Searches for BSM Physics with Polarized Slow Neutrons and Nuclei

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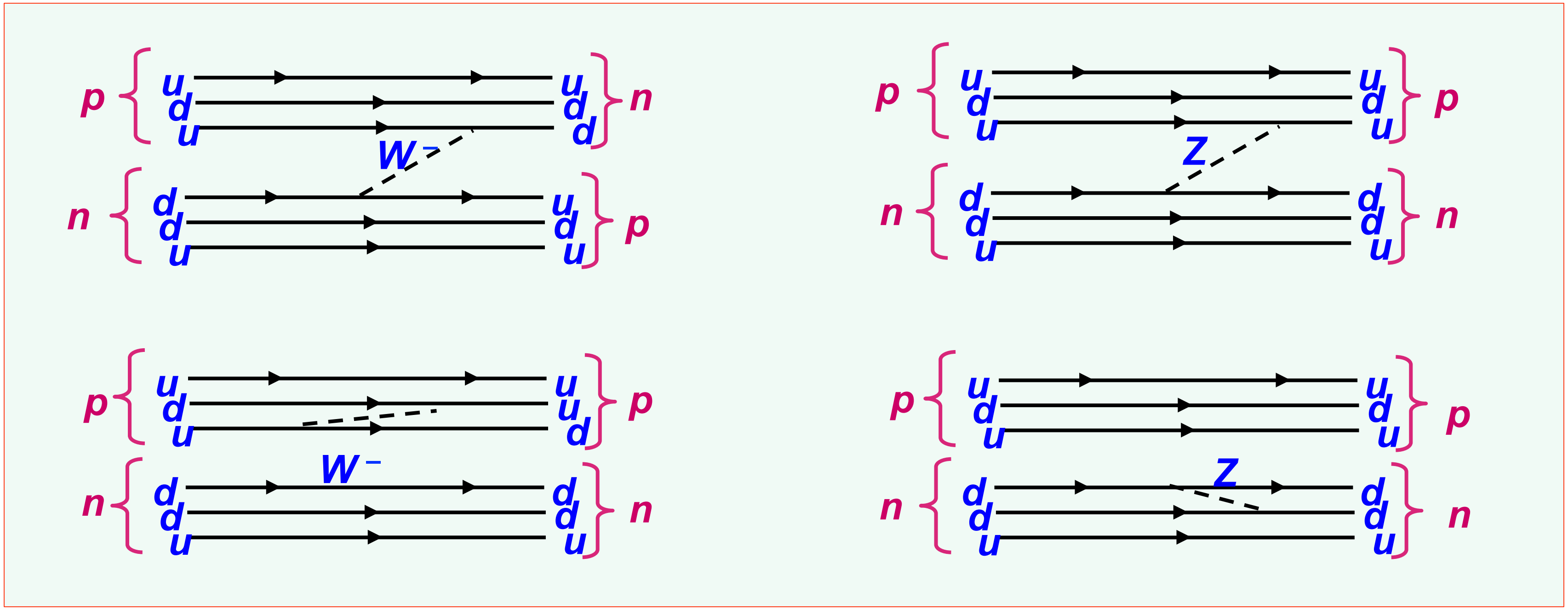
0. P-odd neutron-nucleon interactions/SM test in n-4He neutron spin rotation
1. Proposed search for P-odd and T-odd interactions in polarized neutron optics
2. Searches for exotic spin dependent interactions of neutrons and electrons
3. Searches for exotic spin dependent interactions using polarized nuclei

Thanks for slides to: H. Shimizu, G. Pignol,…

NN Weak Interaction: the nucleons are the "problem"

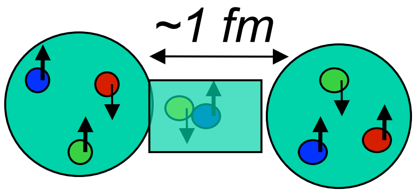
In the Standard Model, the structure of the quark-quark weak interaction is known from the electroweak sector.

However, strong QCD confines color and breaks chiral symmetry by correlating the quarks in both the initial and final nucleon ground states. The dynamical mechanisms which do this in QCD are not yet understood.



Two aspects of the qq weak interaction make it useful as an interesting probe of QCD:
(1) Since it is weak, it probes the nucleons in their ground states without exciting them.
(2) Since it is short-ranged compared with the size of the nucleon, NN weak amplitudes should be first-order sensitive to quark-quark correlation effects in the nucleon.

N- N Weak Interaction: Size and Mechanism

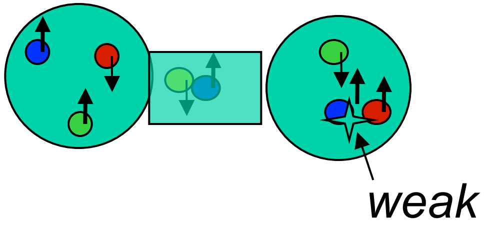


NN repulsive core → 1 fm range for NN strong force

$|N\rangle = |qqq\rangle + |qqqq\bar{q}\rangle + \cdots$ *= 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.

NN Weak Amplitudes EFT: 5 s-p Amplitudes, 2 lead in N_c

$$\mathcal{H}^{\Delta S=0}=\frac{G_F}{\sqrt{2}}\left[\cos^2\theta_c J_W^{0\dagger}J_W^0+\sin^2\theta_c J_W^{1\dagger}J_W^1+J_Z^{0\dagger}J_Z^0+J_Z^{1\dagger}J_Z^1+J_Z^{0\dagger}J_Z^1+J_Z^{1\dagger}J_Z^0\right]$$

$$\begin{aligned}
V_{LO}^{PNC}(\boldsymbol{r}) \;=\;& \Lambda_0^{{}^1S_0-{}^3P_0}\left(\frac{1}{i}\frac{\overleftrightarrow{\boldsymbol{\nabla}}_A}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)-\frac{1}{i}\frac{\overleftrightarrow{\boldsymbol{\nabla}}_S}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot i(\boldsymbol{\sigma}_1\times\boldsymbol{\sigma}_2)\right)\\
+\;& \Lambda_0^{{}^3S_1-{}^1P_1}\left(\frac{1}{i}\frac{\overleftrightarrow{\boldsymbol{\nabla}}_A}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)+\frac{1}{i}\frac{\overleftrightarrow{\boldsymbol{\nabla}}_S}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot i(\boldsymbol{\sigma}_1\times\boldsymbol{\sigma}_2)\right)\\
+\;& \Lambda_1^{{}^1S_0-{}^3P_0}\left(\frac{1}{i}\frac{\overleftrightarrow{\boldsymbol{\nabla}}_A}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)(\tau_{1\,z}+\tau_{2\,z})\right)\\
+\;& \Lambda_1^{{}^3S_1-{}^3P_1}\left(\frac{1}{i}\frac{\overleftrightarrow{\boldsymbol{\nabla}}_A}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot(\boldsymbol{\sigma}_1+\boldsymbol{\sigma}_2)(\tau_{1\,z}-\tau_{2\,z})\right)\\
+\;& \Lambda_2^{{}^1S_0-{}^3P_0}\left(\frac{1}{i}\frac{\overleftrightarrow{\boldsymbol{\nabla}}_A}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)(\boldsymbol{\tau}_1\otimes\boldsymbol{\tau}_2)_{20}\right),
\end{aligned}$$

$$\Lambda_0^{-}\equiv\frac{1}{4}\Lambda_0^{{}^3S_1-{}^1P_1}-\frac{3}{4}\Lambda_0^{{}^1S_0-{}^3P_0}\quad\sim\quad 1/N_c$$

$$\Lambda_1^{{}^1S_0-{}^3P_0}\quad\sim\quad\sin^2\theta_w$$

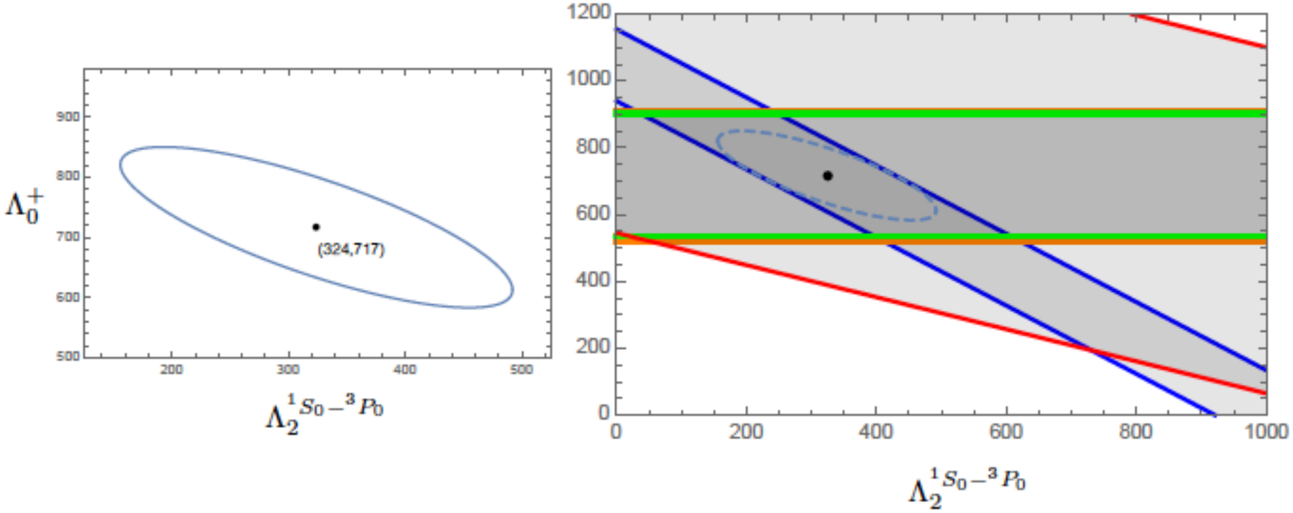
$$\Lambda_1^{{}^3S_1-{}^3P_1}\quad\sim\quad\sin^2\theta_w$$

$$\Lambda_0^{+}\equiv\frac{3}{4}\Lambda_0^{{}^3S_1-{}^1P_1}+\frac{1}{4}\Lambda_0^{{}^1S_0-{}^3P_0}\quad\sim\quad N_c$$

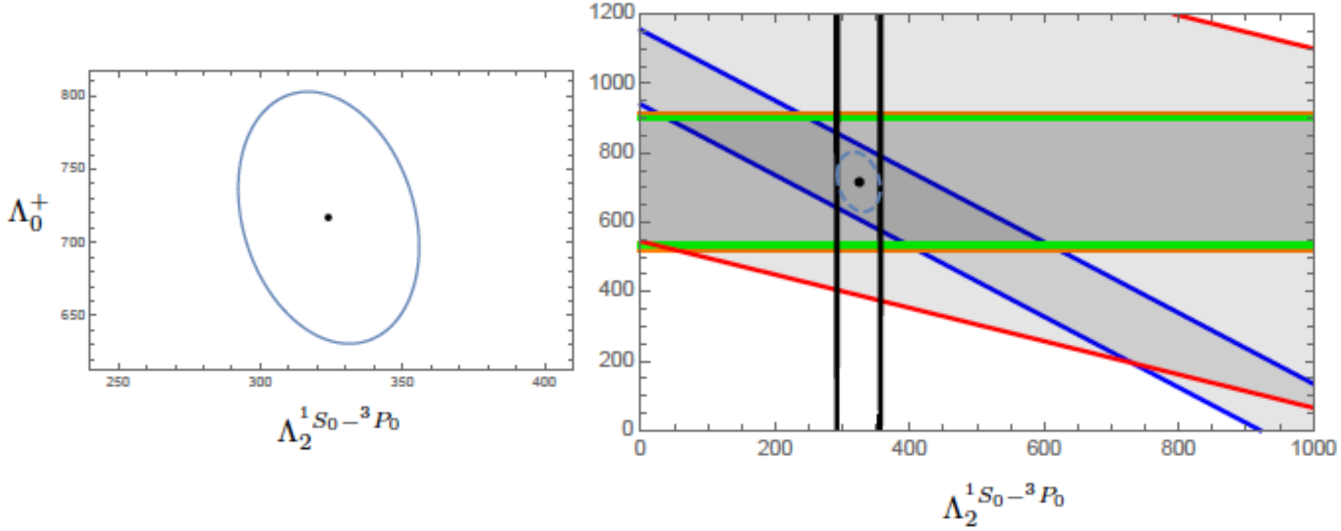
$$\Lambda_2^{{}^1S_0-{}^3P_0}\quad\sim\quad N_c,$$

$1/N_c$ analysis: Phillips, Samart, Schat, arXiv:1410.1157, PRL 114, 062301 (2015)
Schindler, Springer, Vanasse, arXiV:1510.07598, PRC 93, 025502 (2016)

NN Weak Amplitudes in EFT+ $1/N_c$: $\Delta I=0$ and $\Delta I=2$



Constraints from existing NN parity experiments (pp, pα, ^{19}F)

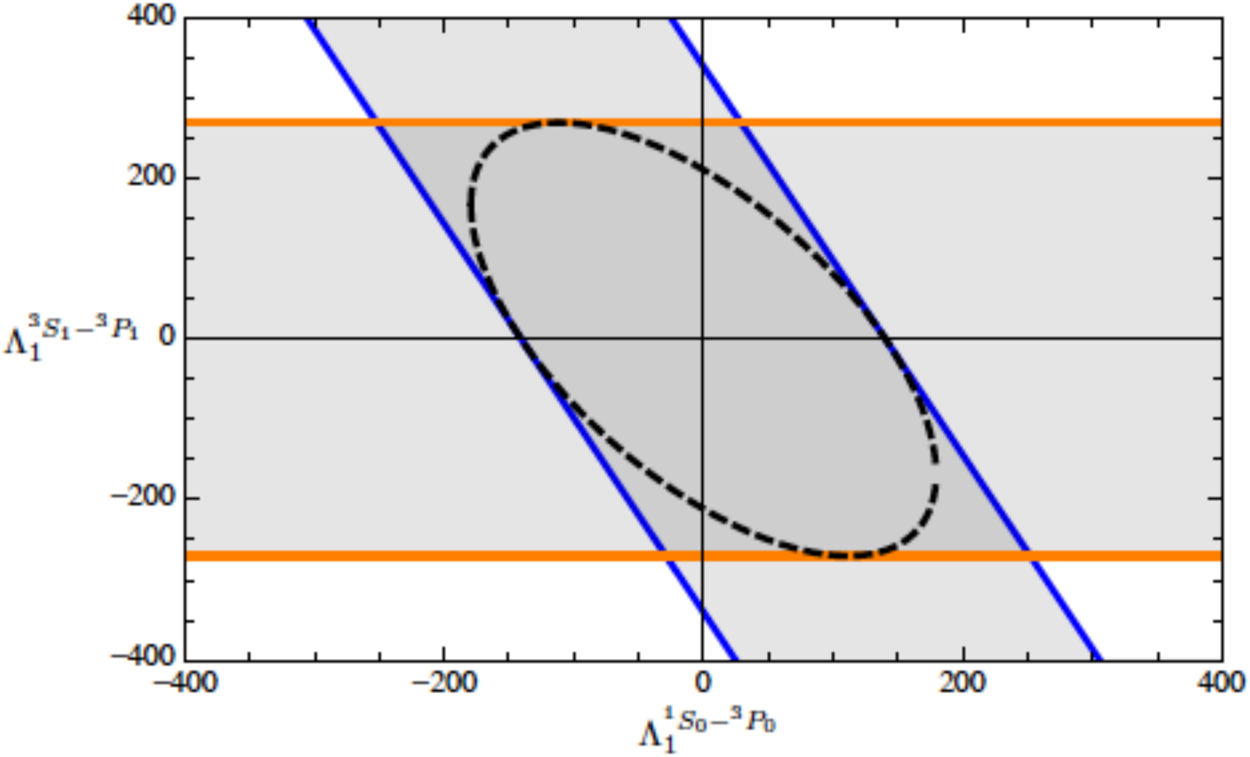


Impact of planned lattice calculation of $\Delta I=2$ NN weak amplitude

This will determine the two leading order NN weak amplitudes.
The other three amplitudes are suppressed by $1/N_c^2$ or $\sin^2\theta_W/N_c \sim 1/10$

from Gardner, Haxton, Holstein, arXiv: 1704.02617

NN Weak Amplitudes in EFT+ $1/N_c$: ΔI=1 Amplitudes



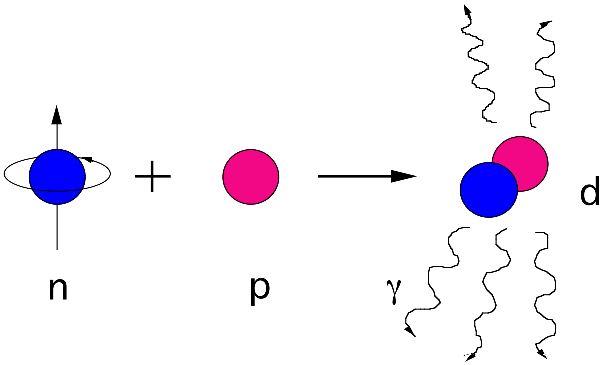
Constraints from one existing NN parity experiment (^{18}F, ~vertical band) and one to be announced soon (NPDGamma, horizontal band)

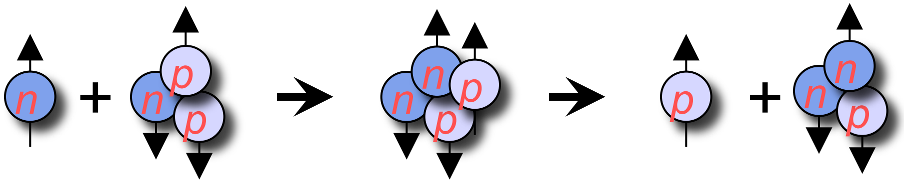
This will determine the two ΔI=1 amplitudes which are suppressed by $1/N^2_c$ or $\sin^2\theta_W/N_c$ ~1/10

