Searches for Exotic Interactions with Neutrons and Nuclei

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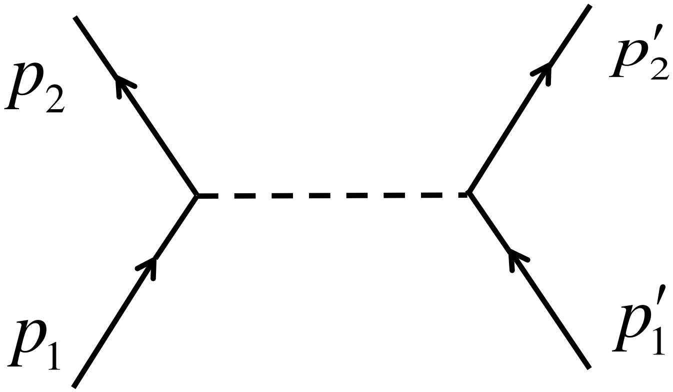
0. (General) Motivations to search for weakly-coupled, long range interactions
1. Searches for exotic spin dependent interactions of neutrons and electrons
2. Proposed search for P-odd and T-odd interactions in polarized neutron optics
3. Constraining possible new short-range Yukawa interactions using neutron scattering from an ideal gas

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

Searches for light, weakly interacting particles: complementary to LHC



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

(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)

Long-Range Interactions from Sub-GeV Dark Matter

$$\mathcal{O}_a^0 = \frac{1}{\Lambda}\bar{N}N|\phi|^2, \qquad \mathcal{O}_a^{1/2} = \frac{1}{\Lambda^2}\bar{N}N\bar{\chi}\chi,$$

$$\mathcal{O}_b^0 = \frac{1}{\Lambda^2}\bar{N}\gamma^\mu N\phi^* i\overleftrightarrow{\partial}_\mu\phi, \qquad \mathcal{O}_b^{1/2} = \frac{1}{\Lambda^2}\bar{N}\gamma^\mu N\bar{\chi}\gamma^\mu\chi,$$

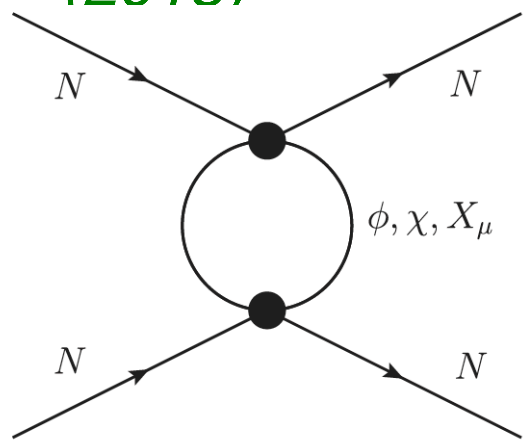
$$\mathcal{O}_c^0 = \frac{1}{\Lambda^3}\bar{N}N\partial^\mu\phi^*\partial_\mu\phi, \qquad \mathcal{O}_c^{1/2} = \frac{1}{\Lambda^2}\bar{N}\gamma^\mu N\bar{\chi}\gamma^\mu\gamma^5\chi,$$

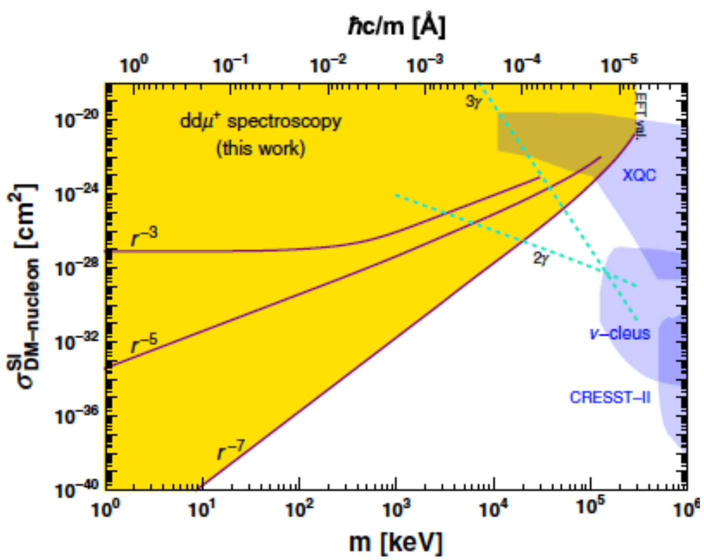
$$\mathcal{O}_a^1 = \frac{m^2}{\Lambda^3}\bar{N}N|X^\mu + \partial^\mu\pi|^2,$$

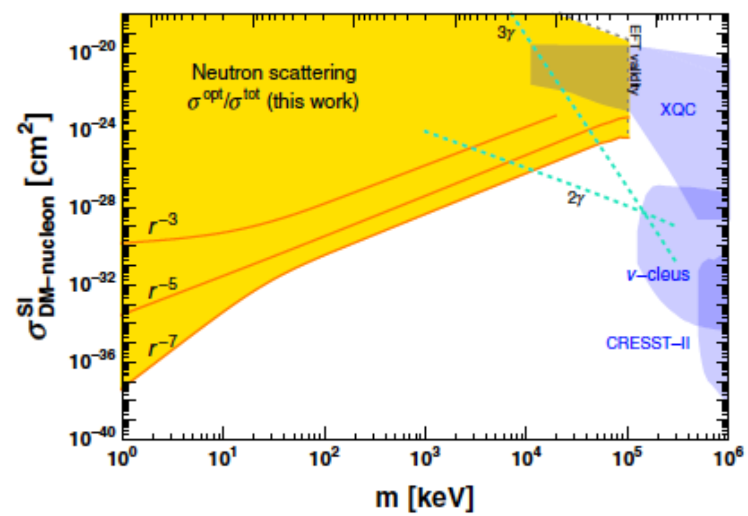
$$\mathcal{O}_b^1 = \frac{1}{\Lambda^2}2\bar{N}\gamma^\mu N\mathrm{Im}[X^*_{\mu\nu}X^\nu + \partial^\nu(X_\nu X^*_\mu) + \partial^\mu\bar{c}c^*],$$

$$\mathcal{O}_c^1 = \frac{1}{\Lambda^3}\bar{N}N|X^{\mu\nu}|^2, \qquad \mathcal{O}_d^1 = \frac{1}{\Lambda^3}\bar{N}NX^{\mu\nu}\tilde{X}^{\mu\nu},$$

S. Fichet, PRL, 120, 131801 (2018)







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*

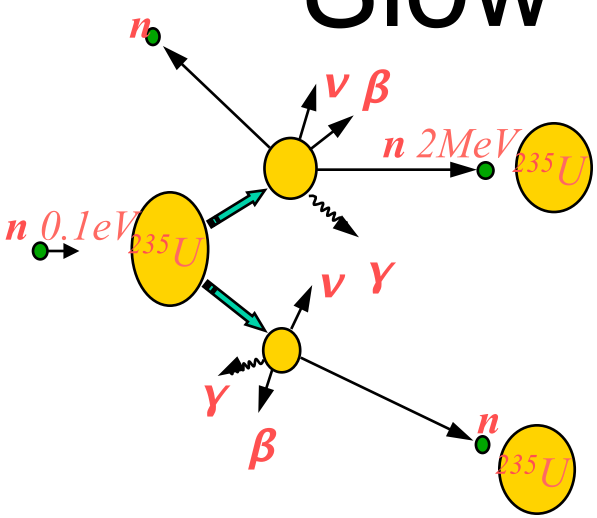
3. *Coherent interactions with matter->phase sensitive measurements possible*

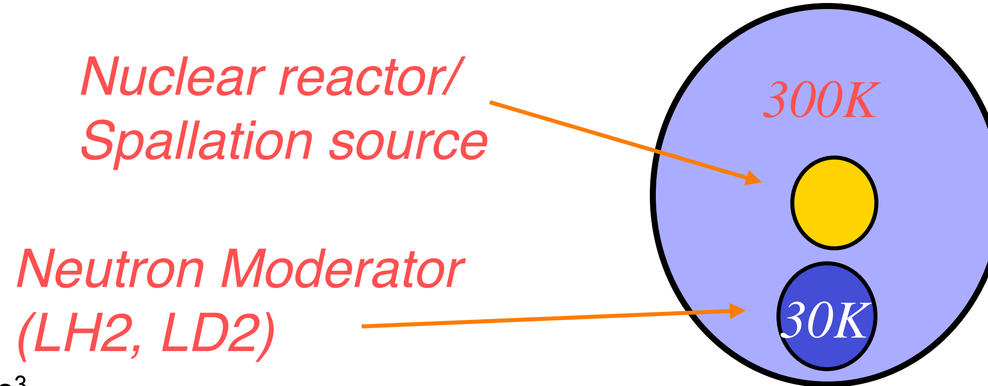
4. *High neutron polarization (>~99%) routine for slow neutrons ->important in searching for spin-dependent interactions*

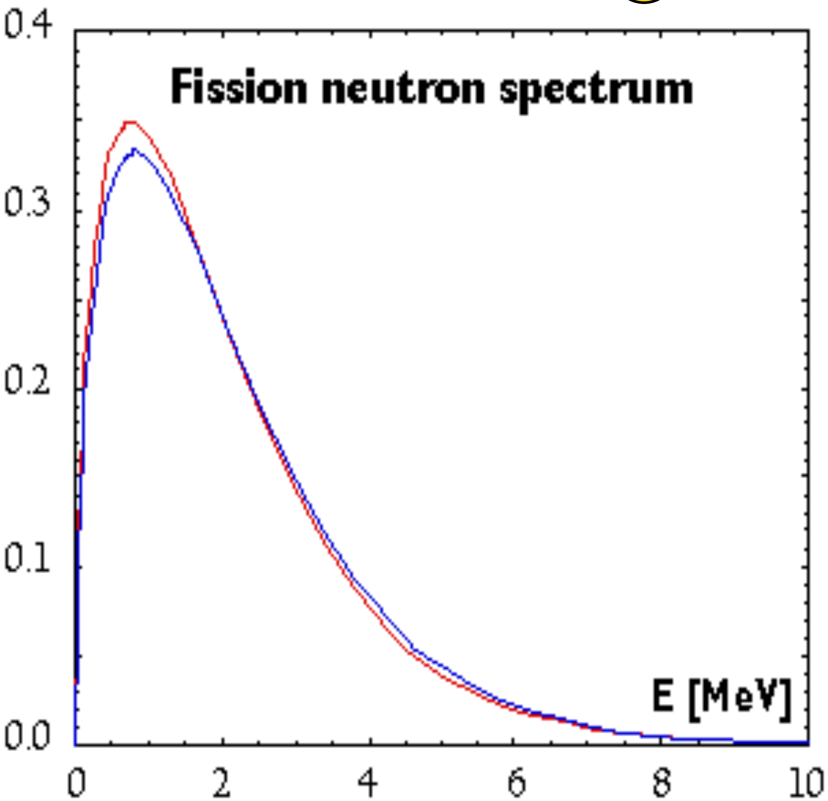
4. *A broad set of facilities for experimental work is available*

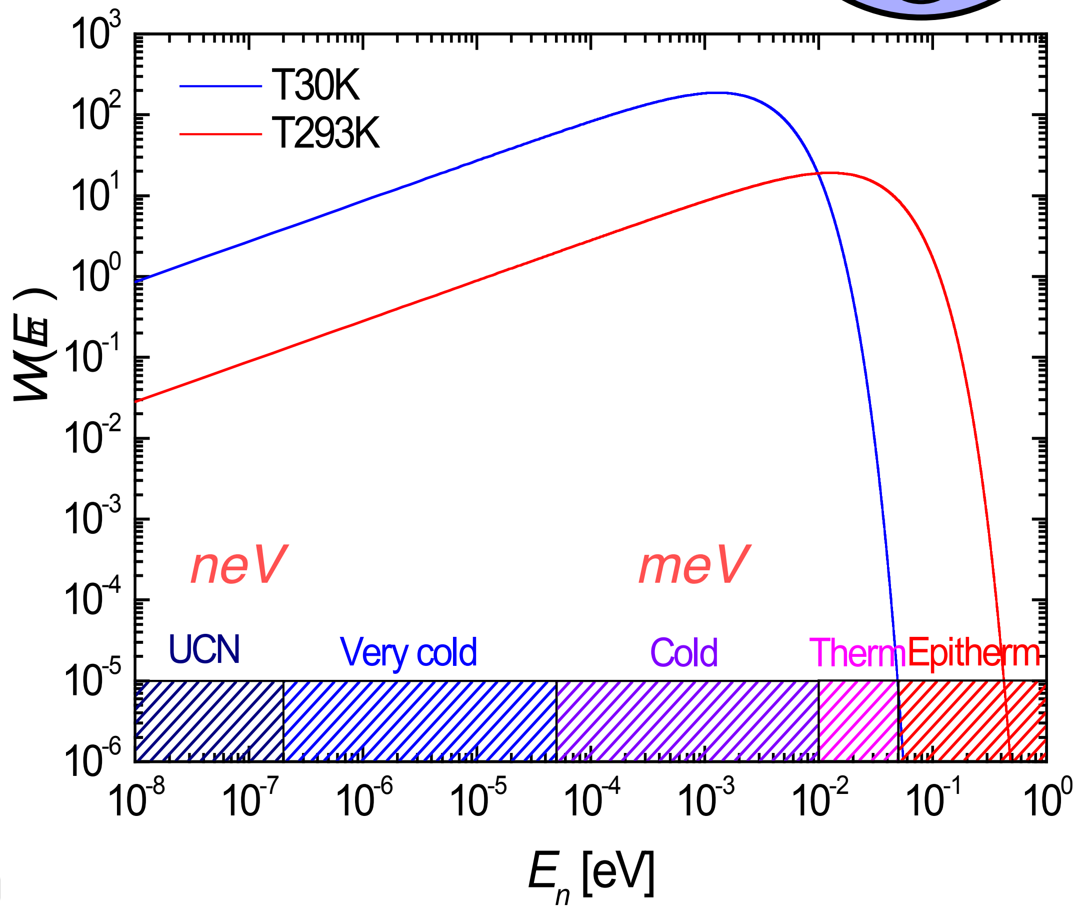
J. Nico and W. M. Snow, Annual Reviews of Nuclear and Particle Science ***55****, 27-69 (2005).*
H. Abele, Progress in Particle and Nuclear Physics ***60****, 1-81 (2008).*
D. Dubbers and M. Schmidt, Reviews of Modern Physics (2011).

“Slow” Neutrons: MeV to neV

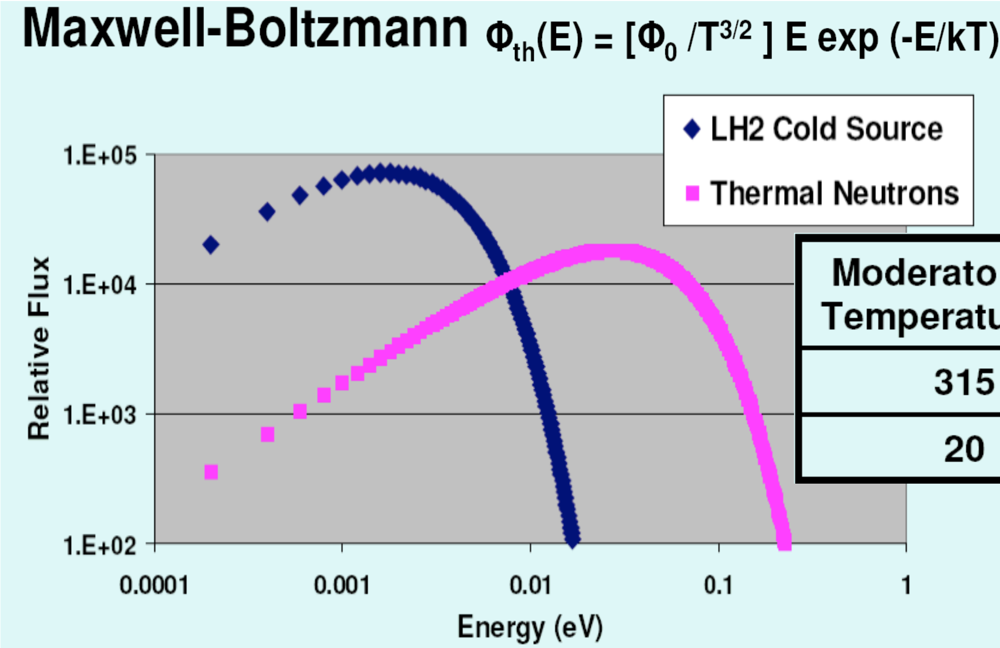








Neutron Energy, Momentum, and Wavelength



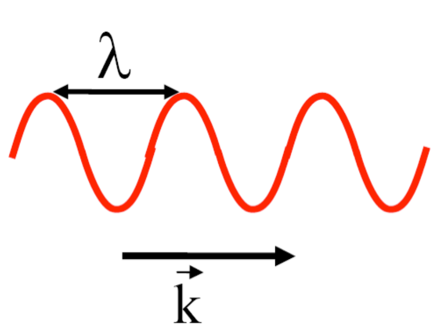
Moderator Temperature (K)	Most Probable Energy (meV)	Wavelength (Angstroms)
315	30	1.6
20	2	6.4

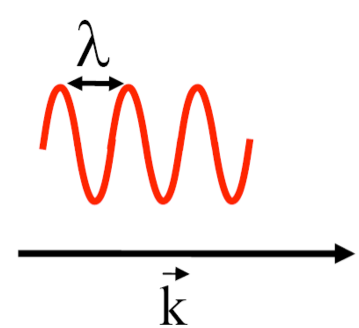
Energy:

$$E = \frac{1}{2} m v^2 = \frac{\hbar^2}{2m} k^2 = \hbar\omega$$

Momentum:

$$m\vec{v} = \vec{p} = \hbar\vec{k} = \hbar\,\frac{2\pi}{\lambda}$$





Potential step -> neutron index of refraction

with

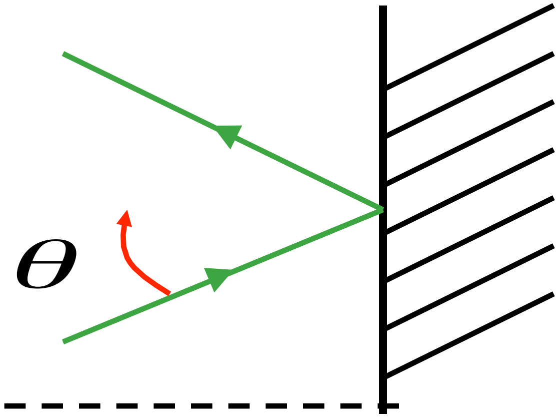
$$n = \sqrt{1 - \frac{V_0}{E_n}}$$

$$V_0 = \frac{2\pi a\hbar^2 n_0}{m_n}$$

Neutron kinetic energy

If a > 0, total external reflection

$$\mathbf{n_{out} = 1}$$



$$\mathbf{n_{in} = \sqrt{1 - \frac{V_0}{E}}}$$

All forces contribute to the neutron optical potential:

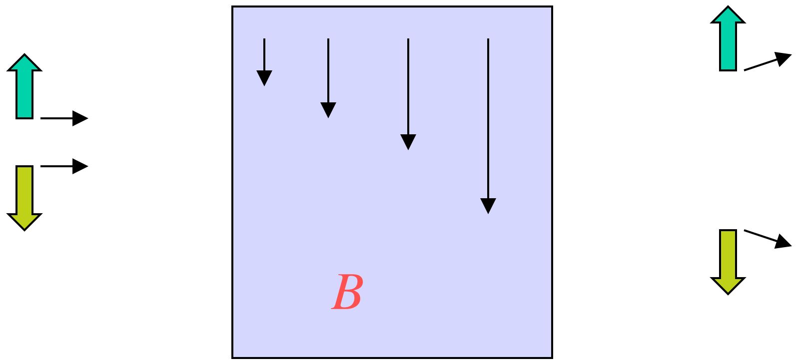
$\langle V_{strong} \rangle = 2\pi h^2 \rho b_s/m$, ~+/- 100 neV

$\langle V_{mag} \rangle = \mu B$, ~+/- 60 neV/Tesla

$\langle V_{grav} \rangle = mgz$ ~100 neV/m

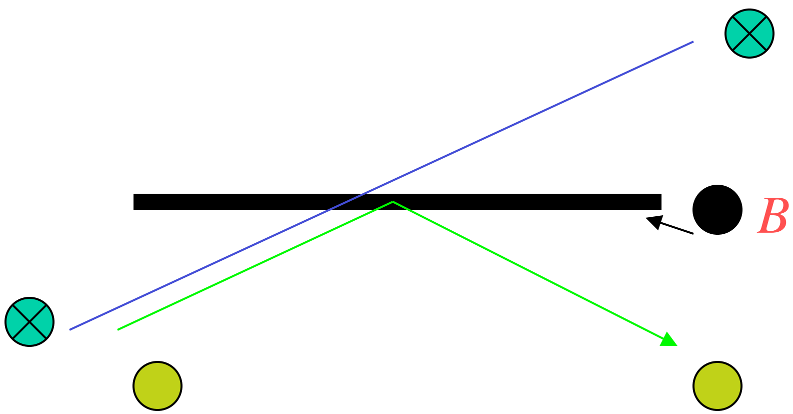
$\langle V_{weak} \rangle = [2\pi h^2 \rho b_w/m] s\cdot k/|k| \sim 10^{-7} \langle V_{strong} \rangle$

What methods are used to polarize neutrons?



