Searches for T Violation with Neutrons

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The scientific motivation

The value of “null tests” of time reversal invariance

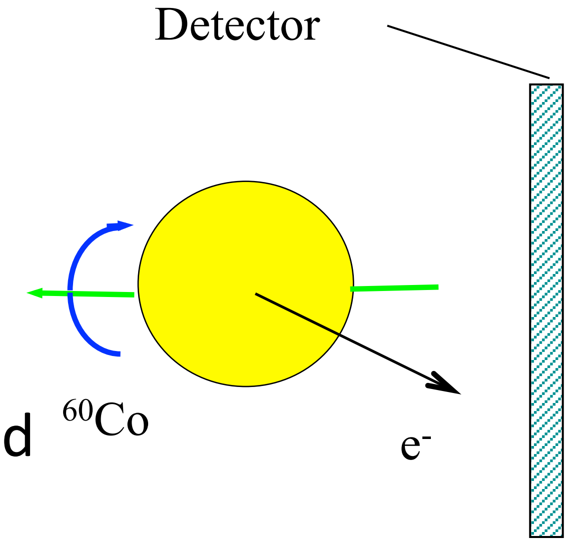
Searches for the neutron electric dipole moment

Polarized neutron optics test of T invariance

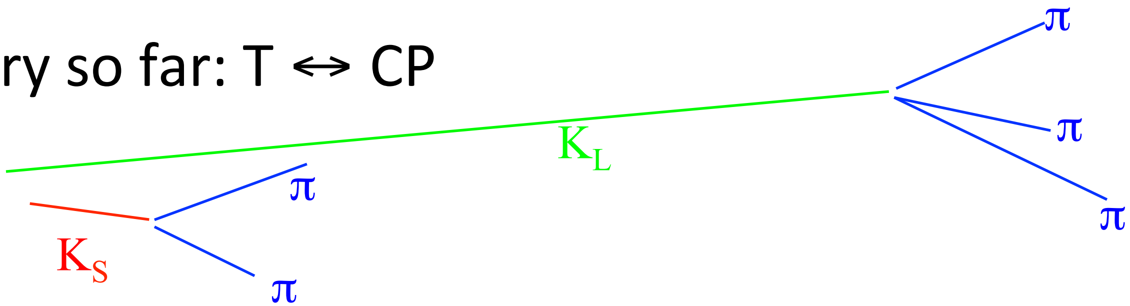
T-violating potential from light boson exchange

Thanks for slides from: D. Bowman, V. Gudkov, H. Shimizu, J-C Peng, M. Kitaguchi, P. Schmidt-Wellenburg,…

P, CP, T, and CPT



- Parity violation (1956)
  - only in weak interaction
- CP violation (1964)
  - Parametrized (CKM!) but not understood
  - Seen in K^0 & B^0 systems
  - Doesn't seem to be responsible for baryon asymmetry of universe
- T violation (1999)
  - CPT is good symmetry so far: T ↔ CP



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

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

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

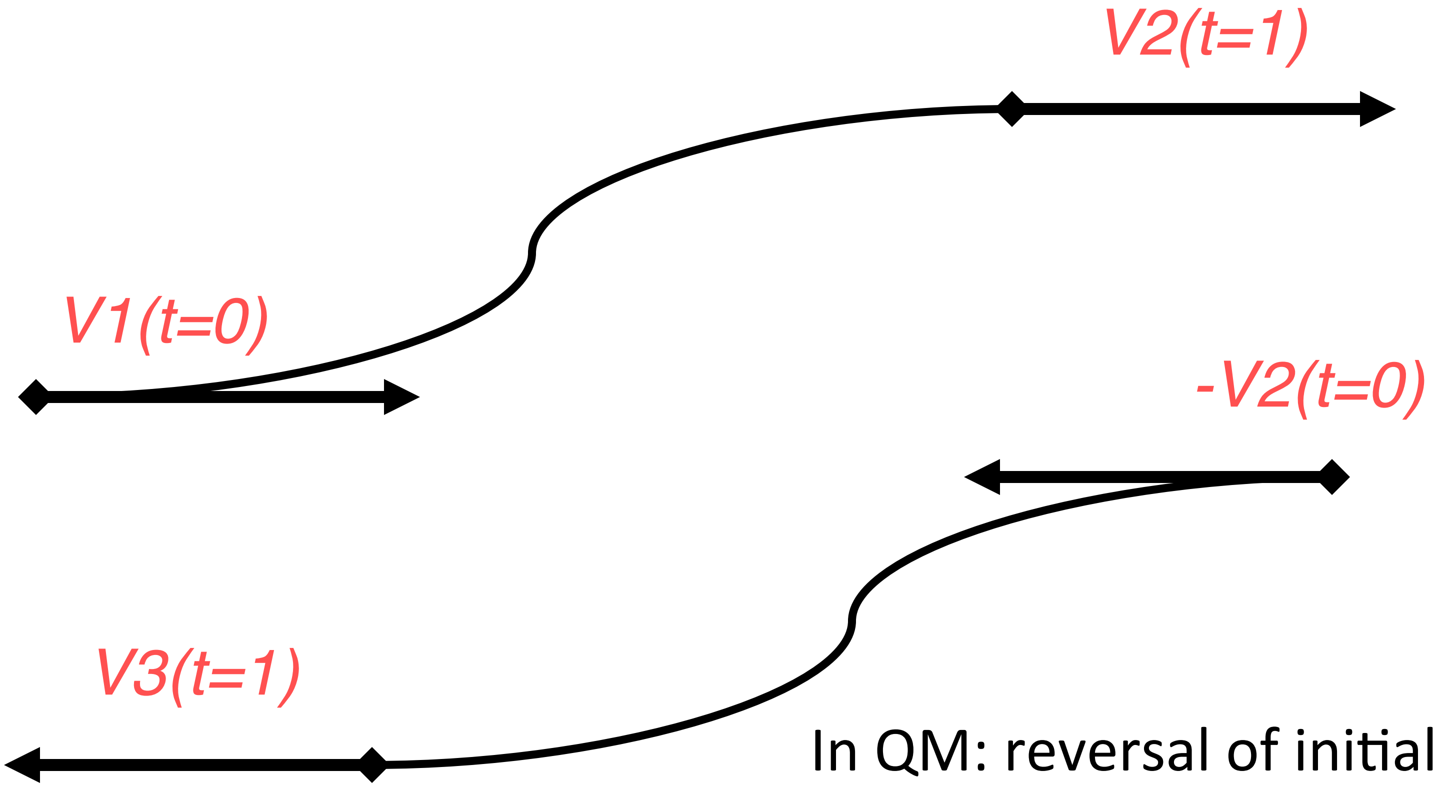
A.D. Sakharov, JETP Lett. 5, 24-27, 1967

Searches for T violation with neutrons:

Electric Dipole Moment Searches (E~0)

T-odd Polarized Neutron Optics (E~6 MeV)

“Time Reversal” -> Motion Reversal



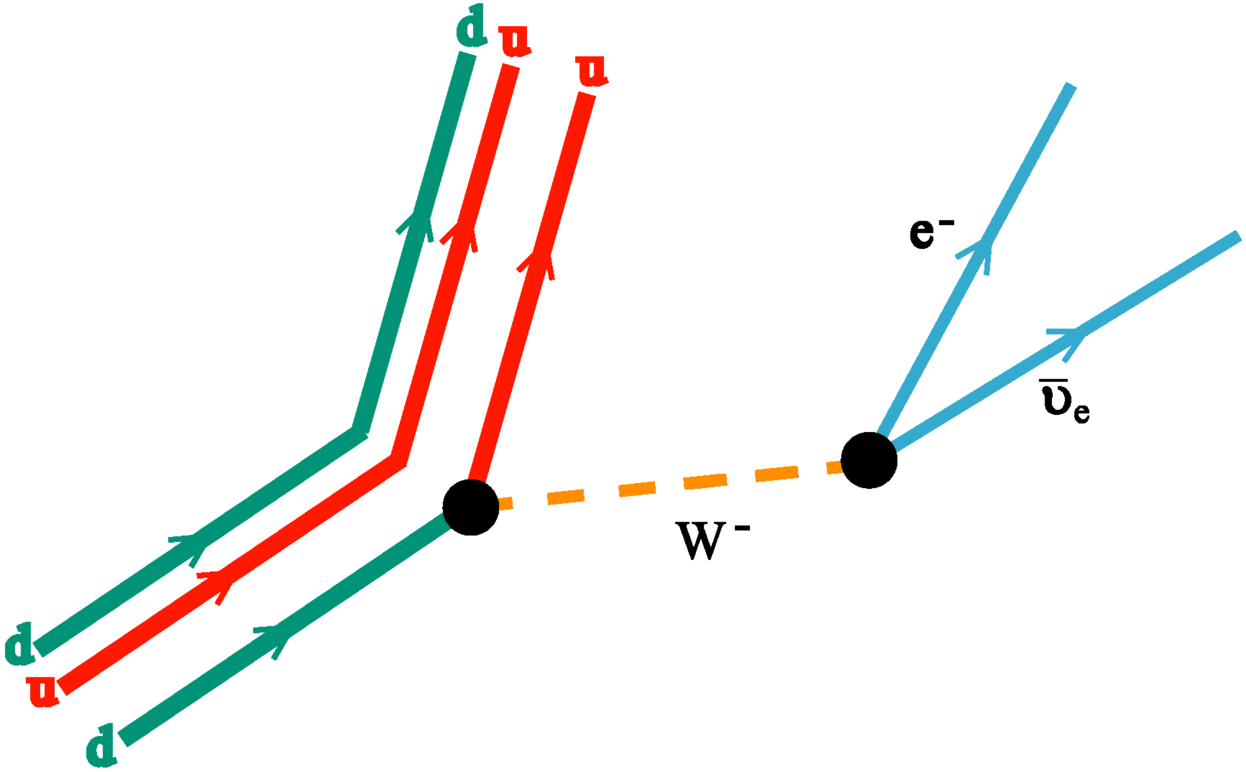
In QM: reversal of initial and final states:

$\langle a|O|b\rangle$ -> $\langle b|O_T|a\rangle$

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*

Neutron decay: not motion reversal invariant

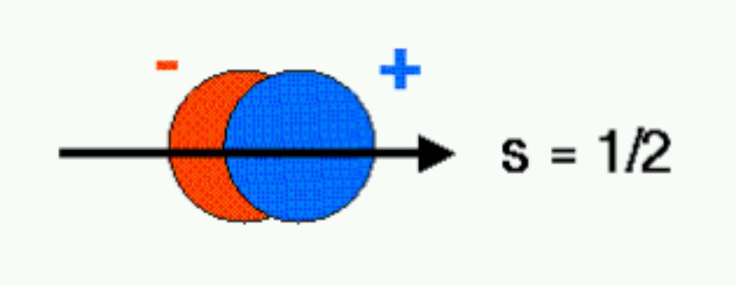


Reversing the electron, neutrino, and proton to get the neutron is impractical.

Still look for formally T-odd correlations of observables

But one must worry about "final state effects" giving T-odd correlation even if no real T violation is present

Electric Dipole Moments: P-odd/ T-odd Observable



$$\vec{d}_n = \int \vec{x}\rho(x)d^3x = d_n\hat{s}$$

Non-zero d_n violates both P and T

Under a parity operation:

$$\hat{s} \longrightarrow \hat{s}\,, \quad \vec{E} \longrightarrow -\vec{E}$$

$$\vec{d}_n \cdot \vec{E} \longrightarrow -\vec{d}_n \cdot \vec{E}$$

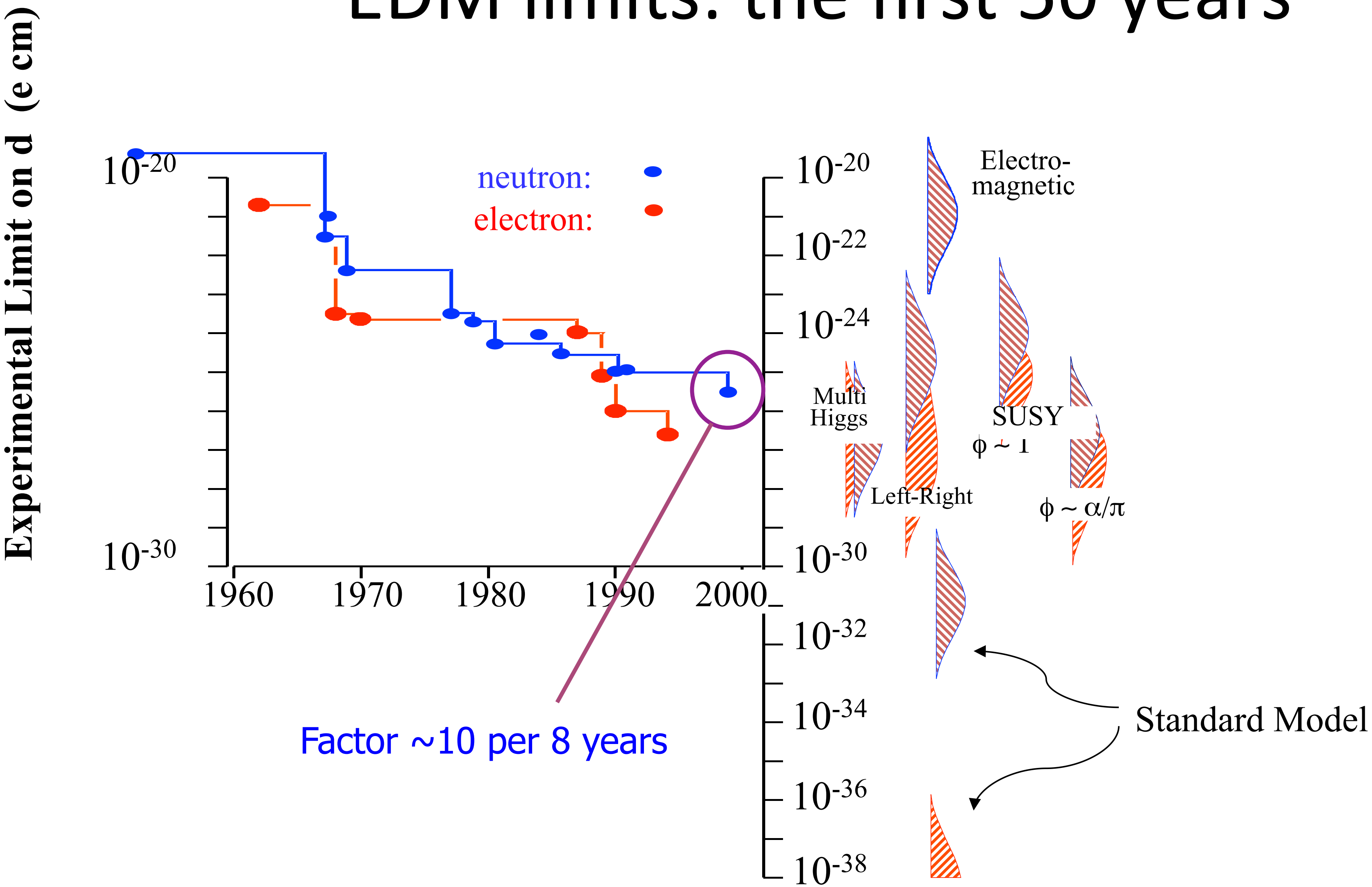
Under a time-reversal operation:

$$\hat{s} \longrightarrow -\hat{s}\,, \quad \vec{E} \longrightarrow \vec{E}$$

$$\vec{d}_n \cdot \vec{E} \longrightarrow -\vec{d}_n \cdot \vec{E}$$

EDMs are “null tests” of time reversal invariance (no “final state effects” can fake an EDM) |i>=|f>

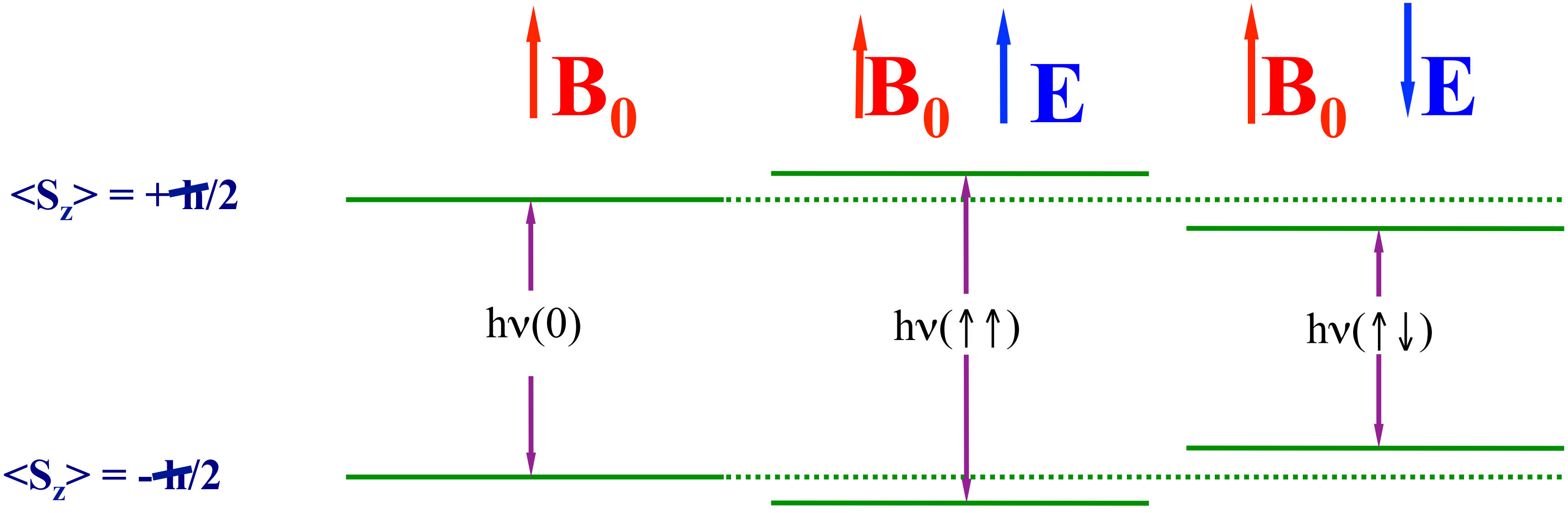
EDM limits: the first 50 years



Factor ~10 per 8 years

Barr: Int. J. Mod Phys. A8
208 (1993)

EDM Measurement Principle/Sensitivity



$$\nu(\uparrow\uparrow) - \nu(\uparrow\downarrow) = -4\,E\,d/\,h$$

assuming **B** unchanged when **E** is reversed.