18F result is already consistent with the predicted suppression in a combination of ΔI=1 partial waves. NPDGamma will determine one (mainly orthogonal) ΔI=1 channel

from Gardner, Haxton, Holstein, arXiv: 1704.02617

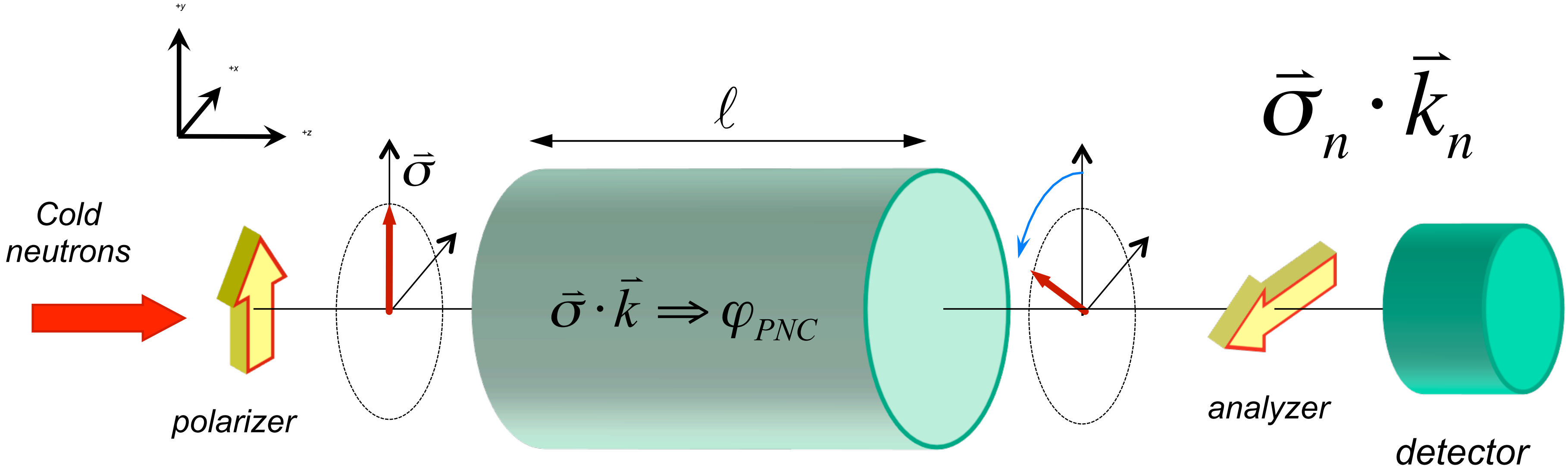
P-odd NN Experiments in progress: n-p, n-3He, and n-4He





$$\vec{\sigma}_n \cdot \vec{k}_\gamma$$

$$\vec{\sigma}_n \cdot \vec{k}_p$$



$$\vec{\sigma}_n \cdot \vec{k}_n$$

The NPDGamma collaboration

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NSERC (CANADA)
CONACYT (MEXICO)
BARC (INDIA)

NPDγ: A Gamma-ray Asymmetry Measurement

$$A_\gamma(t)P_n\cos\theta = \frac{U_\uparrow - D_\uparrow - (U_\downarrow - D_\downarrow)}{U_\uparrow + D_\uparrow + U_\downarrow + D_\downarrow}$$

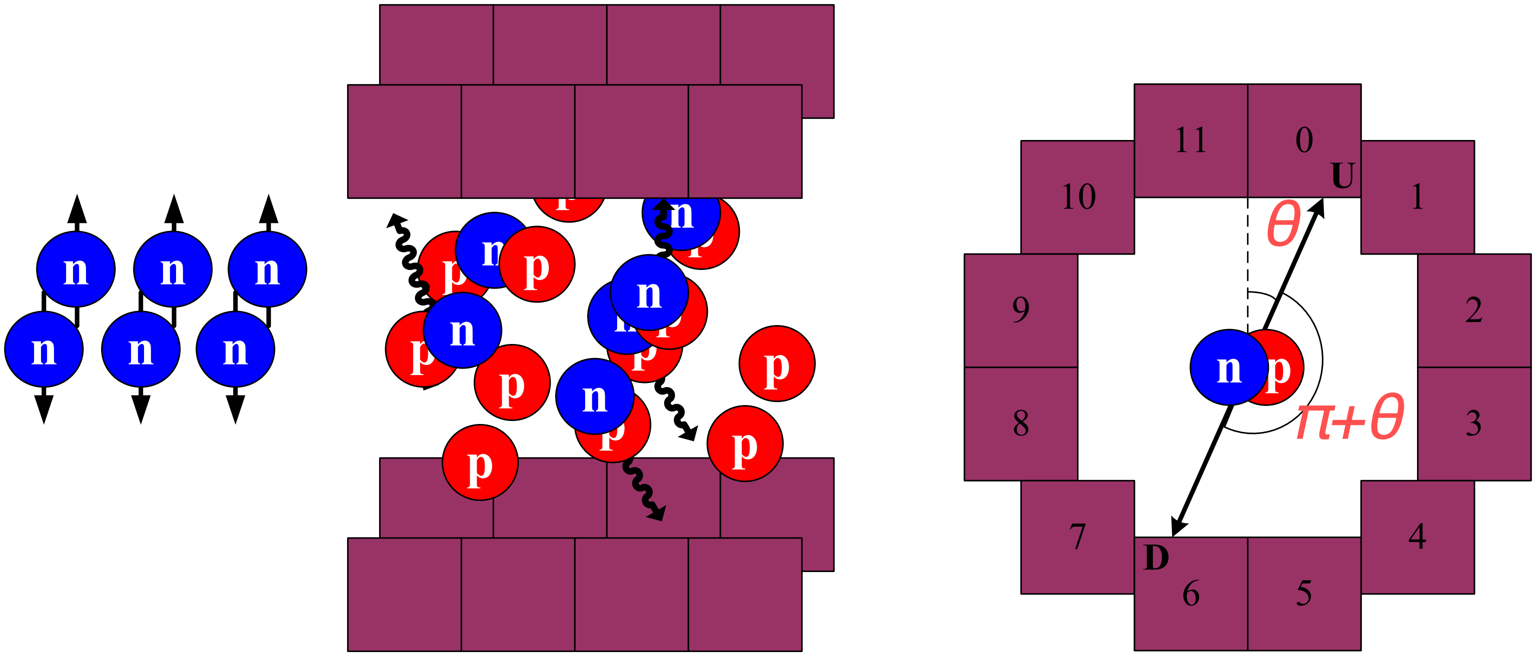
$$A_\gamma = -0.107 f_\pi^1 - 0.001 h_\rho^1 - 0.004 h_\omega^1$$

$$\boxed{A_\gamma^{\vec{n}p} \approx \tilde{C}^{3S1->3P1}}$$

Pionless EFT

$$\boxed{A_\gamma^{\vec{n}p} \approx -0.27\tilde{C}_6^\pi - 0.09 m_\mathrm{N}\rho_\mathrm{t}}$$

Hybrid EFT



- *Reverse the polarization pulse-by-pulse according to the sequence ↑ ↓ ↓ ↑ ↓ ↑ ↑ ↓ to cancel linear and quadratic time-dependent gain drifts*
- *Analyze opposite detector pairs to extract asymmetry as a function of θ*
- *Result for gamma asymmetry exists: ~ 1×10^{-8} statistical error, ~ 10^{-9} systematic error.*
- *Comparable precision to existing 18F measurement, also ΔI=1*

Neutron Spin Rotation (NSR) Collaboration

W.M. Snow[1], E. Anderson[1], L. Barron-Palos[2], B.E. Crawford[3], C. Crawford[4], W. Fox[1], J. Fry[1], C. Haddock[1], B.R. Heckel[5], A. T. Holley[6], C. Hunley[7], K. Korsak[1], M. Maldonado-Velazquez[2], H.P. Mumm[8], J.S. Nico[8], S. Penn[9], S. Santra[10], M.G. Sarsour[7], H.E. Swanson[5], J. Vanderwerp[1]

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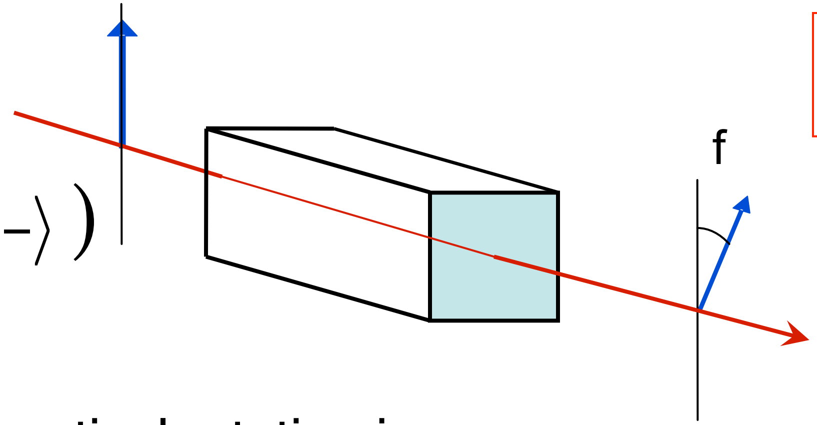
Support: NSF, NIST, DOE, CONACYT, BARC

Parity-odd Neutron Spin Rotation

$$\left|\uparrow\right\rangle_i = \frac{1}{\sqrt{2}}\left(\left|+\right\rangle + \left|-\right\rangle\right)$$



$$\boxed{f(0) = f_{PC} + f_{PV}\left(\vec{\sigma}\cdot\vec{k}\right)}$$

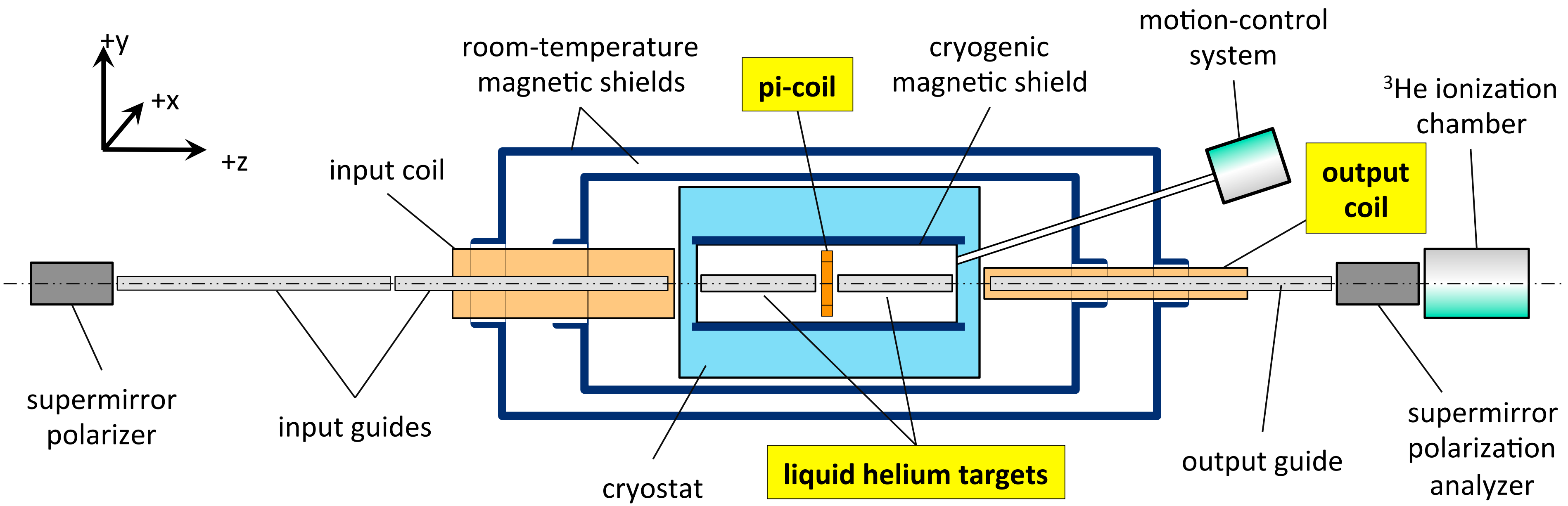
Refractive index dependent on neutron helicity

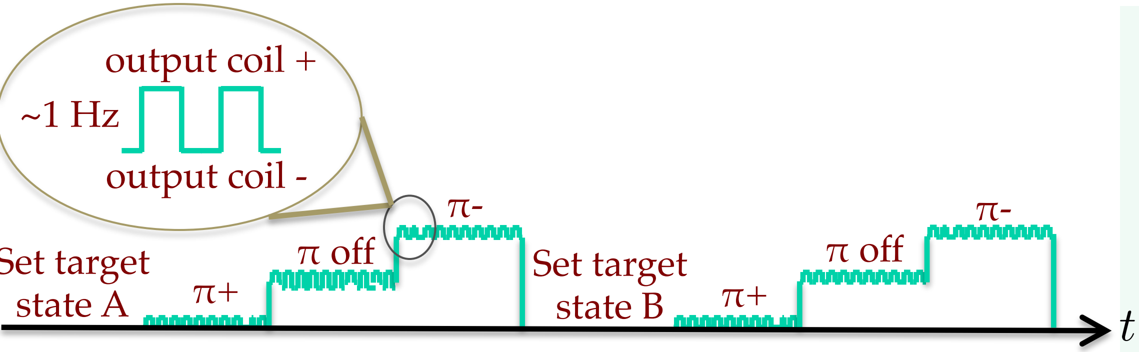
$$\frac{1}{\sqrt{2}}\left(e^{-i(\phi_{PC}+\phi_{PV})}\left|z\right\rangle + e^{-i(\phi_{PC}-\phi_{PV})}\left|-z\right\rangle\right)$$

$$\boxed{\varphi_{PV} = \phi_{+} - \phi_{-} = 2\varphi_{PV} = 4\pi l\rho f_{PV}}$$

- Analogous to optical rotation in an "handed" medium.
- Transversely-polarized neutrons corkscrew from any parity-odd interaction
- *PV Spin Angle* is independent of incident neutron energy in cold neutron regime,
- $d\phi_{PV}/dx \sim 10^{-6}$ rad/m sensitivity achieved so far

N-4He Neutron Spin Rotation Apparatus





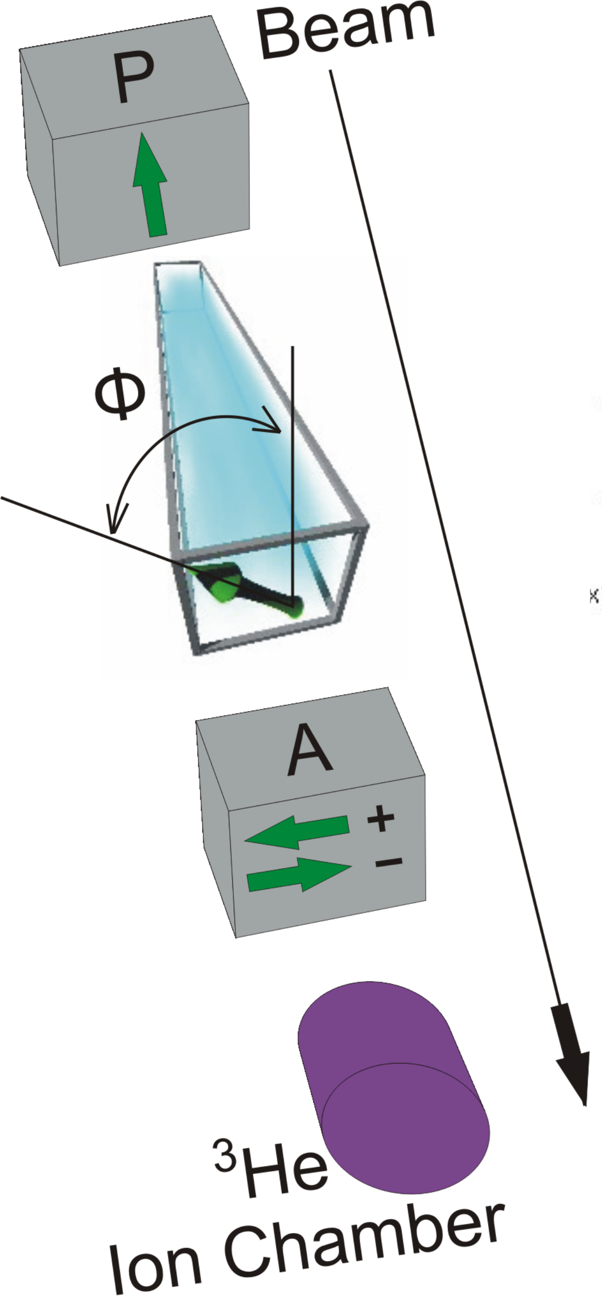
Analyzer direction oscillates at 1 Hz

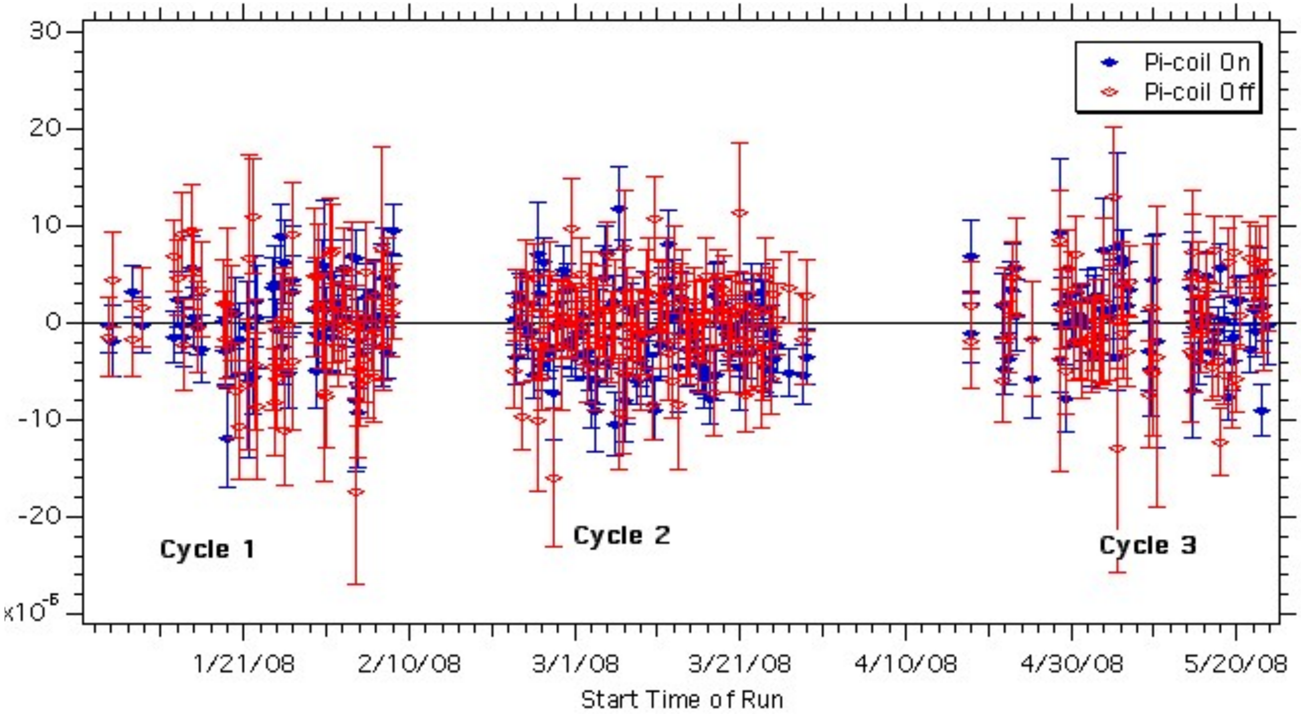
Pi-coil on measures spin rotation

Pi-coil off measures systematics

Liquid motion reverses sign of spin rotation from the liquid, leaves B rotations unchanged

Neutron Spin Rotation result from NIST NG-6





"pi-coil on" → L-R measures PNC asymmetry, L+R measures systematics
"pi-coil off" → must give zero in absence of systematics

$$\varphi_{PNC} = [+1.7 \pm 9.1\ (\mathrm{stat}) \pm 1.4\ (\mathrm{sys})] \times 10^{-7}\ \mathrm{rad/m}$$

C. D. Bass et al., Nucl. Instrum. Meth. A612, 69-82 (2009).
A. M. Micherdzinska et al., Nucl. Instrum. Meth. A631, 80 (2011).
W. M. Snow et al., Phys. Rev. C83, 022501(R) (2011).
Snow, et al., RSI **86**, 055101 (2015)

n-4He Spin Rotation: why measure it to 1E-7 rad/m?