B gradients (Stern-Gerlach, sextupole magnets) electromagnetic

$F=(\mu \bullet \nabla)B$

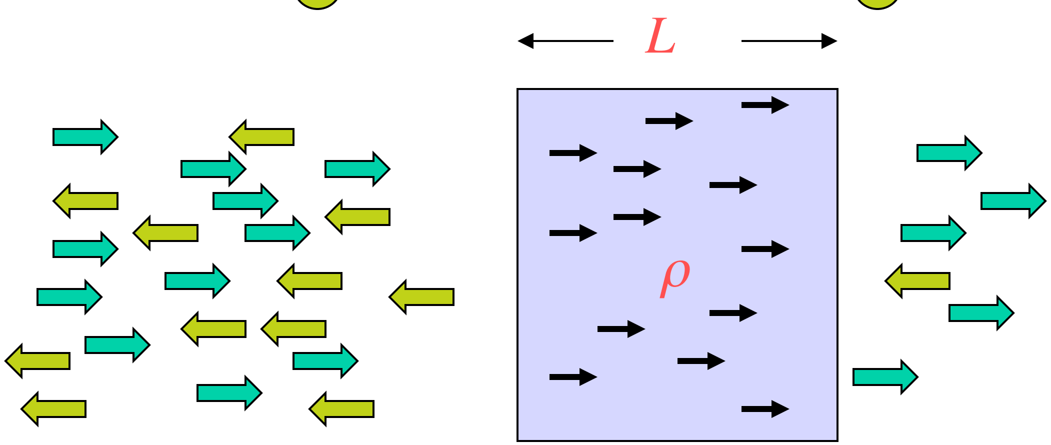


Reflection from magnetic mirror: electromagnetic+ strong

$f\pm=a(strong)\ +/-\ a(EM)$

with $|a(strong)|=|a(EM)|$

$\Rightarrow f+=2a, f-=0$



Transmission through polarized nuclei: strong

$\sigma+ \neq \sigma- \Rightarrow T+ \neq T-$

Spin Filter: $T_{\pm}=\exp[-\rho\sigma_{\pm}L]$

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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Universidad Nacional Autonoma de Mexico [2]

Gettysburg College [3]

University of Kentucky [4]

University of Washington[5]

Tennessee Technological University[6]

Georgia State University [7]

National Institute of Standards and Technology [8]

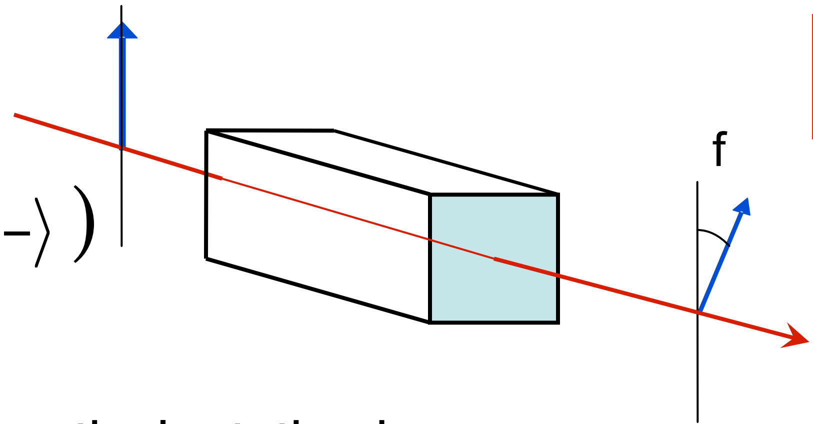
Hobart and William Smith College [9]

Bhabha Atomic Research Centre [10]

Support: NSF, NIST, DOE, CONACYT, BARC

Parity-odd Neutron Spin Rotation

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



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

Refractive index dependent on neutron helicity

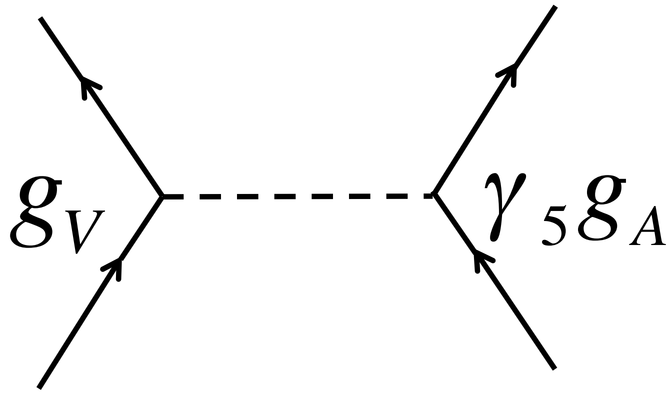
$$\frac{1}{\sqrt{2}}\left(e^{-i(\phi_{PC}+\phi_{PV})}|z\rangle + e^{-i(\phi_{PC}-\phi_{PV})}|-z\rangle\right)$$

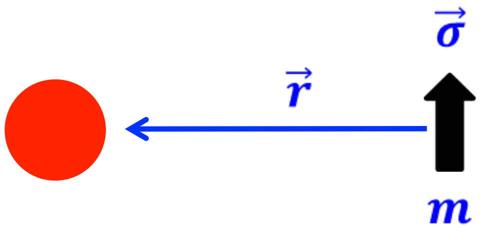
$$\varphi_{PV} = \phi_+ - \phi_- = 2\varphi_{PV} = 4\pi l \rho f_{PV}$$

- 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

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

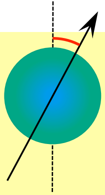
[Dobrescu/Mocioiu 06, general construction of interaction between nonrelativistic fermions]



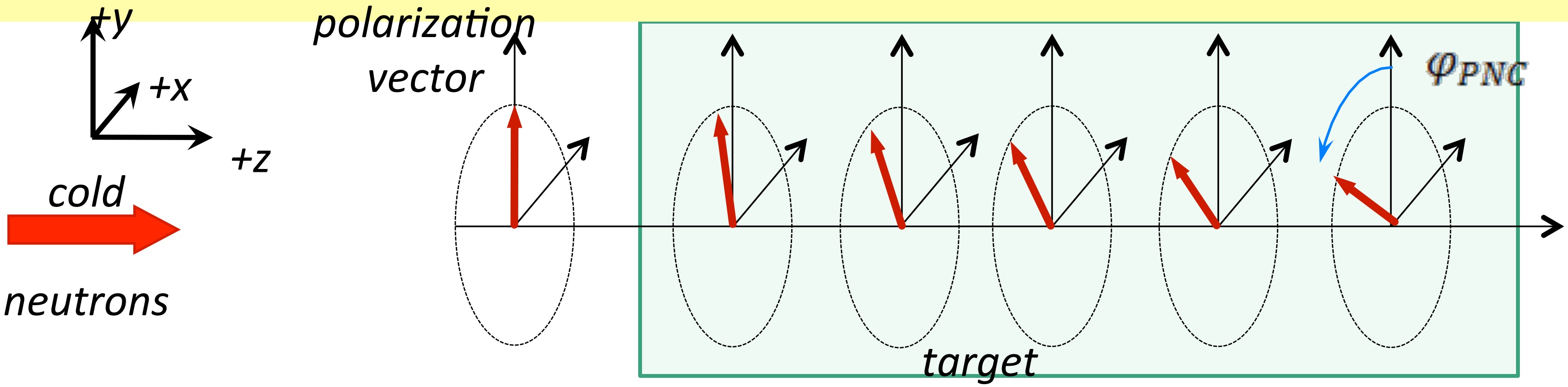


$$V(\vec{\sigma},\vec{r},\vec{v}) = \frac{\hbar}{8\pi mc^2} g_A g_V \vec{\sigma} \bullet \vec{v} \frac{1}{r} e^{-\frac{r}{\lambda}}$$

- *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

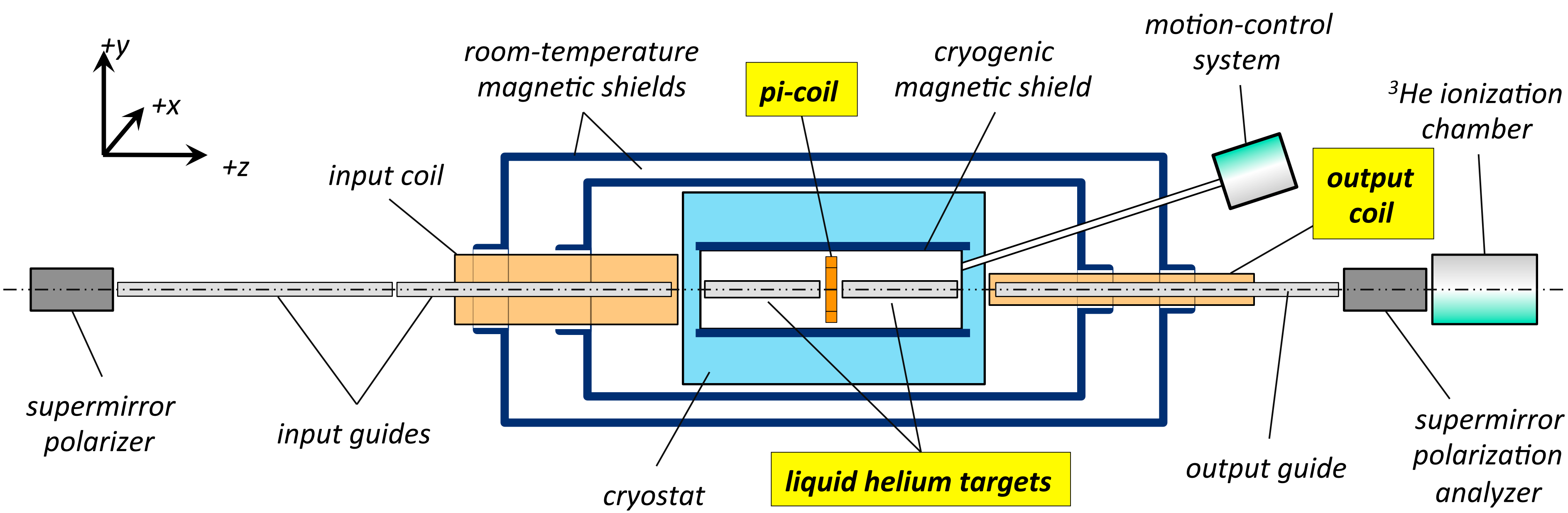
$$\phi_{\pm} = \phi_{strong} \pm \phi_{P-odd}$$

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

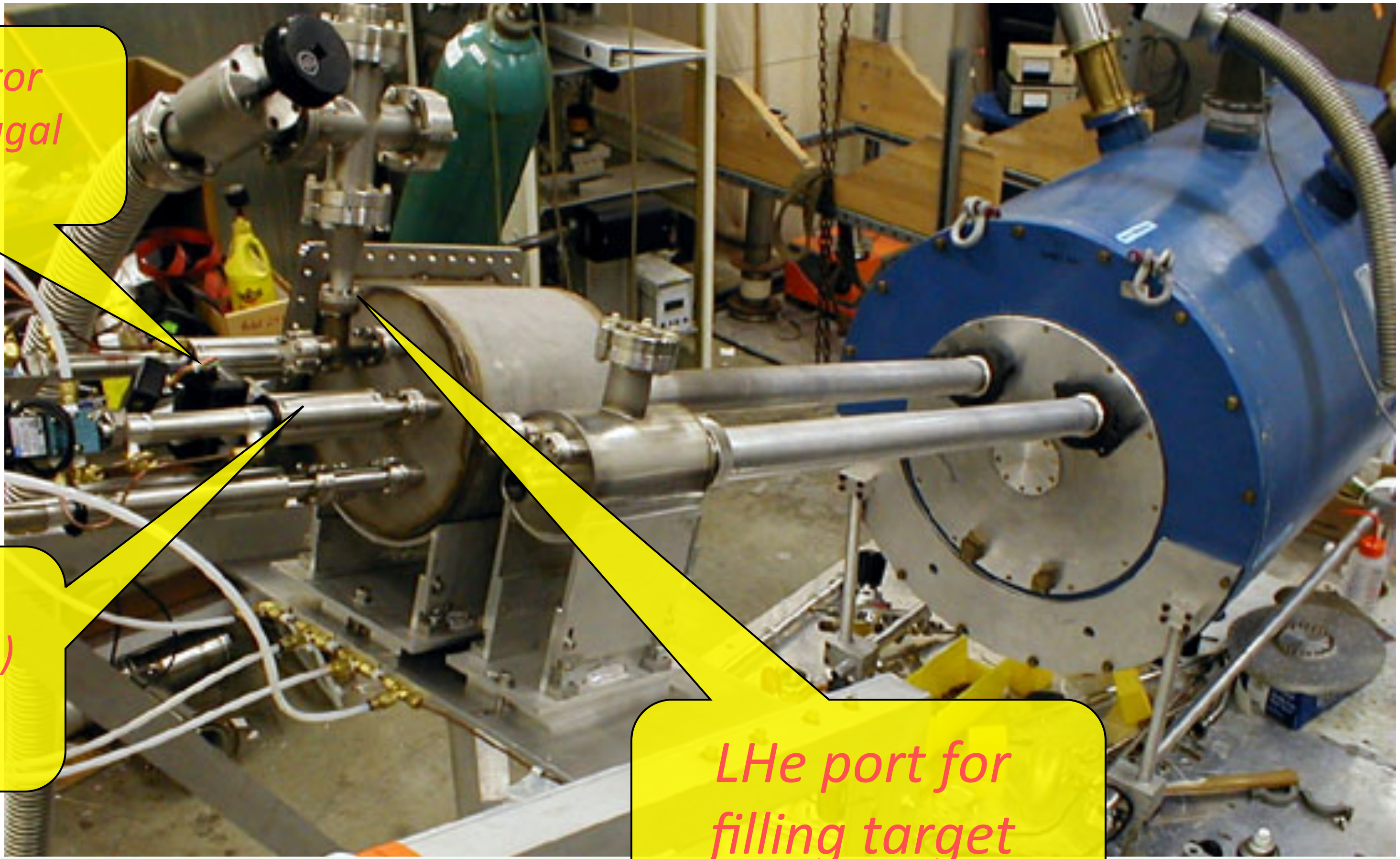
An upper bound on $f_{P\text{-}odd}$ places a constraint on possible new P-odd interactions between neutrons and matter over a broad set of distance scales

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



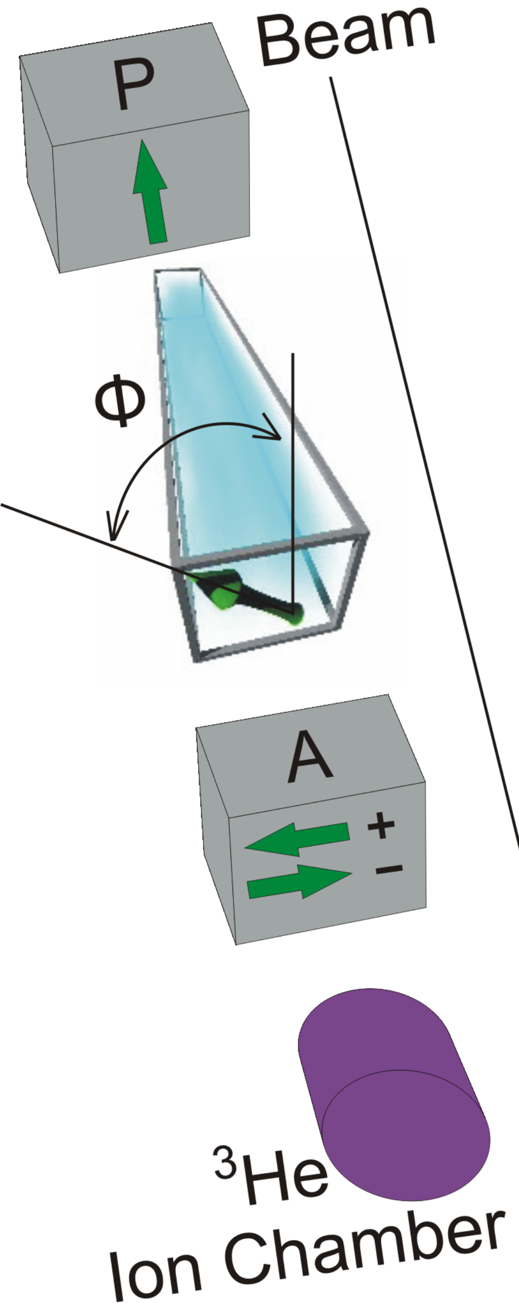
Liquid Helium Cryostat and Motion Control

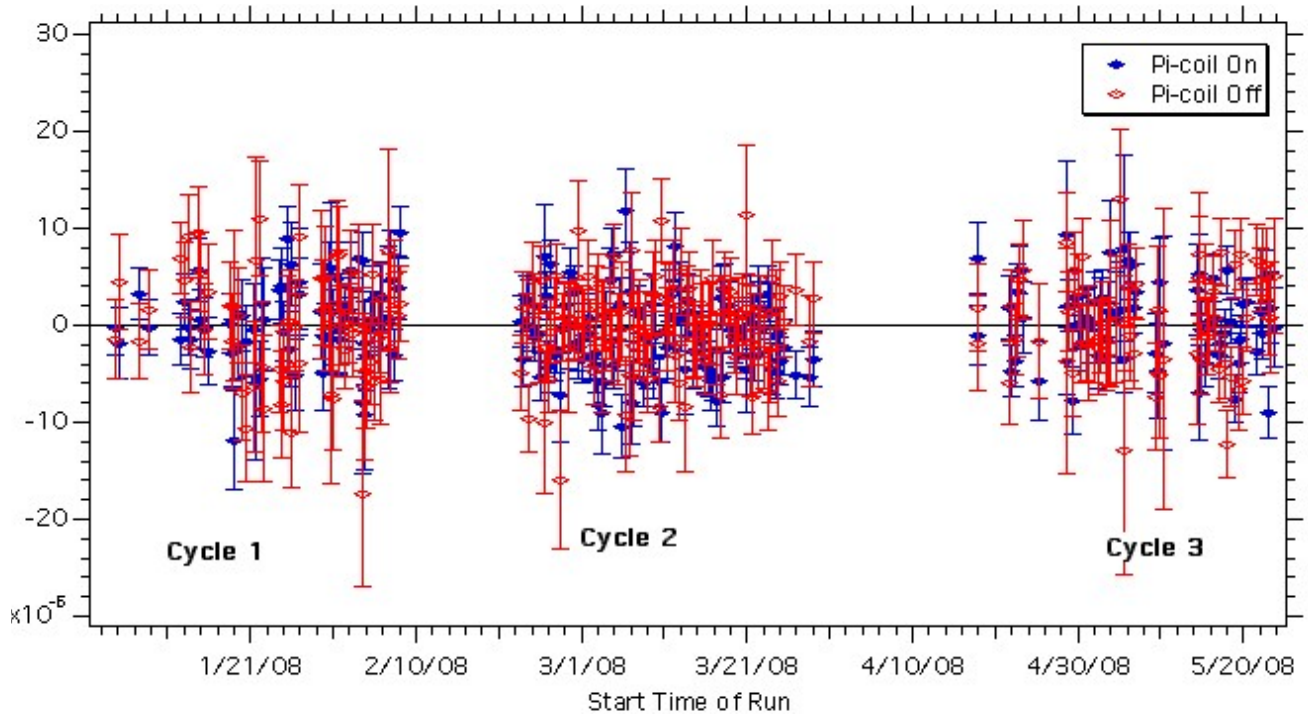


- Nonmagnetic movement of liquid helium.
- Cryogenic target of 4K helium, volume~10 liters

C. D. Bass et al, Nucl. Inst. Meth. A612, 69-82 (2009).

Neutron Spin Rotation in n+4He



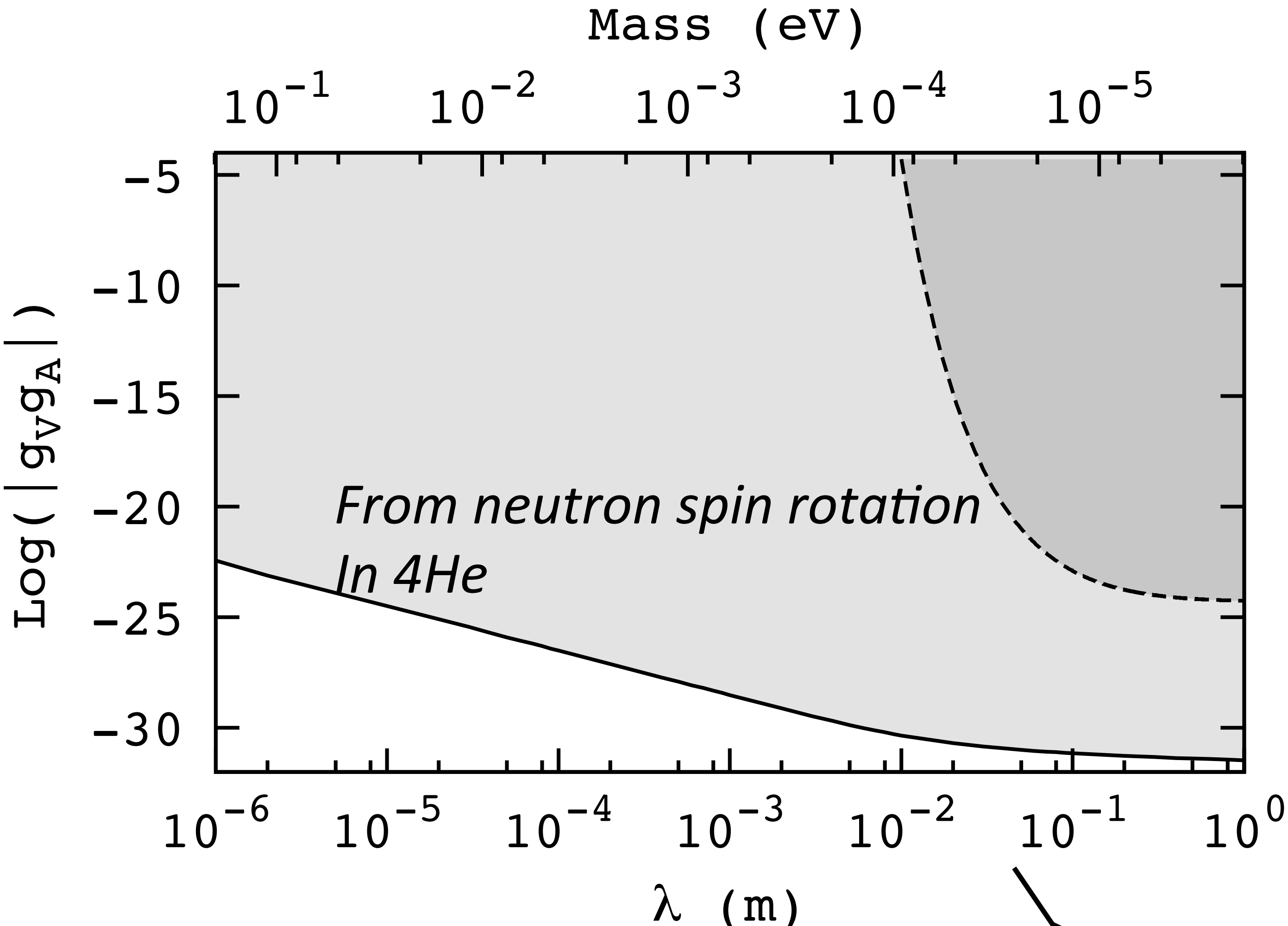


ϕ_{PNC}= [+1.7 ± 9.1 (stat) ±1.4 (sys)] x 10^{-7} rad/m

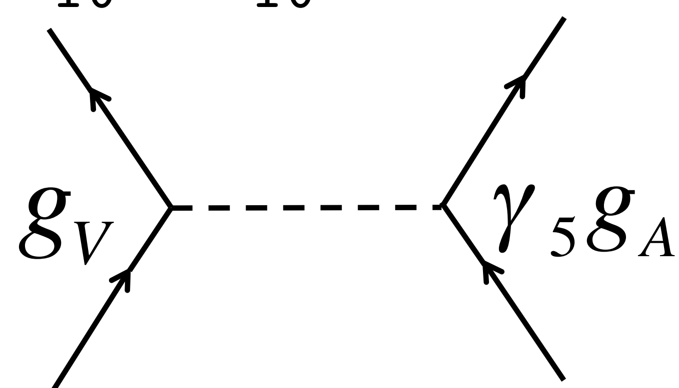
W. M. Snow et al., Phys. Rev. C83, 022501(R) (2011).

