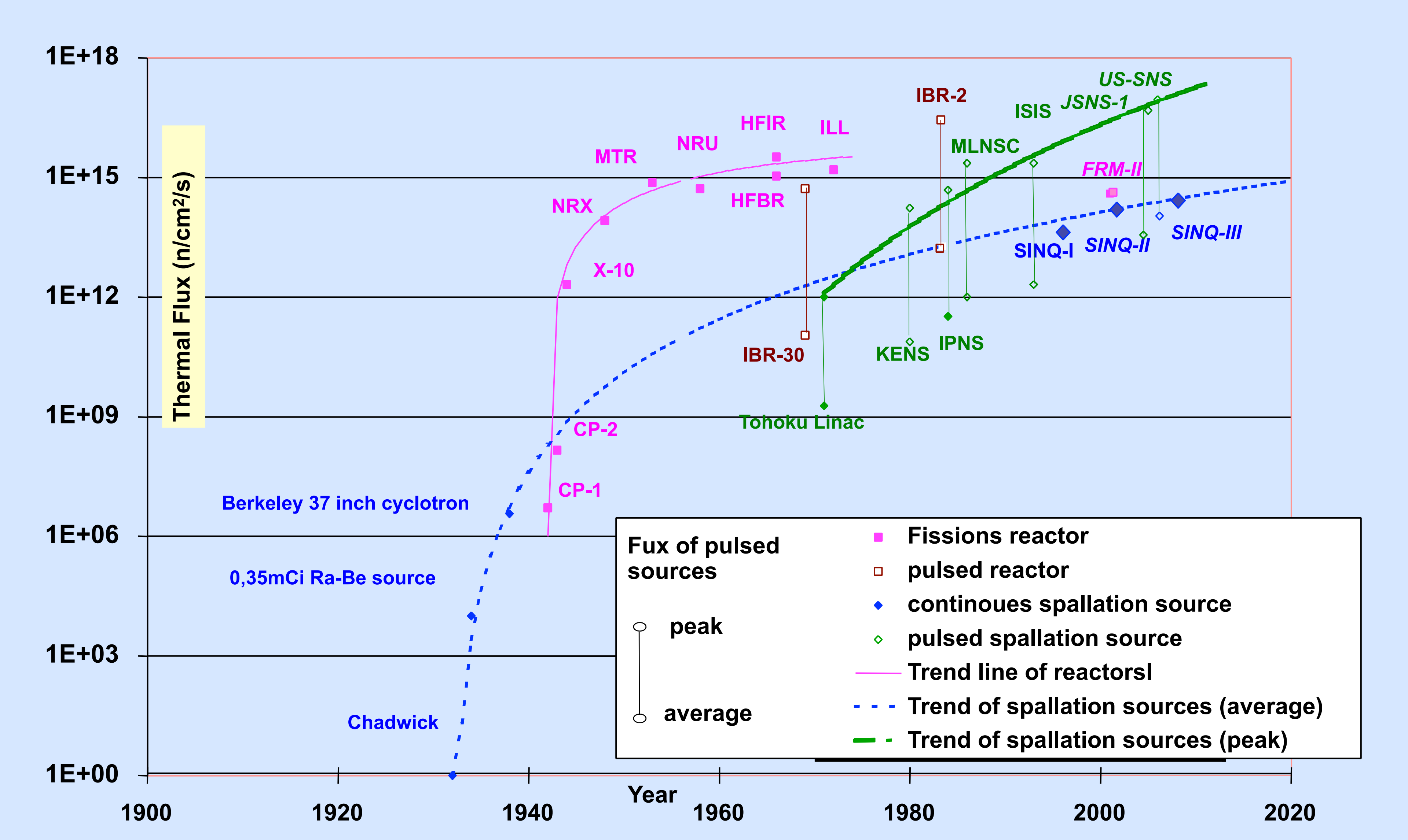


Bowman/Gudkov, arXiv:1407.7004

Experiment Components

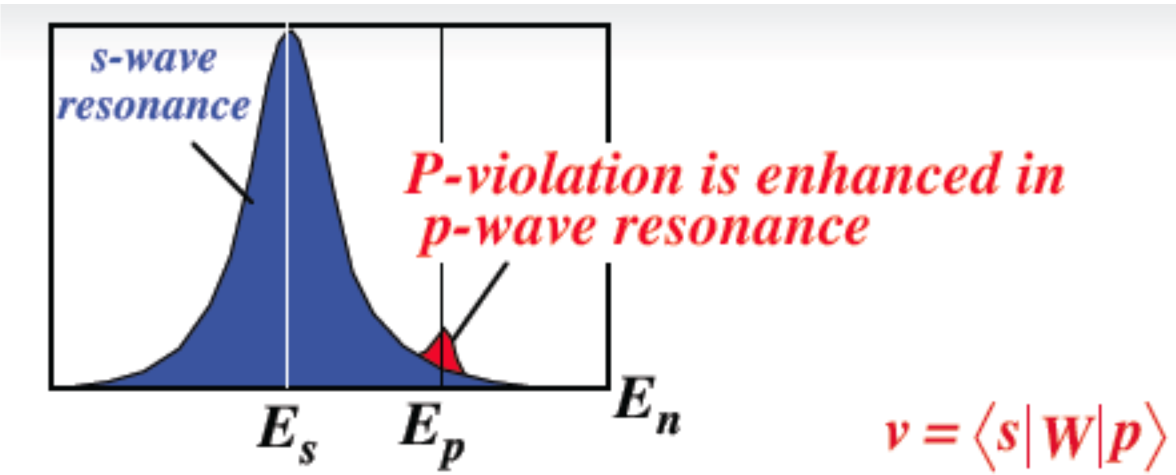
- Intense eV neutron beam
- Polarized eV neutrons
- Ability to flip $\vec{k_n}, \vec{\sigma_n}, \vec{I}$ and B (mechanical rotation of apparatus, B shielding)
- Current mode eV neutron detector
- Polarized nuclear target

Neutron source flux with time. Only within last decade do we have ~MW-class short-pulsed spallation sources

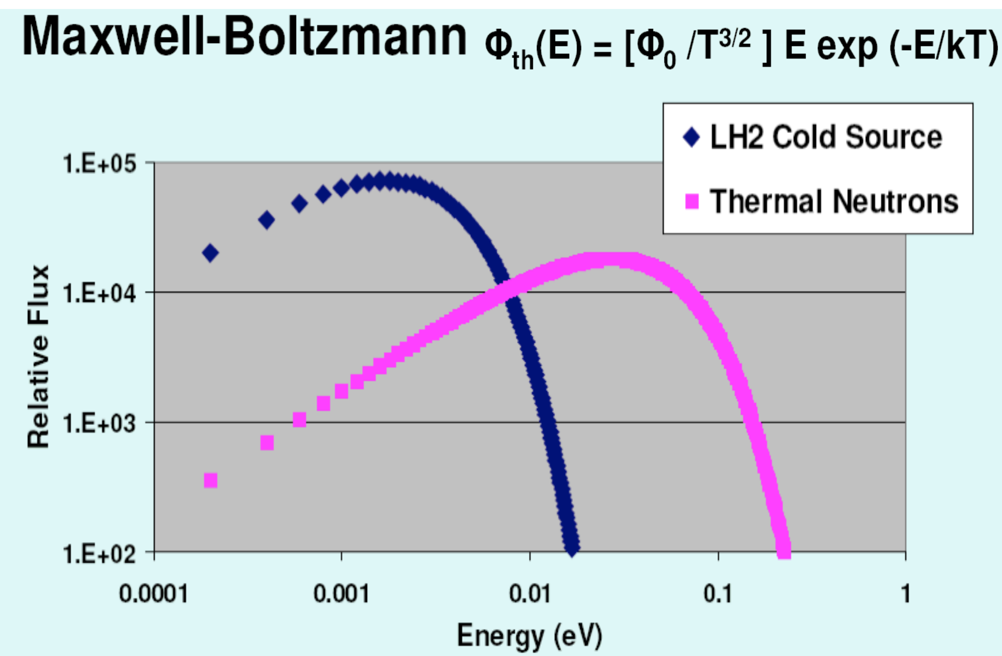


R. Eichler, PSI

Why is a pulsed spallation neutron source important for TREX?



$v = \langle s | W | p \rangle$



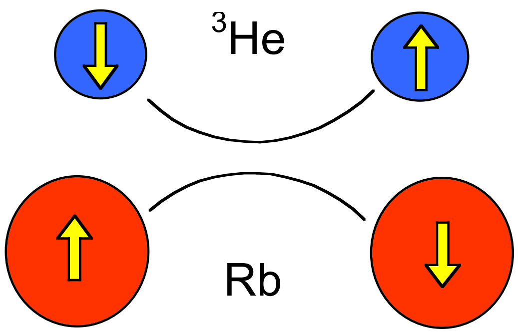
resonance energy ~eV, resonance width ~meVs

Short pulse-> resonance can be resolved using neutron time-of-flight

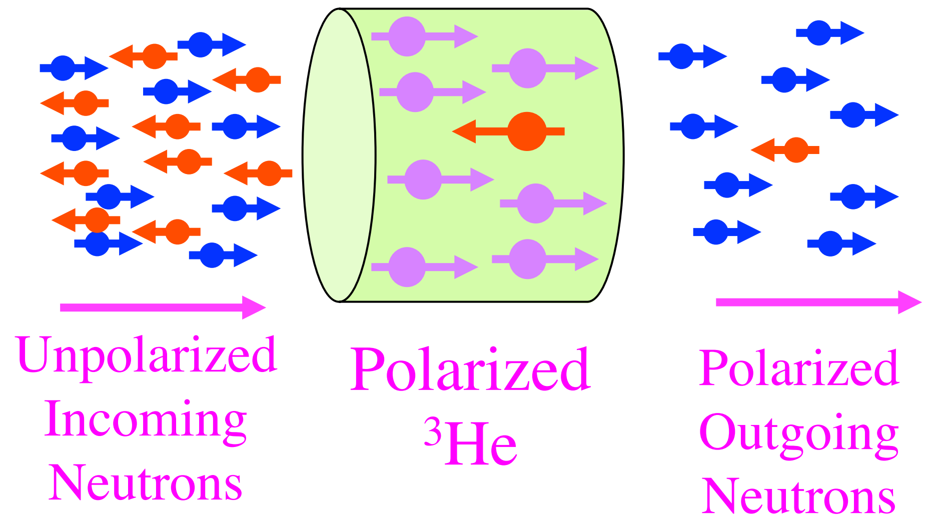
The rest of the neutrons in the beam can be used to characterize possible systematic effects !