(1) n-4He is a simple enough system that P-odd spin rotation can be related to weak NN amplitudes. GFMC calculations possible (*Carlson, Wiringa, Nollett, Schiavilla, Pieper*)

(2) Using recent EFT+1/N analysis+previous NN weak measurements, there is now a prediction for this process to ~15% accuracy.

$$\phi_{\mathrm{PNC}}\left(\vec{n},{}^{4}\mathrm{He}\right) \sim [7 \pm 1] \times 10^{-7}\ \mathrm{rad/m}$$

from Gardner, Haxton, Holstein, arXiv: 1704.02617

Theory calculation in terms of NN weak couplings in DDH meson exchange model:

$$\phi_{PV}\left(\vec{n},{}^{4}\mathrm{He}\right) = -\left(0.97 f_{\pi} + 0.22 h_{\omega}^{0} - 0.22 h_{\omega}^{1} + 0.32 h_{\rho}^{0} - 0.11 h_{\rho}^{1}\right)\mathrm{rad/m}$$

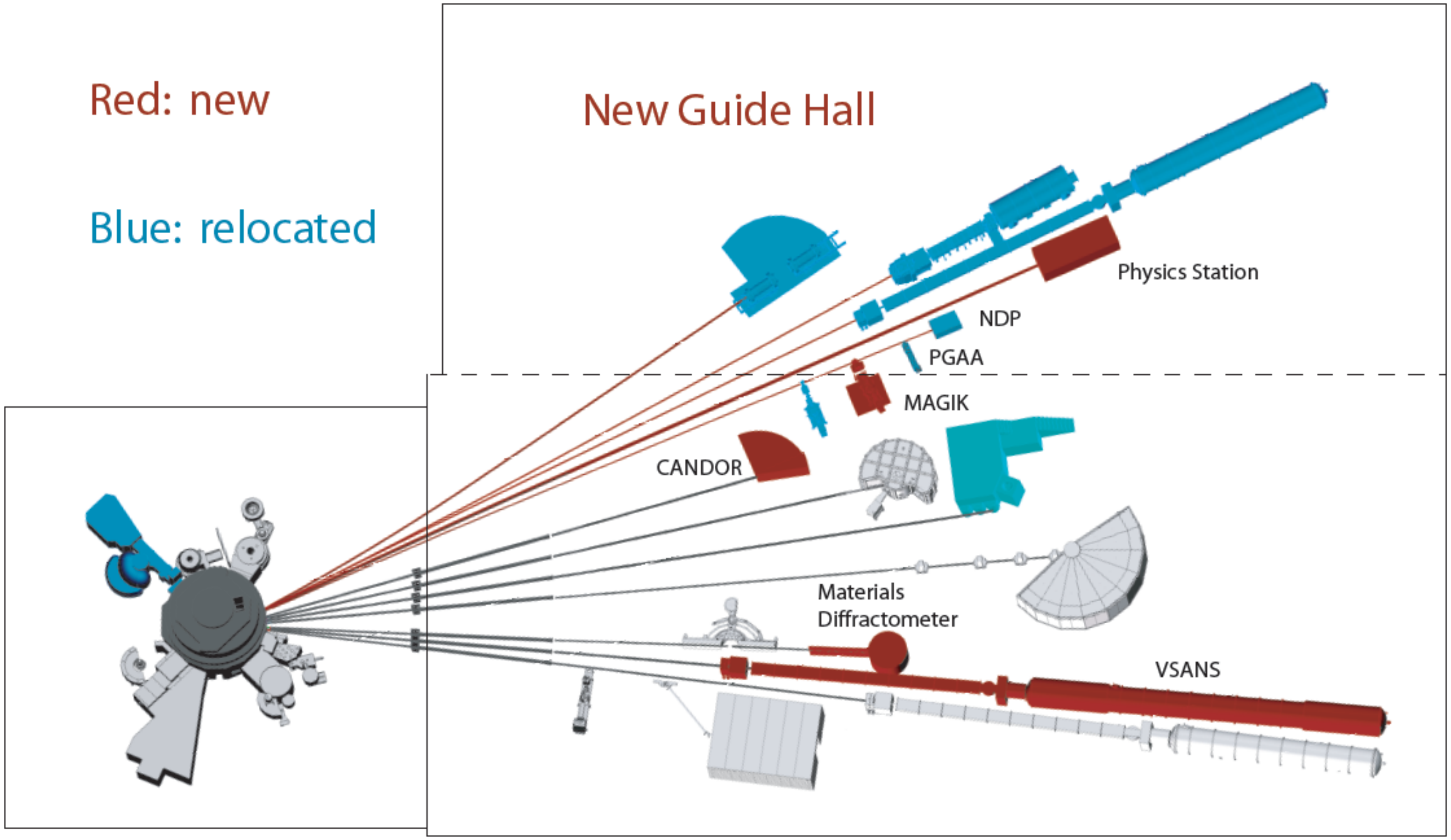
Dmitriev et al. Phys Lett ***125*** *1 (1983)*

Translation into EFT language:

$$\phi_{\mathrm{PV}}(n\,{}^{4}\mathrm{He}) = (0.85\lambda_{s}^{nn} - 0.43\lambda_{s}^{np} + 0.95\lambda_{t} - 1.89\rho_{t})$$

Zhu et al. Nucl. Phys. A ***748*** *435-498 (2005)*

n-4He spin rotation at NIST, 1E-7 rad/m goal



new NG-C beam at NIST [J. Cook, RSI80, 023101 (2009)] ~X80 increase in polarized slow neutron flux through apparatus

STATUS: cryogenic target in construction, all other items in hand and tested at LANSCE

NOPTREX Collaboration

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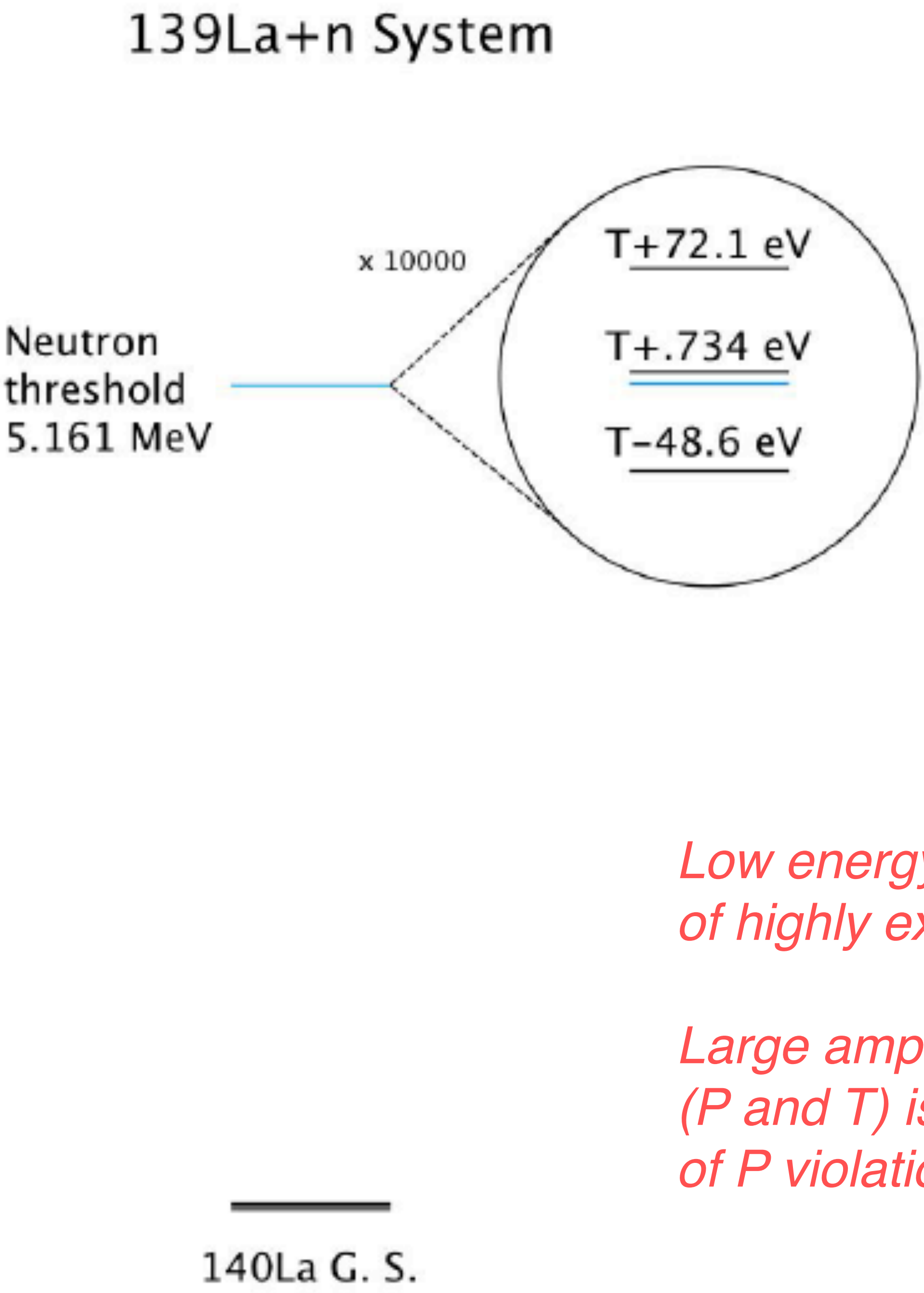
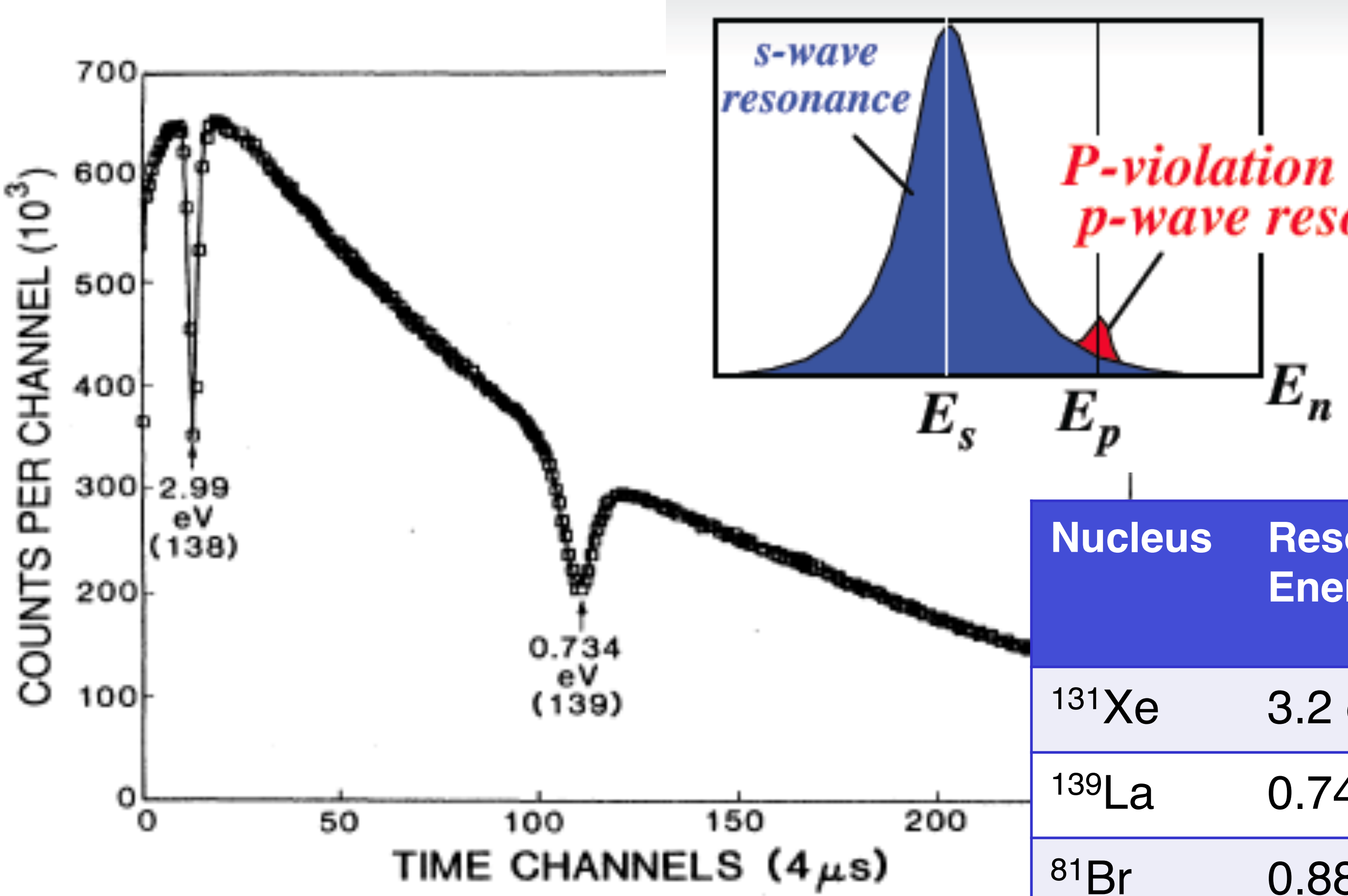
Compound-Nuclear States in ^{139}La+n system



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

Large amplification of discrete symmetry violation (P and T) is possible. Very large amplifications of P violation were observed long ago

Parity Violation in n+ ^{139}La at 0.734 eV $\Delta\sigma/\sigma = 10\%$
Standard Model P Violation Amplified by ~10^6 !



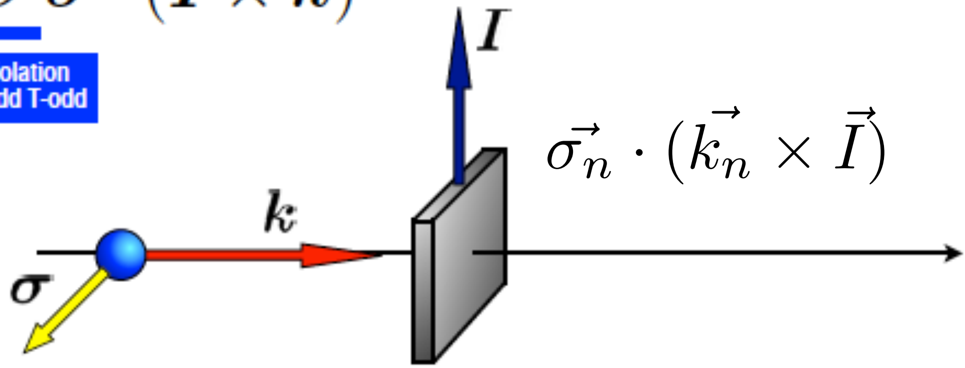
$v = \langle s | W | p \rangle$

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

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
(Sushkov/Flambaum)
Idea is to use the observed enhancement of PV to search for a TRIV asymmetry.

Forward Scattering Ampliltude

$$f = \underbrace{A'}_{\substack{\text{Spin Independent}\\ \text{P-even T-even}}} + \underbrace{B'}_{\substack{\text{Spin Dependent}\\ \text{P-even T-even}}}\boldsymbol{\sigma}\cdot\hat{\boldsymbol{I}} + \underbrace{C'}_{\substack{\text{P-violation}\\ \text{P-odd T-even}}}\boldsymbol{\sigma}\cdot\hat{\boldsymbol{k}} + \underbrace{D'}_{\substack{\text{T-violation}\\ \text{P-odd T-odd}}}\boldsymbol{\sigma}\cdot(\hat{\boldsymbol{I}}\times\hat{\boldsymbol{k}})$$



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

The enhancement of P-odd/T-odd amplitude on p-wave resonance (σ.[K X I]) is (almost) the same as for P-odd amplitude (σ.K).