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

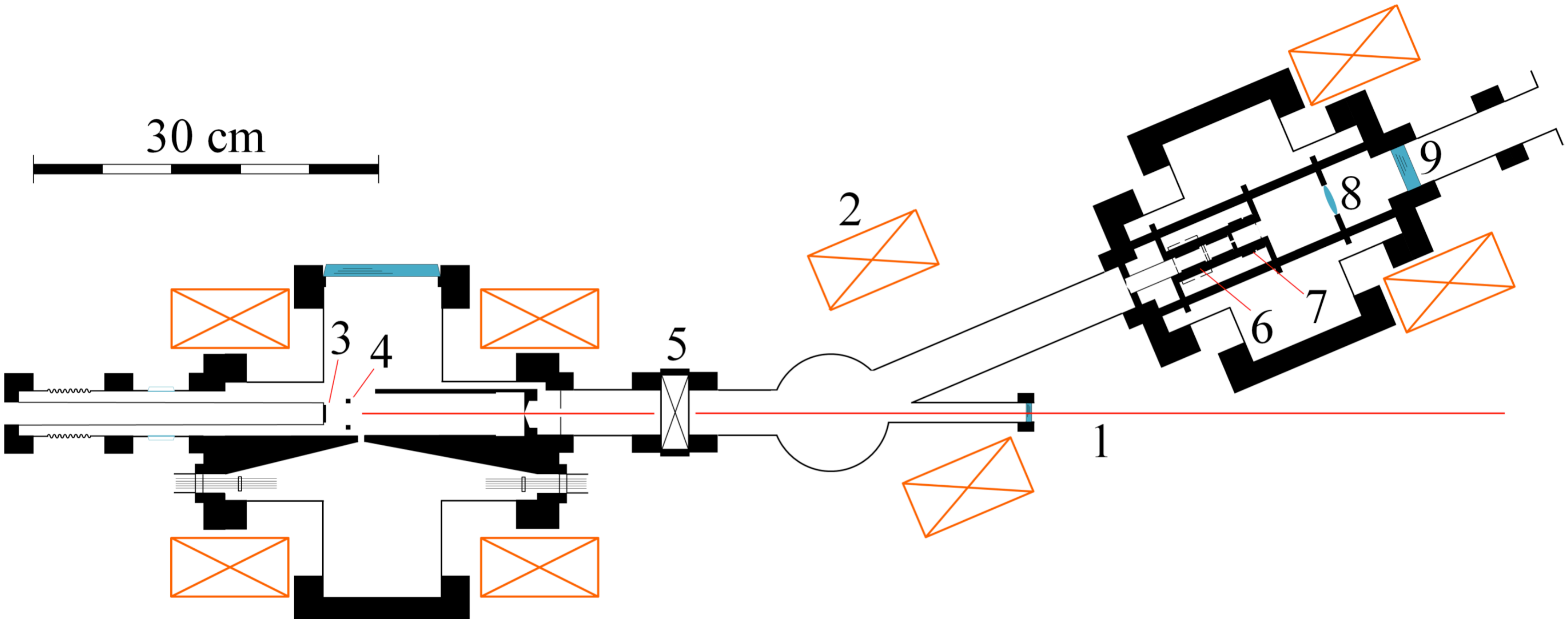


Hard to improve: should see Standard Model parity violation in next step



H. Yan, and W. M. Snow, PRL 110, 082003 (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 Axial Boson Coupling Search

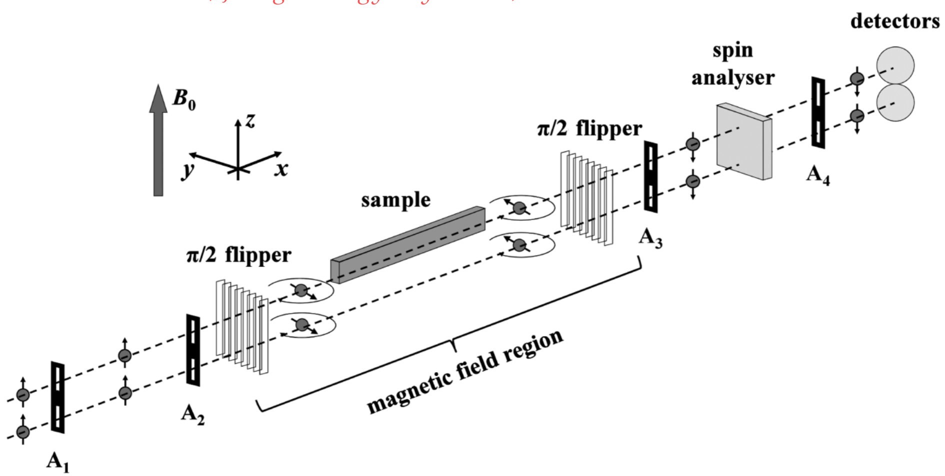
F. Piegsa and G. Pignol placed a first upper bound on the axial coupling constant for a beyond-the-Standard-Model light spin-1 boson in the millimeter range by passing polarized neutrons near one side of a non-magnetic mass and looking for an induced rotation of the polarization direction.

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

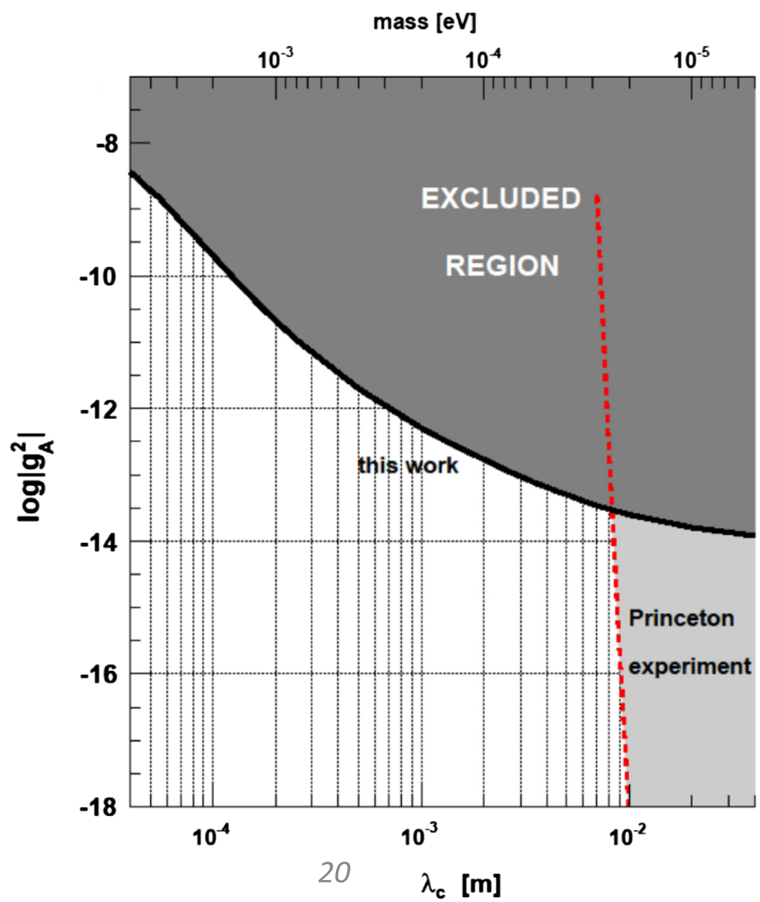
$$\mathcal{L} = \overline{\psi}\left(g_V \gamma^\mu + g_A \gamma^\mu \gamma^5\right)\psi\, X_\mu$$

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

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



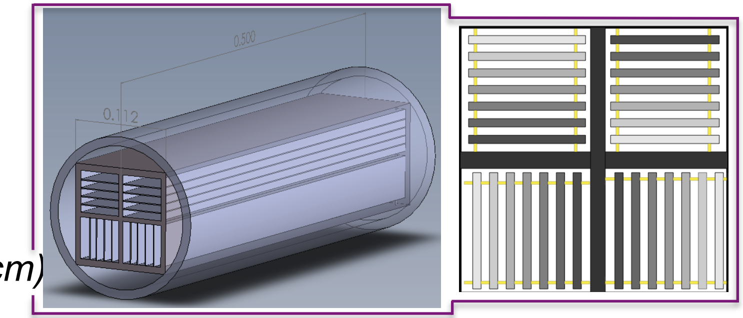
F. Piegsa and G. Pignol, PRL 108, 181801 (2012)

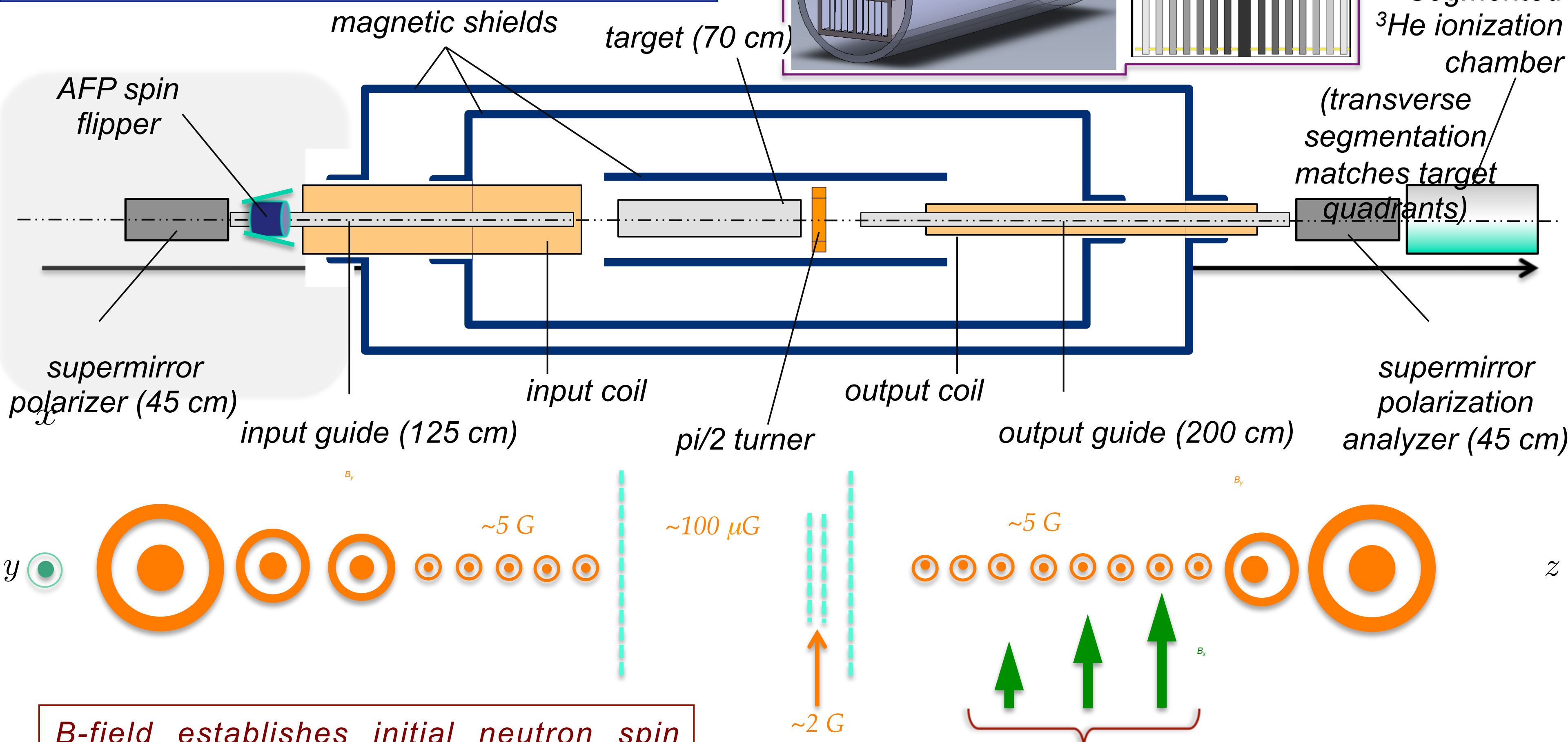


We recently improved on this limit by a few orders of magnitude at Los Alamos.

The Experimental Concept

By using a series of non-magnetic plates with increasing or decreasing nucleon number density we can extract a signal from a large fraction of the neutron flux.

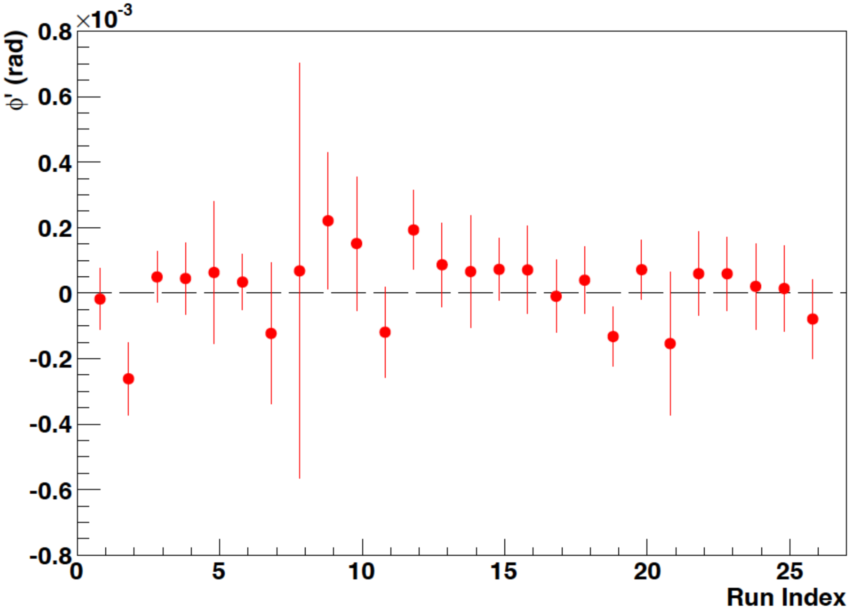


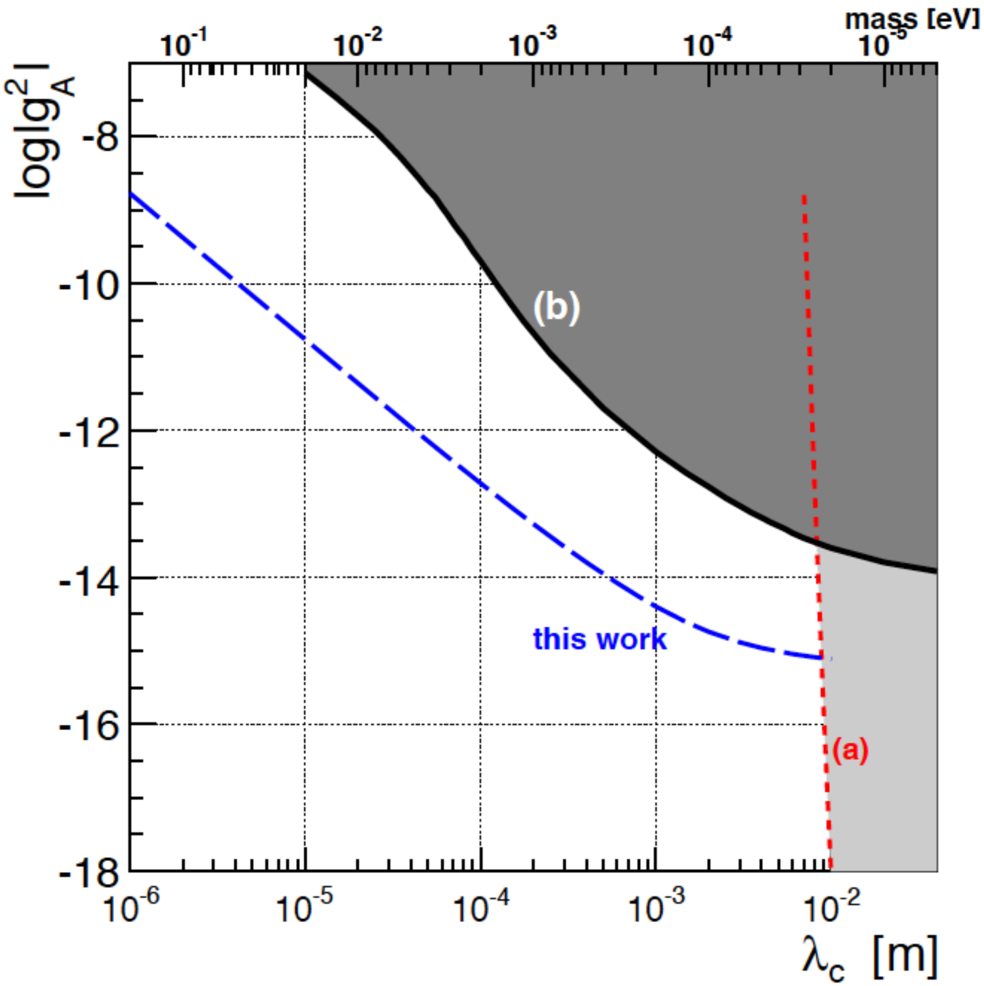


B-field establishes initial neutron spin direction and adiabatically transports neutron spin into target region

Application of a horizontal B-field gradient causes output guide field to rotate by ±90° before reaching the vertical analyzer field.

Results of Axial Coupling Measurement at Los Alamos





2-3 orders of magnitude improvement on $g^2{}_A$ compared to previous work from cm to micron scales

We can improve by another 2-3 orders of magnitude on $g^2{}_A$ at NIST

C. Haddock et al., ***A Search for Possible Long Range Spin Dependent Interactions of the Neutron From Exotic Vector Boson Exchange,*** *Phys. Lett. B* ***783****, 227 (2018).*

NOPTREX Collaboration

Nagoya University

H.M. Shimizu, M. Kitaguchi, K. Hirota, T. Okudaira, A. Okada, K. Nagamoto, M. Yokohashi, T. Yamamoto, I. Itoh, T. Morishama, G. Ichikawa, Y. Kiyanagi

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Univ. British Columbia

T. Momose

Hiroshima University

M. Iinuma

Yamagata University

T. Iwata, Y. Miyachi

RIKEN

N. Yamanaka, Y. Yamagata

KEK

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Kyoto University

M. Hino

Indiana University

J. Curole, J. Doskow, W.M. Snow, J. Vanderwerp

Univ. South Carolina

V. Gudkov

ORNL

J.D. Bowman, P. Jiang, S. Penttila, X. Tong

University of Kentucky

C. Crawford, B. Plaster, D. Schaper

Paul Scherrer Institut

P. Hautle

Southern Illinois University

B.M. Goodson

Ohio University

P. King

Middle Tennessee State University

R. Maruhin

UNAM

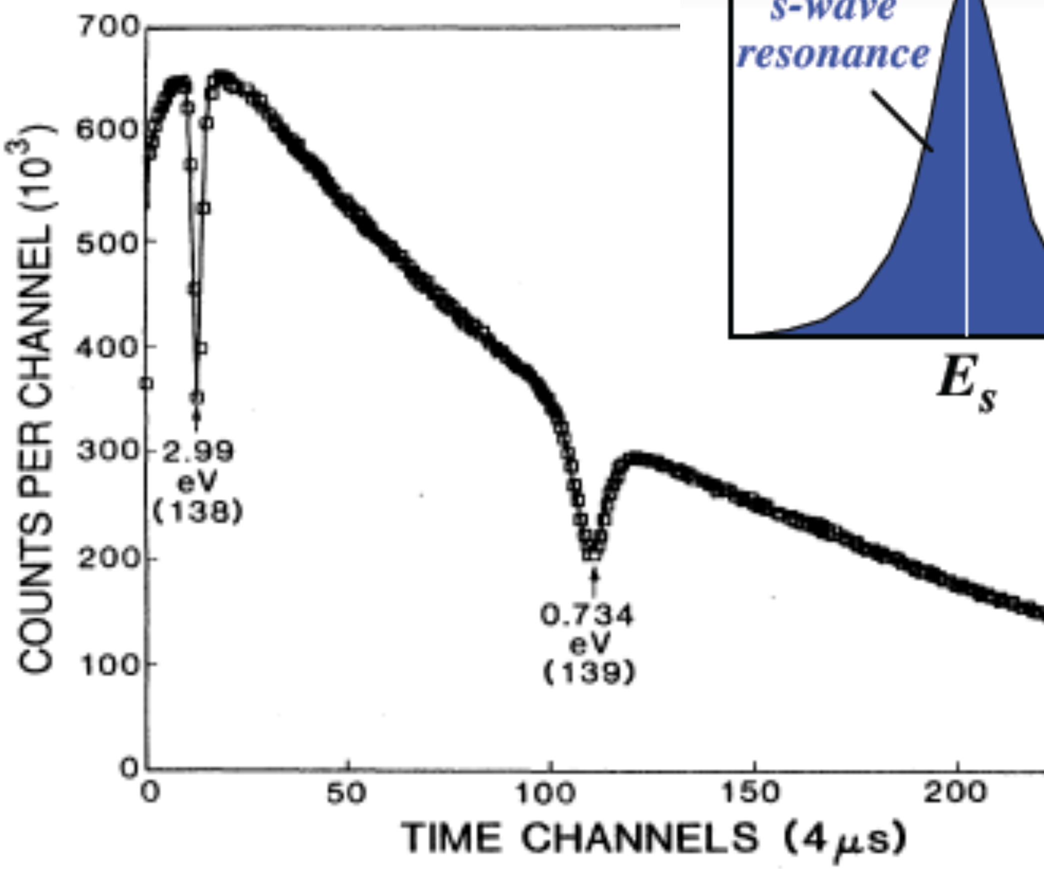
L. Barron-Palos

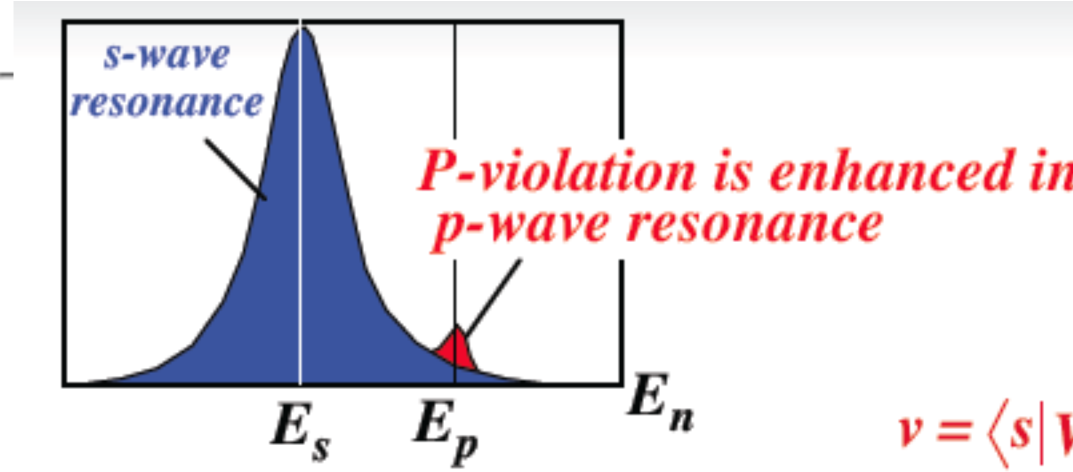
Berea College

M. Veillette

Parity Violation in n+ ^{139}La at 0.734 eV $\Delta\sigma/\sigma = 10\%$

Standard Model P Violation Amplified by ~10^6 !





