Search for P and T Violation in Excited Nuclear Systems

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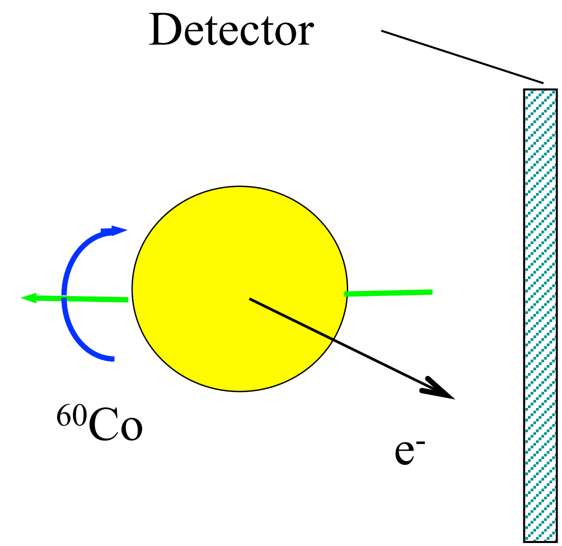
What is T violation and why is it interesting (a reminder)

Sensitivity to T violation of precision experiments in strongly-interacting systems

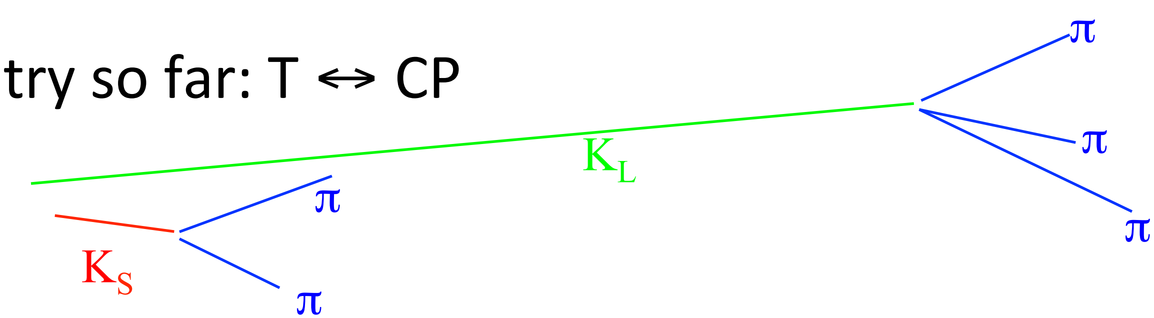
Polarized neutron optics test of T invariance: the idea

QUESTION: can T-odd "noise" from local symmetry violation in exotic QCD phases "leak into" low energy observables in nuclei?

P, CP, T, and CPT



- Parity violation (1956)
  - only in weak interaction
- CP violation (1964)
  - parametrized but not understood
  - only seen so far 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?)

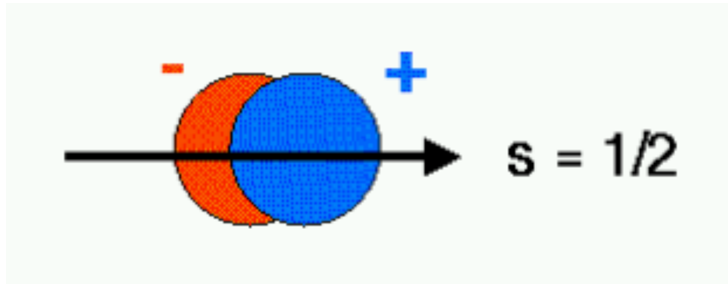
A.D. Sakharov, JETP Lett. 5, 24-27, 1967

Searches for T violation in strongly-interacting systems at low energy:

Electric Dipole Moment Searches (E~0)

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

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:

