Measuring Parity Violation & Time-reversal Violation with Compound Nuclei

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Roadmap

This presentation is centered around Dr. Danielle Schaper's PhD dissertation so it is about the **modular apparatus at LANSE FP12** she assembled and the two individual experiments—**PV** and **TV** measurement–that it can conduct.

Motivation to look for CP- and T-violation

And we can use some scattering experiments…

Scattering toy model

Which gives some advantage to …

Compound nucleus resonance experiment

And here it comes…

NOTREX to search for TV

Double ^{139}La to search for PV

Finally, the improved apparatus looks like:

Modular apparatus at LANSE FP12

But we are not ready yet, so first redo an old experiment with enhanced equipment to get some better results…

Motivation

In the early universe,

roughly same amounts of baryons and antibaryons

high thermal energy $k_B T > m_{Baryon}$: $\gamma + \gamma \leftrightarrow p + \bar{p}$

At some point, thermal freeze out happened:

forward reactions ceased and later backward reactions became rare

Without CP violation, we expect:

$$n_B = n_{\bar{B}} \sim 10^{-18}\, n_\gamma$$

But we observe:

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-9}$$ ⇨ **Baryon asymmetry!**

Sakharov proposed three necessary conditions for this to occur in 1967.

Search for CP- or T-violation

Assuming CTP-symmetry, T-violation implies CP-violation!

Sakharov's three conditions:

- Baryon number violation
- **C- and CP violation**
- Departure from thermal equilibrium.

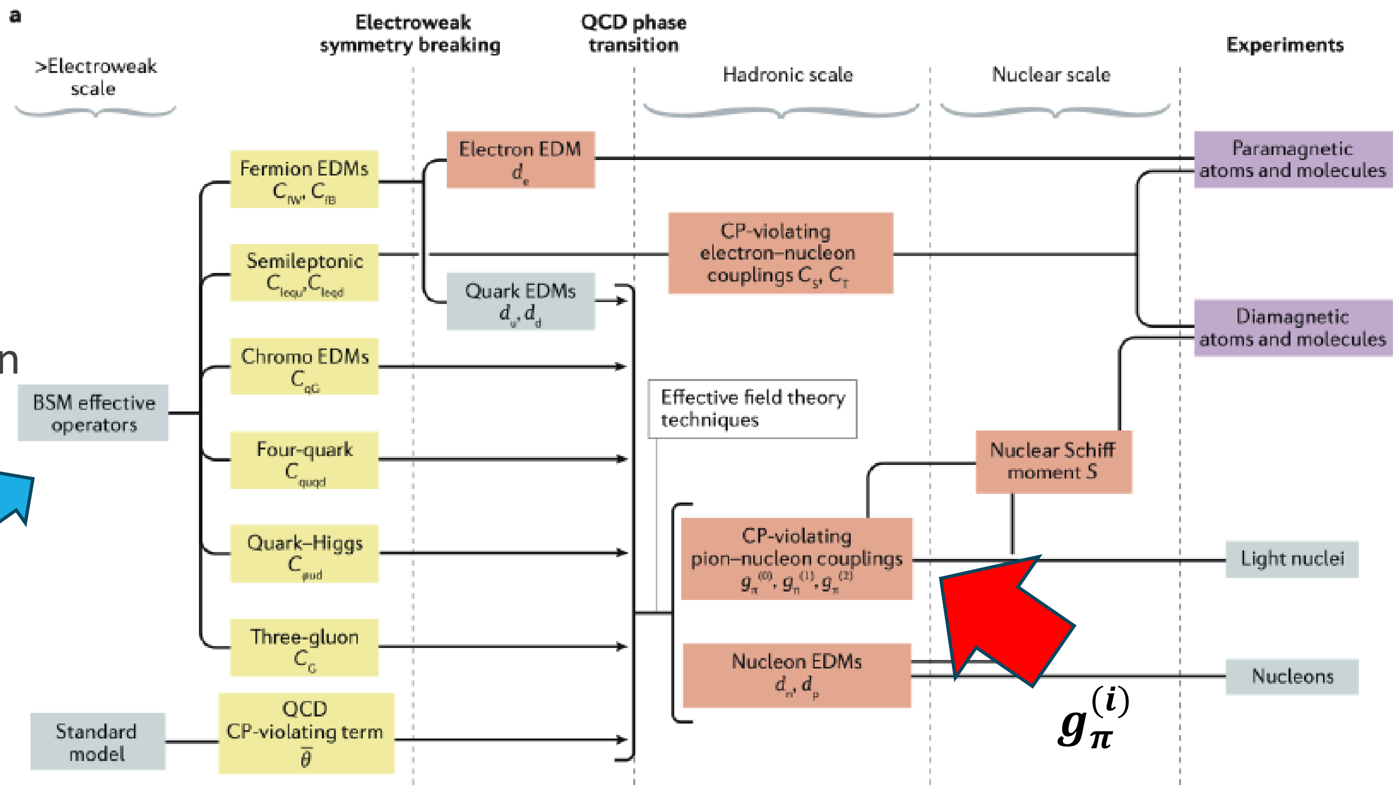
The effective CP-violating Lagrangian can be group into:

$$\mathcal{L}_{CP}^{eff} = \mathcal{L}_{\text{CKM}} + \mathcal{L}_{\text{QCD}} + \boxed{\mathcal{L}_{\text{BSM}}}$$

parametrized by **Wilson coefficients**

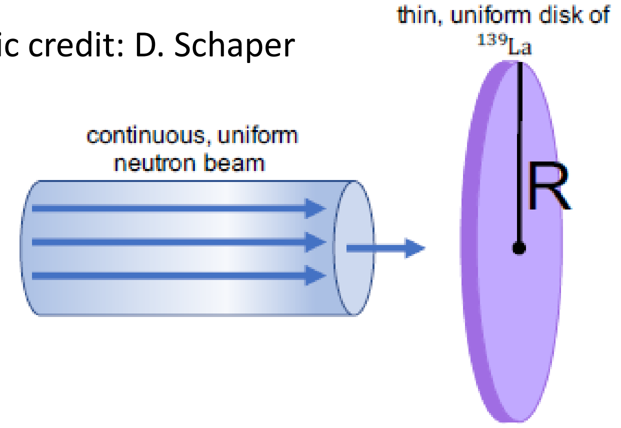
P-violation $\gamma\pi NN$ vertex:

$$\mathcal{L}^{pv}_{\pi\pi NN} = -\frac{ie}{\sqrt{2}f_\pi}\left(h_\nu^0 + \frac{4}{3}h_\nu^2\right)\pi^+\bar{p}A_\mu\gamma^\mu n + \text{h. c.}$$



Pic credit: William B. Cairncross and Jun Ye.

Pic credit: D. Schaper

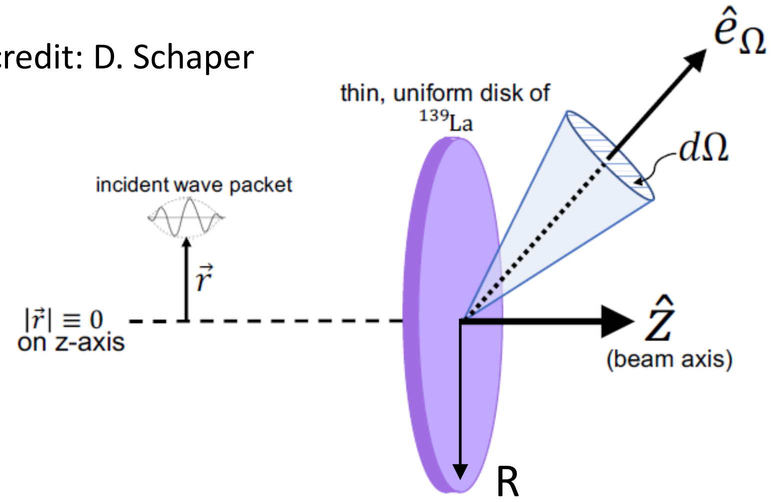


toy model of
experimental setup

Scattering: A Toy Model

Can observe $d\sigma/d\Omega$: differential cross section: "the probability to observe a scattered particle in a given quantum state per unit solid angle"

Pic credit: D. Schaper



Incident neutron as a wave package:

$$\phi(\vec{p}; \vec{r} = 0) \rightarrow \phi_0(\vec{p}) \cdot e^{-i\vec{r}\cdot\vec{p}}$$

But how does it connect to theory?

Define **scattering matrix:** $\boldsymbol{S}$ such that $|\psi_f> = S|\psi_i>$

In the limit where the target is indefinitely heavy, and no KE is transformed:

$$\mathbf{S}(\vec{p}, \vec{p}') - \delta^{(3)}(\vec{p} - \vec{p}') = \delta(|\vec{p}| - |\vec{p}'|)\mathbf{T}(\vec{p}, \vec{p}')$$

Eventually, after carrying out all the integrations:

$$d\sigma = (2\pi p)^2 |\mathbf{T}(p\hat{e}_\Omega), \vec{p}|^2 \propto |f(p\hat{e}_\Omega), \vec{p}|^2 \text{ where } P(\hat{e}_\Omega; \vec{r}) = \int_0^\infty p^2 |\phi_s(p\hat{e}_\Omega; \vec{r})|^2 dp$$

and $d\sigma$ is proportional to the **forward scattering amplitude** $\boldsymbol{f}$

$$\mathbf{T}(p\hat{e}_\Omega), \vec{p} \propto \frac{i}{2\pi p}\left(f(p\hat{e}_\Omega), \vec{p}\right)$$