EDM limits -> ratio (T-odd amplitude in nucleon/strong amplitude)~10^{-11}

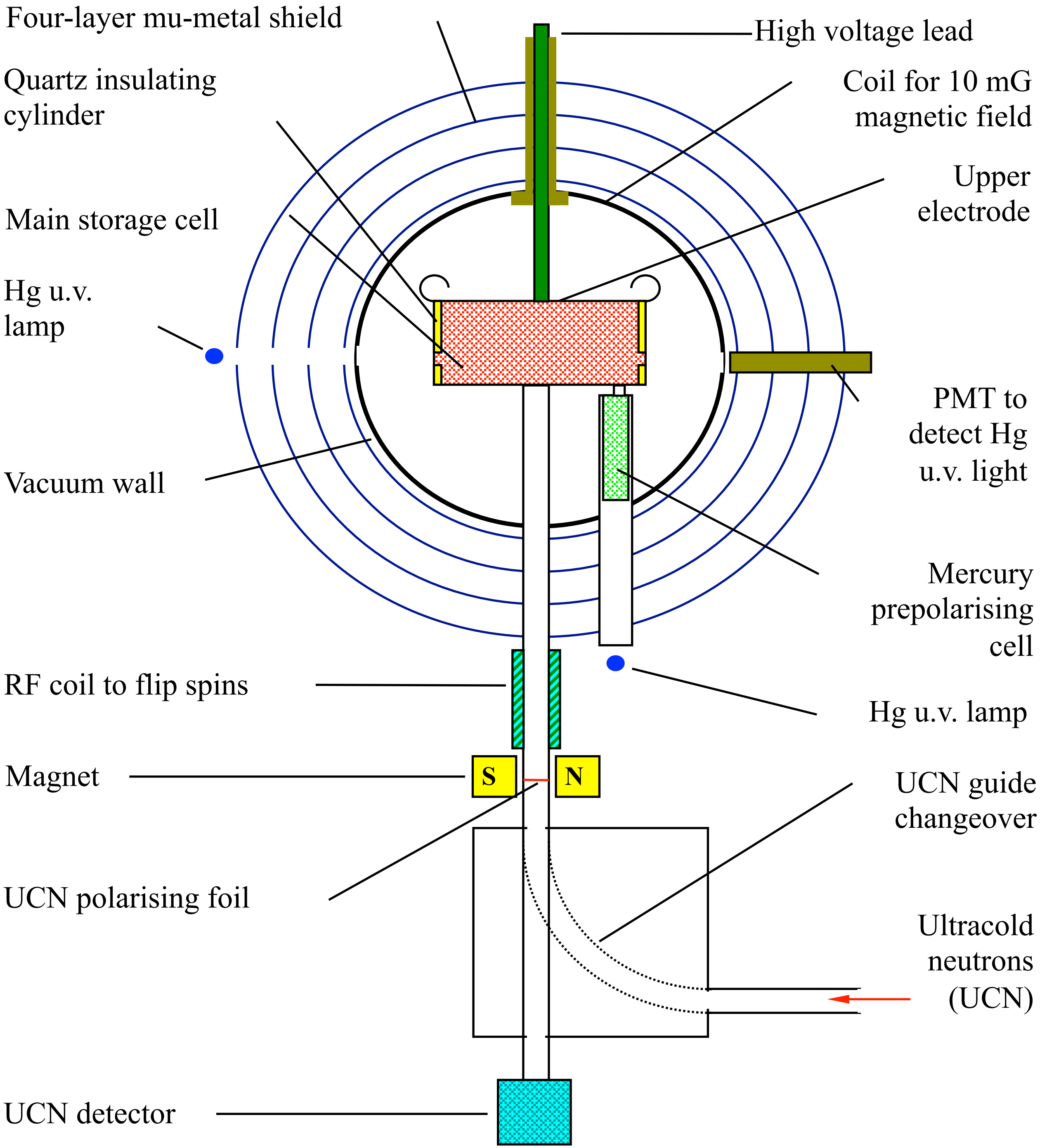
T violation from CKM phases smaller by ~5 orders of magnitude here

EDMs are ground state properties of the system: excitation energy ~0

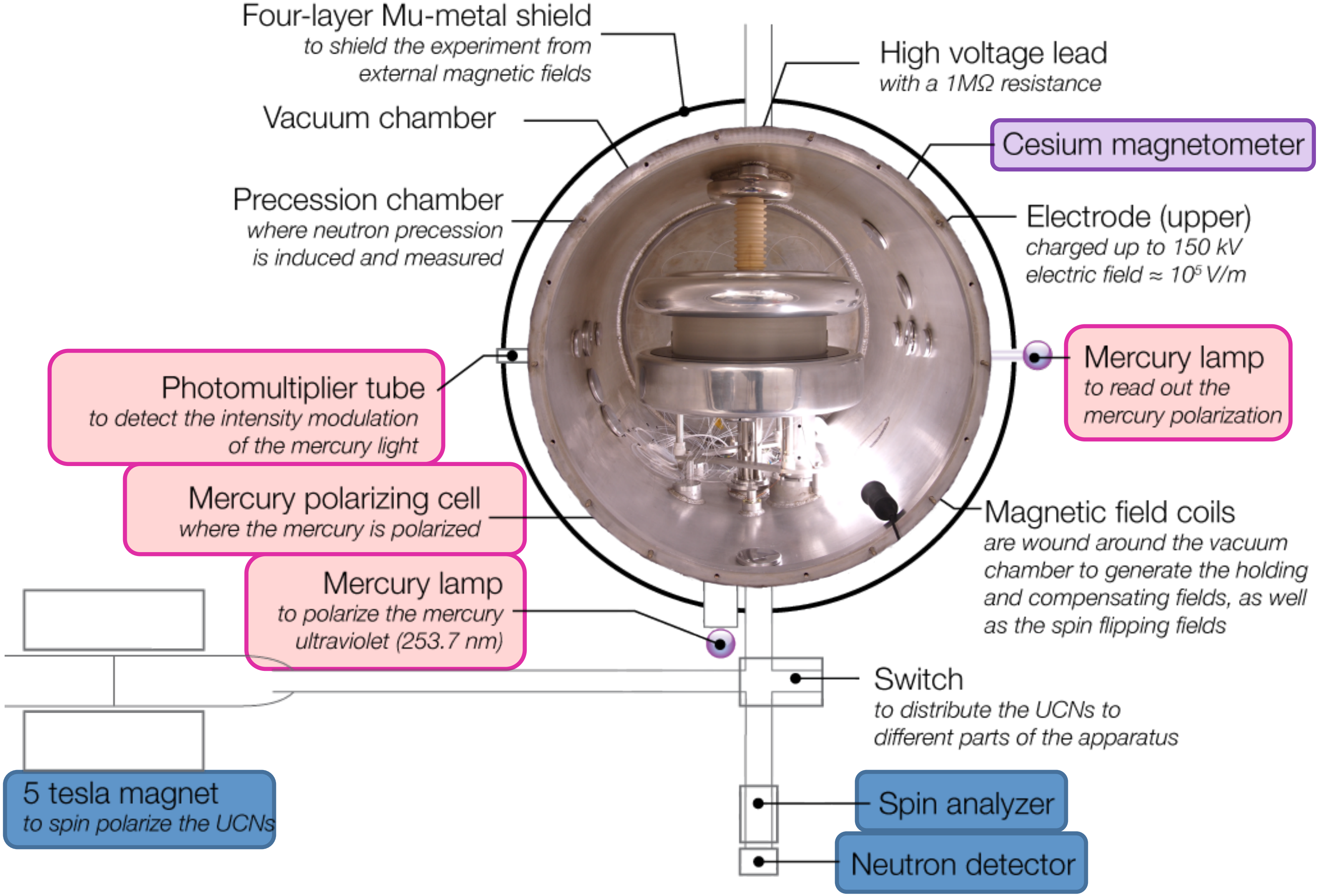
nEDM apparatus at ILL using UCN

Best limit: d<2.9×10^{-26}ecm
Baker *et al.*, PRL**97**(2006)

- Use ^{199}Hg co-magnetometer to sample the variation of B-field in the UCN storage cell
- Limited by low UCN flux of ~ 5 UCN/cm^3
- Figure–of-merit ~ *E(NT)*$^{1/2}$



The nEDM spectrometer at PSI



Four-layer Mu-metal shield
to shield the experiment from external magnetic fields

Vacuum chamber

Precession chamber
where neutron precession is induced and measured

Photomultiplier tube
to detect the intensity modulation of the mercury light

Mercury polarizing cell
where the mercury is polarized

Mercury lamp
to polarize the mercury ultraviolet (253.7 nm)

5 tesla magnet
to spin polarize the UCNs

High voltage lead
with a 1MΩ resistance

Cesium magnetometer

Electrode (upper)
charged up to 150 kV
electric field ≈ 10^5 V/m

Mercury lamp
to read out the mercury polarization

Magnetic field coils
are wound around the vacuum chamber to generate the holding and compensating fields, as well as the spin flipping fields

Switch
to distribute the UCNs to different parts of the apparatus

Spin analyzer

Neutron detector

Neutron EDM sensitivity

$$\sigma = \frac{h}{2\alpha TE\sqrt{N}}$$

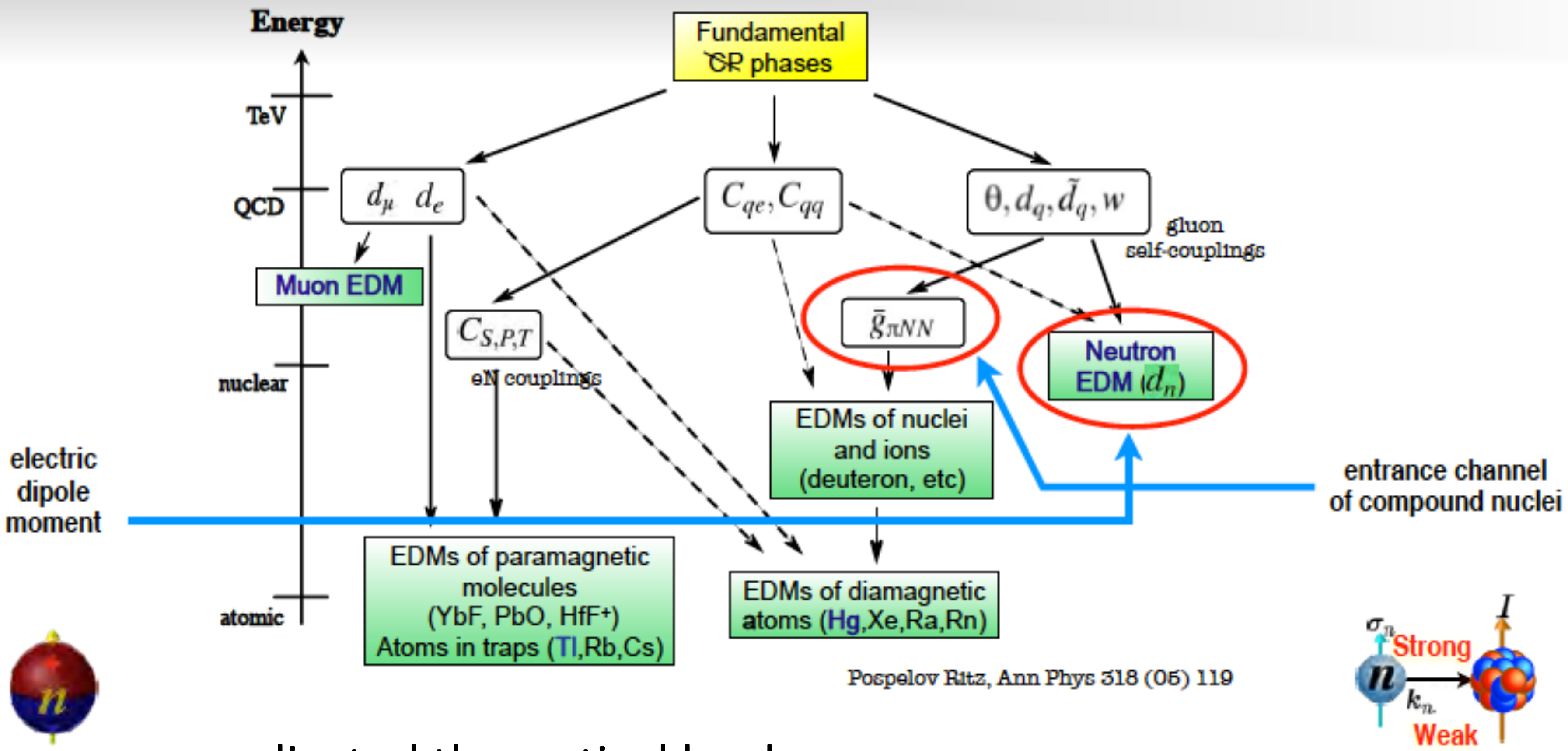
	RAL/Sussex/ILL*		PSI 2013		
	best	avg	best	avg	
E-field	8.8	8.3	12	10.3	
Neutrons	14 000	14 000	10 500	6 500	~7500
T_{free}	130	130	200	180	
T_{duty}	240	240	340	340	
A	0.68	0.51	0.62	0.57	~0.75
(10^{-25}ecm)	2.0	2.8	1.5	2.8	<2

2013 data taking: 3266 cycles
25 days
Stopped by switch break down
2013 accumulated sensitivity 6×10^{-26} e.cm

“We expect with 300 data-days until 2016 a statistical sensitivity of $\sigma \lesssim 10^{-26}$ e·cm” PSI2016

* Best nedm limit:
Baker *et al.*, PRL**97**(2006)

