

Progress towards an experiment to search for time reversal violation in compound-nuclear resonances.

Discovery potential  $\sim 100$

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Why is it important to search for time reversal violation?

TRV is required to create the small matter-anti matter asymmetry that allows the universe as we know it to exist.

The standard model doesn't have enough TRV to create the asymmetry. Some new TRV mechanism must exist. At present the ratio of TRV to PV,  $\lambda$ , is less than  $10^{-3}$ . We estimate the reach of CN studies to be  $10^{-5}$ .

# Constraints on $\lambda$ from EDM's

From  $n$  EDM <sup>(1)</sup>

$$\bar{g}_\pi^{(0)} < 2.5 \cdot 10^{-10}$$

$$d_n = \frac{e}{4\pi m_N} \bar{g}_\pi^{(0)} g_\pi \ln \frac{\Lambda}{m_\pi}$$

From  $^{199}\text{Hg}$  EDM <sup>(2)</sup>

$$\bar{g}_\pi^{(1)} < 0.5 \cdot 10^{-10}$$

$\Rightarrow \frac{\cancel{\mathcal{TP}}}{\cancel{\mathcal{P}}} \sim 10^{-3}$  from the current EDMs

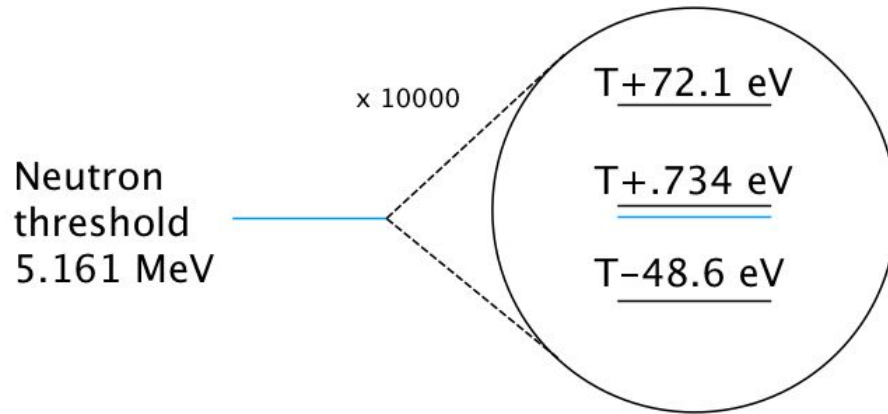
$\equiv$  "discovery potential"  $10^2$  (nucl) --  $10^4$  (nucl & "weak")

- M. Pospelov and A. Ritz (2005)
- V. Dmitriev and I. Khriplovich (2004)

# What is a compound-nuclear resonance?

- A C-N resonance is formed when a neutron is captured by a nucleus, A.
- An excited nuclear state in the A+1 daughter nucleus is formed at  $E_x \sim 5\text{-}10$  MeV
- The separation of states is small  $\sim 10$  to 100 eV.
- A small nucleon-nucleon weak interaction can cause a large mixing of opposite parity states and large cross section asymmetries.

# $^{139}\text{La}+n$ System



Compound nucleus  
as a laboratory for  
Symmetry studies.

States in  $^{139}\text{La}+n$   
system

# Neutron optics and spin structure of neutron-matter interaction

Neutrons propagate through matter optically: without energy loss or scattering. The forward scattering amplitude,  $f$ , depends on the neutron spin operators,  $\sigma_x, \sigma_y, \sigma_z$  and the polarization of the medium

$$f = a_0 + b_0(\vec{\sigma} \cdot \vec{I}) + c_0(\vec{\sigma} \cdot \vec{k}) + d_0(\vec{\sigma} \cdot [\vec{k} \times \vec{I}]),$$