Combining with the partial wave decomposition, we arrive at the Optical Theorem

$$\boxed{\sigma_{tot} = \frac{4\pi}{p} \mathrm{Im} f(\theta = 0)}$$

which relates **total cross section** (**measurable**) to $\boldsymbol{f}$ (**what we can embed asymmetry in**)

Compound Nucleus Model

"Indirect model of nucleus" when incident neutron in low-energy regime (E_n~1eV)

- Incident neuron thought to be briefly **bound to** the target nucleus
- Leading to a **metastable**, excited nuclear state of mass (A+1)
- Can exist for $\sim 10^{-14}$ s

Aside:

Helicity: $h = \frac{\vec{\sigma} \cdot \vec{p}}{|\vec{\sigma} \cdot \vec{p}|}$

Parity odd

Parity Violation in **s-** and **p-wave** Interference :

- measured by the **longitudinal polarization** $\boldsymbol{P} \equiv \frac{\boldsymbol{\sigma_- - \sigma_+}}{\boldsymbol{\sigma_- + \sigma_+}}$
  - where $\sigma_\pm$ is cross section of the positive/negative helicity neutrons
- In the neutron-nucleus compound system $H_{eff} = H_s + H_W = H_0 + W$
- Define R matrix as $R = 2\pi i T = S - I$ and $R_{ab} = 2\pi i < \frac{1}{2} \psi_b^- |W| \psi_a^+ >$, a, b: l levels s, p

χ: wavefunction of the neutron potential scattering
ϕ: wavefunction of the bound states embedded in the continuum

where $$\langle \psi_s^- | W | \psi_p^+ \rangle = \underbrace{A\left(\phi_s^+ W \phi_p^+\right)}_{\text{mixing of compound nuclear states}} + \underbrace{B\left(\phi_s^+ W \chi_p^+\right) + C\left(\chi_s^+ W \phi_p^+\right)}_{\text{transitions of resonant states to/from nuclear continuum states}} + \underbrace{D\left(\chi_s^+ W \chi_p^+\right)}_{\text{mixing of continuum wavefunctions}}$$

From P-Violation to T-Violation

Plug in R's

$$P = \frac{\mathrm{Im}(R_{10} - R_{01})}{\mathrm{Re}(R_{00} + R_{11})} \quad \text{gives} \quad \boxed{P = -2\langle v\rangle\sqrt{\Gamma_s^n\Gamma_p^n} \cdot \frac{(E-E_s)\Gamma_p + (E-E_p)\Gamma_s}{\Gamma_s\Gamma_s^n[p] + \Gamma_p\Gamma_p^n[s] + 4(kR)^2[s][p]}}$$

$< v >$ is the expectation value of the weak interaction mixing of s- and p-wave states

T Violation in **s-** and **p-wave** Interference:

- Similar idea, but helicity is T even so we pick a "triple product"

$$m = \vec{\sigma}_n \cdot (\vec{k}_n \times \vec{I}) \xrightarrow[\text{under T-reversal}]{} (-\vec{\sigma}_n) \cdot ((-\vec{k}_n) \times (-\vec{I})) = -m$$

$$\frac{\sigma_{\not T \not P}}{\sigma_{\not P}} = \frac{G_J^T}{G_J^P}\frac{\langle w\rangle}{\langle v\rangle} \equiv \kappa(J)\frac{\langle w\rangle}{\langle v\rangle}$$

- And now $H_W = \underset{\text{P-V}}{\hat{v}} + i\underset{\text{PT-V}}{\hat{\omega}}$
- Put together

$$\Delta\sigma_{\not P} = \sigma_- - \sigma_+ = \frac{4\pi}{k}\mathrm{Im}\left[\frac{\langle v\rangle\sqrt{\Gamma_s\Gamma_p}}{(E-E_s+\frac{i}{2}\Gamma_s)(E-E_p+\frac{i}{2}\Gamma_p)}\right]$$

$$\Delta\sigma_{\not T \not P} = \sigma_\uparrow - \sigma_\downarrow = \frac{4\pi}{k}\mathrm{Im}\left(-\frac{(2\pi)^2}{k}(-2Ai\langle w\rangle)\right)$$

Dynamical and Kinematic Amplification

Dynamical:

- Recall $\langle v\rangle = \langle \phi_s | H_W | \phi_p \rangle$
- Write $\phi_s = \sum_{i=1}^{N} a_i |\psi_i>$

