TREX: A Proposed Search for T Violation in Polarized Neutron Optics

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IU Center for Spacetime Symmetries

Amplification of parity violation in compound nuclear resonances

Polarized neutron optics test of T invariance: the idea

New developments which now make this experiment attractive to consider

What is to be done? How can we make the polarized target?

Thanks for slides from: D. Bowman, V. Gudkov, Z. Tang, H. Shimizu,...
Time Reversal Experiment “TREX”
Neutron Optics for T Violation “NOP-T”
Proto-collaborations

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T. Tong      ORNL
V. Gudkov    U South Carolina
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C. Crawford  U Kentucky
B. Plaster   U Kentucky
N. Fomin     U Tennessee
Z. Tang      LANL

H Shimizu    Nagoya U
M. Kitaguchi Nagoya U
K. Hirota    Nagoya U
G. Ichikawa  Nagoya U
T. Ino       KEK
T. Shima     Osaka
T. Iwata     Yamakata U
T. Yoshioka  Kyushu U
Y. Yamagata  RIKEN
M. Hino      Kyoto
T. Momose    UBC
K. Asahi     Tokyo I. Tech.
K. Sakai     JAEA
H. Harada    JAEA
A, Kimura    JAEA

NOPTREX?
Low energy neutrons can access a dense forest of highly excited states in the compound nucleus.

Unique phenomena occur in this regime which are not widely known.

One such phenomenon is the large amplification of discrete symmetry violation effects like P and T.
Neutron Time-of-Flight spectrum in transmission through Indium

Excited state energies=\(\sim6\) MeV + (eV->keV)
Narrow resonances (\(\sim100\) 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

\[ |N\rangle = |qqq\rangle + |qqqq\rangle + \cdots = \text{valence + sea quarks + gluons} \]

interacts through NN strong force, mediated by mesons
\[ |m\rangle = |qq\rangle + |qqqq\rangle + \cdots \]

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 $0.734$ eV \[ \Delta \sigma/\sigma = 0.097 \pm 0.005. \]

$10^6$ amplification!

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

(2) Weak amplitude dispersion for $10^6$ Fock space components $\sim \sqrt{10^6} = 1000$

Idea is to use the observed enhancement of PV to search for a TRIV asymmetry.
Apparatus to Measure $\sigma \cdot k$ Parity Violating Asymmetry


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

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

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>$M_{Std}$ (meV)</th>
<th>$M_{Dwy}$ (meV)</th>
<th>$M_{Std+Dwy}$ (meV)</th>
<th>$M_{expt}$ (meV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{239}$U</td>
<td>0.116</td>
<td>0.177</td>
<td>0.218</td>
<td>0.67$^{+0.24}_{-0.16}$</td>
</tr>
<tr>
<td>$^{105}$Pd</td>
<td>0.70</td>
<td>0.79</td>
<td>1.03</td>
<td>2.2$^{+2.4}_{-0.9}$</td>
</tr>
<tr>
<td>$^{106}$Pd</td>
<td>0.304</td>
<td>0.357</td>
<td>0.44</td>
<td>0.20$^{+0.10}_{-0.07}$</td>
</tr>
<tr>
<td>$^{107}$Pd</td>
<td>0.698</td>
<td>0.728</td>
<td>0.968</td>
<td>0.79$^{+0.88}_{-0.36}$</td>
</tr>
<tr>
<td>$^{109}$Pd</td>
<td>0.73</td>
<td>0.72</td>
<td>0.97</td>
<td>1.6$^{+2.0}_{-0.7}$</td>
</tr>
</tbody>
</table>
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 \(\sim 10^{10}\))
- Departure from Thermal Equilibrium (no problem?)

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

Relevant neutron experimental efforts

Neutron-antineutron oscillations (B)
Electric Dipole Moment searches (T=CP)

T Violation in Polarized Neutron Optics (T=CP)
“Time Reversal” -> Motion Reversal

Is the final state of the motion with time-reversed final conditions $V_3(t=1)$ the same as the time-reversed initial condition $-V_1(t=0)$?