>~10^4 more of these "off-resonance" neutrons

Polarized ^{3}He Neutron Spin Filters



Laser-polarized Rb⇒3He nucleus



Uniform polarized neutron beam phase space from absorption in polarized 3He gas

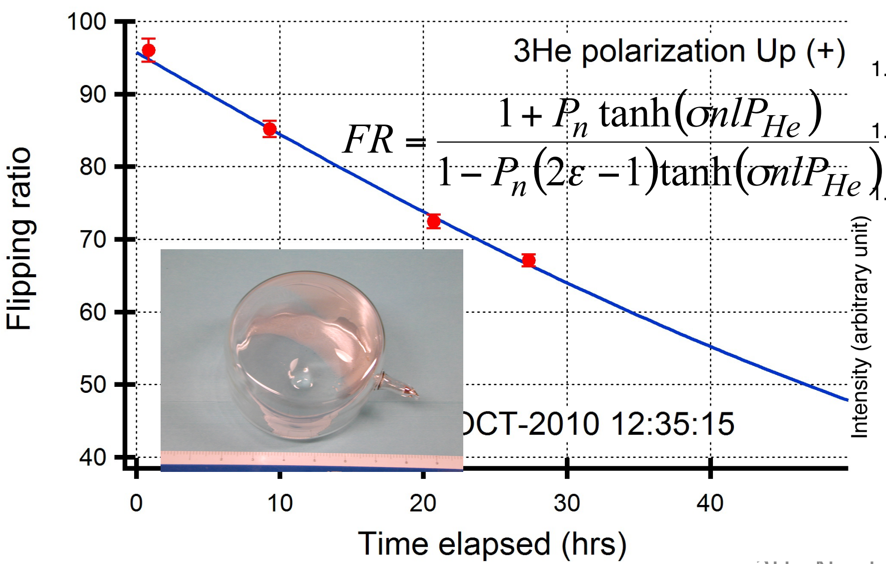
Spin flip by NMR on 3He. By far the best choice for TREX

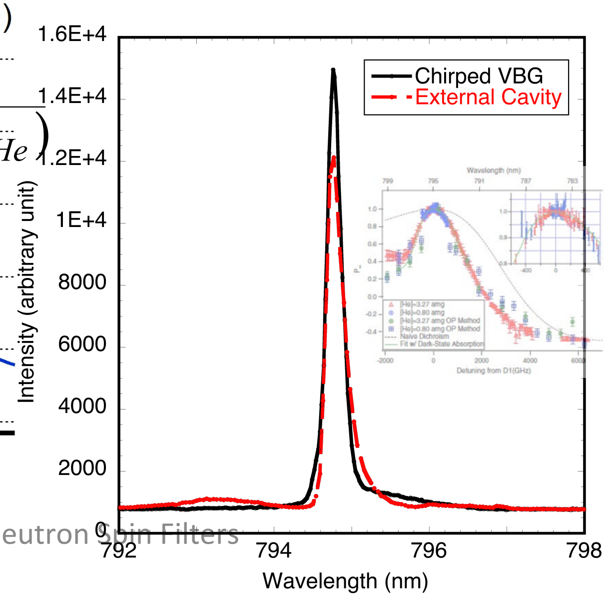
Need more polarized ^{3}He to polarize eV neutrons (σ_a~$1/v_n$)

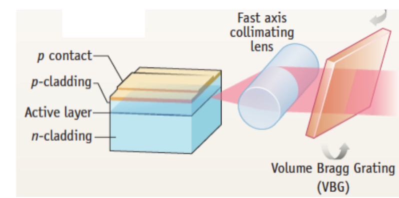
> 80% ^{3}He polarization for neutron spin filters

Cell name	D	V, cm^3	T_{up}, h	T_1, h	X	P_{He}	nl, bar-cm	instrument
Burgundy **2010**	4	895	4.76	NA	NA	0.853±0.012	8.507±0.060	ANDR
Maverick	4	615	4.33	NA	NA	0.821±0.011	8.878±0.060	ANDR
Burgundy **2012**	4	895	6.61	203	0.140	0.851±0.007	8.507±0.071	NG6A
Maverick	4	615	5.76	208	0.177	0.826±0.007	8.878±0.071	NG6A
Syrah	6.2	790	4.03	NA	NA	0.835±0.023	13.16±0.16	BT-7 TAS

Confirmed with pol. n's



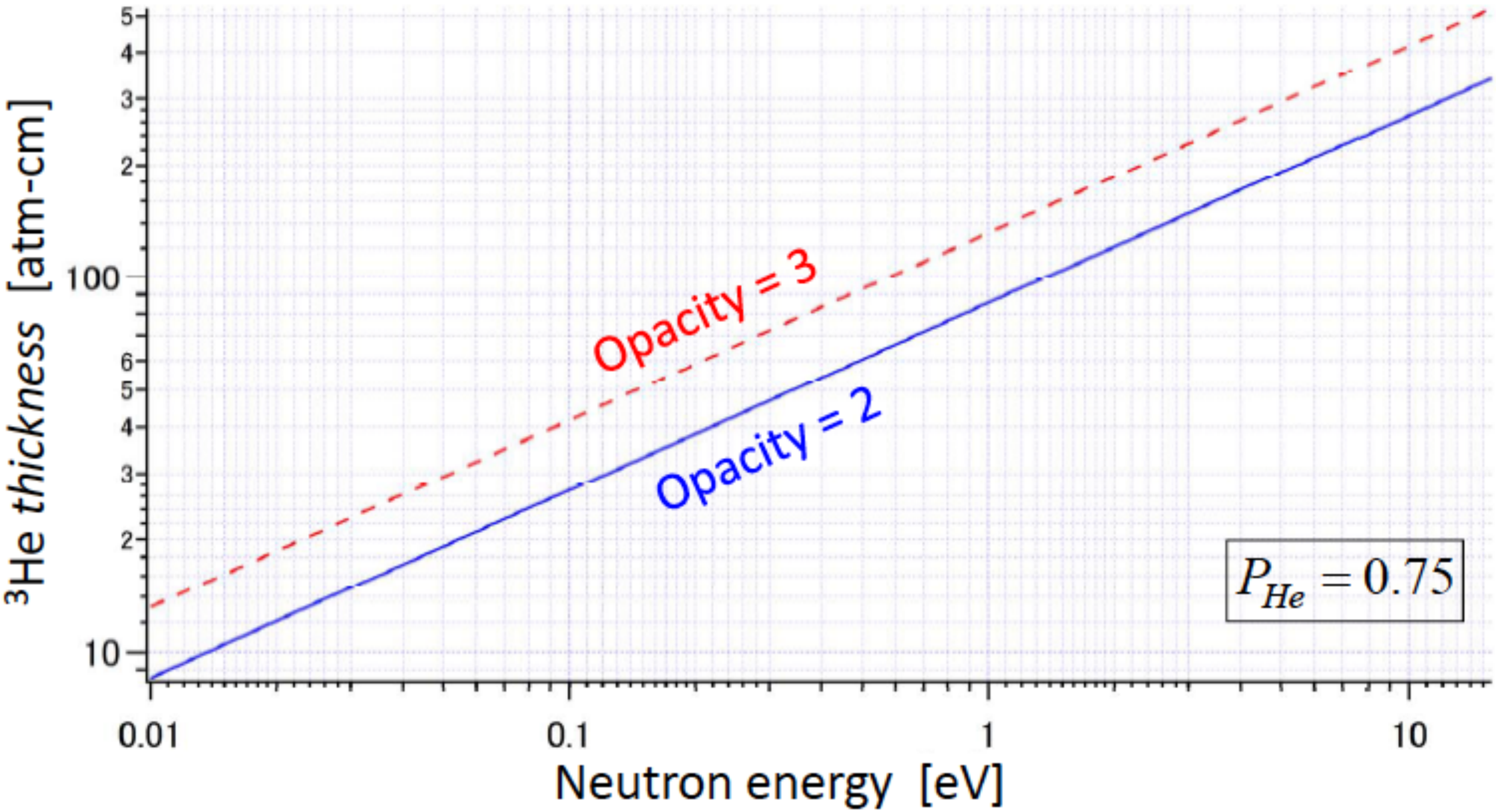




Volume Bragg gratings are bulk slabs of photosensitive glass that contains Bragg planes with varying indices of refraction. They work as a frequency-selective feedback element. Chirped VBGs indicate variable grating periods

