Experimental Tests of P-odd T-odd Interaction in Neutron Optics

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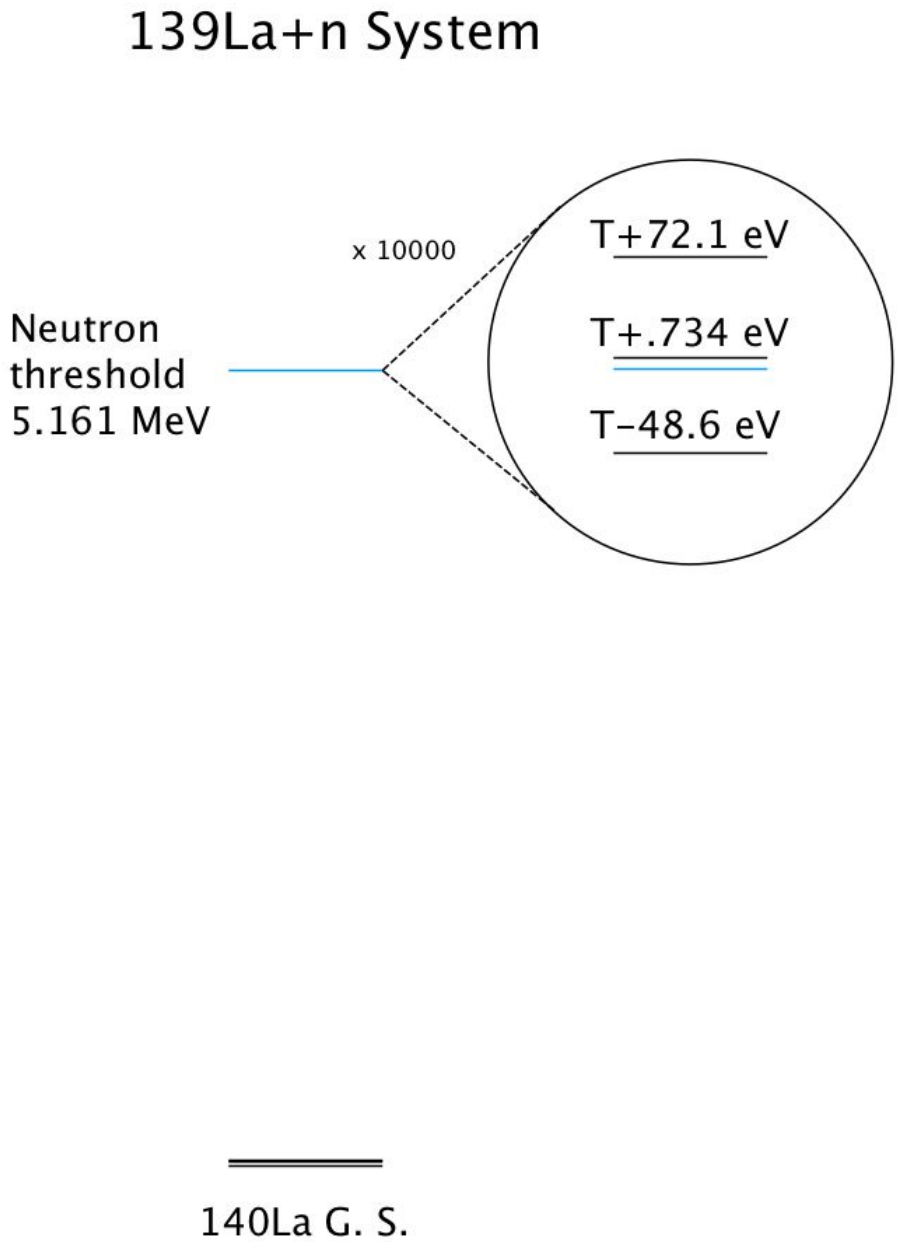
Time-reversal Tests in Nuclear and Hadronic Processes