  $\phi_p = \sum_{j=1}^{N} b|\psi_j>$

  where a_i and $b_j \sim 1/\sqrt{N}$ for normalization
- In Fock space representation, H_W is a two-body operator, and nearly all none zero terms are near the diagonal ($\sim N$)
- the complex coefficients of the states cause the sum to be "random"

$$\langle v\rangle = \underbrace{\sqrt{N}}_{\text{'random walk' factor}} \times \underbrace{\frac{1}{\sqrt{N}}\cdot\frac{1}{\sqrt{N}}}_{\text{normalization}} \overline{\langle \psi_i | H_W | \psi_j \rangle} = \frac{1}{\sqrt{N}} v_0$$

By viewing nucleus as a black box, $N \cong \frac{\overline{D_0}}{\overline{D}}$ or average level spacing of single particle resonance states divided by compound nucleus levels spacing $\sqrt{N} \sim 10^2$

Kinematic:

- Consider the terms in []:

$$P = -2\langle v\rangle \sqrt{\Gamma_s^n \Gamma_p^n} \cdot \left[\frac{(E-E_s)\Gamma_p + (E-E_p)\Gamma_s}{\Gamma_s \Gamma_s^n [p] + \Gamma_p \Gamma_p^n [s] + 4(kR)^2 [s][p]} \right]$$

- Using Wigner's Semicircle Theorem:

$$\underbrace{(E_1 - E_2)}_{\text{ground states}} \approx N \underbrace{(E_1 - E_2)^*}_{\text{excited states}}$$

- For the excited states:

$$\frac{1}{4N(kR)^2} \left[\frac{(E-E_s)^* \, \Gamma_p + (E-E_p)^* \, \Gamma_s}{[s^*][p^*]} \right]$$

- $kR \sim 10^{-3} \rightarrow \frac{1}{N(kR)^2} \sim 10^2$

Each gives us $\sim 10^2$ enhancement!

Neutron Optics Time Reversal EXperiment

Proposed by David Bowman and Vladimir Gudkov in 2014 and collaboration formed in 2015

forward scattering amplitude *f*:

$$f = \mathcal{A} + \mathcal{B}\left(\vec{\sigma}\cdot\hat{I}\right) + \mathcal{C}\left(\vec{\sigma}\cdot\hat{k}\right) + \boxed{\mathcal{D}}\left(\vec{\sigma}\cdot(\hat{k}\times\hat{I})\right)$$

T, P even Spin indep. interaction	T, P even Spin-spin interaction	T even, P odd PV due to resonance mixing	T old, P even PV due to resonance mixing

Observables in this experiment:

- $\vec{k}_n$, the linear momentum of the neutron
- $\vec{\sigma}_n$, the spin of the neutron
- $\vec{I}$, the spin (polarization) of the target nuclei

Unique Feature: absence of false TV signal due to final state interactions (FSI):

using first-order Born approximation to assume reaction matrix T is Hermitian

$$\langle i|T|f\rangle = \langle f|T^*|i\rangle$$

$\Rightarrow |\langle f|T|i\rangle|^2 = |\langle -f|T|-i\rangle|^2$ where $|-i\rangle| = |i\rangle$ (with all spins and momenta reversed)

Hence, the probability of these two processes is an even function of time.
No FSI can mimic the result of T-violation in this case.