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

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

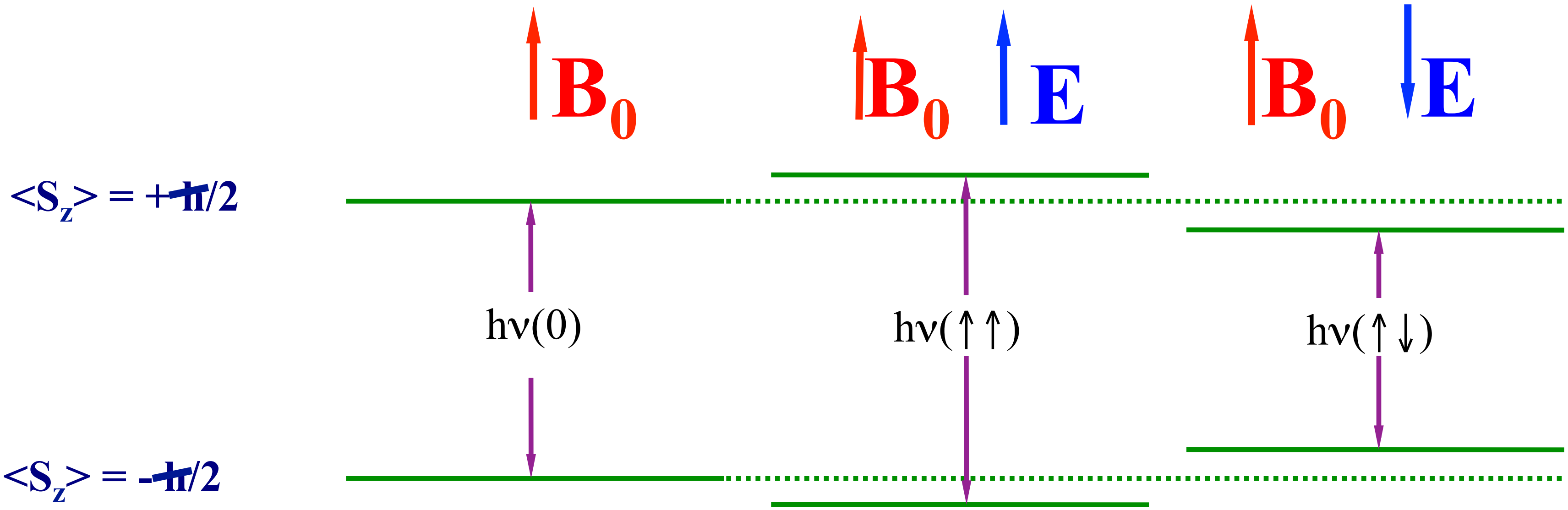
Under a time-reversal operation:

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

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

EDMs are "null tests" of time reversal invariance (no "final state effects" can fake an EDM)

EDM Measurement Principle/Sensitivity



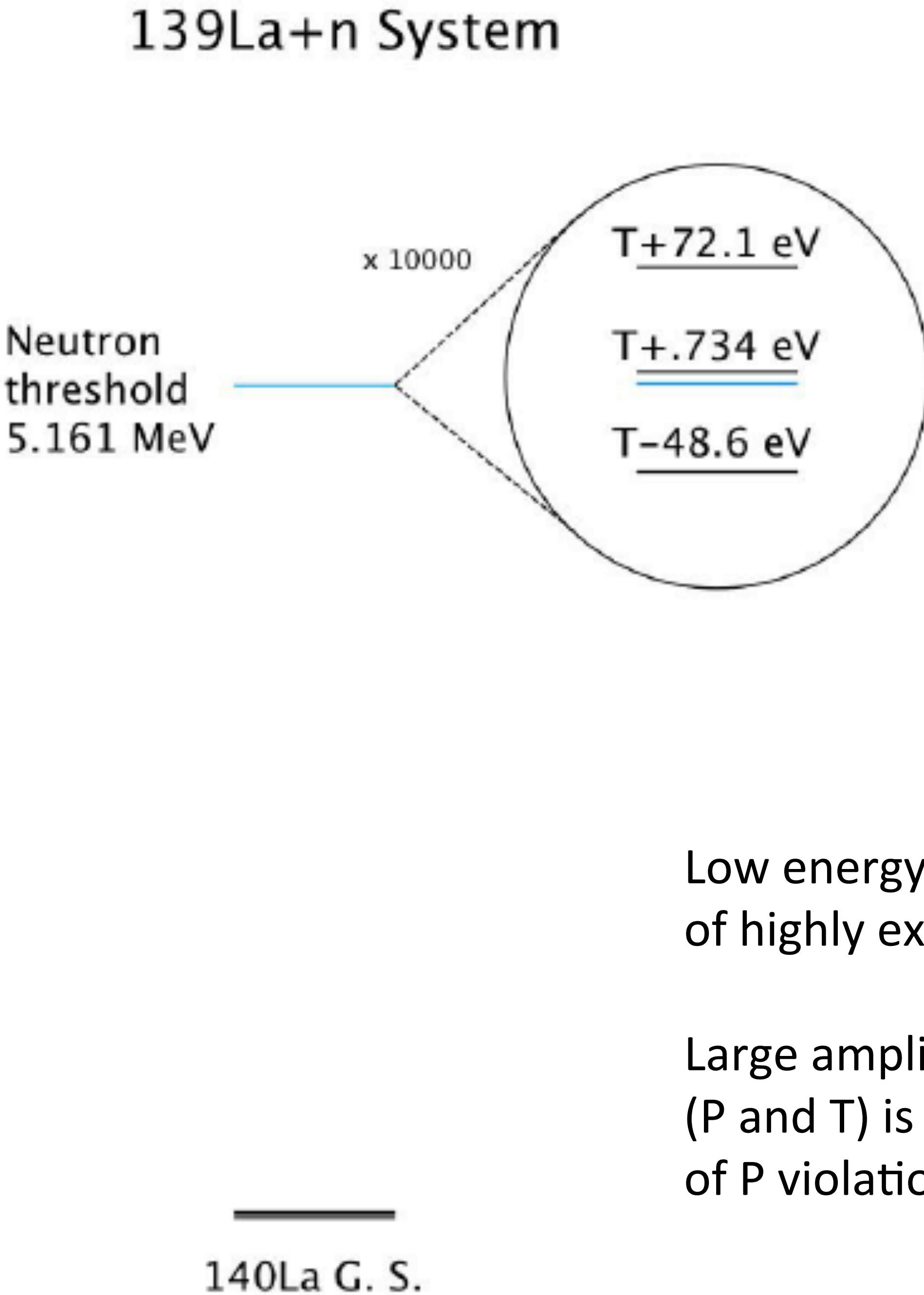
$$\nu(\uparrow\uparrow) - \nu(\uparrow\downarrow) = -4\,E\,d/\,h$$