T violation Searches with EDMs and Compound Nuclei



Pospelov Ritz, Ann Phys 318 (05) 119

d_n

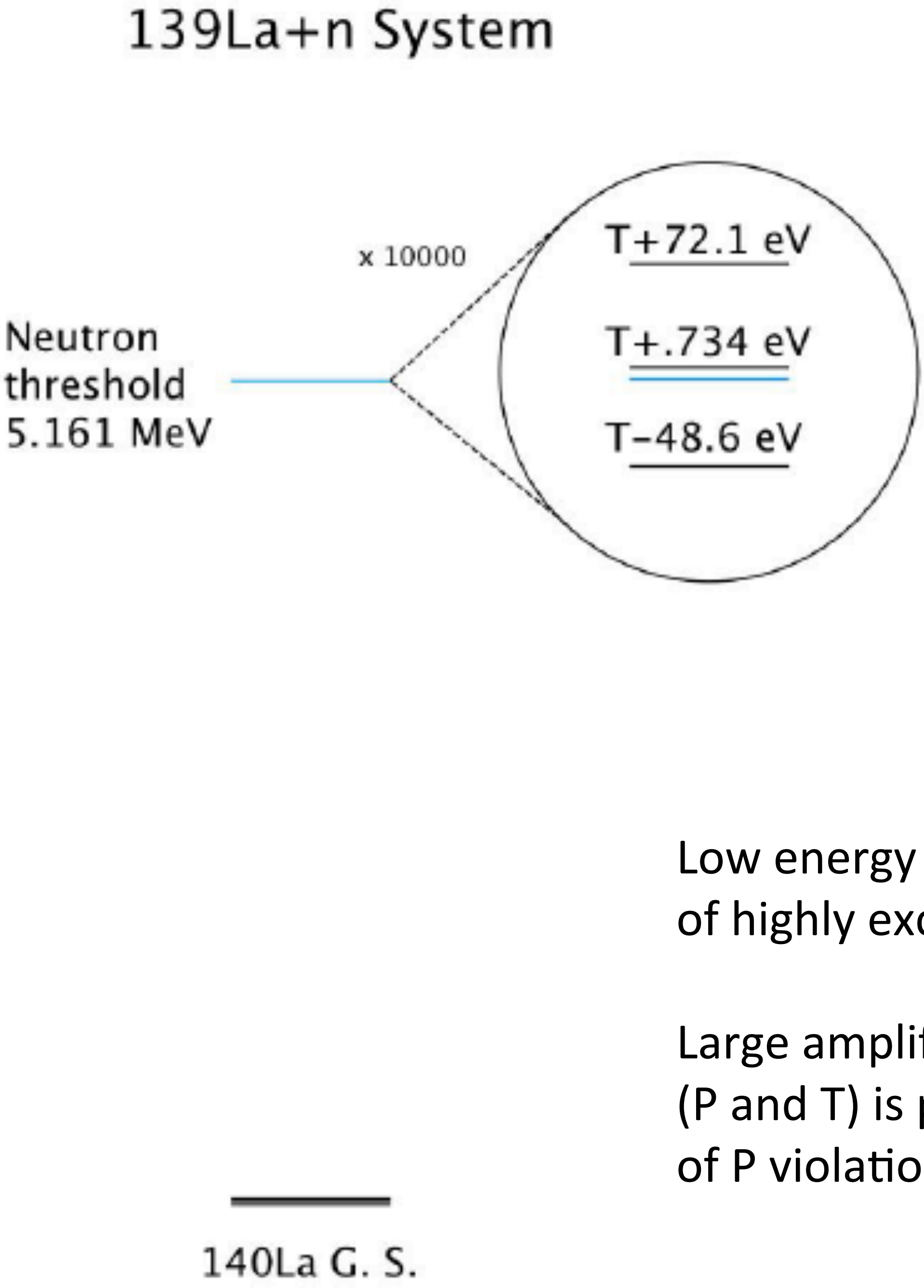
$\sigma_n \cdot (k_n \times I)$

complicated theoretical landscape

important to perform experiments in many systems

Compound nuclei? What is this?

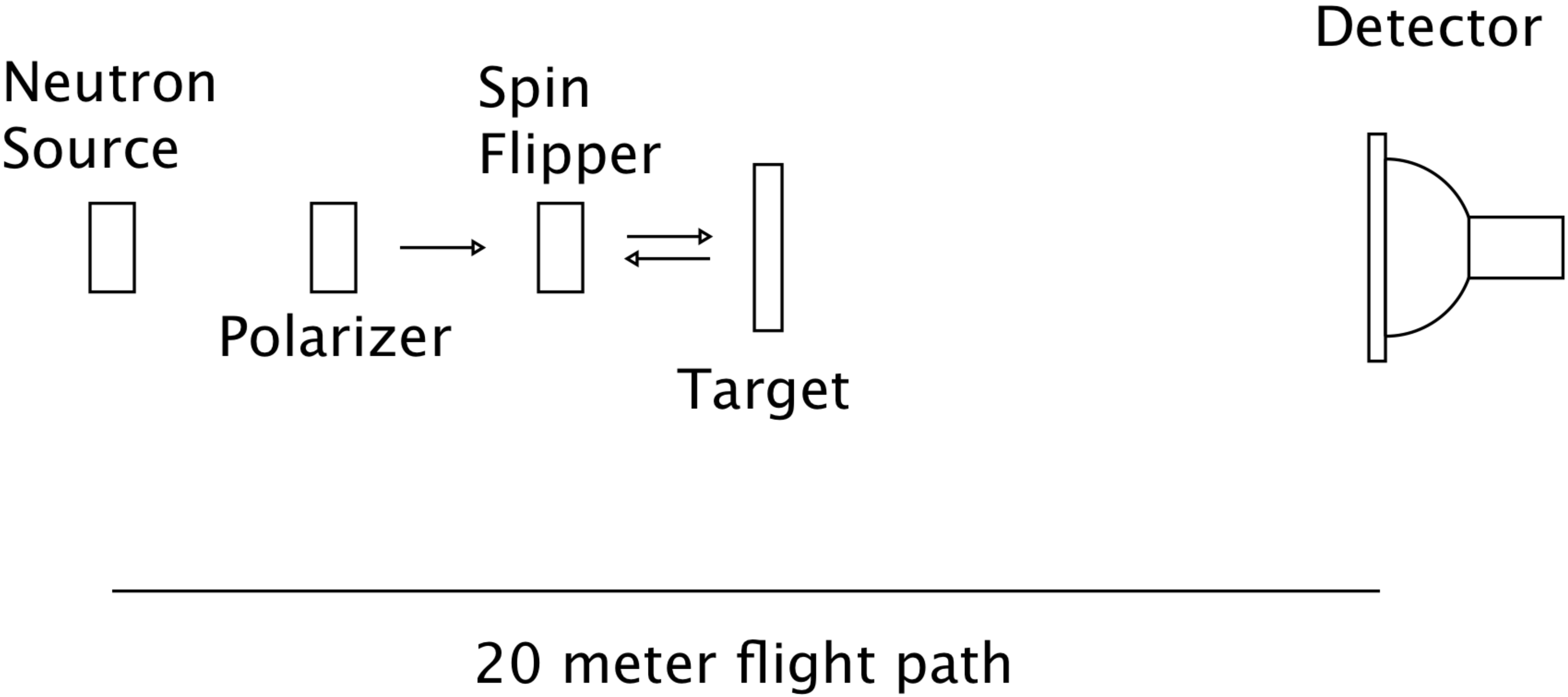
Compound-Nuclear States in ^{139}La+n system



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

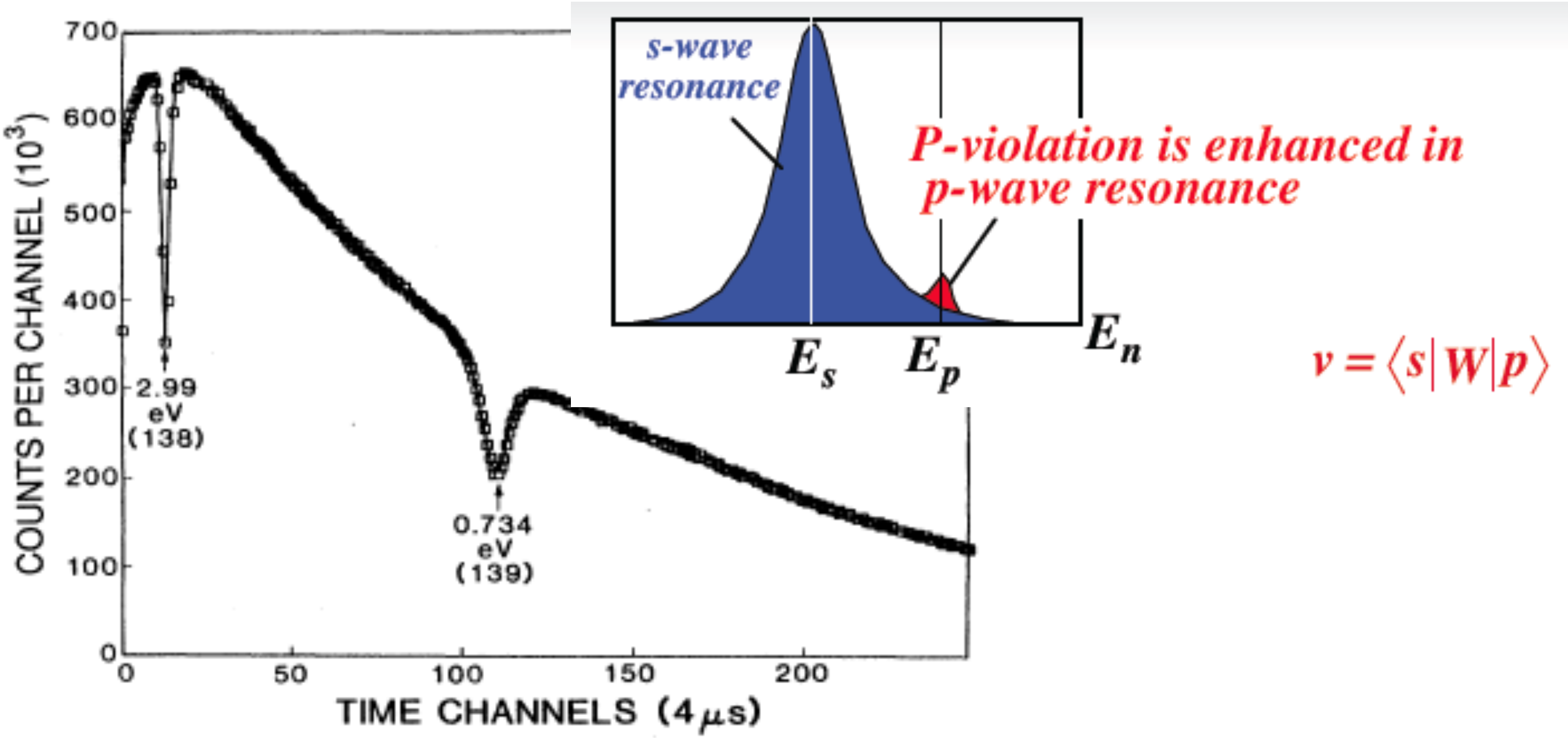
Apparatus to Measure $\sigma \cdot k$ Parity Violating Asymmetry



TRIPLE collaboration measured ~60 parity-odd asymmetries in p-wave resonances in heavy nuclei G. M. Mitchell, J. D. Bowman, S. I. Penttila, and E. I. Sharapov, Phys. Rep. 354, 157 (2001).

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

Parity Violation in n+ ^{139}La at 0.734 eV $\Delta\sigma/\sigma$ =0.097±.005. Larger than dimensional analysis estimate by ~10^6



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

How? (1) Admixture of (large) s-wave amplitude into (small) p-wave ~1/kR~1000
(2) Weak amplitude dispersion for 10^6 Fock space components ~sqrt(10^6)=1000

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

Forward Scattering Ampliltude

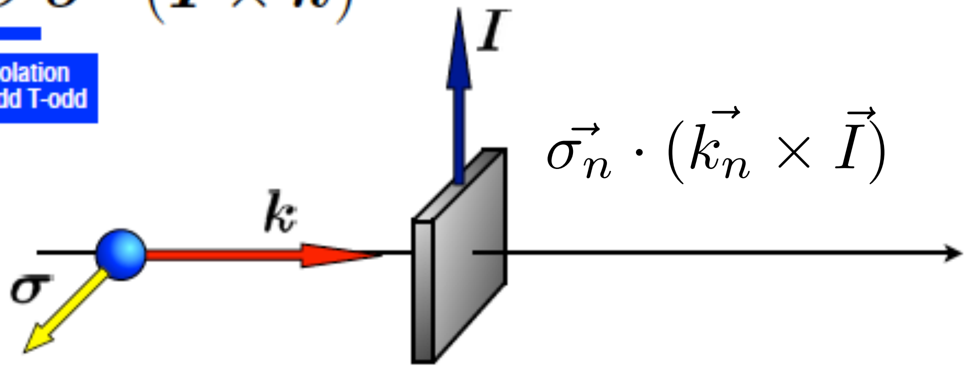
$$f = A' + B'\boldsymbol{\sigma}\cdot\hat{\boldsymbol{I}} + C'\boldsymbol{\sigma}\cdot\hat{\boldsymbol{k}} + D'\boldsymbol{\sigma}\cdot(\hat{\boldsymbol{I}}\times\hat{\boldsymbol{k}})$$

Spin Independent
P-even T-even

Spin Dependent
P-even T-even

P-violation
P-odd T-even

T-violation
P-odd T-odd



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

$|s\rangle$ $J_s E_s \Gamma_s \Gamma_s^n$

$|p\rangle$ $J_p E_p \Gamma_p \Gamma_p^n$

$|p_{1/2}\rangle$ $\Gamma_{p,1/2}^n$

$|p_{3/2}\rangle$ $\Gamma_{p,3/2}^n$

$\langle W\rangle$

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*).

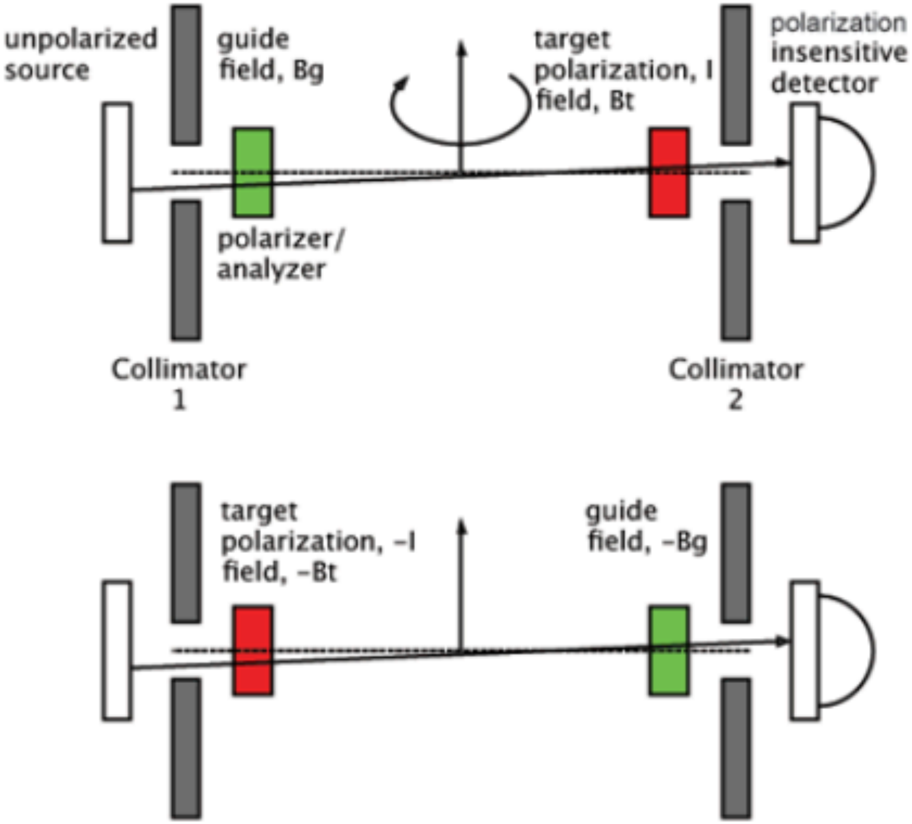
Experimental observable: ratio of P-odd/T-odd to P-odd amplitudes $\lambda_{PT} = \frac{\delta\sigma_{PT}}{\delta\sigma_P}$

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}

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



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.