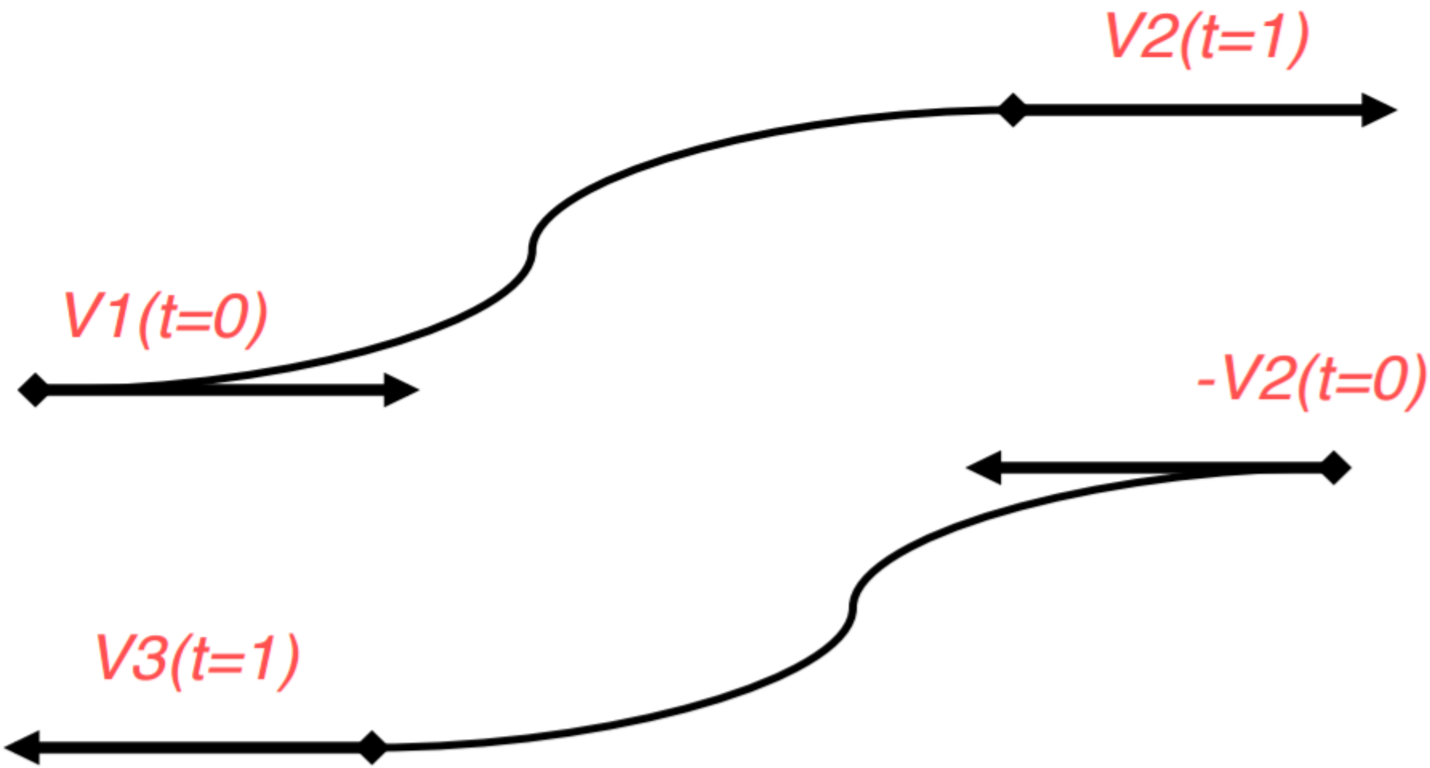
$v = \langle s | W | p \rangle$

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

Idea is to use the observed enhancement of PV to search for a TRIV asymmetry.

“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

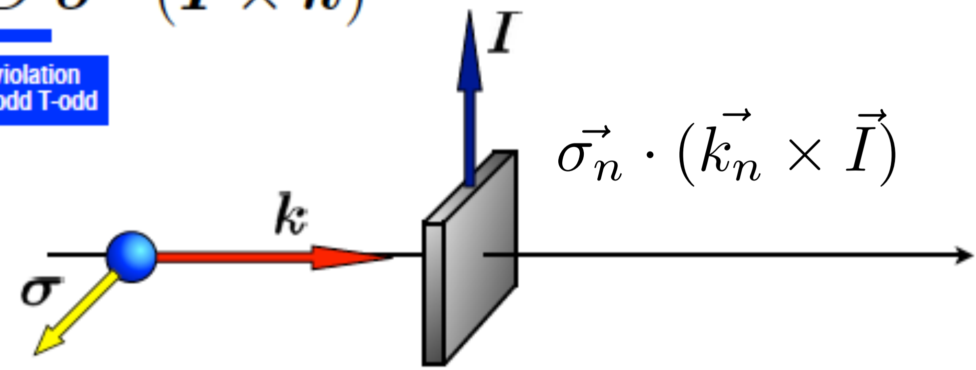
Gotta reverse the spins too

Forward Scattering Ampliltude

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

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

$$\vec{\sigma_n}\cdot(\vec{k_n}\times\vec{I})$$



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

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).

Experimental observable: ratio of P-odd/T-odd to P-odd amplitudes $\lambda_{PT} = \frac{\delta\sigma_{PT}}{\delta\sigma_P}$

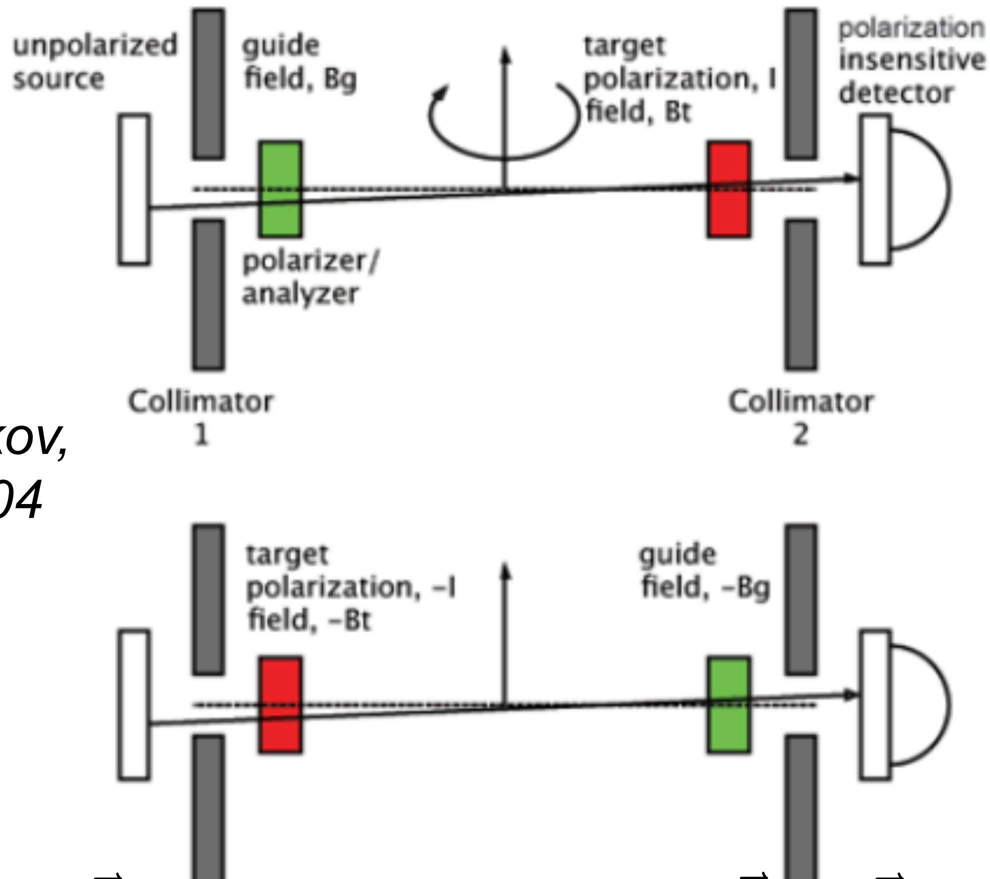
λ can be measured with a statistical uncertainty of ~1 10^{-5} in 10^{7} sec at MW-class spallation neutron sources. Ratio (T-odd amplitude in nucleon/strong amplitude)~10^{-12}. Statistical sensitivity comparable to neutron EDM goals.

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

EDITORS' SUGGESTION Phys. Rev. C (2015)

Search for time reversal invariance violation in neutron transmission

J. David Bowman and Vladimir Gudkov



Bowman/Gudkov, arXiv:1407.7004

NOPTREX Collaboration (Japan/US)

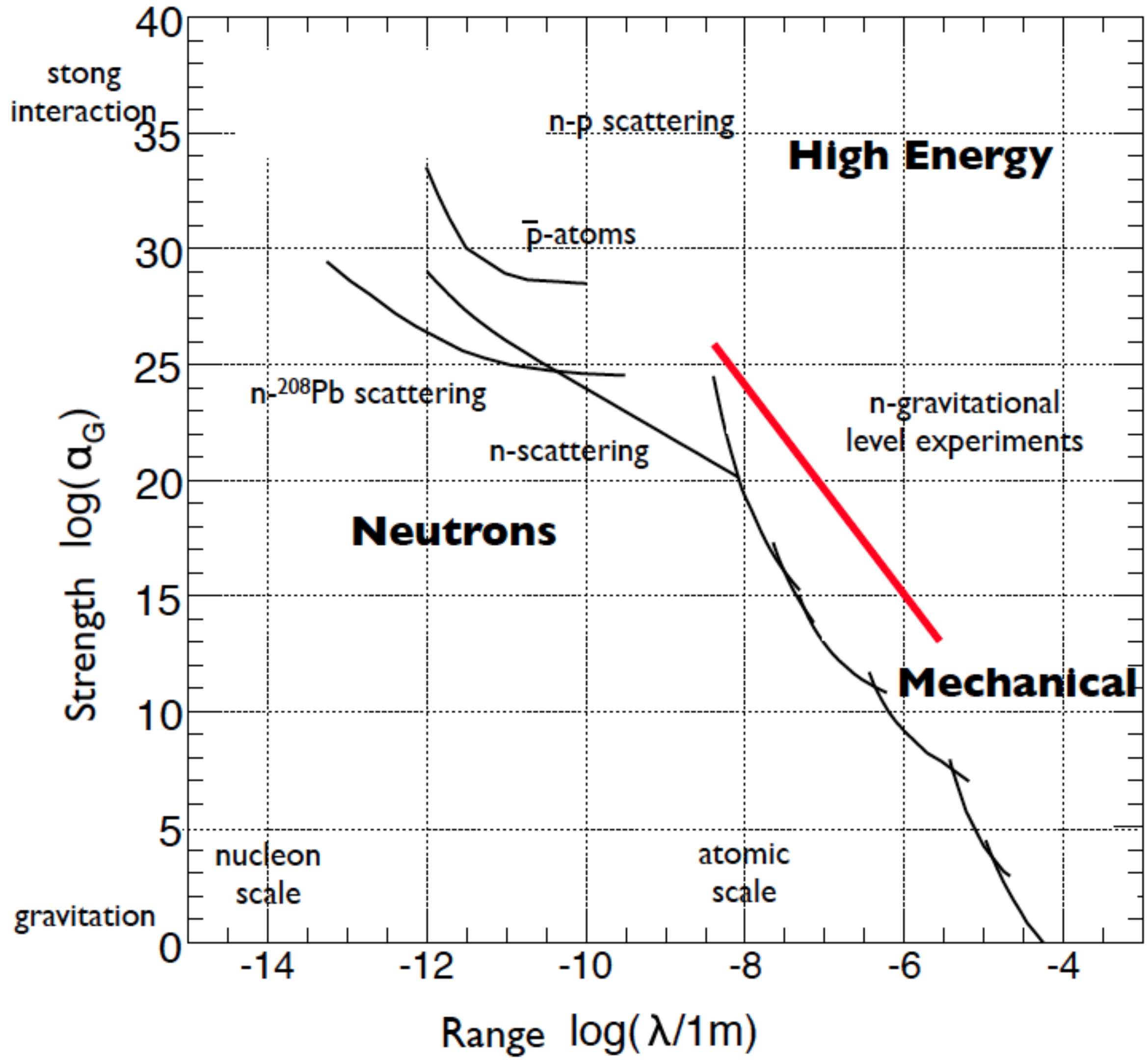
See J. Curole, D. Schaper talks Saturday C6

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

$f_3 << f_1, f_2$

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.

Searches for new Yukawa interactions from mm to nm



$$V(r) = G\frac{m_1 \cdot m_2}{r}(1 + \alpha \cdot e^{-r/\lambda})$$

Neutron measurements are the most sensitive from atomic to subnuclear scales

Neutron-Xenon Gas Scattering Search for Yukawa Interaction at J-PARC Spallation Neutron Source H. M. Shimizu, K. Hirota, M. Kitaguchi, C. Haddock,W. M. Snow, K. Mishima, T. Yoshioka, T. Ino, S. Matsumoto, T. Shima

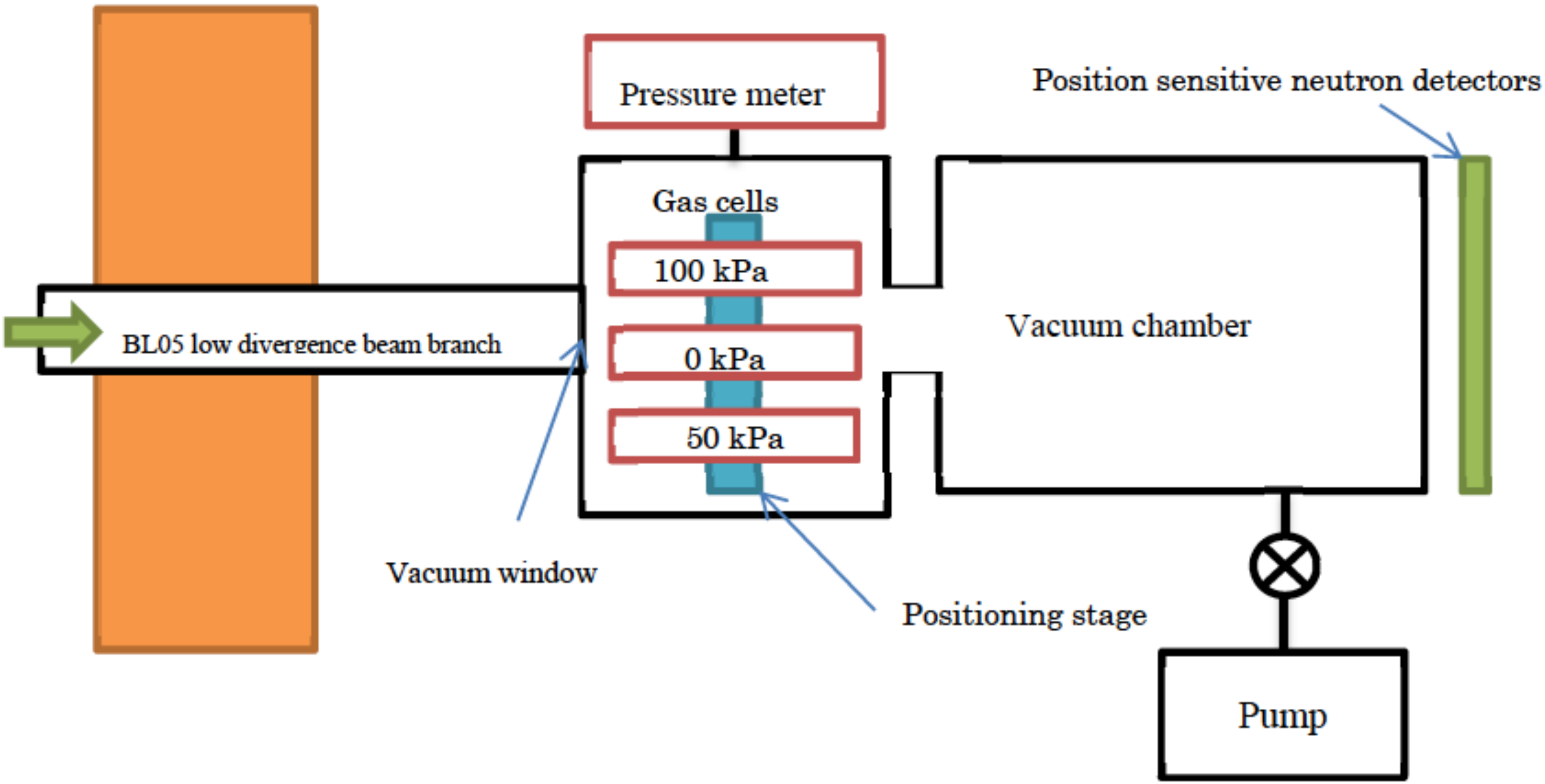
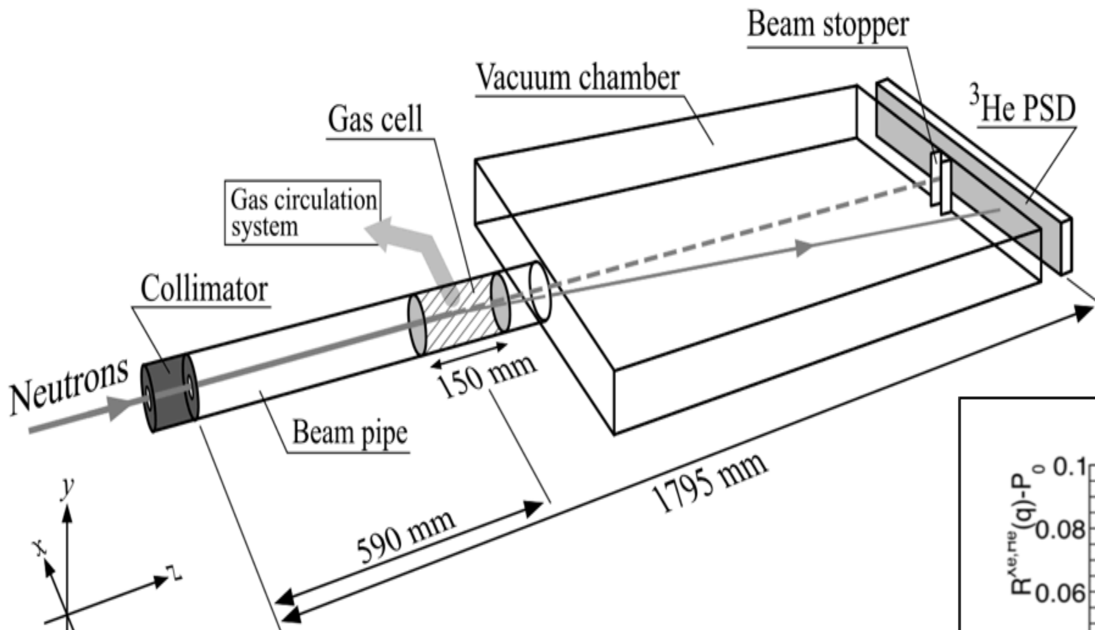


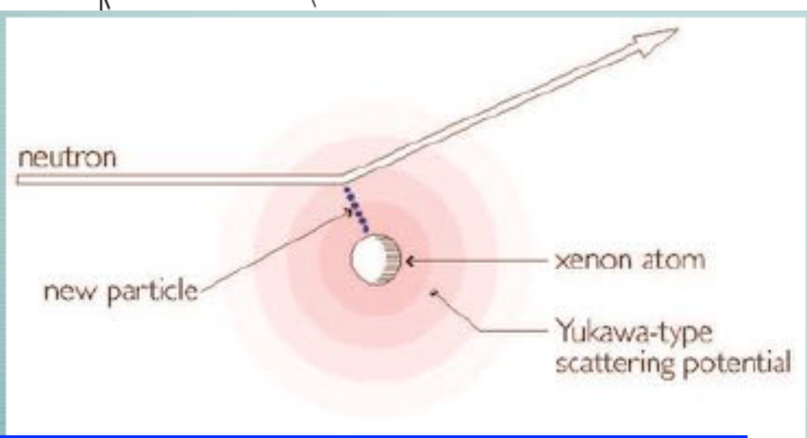
Figure.4. Experimental apparatus.