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

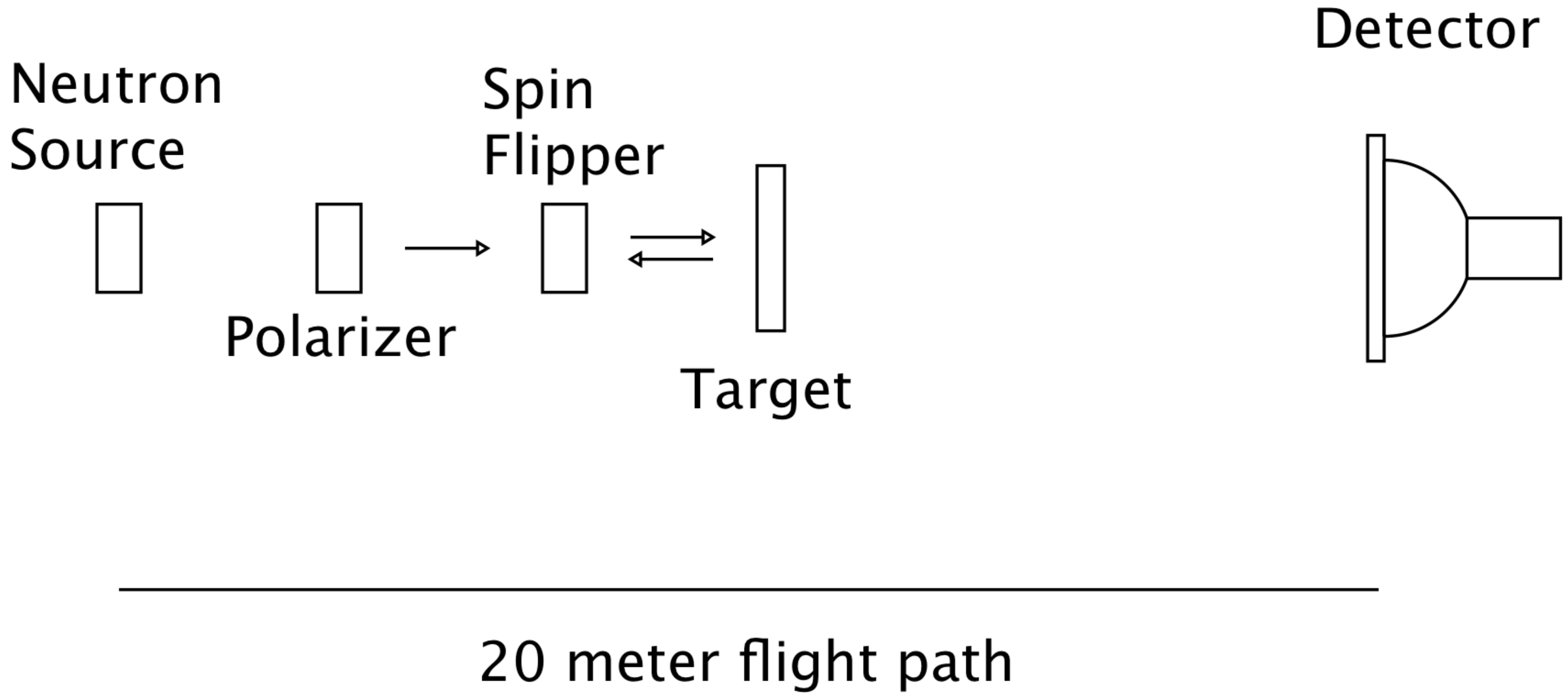


Compound-Nuclear States in ^{139}La+n system

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).