Plan for experiment at J-PARC

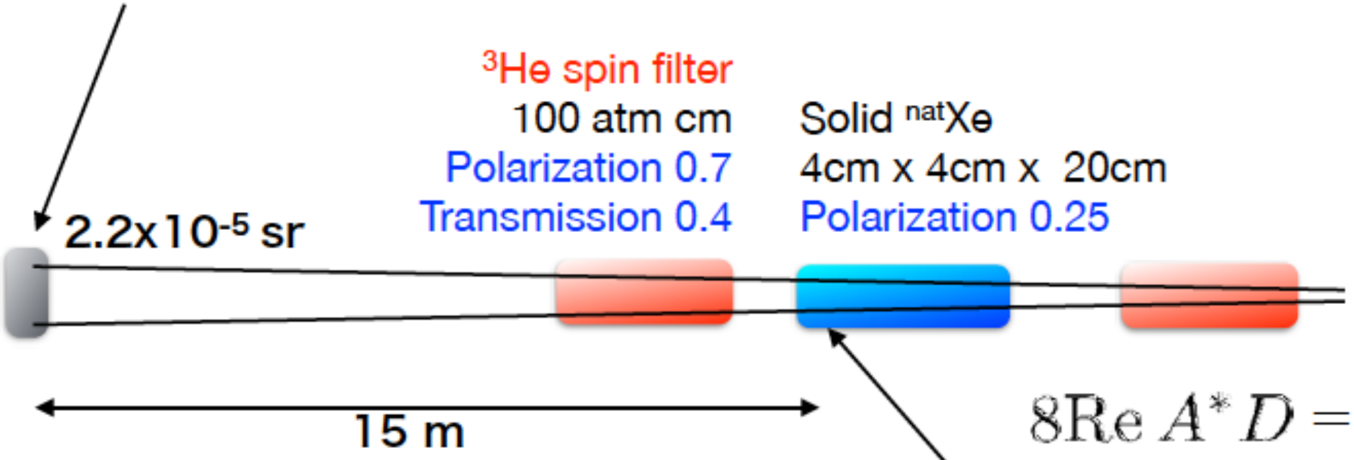
Experimental plan

p-wave resonance $E_n = 3.2$ eV

$\Gamma_n = 0.1$ eV

10^{11} n cm^{-2} s^{-1} sr^{-1} eV^{-1} MW^{-1}

J-PARC BL07（Poisoned Moderator）



2.2×10^{-5} sr

^{3}He spin filter
100 atm cm
Polarization 0.7
Transmission 0.4

Solid ^{nat}Xe
4cm x 4cm x 20cm
Polarization 0.25

epi-thermal neutron detector

15 m

$$8 \mathrm{Re}\, A^* D = 1.0\times10^{-6}$$

$$\kappa(J) = 1$$

$$\frac{w}{v} = \frac{g_{\mathrm{CP}}}{g_{\mathrm{P}}} = 10^{-3}$$

7 x 10^6 n s^{-1} at sample position

~ 5 days

NOPTREX collaboration (Nagoya U +…) is becoming serious

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

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

2. Specific theoretical ideas (axions, extra dimensions for gravity) imply new interactions at ~mm-μm scales

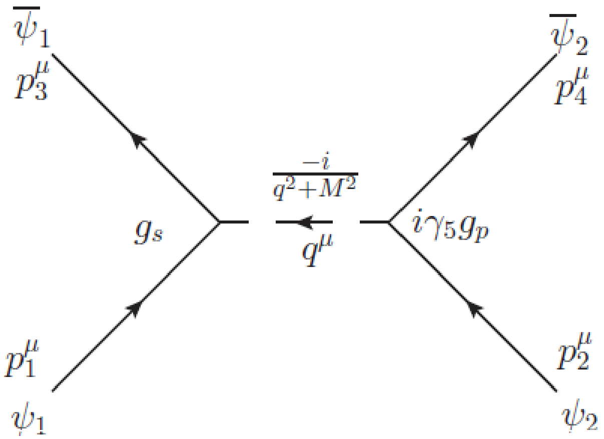
3. Dimensional analysis: dark energy->100 microns

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

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))

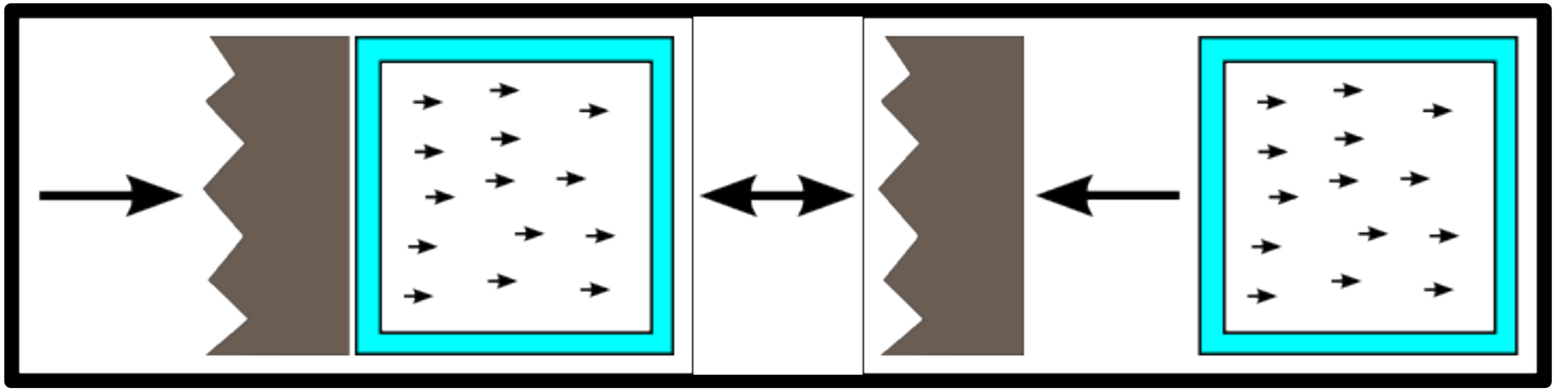
Induces an interaction between polarized and unpolarized matter

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

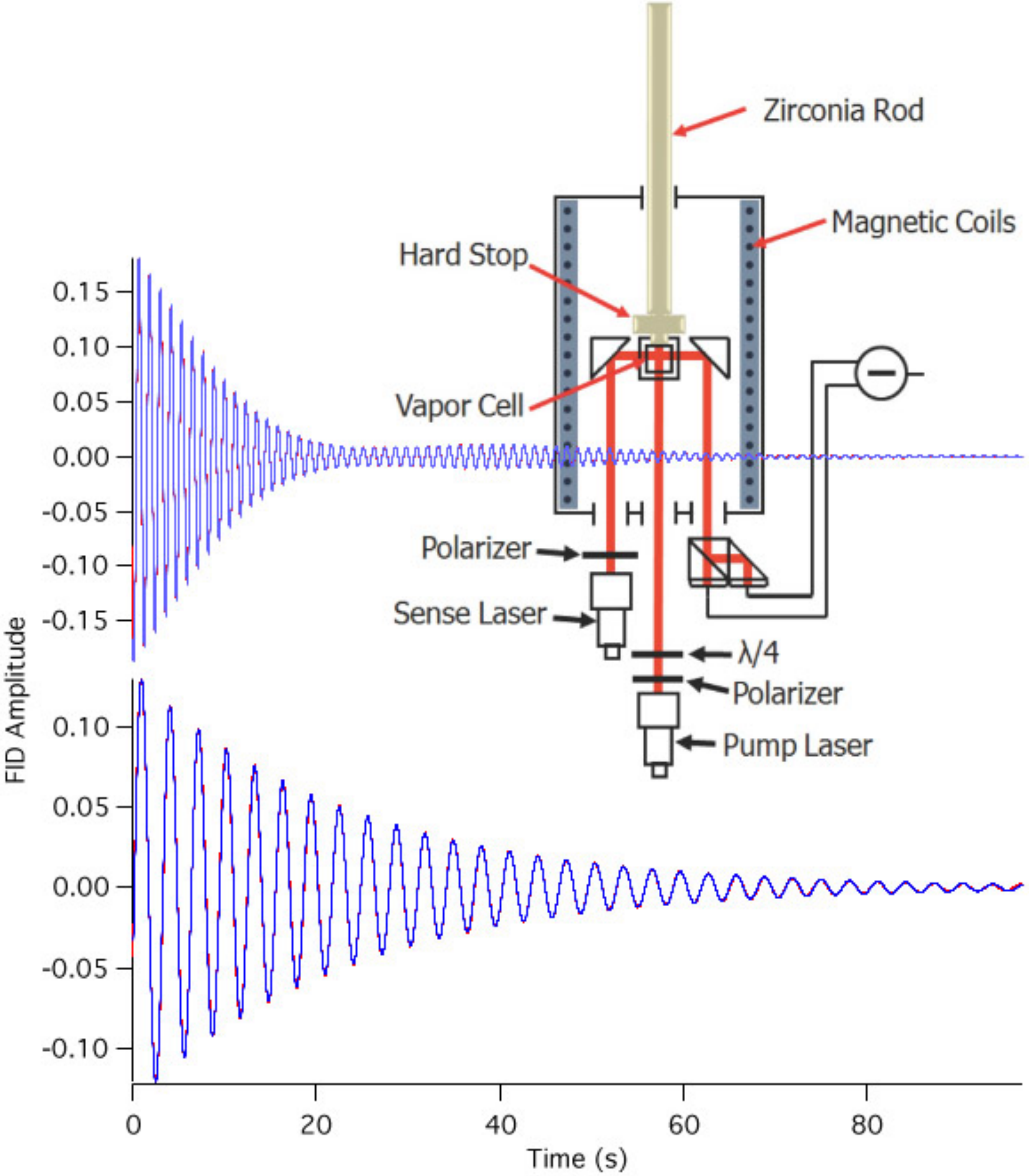
PHYS. REV. LETT. 111, 102001 (2013)

Experimental Setup

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

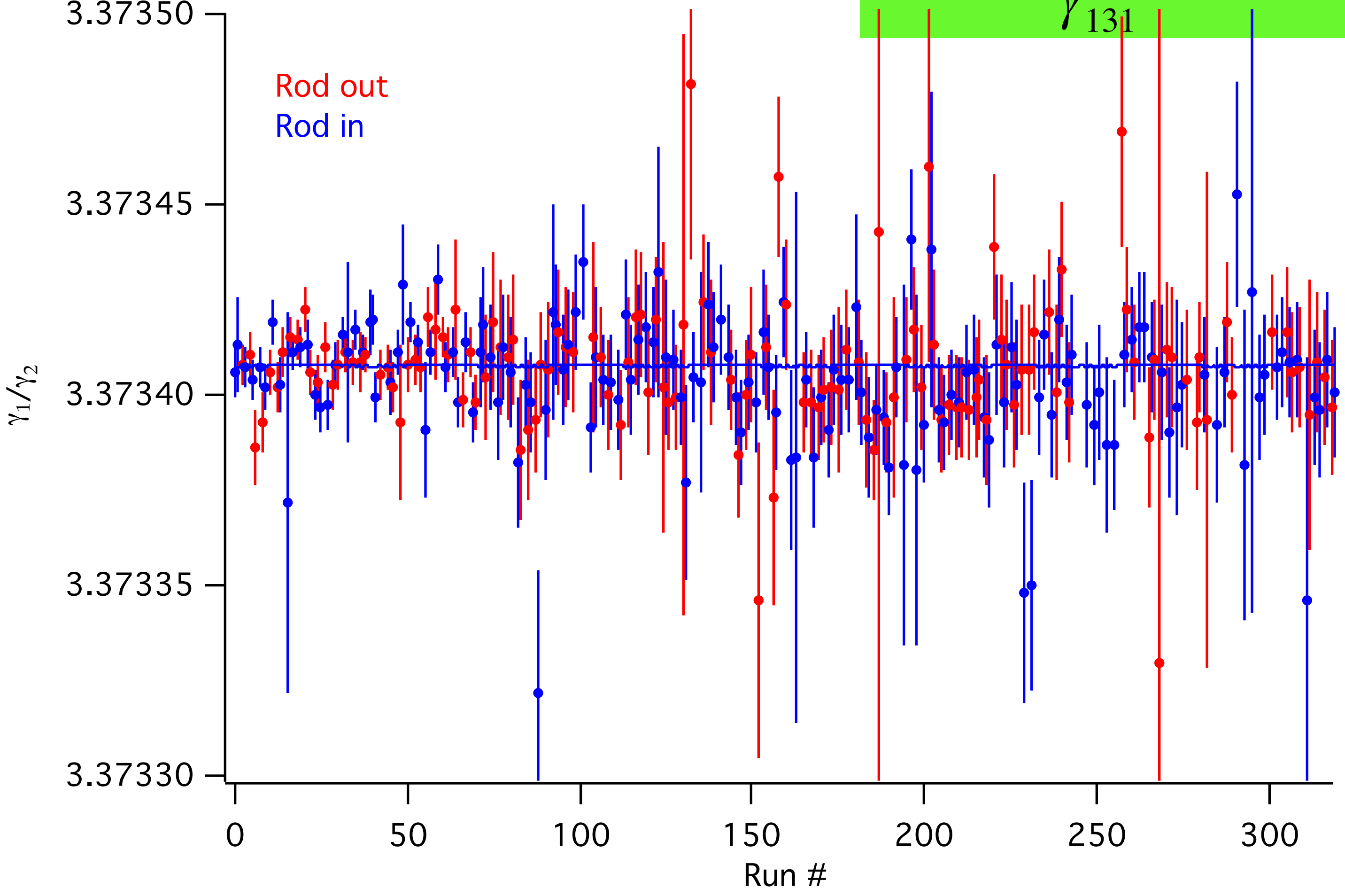
The Rb magnetometer measures the Free Induction Decay (FID) of the two xenon isotopes as an amplitude modulation of the Rb spin projection.

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

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



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

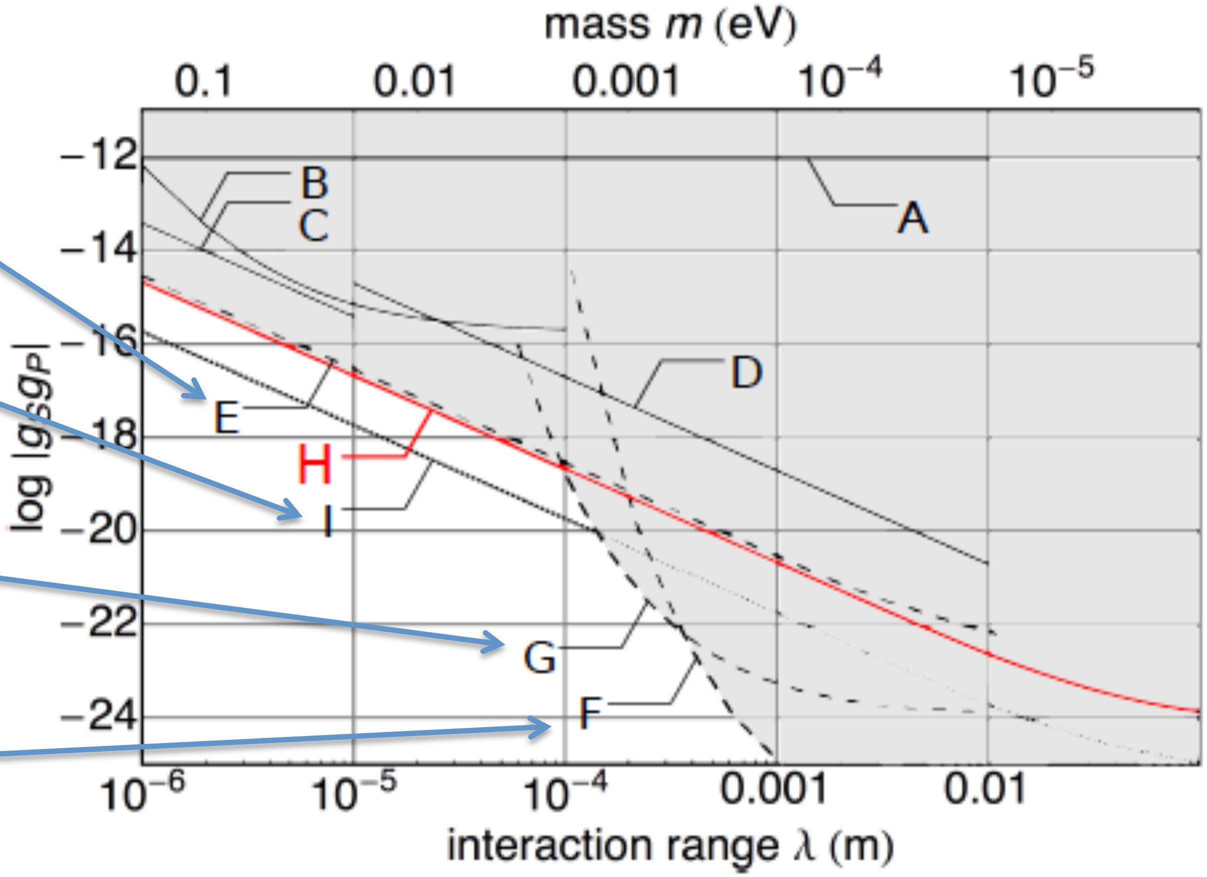
Constraints on Monopole-Dipole Interactions