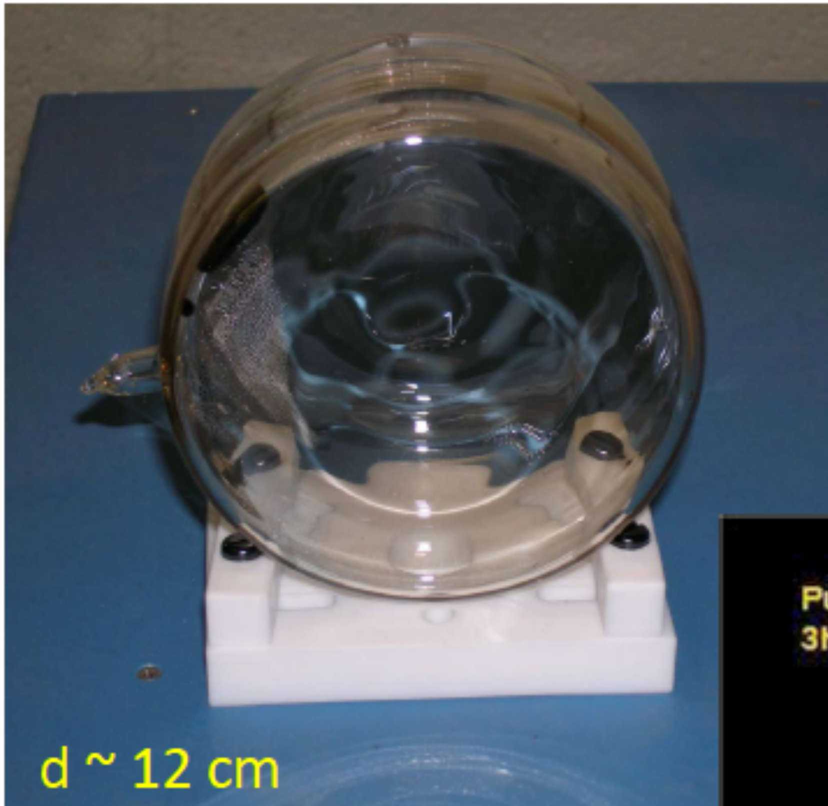
^{3}He NSF : optimum *thickness* of ^{3}He gas

ρd at 0°C



ρd : 150~200 atm-cm at 3.2 eV

^{3}He cells & polarization



^{3}He cell at NIST

^{3}He pressure ~ 1 atm

^{3}He *thickness* 10 ~ 20 atm-cm

P_{He} ~ 80%

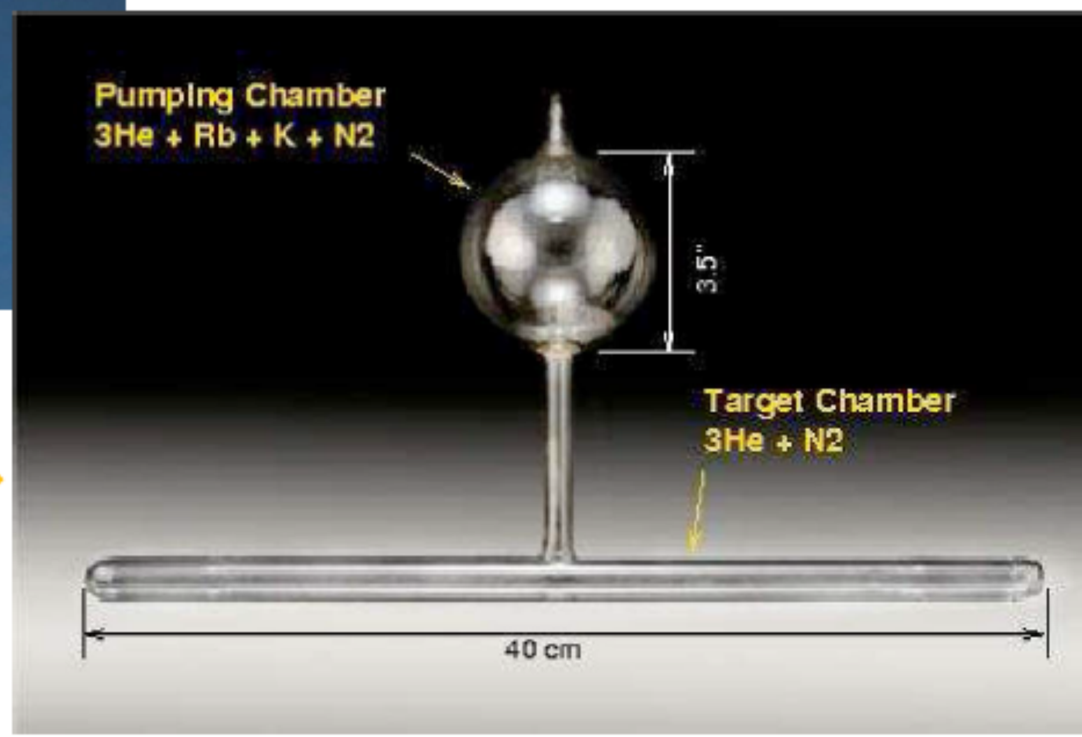
^{3}He cell for JLab exp.

Double chambers

^{3}He pressure ~ 7 atm

^{3}He *thickness* ~ 280 atm-cm

P_{He} ~ 70%



^{3}He Program at SNS

In-house cell fabrication

- ^{3}He polarization ~80%
- Long lifetime 100 – 400 hrs, approaching dipole-dipole relaxation limit
- Dimensions / pressures:
  - 8 – 12 cm in length
  - 1 – 3 bars
  - Suitable for thermal/cold neutrons

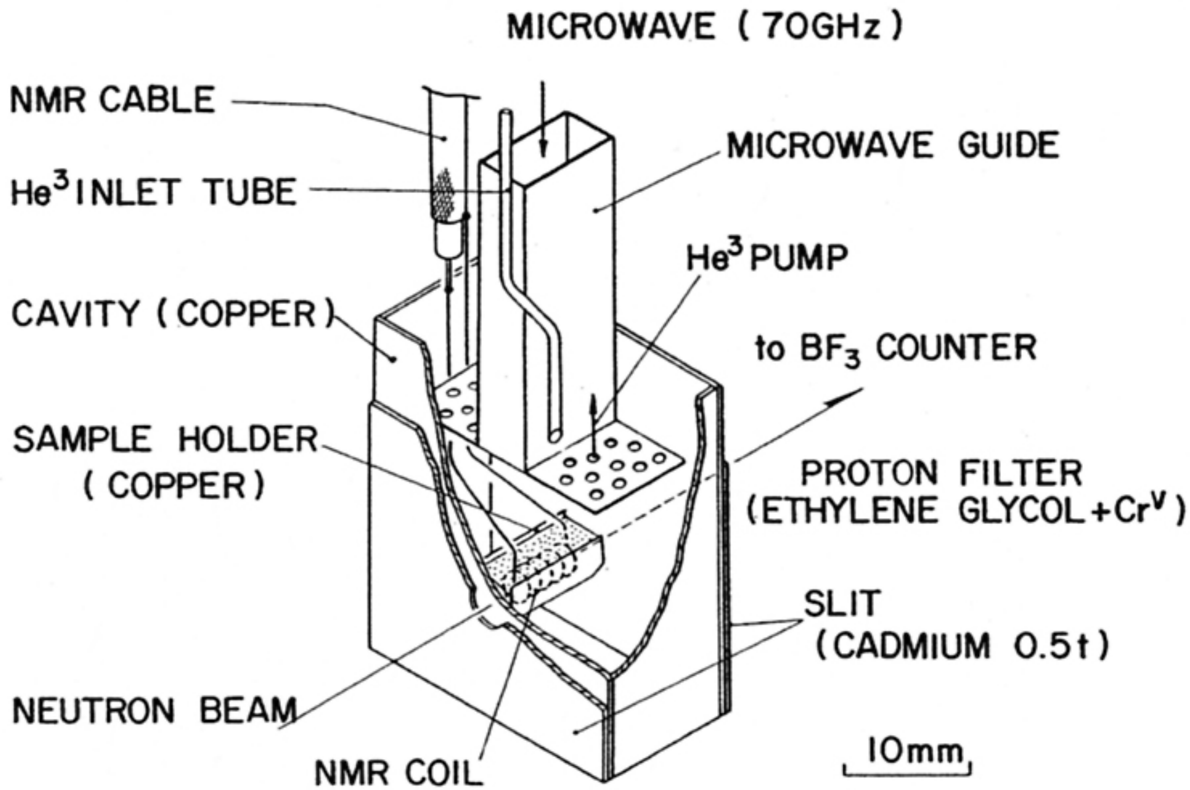
Need longer cells for polarizing epi-thermal neutrons

C.Y. Jiang, X. Tong, et al. *Physics Procedia 42 (2013) 191 - 199*

Factors influencing choice of target and state for TR studies

- Large PV asymmetry
  - Barrier-penetration enhancement $\sim 1/k \sim E^{-1/2}$
- Low energy resonance
  - Neutron flux at a spallation source ~ 1/E
- ^{139}La
  - 10% PV
  - E=.734 eV
- Possibility to polarize
  - Several groups have reported 40% polarized La targets

Polarized target: the hardest part of the apparatus? Serious cryogenics for large volume



Dynamic Nuclear Polarization using microwaves

Nucleus	Resonance Energy	PV asymmetry
^{131}Xe	3.2 eV	0.043
^{139}La	0.748 eV	0.096
^{81}Br	0.88 eV	0.02

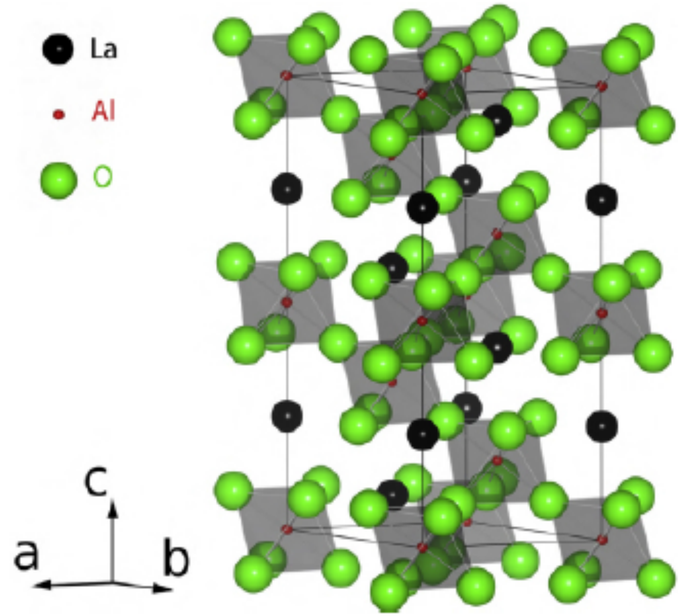
Our nuclei are not so easy to polarize. All are J>=3/2-> spin relaxation by quadrupolar fields etc.