Implementing **NOTREX**

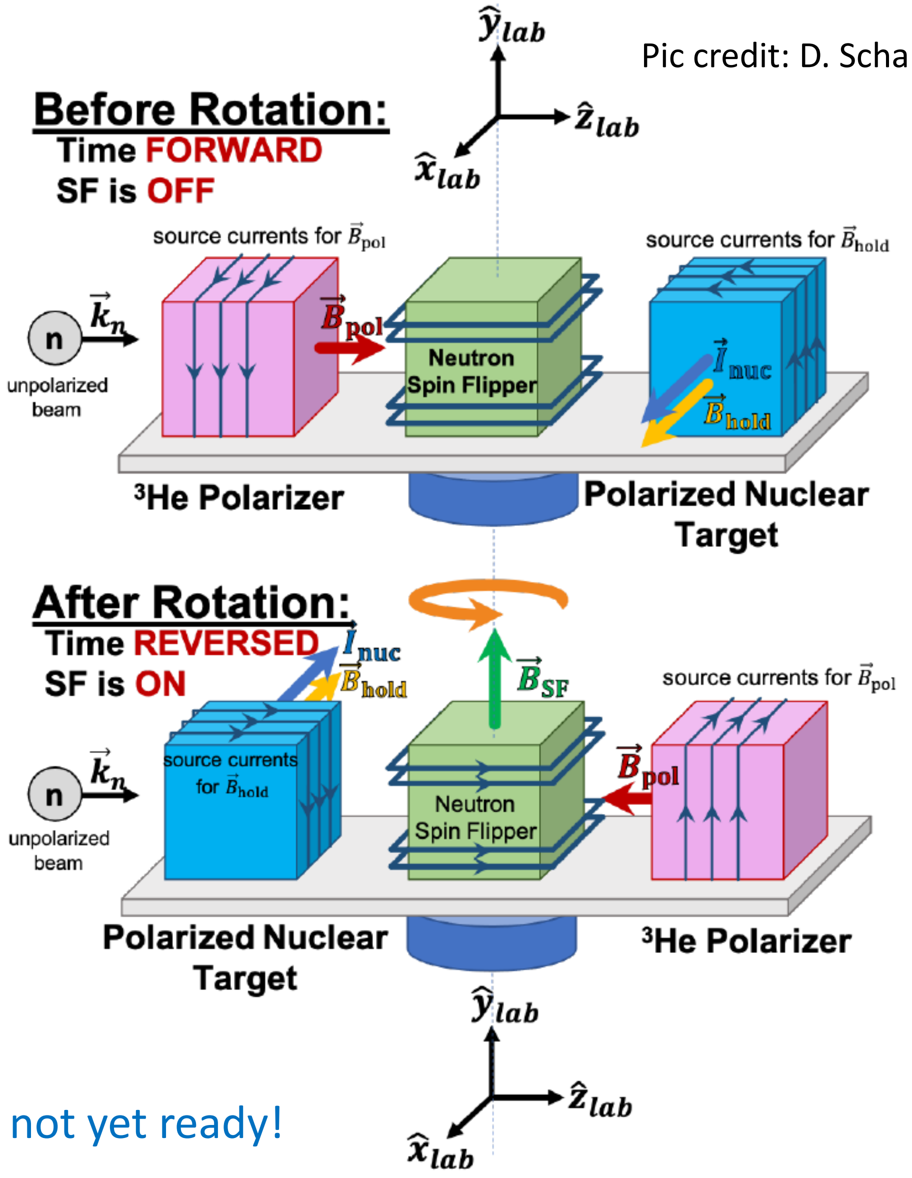
At **L**os **A**lamos **N**eutron **S**cience **CE**nter (**LANSCE**)
in Los Alamos National Lab

Simple idea: shoot unpolarized neutron beams onto nuclear target. We can do it forward in time, and then backward in time to compare the difference.

PROBLEM! UNABLE TO REVERSE TIME!

Solution: reverse the dynamics of the whole system
In other words: time reversed + dynamic evolved
=time evolved + dynamic reversed
Done by $180°$ **rotation** (reverse the order of system from neutron point of view) + **neutron spin flipper** (flip the neutron spin that otherwise won't be changed by reversing the order).

Pic credit: D. Schaper

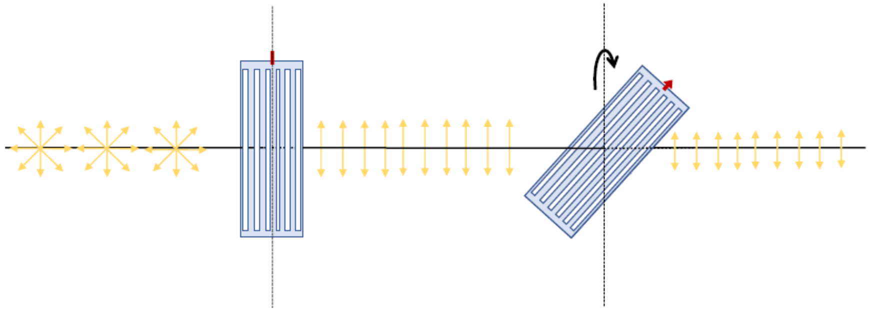


But not yet ready!

Double Lanthanum

Interested in the asymmetry of ^{139}La p-wave: A_ω such that $\sigma_\pm = \sigma_0(1 \pm A_\omega)$, where $\sigma_\pm$ is the helicity dependent cross-section