A. Pethkhov et al, PRL 105, 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)

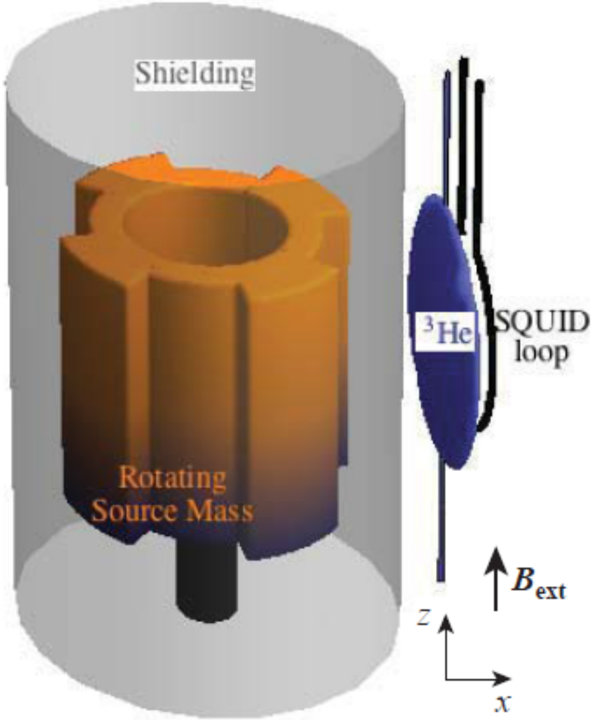


Constraints on general P-odd T-odd interactions in mm range

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).

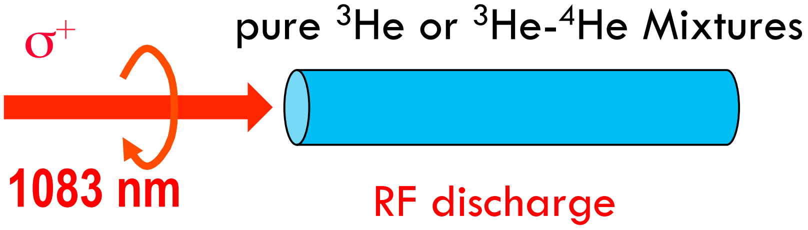


ARIADNE Collaboration:

Asimina Arvanitaki (Perimeter)
Aharon Kapitulnik (Stanford)
Eli Levenson-Falk (Stanford)
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)

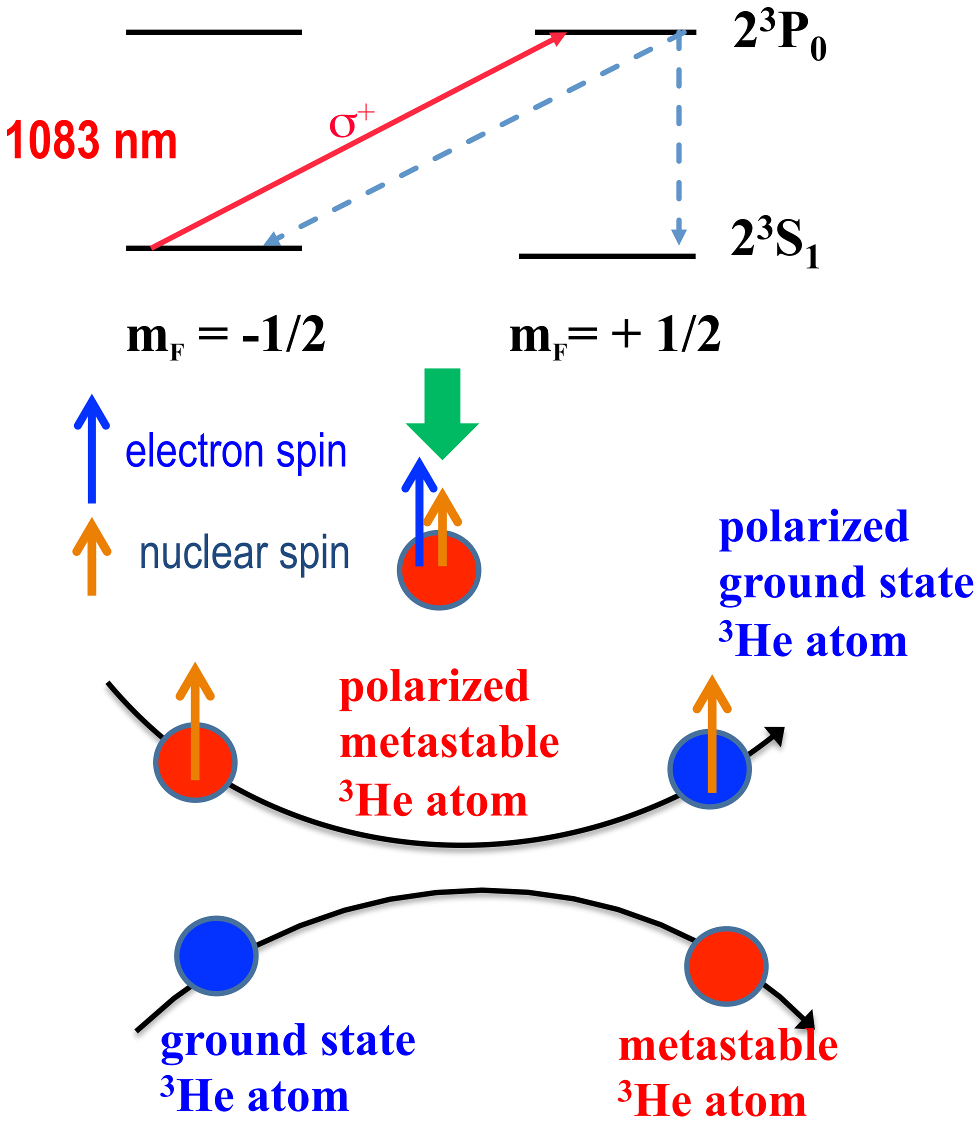
NSF PHY-1306942

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*

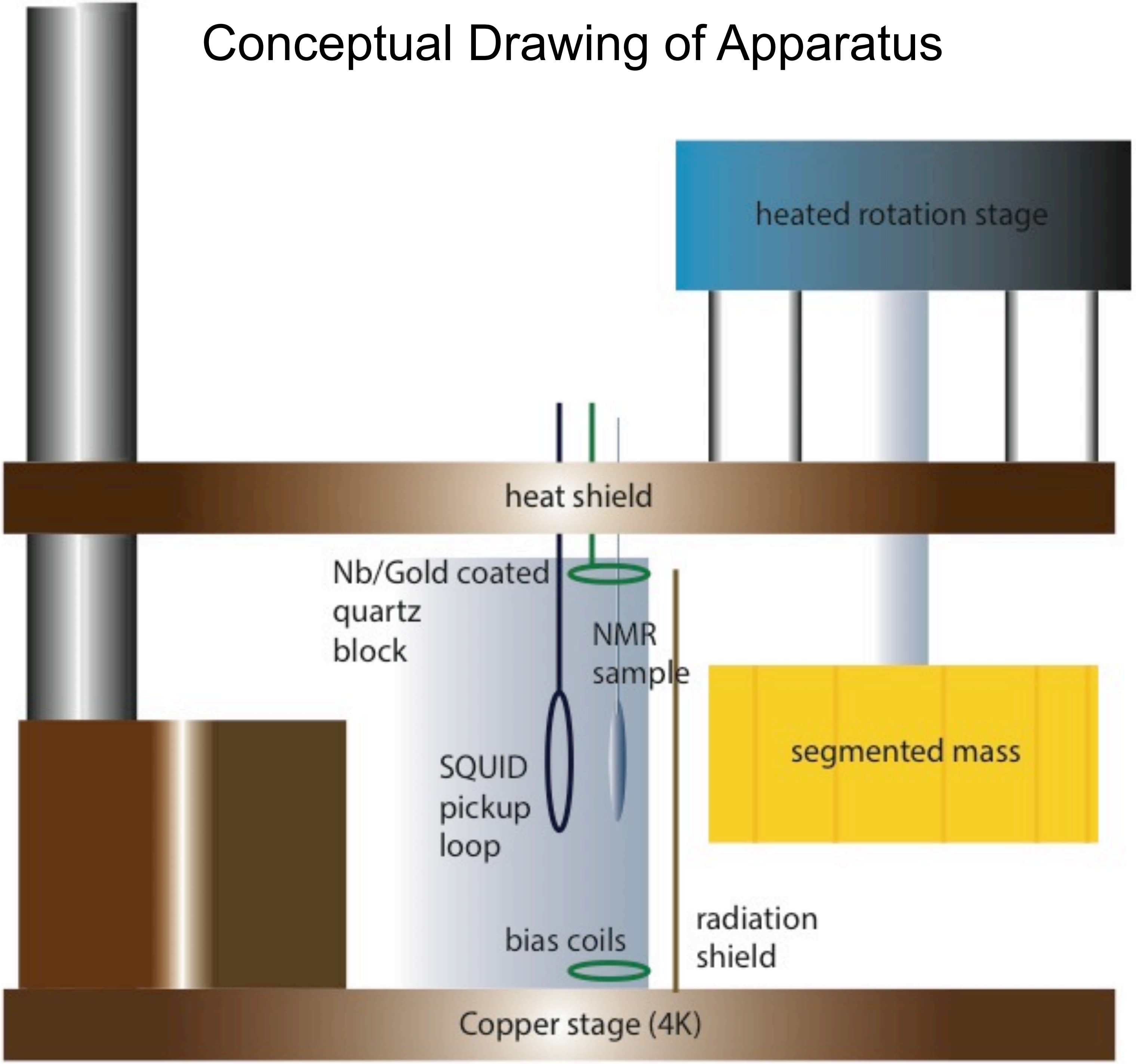


METASTABILITY EXCHANGE

Excitation exchanged in fast collision

Nuclear spins unperturbed

Conceptual Drawing of Apparatus



Use laser polarized 3He gas at 4K Larmor frequency: ω

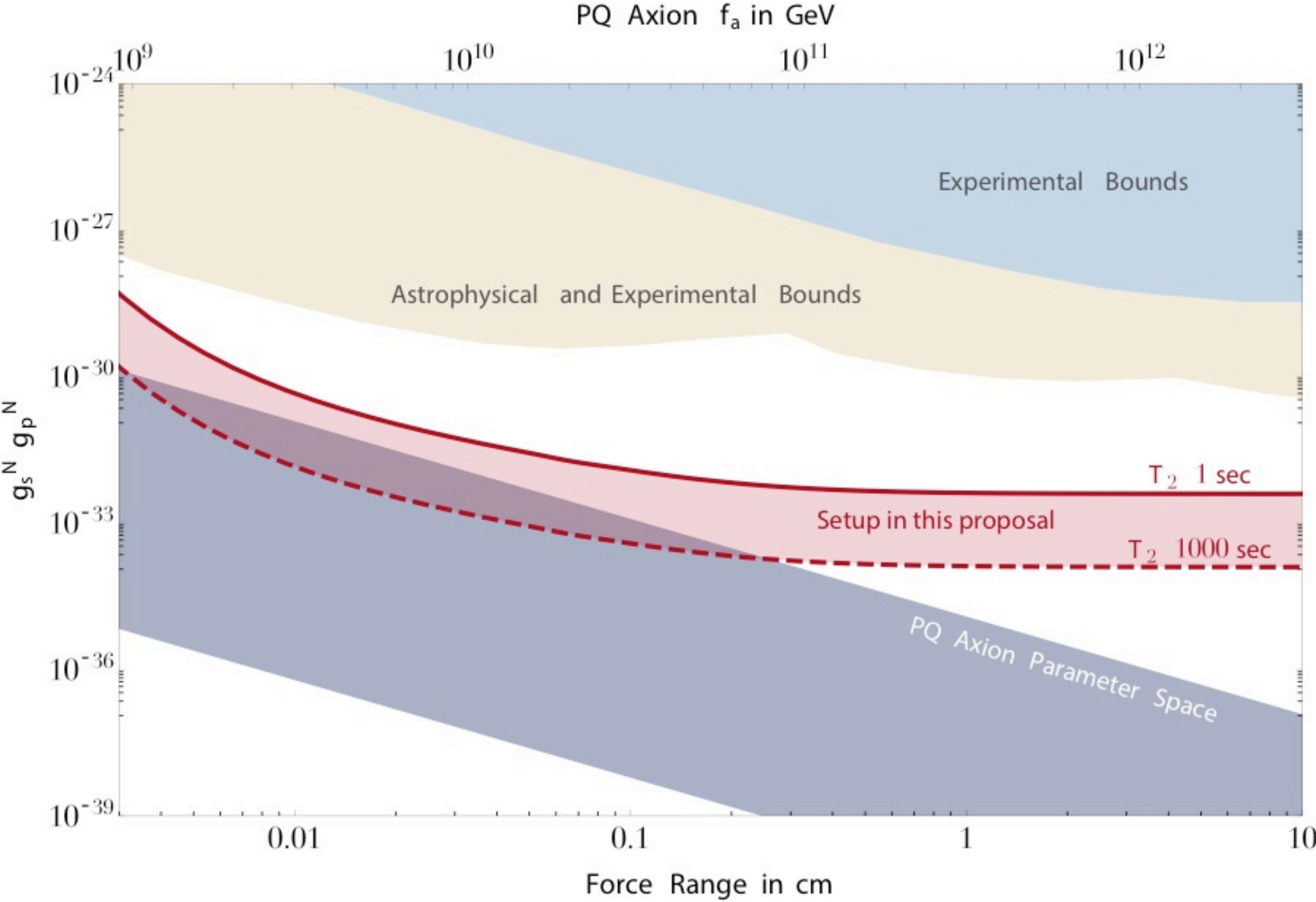
Rotating tungsten mass oscillates force in resonance at nω

Superconducting B shield

Ellipsoidal sample

SQUID magnetometry

ARIADNE SCIENTIFIC REACH FOR ALPS



Conclusions

Any discovery of a new source of T violation is of fundamental importance for physics, and possibly also for cosmology