P T      ++              ++              -+              --

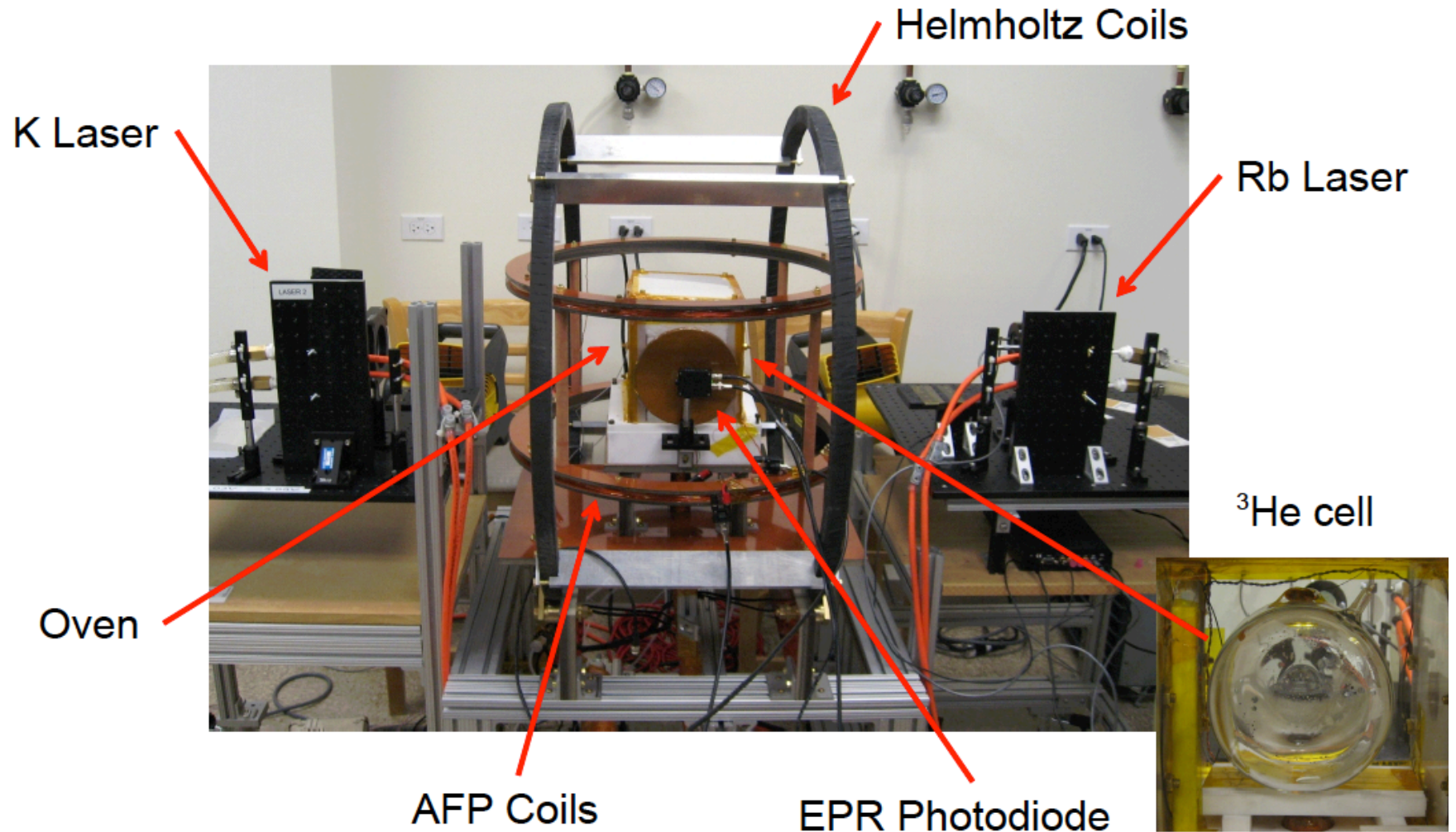
$k$  is the neutron momentum,

$I$  is the target polarization

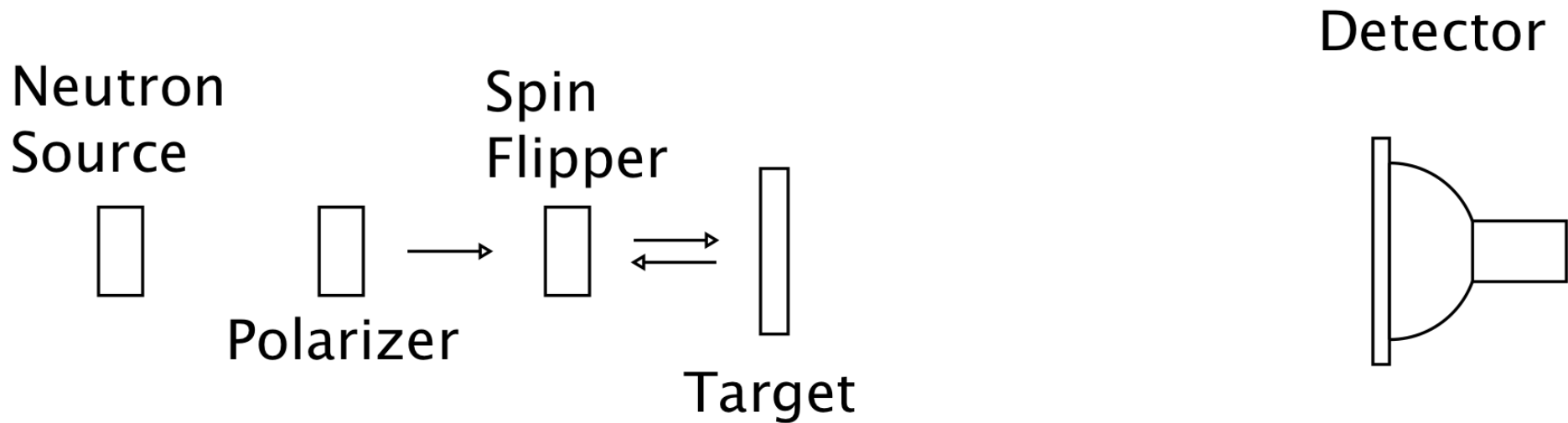
$b_0$  and  $c_0$  and are even under TR.  $d_0$  is odd.

$c_0$  and  $d_0$  come from the weak interaction.

# Polarized $^3\text{He}$ Neutron Polarizer Optical Pumping Station



# Apparatus to Measure $\sigma \cdot k$ TR even Parity Violating Asymmetry



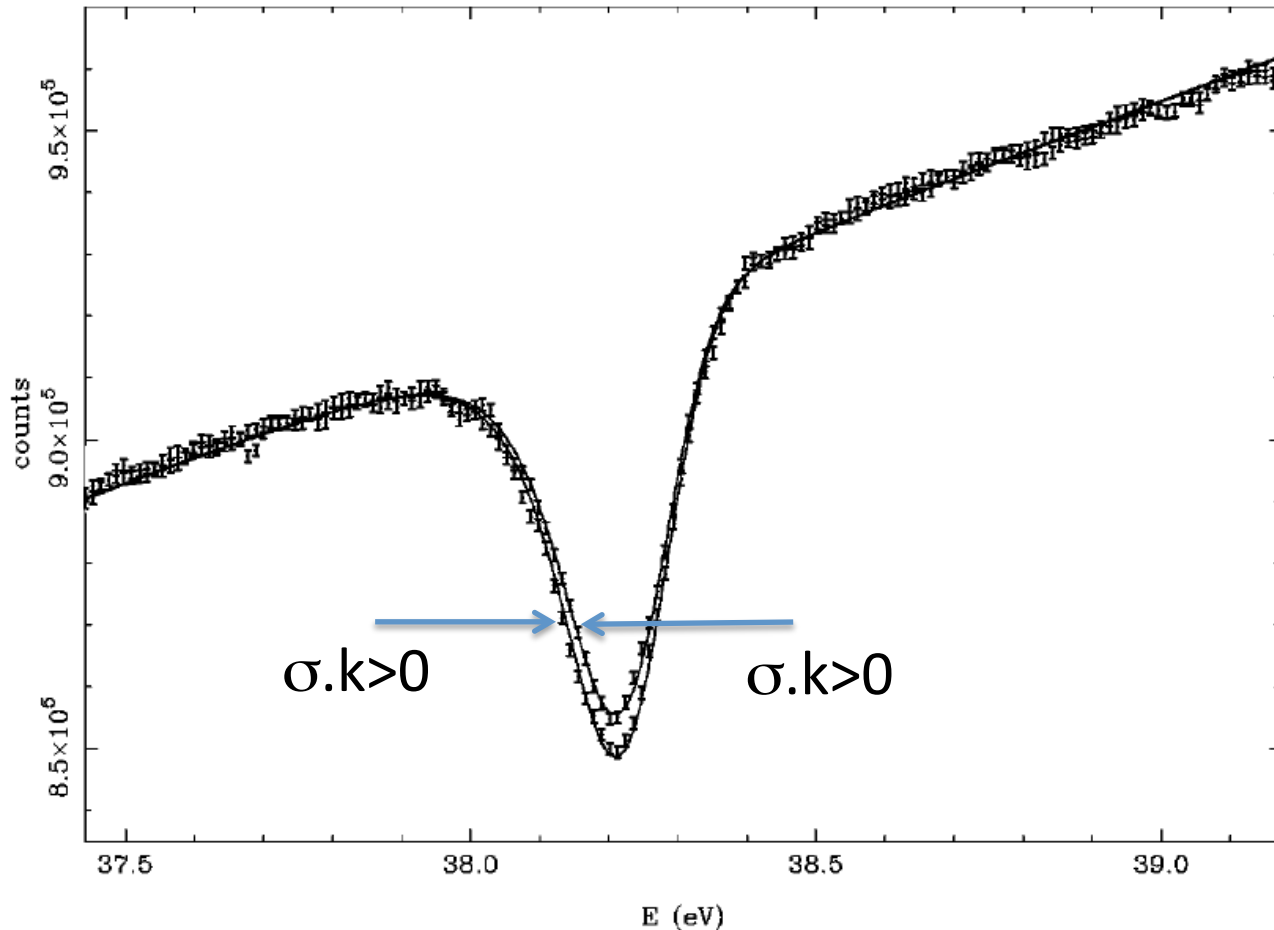
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20 meter flight path