Uses angular distribution on n-Xe scattering to search for exotic Yukawa interactions at very short ranges at JPARC

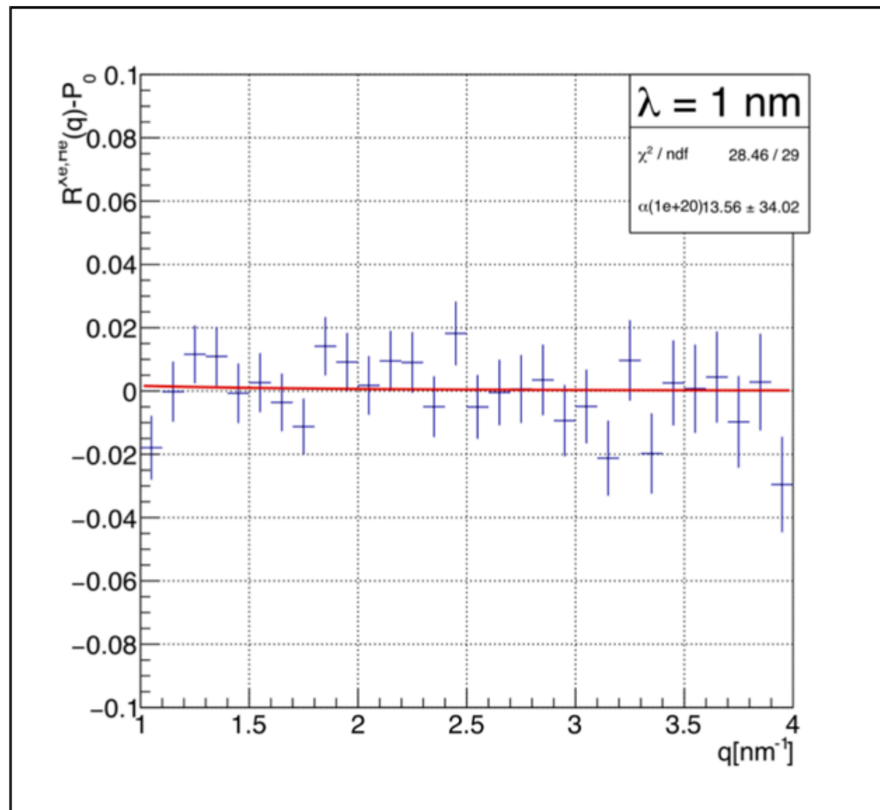
Idea and Experimental Layout



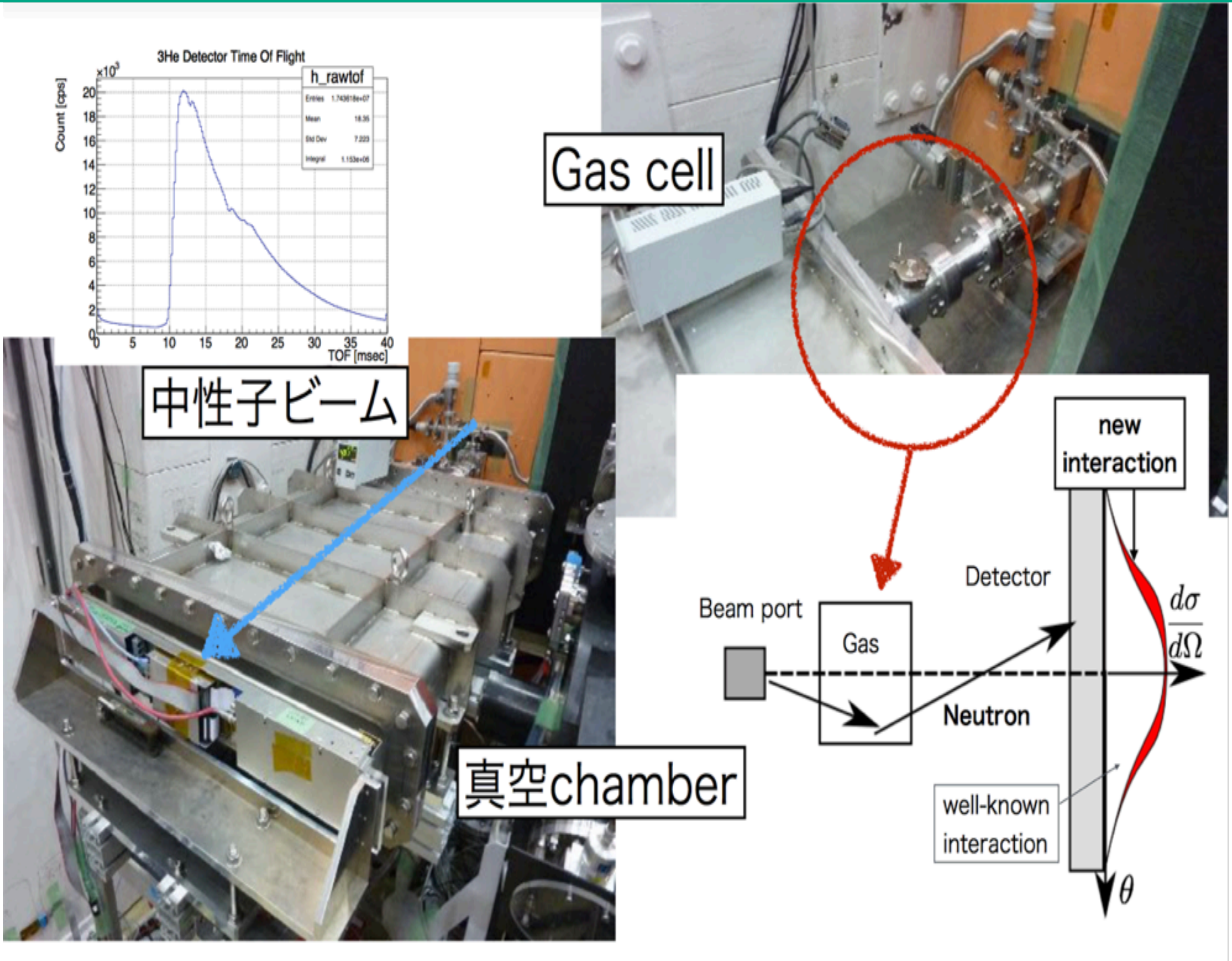
Look at angular distribution of neutron scattering from an ideal gas



$$V(r) = G\frac{m_1 \cdot m_2}{r}(1 + \alpha \cdot e^{-r/\lambda})$$



Setup / devices at BL05 at JPARC

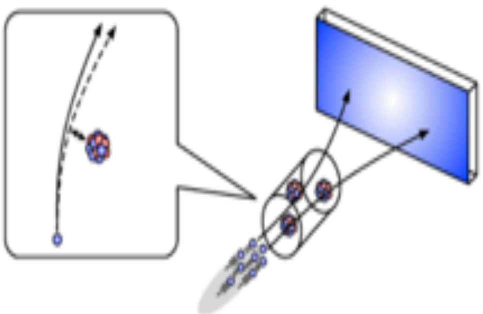


Physics ABOUT BROWSE PRESS COLLECTIONS

Synopsis: Neutron Test for Newton's Gravity

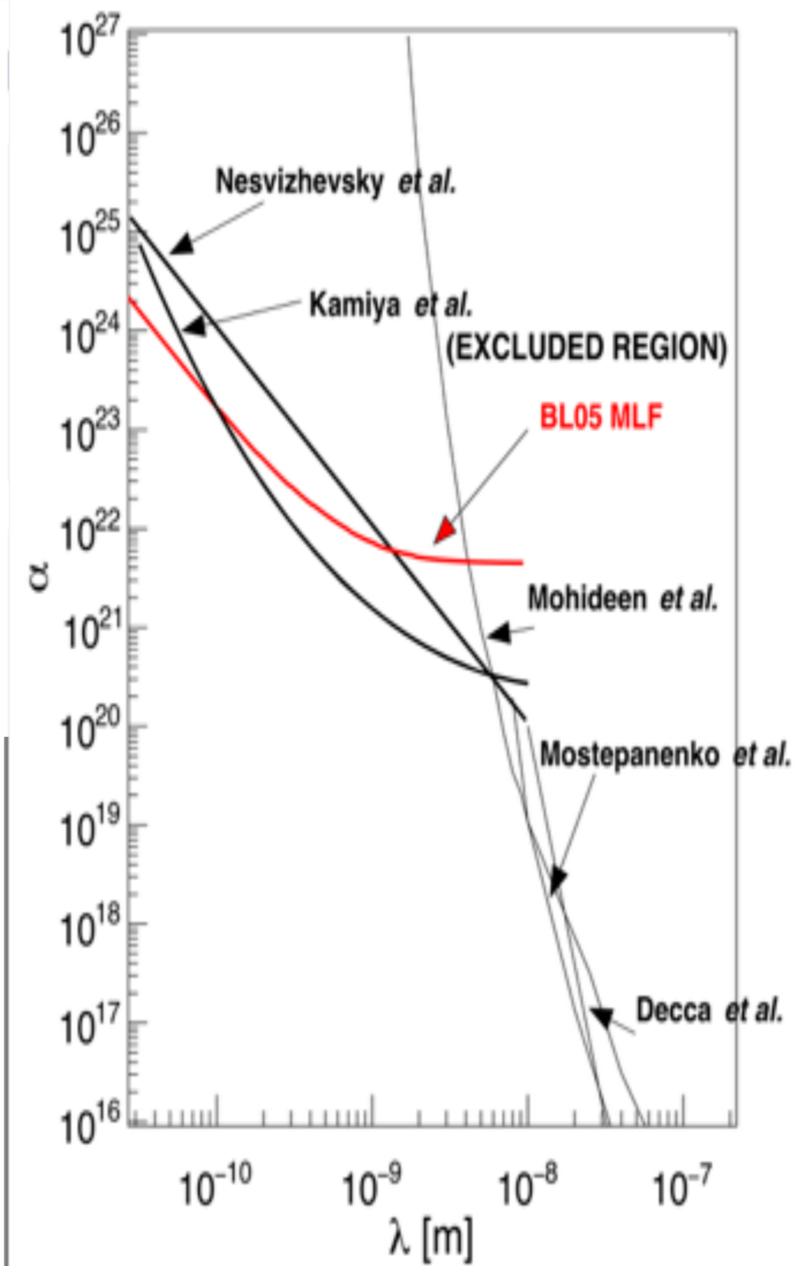
March 22, 2018

Experiments with neutrons search for violations of gravity's inverse square law at subnanometer distances.



M. Kitaguchi/Nagoya University

C. Haddock et al., ***A search for deviations from the inverse square law of gravity at nm range using a pulsed neutron beam,*** *Phys. Rev. D* ***97****, 062002 (2018).*



best neutron limit for at a range of 10^{-11} m

ongoing work will improve it

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 and improved constraints on short-range Yukawas.

Measurements are not yet limited by systematic errors

References for the results presented in this talk

C. Haddock, J. Amadio, E. Anderson, L. Barron-Palos, B. Crawford, C. Crawford, D. Esposito, W. Fox, I. Francis, J. Fry, H. Gardiner, H. E. Swanson, A. Holley, K. Korsak, J. Lieffers, S. Magers, M. Maldonado-Velazquez, D. Mayorov, J. S. Nico, T. Okudaira, C. Paudel, S. Santra, M. Sarsour, H. M. Shimizu, W. M. Snow, A. Sprow, K. Steffen, F. Tovesson, J. Vanderwerp, and P. A. Yergeau, ***A Search for Possible Long Range Spin Dependent Interactions of the Neutron From Exotic Vector Boson Exchange,*** *Phys. Lett. B* ***783****, 227 (2018).*

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R. Lehnert, W. M. Snow, Z. Xiao, and R. Xu, ***Constraining Spacetime Nonmetricity with Neutron Spin Rotation in Liquid ^{4}He****, Phys. Lett. B* ***772****, 865 (2017).*

R. Lehnert, W. M. Snow, and H. Yan, ***A First Experimental Limit on In-matter Torsion from Neutron Spin Rotation in Liquid ^{4}He****, Phys. Lett. B* ***730****, 353 (2014).*

H. Yan, and W. M. Snow, ***A New Limit on Possible Long-Range Parity-odd Interactions of the Neutron from Neutron Spin Rotation in Liquid ^{4}He****, Phys. Rev. Lett.* ***110****, 082003 (2013).*

W. M. Snow, C. D. Bass, T. D. Bass, B. E. Crawford, K. F. Gan, B. R. Heckel, D. Luo, D. M. Markoff, A. M. Micherdzinska, H. P. Mumm, J. S. Nico, A, K. Opper, M. Sarsour, E. I. Sharapov, H. E. Swanson, S. B. Walbridge, and V. Zhumabekova, ***An Upper Bound on Parity Violating Neutron Spin Rotation in ^{4}He,*** *Phys. Rev.* ***C83****, 022501(R) (2011).*

Torsion: A Geometric Property

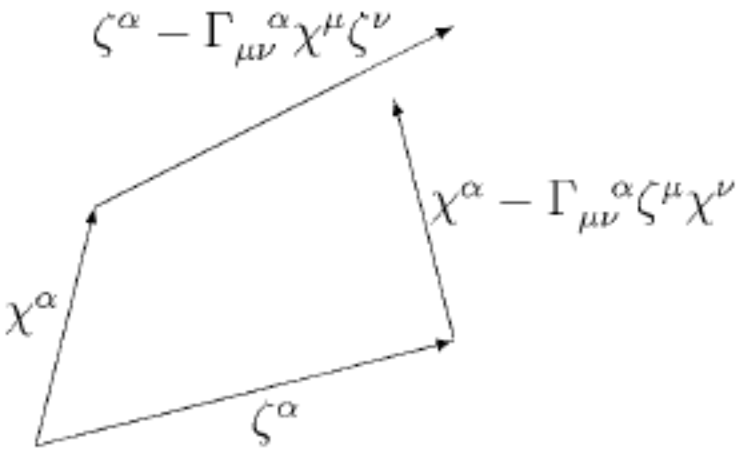


Figure 1. The infinitesimal vector ζ^μ is parallel transported along χ^μ, and vice versa. The non-closure is proportional to the torsion.

Parallel transport one small vector along the direction of another small vector in both orders in a (curved) space according to the connection $\Gamma^\alpha_{\mu\nu}$

If it closes, you can define an area

$$\Delta A^\sigma \equiv 1/2 A^\nu R^\sigma_{\beta\mu\nu} \oint \zeta^\mu dx^\beta$$

and $R^\sigma_{\beta\mu\nu}$ *is the curvature tensor. The difference* $C^\alpha = 2S^\alpha_{\mu\nu}\zeta^\mu\chi^\nu$ *defines the torsion tensor* $S^\alpha_{\mu\nu} \equiv 1/2[\Gamma^\alpha_{\mu\nu} - \Gamma^\alpha_{\nu\mu}]$

In a geometry with zero torsion: the parallelogram closes, and $S^\alpha_{\mu\nu} \equiv 1/2[\Gamma^\alpha_{\mu\nu} - \Gamma^\alpha_{\nu\mu}] = 0$

So far: only geometry, no physics

Torsion: Particle States and Geometries

States of a free point particle are labeled by two independent properties: mass and spin (Wigner, a long time ago)

Geometries with metrics are characterized by two independent quantities: curvature and torsion (Cartan, also a long time ago)

We have a theory, GR, which relates curvature to mass density "Space tells matter how to move, matter tells space how to curve" (Einstein, a really long time ago)

If you like theories which geometrize the physical effects of particle properties, why not relate the spin density to the torsion.

And since this is a fundamental theory, it should use the simplest nonzero spin objects (spin ½) as the torsion source

Torsion: Experimental Constraints from SME Analysis

$$
\begin{aligned}
\mathcal{L}_n = & \tfrac{1}{2} i \overline{\psi} \gamma^\mu \overleftrightarrow{\partial}_\mu \psi - m \overline{\psi} \psi \\
& + [\xi_1^{(4)} T_\mu + \xi_3^{(4)} A_\mu] \overline{\psi} \gamma^\mu \psi \\
& + [\xi_2^{(4)} T_\mu + \xi_4^{(4)} A_\mu] \overline{\psi} \gamma_5 \gamma^\mu \psi \\
& + \tfrac{1}{2} i [\xi_1^{(5)} T^\mu + \xi_3^{(5)} A^\mu] \overline{\psi} \overleftrightarrow{\partial}_\mu \psi \\
& + \tfrac{1}{2} [\xi_2^{(5)} T^\mu + \xi_4^{(5)} A^\mu] \overline{\psi} \gamma_5 \overleftrightarrow{\partial}_\mu \psi \\
& + \tfrac{1}{2} i [\xi_6^{(5)} T_\mu + \xi_7^{(5)} A_\mu] \overline{\psi} \sigma^{\mu\nu} \overleftrightarrow{\partial}_\nu \psi \\
& + \tfrac{1}{2} i \epsilon^{\kappa\lambda\mu\nu} [\xi_8^{(5)} T_\kappa + \xi_9^{(5)} A_\kappa] \overline{\psi} \sigma_{\lambda\mu} \overleftrightarrow{\partial}_\nu \psi \, .
\end{aligned}
$$

Lagrangian of a fermion coupled to vector fields involving the torsion tensor

$$T_\mu \equiv g^{\alpha\beta} T_{\alpha\beta\mu} \qquad A^\mu \equiv \tfrac{1}{6} \epsilon^{\alpha\beta\gamma\mu} T_{\alpha\beta\gamma}$$

Idea: treat torsion as a long-range background field, then apply existing SME constraints. Works to tightly constrain 19/24 torsion components

TABLE I: Examples of recently obtained sensitivity levels for torsion searches. Note that all these searches assume that torsion extends outside the matter sourcing it.

Source	Probe	Sensitivity (GeV)	Refs.
cosmological	Xe/He maser	$10^{-27} - 10^{-31}$	[4, 5]
cosmological	Torsion pendulum	$10^{-29} - 10^{-31}$	[4, 6]
Sun	Xe/He maser	10^{-31}	[4, 5]
Sun	Torsion pendulum	$10^{-29} - 10^{-31}$	[4, 6]
Earth	Torsion pendulum	10^{-29}	[4, 6]

[4] V.A. Kostelecký, N. Russell, and J.D. Tasson, Phys. Rev. Lett. **100**, 111102 (2008).
[5] F. Canè *et al.*, Phys. Rev. Lett. **93**, 230801 (2004).
[6] B.R. Heckel *et al.*, Phys. Rev. Lett. **97**, 021603 (2006); B.R. Heckel *et al.*, Phys. Rev. D **78**, 092006 (2008);

Parity-odd Torsion in Matter: Constraints from neutrons

$$\begin{aligned}\mathcal{L}_n &= \tfrac{1}{2} i \overline{\psi} \gamma^\mu \overleftrightarrow{\partial}_\mu \psi - m\overline{\psi}\psi \\ &+ [\xi_1^{(4)} T_\mu + \xi_3^{(4)} A_\mu] \overline{\psi}\gamma^\mu\psi \\ &+ [\xi_2^{(4)} T_\mu + \xi_4^{(4)} A_\mu] \overline{\psi}\gamma_5\gamma^\mu\psi \\ &+ \tfrac{1}{2} i [\xi_1^{(5)} T^\mu + \xi_3^{(5)} A^\mu] \overline{\psi} \overleftrightarrow{\partial}_\mu \psi \\ &+ \tfrac{1}{2} [\xi_2^{(5)} T^\mu + \xi_4^{(5)} A^\mu] \overline{\psi}\gamma_5 \overleftrightarrow{\partial}_\mu \psi \\ &+ \tfrac{1}{2} i [\xi_6^{(5)} T_\mu + \xi_7^{(5)} A_\mu] \overline{\psi}\sigma^{\mu\nu} \overleftrightarrow{\partial}_\nu \psi \\ &+ \tfrac{1}{2} i \epsilon^{\kappa\lambda\mu\nu} [\xi_8^{(5)} T_\kappa + \xi_9^{(5)} A_\kappa] \overline{\psi}\sigma_{\lambda\mu} \overleftrightarrow{\partial}_\nu \psi .\end{aligned}$$

Lagrangian of a fermion coupled to vector fields involving the isotopic parts of the torsion tensor

$$T_\mu \equiv g^{\alpha\beta} T_{\alpha\beta\mu} \qquad A^\mu \equiv \tfrac{1}{6} \epsilon^{\alpha\beta\gamma\mu} T_{\alpha\beta\gamma}$$

After taking the nonrelativistic limit (-> only time components important), and noting that ^{4}He will only generate isotopic torsion fields

$$H = \frac{\vec{p}^2}{2m} + \delta\vec{b}\cdot\vec{\sigma}$$

$$\delta\vec{b} = +[\vec{M} - \vec{\zeta}] + [\zeta_0 \hat{p} + \vec{M}_-]\frac{p}{m}$$

$$\zeta^\mu \equiv [2m\xi_8^{(5)} - \xi_2^{(4)}] T^\mu + [2m\xi_9^{(5)} - \xi_4^{(4)}] A^\mu$$

Picking out the parity-odd term, the interaction term with the neutron spin is

$$(\zeta/m)\,\vec{\sigma}\cdot\vec{p}.$$

Whose form is the same as before, so it also rotates the neutron plane of polarization

$$\frac{d\phi_{P-odd}}{dL} = 2\zeta$$

Our limit: $|\zeta| \leq 9\times 10^{-23}\, eV$

R. Lehnert, H. Yan, W. M. Snow, Phys. Lett ***B730****, 353 (2014),* ***B744****, 415 (2015), arXiv:1311.0467*

Nonmetricity: Another Possible Affine Connection Component

As known from differential geometry (see, e.g., [25, 33]), generic affine connection can be decomposed into three parts,

$$\Gamma^{\lambda}{}_{\mu\nu} = \{{}^{\lambda}{}_{\mu\nu}\} + K^{\lambda}{}_{\mu\nu} + L^{\lambda}{}_{\mu\nu} \,, \tag{2}$$

viz., the Levi-Civita connection of the metric $g_{\mu\nu}$,

$$\{{}^{\lambda}{}_{\mu\nu}\} \equiv \frac{1}{2} g^{\lambda\beta} \left(\partial_\mu g_{\beta\nu} + \partial_\nu g_{\beta\mu} - \partial_\beta g_{\mu\nu} \right) \,, \tag{3}$$

contortion

$$K^{\lambda}{}_{\mu\nu} \equiv \frac{1}{2} g^{\lambda\beta} \left(T_{\mu\beta\nu} + T_{\nu\beta\mu} + T_{\beta\mu\nu} \right) = -K_{\nu\mu}{}^{\lambda} \,, \tag{4}$$

and disformation

$$L^{\lambda}{}_{\mu\nu} \equiv \frac{1}{2} g^{\lambda\beta} \left(-Q_{\mu\beta\nu} - Q_{\nu\beta\mu} + Q_{\beta\mu\nu} \right) = L^{\lambda}{}_{\nu\mu} \,. \tag{5}$$

The last two quantities are defined via torsion

$$T^{\lambda}{}_{\mu\nu} \equiv \Gamma^{\lambda}{}_{\mu\nu} - \Gamma^{\lambda}{}_{\nu\mu} \tag{6}$$

and nonmetricity

$$Q_{\rho\mu\nu} \equiv \nabla_\rho g_{\mu\nu} = \partial_\rho g_{\mu\nu} - \Gamma^{\beta}{}_{\rho\mu} g_{\beta\nu} - \Gamma^{\beta}{}_{\rho\nu} g_{\mu\beta} \,. \tag{7}$$

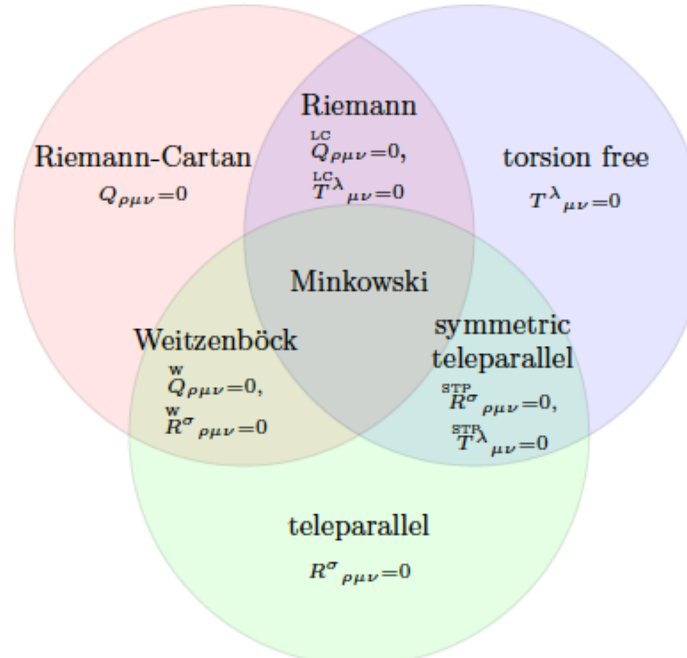


FIG. 1. Subclasses of metric-affine geometry, depending on the properties of connection.