Amherst Center for Fundamental Interactions

10/6-8/2014

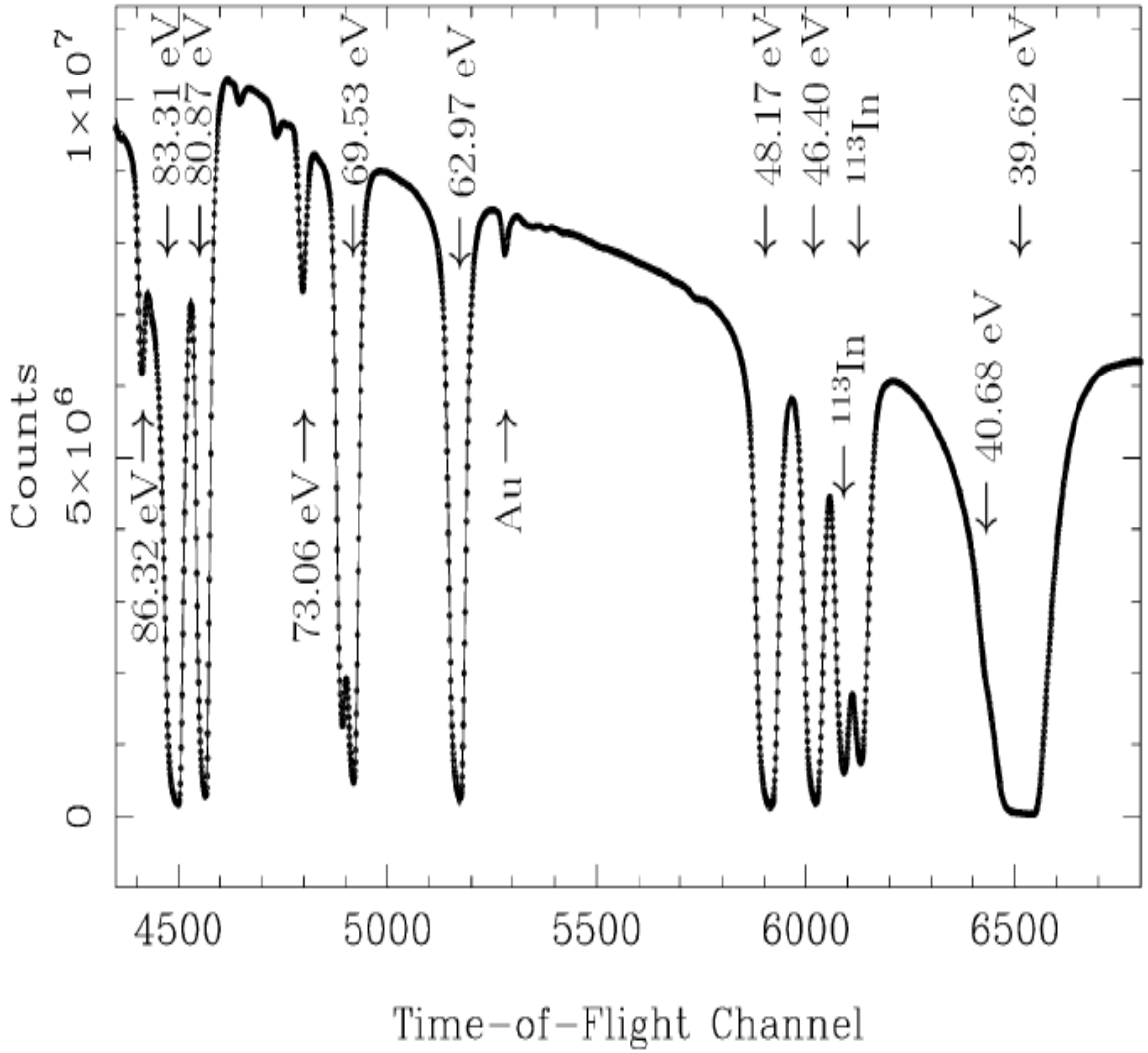


Compound-Nuclear States in ^{139}La+n system

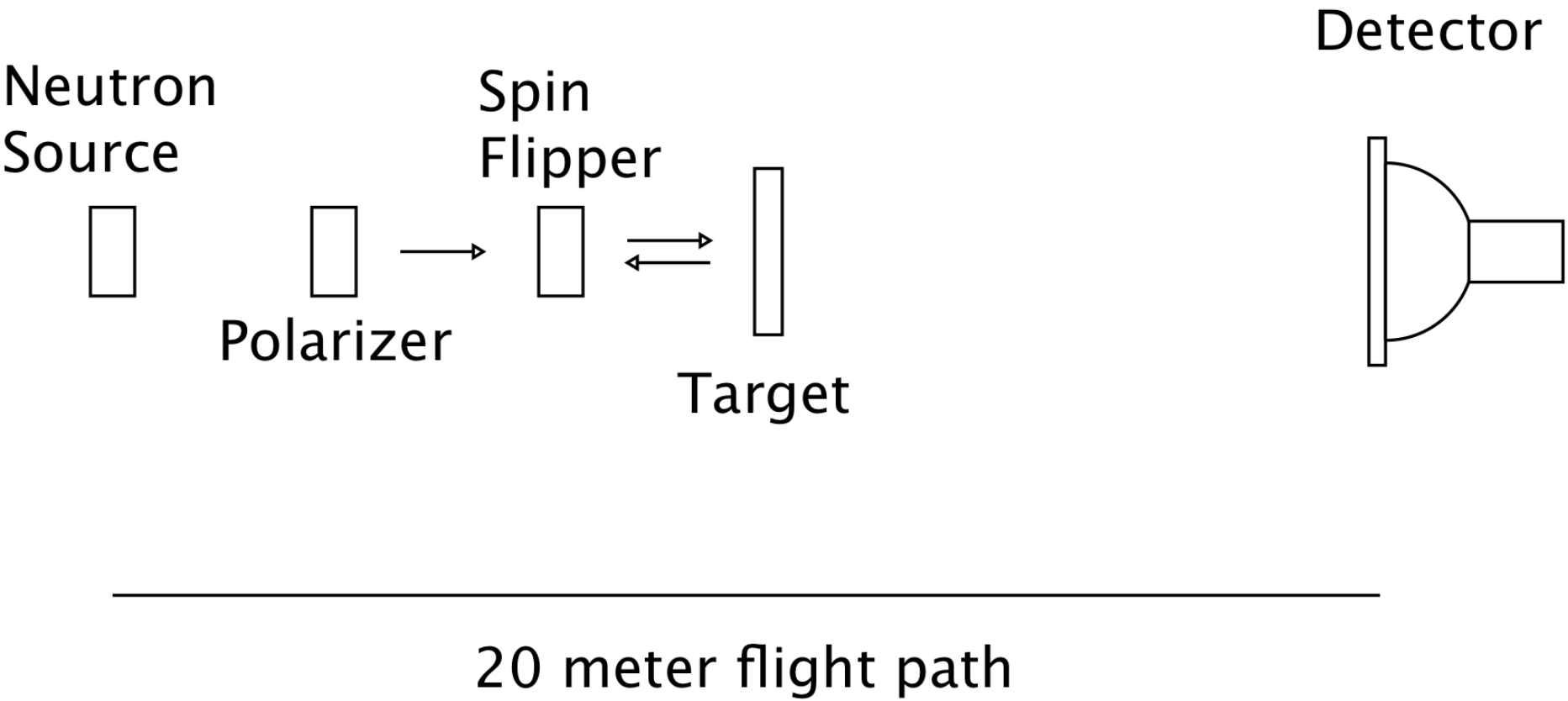
The compound-nuclear system as a laboratory for symmetry violation

- Neutron kinetic energy $T=E_x-E_t$. Neutron ToF provides a window on nuclear structure at excitation energies from 0 to few KeV above neutron threshold ~7 MeV
- Small level spacings – large mixing
- PV and TR are enhanced (10^6) by mixing of strong (s-wave) resonances into weak opposite parity (p-wave) resonances.
- $\sigma_s/\sigma_p \sim 1/k$