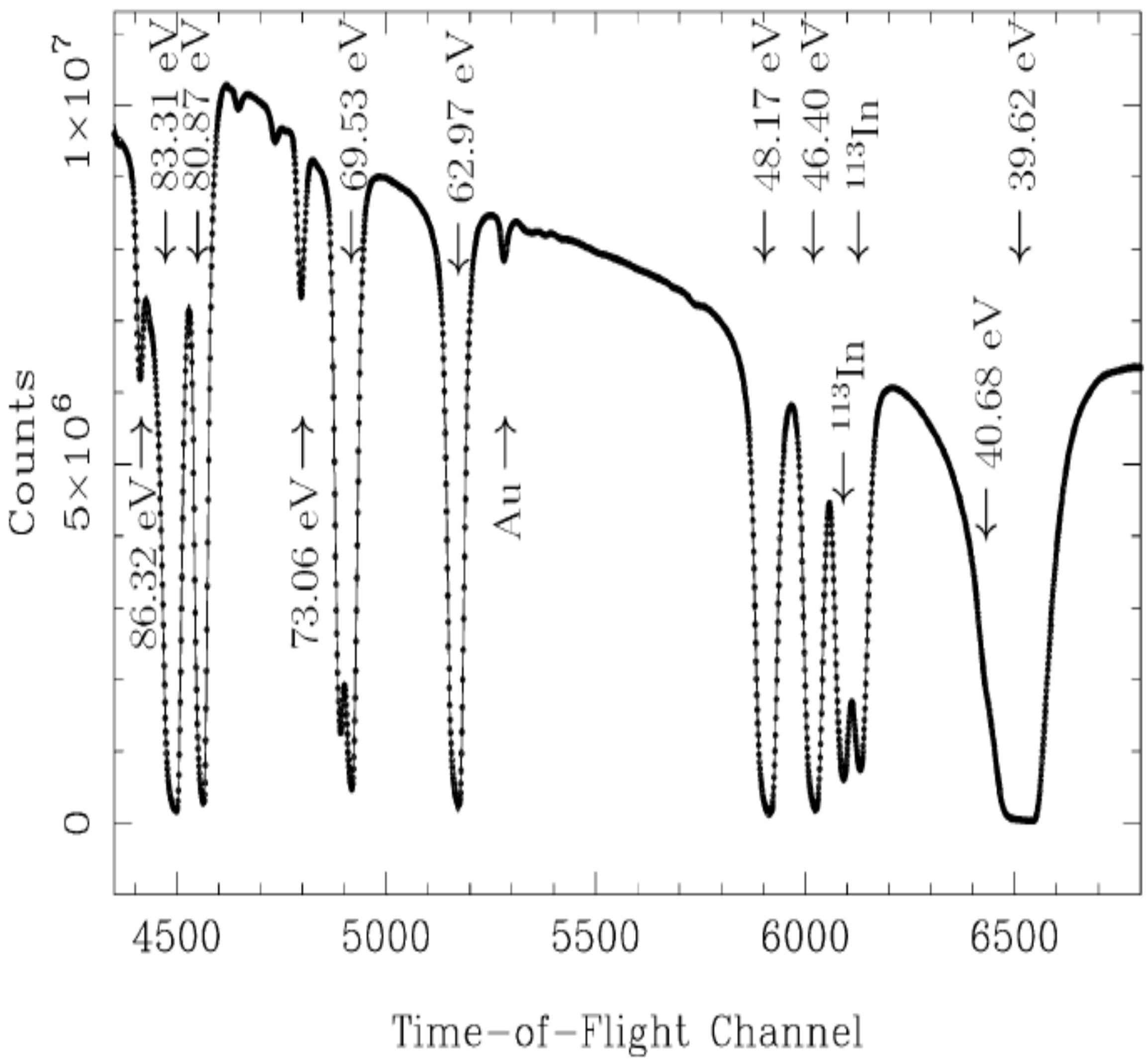
EDMs and T violation in epithermal neutron resonances are both true “null tests” for T violation and are sensitive searches for T in strongly interacting systems

ratio (T-odd amplitude in nucleon/strong amplitude)~10^{-11}-10^{-12}

Excitation energy (EDMs)~0 Excitation energy (n resonances)~few MeV

We usually think that the new physics should come from small virtual effects from high energy, but be careful: it could be a very weakly-coupled effect at low energy as well.

Neutron Time-of-Flight spectrum in transmission through Indium

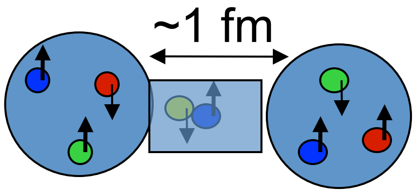


Excited state energies=~6 MeV +(eV->keV)

Narrow resonances (~100 meV)

High density of levels per unit energy

N- N Weak Interaction: Size and Mechanism

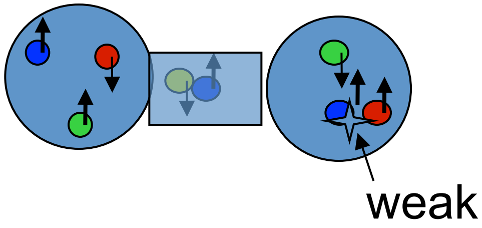


NN repulsive core → 1 fm range for NN strong force

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

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

QCD possesses only vector quark-gluon couplings → conserves parity



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

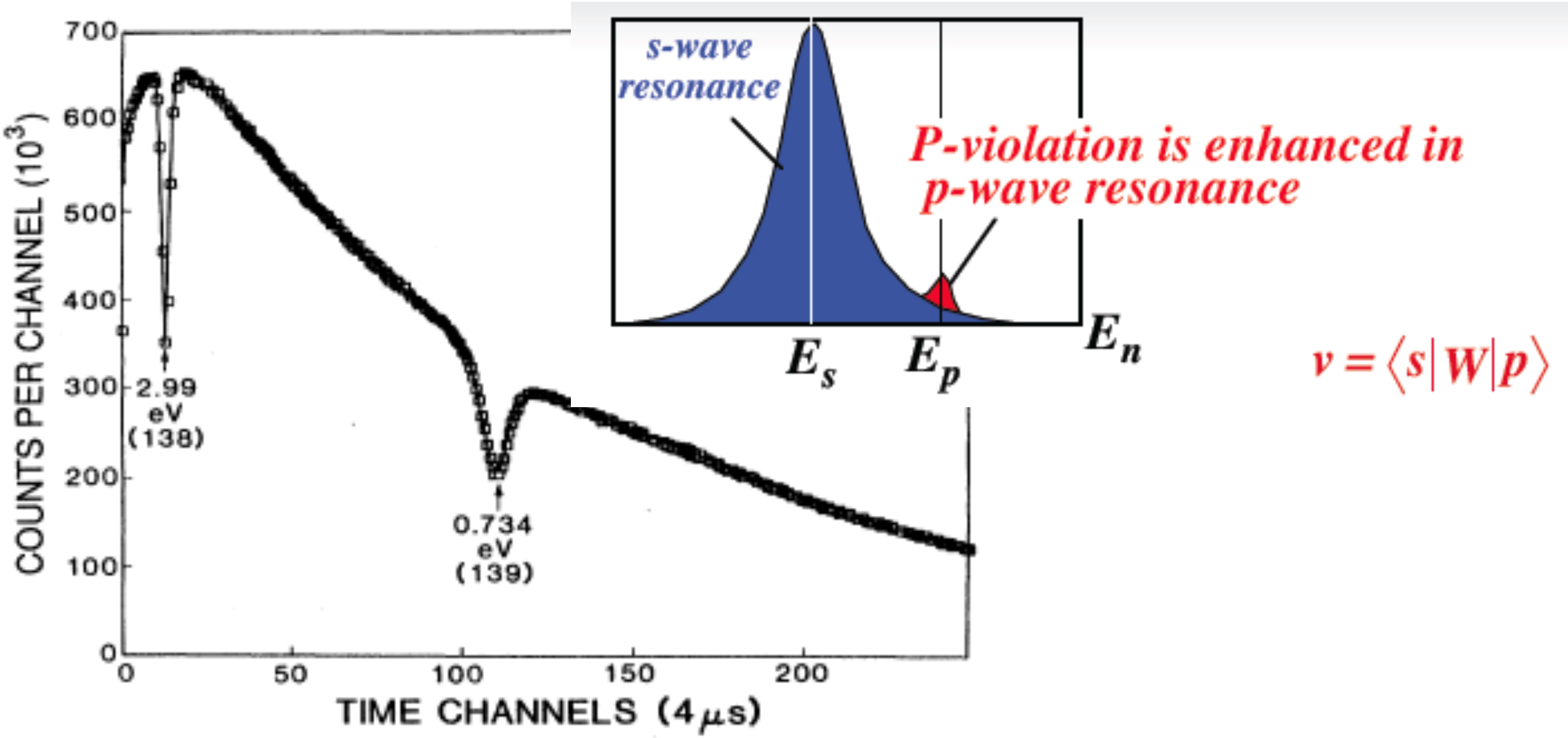
Relative strength of weak / strong amplitudes: $\left(\frac{e^2}{m_W{}^2}\right)/\left(\frac{g^2}{m_\pi{}^2}\right) \approx 10^{-6}$

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

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

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

10^6 amplification!