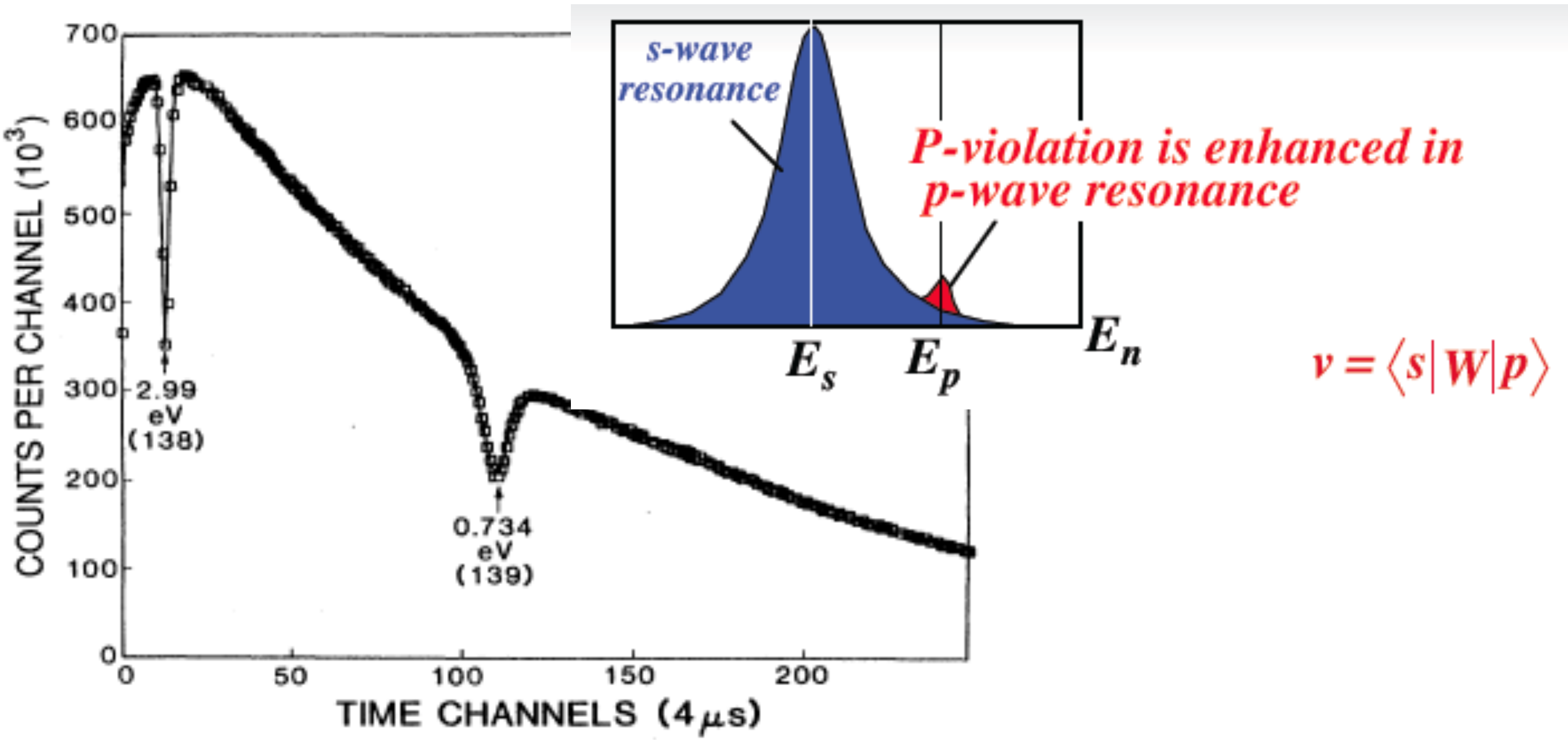
Quantitative analysis of distribution of parity-odd asymmetries conducted using nuclear statistical spectroscopy S. Tomsovic, M. B. Johnson, A. Hayes, and J. D. Bowman, Phys. Rev. C 62, 054607 (2000).

Large Parity Violation in the Compound Nucleus
~60 P-odd asymmetries measured

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

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



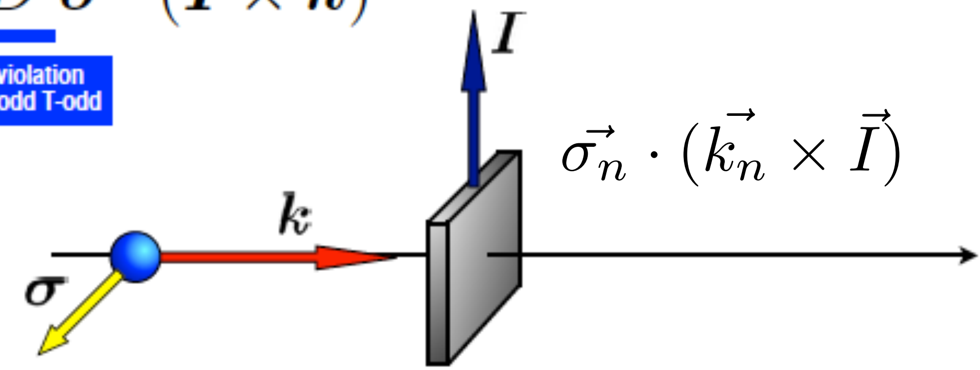
How? (1) Admixture of (large) s-wave amplitude into (small) p-wave ~1/kR~1000
(2) Weak amplitude dispersion for 10^6 Fock space components ~sqrt(10^6)=1000