Observable: ratio of P-odd/T-odd to P-odd cross sections

$$\lambda_{PT} = \frac{\delta\sigma_{PT}}{\delta\sigma_P}$$

λ can be measured with a statistical uncertainty of ~1 10^{-5} in 10^{7} sec at MW-class spallation neutron sources. Sensitivity ~ 100 times higher than present nEDM limit, completely different system

Forward scattering neutron optics limit is null test for T (no final state effects)

P-odd/T-odd Reaction Theory

Optical theorem connects cross section difference to P-odd T-odd forward amplitude. Equations are simple for mixing of one p-wave and one s-wave resonance (Gudkov, Physics Reports):

$$\Delta\sigma_{PT} = \frac{4\pi}{k}\mathrm{Im}(f_{\uparrow} - f_{\downarrow}) \qquad \Delta\sigma_{P} = \frac{4\pi}{k}\mathrm{Im}(f_{+} - f_{-})$$

$$f = < f \,|\, (V_P + V_{PT}) \,|\, i > = \frac{(v + iw)\sqrt{\Gamma_p^n \Gamma_s^n}}{(E - E_s + \frac{i\Gamma_s}{2})(E - E_p + \frac{i\Gamma_p}{2})}$$

$$v + iw = < \phi_p \,|\, (V_P + V_{PT}) \,|\, \phi_s >$$

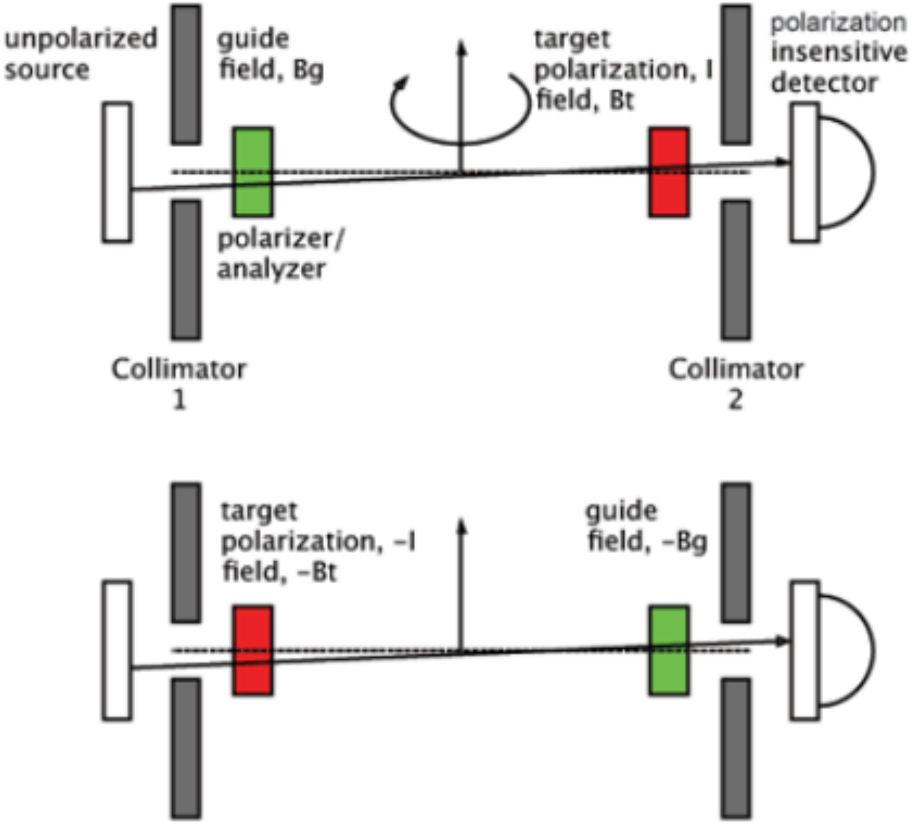
$$\frac{\Delta\sigma_{PT}}{\Delta\sigma_{P}} = \kappa(J)\frac{w}{v}$$

Cross section ratio directly related to ratio of amplitudes between s and p resonances

EDITORS' SUGGESTION Phys. Rev. C (2015)

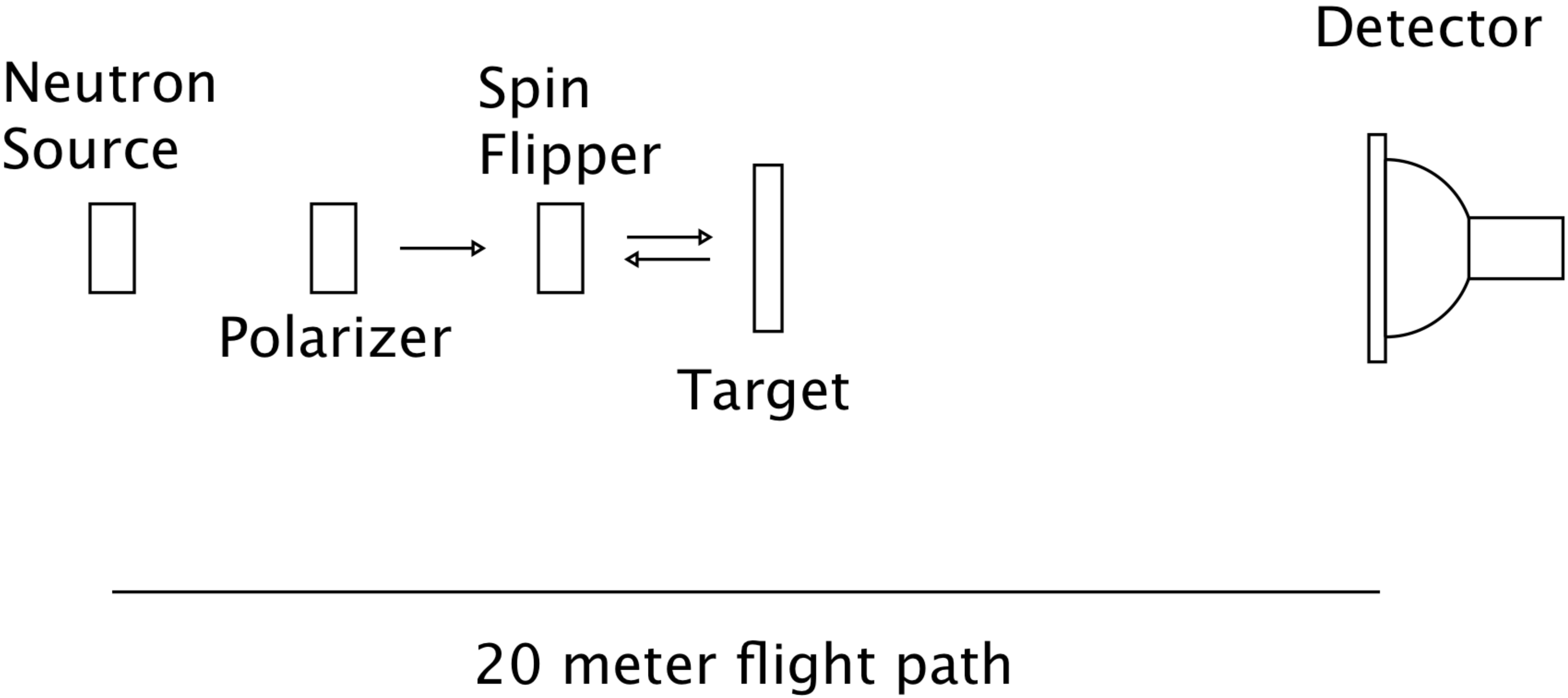
Search for time reversal invariance violation in neutron transmission

J. David Bowman and Vladimir Gudkov



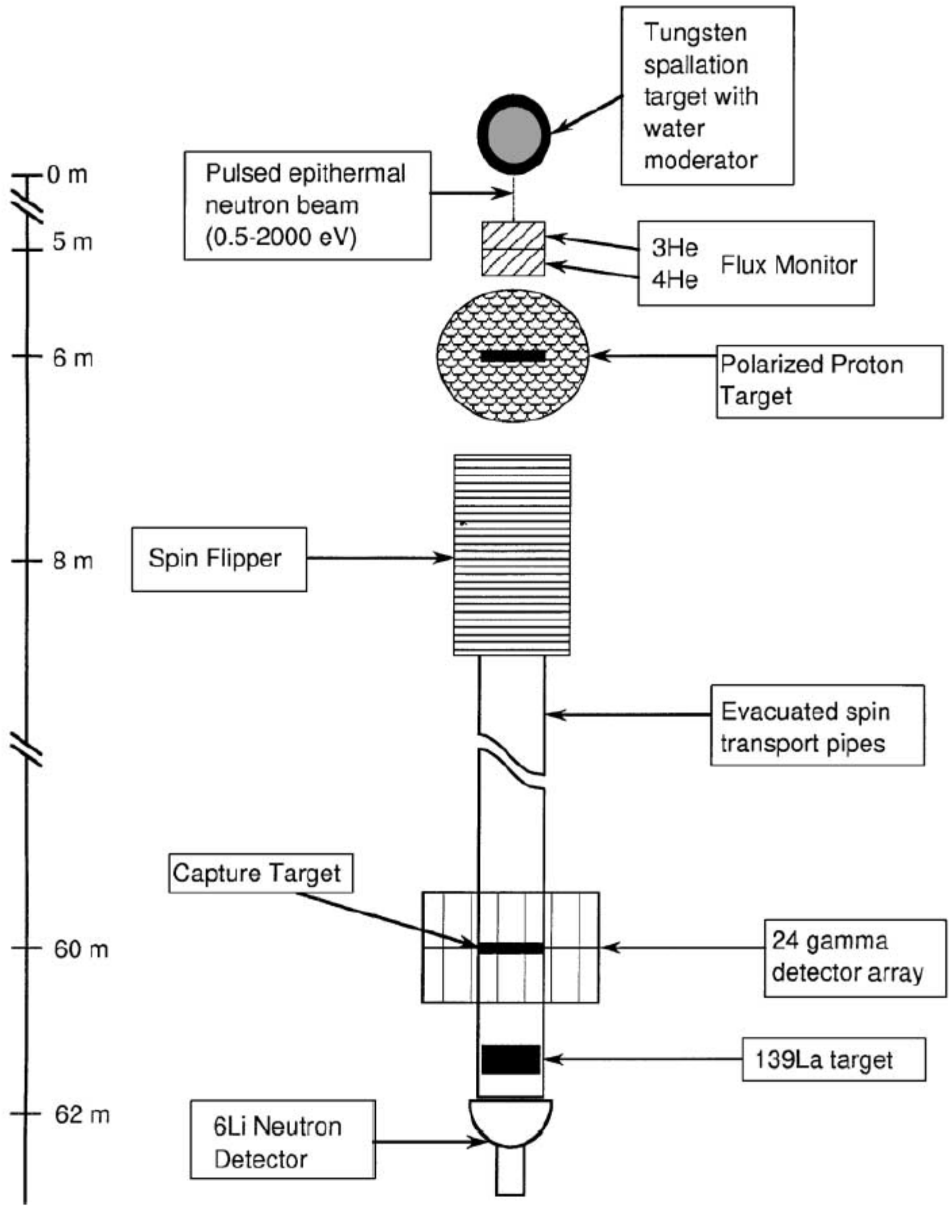
The authors analyze a novel null test to search for time reversal invariance in a model neutron transmission experiment. The proposed experimental procedure involves nuclear reactions and is sensitive to the neutron-nucleus interactions. The approach could significantly increase the discovery potential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

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 extracts correct size of NN weak amplitudes S. Tomsovic, M. B. Johnson, A. Hayes, and J. D. Bowman, Phys. Rev. C 62, 054607 (2000).

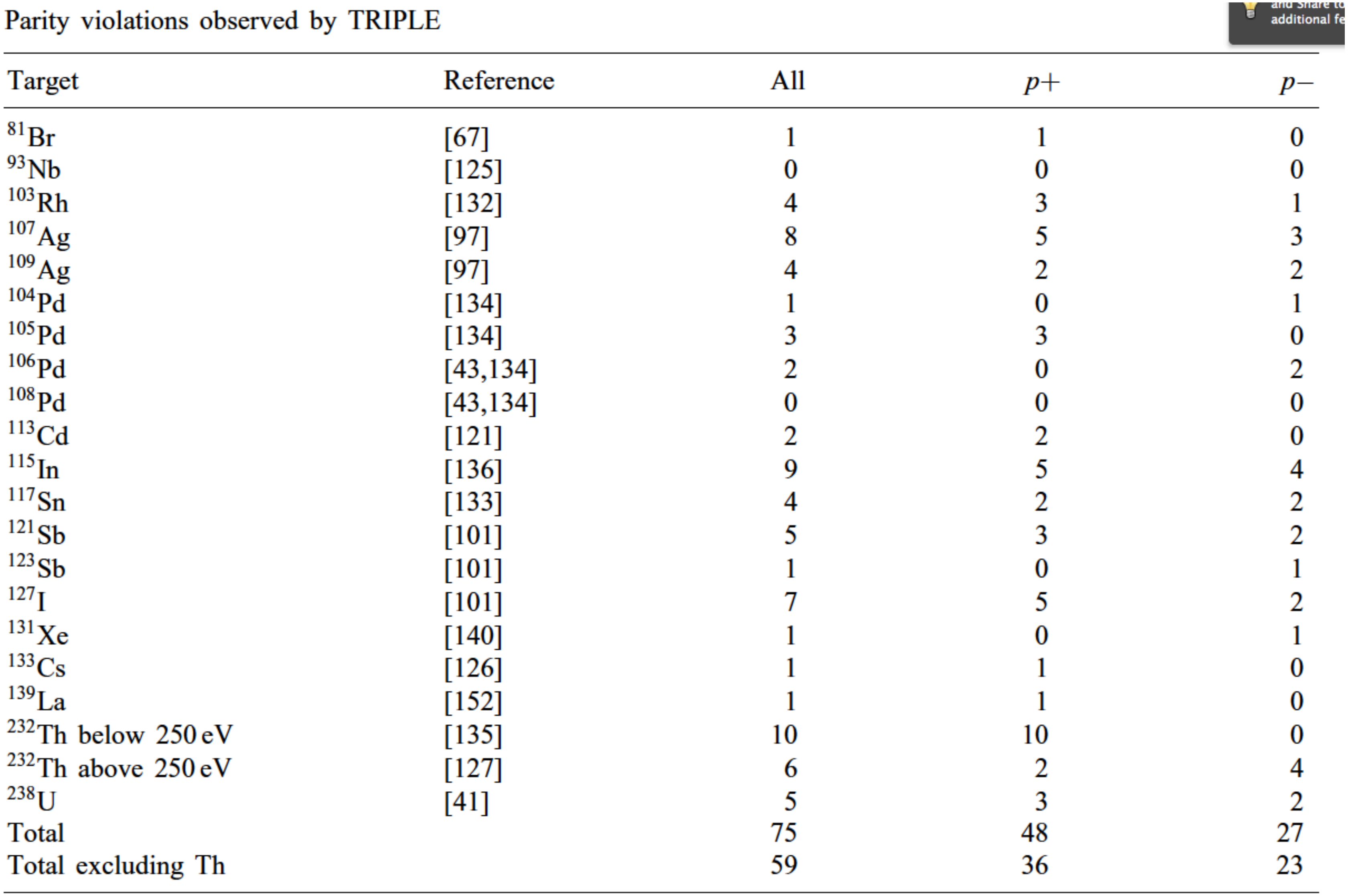


Apparatus for PV at a spallation neutron source

Polarized proton target to make polarized neutrons

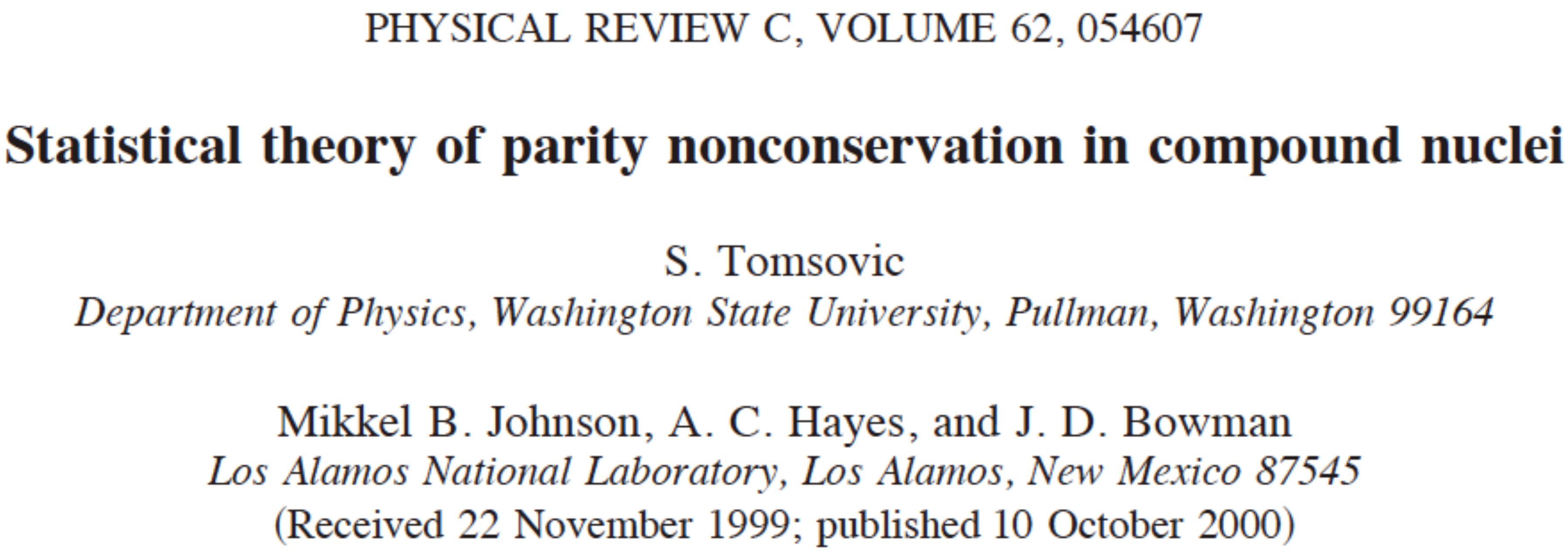
Look for σ.k dependence of total cross section

Study of Parity Violation in the Compound Nucleus



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 with NN weak amplitudes: agreement at the ~factor of 2 level

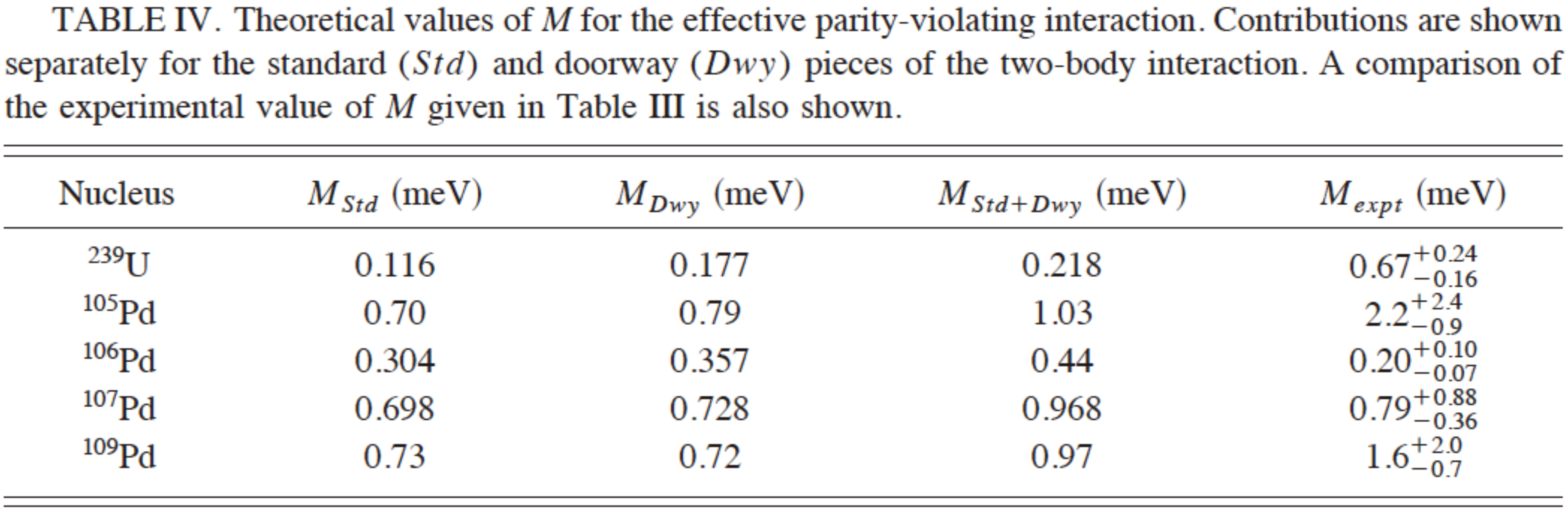


TABLE IV. Theoretical values of M for the effective parity-violating interaction. Contributions are shown separately for the standard (Std) and doorway (Dwy) pieces of the two-body interaction. A comparison of the experimental value of M given in Table III is also shown.