This is an experimental question. Gotta reverse the spins too.
Forward Scattering Amplitude

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

- **Spin Independent** P-even T-even
- **Spin Dependent** P-even T-even
- **P-violation** P-odd T-even
- **T-violation** P-odd T-odd

\[ |s\rangle \]
\[ J_s E_s \Gamma_s \Gamma_s^n \]
\[ |p\rangle \]
\[ J_p E_p \Gamma_p \Gamma_p^n \]
\[ |p_{1/2}\rangle \]
\[ \Gamma_p^{n,1/2} \]
\[ |p_{3/2}\rangle \]
\[ \Gamma_p^{n,3/2} \]
\[ \langle W \rangle \]
T violation Searches with EDMs and Compound Nuclei

[Diagram showing relationships between various electric dipole moments and fundamental phases]

- $d_\mu$, $d_e$
- $C_{qe}, C_{qq}$
- $\theta, d_q, \bar{d}_q, w$
- Gluon self-couplings
- Neutron EDM ($d_n$)
- EDMs of nuclei and ions (deuteron, etc.)
- EDMs of paramagnetic molecules (YbF, PbO, HfF$^+$)
- Atoms in traps (Tl, Rb, Cs)
- EDMs of diamagnetic atoms (Hg, Xe, Ra, Rn)

Reference: Pospelov Ritz, Ann Phys 318 (05) 119

$d_n$
The enhancement of PVTR ($\sigma.[K \times \mathbb{I}]$) is (almost) the same as for PV ($\sigma.K$). Sensitivity expressed as a ratio of P-odd/T-odd to P-odd amplitudes

$$\frac{\Delta \sigma_T}{\Delta \sigma_P} \sim \lambda = \frac{g_T}{g_P} \quad \sim - ?$$

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

sensitivity $\sim$ 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) \( \sigma_n^{-} \cdot (k_n^{-} \times \vec{I}) \)
- 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-\(\rightarrow\Delta \sigma_{PT}/\Delta \sigma_{P}\sim 1E-5\)
- The nuclei of interest, resonance energies, and P-odd asymmetry amplifications are measured

<table>
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<th>Nucleus</th>
<th>Resonance Energy</th>
<th>PV asymmetry</th>
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<td>(^{81}\text{Br})</td>
<td>0.88 eV</td>
<td>0.02</td>
</tr>
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</table>
So why has this experiment never been done?

How to design experiment that can realize a “null test”?

How to get enough polarized eV neutrons on resonance?

How best to characterize/eliminate “non-optical” systematic effects?

Russian/Japanese/US groups looked into it in ~1990s:
“death by a thousand cuts”

Now the situation is greatly improved

Last remaining difficulty: POLARIZED TARGET
False TR asymmetries caused by TRI interactions

Ideally, the spin is along $y$ such that $\sigma \cdot l \times k$ 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 $\sim \sin(\theta)$. 
Thinking of the 90s: Make the apparatus “symmetric” by having both a neutron polarizer and a neutron polarization analyzer.