DNP of La in Nd^{3+} doped $LaAlO_3$

it is not a new territory : it can be polarized via the Solid Effect

[Maekawa et al., NIM A **366** (1995) 115]

- P (^{139}La) ~ 20%
- T ~ 1.5 K B ~ 2.3 T



last experiments: at PSI in1997!

[Hautle & Iinuma, NIM A **440** (2000) 638]

- P (^{139}La) ~ 50 % / P(^{27}Al) ~ 65 %
- Dlution refrigerator, T < 300 mK B ~ 2.3 T

Crystals size: 15 x 15 x 4 mm

Nd^{3+} doping: 0.03 mol% ~ 5 x 10^{18} spins/ccm

(0.1 mol% / 0.3 mol%)

Nd^{3+} ion replaces ^{139}La nucleus

two *g*-factors: $g_{\parallel} = 2.12$ $g_{\perp} = 2.68$

Conclusion from $Nd^{3+}:LaAlO_3$ experiments I

general

- large polarzation values can be achieved by known technique
- polarization was achieved in a dilution fridge
- crystal used so far were of not sufficient quality

Questions that have to be answered before going on

- how precise the polarization value needs to be known
- way to measure the polarization besides NMR (spin-dependent transmission, pseudomagnetic precession, Ramsey resonance)
- tolerable polarization inhomogeneity
- stability of polarization over time / frozen spin mode
- polarization cannot be easily flipped (like ^3He) for the rotated configuration
- target size
- polarization level needed
- tolerabel magnetic field (=> stray fields)
- overall size of PT apparatus
- ^3He on beam (dilution refrigerator)

Conclusion from Nd^{3+}:$LaAlO_3$ experiments II

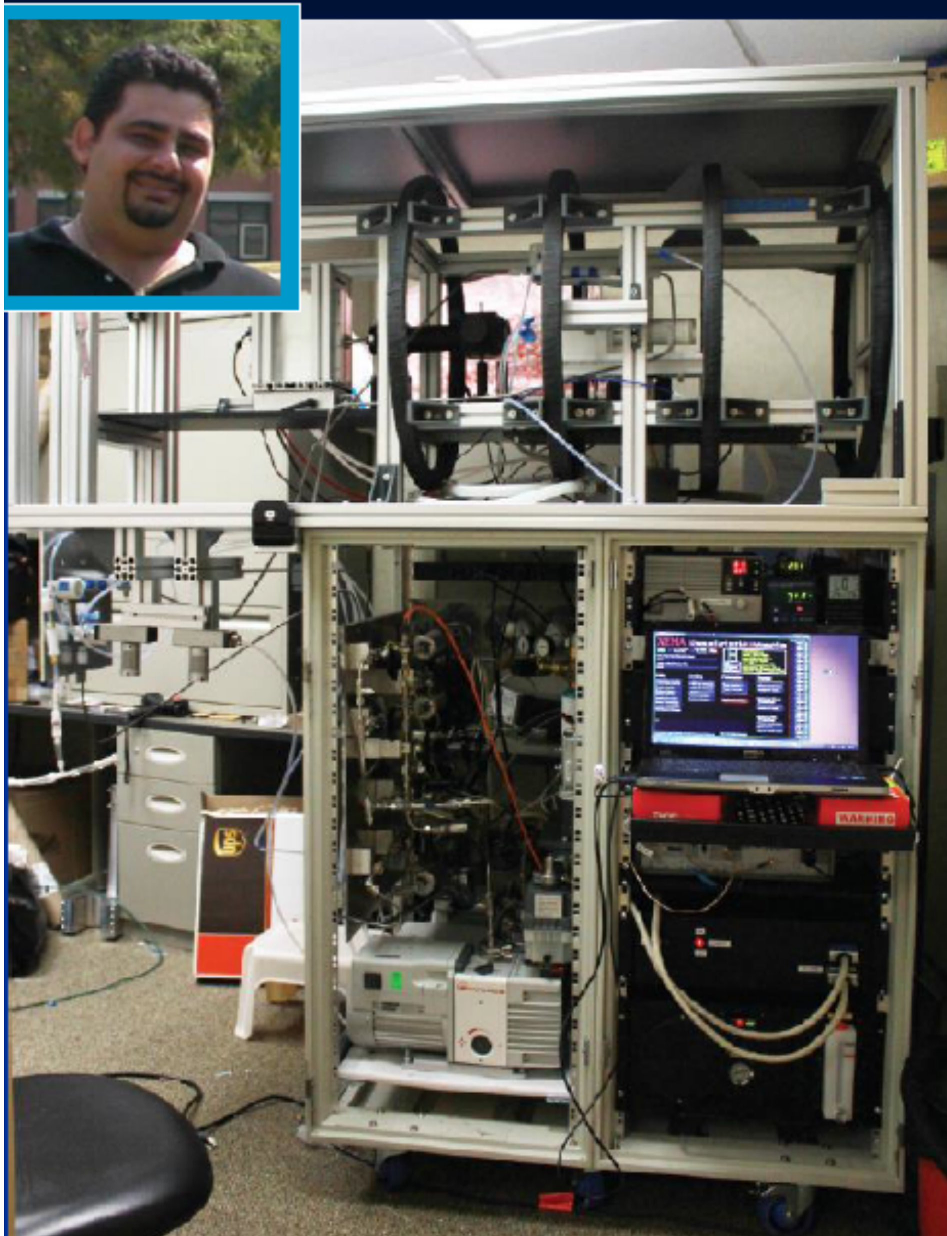
Answers to above questions could largely determine & constrain the requirements and layout of a polarized target system
or
make it even impossible ??

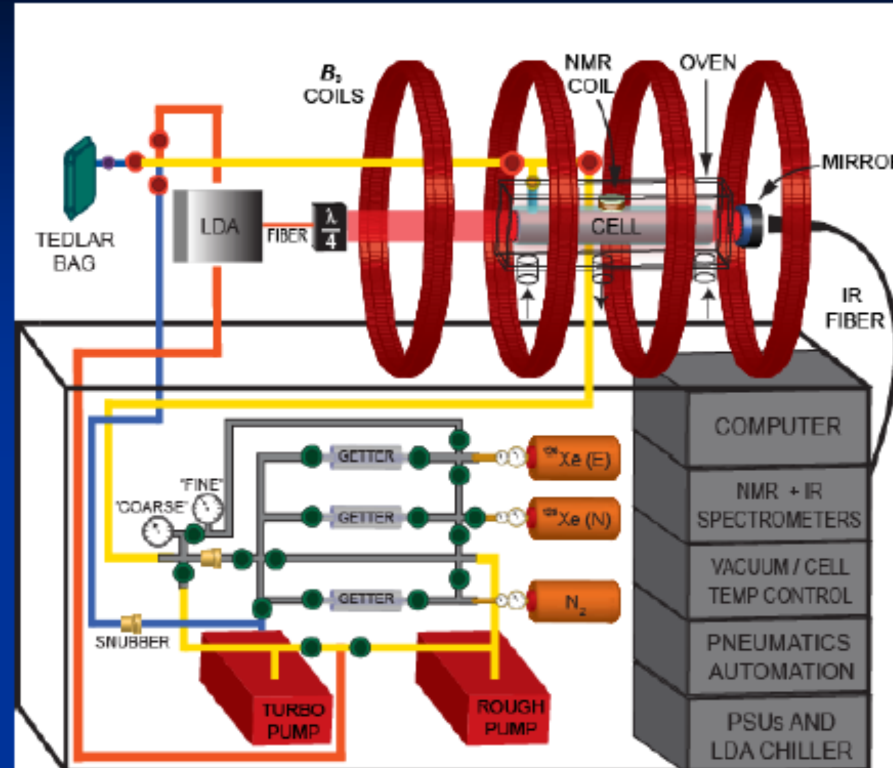
what to do, suggestions

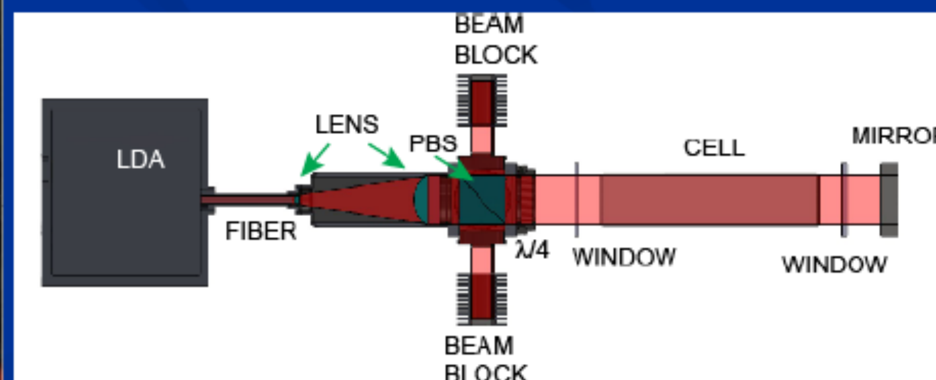
- define the possible options before start of further R&D
- get really good crystals (commercially available?)
- establish experimental data base to decide on the type of apparatus most suited for the experiment:

check DNP performance & relaxation at different temperature / field combinations (1K / 5T or DR / 2.5T)