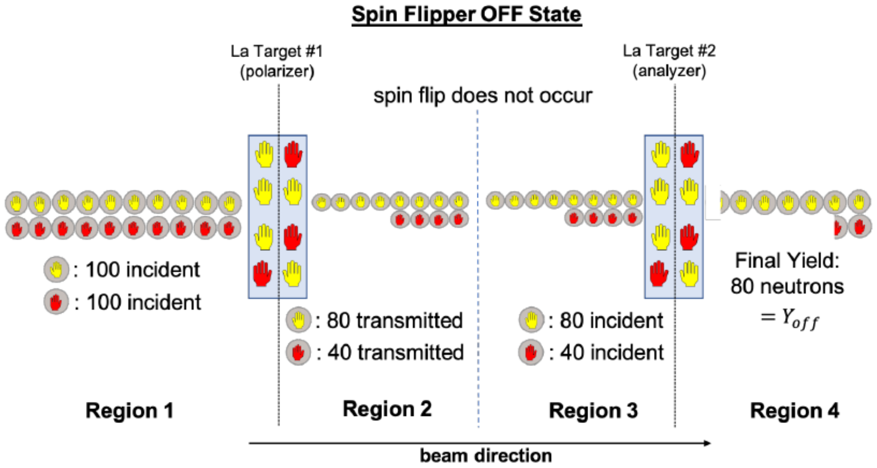
Current(~2021) operating experiment; originally published by Yuan, et al. in 1991

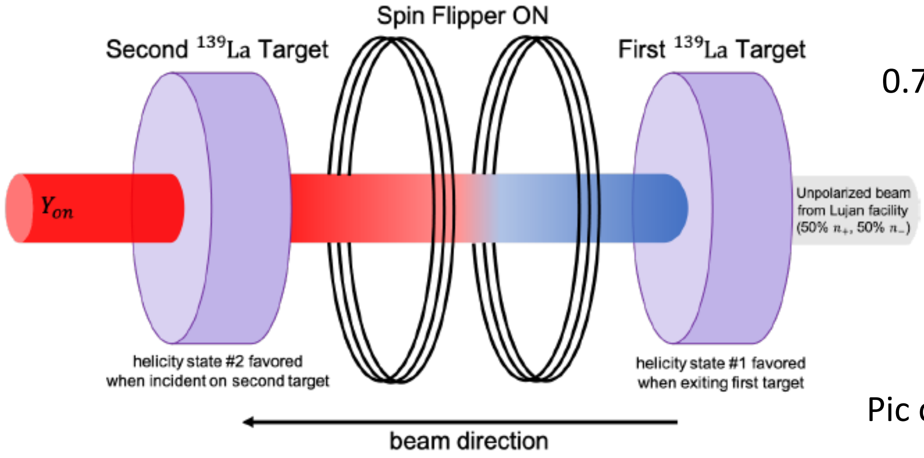


Pic credit: D. Schaper

Analogous to measuring light through a polarizer and an analyzer, but now we want to "**characterize the polarizing properties** of the analyzer" (^{139}La).

Shoot an unpolarized neutron beam onto 2 ^{139}La targets twice; one with spin flipper on and the other one without.