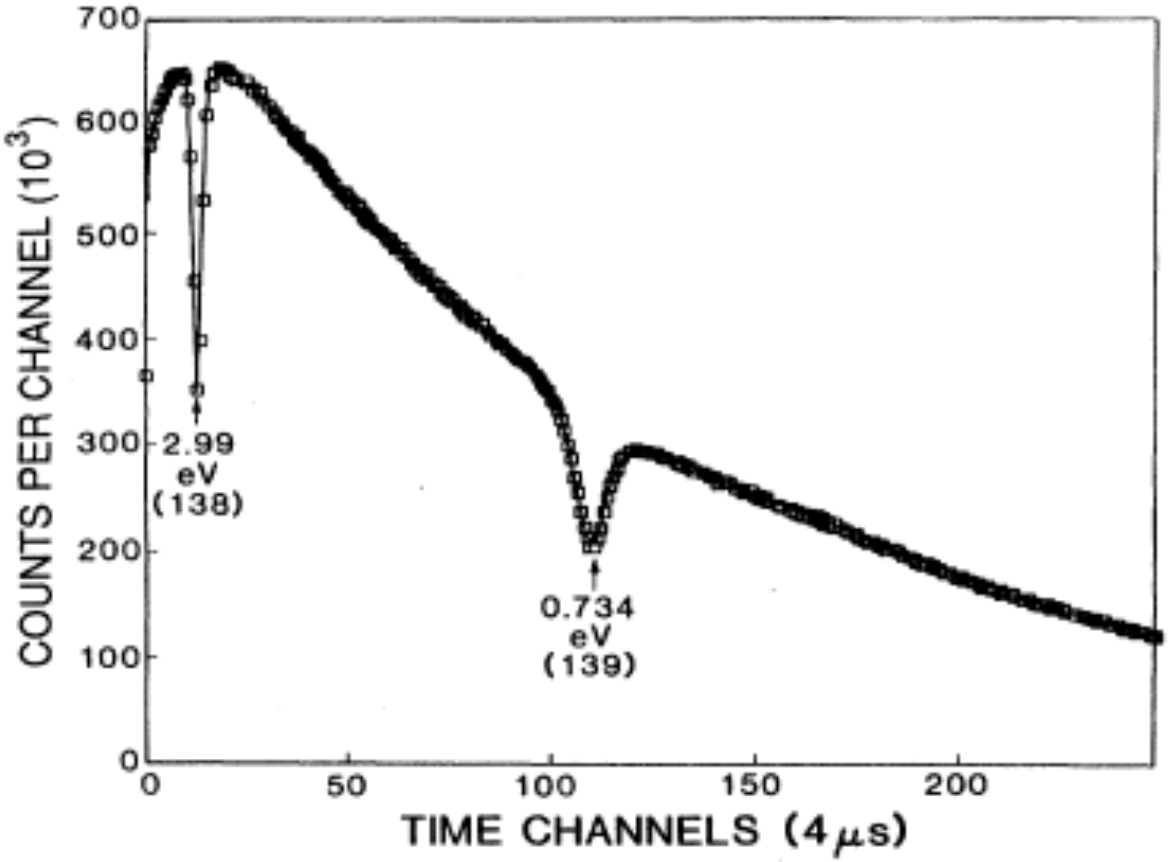
Indium TOF spectrum



Apparatus to Measure $\sigma \cdot k$ or $\sigma \cdot l \times k$ Parity Violating Asymmetry



Parity Violation in ^{139}La .734 eV
$\Delta\sigma/\sigma$ =0.097±.005. 10^6 amplification



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

Factors influencing choice of target and state for TR studies

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

Interactions of neutron spin

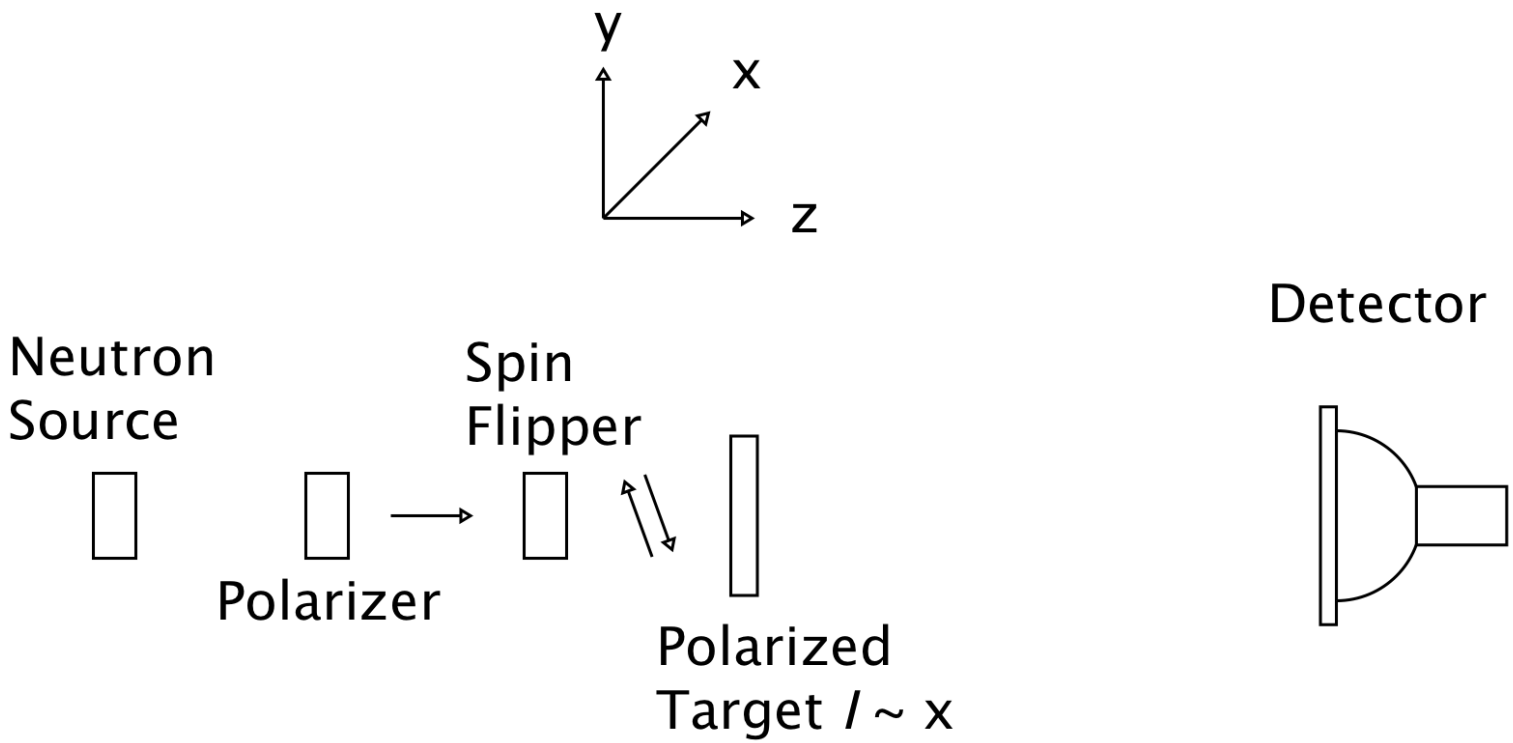
$\sigma=(\sigma_x, \sigma_y, \sigma_z)$, a pseudo vector.