HXTC (XENA) "Open-Source" Xe Polarizer







Peter Nikolaou, SIUC / Vanderbilt

HXTC Goal: Make Human-Scale LPXe, easier, cheaper, and open-source

Direct ^{131}Xe SEOP

Best result to date:

Stupic et al. JMR 208 58-69, 2011)

- *P*=2.2% for 5% ^{131}Xe in 1.5 bar
- (5000-fold at 9.4 T)
- Successful separation from Rb, SEOP Cell

How to do better?

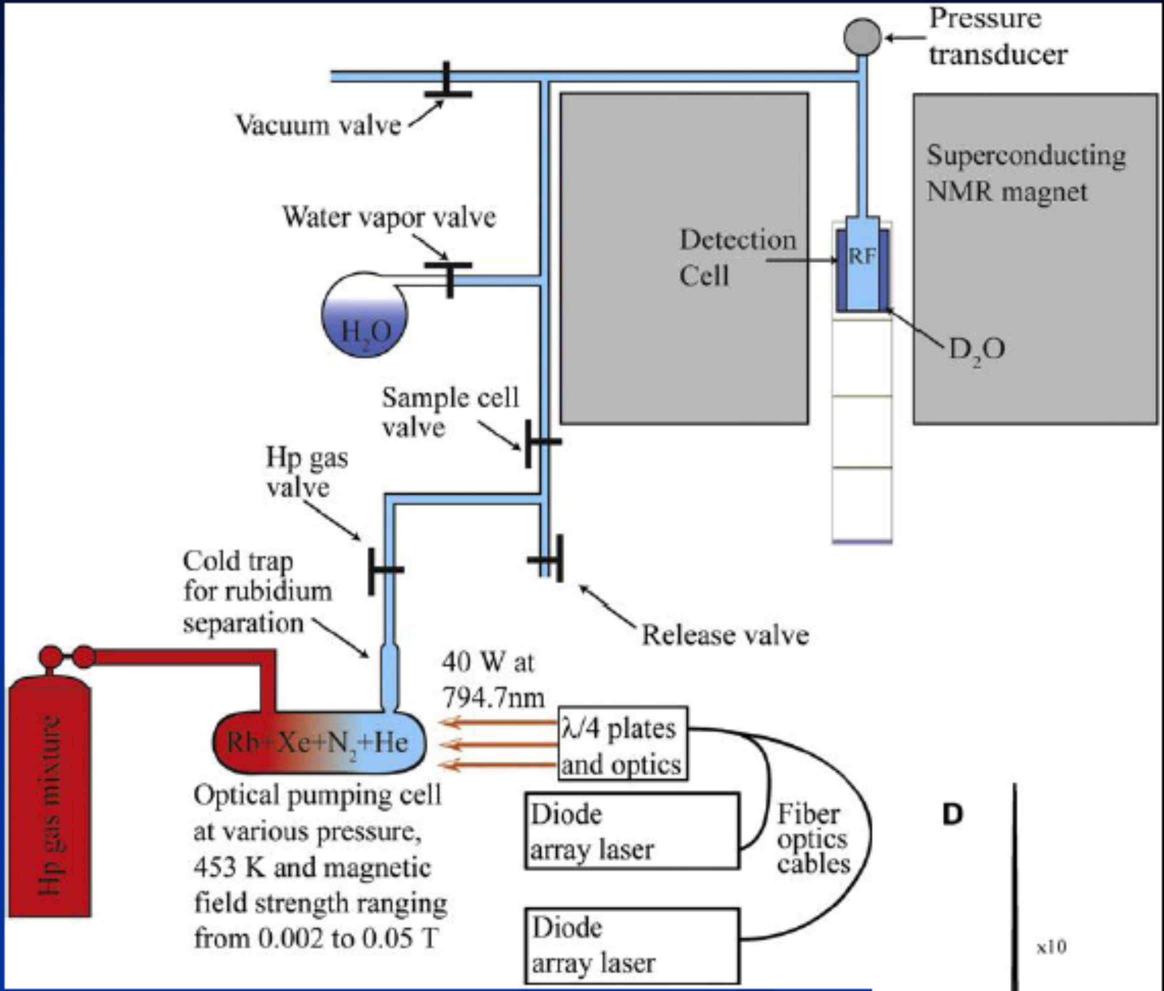
- Use more powerful, narrowed laser (above was un-narrowed 40 W)
- Keep ^{131}Xe partial pressure low during SEOP

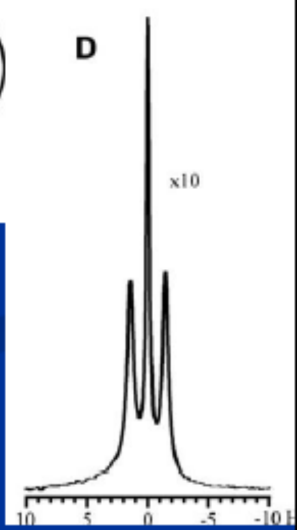
($\Gamma > \gamma_{SE}$ at above ~1/3 bar);

but would need to quickly

re-pressurize for target somehow?

- Throw kitchen sink at it (try Cs, Rb/Cs hybrid, huge cells / low pressure, etc.?). *P*=10% "should" be possible; "More = Difficult".
- May necessitate stopped-flow delivery of HP ^{131}Xe to increase [Xe], but cont. flow w/o cryo-collection could allow much higher [AM]…





Xenon

DNP has been recently performed for Xenon doped at low temp.

a) Xe is liquid around 165K

b) TEMPO dissolved in iso-butanol

Mix them with a) 50% and b) 50% in weight.

PRL 105, 018104 (2010) PHYSICAL REVIEW LETTERS week ending 2 JULY 2010

Hyperpolarizing Gases via Dynamic Nuclear Polarization and Sublimation

A. Comment,[1,2,3,*] S. Jannin,[4] J.-N. Hyacinthe,[5] P. Miéville,[4] R. Sarkar,[4] P. Ahuja,[4] P. R. Vasos,[4] X. Montet,[5] F. Lazeyras,[5] J.-P. Vallée,[5] P. Hautle,[6] J. A. Konter,[6] B. van den Brandt,[6] J.-Ph. Ansermet,[3] R. Gruetter,[1,2,5] and G. Bodenhausen[4,7,*]

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[7]*Department of Chemistry, Ecole Normale Supérieure, F-75230 Paris cedex 05, France*

(Received 11 March 2010; published 1 July 2010)

A high throughput method was designed to produce hyperpolarized gases by combining low-temperature dynamic nuclear polarization with a sublimation procedure. It is illustrated by applications to ^{129}Xe nuclear magnetic resonance in xenon gas, leading to a signal enhancement of 3 to 4 orders of magnitude compared to the room-temperature thermal equilibrium signal at 7.05 T.

[DNP result]

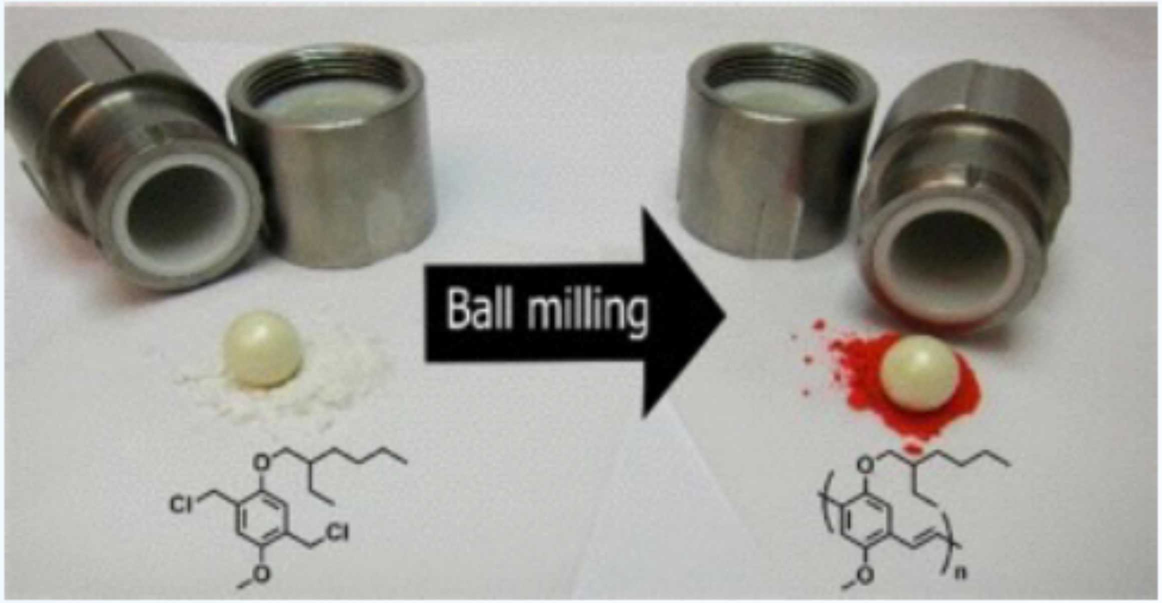
1.2K at 3.35T, Pol(Xe129)=5.1%,

1.2K at 5T, Pol(Xe129)=7.2%

However, due to as much as 50% of iso-butanol, fraction of Xe is limited to 50%.