0.734 eV neutron

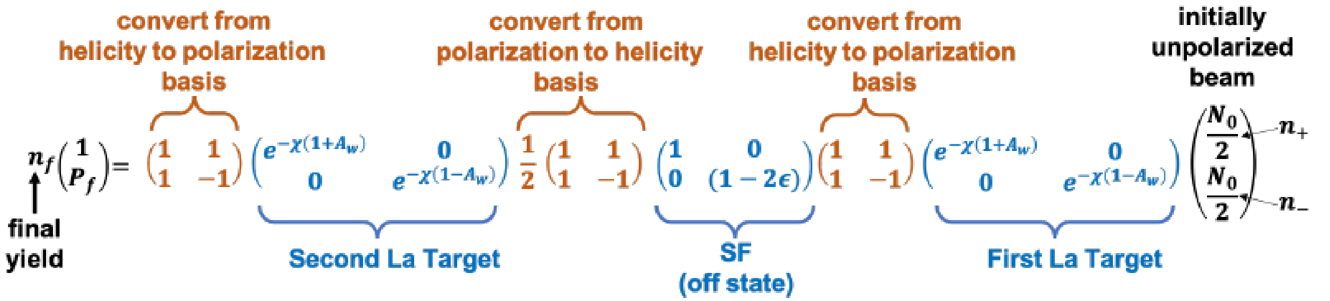
Pic credit: D. Schaper

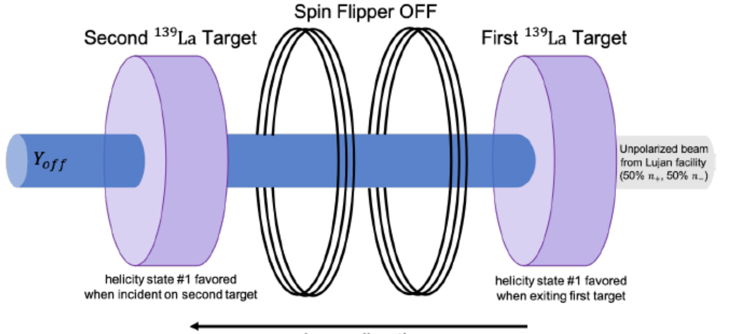
Calculation

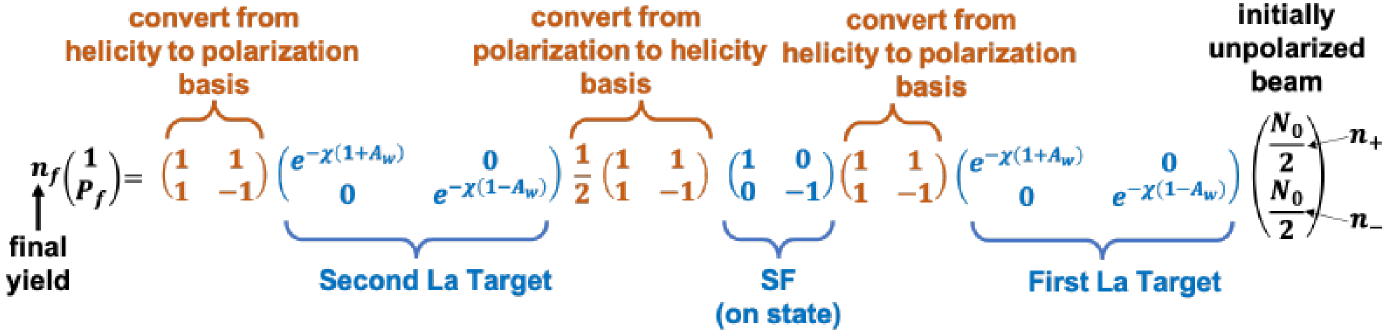
$\sigma_{\pm} = \sigma_0(1 \pm A_{\omega})$

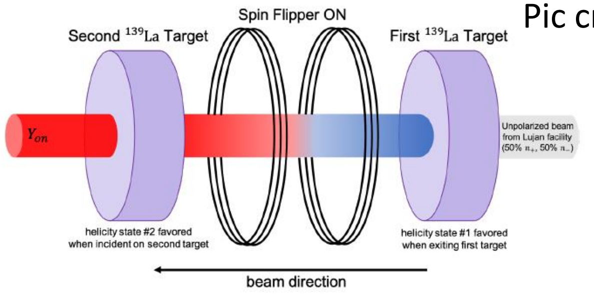
From Yuan et al.:

$|P| = 0.0955 \pm 0.0035.$









Pic credit: D. Schaper

$n_{\pm}$ is the number of neutrons in $\pm$ helicity state;

$P \equiv \frac{n_+ - n_-}{n_+ + n_-}$ is the polarization of neutrons;

ϵ accounts for the imperfection of the spin flipper (assume to be 0 in ideal world);

$I = I_0 e^{-\rho l \sigma}$ describes the attenuation of the neutron beam in thick La target;