H must be a scalar

σ interacts with vectors

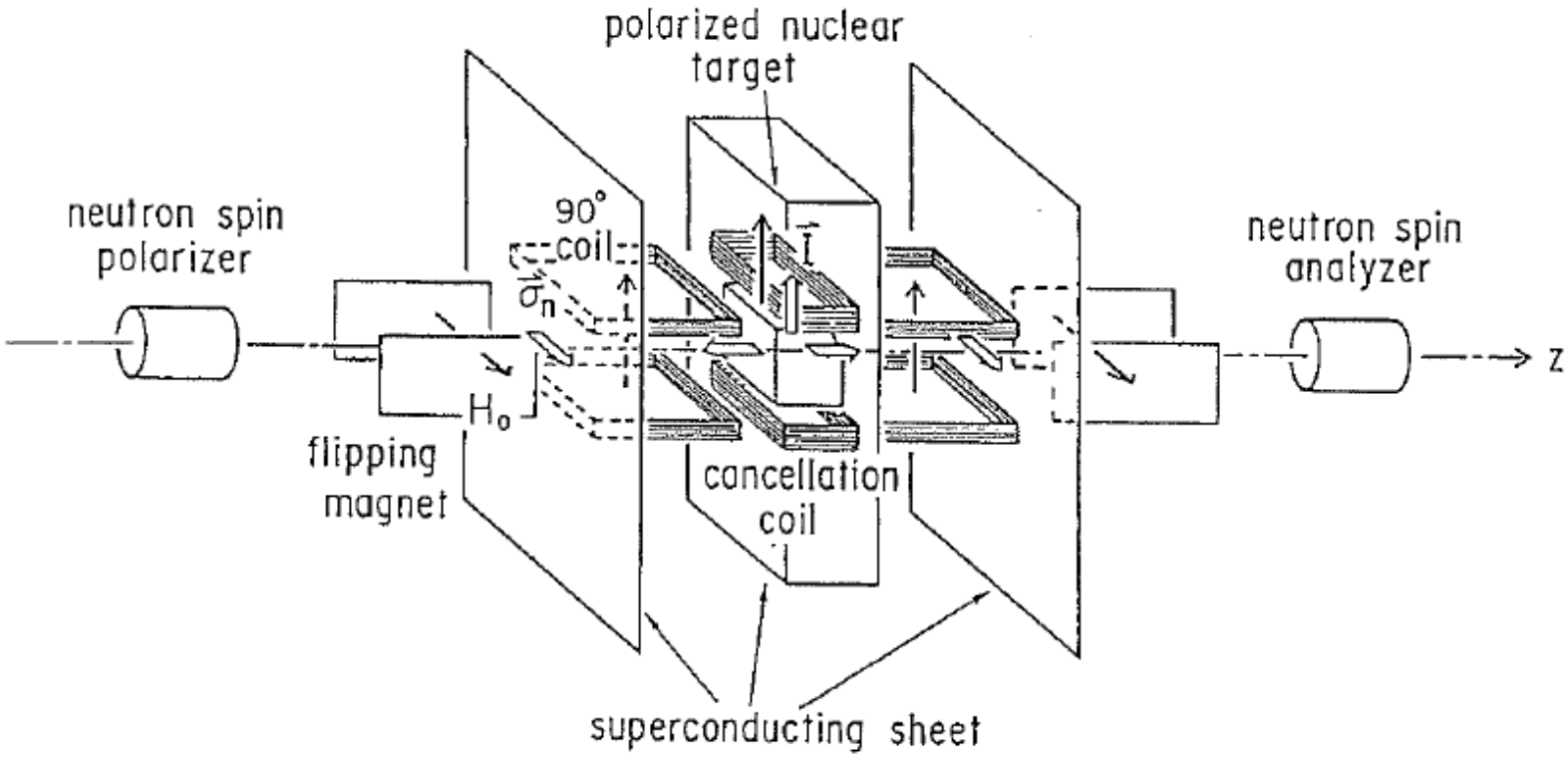
- Opp P T description
- ———————————————————————————————————
- σ.B + + precession about B
- σ.k - + precession about k, attenuation WRT helicity
- σ.I + + precession, attenuation WRT I
- σ.Jxk - - precession, attenuation WRT Ixk

False TR asymmetries caused by TRI interactions



Ideally, the spin is along y such that $\sigma.I \times k$ is maximal and $\sigma.k$ is zero. σ is shown making a small angle, $+/-\theta$, in the y-z plane. Because $\sigma.k$ is non-zero there is a PV asymmetry ~ Sin(θ).