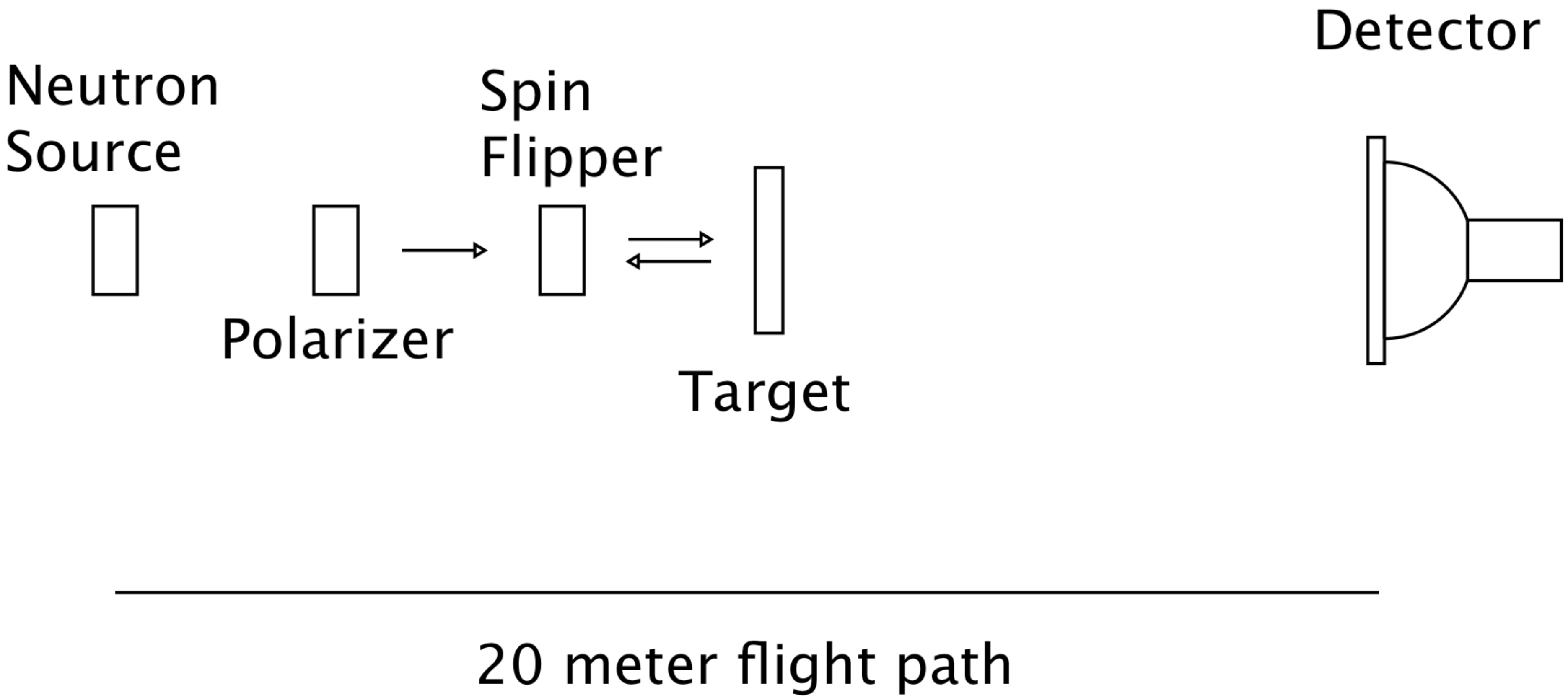
$v = \langle s | W | p \rangle$

How? (1) Admixture of (large) s-wave amplitude into (small) p-wave ~1/kR~1000

(2) Weak amplitude dispersion for 10^6 Fock space components ~sqrt(10^6)=1000

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

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



Neutron Source

Polarizer

Spin Flipper

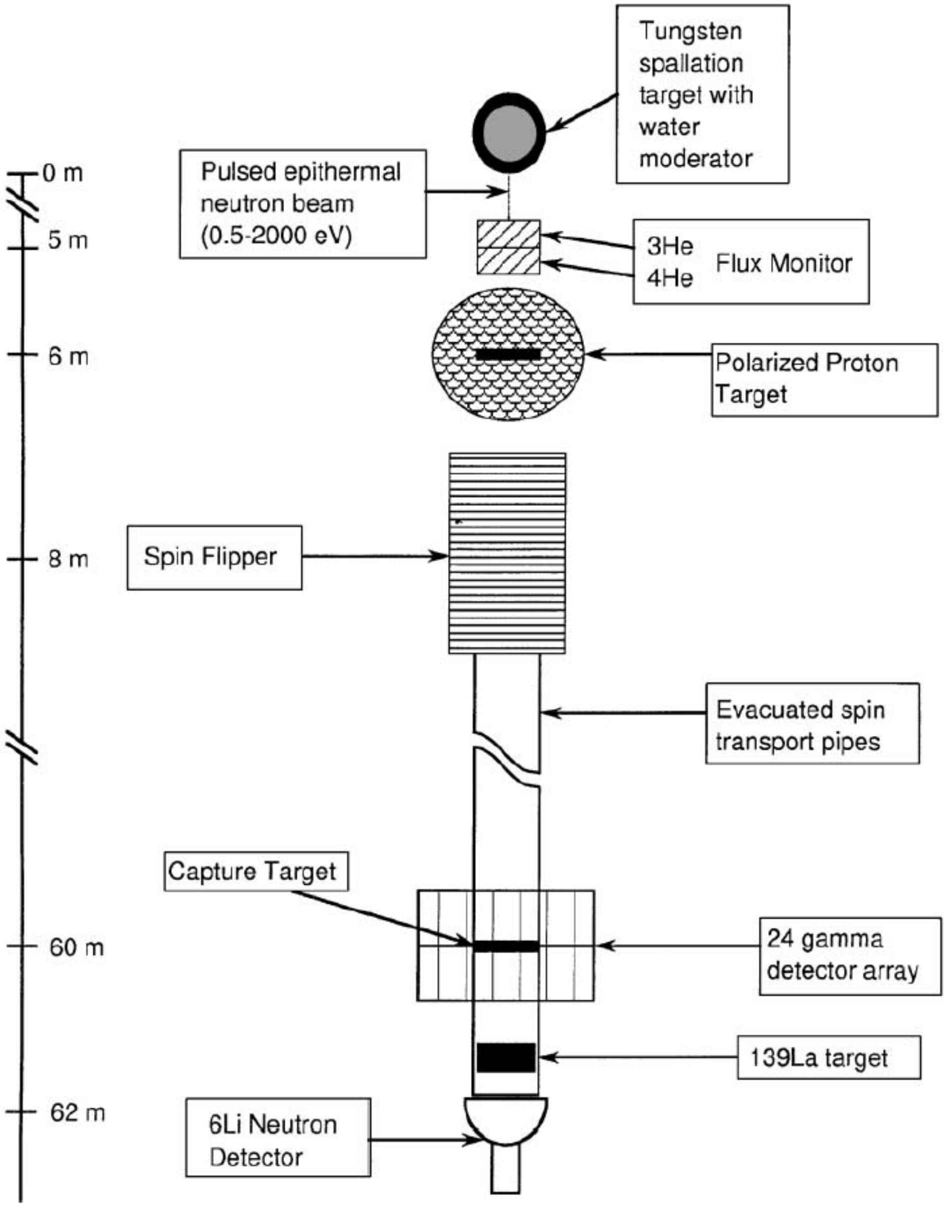
Target

Detector

20 meter flight path

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

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

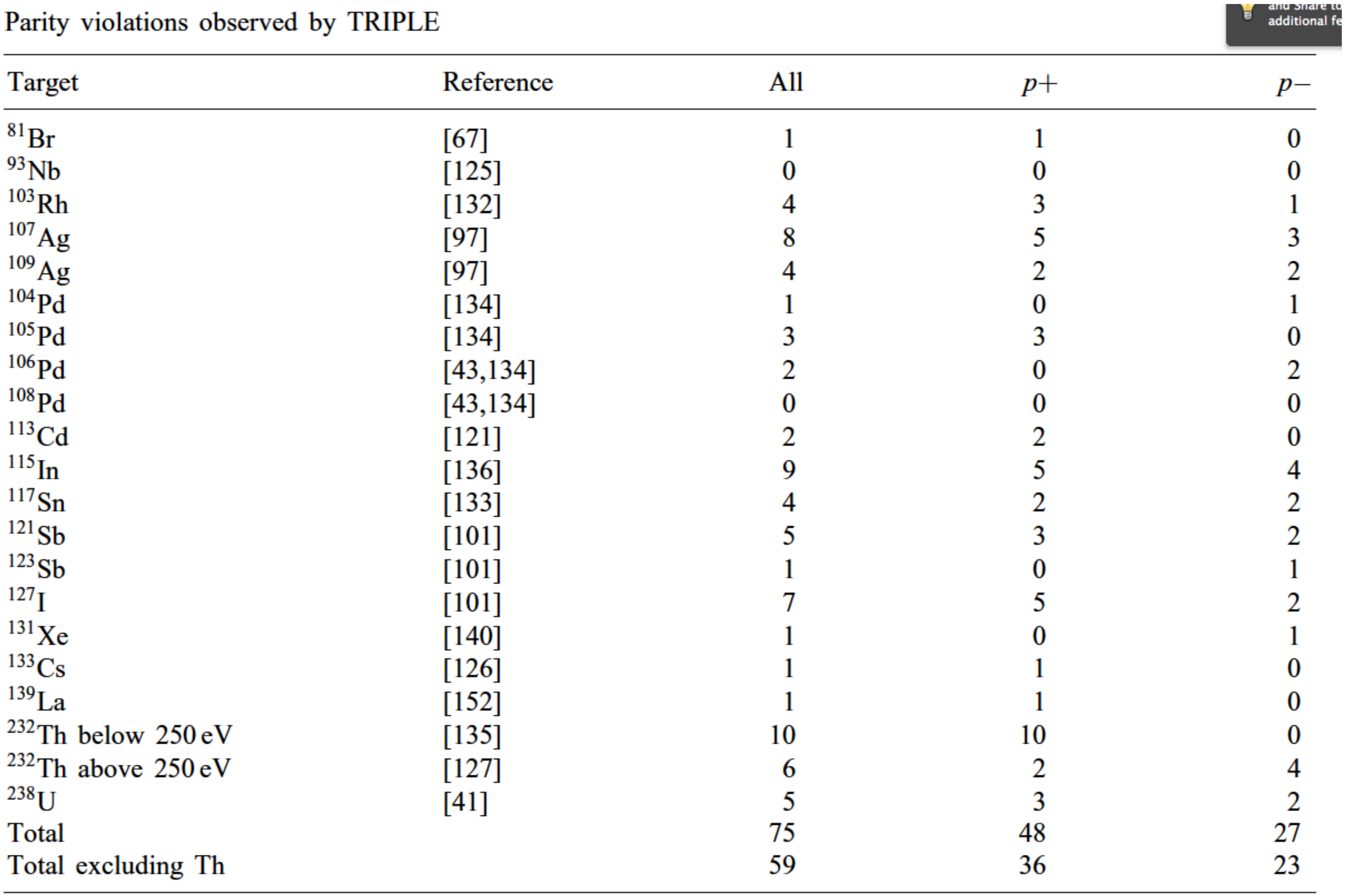


Apparatus for PV at a spallation neutron source

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

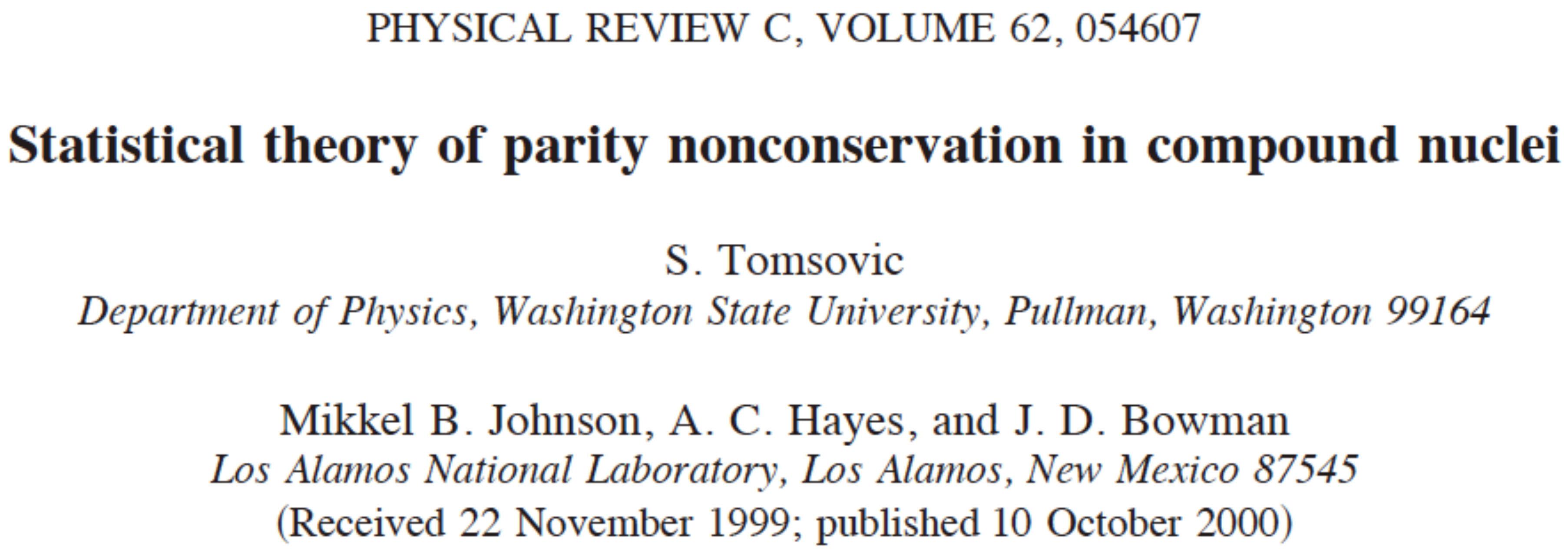
Look for $\sigma.k$ dependence of total cross section

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



Parity violations observed by TRIPLE

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



PHYSICAL REVIEW C, VOLUME 62, 054607

Statistical theory of parity nonconservation in compound nuclei

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(Received 22 November 1999; published 10 October 2000)

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

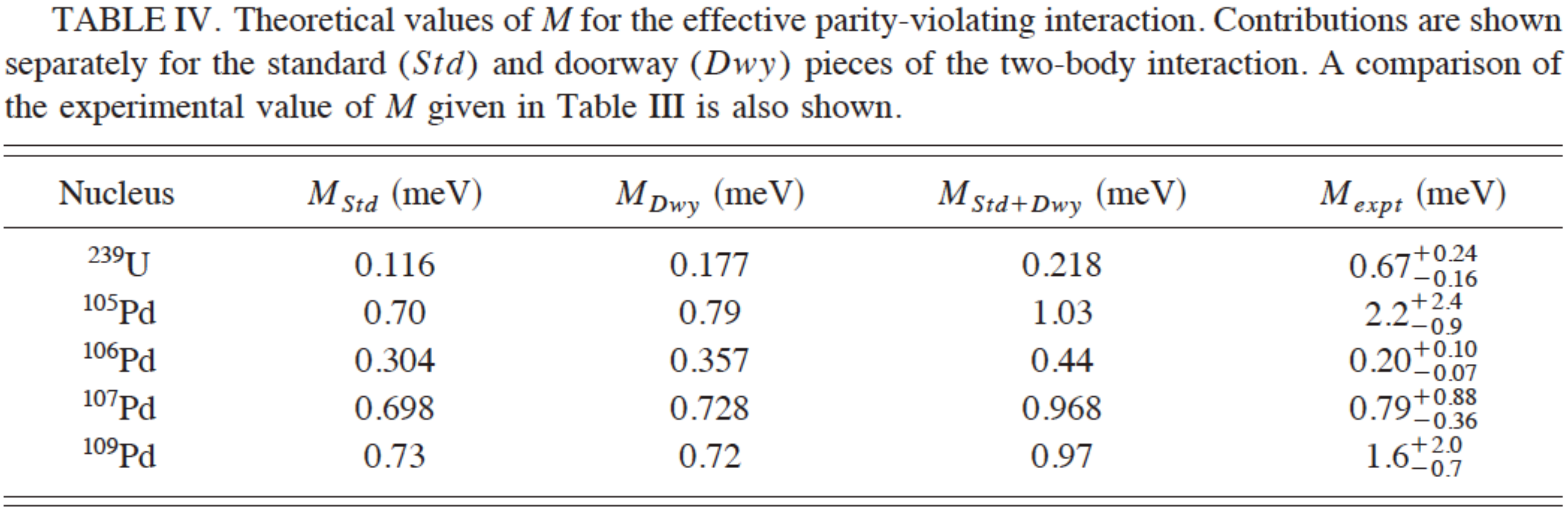
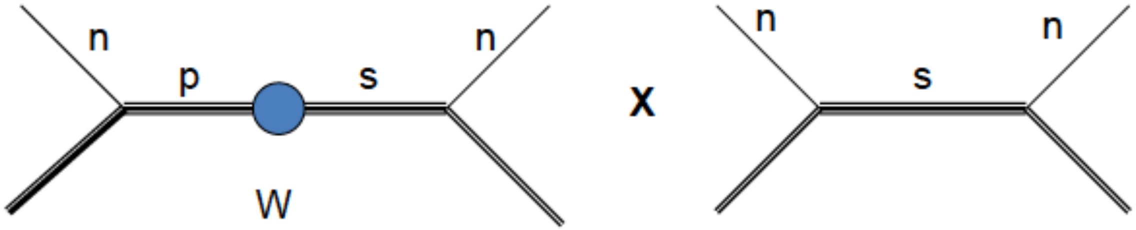


TABLE IV. Theoretical values of M for the effective parity-violating interaction. Contributions are shown separately for the standard (Std) and doorway (Dwy) pieces of the two-body interaction. A comparison of the experimental value of M given in Table III is also shown.

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

P- and T-violation in Neutron transmission



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

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

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

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

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

T violation in Neutron Optics

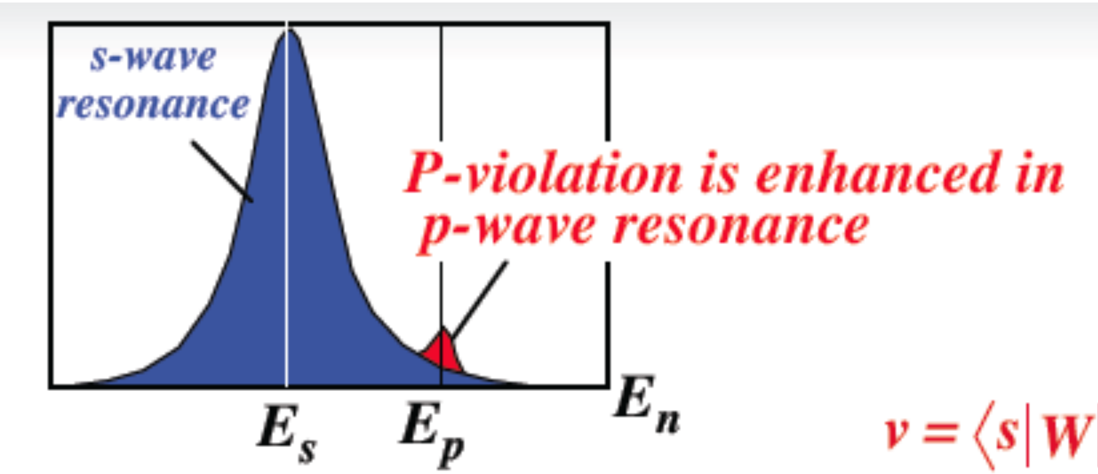
- T – odd term in FORWARD scattering amplitude (a null test, like EDMs) with polarized n beam and polarized nuclear target
- P-odd/T-odd (most interesting) $\vec{\sigma_n} \cdot (\vec{k_n} \times \vec{I})$
- Amplified on select P-wave epithermal neutron resonances by ~5-6 orders of magnitude
- Estimates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

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

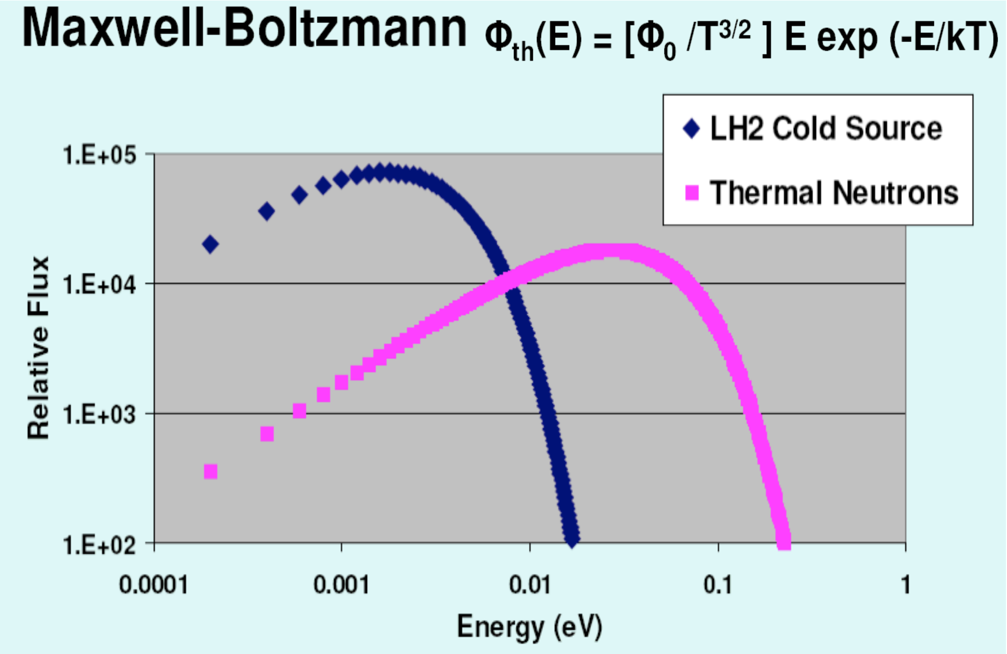
- The nuclei of interest, resonance energies, and P-odd asymmetry amplifications are measured

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

Why is a pulsed spallation neutron source important for TREX?