Mechanical Alloying (MA)

Using a ball mill, one crushes material into very fine power in nanometer scale and mixes them resulting in even chemical reactions



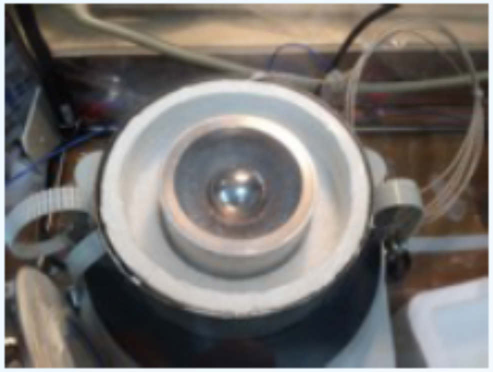
Ten minutes of processing in a ball mill polymerizes a white monomer (left) into a bright red conducting polymer, poly(2-methoxy-5-2´-ethylhexyloxy phenylene vinylene) (right). Credit: *ACS Macro Lett.*
http://cen.acs.org/articles/92/web/2014/03/Ball-Mill-Grinds-Monomers-Polymer.htm

It may be applicable to doping of most of "solid" material including solid Xeon.

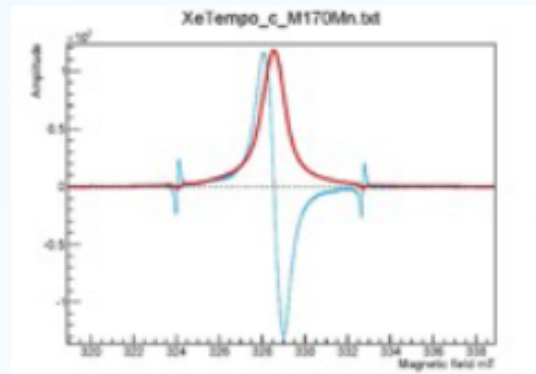
MA with Xe and TEMPO

Xe (20g) + TEMPO (12.5 mg) → 2.4×10^{18} TEMPO/g
milling time: 60 min.
Temp. : around 93K

(0.52×10^{-3} TEMPO/Xe)

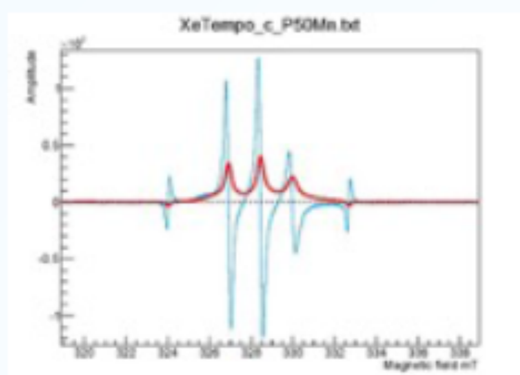


ESR (Xe+TEMPO) 103K

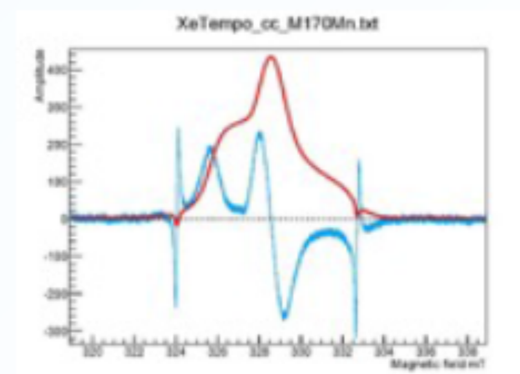


Symmetric and relatively narrow ESR spectrum
→ suggesting uniform distribution of TEMPO

ESR(TEMPO) +50 deg. C.



ESR(TEMPO) 103K

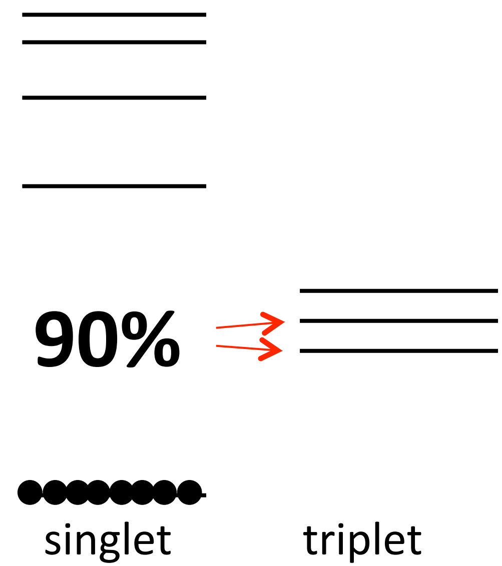


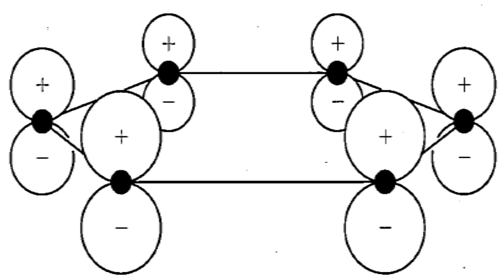
How to Polarize Br: Triplet-DNP method?

- High electron polarization spontaneously produced in photo-excited aromatic molecule

A. Henstra et al. Phys. Lett. A 134 (1988) 134.

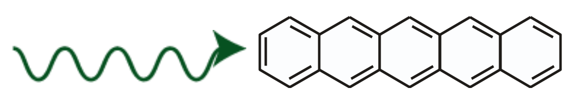
Very weak dependence on B and T





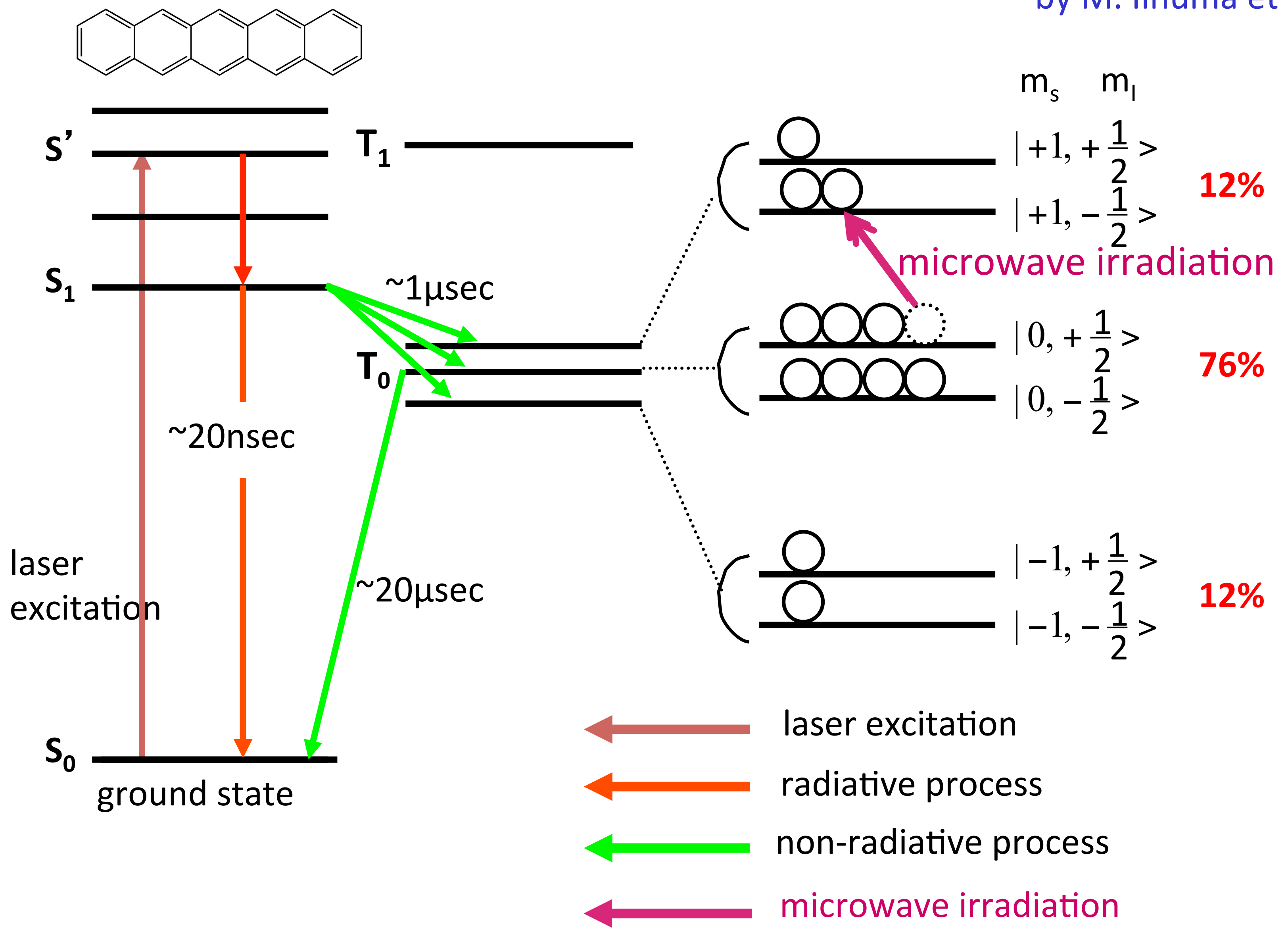
Can bromine be polarized by substituting it into the aromatic molecules (pentacene/napthalene) used for this?