Masuda's and Serberov's early approaches to control false TR asymmetries. Add more spin flips.



Masuda's analysis of systematic uncertainties from alignment

$$A = (R_+ - R_-)/(R_+ + R_-),$$

$$R_+ = R_{++} + R_{+-} = \mathrm{Tr}(t\rho(P_o, \varepsilon_x, \varepsilon_y)t\dagger),$$

$$R_- = R_{-+} + R_{--} = \mathrm{Tr}(t\rho(-P_o, \varepsilon_x, \varepsilon_y)t\dagger),$$

$$R_+ - R_- = \exp(-2\mathrm{Im}(\phi_0))$$

$$\{[2\varepsilon_x P_o + 2\varepsilon_y P_o \delta_y + 2P_o\delta_z]P_I\,\mathrm{Im}[\cos b\ (\sin b/b\ )^*\ \phi_1{}^*]$$

$$+ 2P_o\ \ \mathrm{Im}[\cos b\ (\sin b/b\ )^*\ \phi_3{}^*]$$

$$+ [2\varepsilon_x P_o \delta_y - 2\varepsilon_y P_o]P_I\ \mathrm{Im}[(\sin b/b)(\sin b/b)^*\ \phi_1\phi_3{}^*]$$

$$+ 2P_o\ P_I{}^2\ \mathrm{Im}[(\sin b/b)(\sin b/b)^*\ \phi_1\phi_2{}^*]\ \},$$

$$P = (R_{0+} - R_{0-})/(R_{0+} + R_{0-}),$$

$$R_{0+} = R_{++} + R_{-+} = \mathrm{Tr}(P(P_a,\xi_x, \xi_y)tt\dagger),$$

$$R_{0-} = R_{+-} + R_{--} = \mathrm{Tr}(P(-P_a,\xi_x, \xi_y)tt\dagger),$$

$$R_{0+} - R_{0-} = \exp(-2\mathrm{Im}(\phi_0))$$

$$\{[2\xi_x P_a + 2\xi_y P_a \delta_y + 2P_a\delta_z]P_I\,\mathrm{Im}[\cos b\ (\sin b/b\ )^*\ \phi_1{}^*]$$

$$+ 2P_a\ \ \mathrm{Im}[\cos b\ (\sin b/b\ )^*\ \phi_3{}^*]$$

$$+ [-2\xi_x P_a \delta_y + 2\xi_y P_a]P_I\ \mathrm{Im}[(\sin b/b)(\sin b/b)^*\ \phi_1\phi_3{}^*]$$

$$- 2P_a\ P_I{}^2\ \mathrm{Im}[(\sin b/b)(\sin b/b)^*\ \phi_1\phi_2{}^*]\ \},$$

The ratio X is

$$X \cong P_o/P_a\ [\ 1 +$$

$$\{[2(\varepsilon_x-\xi_x) + 2(\varepsilon_y-\xi_y)\delta_y\ ]P_I\ \mathrm{Im}[\cos b\ (\sin b/b\ )^*\ \phi_1{}^*]$$

$$+[2(\varepsilon_x+\xi_x P)\delta_y - 2(\varepsilon_y+\xi_y)]P_I\ \mathrm{Im}[(\sin b/b)(\sin b/b)^*\ \phi_1\phi_3{}^*]$$

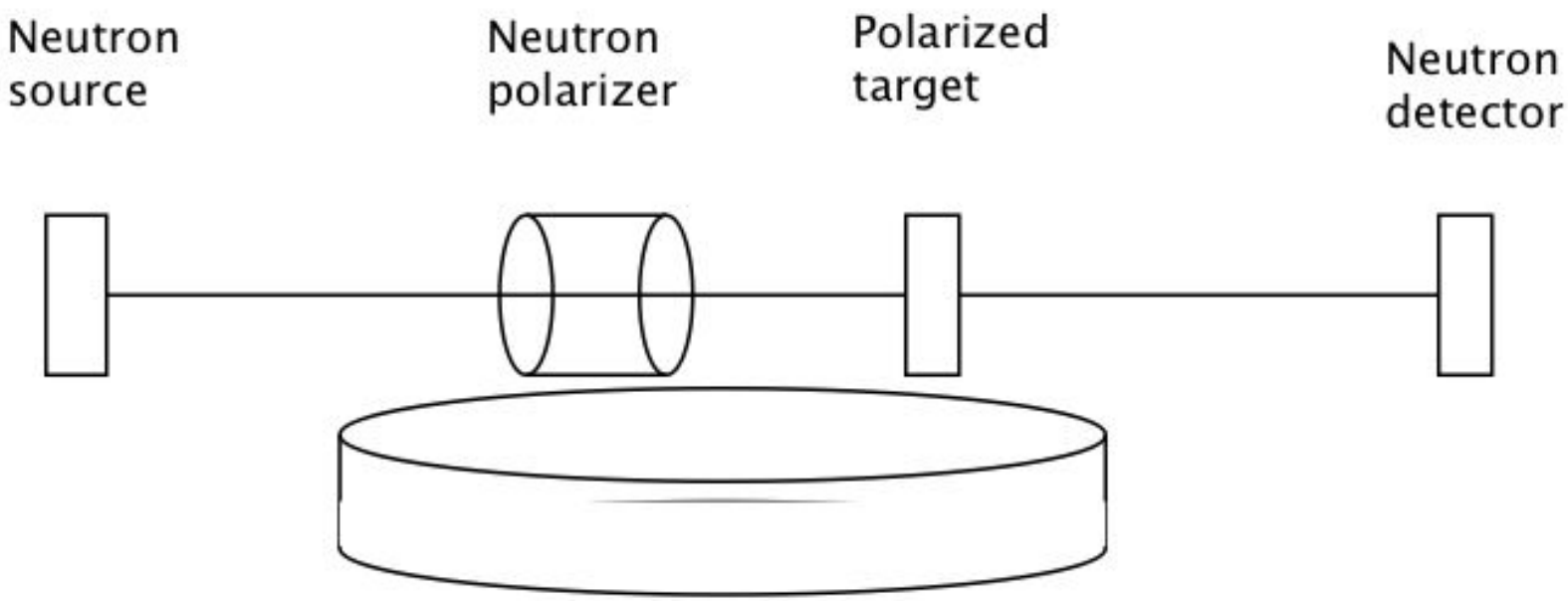
$$4P_I{}^2\ \mathrm{Im}[(\sin b/b)(\sin b/b)^*\ \phi_1\phi_2{}^*]$$