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

Forward Scattering Ampliltude

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

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



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

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

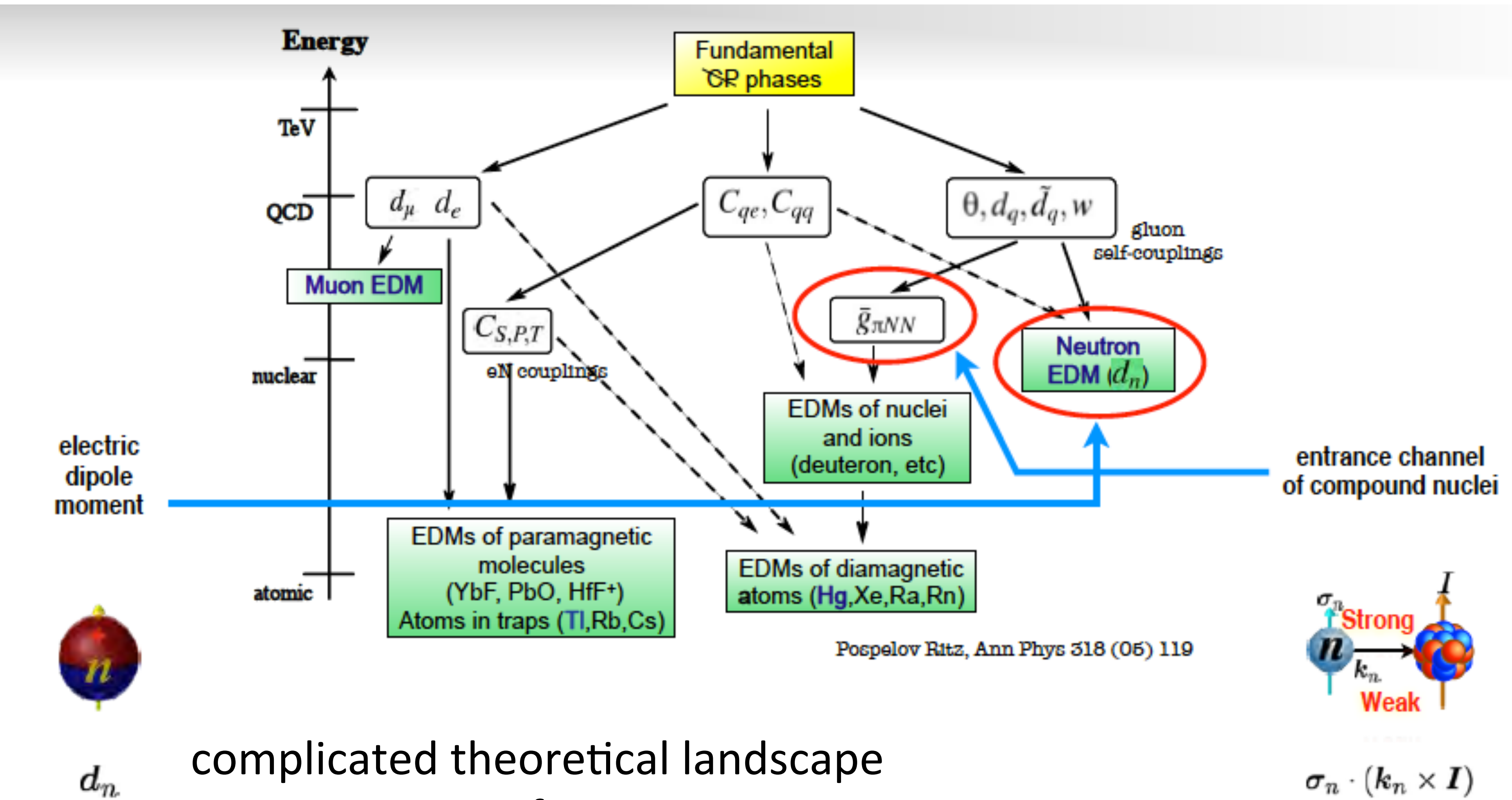
λ can be measured with a statistical uncertainty of ~1 10^{-5} in 10^7 sec at MW-class spallation neutron sources.

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

Excitation energy (~few MeV) is not zero.

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

T violation Searches with EDMs and Compound Nuclei



complicated theoretical landscape
important to perform experiments in many systems

Conclusions/Question

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

local symmetry violation in exotic QCD phases can make T-odd “noise”
ratio (T-odd noise from local symmetry violation/strong amplitude)~10^{-2}

local symmetry violation effects: do they completely go away in a different phase?

QUESTION: can T-odd “noise” from local symmetry violation in exotic QCD phases “leak into” low energy observables in nucleons/nuclei?