More than 50 PV asymmetries have been  
Observed.

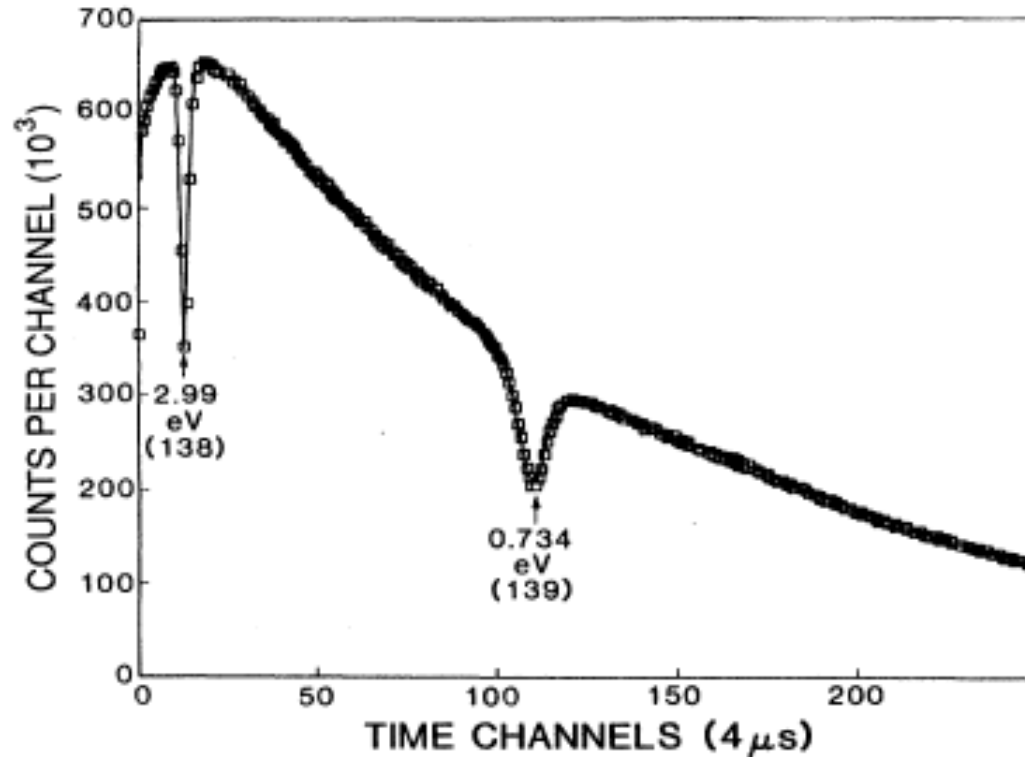


Transmission spectrum of neutrons through  $^{232}\text{Th}$  near 32.4 eV resonance.  
PV asymmetry is 15%.