The 13 Greek letters are alignment errors

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

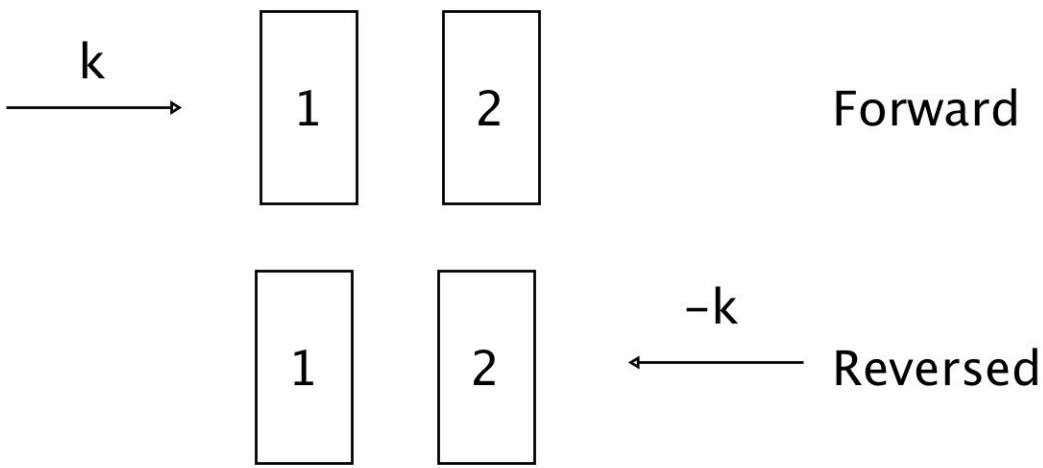
over 1 mm. Any experimental investigation must include evidence that the systematic effects discussed here do not mimic or mask a true P, T-violating interaction. It is unlikely that such evidence could be obtained directly from the neutron transmission.

How to eliminate the zoo of alignment angles:
Think of the experiment to find a σ.Jxk interaction as comparing the transmission in two different configurations of the apparatus



Rotate table that supports apparatus by 180 degrees and change the sign of all classical fields, B and J.

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



We repeatedly use the identity $(\sigma.U)(\sigma.V)=U.V+i\ \sigma.(UxV)$.

For each slab, the evolution operator is $\alpha_m+\beta_m.\sigma$ m=1,2

The forward evolution operator for 2 slabs is
$f=(\alpha_1+\beta_1.\sigma)\ (\alpha_2+\beta_2.\sigma)=\alpha_1\alpha_2+\alpha_1\beta_2.\sigma)+\alpha_2(\alpha_1+\beta_1.\sigma)+i\ \sigma.(\beta_1 x\beta_2)$
$=A+B.\sigma$
The reversed evolution operator is
$g=(\alpha_2-\beta_2.\sigma)\ (\alpha_1-\beta_1.\sigma)=\alpha_1\alpha_2-\alpha_1\beta_2.\sigma)-\alpha_2(\alpha_1+\beta_1.\sigma)-i\ \sigma.(\beta_1 x\beta_2)$
$= A-B.\sigma$

$\frac{1}{2}\ Tr[T(f^*)f]=\frac{1}{2}\ [AA^*+B.B^*]=\frac{1}{2}\ Tr[T(g^*)g]$

The proof for an arbitrary number of slabs follows by induction

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 σ, B, and I reverse.

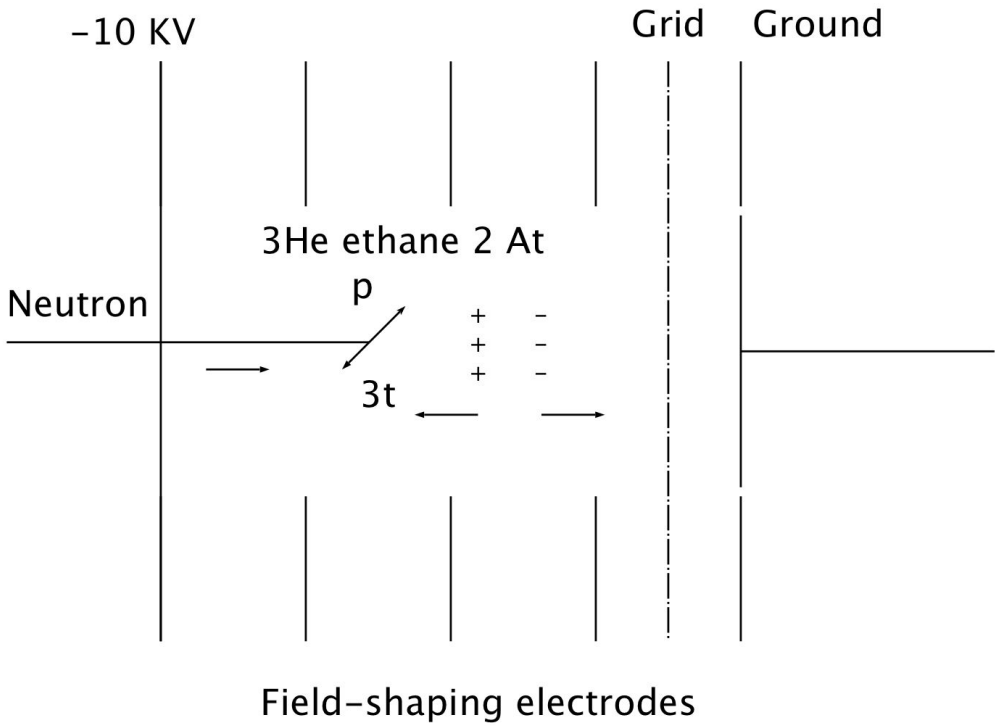
Estimate of the TRIV/PV at SNS

Moderator brightness measured at LANSCE
100 cm^2 40% polarized $n\sigma$=1 ^{139}La target
$n\sigma$ =1, 70% polarized, ^{3}He polarizer
10^7 seconds run time.
50% efficient detector.
$n\sigma$ =1 window scattering.