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	$1.6^{+2.0}_{-0.7}$

EFT+1/N analysis of P-odd and T-odd NN amplitudes is in hand

Chiral effective field theory

- Leading order TV potential

$$
\begin{aligned}
V_{\not{T}\not{P}}^{\mathrm{EFT}} = & - i\frac{\bar{C}_1}{2}\left(\vec{\sigma}_1 - \vec{\sigma}_2\right)\cdot\vec{p}_- \\
& - i\left(\frac{g_A[\bar{g}_\pi^{(0)} - \bar{g}_\pi^{(2)}]}{2F_\pi}\frac{1}{(\vec{p}_-^2 + M_\pi^2)} + \frac{\bar{C}_2}{2}\right)\vec{\tau}_1\cdot\vec{\tau}_2\left(\vec{\sigma}_1 - \vec{\sigma}_2\right)\cdot\vec{p}_- \\
& - i\frac{g_A\bar{g}_\pi^{(1)}}{2F_\pi}\frac{1}{(\vec{p}_-^2 + M_\pi^2)}\left(\vec{\sigma}_1\tau_1^z - \vec{\sigma}_2\tau_2^z\right)\cdot\vec{p}_-
\end{aligned}
$$

- $\bar{g}_\pi^{(1)}$: Leading large-N_c term
- $\bar{g}_\pi^{(0,2)}$ suppressed by $1/N_c$ compared to $\bar{g}_\pi^{(1)}$
- Contact terms $\bar{C}_1 \sim N_c^0$, $\bar{C}_2 \lesssim N_c^0$

Schindler, Phillips, Samart, Schat

Conclusion on P-odd/T-odd NN Search

NOPTREX search for P-odd T-odd forward amplitude in polarized neutron transmission on p-wave resonance can reach ~1E-5 sensitivity compared to already-measured P-odd amplitude. Same ratio for present nEDM limit is ~1E-3. Discovery potential is there.

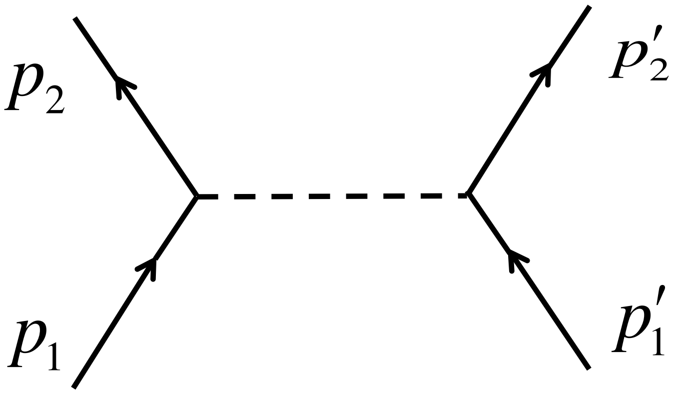
What is needed for theoretical interpretation of such a result?

(1) Calculation of (P-odd &T-odd)/P-odd forward amplitude on p-wave n-A resonance (Gudkov/Tomsovic/Bowman, in progress)
(2) EFT+1/N analysis of NN weak amplitudes (done)
(3) P-odd and T-odd reaction theory for n-A resonances (done)

Theory approach can be checked using P-odd case: we have

(A) NN weak amplitude data from many experiments
(B) New data on NN weak interaction in nuclei from anapoles
(C) Data+statistical analysis of P-odd effects in n-A resonances

Searches for light, weakly interacting particles: complementary to LHC



$$\boxed{V(\vec{r}) = g^2 \frac{1}{r} e^{-\frac{r}{\lambda}}}$$

(Most) high energy physics explores: g~1, λ as small as possible

This work emphasizes a different regime:

g small, λ “large” (millimeters-microns), but not infinite

New interactions with ranges from millimeters to microns… "Who ordered that?"

1. *Weakly-coupled, long-range interactions are a generic consequence of spontaneously broken continuous symmetries (Goldstone theorem)*

2. *Specific theoretical ideas (axions, extra dimensions from string theory,…) can produce new ultraweak interactions which act over ~mm-μm scales*

3. *Dimensional analysis: dark energy->100 microns*

Experiments should look!

Antionadis et al, Comptes Rendus Physique 12, 755-778 (2011)
J. Jaeckel and A. Ringwald, Ann. Rev. Nucl. Part. Sci. 60, 405 (2010).

Spin-dependent macroscopic interactions meditated by light bosons: general classification

$$\mathcal{O}_1 = 1 \ ,$$

$$\mathcal{O}_2 = \vec{\sigma} \cdot \vec{\sigma}' \ ,$$

$$\mathcal{O}_3 = \frac{1}{m^2} (\vec{\sigma} \cdot \vec{q}) \ (\vec{\sigma}' \cdot \vec{q}) \ ,$$

$$\mathcal{O}_{4,5} = \frac{i}{2m^2} (\vec{\sigma} \pm \vec{\sigma}') \cdot \left(\vec{P} \times \vec{q}\right) \ ,$$

$$\mathcal{O}_{6,7} = \frac{i}{2m^2} \left[\left(\vec{\sigma} \cdot \vec{P}\right) \ (\vec{\sigma}' \cdot \vec{q}) \pm (\vec{\sigma} \cdot \vec{q}) \ \left(\vec{\sigma}' \cdot \vec{P}\right)\right] \ ,$$

$$\mathcal{O}_8 = \frac{1}{m^2} \left(\vec{\sigma} \cdot \vec{P}\right) \ \left(\vec{\sigma}' \cdot \vec{P}\right) \ .$$

$$\mathcal{O}_{9,10} = \frac{i}{2m} (\vec{\sigma} \pm \vec{\sigma}') \cdot \vec{q} \ ,$$

$$\mathcal{O}_{11} = \frac{i}{m} (\vec{\sigma} \times \vec{\sigma}') \cdot \vec{q} \ ,$$

$$\mathcal{O}_{12,13} = \frac{1}{2m} (\vec{\sigma} \pm \vec{\sigma}') \cdot \vec{P} \ ,$$

$$\mathcal{O}_{14} = \frac{1}{m} (\vec{\sigma} \times \vec{\sigma}') \cdot \vec{P} \ ,$$

$$\mathcal{O}_{15} = \frac{1}{2m^3} \left\{ \left[\vec{\sigma} \cdot \left(\vec{P} \times \vec{q}\right)\right] (\vec{\sigma}' \cdot \vec{q}) + (\vec{\sigma} \cdot \vec{q}) \left[\vec{\sigma}' \cdot \left(\vec{P} \times \vec{q}\right)\right] \right\}$$

$$\mathcal{O}_{16} = \frac{i}{2m^3} \left\{ \left[\vec{\sigma} \cdot \left(\vec{P} \times \vec{q}\right)\right] \left(\vec{\sigma}' \cdot \vec{P}\right) + \left(\vec{\sigma} \cdot \vec{P}\right) \left[\vec{\sigma}' \cdot \left(\vec{P} \times \vec{q}\right)\right] \right\} .$$

- *16 independent scalars can be formed: 8 P-even, 8 P-odd*
- *15/16 depend on spin*
- *Traditional "fifth force" searches constrain* O_1

B. Dobrescu and I. Mocioiu, J. High Energy Phys. 11,005 (2006)

Why use slow neutrons to search?

1. *Zero electric charge, small magnetic moment, very small electric polarizability->low "background" from Standard Model interactions*

2. *Deep penetration distance into macroscopic amounts of matter*

3. *Coherent interactions with matter->phase sensitive measurements possible*

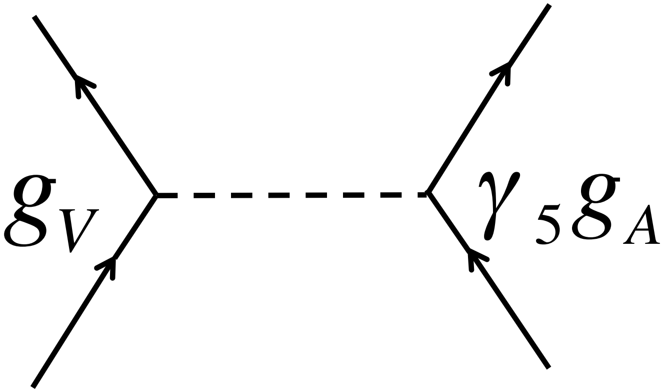
4. *High neutron polarization (>~99%) routine for slow neutrons ->important in searching for spin-dependent interactions*

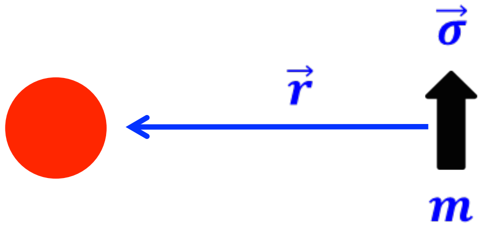
4. *A broad set of facilities for experimental work is available*

*J. Nico and W. M. Snow, Annual Reviews of Nuclear and Particle Science **55**, 27-69 (2005).*
*H. Abele, Progress in Particle and Nuclear Physics **60**, 1-81 (2008).*
D. Dubbers and M. Schmidt, Reviews of Modern Physics (2011).

Example of a nonstandard P-odd interaction from spin 1 boson exchange:

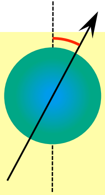
[Dobrescu/Mocioiu 06, general construction of interaction between nonrelativistic fermions]



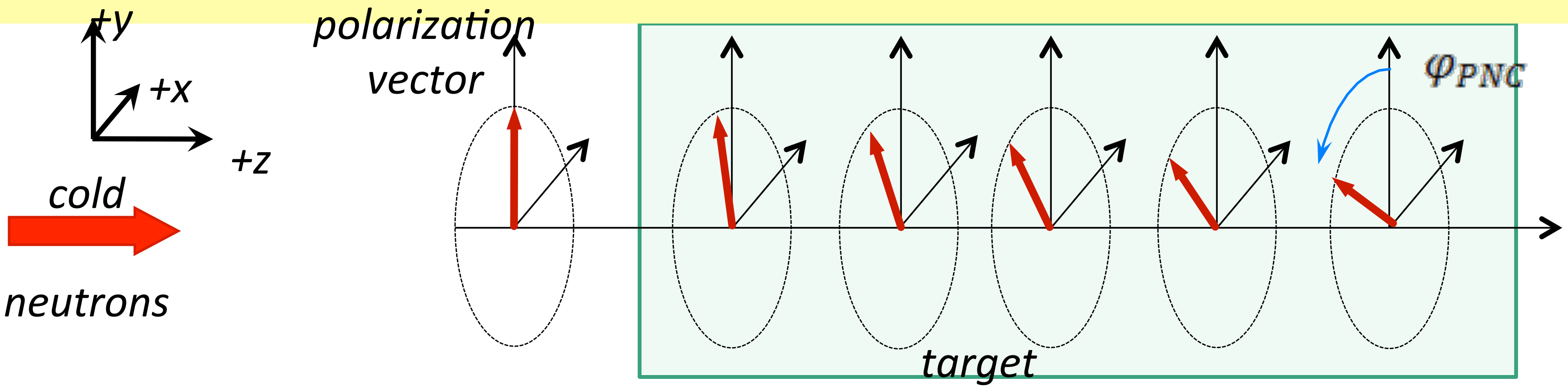


$$V(\vec{\sigma},\vec{r},\vec{v}) = \frac{\hbar}{8\pi mc^2} g_A g_V \vec{\sigma} \bullet \vec{v} \frac{1}{r} e^{-\frac{r}{\lambda}}$$

- *Induces an interaction between polarized and unpolarized matter*
- *Violates P symmetry*
- *Not very well constrained over “mesoscopic” ranges(millimeters to microns)*
- *Best investigated using a beam of polarized particles*



Parity-odd interaction of neutron with matter will produce neutron spin rotation:



$$f(0) = f_{strong} + f_{P-odd}(\vec{\sigma}\cdot\vec{p})$$

Forward scattering amplitude of neutron in matter sensitive to all neutron-matter interactions

$$f_{P-odd} = g_A g_V \lambda^2$$

Parity-odd interaction gives helicity-dependent phase shift and therefore rotation of plane of polarization vector

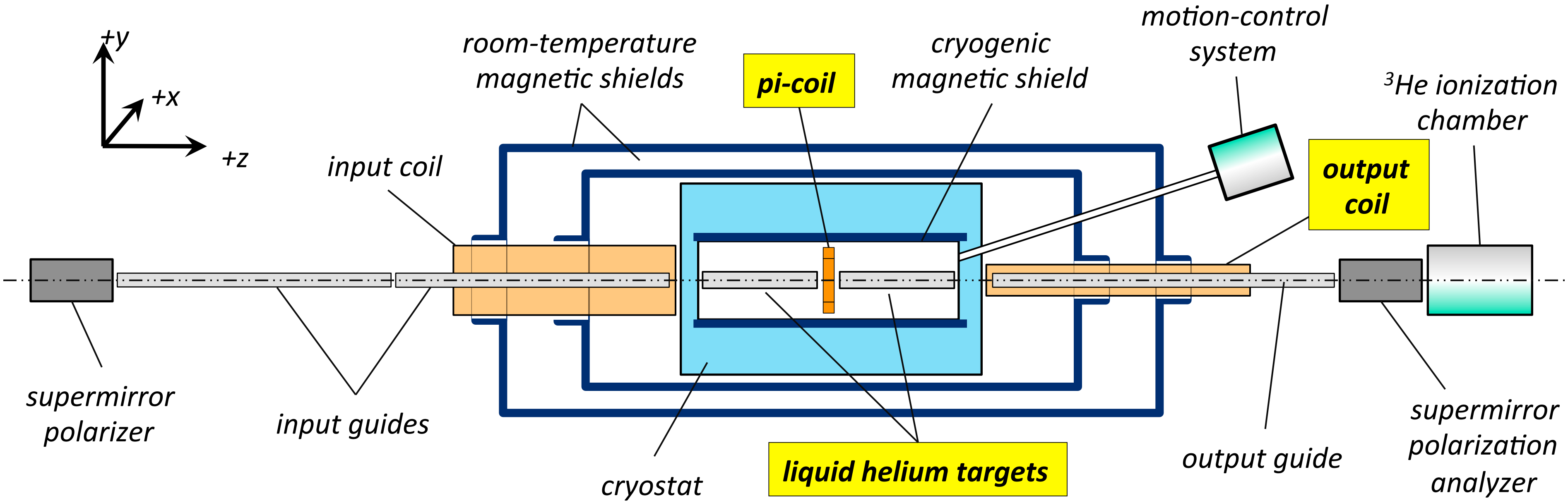
$$\phi_{\pm} = \phi_{strong} \pm \phi_{P-odd}$$

$$\frac{d\phi_{P-odd}}{dL} = 4 g_A g_V \rho \lambda^2$$

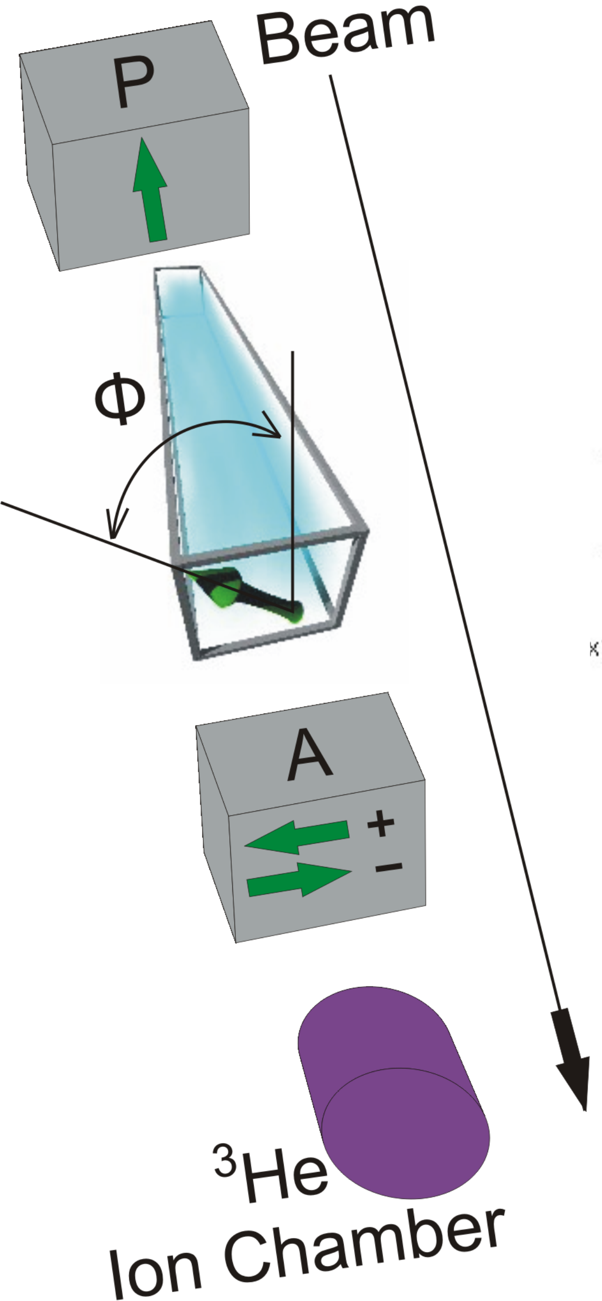
An upper bound on $f_{P\text{-}odd}$ places a constraint on possible new P-odd interactions between neutrons and matter over a broad set of distance scales