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



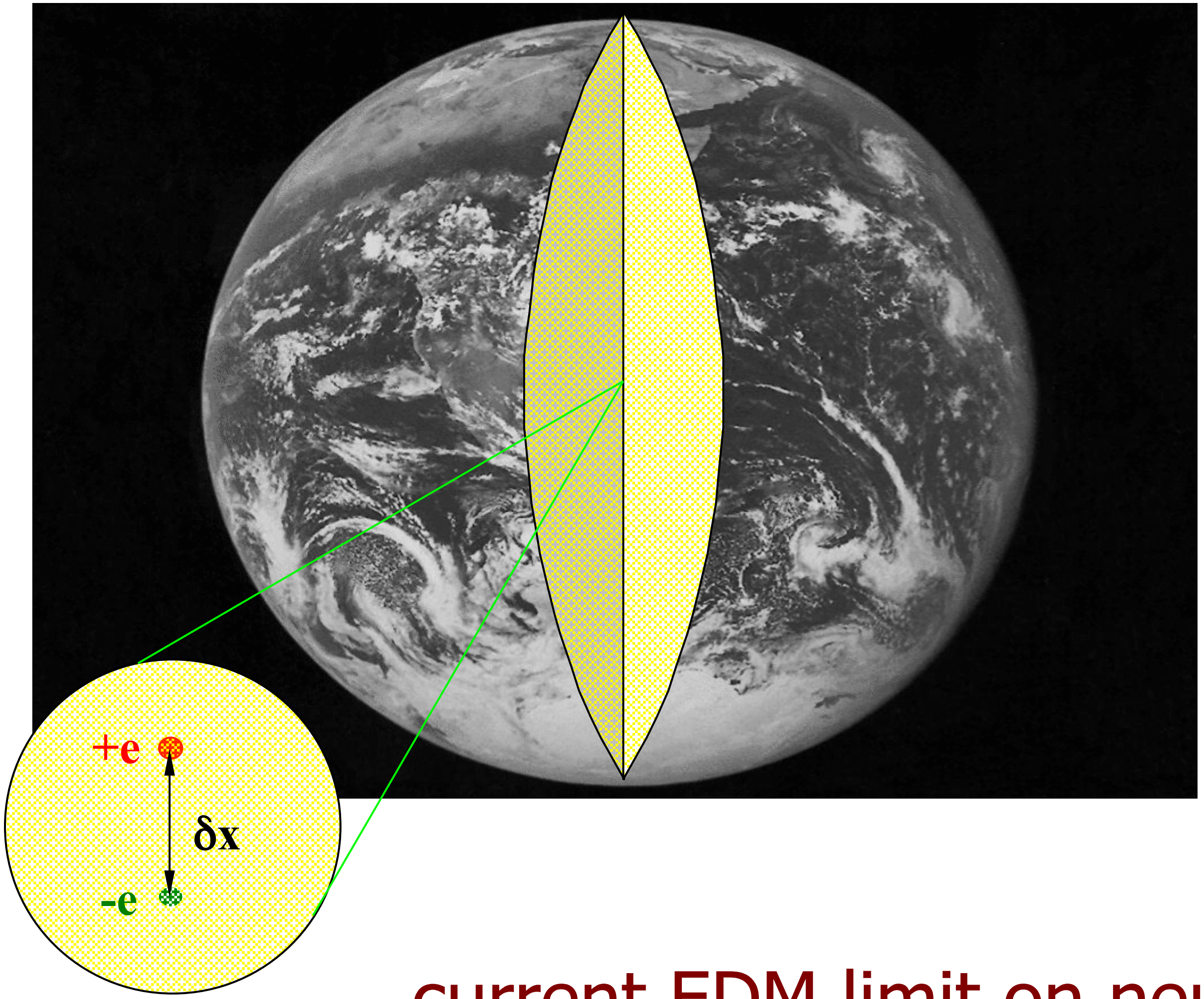
resonance energy ~eV, resonance width ~meVs

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

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

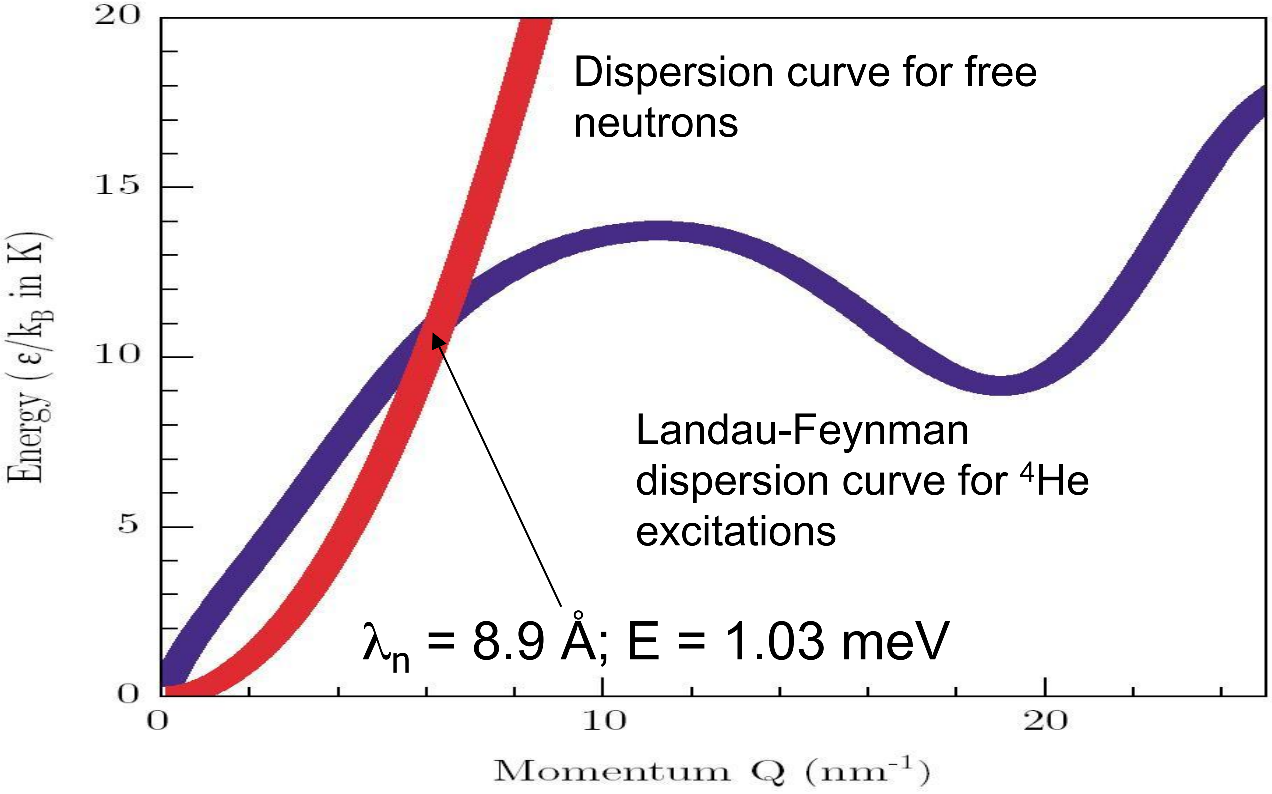
>~10^4 more of these "off-resonance" neutrons

Reality check



... current EDM limit on neutron would correspond to charge separation of
$\delta x \approx 10\ \mu$

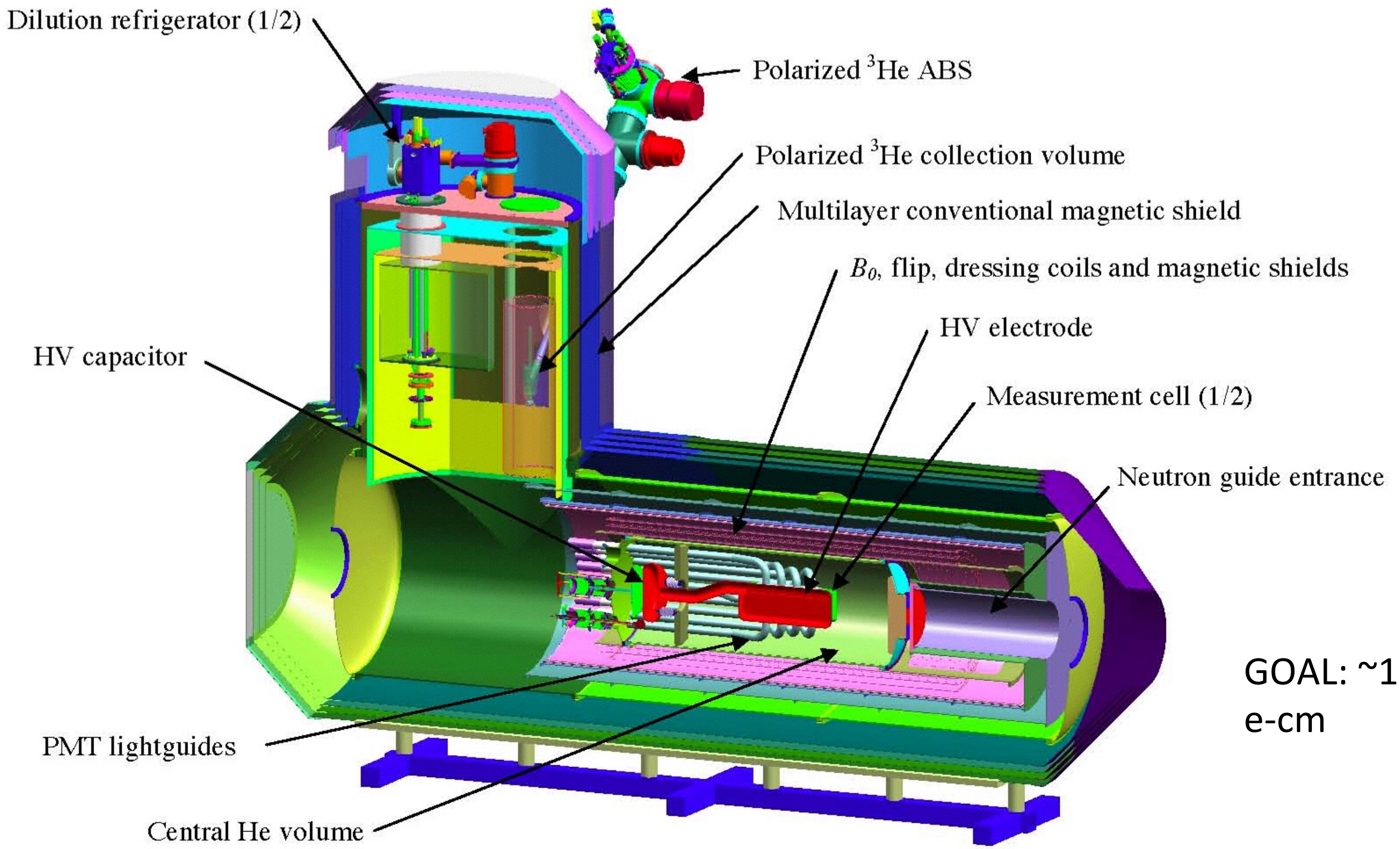
UCN production in liquid helium



R. Golub and J.M. Pendlebury
Phys. Lett. **53A** (1975),
Phys. Lett. **62A** (1977)

- 1.03 meV (11 K) neutrons downscatter by emission of phonon in liquid helium at 0.5 K
- Upscattering suppressed: Boltzmann factor $e^{-E/kT}$ is small if T<<11K

nEDM experiment at SNS



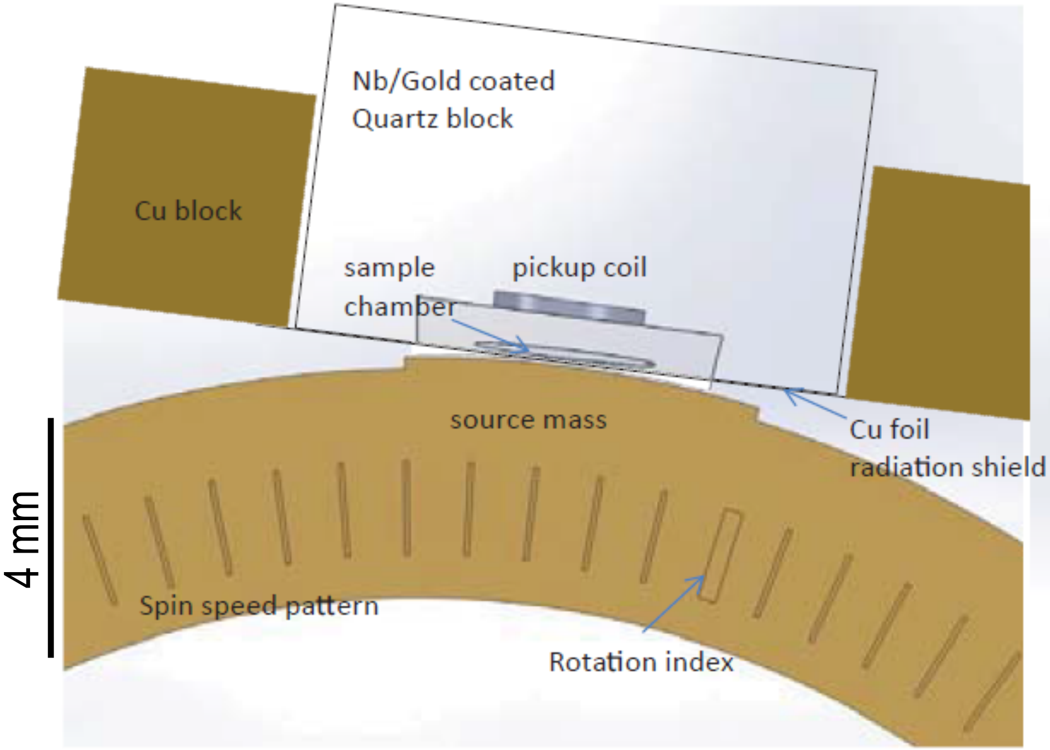
GOAL: ~1E-28 e-cm

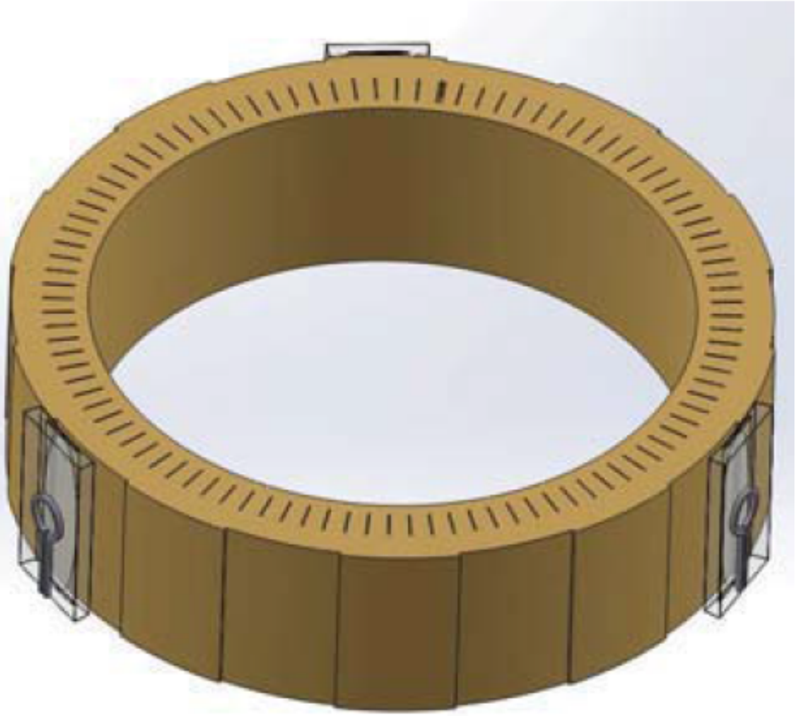
Figure–of-merit ~ $E(NT)^{1/2}$

New approach aims at N → 100 N, T → 5 T, E → 5 E

APPARATUS DETAIL

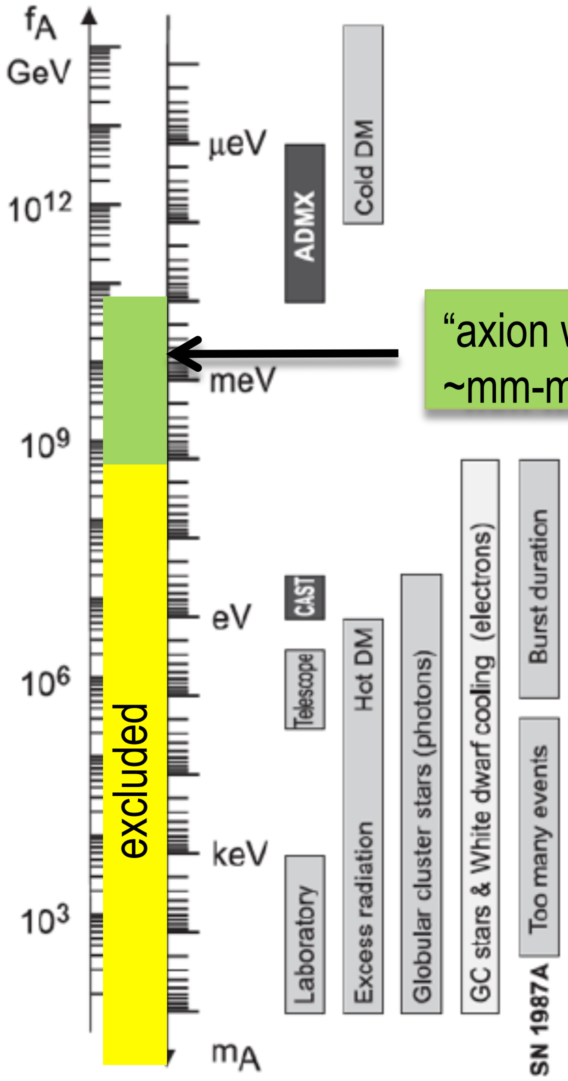
Experimental parameters:
11 segments
100 Hz nuclear spin precession frequency
2 x 10^{21} / cc ^{3}He density
10 mm x 3 mm x 150 µm volume
Separation 200 µm
Tungsten source mass (high nucleon density)





QCD AXION PARAMETER SPACE

$m_A f_A \approx 6$ MeV - Allows for a nice 1D plot:



"axion window" corresponds to ~mm-micron interaction ranges

Lab and Astrophysical bounds

Energy loss from stars puts strict upper limits on Axion coupling