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

We must operate the detector in current mode because neutrons are detected at several GHz. The detector must be effeceint >50%. The time response must be compact <few μsec.

Solution 3He-ethane gridded ion chamber.
At 1 KV/cm the drift velocity of electrons is the same as .734 eV neutrons 1.2 million cm/sec.
The range of p and 3t from n+3He->p+3t is 2 cm @ 2 at.



Elastic or inelastic scattering from objects with spin and long-range order can produce forward peaked spin dependent scattering and false asymmetries.

Mike Snow will address these issues in his talk.

Conclusions

- Compound-nuclear resonances provide an opportunity to study T-odd P-odd interactions with enhanced (λ=10^5) sensitivity
- The seemingly intractable zoo of misalignment systematics can be addressed by rotating the apparatus and reversing *B*, *I*, and ^{3}He polarization
- An intense spallation neutron source is necessary
- Systematic uncertainties due to scattering from long range order in the polarized target must be investigated

^{139}La capture γ TOF spectrum

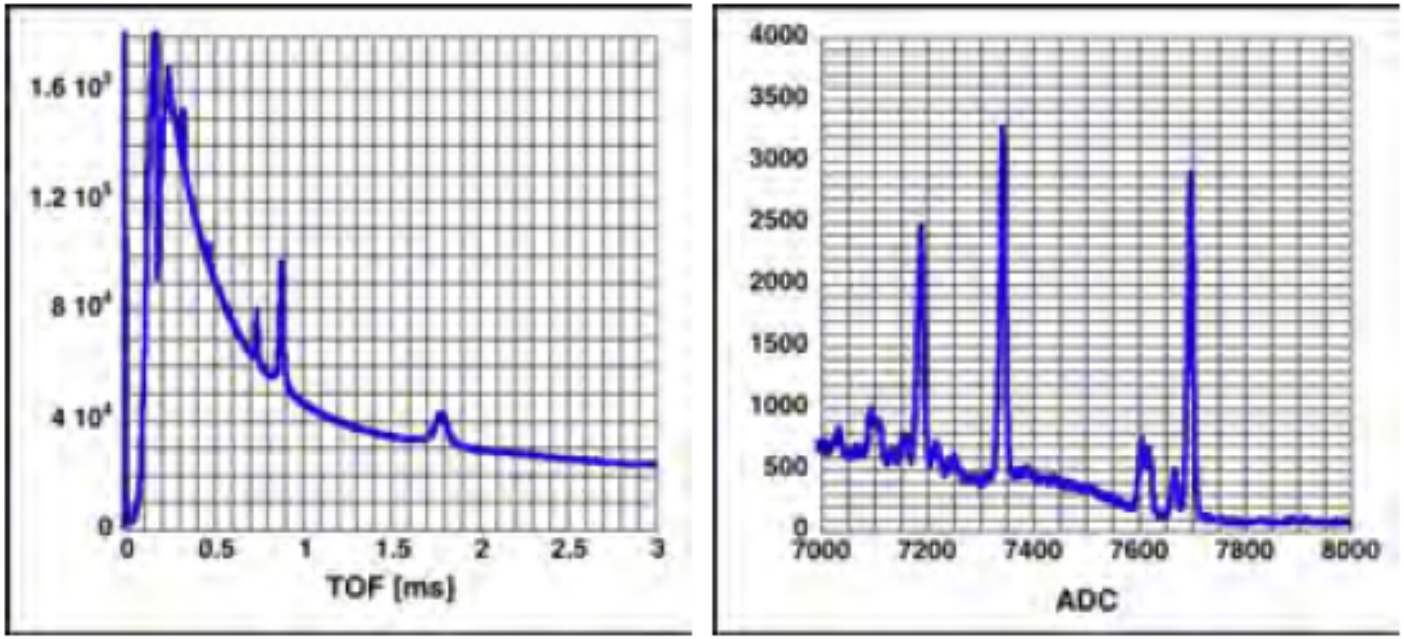
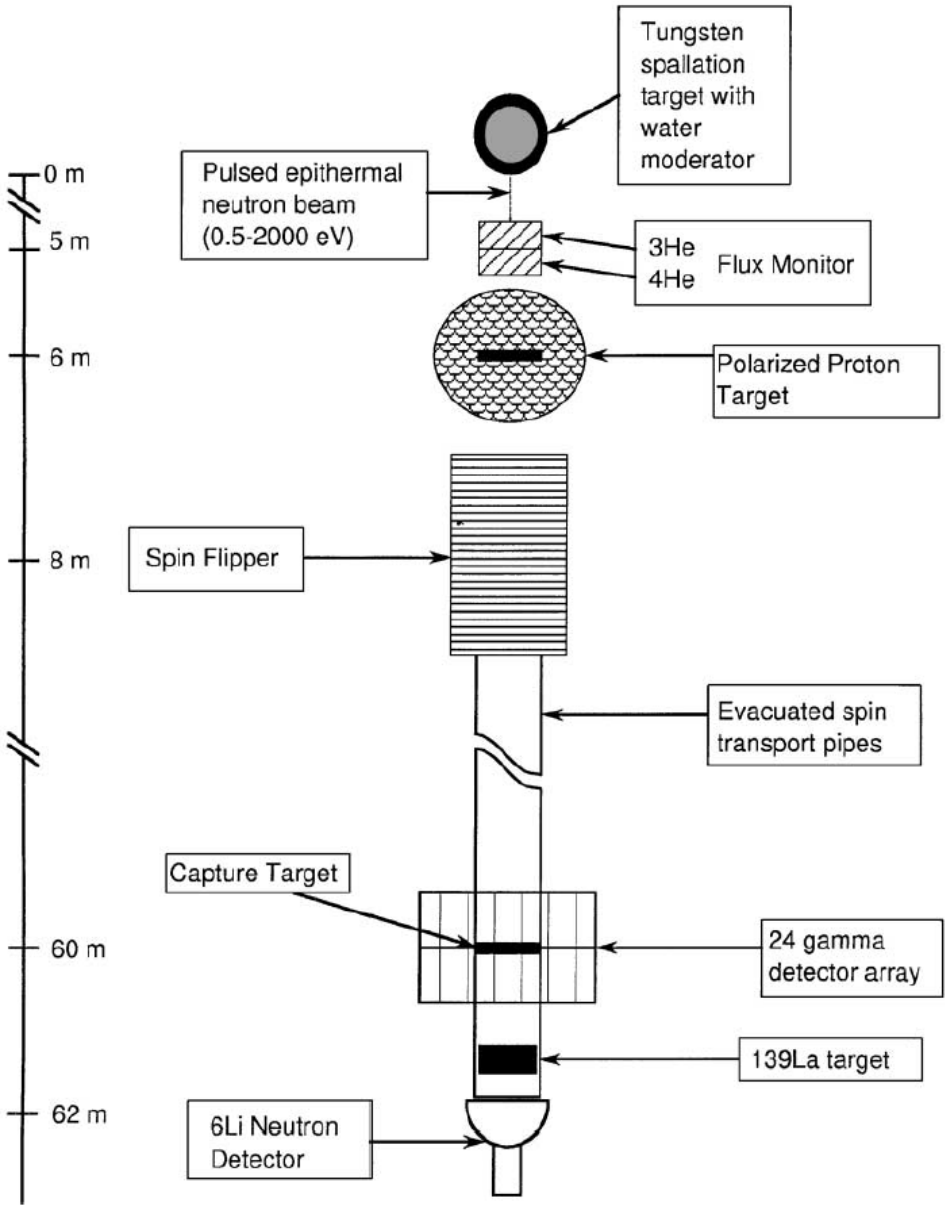