Nonmetricity formulation of general relativity and its scalar-tensor extension

Laur Järv, Mihkel Rünkla, Margus Saal, and Ott Vilson
Phys. Rev. D 97, 124025 (2018)

Nonmetricity: Constraints from SME analysis

$$\mathcal{L}_N^{(4)} = \zeta_1^{(4)} (N_1)_\mu \overline{\psi}\gamma^\mu\psi + \zeta_2^{(4)} (N_1)_\mu \overline{\psi}\gamma_5\gamma^\mu\psi + \zeta_3^{(4)} (N_2)_\mu \overline{\psi}\gamma^\mu\psi + \zeta_4^{(4)} (N_2)_\mu \overline{\psi}\gamma_5\gamma^\mu\psi\,,$$

$$\begin{aligned}\mathcal{L}_N^{(5)} = & -\tfrac{1}{2}i\zeta_1^{(5)} (N_1)^\mu \overline{\psi}\overleftrightarrow{\partial}_\mu\psi - \tfrac{1}{2}\zeta_2^{(5)} (N_1)^\mu \overline{\psi}\gamma_5\overleftrightarrow{\partial}_\mu\psi \\ & -\tfrac{1}{2}i\zeta_3^{(5)} (N_2)^\mu \overline{\psi}\overleftrightarrow{\partial}_\mu\psi - \tfrac{1}{2}\zeta_4^{(5)} (N_2)^\mu \overline{\psi}\gamma_5\overleftrightarrow{\partial}_\mu\psi \\ & -\tfrac{1}{4}i\zeta_5^{(5)} M_{\mu\nu}{}^{\rho} \overline{\psi}\sigma^{\mu\nu}\overleftrightarrow{\partial}_\rho\psi \\ & +\tfrac{1}{8}i\zeta_6^{(5)} \epsilon_{\kappa\lambda\mu\nu} M^{\kappa\lambda\rho} \overline{\psi}\sigma^{\mu\nu}\overleftrightarrow{\partial}_\rho\psi \\ & +\tfrac{1}{2}i\zeta_7^{(5)} (N_1)_\mu \overline{\psi}\sigma^{\mu\nu}\overleftrightarrow{\partial}_\nu\psi + \tfrac{1}{2}i\zeta_8^{(5)} (N_2)_\mu \overline{\psi}\sigma^{\mu\nu}\overleftrightarrow{\partial}_\nu\psi \\ & -\tfrac{1}{4}i\zeta_9^{(5)} \epsilon^{\lambda\mu\nu\rho}(N_1)_\lambda \overline{\psi}\sigma_{\mu\nu}\overleftrightarrow{\partial}_\rho\psi \\ & -\tfrac{1}{4}i\zeta_{10}^{(5)} \epsilon^{\lambda\mu\nu\rho}(N_2)_\lambda \overline{\psi}\sigma_{\mu\nu}\overleftrightarrow{\partial}_\rho\psi\,,\end{aligned}$$

$$\begin{aligned}\mathcal{L}_N^{(6)} \supset & -\tfrac{1}{4}\zeta_1^{(6)} S_\lambda{}^{\mu\nu} \overline{\psi}\gamma^\lambda\partial_\mu\partial_\nu\psi + \text{h.c.} \\ & -\tfrac{1}{4}\zeta_2^{(6)} S_\lambda{}^{\mu\nu} \overline{\psi}\gamma_5\gamma^\lambda\partial_\mu\partial_\nu\psi + \text{h.c.}\end{aligned}$$

"normal" gravity
~10^{-27} GeV^{-1}

34 of the 40 independent nonmetricity components constrained for the first time

Lagrangian of a fermion coupled to fields involving the nonmetricity tensor

$$\begin{aligned}N_{\mu\alpha\beta} = & \tfrac{1}{18}(5N_{1\mu}g_{\alpha\beta} - N_{1\alpha}g_{\beta\mu} - N_{1\beta}g_{\mu\alpha} \\ & -2N_{2\mu}g_{\alpha\beta} + 4N_{2\alpha}g_{\beta\mu} + 4N_{2\beta}g_{\mu\alpha}) \\ & +S_{\mu\alpha\beta} + M_{\mu\alpha\beta},\end{aligned}$$

J. Foster, A. Kostelecky, R. Xu
Phys. Rev. D 95, 084033 (2017)

TABLE I. Laboratory constraints on nonmetricity.

Quantity	Constraint	Quantity	Constraint
$\zeta_2^{(4)}N_{1T}$	10^{-27} GeV	$\zeta_9^{(5)}N_{1T}$	10^{-27}
$\zeta_2^{(4)}N_{1X}$	10^{-33} GeV	$\zeta_9^{(5)}N_{1X}$	10^{-33}
$\zeta_2^{(4)}N_{1Y}$	10^{-33} GeV	$\zeta_9^{(5)}N_{1Y}$	10^{-33}
$\zeta_2^{(4)}N_{1Z}$	10^{-29} GeV	$\zeta_9^{(5)}N_{1Z}$	10^{-29}
$\zeta_4^{(4)}N_{2T}$	10^{-27} GeV	$\zeta_{10}^{(5)}N_{2T}$	10^{-27}
$\zeta_4^{(4)}N_{2X}$	10^{-33} GeV	$\zeta_{10}^{(5)}N_{2X}$	10^{-33}
$\zeta_4^{(4)}N_{2Y}$	10^{-33} GeV	$\zeta_{10}^{(5)}N_{2Y}$	10^{-33}
$\zeta_4^{(4)}N_{2Z}$	10^{-29} GeV	$\zeta_{10}^{(5)}N_{2Z}$	10^{-29}
$\zeta_5^{(5)}M_{TXX}$		$\zeta_6^{(5)}M_{TXX}$	10^{-26}
$\zeta_5^{(5)}M_{TXY}$	10^{-29}	$\zeta_6^{(5)}M_{TXY}$	10^{-27}
$\zeta_5^{(5)}M_{TYY}$		$\zeta_6^{(5)}M_{TYY}$	10^{-27}
$\zeta_5^{(5)}M_{TYZ}$	10^{-33}	$\zeta_6^{(5)}M_{TYZ}$	10^{-27}
$\zeta_5^{(5)}M_{TZX}$	10^{-33}	$\zeta_6^{(5)}M_{TZX}$	10^{-27}
$\zeta_5^{(5)}M_{XTT}$	10^{-27}	$\zeta_6^{(5)}M_{XTT}$	10^{-33}
$\zeta_5^{(5)}M_{XTY}$	10^{-29}	$\zeta_6^{(5)}M_{XTY}$	10^{-27}
$\zeta_5^{(5)}M_{XYY}$	10^{-27}	$\zeta_6^{(5)}M_{XYY}$	
$\zeta_5^{(5)}M_{XYZ}$	10^{-26}	$\zeta_6^{(5)}M_{XYZ}$	
$\zeta_5^{(5)}M_{YTT}$		$\zeta_6^{(5)}M_{YTT}$	10^{-33}
$\zeta_5^{(5)}M_{YXX}$	10^{-26}	$\zeta_6^{(5)}M_{YXX}$	
$\zeta_5^{(5)}M_{ZTT}$	10^{-26}	$\zeta_6^{(5)}M_{ZTT}$	10^{-29}
$\zeta_5^{(5)}M_{ZTX}$	10^{-33}	$\zeta_6^{(5)}M_{ZTX}$	10^{-27}
$\zeta_5^{(5)}M_{ZTY}$	10^{-33}	$\zeta_6^{(5)}M_{ZTY}$	10^{-27}
$\zeta_5^{(5)}M_{ZXX}$	10^{-26}	$\zeta_6^{(5)}M_{ZXX}$	
$\zeta_5^{(5)}M_{ZXY}$	10^{-27}	$\zeta_6^{(5)}M_{ZXY}$	
$\zeta_1^{(6)}S_{TTT}$	10^{-34} GeV^{-1}	$\zeta_2^{(6)}S_{TTT}$	
$\zeta_1^{(6)}S_{TTX}$		$\zeta_2^{(6)}S_{TTX}$	10^{-26} GeV^{-1}
$\zeta_1^{(6)}S_{TTY}$		$\zeta_2^{(6)}S_{TTY}$	10^{-26} GeV^{-1}
$\zeta_1^{(6)}S_{TTZ}$		$\zeta_2^{(6)}S_{TTZ}$	10^{-26} GeV^{-1}
$\zeta_1^{(6)}S_{XXX}$		$\zeta_2^{(6)}S_{XXX}$	10^{-23} GeV^{-1}
$\zeta_1^{(6)}S_{XXY}$		$\zeta_2^{(6)}S_{XXY}$	10^{-23} GeV^{-1}
$\zeta_1^{(6)}S_{XXZ}$		$\zeta_2^{(6)}S_{XXZ}$	10^{-23} GeV^{-1}
$\zeta_1^{(6)}S_{XYY}$		$\zeta_2^{(6)}S_{XYY}$	10^{-23} GeV^{-1}
$\zeta_1^{(6)}S_{YYY}$		$\zeta_2^{(6)}S_{YYY}$	10^{-23} GeV^{-1}
$\zeta_1^{(6)}S_{YYZ}$		$\zeta_2^{(6)}S_{YYZ}$	10^{-23} GeV^{-1}

Parity-odd Nonmetricity in Matter: Constraints from neutrons

Assume that matter sources nonmetricity. Take the nonrelativistic limit and note that ^{4}He would only generate isotopic nonmetricity components. This gives a low energy effective Hamiltonian whose spin-dependent term is:

$$\delta h_s = \left[\left(\zeta_2^{(4)} - m\,\zeta_9^{(5)}\right)(N_1)_j + \left(\zeta_4^{(4)} - m\,\zeta_{10}^{(5)}\right)(N_2)_j\right]\sigma^j$$
$$+\left[\left(\zeta_2^{(4)} - m\,\zeta_9^{(5)}\right)(N_1)_0 + \left(\zeta_4^{(4)} - m\,\zeta_{10}^{(5)}\right)(N_2)_0\right]\frac{\vec{p}\cdot\vec{\sigma}}{m}$$
$$+\tfrac{1}{2}\left[\zeta_5^{(5)}\tilde{M}_{j\alpha\beta} + \tfrac{3}{2}\,\zeta_6^{(5)}M_{j\alpha\beta} + m\,\zeta_2^{(6)}S_{j\alpha\beta}\right]\frac{p^\alpha p^\beta \sigma^j}{m}$$
$$+\tfrac{1}{2}\zeta_2^{(6)}S_{0\alpha\beta}\,\frac{p^\alpha p^\beta\,\vec{p}\cdot\vec{\sigma}}{m}\,.$$

The parity-odd term rotates the neutron plane of polarization by an amount

$$\frac{d\phi_{PV}}{dL} = 2\left(\zeta_2^{(4)} - m\,\zeta_9^{(5)}\right)(N_1)_0 + 2\left(\zeta_4^{(4)} - m\,\zeta_{10}^{(5)}\right)(N_2)_0$$
$$+m^2\zeta_2^{(6)}S_{000}\,,$$

Our limits on in-matter nonmetricity.
First limit on $\zeta_2^{(6)}S_{000}$

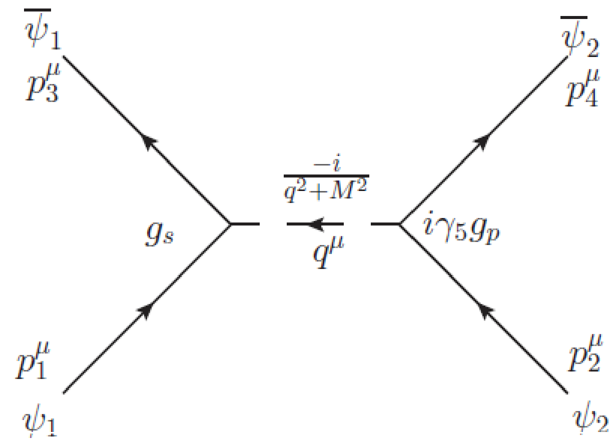
$$|\zeta_2^{(4)}(N_1)_0| < 10^{-22}\,\mathrm{GeV}\,, \qquad |\zeta_4^{(4)}(N_2)_0| < 10^{-22}\,\mathrm{GeV}$$
$$|\zeta_9^{(5)}(N_1)_0| < 10^{-22}\,, \qquad |\zeta_{10}^{(5)}(N_2)_0| < 10^{-22}\,,$$
$$|\zeta_2^{(6)}S_{000}| < 10^{-22}\,\mathrm{GeV}^{-1}\,.$$

R. Lehnert, W. M. Snow, Z. Xiao, and R. Xu. Phys. Lett **B772**, 865 (2017)

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 (1

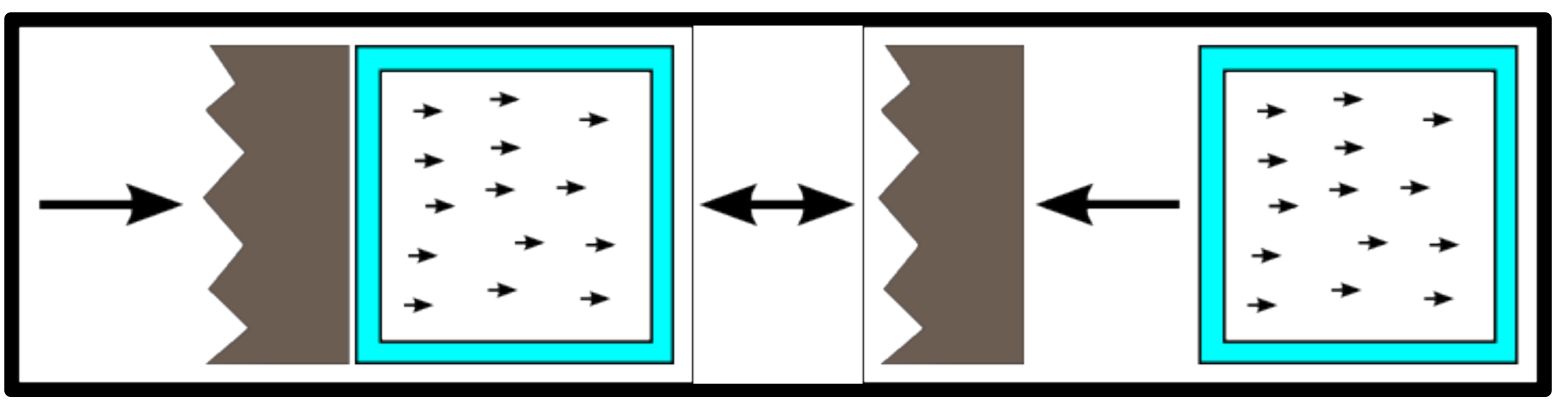
Induces an interaction between polarized and unpolarized matter

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

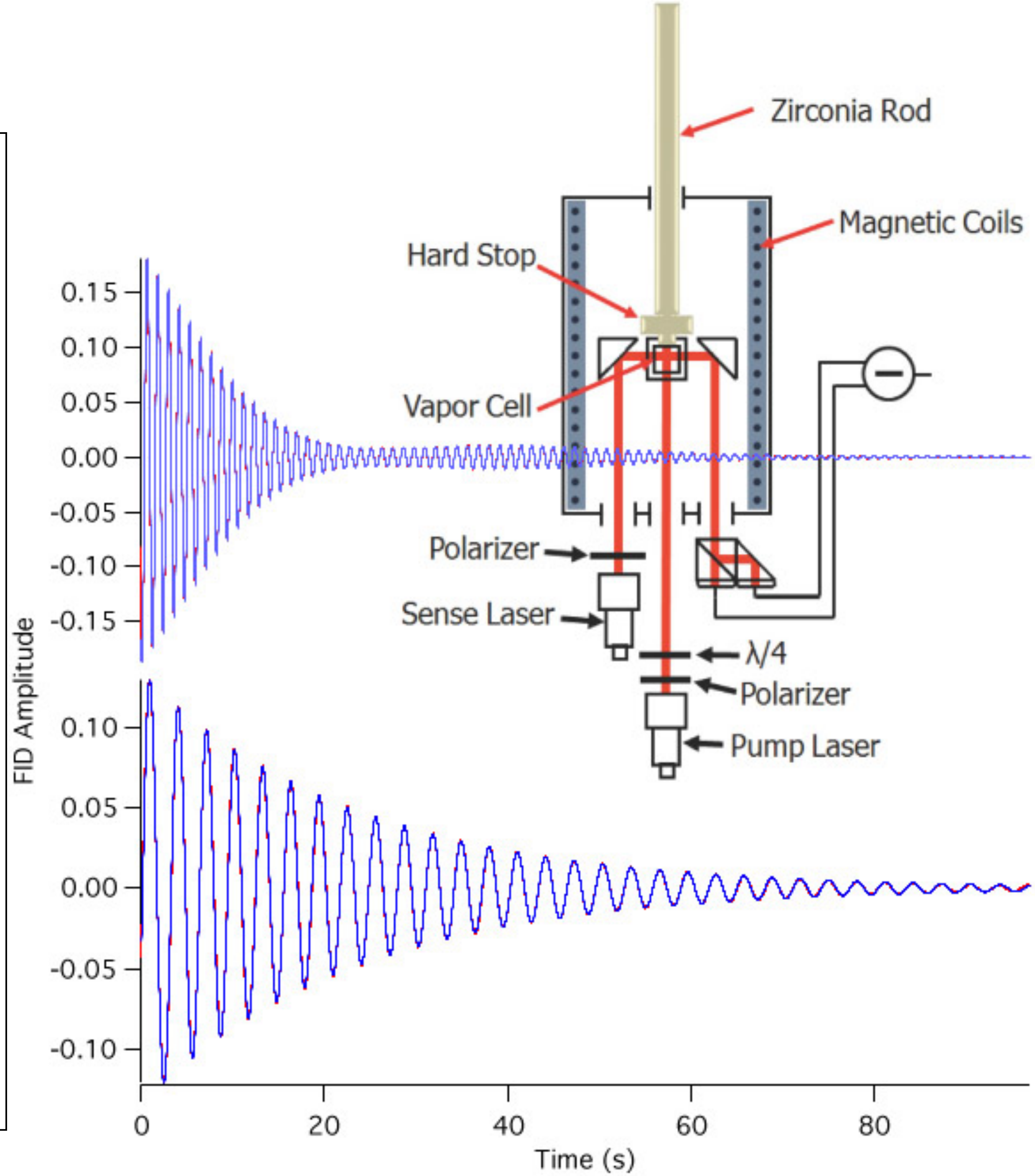
PHYS. REV. LETT. 111, 102001 (2013)

Experimental Setup

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

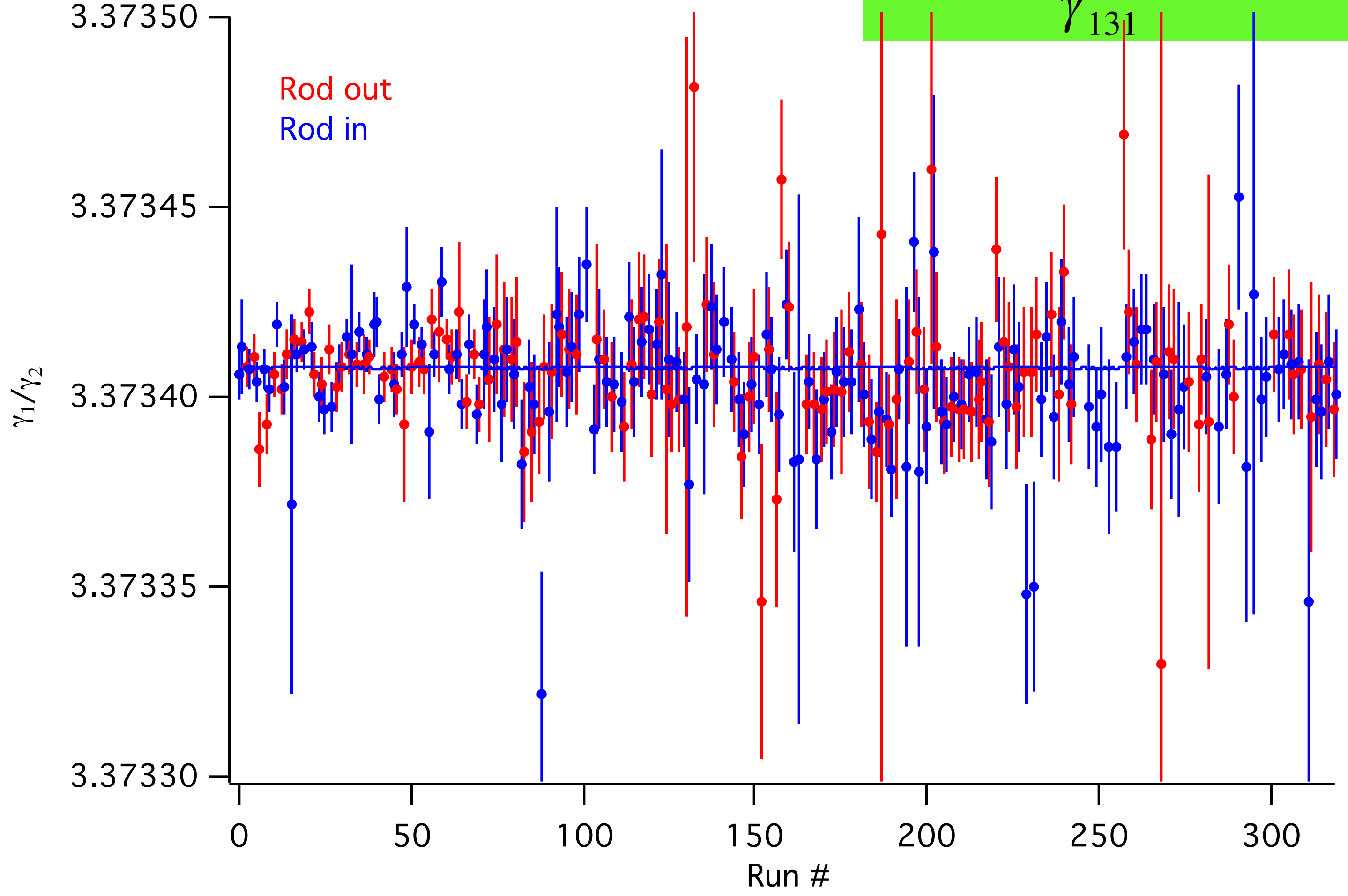
The Rb magnetometer measures the Free Induction Decay (FID) of the two xenon isotopes as an amplitude modulation of the Rb spin projection.