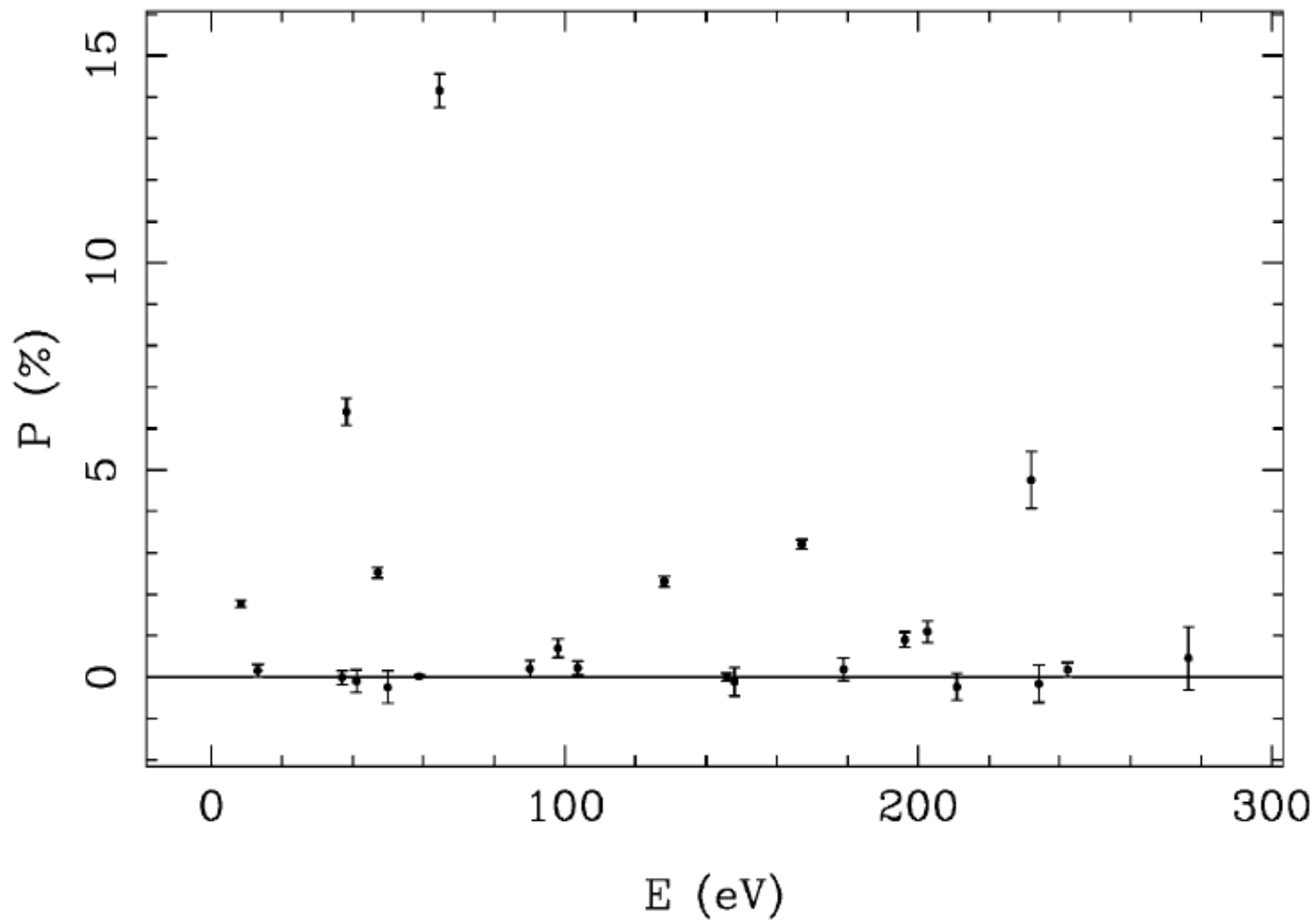


PV in  $^{139}\text{La}$  .734 eV

$\Delta\sigma/\sigma = 0.097 \pm 0.005 \cdot 10^6$  amplification



A dimensional estimate for the size of P-V asymmetries is  $A \sim G_{\text{Fermi}} m_{\pi} \sim 10^{-7}$ . In  $^{139}\text{La}$  the asymmetry is  $10^6$  larger. Why?



10 PV asymmetries in  $^{232}\text{Th}$

What makes the PV and TR transmission asymmetries large?

The level spacing is small,  $\sim 10$  eV. A small matrix element can produce a large admixture.

We study PV in  $L=1$  levels whose cross sections are suppressed by the angular momentum barrier. The admixed  $L=0$  levels have large cross sections. Each of these enhancements can be  $\sim 1000$ .

The 10% asymmetry is a fact we wish to exploit. Vladimir Gudkov will show that TR and PV have the same  $10^6$  enhancement.

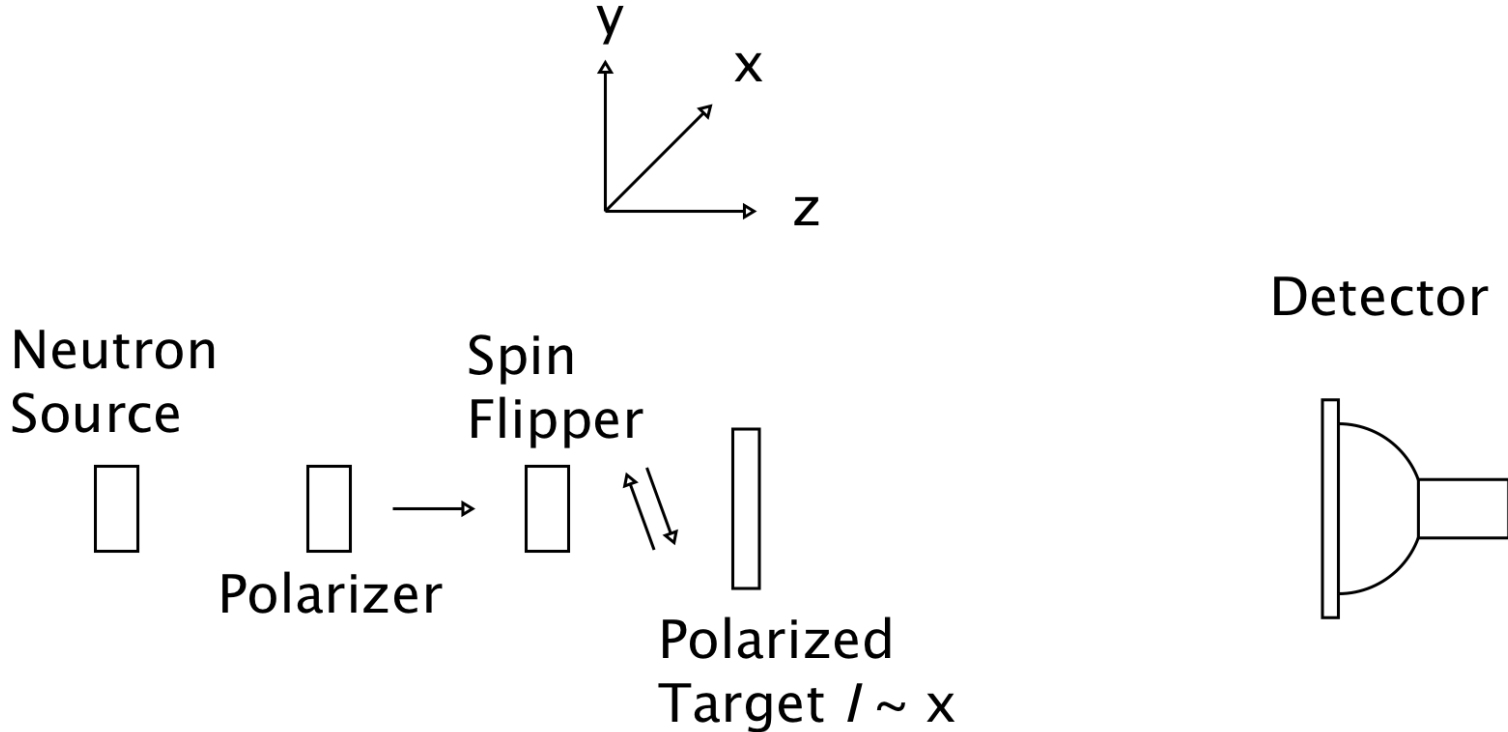
Immediately after PV was observed (1980) Stodolsky (1982) and Kabir (1982) suggested that  $s.(k \times l)$  asymmetries could reveal small P odd T odd interactions.