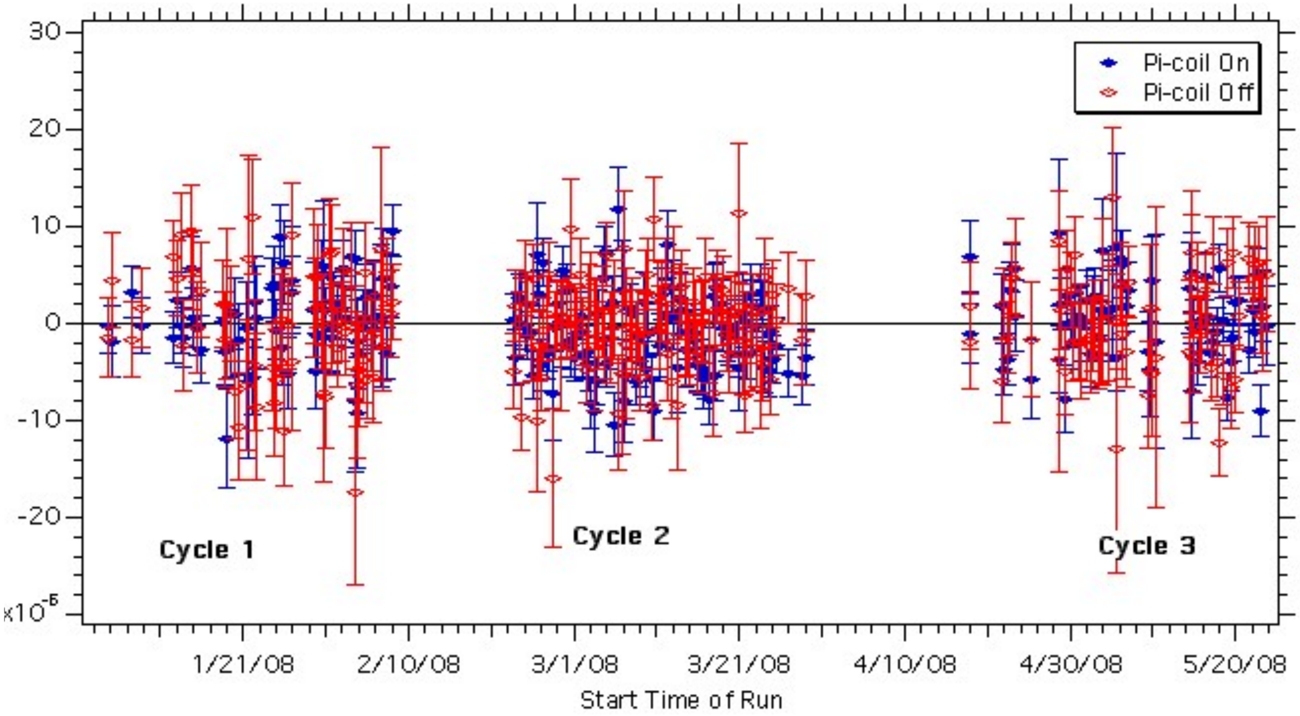
Neutron Spin Rotation in Liquid Helium

Apparatus measures the horizontal component of neutron spin generated in the liquid target starting from a vertically-polarized beam



Neutron Spin Rotation in n+4He



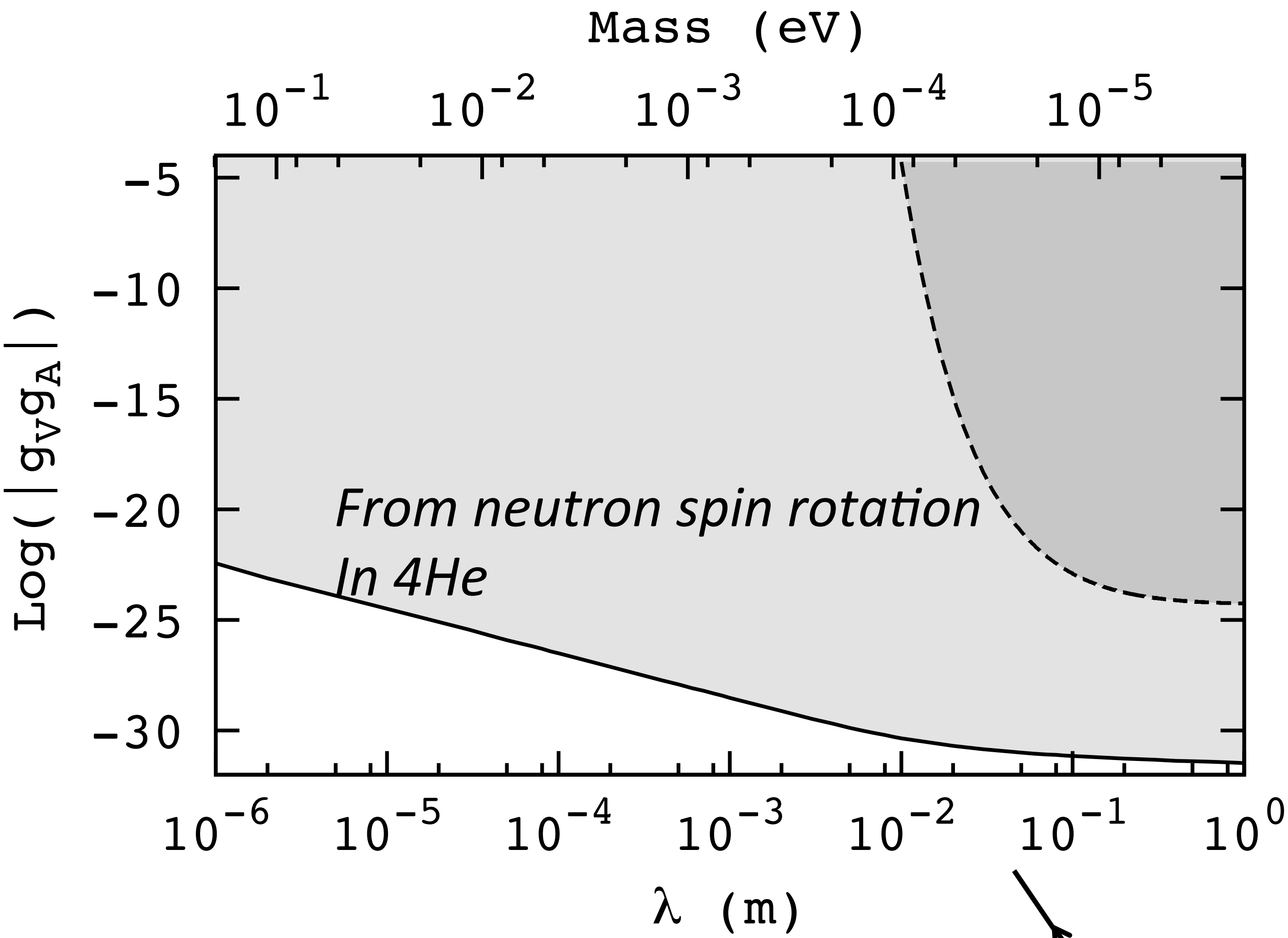


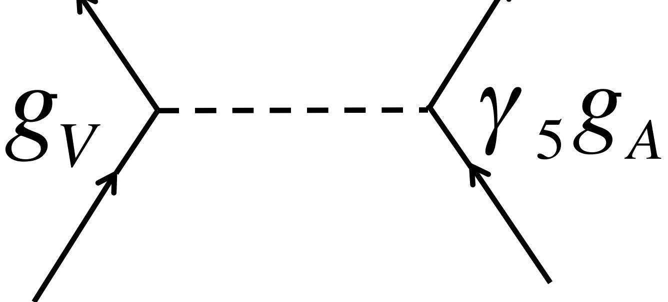
$\phi_{PNC} = [+1.7 \pm 9.1\ (stat) \pm 1.4\ (sys)] \times 10^{-7}\ rad/m$

W. M. Snow et al., Phys. Rev. C83, 022501(R) (2011).

*Result analyzed to constrain short-range gravitational torsion: R. Lehnert, H. Yan, W. M. Snow, Phys. Lett **B730**, 353 (2014), **B744**, 415 (2015), arXiv:1311.0467*

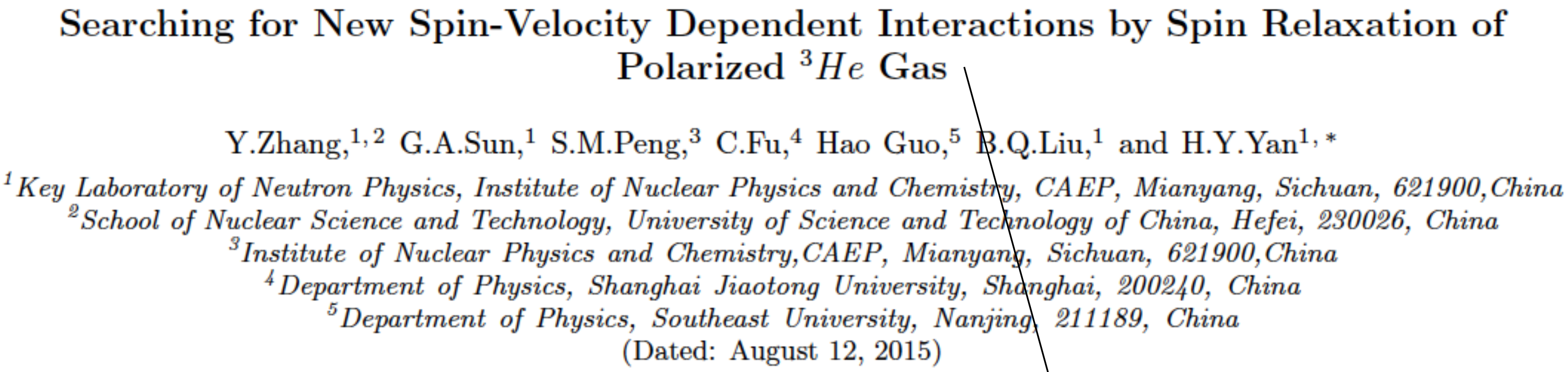
Constraints on exotic V-A interactions





H. Yan, and W. M. Snow, PRL 110, 082003 (2013).

More Constraints on exotic V-A interactions

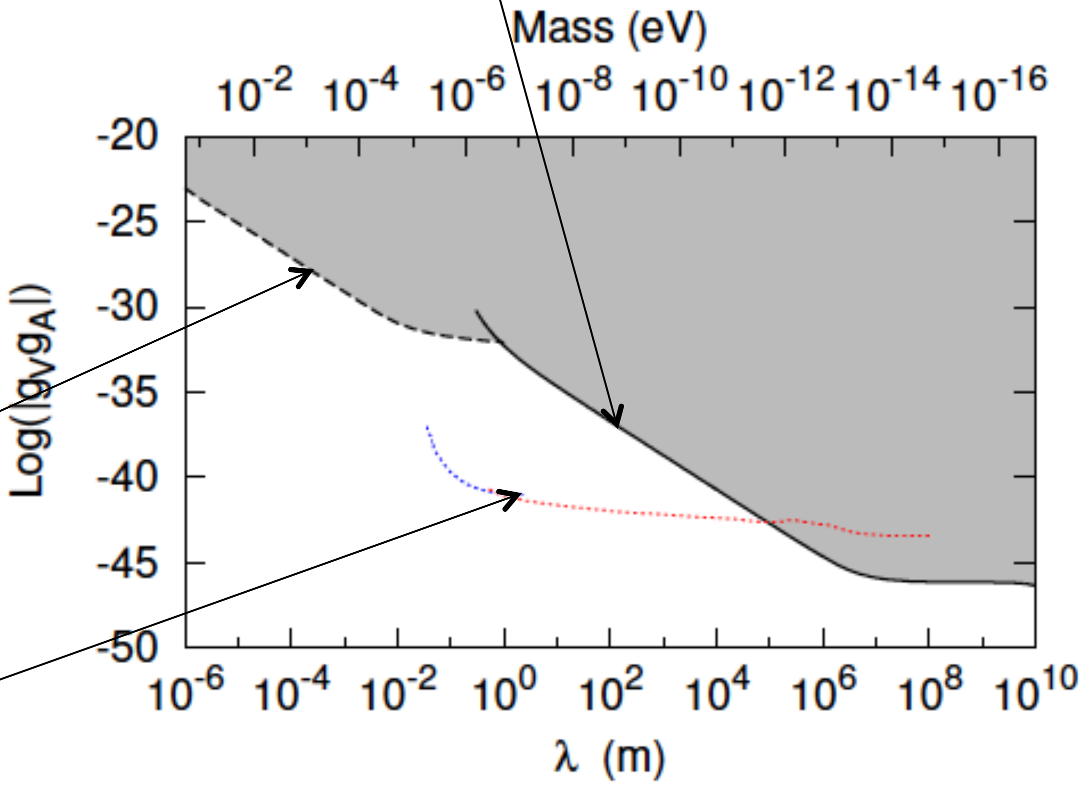


Searching for New Spin-Velocity Dependent Interactions by Spin Relaxation of Polarized ^3He Gas

Y.Zhang,[1,2] G.A.Sun,[1] S.M.Peng,[3] C.Fu,[4] Hao Guo,[5] B.Q.Liu,[1] and H.Y.Yan[1,*]

[1] *Key Laboratory of Neutron Physics, Institute of Nuclear Physics and Chemistry, CAEP, Mianyang, Sichuan, 621900,China*
[2] *School of Nuclear Science and Technology, University of Science and Technology of China, Hefei, 230026, China*
[3] *Institute of Nuclear Physics and Chemistry,CAEP, Mianyang, Sichuan, 621900,China*
[4] *Department of Physics, Shanghai Jiaotong University, Shanghai, 200240, China*
[5] *Department of Physics, Southeast University, Nanjing, 211189, China*
(Dated: August 12, 2015)

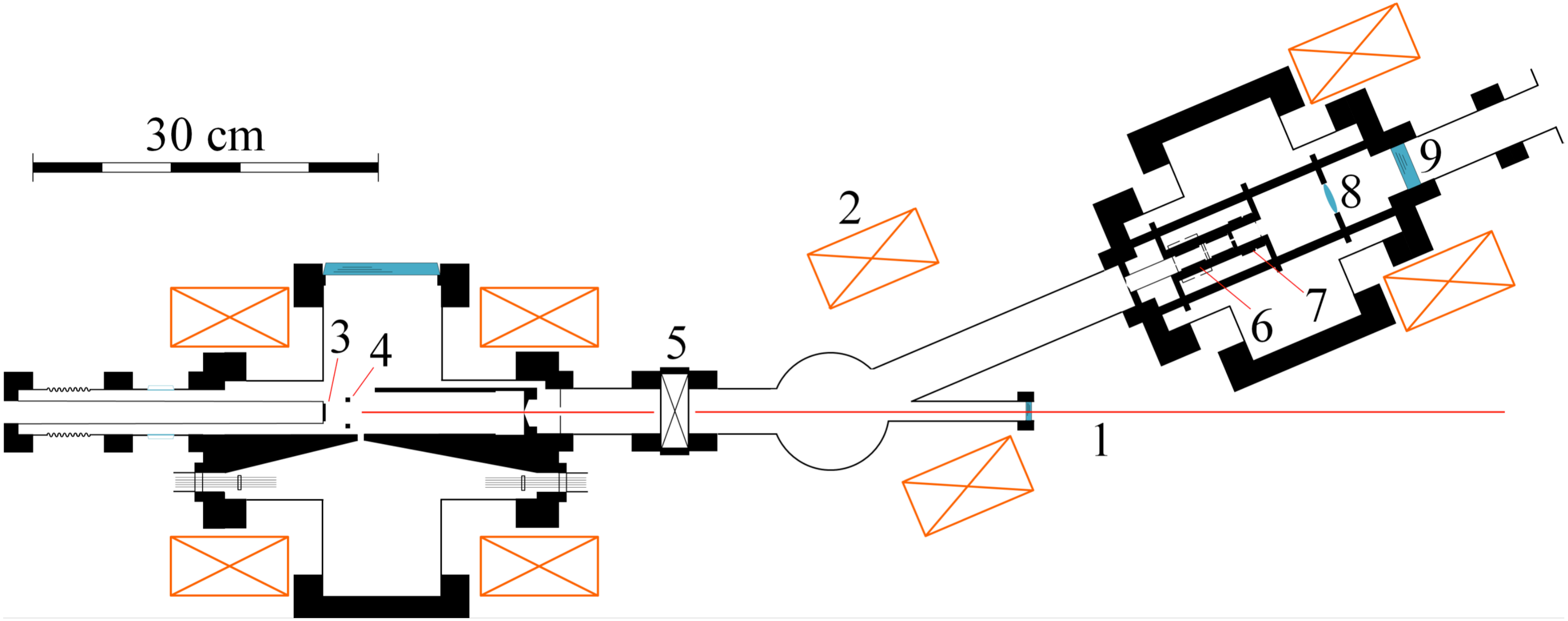
This led to more work to constrain parity-odd interactions of the neutron



H. Yan and W. M. Snow, PRL 110, 082003 (2013)

E. G. Adelberger and T. A. Wagner, PRD 88, 031101 (2013)

Search for exotic parity-odd interactions of electrons



Polarized electron transmission asymmetry measurement in argon gas at 8eV and 14 eV, performed at U Nebraska

Search for parity-odd electron transmission asymmetry $\Delta\sigma/\sigma$ consistent with zero at 1E-5 level.