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



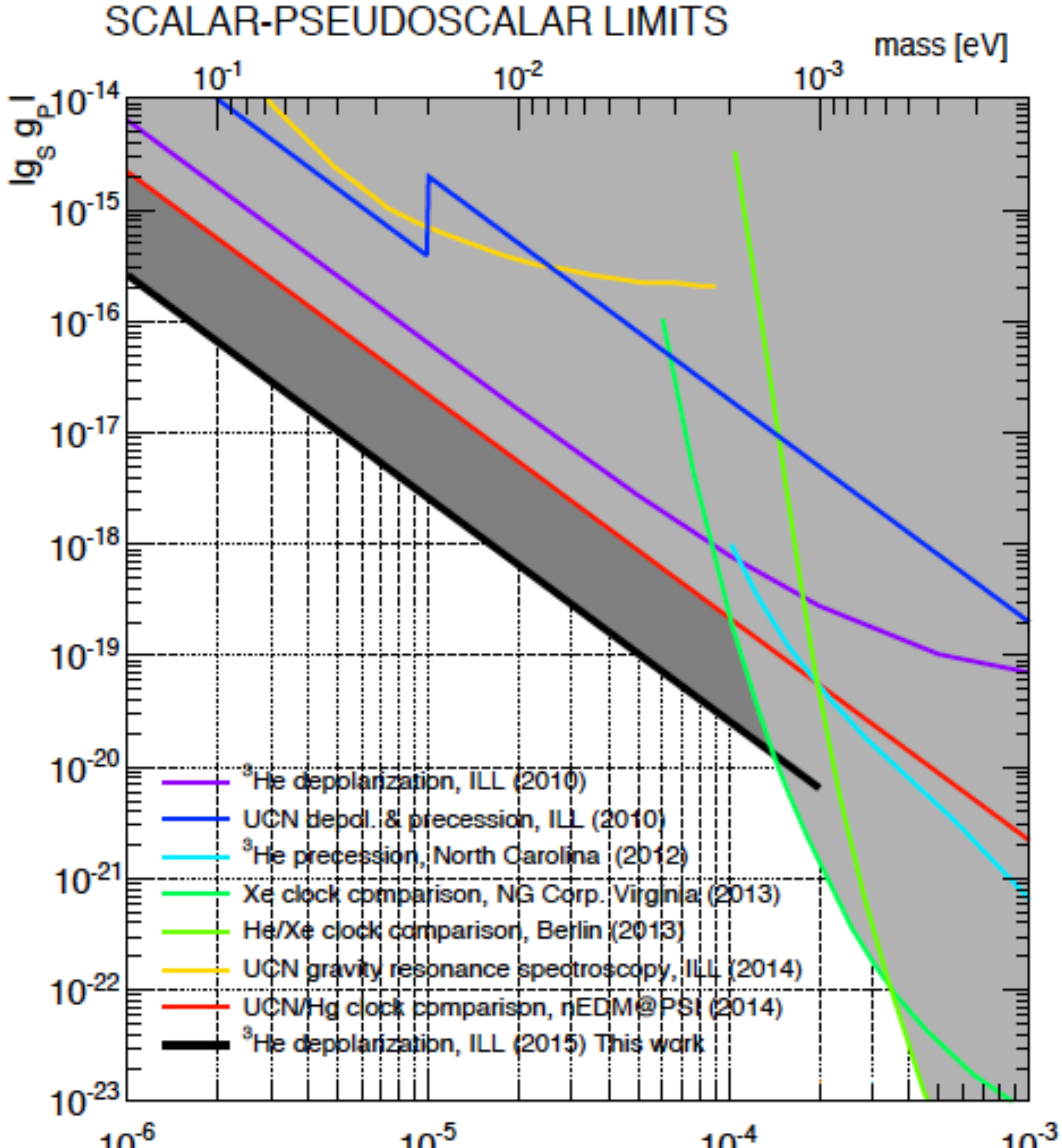
Results from Northrop/Grumman

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



Frequency shift zero at 2E-5 Hz level in ~3-day experiment on their "test" apparatus

Constraints on Monopole-Dipole Interactions of Polarized Nucleons

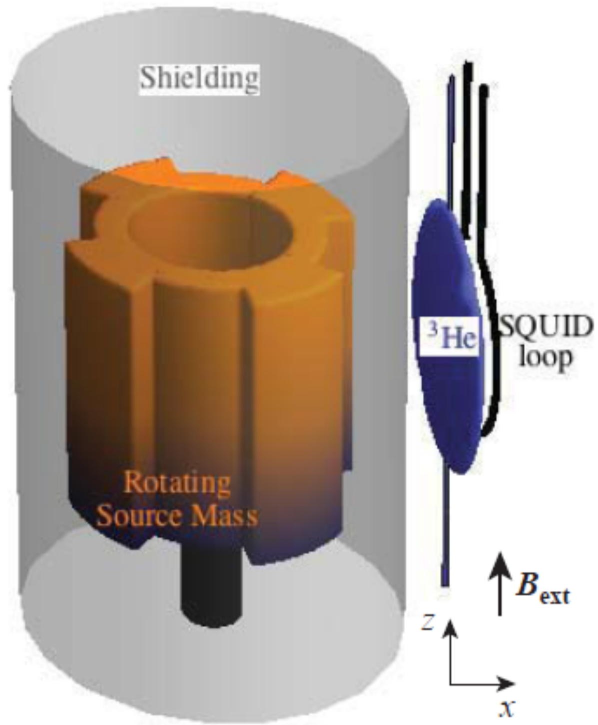


From: M. Guigue et al, PRD 92, 114001 (2015)

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

Most experiments use Polarized noble gases!

The Axion Resonant InterAction DetectioN Experiment (ARIADNE)



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

ARIADNE Collaboration:

Asimina Arvanitaki *(Perim*
Aharon Kapitulnik *(Stanf*
Eli Levenson-Falk (Stanfor
Josh Long *(Indiana)*
Chen-Yu Liu *(Indiana)*
Mike Snow *(Indiana)*
Erick Smith (Indiana)
Justin Shortino (Indiana)
Yannis Semertzidis *(CAPP*
Yunchang Shin (CAPP)
Andrew Geraci *(UNR)*
Suyesh Koyu (UNR)
Jordan Dargert (UNR)

NSF PHY-1306942

INDIANA UNIVERSITY

IUCSS

Institute for Basic Science

EPSCoR NEVADA

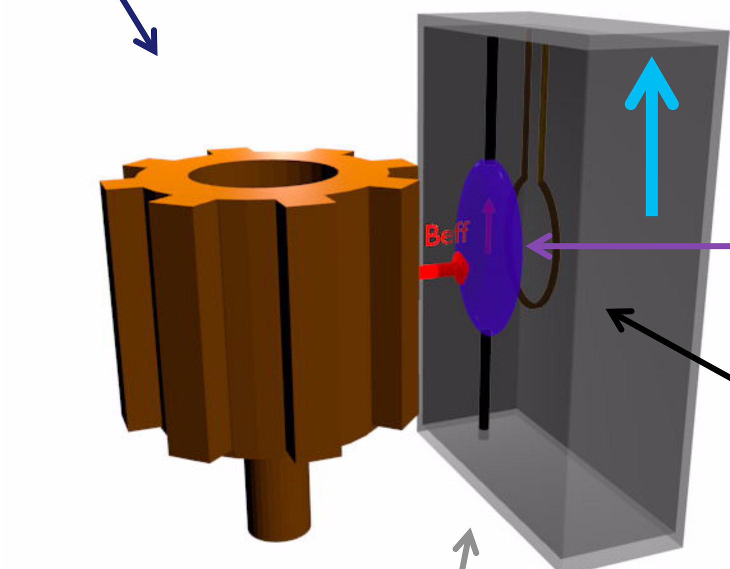
University of Nevada, Reno

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

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



Applied Bias field B_{ext}

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

squid pickup loop (CAPP)

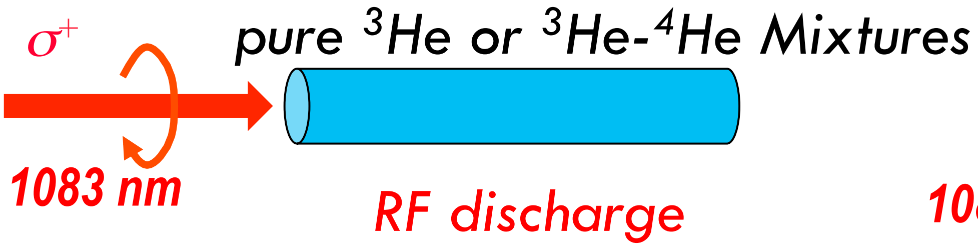
Superconducting shielding (Stanford)

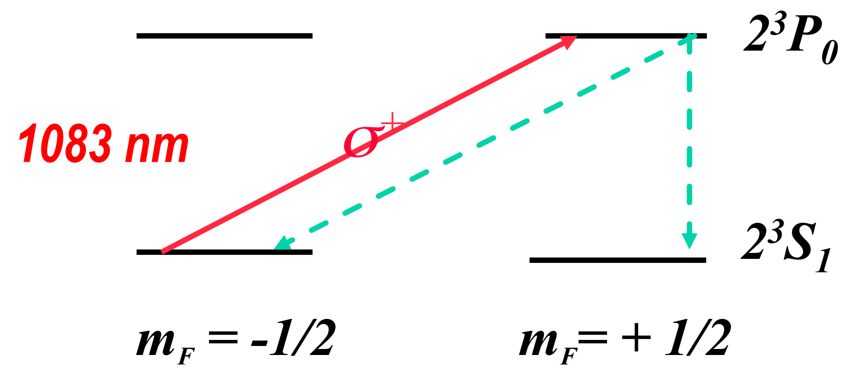
Limit: Transverse spin projection noise

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

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

MEOP (Metastability Exchange Optical Pumping) Works on Arbitrary 3He/4He Mixtures





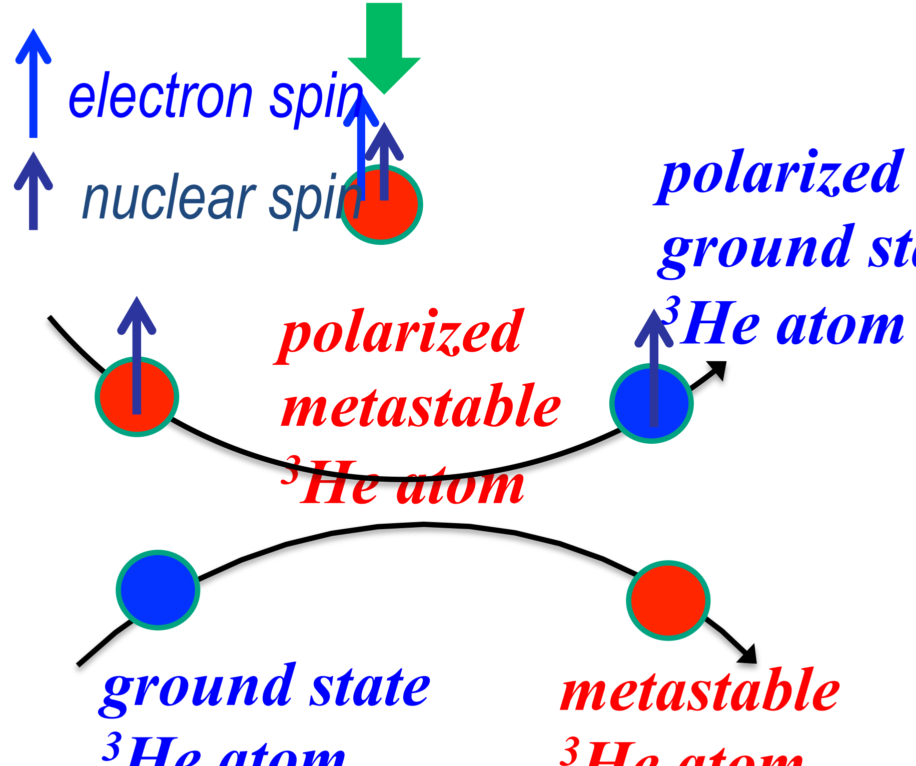
OPTICAL PUMPING of METASTABLE 3He

- ***RF discharge excites metastable***
- ***1083 nm light pumps metastable***
- ***Hyperfine interaction polarizes nucleus***

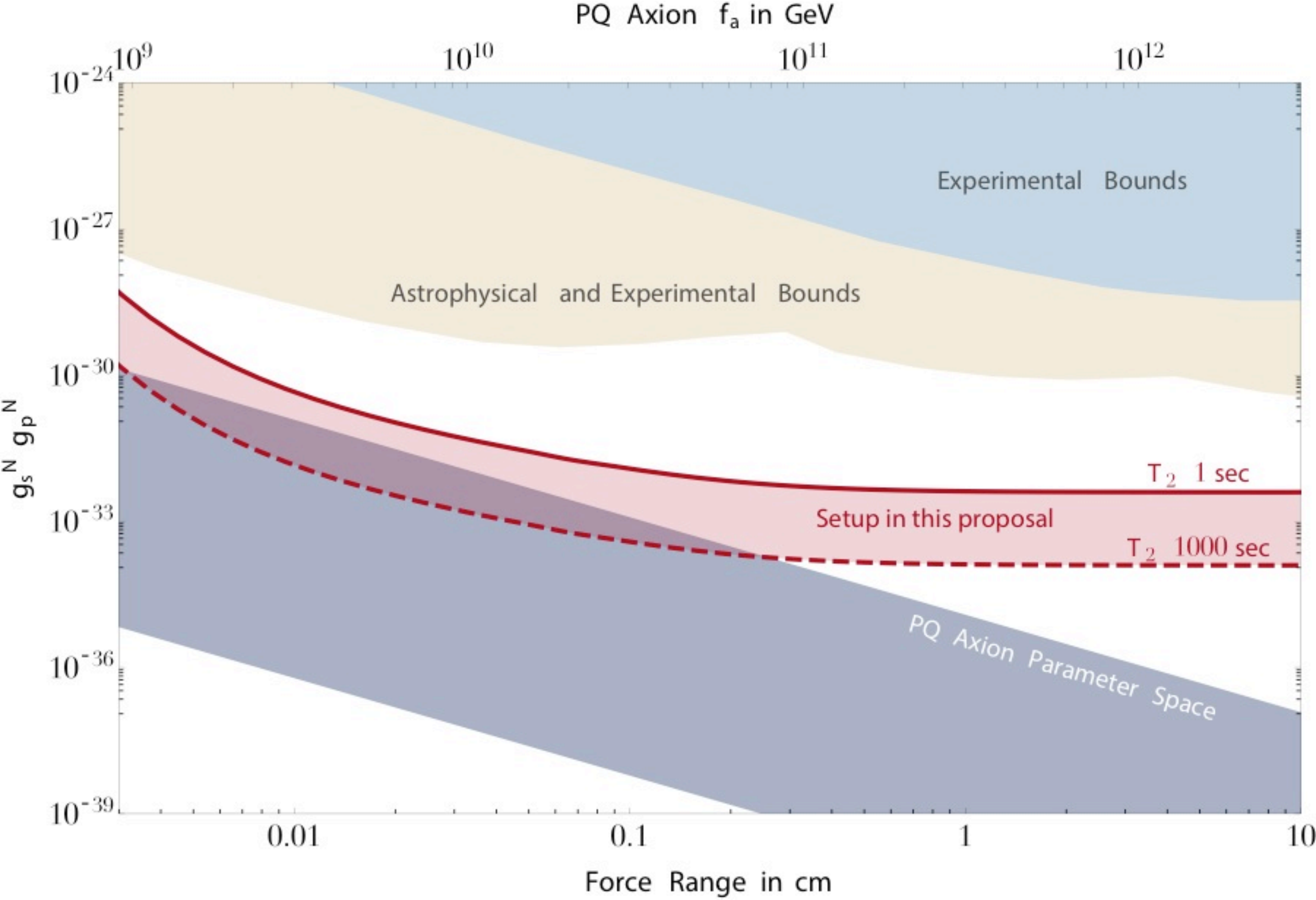
METASTABILITY EXCHANGE

Excitation exchanged in fast collision

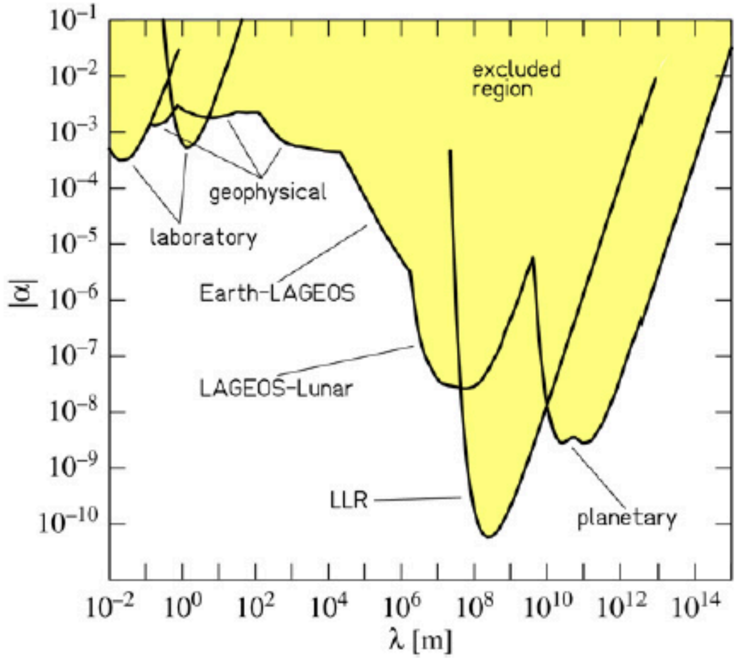
Nuclear spins unperturbed

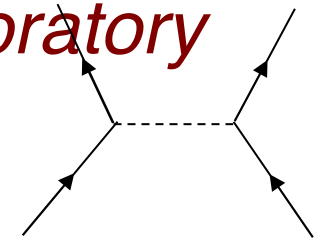


ARIADNE SCIENTIFIC REACH FOR ALPS



Limits on ultra-light bosons from laboratory experiments

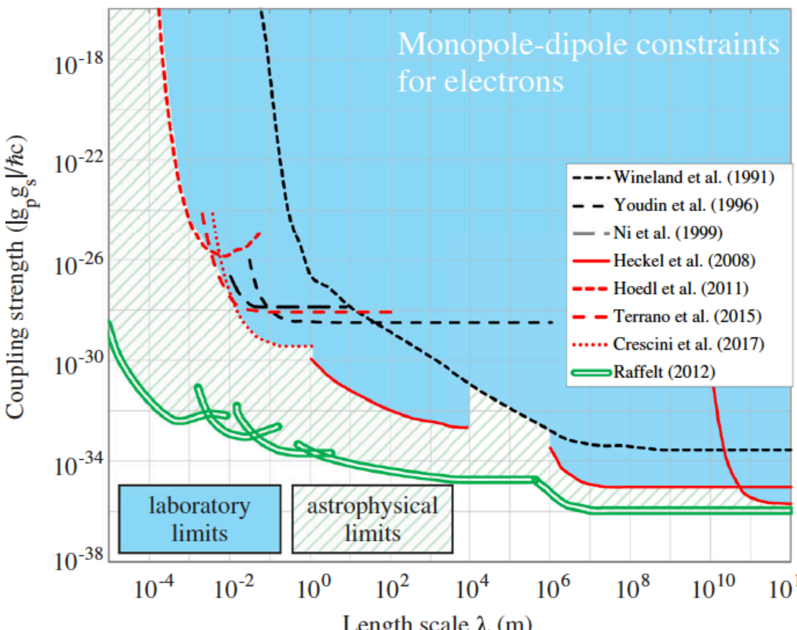


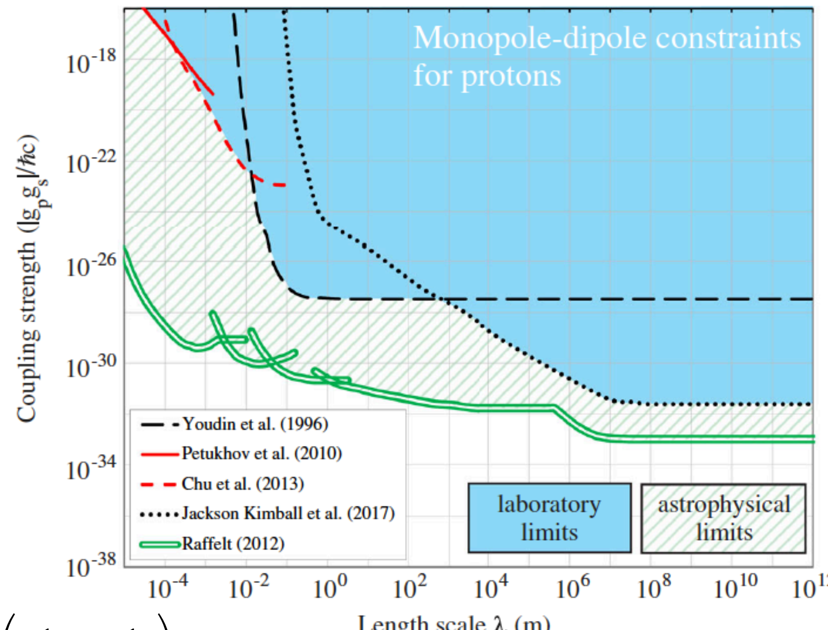


$$V(r) = -\frac{G m_1 m_2}{r}\left(1 + \alpha e^{-r/\lambda}\right)$$

$$\alpha = \frac{\hbar c}{4\pi G m_1 m_2}\left(g_S^X g_S^Y - g_V^X g_V^Y\right)$$

$$\lambda = \frac{1}{\mu}$$





$$V_{S-P} = \frac{g_S g_P}{8\pi m}(\vec{\sigma}\cdot\hat{r})\left(\frac{1}{\lambda r} + \frac{1}{r^2}\right)e^{-r/\lambda}$$

Reviews of Modern Physics, 90, 025008 (2018).

Search for new physics with atoms and molecules

M. S. Safronova

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(published 29 June 2018)

This article reviews recent developments in tests of fundamental physics using atoms and molecules, including the subjects of parity violation, searches for permanent electric dipole moments, tests of the *CPT* theorem and Lorentz symmetry, searches for spatiotemporal variation of fundamental constants, tests of quantum electrodynamics, tests of general relativity and the equivalence principle, searches for dark matter, dark energy, and extra forces, and tests of the spin-statistics theorem. Key results are presented in the context of potential new physics and in the broader context of similar investigations in other fields. Ongoing and future experiments of the next decade are discussed.

DOI: 10.1103/RevModPhys.90.025008

Reviews of Modern Physics, 90, 025008 (2018).

Search for new physics with atoms

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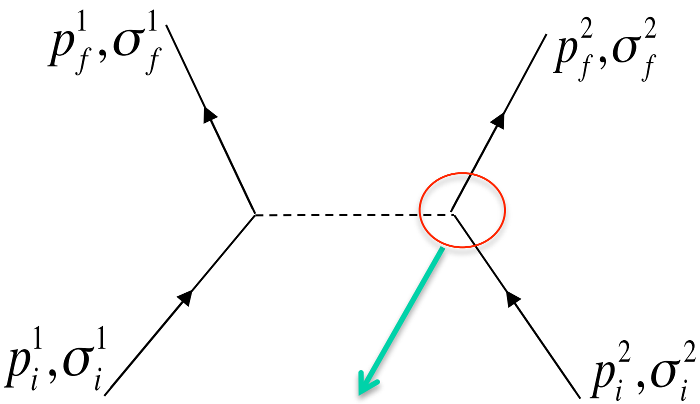
VII. Review of Laboratory Searches for Exotic Spin-dependent Interactions

Motivation for New Long-Range Interactions

Standard Model extensions possess spontaneously broken continuous symmetries producing Weakly Interacting Sub-eV Particles (WISPs) such as axions, arions, familons, Majorons, etc.