Many experimental and theoretical problems Seemed to stand in the way of realizing this goal.

Techniques: neutron intensity, spin flippers, polarizers, polarized targets...

Conceptual problems: T even effects false TR Asymmetries.

Optimal apparatus to measure  $d_0$  the TR odd PV asymmetry and a source of false asymmetry.

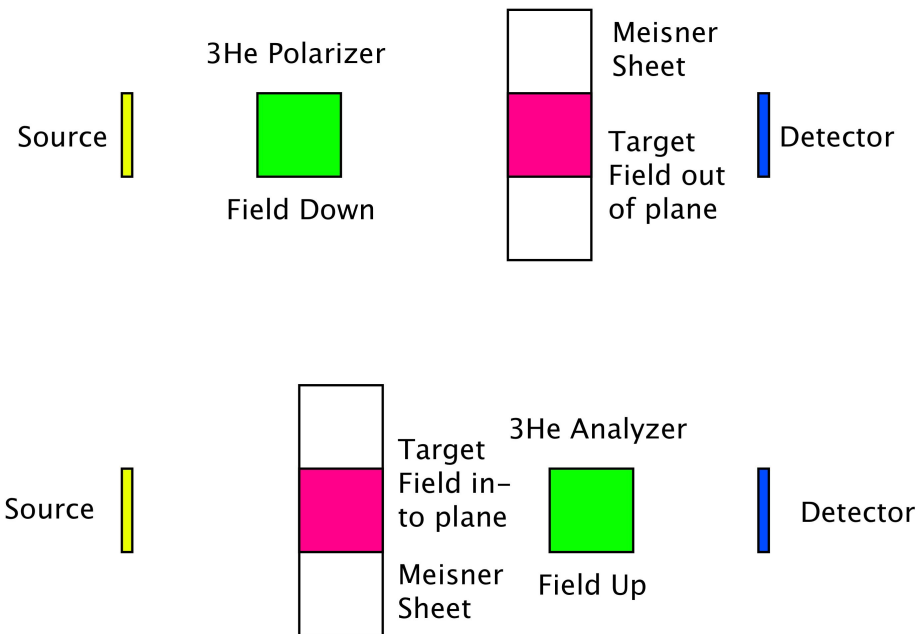


Ideally, the spin is along  $y$  such that  $\sigma \cdot k$  is maximal and  $\sigma \cdot x$  is zero.  $\sigma$  is shown making a small angle,  $+/-\theta$ , in the  $y$ - $z$  plane. Because  $\sigma \cdot k$  is non-zero there is a PV asymmetry  $\sim \sin(\theta)$ .

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

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

# Neutron optics time reversal theorem



Reverse the order of polarizer and polarized target

Reverse polarizer and polarized target directions

Reverse magnetic fields

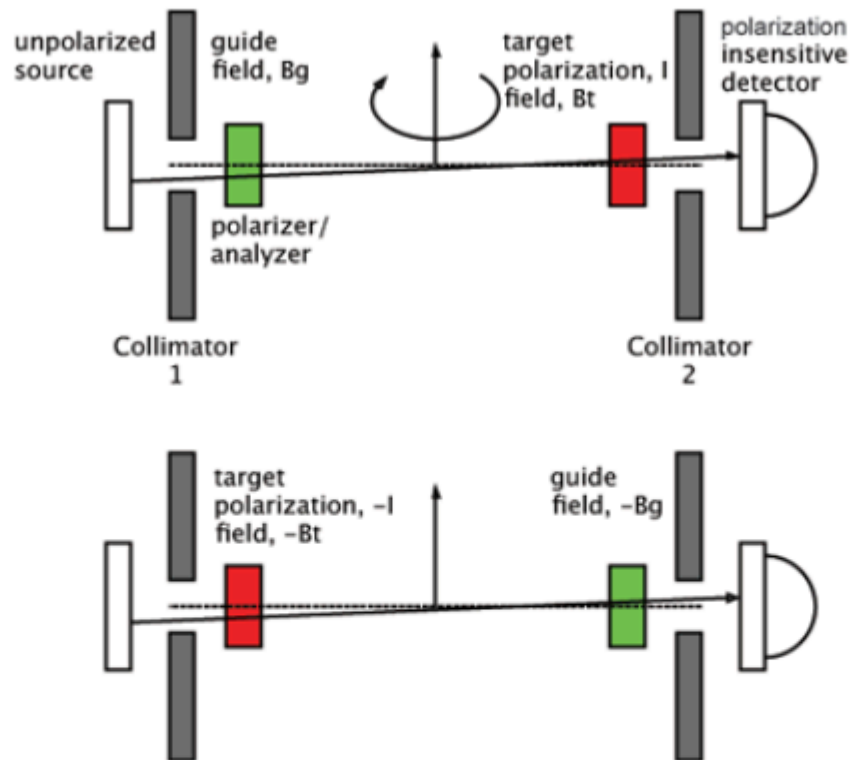
If  $d_0=0$ , the forward and backward transmissions are the same.

There is a transmission asymmetry if and only if  $d \neq 0$ .



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Search for time reversal invariance violation in neutron transmission:  
Reverse  $k$  by a rigid rotation of the apparatus and reversing  $B$  and  $I$



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.