J. Dreiling, T. Gay, W. M. Snow, in progress

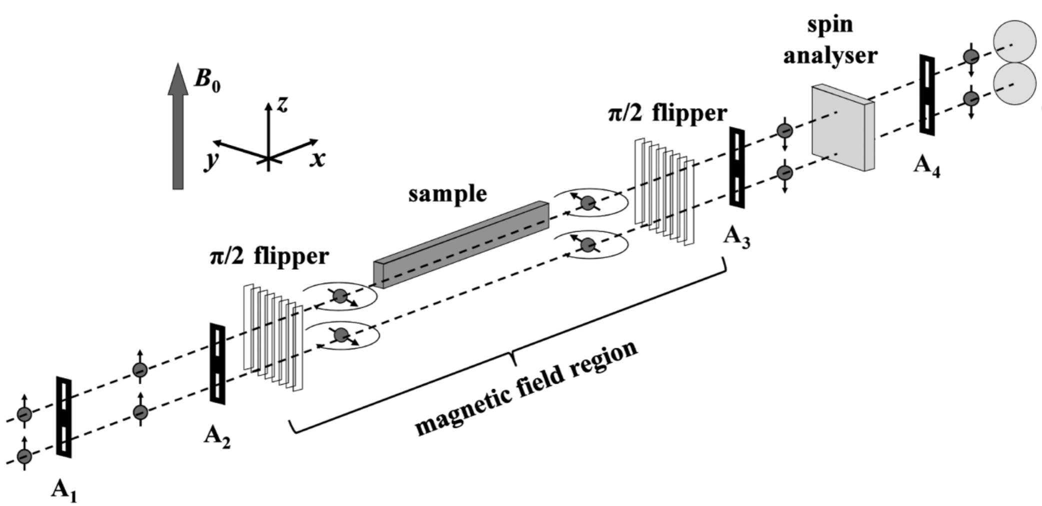
A Spin-1 Boson Axial Coupling Search at PSI

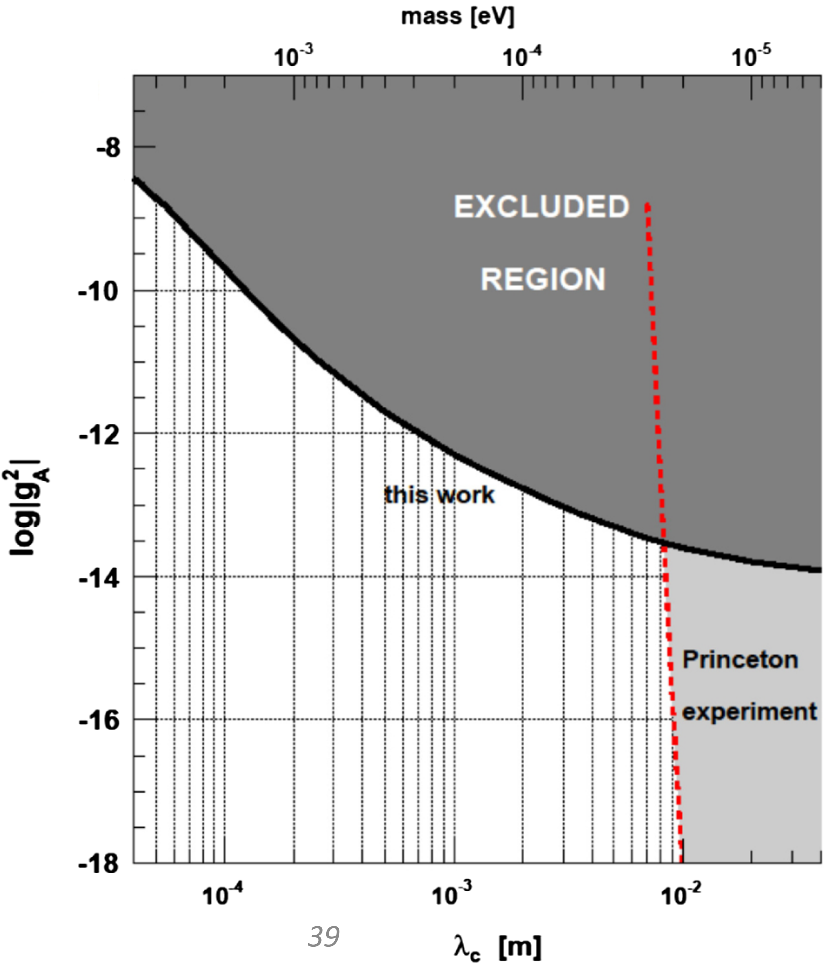
F. Piegsa and G. Pignol placed a first upper bound on the axial coupling constant for a beyond-the-Standard-Model light spin-1 boson in the millimeter range by passing polarized neutrons near one side of a non-magnetic mass and looking for an induced rotation of the polarization direction.

$$\mathcal{L} = \overline{\psi}\left(g_V\gamma^\mu + g_A\gamma^\mu\gamma^5\right)\psi\, X_\mu$$

$$V_{AA} \propto g_A^2\, \vec{\sigma}\cdot(\vec{v}\times\hat{r})\left(\frac{1}{\lambda}+\frac{1}{r}\right)\frac{e^{-r/\lambda}}{r}$$

B. Dobrescu and I. Mocioiu, J. High Energy Physics. 11, 005 (2006)



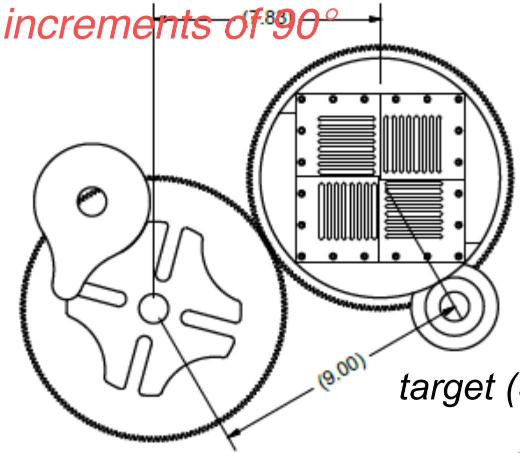


F. Piegsa and G. Pignol, PRL 108, 181801 (2012)

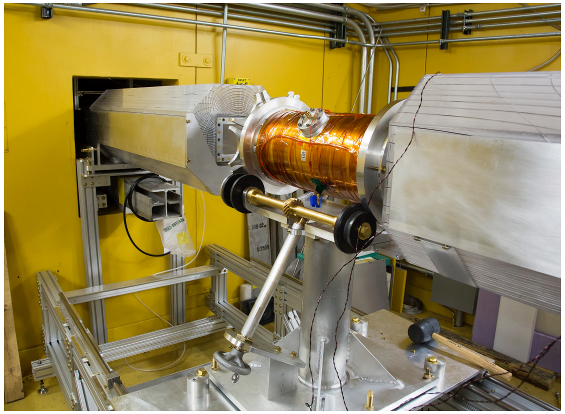
Spin-1 Boson Axial Coupling Search at LANSCE

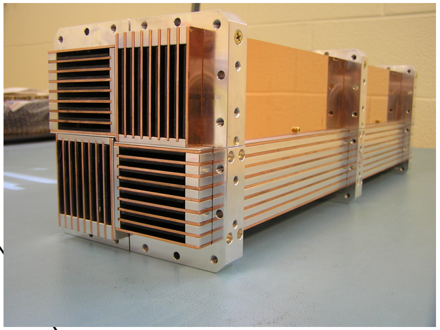
Geneva Mechanism:

Rotate the target by increments of 90°

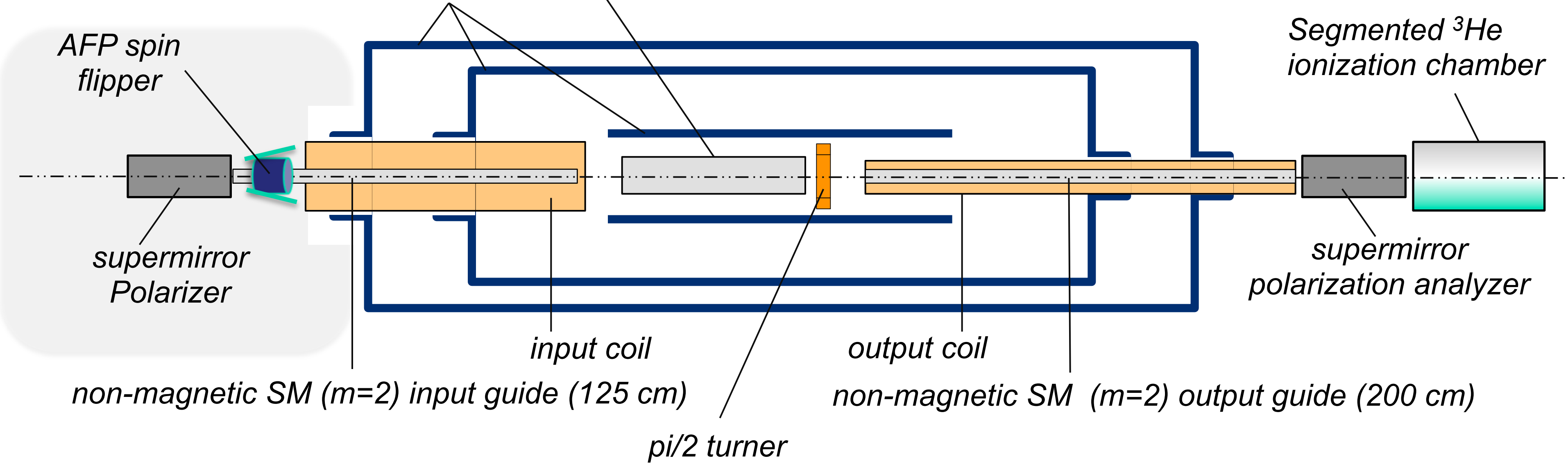


View inside FP12 cave showing input/output supermirror guides and coils and target vacuum chamber. Neutron supermirror polarizer/analyzer, ion chamber, magnetic shielding not shown.





Plates of different nucleon density N are assembled so that the polarized neutrons traveling between the gaps will always see a density gradient.

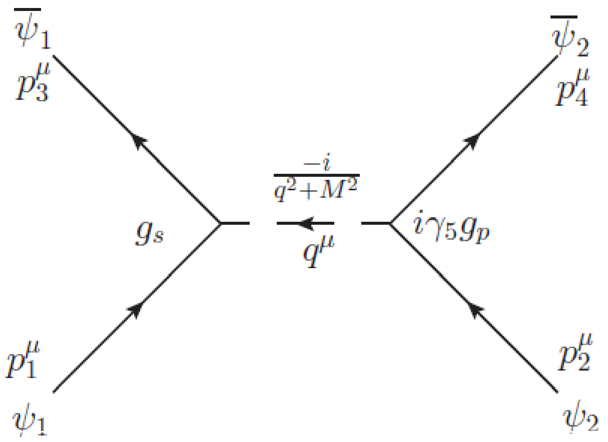


C. Haddock thesis data under analysis

P-ODD AND T-ODD SPIN-DEPENDENT INTERACTIONS

Amplitude For Monopole-Dipole Interaction:

$$g_s g_p \frac{\overline{\psi}_1(\mathbf{p}_3)\,\psi_1(\mathbf{p}_1)\,\overline{\psi}_2(\mathbf{p}_4)\,\gamma_5\psi_2(\mathbf{p}_2)}{q^2+M^2}$$



$$U(r) = \frac{\hbar^2 g_s g_p}{8\pi m_f}\left(\frac{1}{r\lambda_a}+\frac{1}{r^2}\right)e^{-r/\lambda_a}(\hat{\sigma}\cdot\hat{r})$$

Non-Relativistic Limit,
position space

J. E. Moody, F. Wilczek,
Phys . Rev. D, 30, 130 (1984))

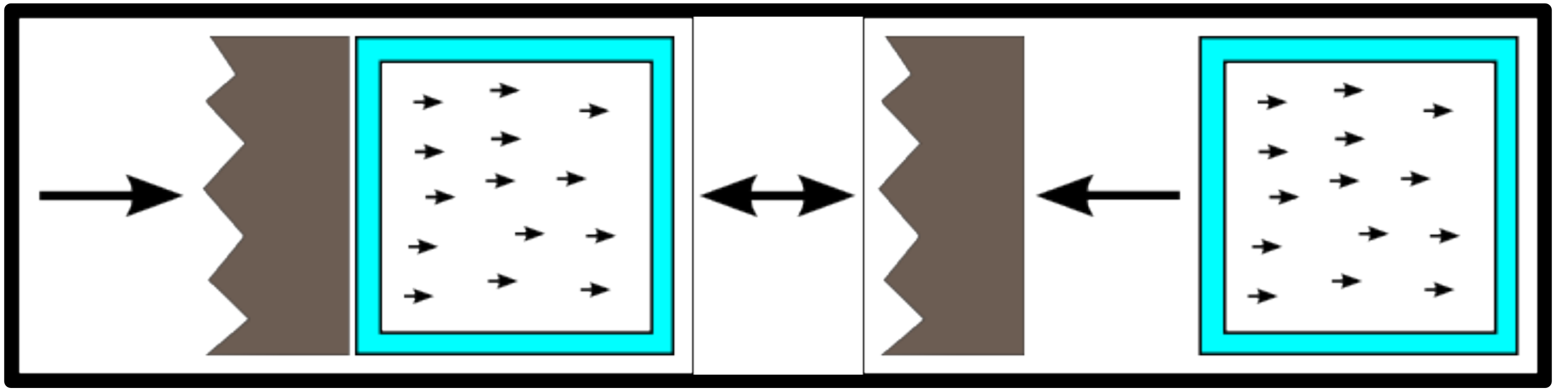
Induces an interaction between polarized and unpolarized matter

Violates both P and T symmetry

Poorly constrained over “mesoscopic” ranges(millimeters to microns)
From axions or “axion-like particles”

SIMPLE MEASUREMENT CONCEPT

- *Use a sensitive NMR magnetometer consisting of spin polarized nuclei*
- *Oscillate a low magnetic susceptibility, unpolarized mass near and far from the ensemble*
- *Look for changes in the NMR frequency of the magnetometer induced by the change in the potential energy*
- *Any magnetic effects from the oscillating mass would appear as a systematic error*



LABORATORY SEARCH FOR A LONG-RANGE, SCALAR-PSEUDOSCALAR INTERACTION USING DUAL-SPECIES NMR WITH POLARIZED ^{129}XE AND ^{131}XE GAS

M. Bulatowicz, R. Griffith, M. Larsen, J. Mirijanian, and J. Pavell
Northrop Grumman Corporation, Woodland Hills, California 91367, USA

C.B. Fu, E. Smith, W. M. Snow, and H. Yan
Indiana University, Bloomington, Indiana 47408, USA and
Center for Exploration of Energy and Matter, Indiana University,
Bloomington, IN 47408

T. G. Walker
University of Wisconsin, Madison, Wisconsin 53706, USA

Supported By:
NSF grants PHY-1068712 and PHY-0116146, IU Faculty Research Support program, the Indiana University Center for Spacetime Symmetries, NGC IRAD funding, and the DoE

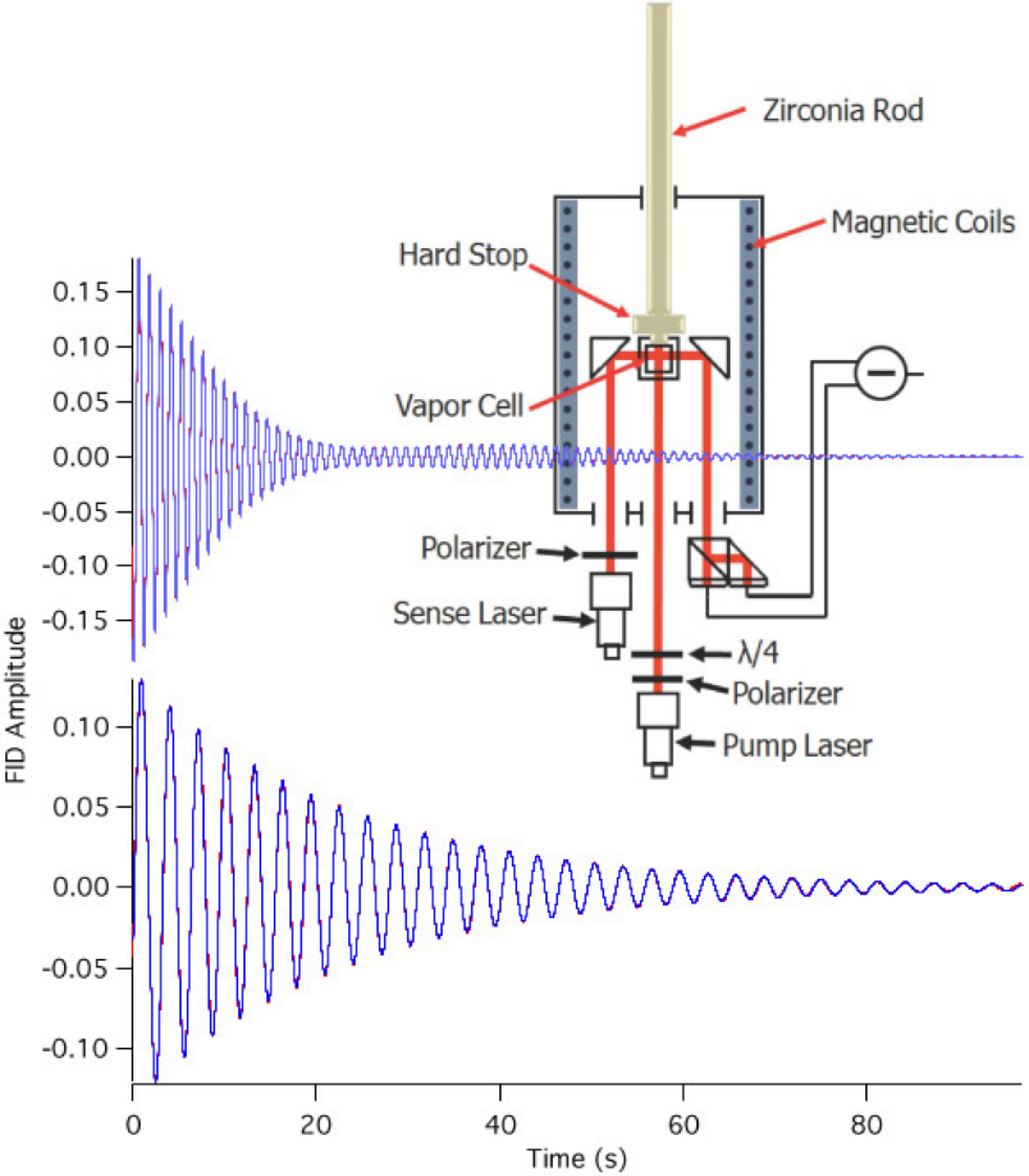
PHYS. REV. LETT. 111, 102001 (2013)