Laser excitation



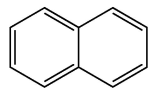
Polarization of Pentacene Molecule at High Temperature*

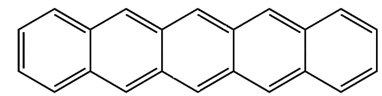
by M. Iinuma et al.



DNP at High Temperature and Low Field

Single crystal of naphthalene doped with pentacene





It can be polarized at 77 K / 270 K and 0.3 T, and held at 0.0007 T

1) laser irradiation → pentacene is excited to the triplet state.

2) microwave irradiation & sweep of the field within the lifetime of the triplet state → population transfer

3) transition from the triplet state to the diamagnetic ground state spontaneously, where no spin-spin interaction between e and p.

4) diffusion of proton spin from pentacene to naphthalene → proton polarization in naphthalene

B

Systematic Errors!

(1) Imperfect flipping of $\vec{k_n}, \vec{\sigma_n}, \vec{I}$ and B

$$f = f_0 + f_1 \vec{\sigma_n} \cdot \vec{I} + f_2 \vec{\sigma_n} \cdot k_n + f_3 \vec{\sigma_n} \cdot (\vec{k_n} \times \vec{I})$$

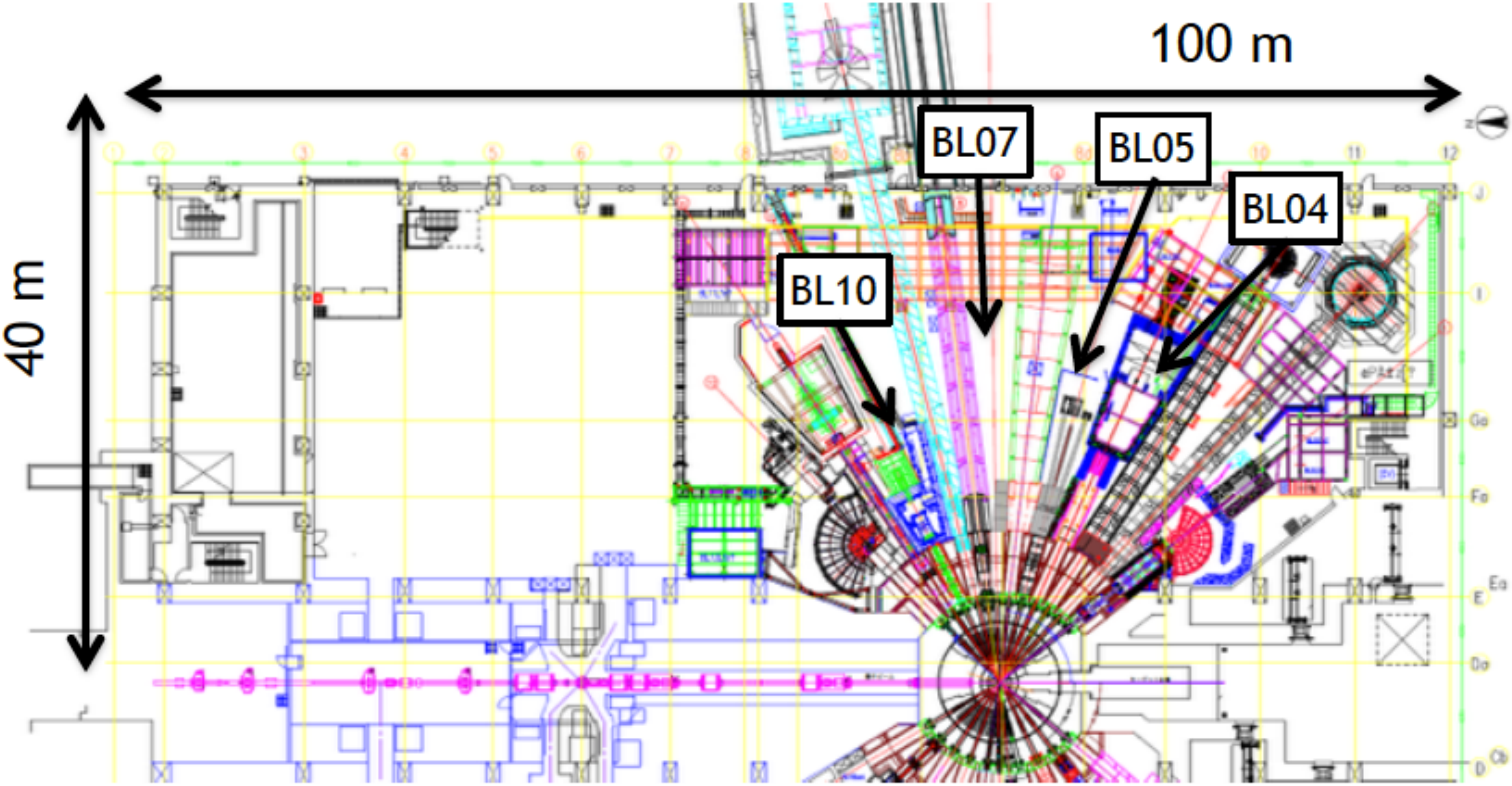
Solution: (superconducting?) magnetic shielding? Implemented in neutron scattering instruments (CRYOPAD at ILL)

(2) Nonforward scattering: use neutron TOF+nonforward neutron detector?

(3) Polarized target nonuniformities/time dependence: polarized neutron imaging.

(4) Washout of signal from pseudomagnetic precession: how to mininize?

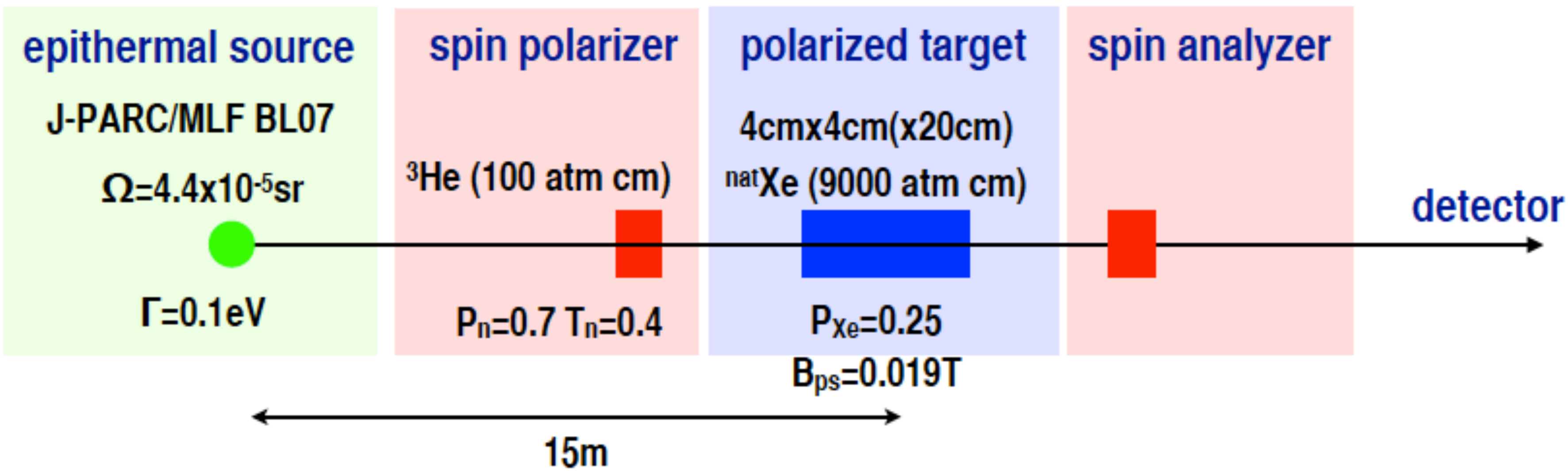
MLF 1st Experimental Hall



BL07/Poisoned (Thinner Side) / Not assigned

KEK-2015S12

NOP-T



J-PARC/MLF

ORNL/SNS

^{3}He Laser

p DNP

MIONP (Triplet DNP)