The target polarization term,  $c_0 \sigma \cdot l$ , causes the neutron spin to precess about  $l$ . This “pseudo magnetism” can wash out the TRV asymmetry because the neutron spin does not remain along  $k \times l$ .

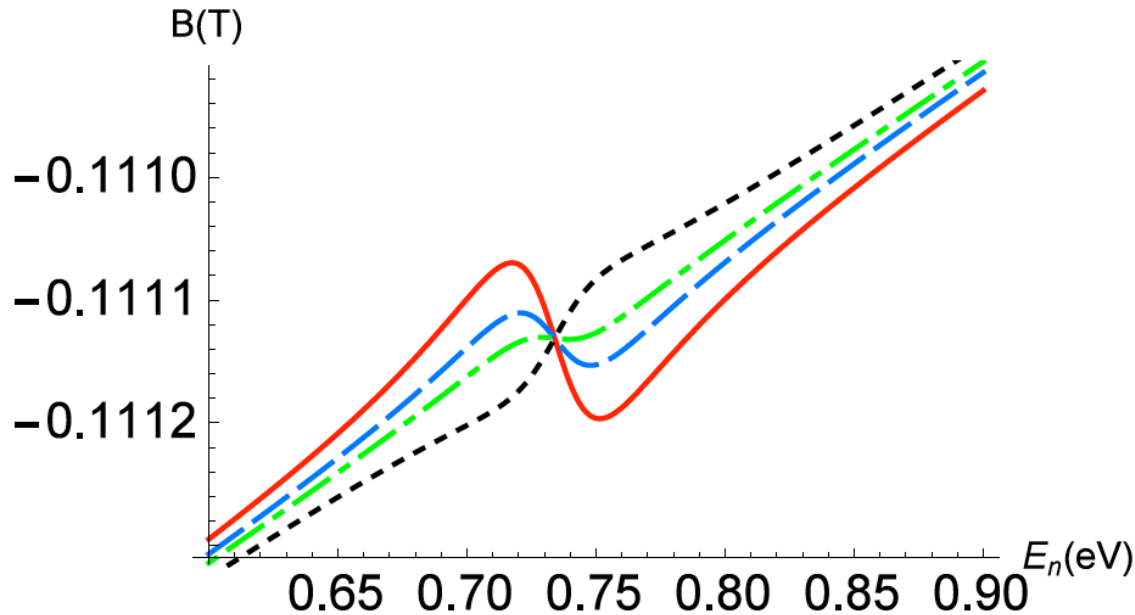
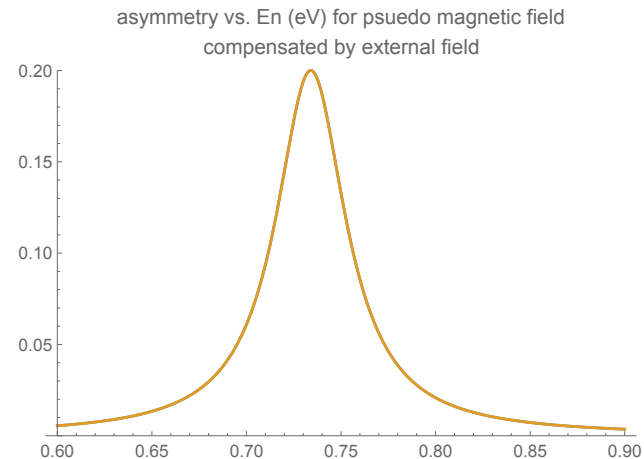
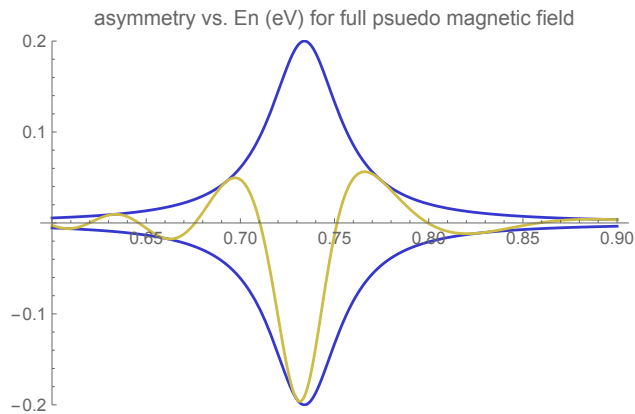


FIG. 4. Pseudomagnetic field in fully polarized  $\text{LaAlO}_3$  target

Gudkov and Shimizu, PRC 95,045501(2017), calculated the pseudo magnetic field. There is a large (1 KG) constant part, a small linear dependence on neutron energy ( 1 Gauss per eV), and a dispersive part at the resonance energy (1 Gauss)

A one Gauss field causes a neutron to precess about the field at 3 KHz. The size of the psuedo magnetic field is  $\sim 1$  Kgauss. A .734 eV neutron has a velocity of  $1.2 \cdot 10^4$  meters/sec and spends  $8.3 \mu\text{sec}$  in a 10 cm target. The precession angle in the target is  $\sim 25$  radians. This large angle will average out the asymmetry.

# Cancellation of the pseudo magnetic field by the application of an external magnetic field.



# Experimental and Theoretical Progress

What was an interesting idea in 1982 has come within reach

- Candidate resonance in  $^{139}\text{La}$  has 10% PV asymmetry.
- Polarized La target developed (Maekawa et al., Inuma et al.)
- Theory: PV and TR enhancement the same
- TR theorem for neutron optics eliminates many false asymmetries
- Careful measurements of spectroscopic data for  $^{139}\text{La}$
- Optimal configuration for TR measurements identified (Polarizer-Polarized  $^{139}\text{La}$ )-(Polarized  $^{139}\text{La}$ -Analyzer)
- Large  $^3\text{He}$  Polarizer/Analyzer routinely available.
- Reach of experiment is  $10^2$  improvement for TR search