T violation in Neutron Optics

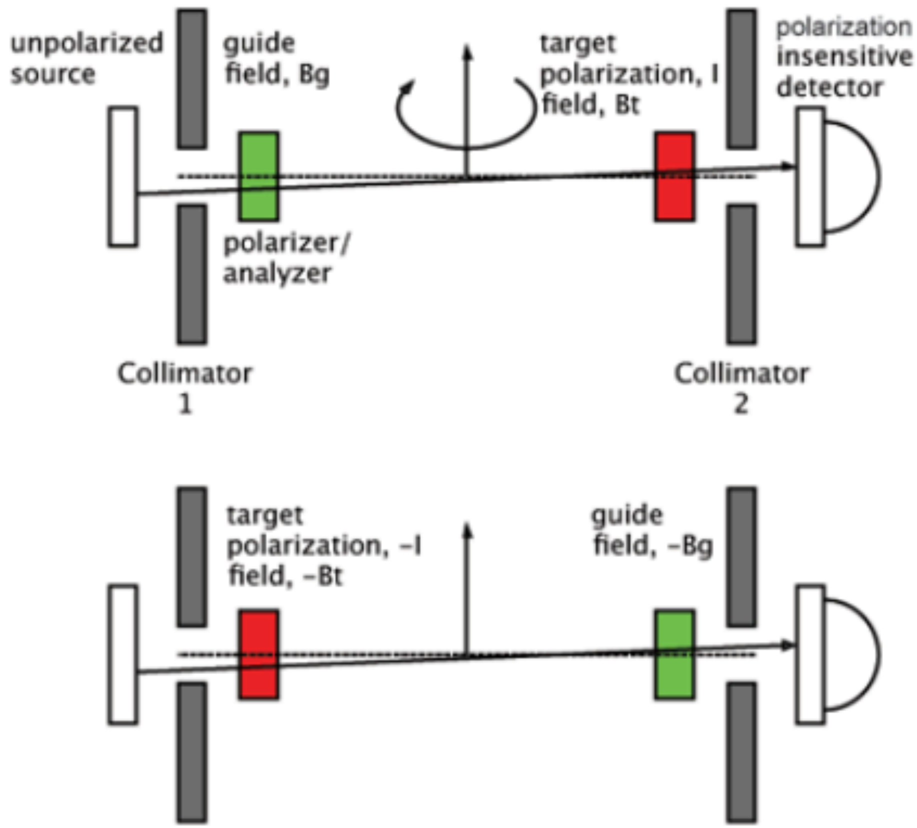
- T – odd term in FORWARD scattering amplitude (a null test, like EDMs) with polarized n beam and polarized nuclear target
- P-odd/T-odd (most interesting) $\vec{\sigma_n} \cdot (\vec{k_n} \times \vec{I})$
- Amplified on select P-wave epithermal neutron resonances by ~5-6 orders of magnitude
- Estimates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

EDITORS' SUGGESTION Phys. Rev. C (2015)
Search for time reversal invariance violation in neutron transmission
J. David Bowman and Vladimir Gudkov