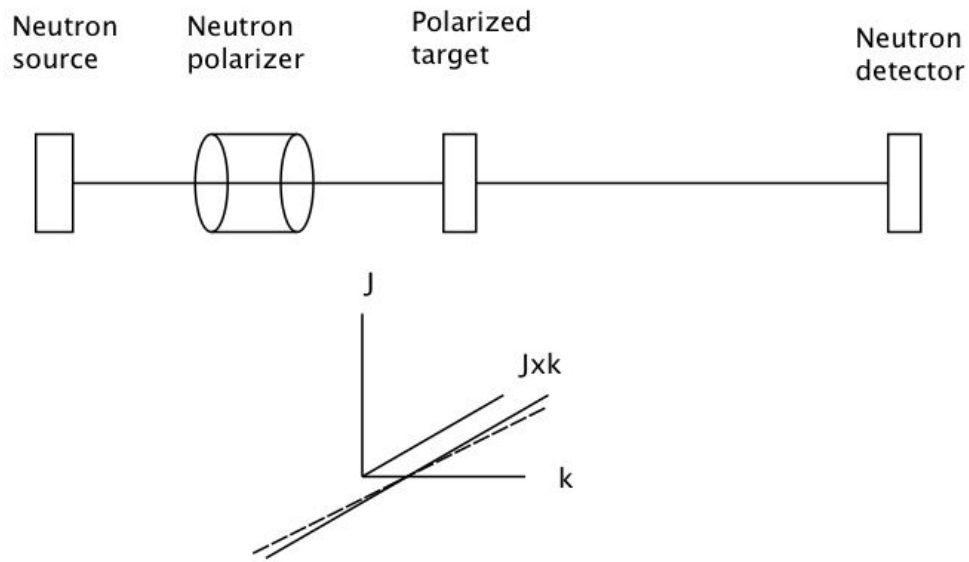
Figure 3: γ-ray count of ^{139}La(n,γ) projected on to (left) the neutron time-of-flight and (right) γ-ray energy. The length of flight was 21.50 m.



Apparatus for PV at a spallation source

σ.k interaction

Notional TR apparatus



The polarizer prepares a beam with σ parallel or anti parallel to Jxk.
The TR odd interaction σ.Jxk attenuates the beam and produces a trans-mission asymmetry as the polarization is reversed.
False asymmetries:
If the polarization has a component along k, -------, then the σ.k Interaction produces a false asymmetry.
The several interactions and misalignments can produce false asymmetries

Break each component of the apparatus into many Thin slabs. For each write the scattering amplitude, *f*, as the sum of 4 terms $f = a + b\ \sigma.l + c\ \sigma.k + d\ \sigma.\ l \times k$.
Forward evolution operator

$$U_F = \prod_{j=1}^{m}\left(1 - \frac{idt}{\hbar}H_j^F\right) = \alpha + \beta\sigma_x + \gamma\sigma_y + \delta\sigma_z$$

Rotate the table. $k_x \to -k_x$, $k_y \to k_y$, $k_z \to -k_z$.
Reverse *B*, ^{3}He polarization, and *l*

Backward, rotated, evolution operator

$$U_R = \prod_{j=m}^{1}\left(1 - \frac{idt}{\hbar}H_j^R\right) = \alpha - \beta\sigma_x - \gamma\sigma_y + \delta\sigma_z$$

If *d*=0, the transmission is unchanged.

Processes such as $\theta \neq 0$ neutron scattering from polarized long-range order in the target can produce spin-dependent asymmetries. Mike Snow will address these issues in his talk