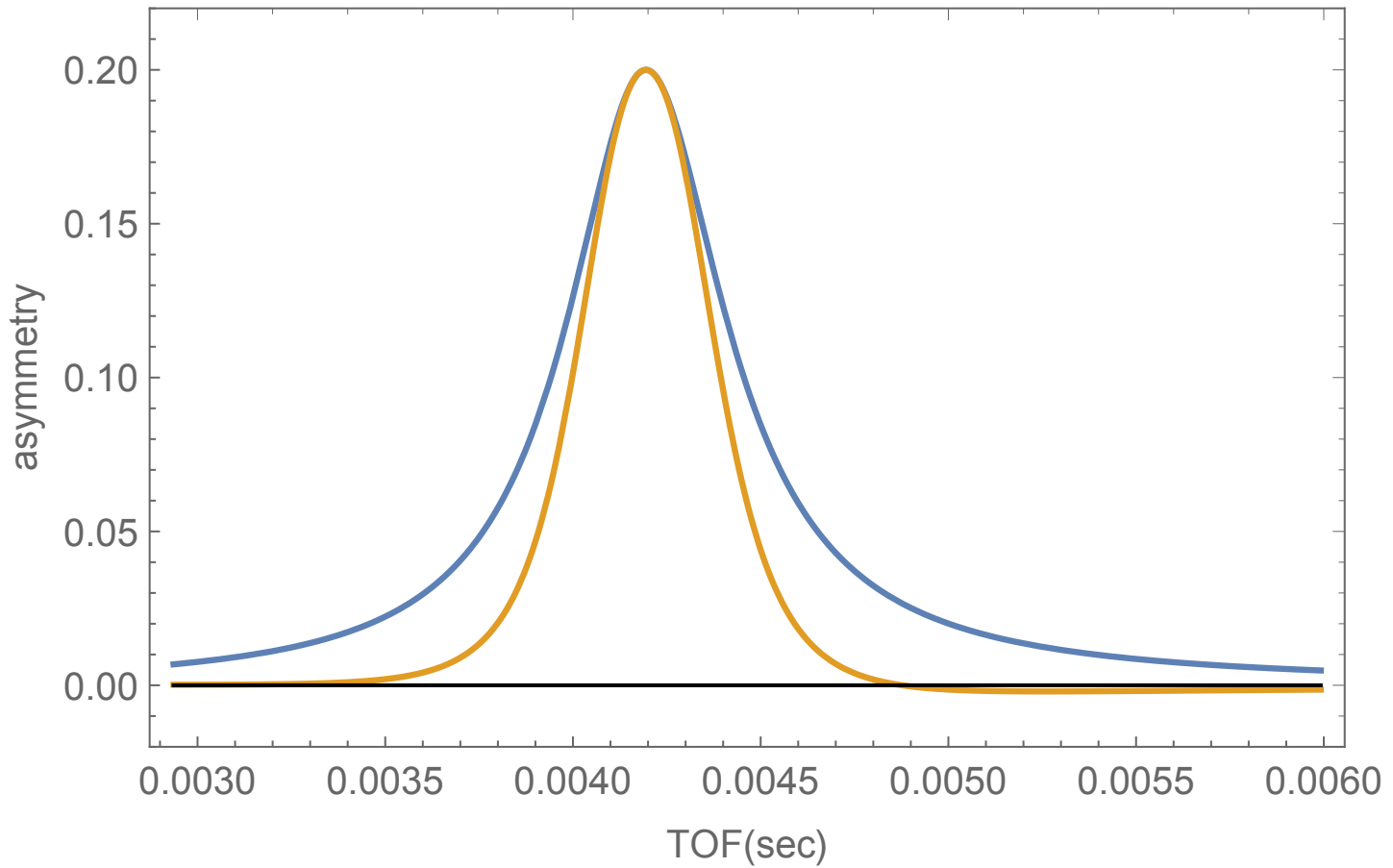
What seemed to be a good idea but an impossible task in 1982 has come within reach

- Technical developments
  - $^3\text{He}$  polarizers/analyzers, polarized target, neutron beams, detectors, spin flippers ...
- Theoretical developments
  - TR = PV enhancement, Time reversal theorem solves many alignment problems

# Neutron EDM to search for TV was highest priority in the last 2 long range plans for Nuclear Physics. Why?

- The matter-antimatter asymmetry in the universe is  $10^{-8}$
- Insufficient TV in the standard model to create this asymmetry.
- New TV interactions must exist
- The race is on to find them at either very high energies (LHC) or very low energies (SNS, atoms, ...)

partial quenching of asymmetry by psuedo  
magnetic field from resonance absorbtion





Reach of new experimental approach

$$TV/PV < 10^{-5}$$

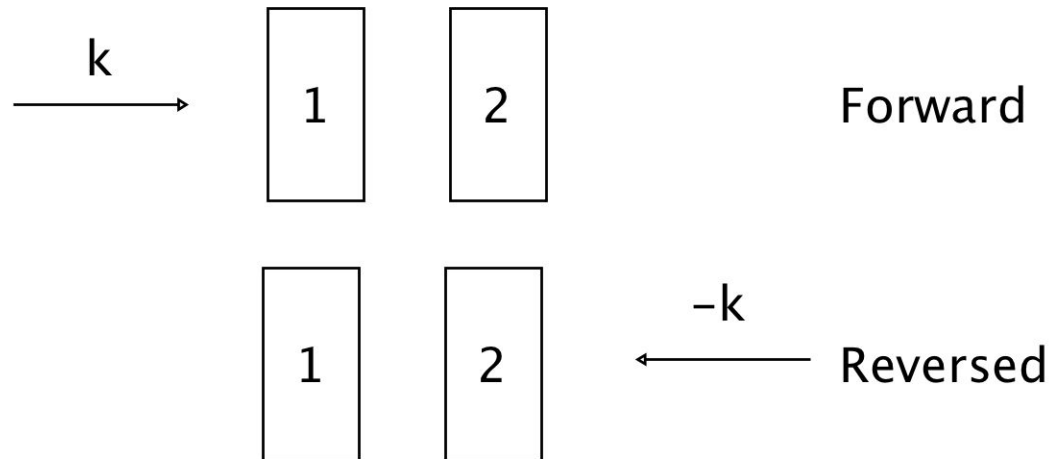
Different systematic uncertainties

Initial experiment to reach

$$T/P < 10^{-3}$$

Cost \$ 5-10 M

In the forward configuration we have  $k$ ,  $B$ , and  $l$ .  
 The interactions of the spin are  $\sigma.B$ ,  $\sigma.l$ ,  $\sigma.k$ ,  $\sigma.(l \times k)$ .  
 Under reversal, the first 3 reverse and the fourth is unchanged.  
 We want to show that if the 4<sup>th</sup> interaction is absent, the  
 Forward and reversed transmissions are the same, if we  
 reverse  $B$ ,  $l$ , and  $k$  as well as the order of interactions.  
 We consider a neutron passing through two slabs



# The misalignments are no longer relevant

- The collimation system must accept the same set of trajectories through the target in both rotation states
- The earth's field must be compensated or shielded in order that  $\sigma$ ,  $B$ , and  $I$  reverse.