Xe (gas,liq,solid) Laser

La ($LaAlO_3$) DNP

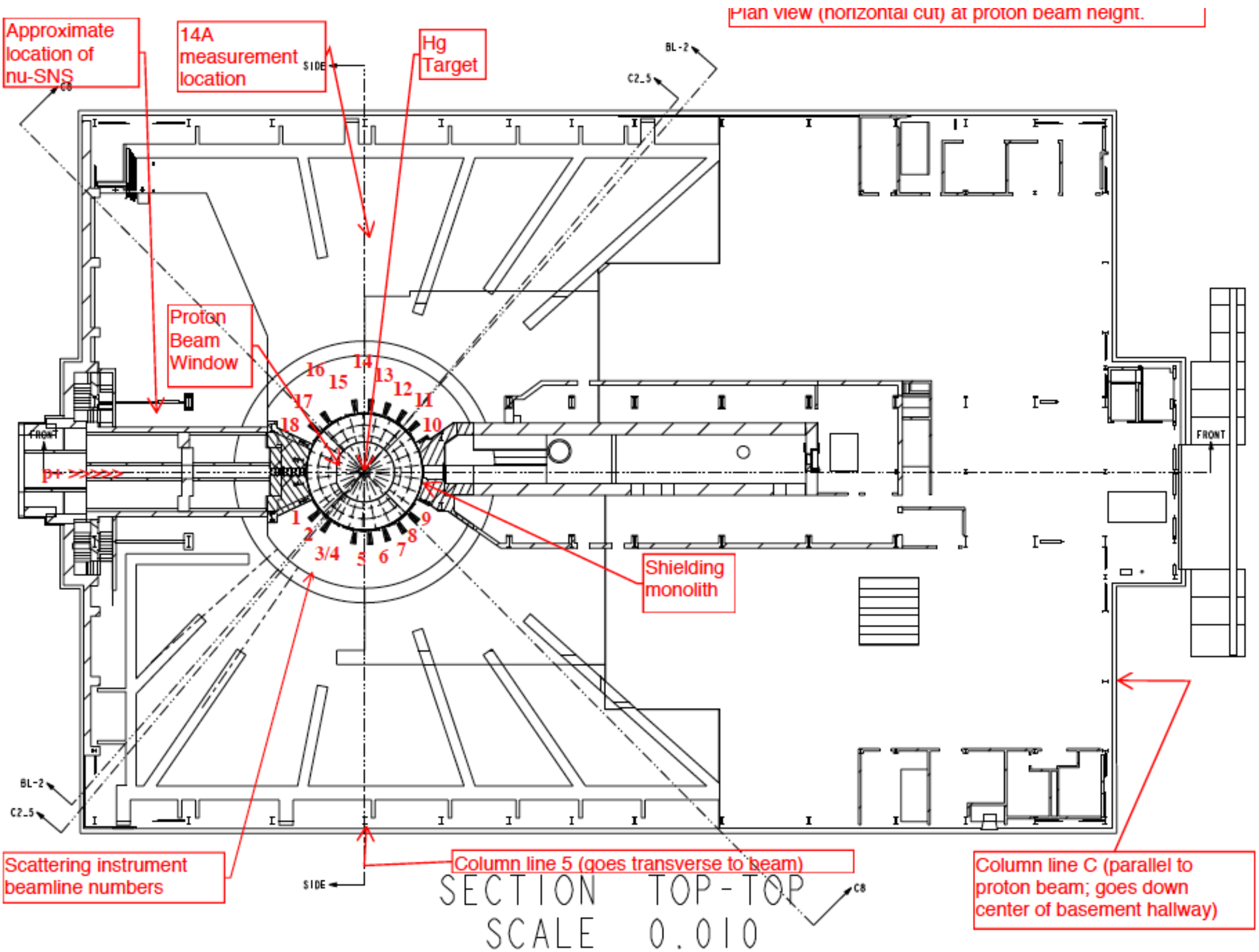
Br (?) DNP

MIONP (Triplet DNP)

Li-glass

^{10}B-loaded Liq. Sci.

SNS beam #1 (Seppo Penttila)



ORNL statement:

If you can secure the resources for the experiment, you can have a beam at SNS

Present Activities

A Proposal to Test an eV Neutron Detector based on ^{10}B/NaI(Tl) at LANSCE FP5 for future experiments on Time Reversal Violation in Neutron Resonances

J. Curole, Z. Grube, C. Haddock, D. Moss, W. M. Snow, G. Visser
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University of Kentucky, Lexington, KY 40506 USA

D. Bowman, S Penttila
Oak Ridge National Lab, Oak Ridge, TN 37831 USA

S. Vogel, Z. Tang
Los Alamos National Lab, Los Alamos, NM 87545 USA
(Dated: July 24, 2015)

LANSCE proposal successful: beamtime in Dec. 2015

Possibility at LANSCE: IU ^{3}He polarizer+spin flipper+eV n detector, search for new large p–wave resonances. Soonest possible experiment ~fall 2016.

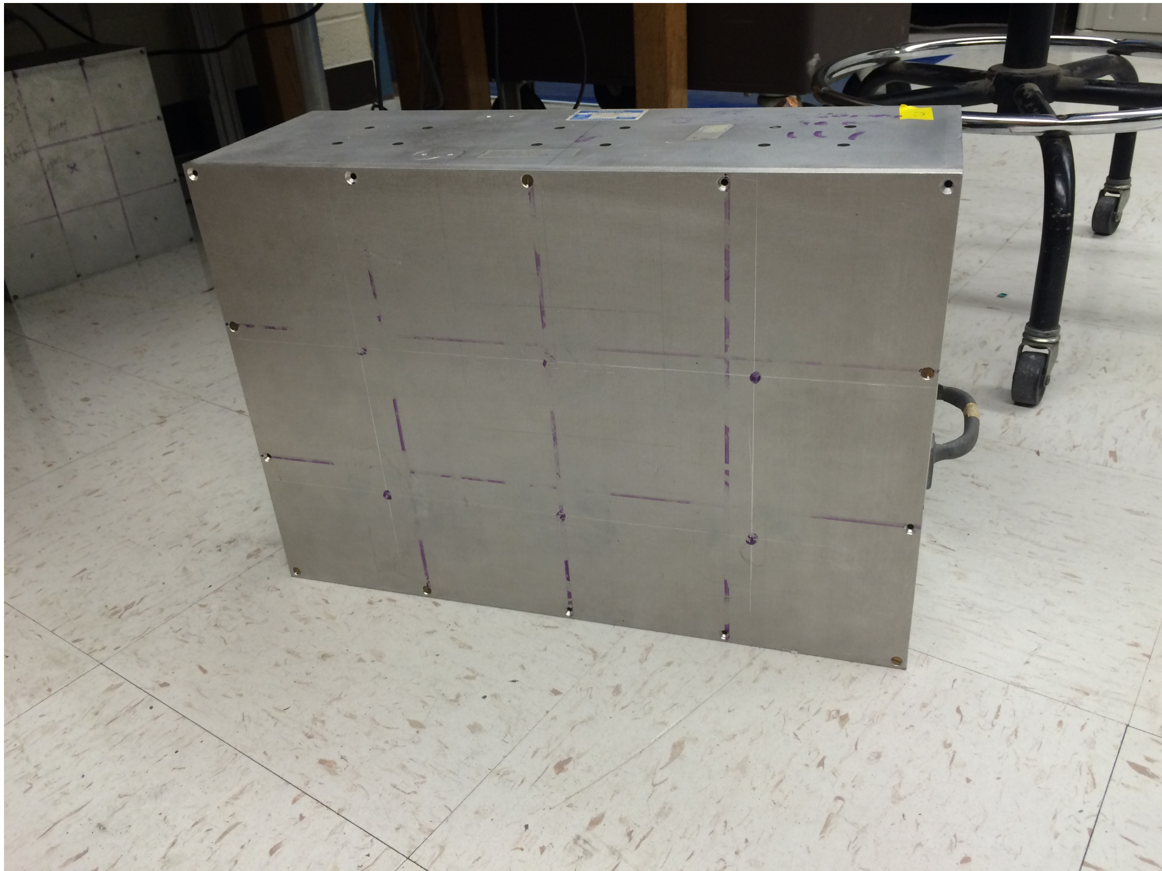
Current Activities: eV Current-Mode Neutron Detector Development

One of three large area (~50 cm x 50 cm)
NaI(Tl) Xtal arrays at IU

$n + {}^{10}B \rightarrow {}^{11}B \rightarrow {}^{4}He + {}^{7}Li^{*} \rightarrow 0.448$ MeV gamma$+{}^{7}Li$

Detect 0.488 MeV gamma in current mode using NaI(Tl)

NaI(Tl) scintillation light is fast enough that time response of this detector can resolve many neutron TOF bins across the p-wave resonance



T violation in Neutron Optics: TREX

- T – odd term in FORWARD scattering amplitude (a null test, like EDMs) with polarized n beam and polarized nuclear target $\vec{\sigma_n} \cdot (\vec{k_n} \times \vec{I})$
- P-odd/T-odd (most interesting)
- Amplified on select P-wave epithermal neutron resonances by ~5-6 orders of magnitude
- Estimates of stat sensitivity at SNS/JSNS look very interesting:

Existing technology/sources->$\Delta\sigma_{PT}/\Delta\sigma_P$~1E-5. sensitivity can be ~x100 present n EDM limit

- The nuclei of interest, resonance energies, and P-odd asymmetry amplifications are measured. ^{139}La can be polarized using DNP ($LaAlO_3$). ^{3}He with SEOP can be used as a polarizer for eV neutrons

- Can ^{139}La, ^{131}Xe, ^{81}Br be polarized in large quantities for this experiment?

Nucleus	Resonance Energy	PV asymmetry
^{131}Xe	3.2 eV	0.043
^{139}La	0.748 eV	0.096
^{81}Br	0.88 eV	0.02

Conclusions

On-resonance T violation in epithermal neutron resonances can now be measured with interesting sensitivity

MW-class, short-pulsed spallation neutron sources (SNS, JPARC) are beautiful sources to use for the experiment: neutron time-of-flight can be used to great advantage to characterize possible systematic errors, especially to “dig out” any non-forward scattering in the transmitted beam

Individual components/operation modes for the experiment have been realized: hardest part is the polarized target