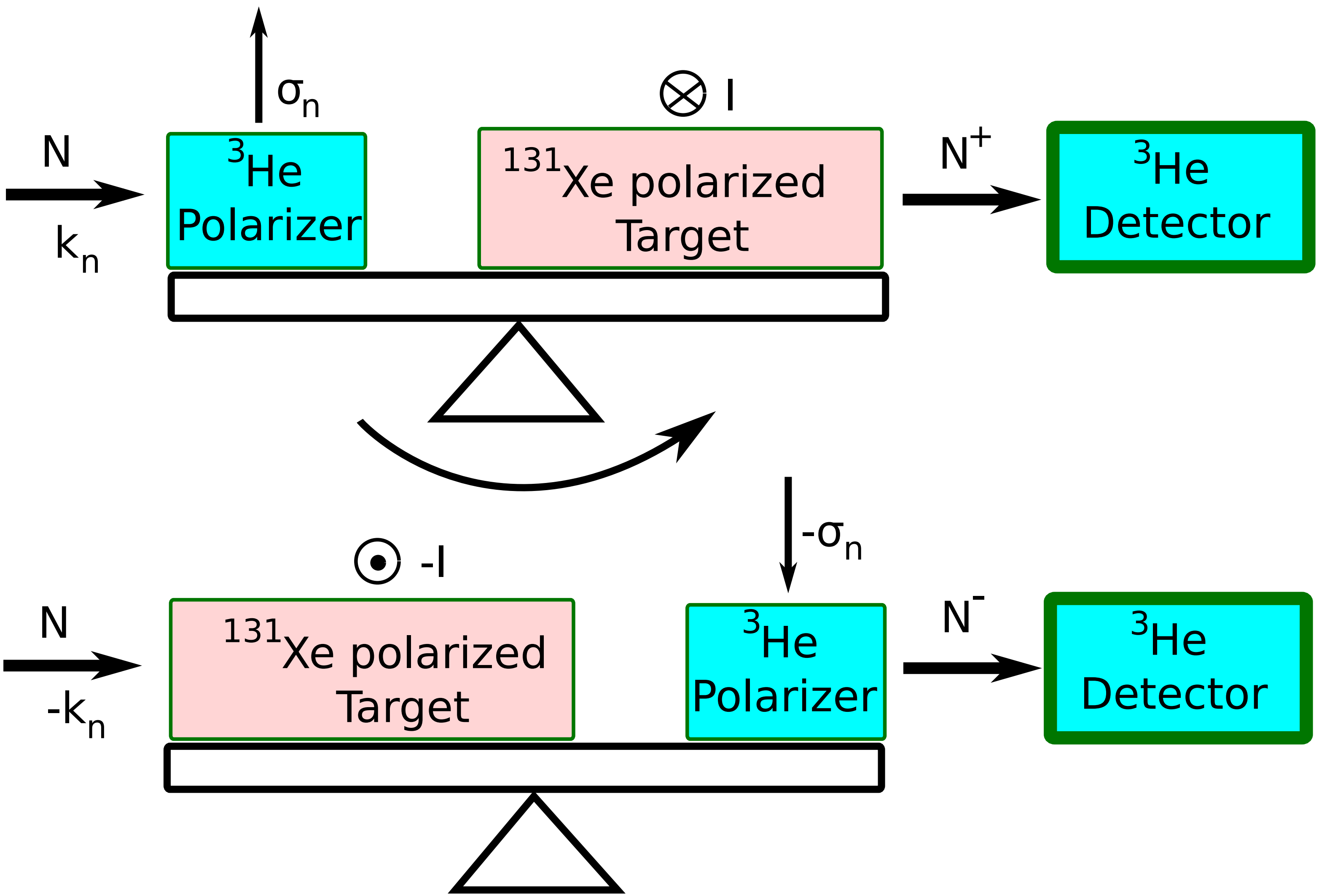


The authors analyze a novel null test to search for time reversal invariance in a model neutron transmission experiment. The proposed experimental procedure involves nuclear reactions and is sensitive to the neutron-nucleus interactions. The approach could significantly increase the discovery potential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

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

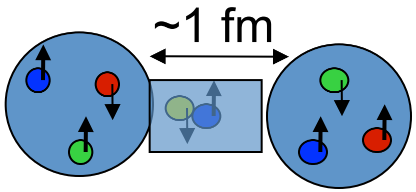
$$f = f_0 + f_1 \vec{\sigma_n} \cdot \vec{I} + f_2 \vec{\sigma_n} \cdot k_n + f_3 \vec{\sigma_n} \cdot (\vec{k_n} \times \vec{I})$$

$f_3 << f_1, f_2$



Bowman/Gudkov, arXiv:1407.7004

N- N Weak Interaction: Size and Mechanism

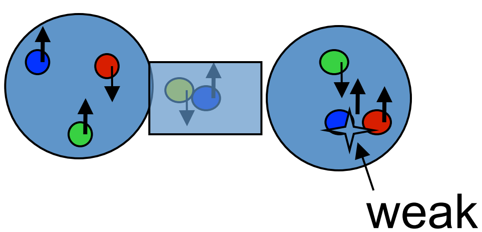


NN repulsive core → 1 fm range for NN strong force

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

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

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V. Gudkov	U South Carolina
C. Gould	North Carolina State U
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N. Fomin	U Tennessee
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K. Hirota	Nagoya U
G. Ichikawa	Nagoya U
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T. Shima	Osaka
T. Iwata	Yamakata U
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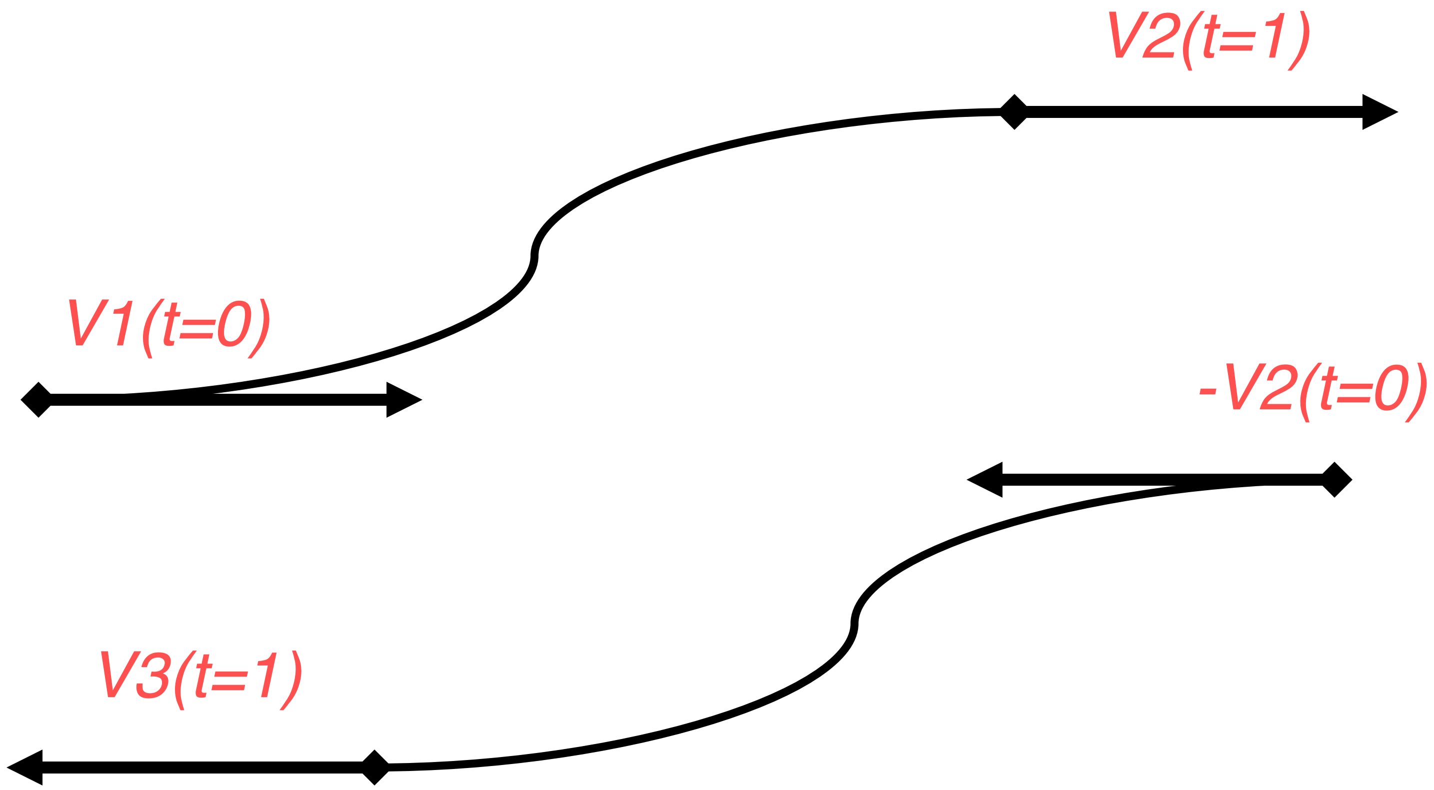
M. Hino	Kyoto
T. Momose	UBC
K. Asahi	Tokyo I. Tech.
K. Sakai	JAEA
H. Harada	JAEA
A, Kimura	JAEA