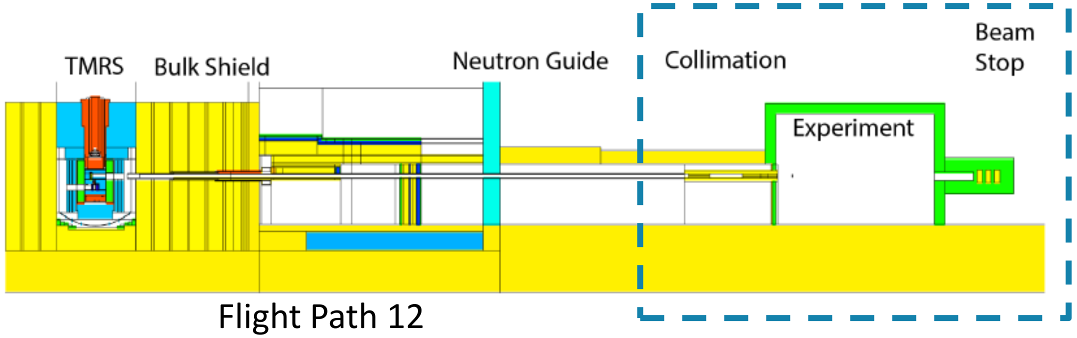
$\chi = \rho l \sigma_0$

$$Y_{on} = N_0 e^{-2\chi}$$

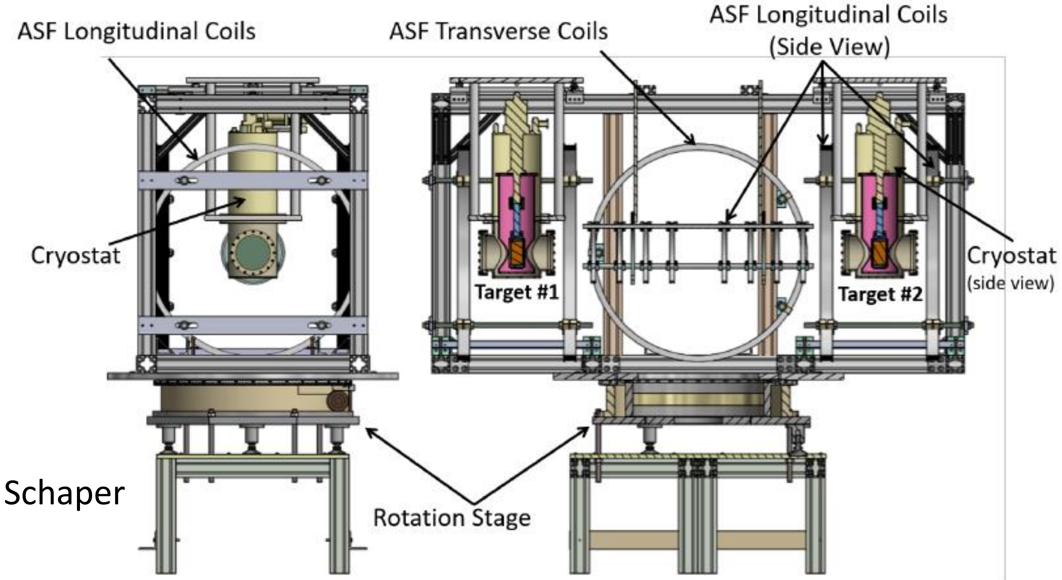
$$Y_{off} = N_0 e^{-2\chi}\left[(1-\epsilon)\cosh(2A_w\chi) + \epsilon\right]$$

$$\frac{Y_{off}}{Y_{on}} = (1-\epsilon)\left[1 + 2(\rho\ell\sigma_0)^2 A_w^2\right] + \epsilon$$

Experimental Apparatus



Flight Path 12



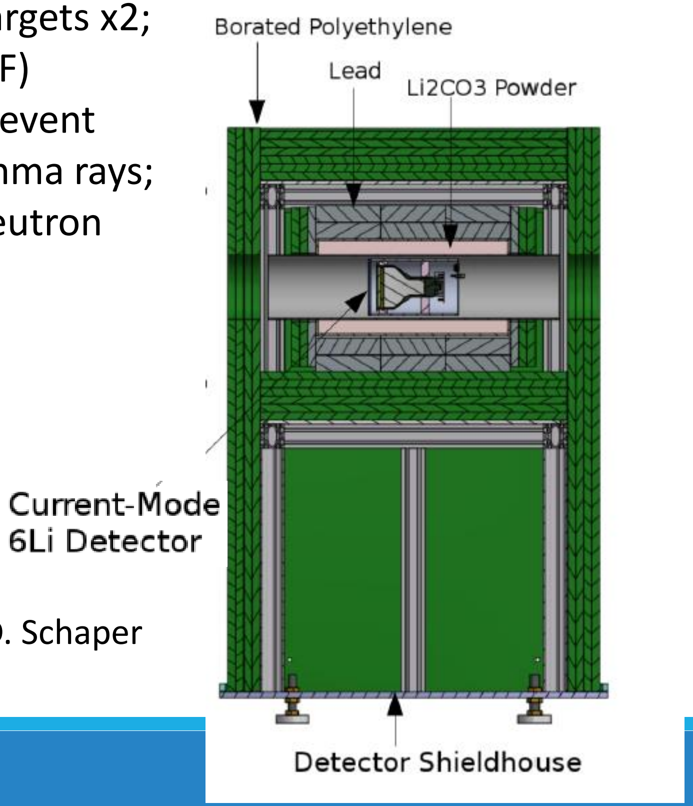
Pic credit: D. Schaper

Mechanical apparatus:

Collimator: define the neutron beam and minimize background neutrons and gamma rays with borated polyethylene and ^{6}Li-loaded fluorinated plastic

Main apparatus: 139La targets x2; Adiabatic Spin Flipper (ASF)

Shieldhouse/detector: prevent ourside neutrons and gamma rays; uses ^{6}Li-rich scintillator neutron detector



Pic credit: D. Schaper

Reference

D. Schaper. Neutron Spectroscopy of the Parity-Violating 0.734 eV Neutron Resonance in Lanthanum-139 in Preparation for the NOPTREX Time Reversal Violation Experiment. PhD Dissertation. 2022

V. W. et al. Yuan. Parity nonconservation in polarized-neutron transmission through La-139. Phys. Rev. C, 44:2187-2194, 1991.

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William B. Cairncross and Jun Ye. Atoms and molecules in the search for time-reversal symmetry violation. Nature Reviews Physics, 1(8):510-521, July 2019.