- ✓ *Scalar*
- ✓ *Pseudoscalar*
- ✓ *Vector*
- ✓ *Axial-vector*

The two-body interaction in coordinate space

$$V(r^2, P^2, \vec{r} \bullet \vec{P}) = \sum_{i=1}^{16} O_i \frac{e^{-\mu r}}{4\pi r}$$

$$O_i = f_1,\ f_2\ \vec{\sigma}_1 \bullet \vec{\sigma}_2,\ f_3\ \vec{\sigma}_1 \bullet \nabla\ \vec{\sigma}_2 \bullet \nabla,\ f_{4,5}\ (\vec{\sigma}_1 \pm \vec{\sigma}_2) \bullet P \times \nabla,$$
$$f_6\ \vec{\sigma}_1 \bullet P\ \vec{\sigma}_2 \bullet \nabla,\ f_7\ \vec{\sigma}_1 \bullet P\ \vec{\sigma}_2 \bullet P, \ldots\ldots,\ f_{16}\ \vec{\sigma}_1 \bullet (P \times \nabla)\ \vec{\sigma}_2 \bullet P$$

f : a dimensionless constant α g^2

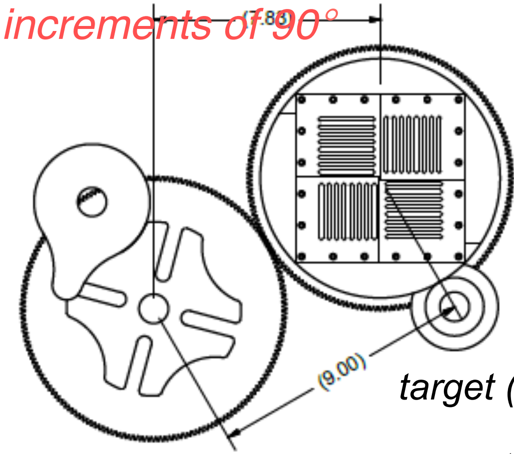
Laboratory experiments provide very sensitive and model-independent probes of such particles [See Rev. of Mod. Phys. 90, 025008 (2018)].

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

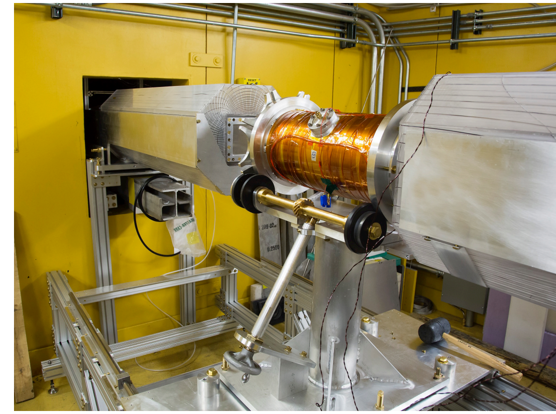
Spin-1 Boson Axial Coupling Search at LANSCE

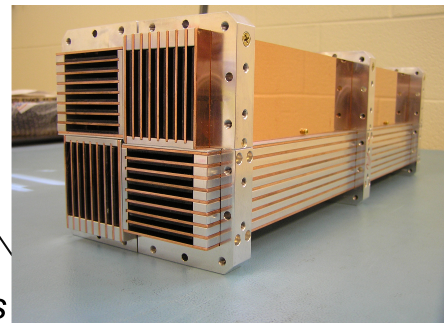
Geneva Mechanism:

Rotate the target by increments of 90°

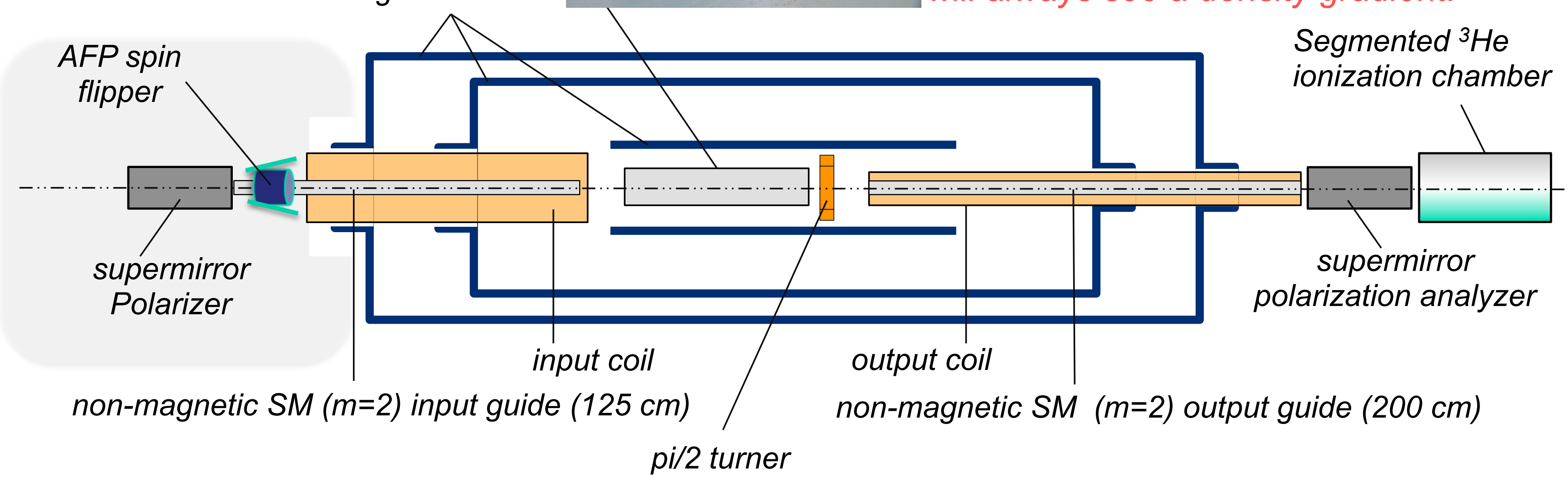


View inside FP12 cave showing input/output supermirror guides and coils and target vacuum chamber. Neutron supermirror polarizer/analyzer, ion chamber, magnetic shielding not shown.



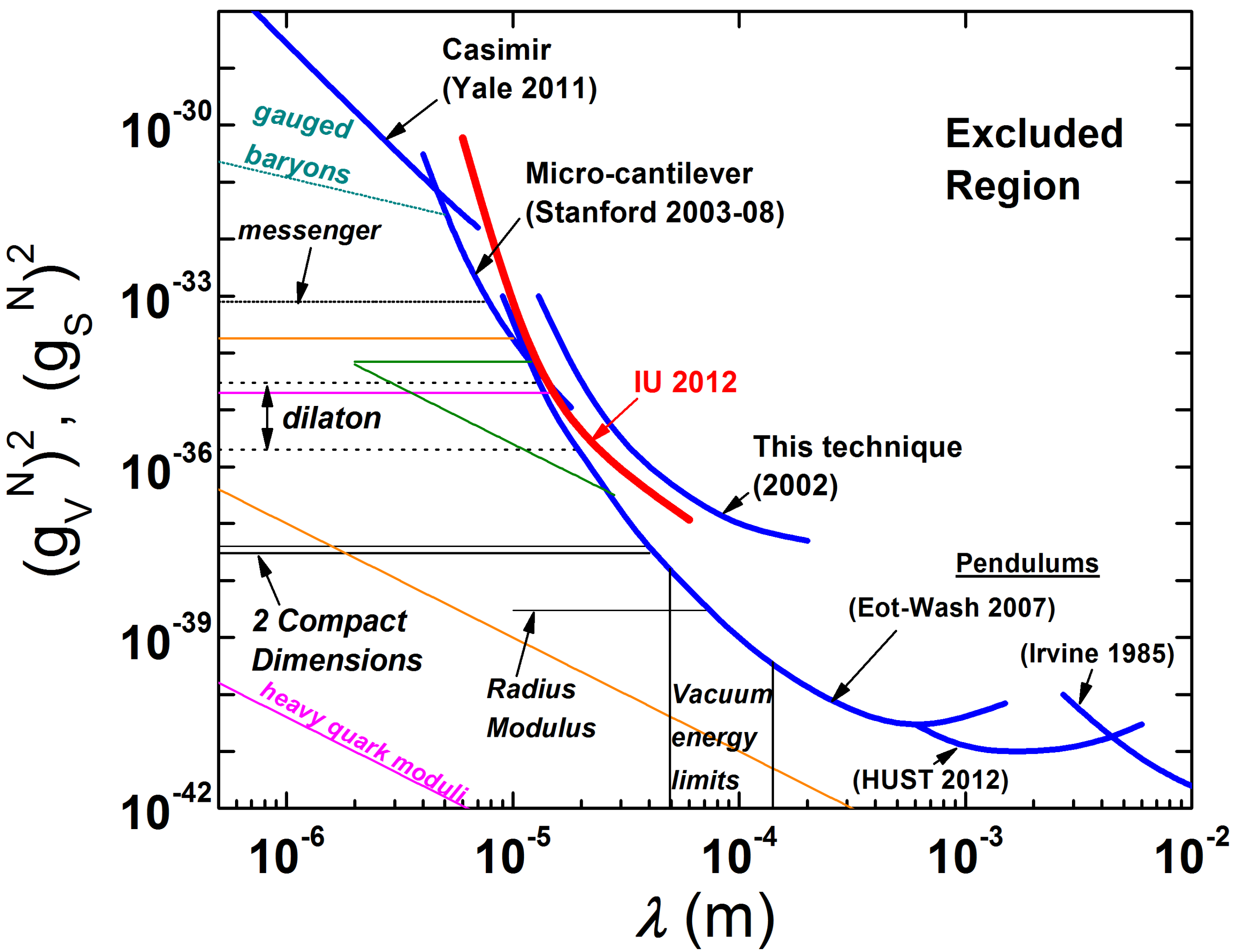


Plates of different nucleon density N are assembled so that the polarized neutrons traveling between the gaps will always see a density gradient.



See C. Haddock poster

Constraints on new Yukawa interactions are Fantastic: What else can we do with them?



$$V_{S.V} = -\frac{g_{S,V}^2}{4\pi r} e^{-r/\lambda}$$

Consider the effect of Yukawa-like term in neutron scattering amplitude

$$V(r) = -G_N \frac{m_1 m_2}{r}\left(1 + \alpha \exp\left(-\frac{r}{\lambda}\right)\right) \qquad \lambda = \frac{\hbar}{m_0 c}$$

In the Born Approximation, scattering amplitude is proportional to the Fourier transform of the potential:

$$f_Y(q) \sim \int V(r) e^{-i\vec{q}\cdot\vec{r}} d\vec{r}$$

Inserting constants, integrating gives amplitude “b_Y”:

$$b_Y(q) = \alpha\left(\frac{2G_N m_n^2 M_A}{\hbar^2}\right)\frac{1}{\lambda^{-2} + q^2}$$

More Constraints on exotic V-A interactions

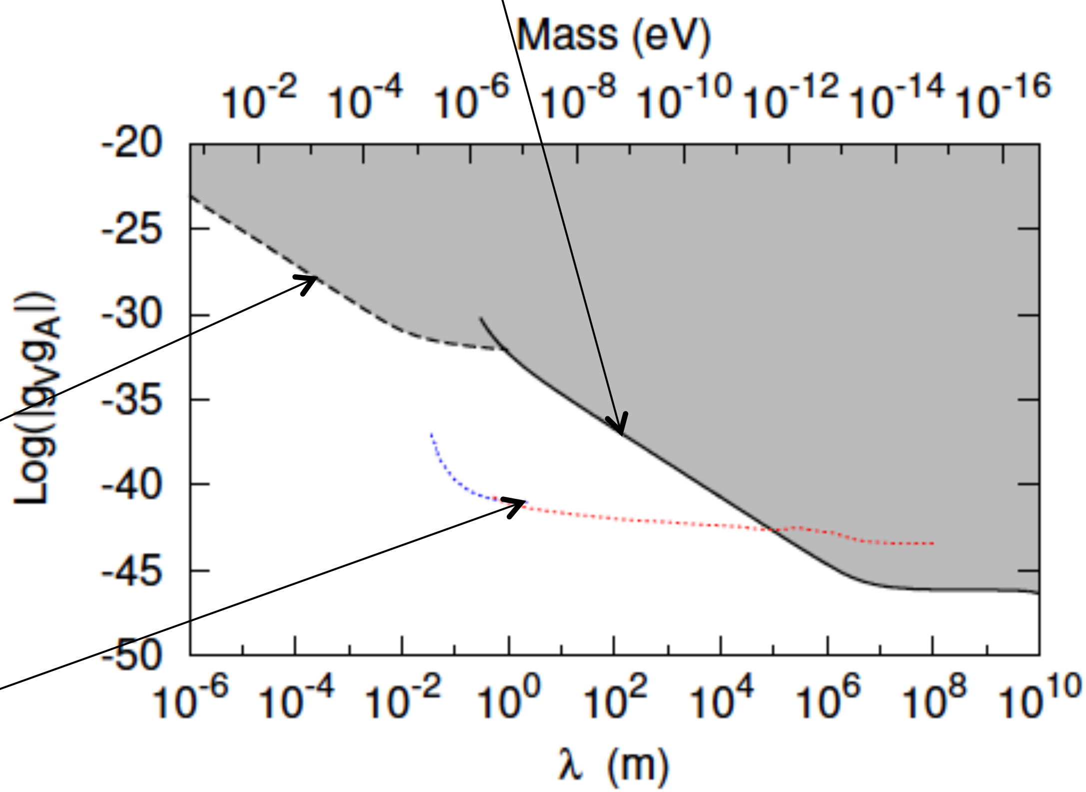
Searching for New Spin-Velocity Dependent Interactions by Spin Relaxation of Polarized ^3He Gas

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)

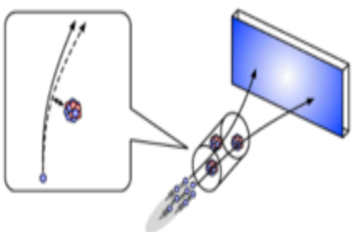
Day of publication on PRD : APS Highlighted Article(March 22, 2018)

Physics ABOUT BROWSE PRESS COLLECTIONS

Synopsis: Neutron Test for Newton's Gravity

March 22, 2018

Experiments with neutrons search for violations of gravity's inverse square law at subnanometer distances.

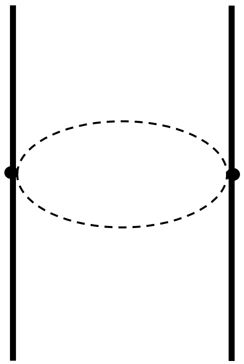


M. Kitaguchi/Nagoya University

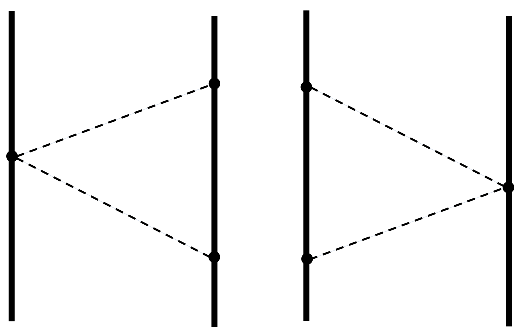
Newton's law of universal gravitation predicts that the gravitational force between two objects is proportional to the objects' masses and inversely proportional to the square of the distance between them. The law, which applies to weakly interacting objects traveling at speeds much slower than that of light, has survived test after test. However, some quantum gravity theories anticipate that the law might break down at small distances. Now, through experiments with a pulsed neutron beam, Christopher Haddock of Nagoya University, Japan, and colleagues have checked Newton's law on subnanometer scales. So far, the team has found no deviations from Newtonian predictions.

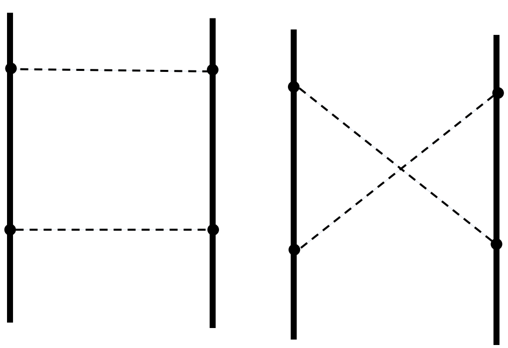
The team fired pulses of neutrons at a chamber filled with either helium or xenon gas and monitored both the travel time of the neutrons through the gas and the neutrons' scattering angles. From these measurements, they reconstructed the scattering process with the aid of simulations. They found that the scattering-angle distribution fit the predictions—based only on known laws of physics—for neutrons bouncing off gas nuclei. This result indicates that, within the sensitivity of the experiment, no unexplained force—be it modified gravity or another type of interaction—acts on length scales below 0.1 nm. However, the researchers were only able to determine an extremely large upper limit on the strength of such a force: 10^{24} times that of gravity. Still, this is the strictest limit set by any experiment on these spatial scales. The team is currently upgrading the setup to reduce sources of noise and envisions achieving order-of-magnitude sensitivity improvements in the near future.

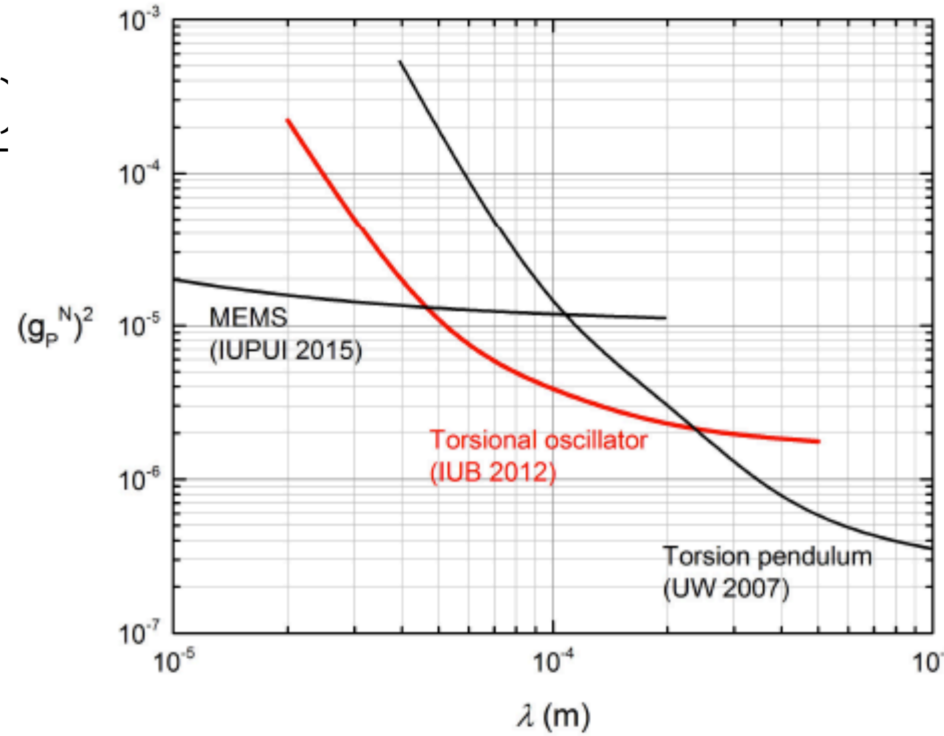
Example: Spin-Independent Effects from Two-Boson Exchange with Spin-Dependent Couplings



$$V_1(r) = -\frac{g_P^4}{m^2}\frac{\mu K_1(2\mu r)}{32\pi^3 r^2}$$







See S. Aldaihan talk Sunday J2

$$V_2 = \left(\frac{g_S^2 g_P^2}{m} - 2\frac{g_V^2 g_A^2}{m}\right)\frac{e^{-2\mu r}}{32\pi^2 r^2}$$

$$V_3 = -\frac{3g_A^4}{2\pi^2 r}\left[e^{-\mu r}K_0(\mu r) - K_0(2\mu r)\right]$$

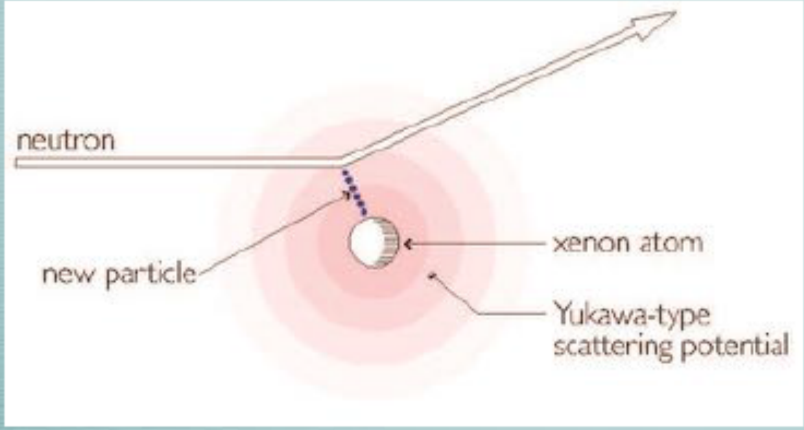
S.Aldaihan, D. Krause, J. Long, and W. M. Snow, arXiv:1611.01580 [hep-ph] (sub. to Phys. Rev. D)

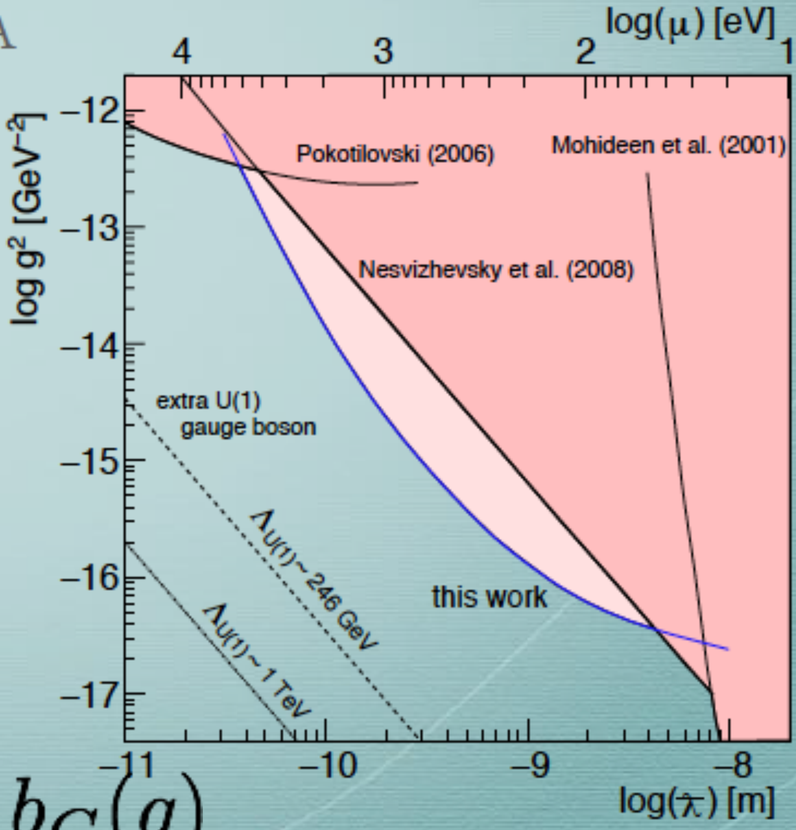
Search for new gravity-like interactions and test of the equivalence principle using slow neutrons

Yoshio Kamiya, Koji Yamada, Kenta Uchida, Yoshihiro Sasayama, Keita Itagaki, Misato Tani, Sachio Komamiya, and Guinyun Kim

The Univ. of Tokyo / Kyngpook Nat. Univ.

We report on a new constraint on gravity-like interactions obtained by measuring the angular distribution of 5 A neutrons scattering off atomic Xe gas.





$$b_c(q) = (b_c - b_e Z(1 - f(q)) + b_G(q)$$

Y. Kamiya et al., Phys. Rev. Lett. (2015)   Done at HANARO (Korea)