Merge the acronyms: NOPTREX

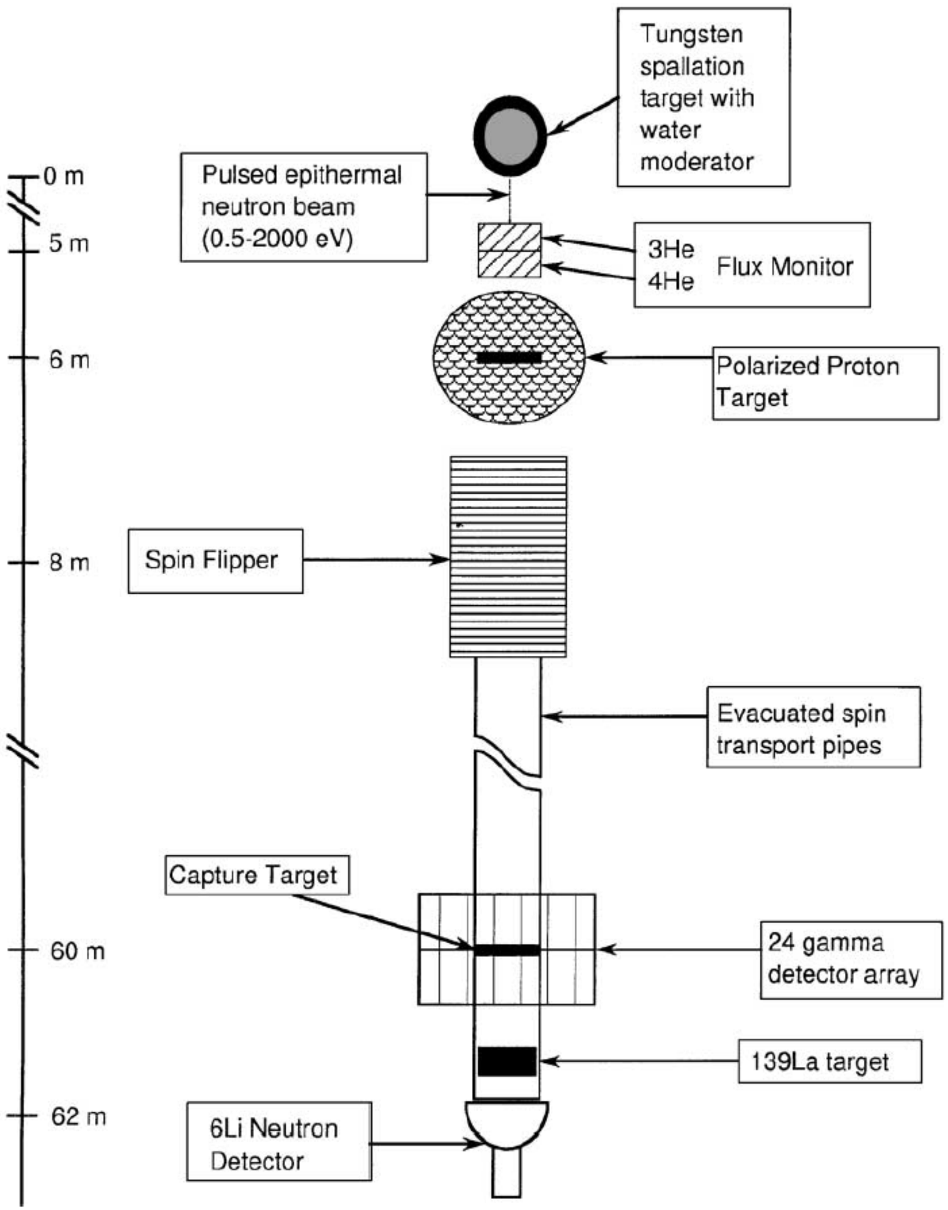
“Time Reversal” -> Motion Reversal



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



Apparatus for
PV at a spallation neutron source

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

Look for σ.k dependence of total cross section

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