# Factors influencing choice of target and state for TR studies

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

# Conclusion

- The time spent in the target is  $.1 \text{ meter} / 1.2 \times 10^4 \text{ meters/sec} = 8 \mu \text{ sec}$ .
- The precession rate from the 1 KG pseudo magnetic field is 1.9 M Hz

# Estimate of the TRIV/PV at SNS

Moderator brightness measured at LANSCE

100 cm<sup>2</sup> 40% polarized  $n\sigma=1$  <sup>139</sup>La target

$n\sigma=1$ , 70% polarized, <sup>3</sup>He polarizer

10<sup>7</sup> seconds run time.

50% efficient detector.

$n\sigma=1$  window scattering.

$$\delta \lambda = \delta (\text{TRIV/PV}) = 6 \cdot 10^{-6}.$$

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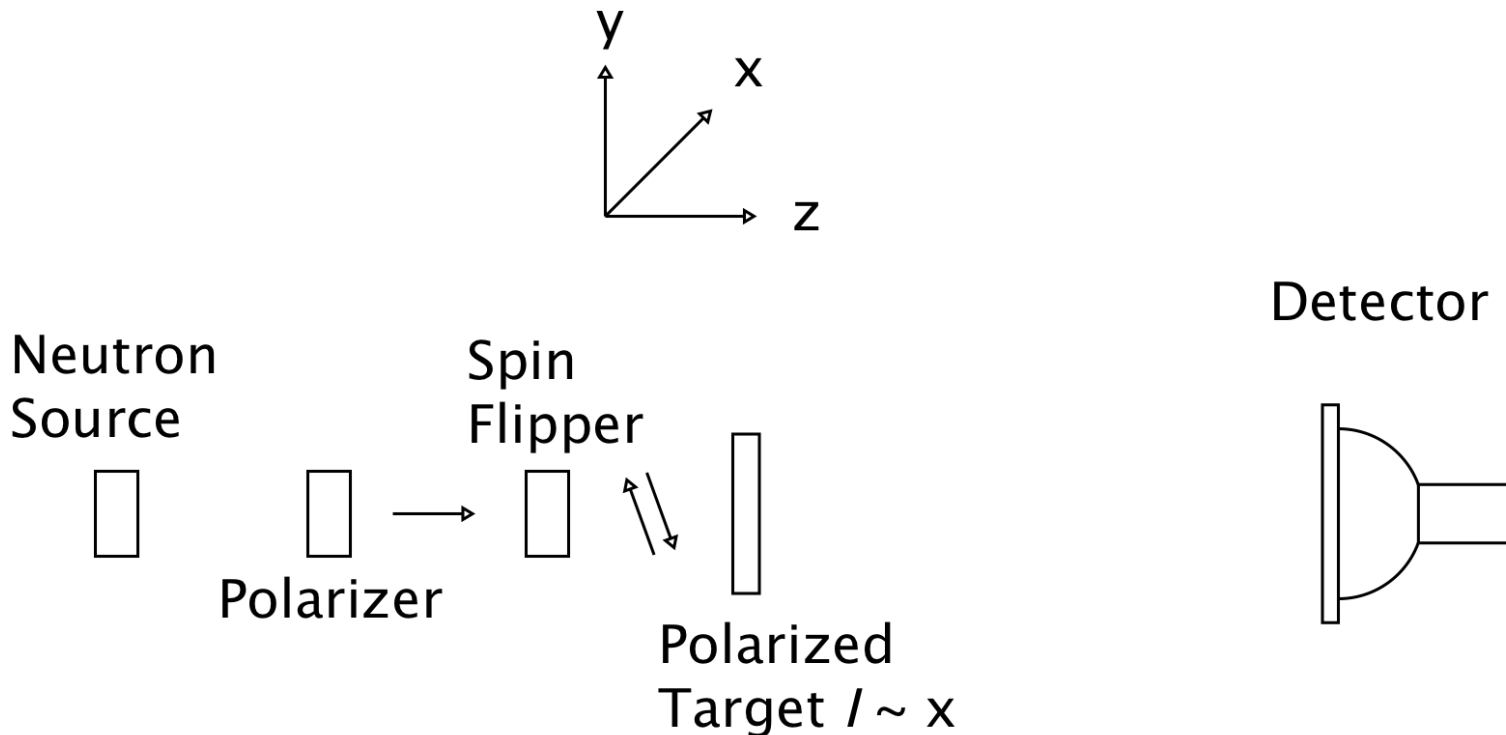
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- Insufficient TV in the standard model to create this asymmetry.
- New TV interactions must exist
- The race is on to find them at either very high energies (LHC) or very low energies (SNS, atoms, ...)

Best existing limit from neutron  
EDM:  $TV < 10^{-3}$  of Parity Violation(PV)  
NEDM at SNS and Several experiments  
worldwide aim to reach  $TV/PV < 10^{-4}$  and  
below

Each costs  $\sim$  \$30-60 M  
Results  $\sim$  2020?



# False TR asymmetries caused by TRI interactions



Ideally, the spin is along  $y$  such that  $\sigma \cdot \hat{x} k$  is maximal and  $\sigma \cdot k$  is zero.  $\sigma$  is shown making a small angle,  $+/-\theta$ , in the  $y$ - $z$  plane. Because  $\sigma \cdot k$  is non-zero there is a PV asymmetry  $\sim \sin(\theta)$ .