Experimental Setup

The experimental system uses a ^{85}Rb-^{129}Xe-^{131}Xe co-magnetometer configuration with a zirconia rod as the unpolarized source

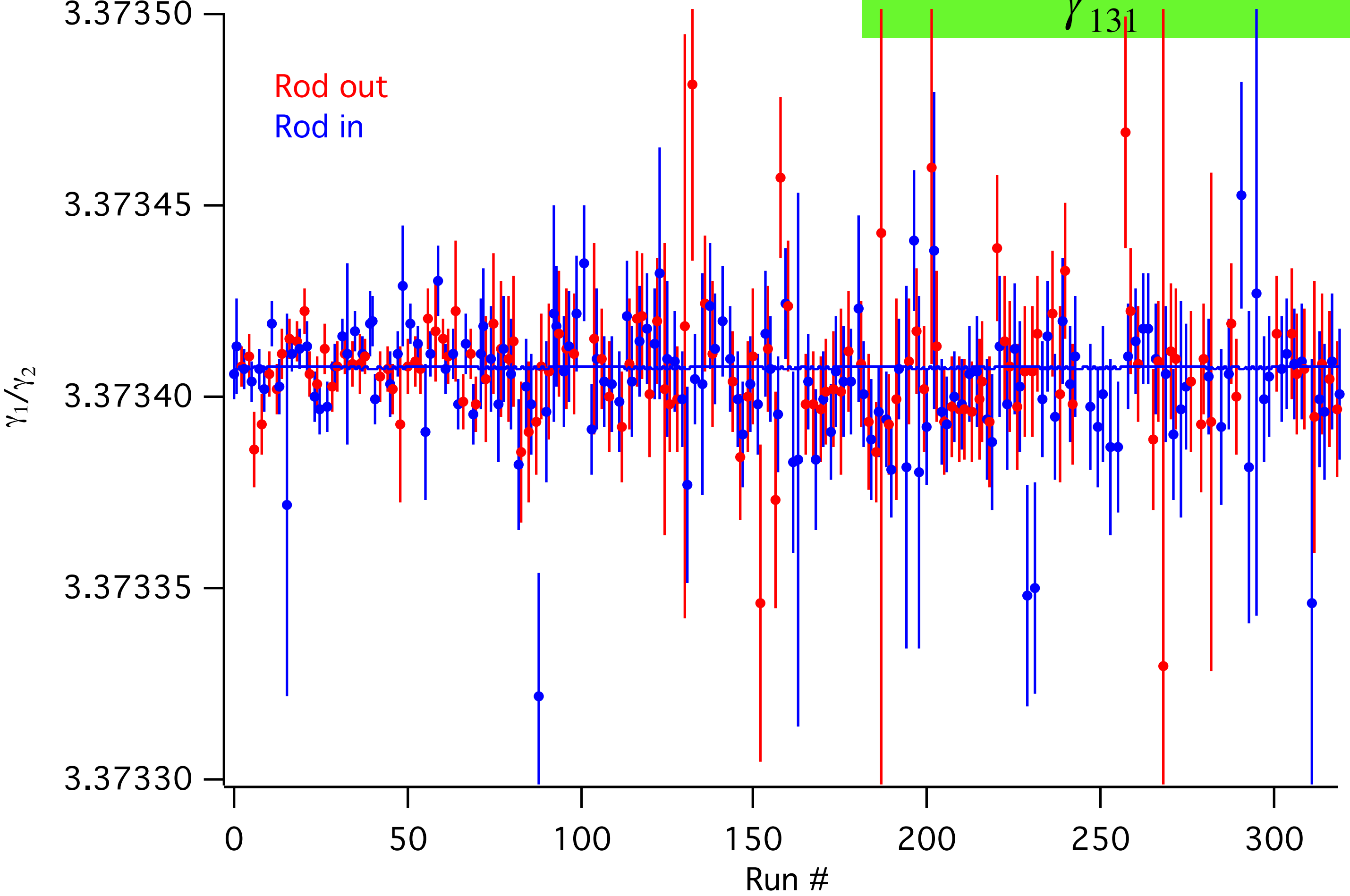
The Rb magnetometer measures the Free Induction Decay (FID) of the two xenon isotopes as an amplitude modulation of the Rb spin projection.

This signal is read by optical Faraday rotation and demodulated to give the sum of the two Xe Larmour precession signals



Results from Northrop/Grumman experiment

$$\delta\Omega_{129} + \frac{\gamma_{129}}{\gamma_{131}}\delta\Omega_{131} = -8 \pm 23 \times 10^{-6}\,Hz$$



Frequency shift zero at 2E-5 Hz level in ~3-day experiment on their “test” apparatus
Apparatus improvements can achieve ~1E-9 Hz precision

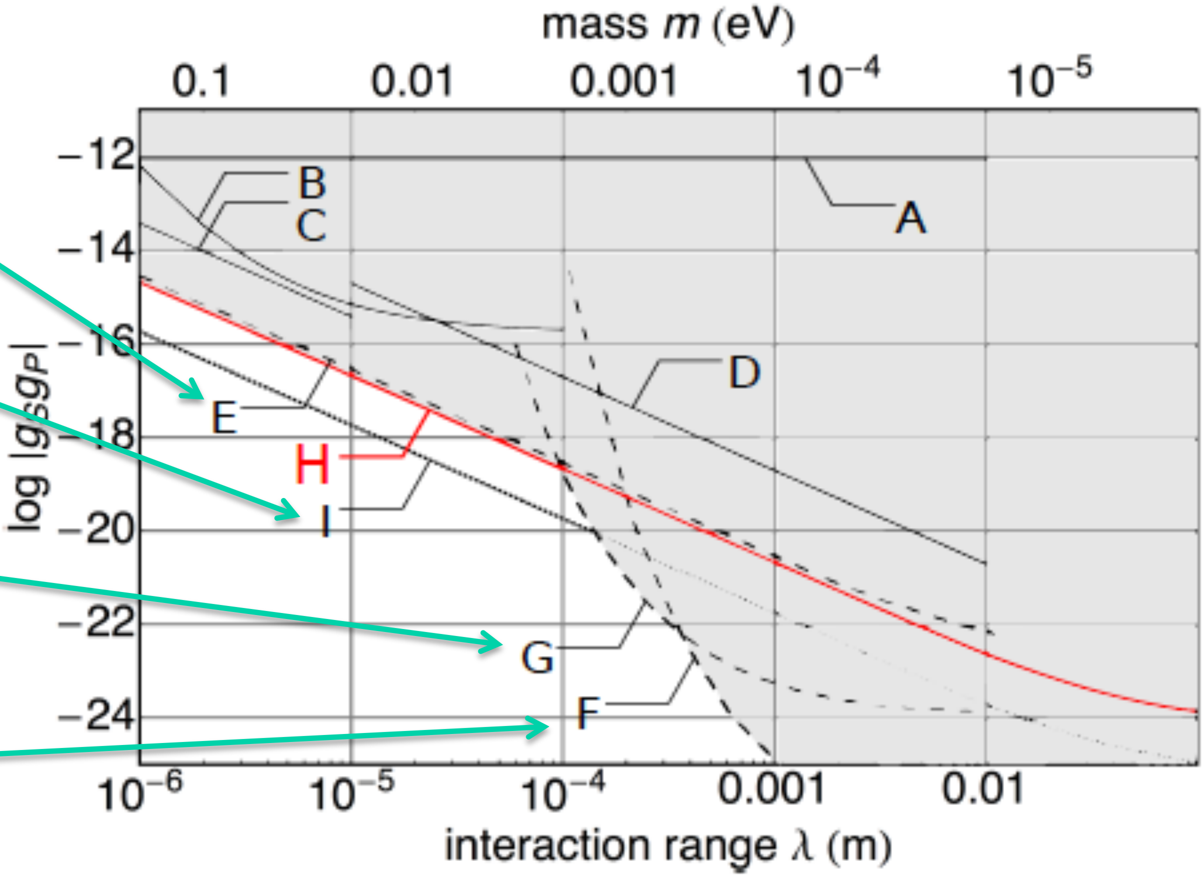
Constraints on Monopole-Dipole Interactions

A.Pethkhov et al, PRL 170401 (2010)

S. Afach et al, arXiv 1412.3679

M. Bulatowicz et al, arXiv 1301.5224 PRL 111, 102001 (2013)

K. Tullney et al, PRL 111, 100801 (2013)

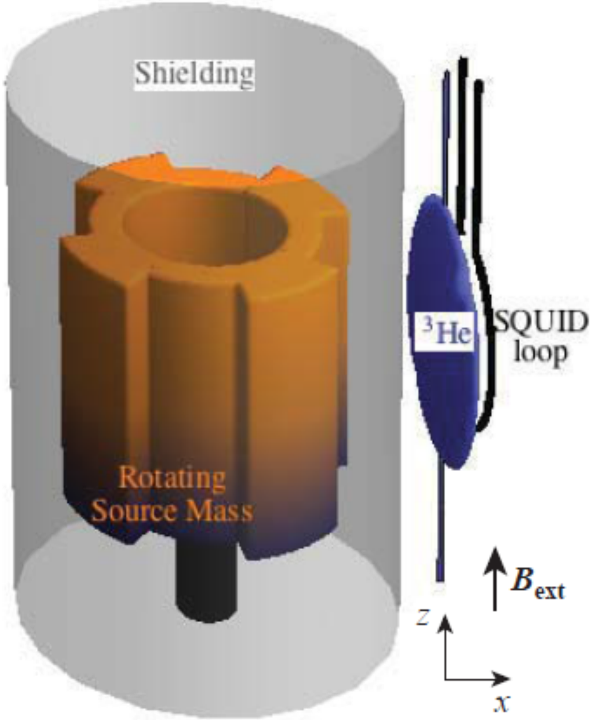


Constraints on general P-odd T-odd interactions in mm range

Note: neutron/atom EDM limits are less stringent for generic light scalars in this range (S. Mantry et al, PRD 90, 054016 (2014)

The Axion Resonant InterAction DetectioN Experiment (ARIADNE)

A.Arvanitaki and AG.,
Phys. Rev. Lett. 113,161801 (2014).



ARIADNE Collaboration:

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INDIANA UNIVERSITY

IUCSS

ibS Institute for Basic Science

EPSCoR NEVADA

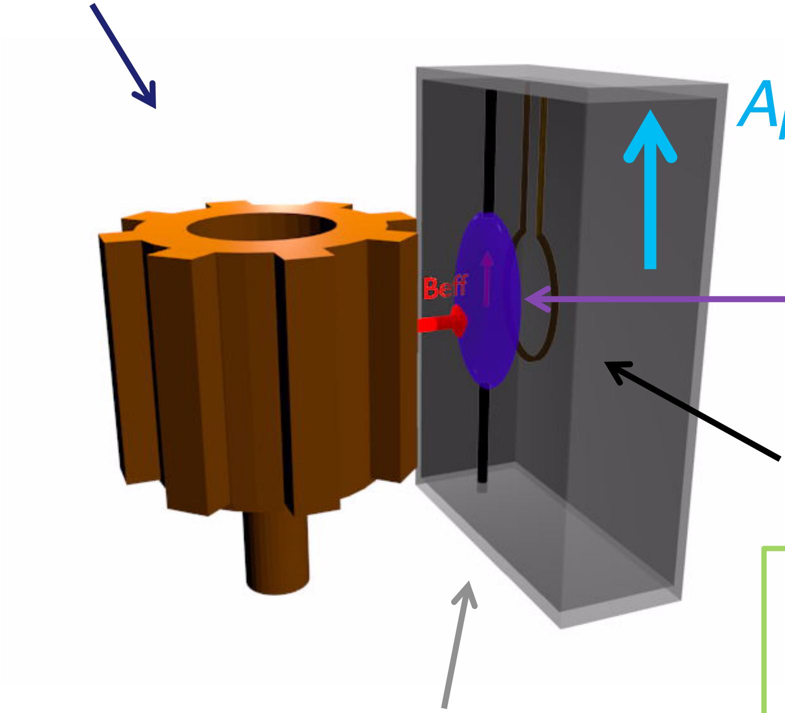
University of Nevada, Reno

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

Concept for ARIADNE

unpolarized tungsten segmented cylinder sources axion/ALP B_{eff} oscillated at Larmour frequency of polarized ^{3}He

$$\omega = \frac{2\mu_N \cdot B_{\mathrm{ext}}}{\hbar}$$



Applied Bias field B_{ext}

Laser Polarized ^{3}He gas senses B_{eff} (Indiana U)

squid pickup loop (CAPP)

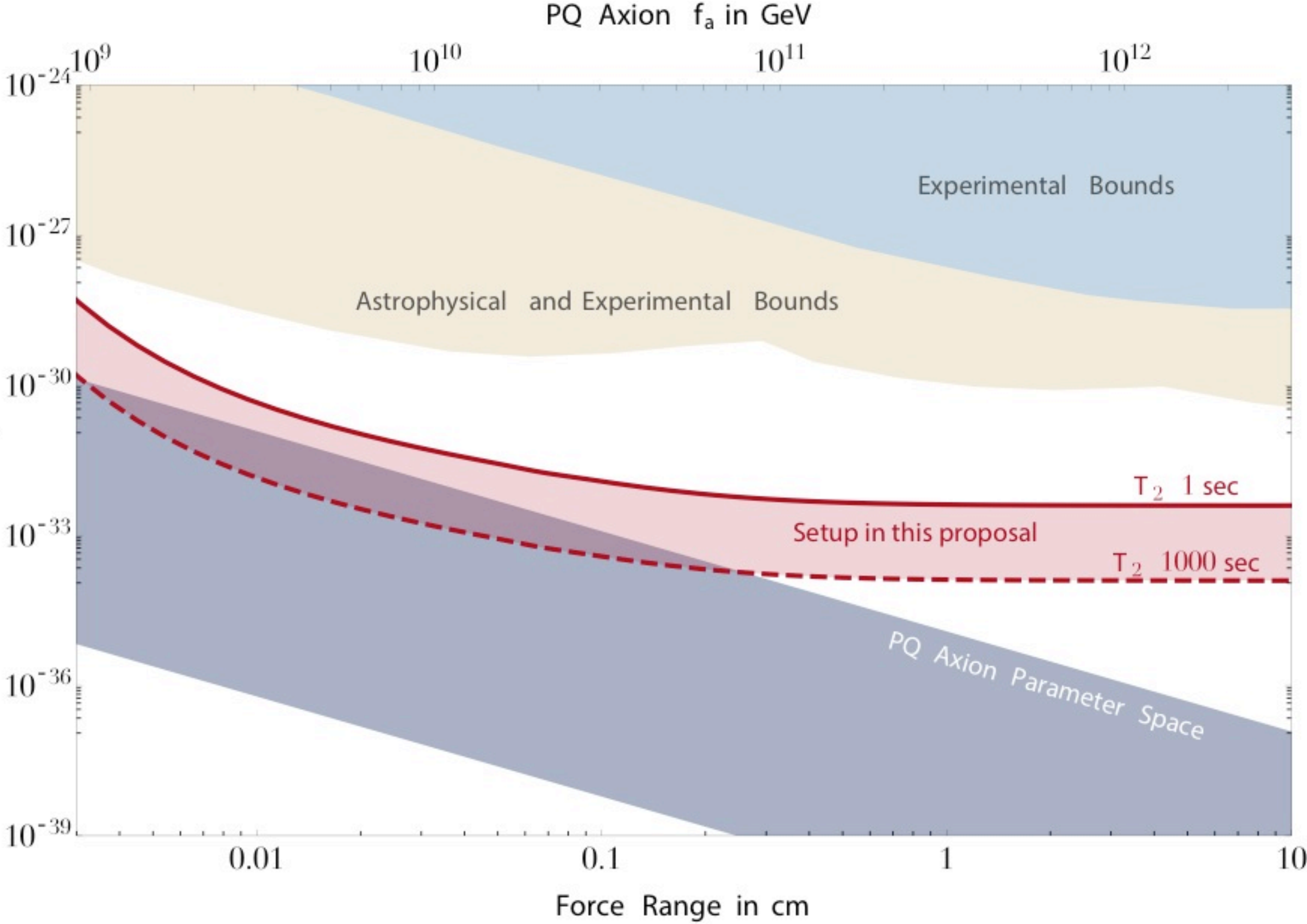
Superconducting shielding (Stanford)

Limit: Transverse spin projection noise

$$B_{\min} \approx p^{-1}\sqrt{\frac{2\hbar}{n_s \mu_{^3\mathrm{He}} \gamma V T_2}} = 10^{-20}\frac{T}{\sqrt{Hz}} \times \left(\frac{1}{p}\right)\left(\frac{1\ \mathrm{cm}^3}{V}\right)^{1/2}\left(\frac{10^{21}\ \mathrm{cm}^{-3}}{n_s}\right)^{1/2}\left(\frac{1000\ \mathrm{sec}}{T_2}\right)^{1/2}$$

A. Arvanitaki and A. Geraci, Phys. Rev. Lett. 113, 161801 (2014).

ARIADNE SCIENTIFIC REACH



Conclusions

Experimental searches for weakly-coupled interactions with ranges from the millimeter to the atomic scale are actively pursued experimentally and appear in various theoretical scenarios

The properties of slow neutrons are well-suited to search for new interactions in this regime

Rapid experimental progress has occurred over the last few years, with the first measurements for certain spin-dependent interactions over sub-millimeter ever conducted.

Measurements are not yet limited by systematic errors

Goal is to increase sensitivity to the point where one can improve on astrophysical bounds and (maybe) say something about axions