Masuda’s analysis of systematic uncertainties from alignment

\[ A = \frac{(R_+ - R_-)}{(R_+ + R_-)}, \]
\[ R_+ = R_{++} + R_{+-} = \text{Tr}(\rho(P_0, \varepsilon_x, \varepsilon_y) t^\dagger), \]
\[ R_- = R_{-+} + R_{--} = \text{Tr}(\rho(-P_0, \varepsilon_x, \varepsilon_y) t^\dagger), \]
\[ R_+ - R_- = \exp(-2\text{Im}(\phi_0)) \]
\[ \{ [2\varepsilon_x P_0 + 2\varepsilon_y P_0 \delta_y + 2\varepsilon_0 \delta_2] P_1 \text{Im}[\cos b (\sin b/b) \ast \phi_1 \ast] + 2P_0 \text{Im}[\cos b (\sin b/b) \ast \phi_3 \ast] \]
\[ + [2\varepsilon_x P_0 \delta_y - 2\varepsilon_y P_0] P_1 \text{Im}[(\sin b/b)(\sin b/b) \ast \phi_1 \phi_3 \ast] + 2P_0 P_1^2 \text{Im}[(\sin b/b)(\sin b/b) \ast \phi_1 \phi_2 \ast] \}, \]
\[ P = \frac{(R_{0+} - R_{0-})}{(R_{0+} + R_{0-})}, \]
\[ R_{0+} = R_{++} + R_{+-} = \text{Tr}(P_a \xi_x, \xi_y) t^\dagger), \]
\[ R_{0-} = R_{-+} + R_{--} = \text{Tr}(P_a \xi_x, \xi_y) t^\dagger), \]
\[ R_{0+} - R_{0-} = \exp(-2\text{Im}(\phi_0)) \]
\[ \{ [2\xi_x P_a + 2\xi_y P_a \delta_y + 2P_a \delta_2] P_1 \text{Im}[\cos b (\sin b/b) \ast \phi_1 \ast] + 2P_a \text{Im}[\cos b (\sin b/b) \ast \phi_3 \ast] \]
\[ + [-2\xi_x P_a \delta_y + 2\xi_y P_a] P_1 \text{Im}[(\sin b/b)(\sin b/b) \ast \phi_1 \phi_3 \ast] - 2P_a P_1^2 \text{Im}[(\sin b/b)(\sin b/b) \ast \phi_1 \phi_2 \ast] \}, \]

The ratio \( X \) is

\[ X \equiv P_0 / P_a [1 + \]
\[ \{ [2(\varepsilon_x - \xi_x) + 2(\varepsilon_y - \xi_y) \delta_y ] P_1 \text{Im}[\cos b (\sin b/b) \ast \phi_1 \ast] \]
\[ + [2(\varepsilon_x + \xi_x) P] \delta_y - 2(\varepsilon_y + \xi_y)] P_1 \text{Im}[(\sin b/b)(\sin b/b) \ast \phi_1 \phi_3 \ast] \]
\[ 4P_1^2 \text{Im}[(\sin b/b)(\sin b/b) \ast \phi_1 \phi_2 \ast] \]

The 13 Greek letters are alignment errors.
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.
How to eliminate the zoo of alignment angles:
Think of the experiment to find a $\sigma$.Jxk interaction as comparing the transmission in two different configurations of the apparatus

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.
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)

\[ f = f_0 + f_1 \sigma_n \cdot \vec{I} + f_2 \sigma_n \cdot k_n + f_3 \sigma_n \cdot (k_n \times \vec{I}) \quad f_3 \ll f_1, f_2 \]
Experiment Components

• Intense eV neutron beam
• Polarized eV neutrons
• Ability to flip \( \vec{k}_n, \vec{\sigma}_n, \vec{I} \) and B (mechanical rotation of apparatus, B shielding)
• Current mode eV neutron detector
• Polarized nuclear target
Neutron source flux with time. Only within last decade do we have ~MW-class short-pulsed spallation sources

![Graph of neutron source flux over time with various sources such as Chadwick, Berkeley 37 inch cyclotron, 0.35mCi Ra-Be source, and current sources like Tohoku Linac, ISIS, and US-SNS. The graph includes trend lines for reactors and spallation sources, marked with symbols such as peaks and averages.](image)
Why is a pulsed spallation neutron source important for TREX?

resonance energy $\sim$eV, resonance width $\sim$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!

$\sim 10^4$ more of these “off-resonance” neutrons
Polarized $^3\text{He}$ Neutron Spin Filters

Laser-polarized Rb $\rightarrow ^3\text{He}$ nucleus

Uniform polarized neutron beam phase space from absorption in polarized $^3\text{He}$ gas

Spin flip by NMR on $^3\text{He}$. By far the best choice for TREX

Need more polarized $^3\text{He}$ to polarize eV neutrons ($\sigma_a \sim 1/\nu_n$)
> 80% $^3$He polarization for neutron spin filters

<table>
<thead>
<tr>
<th>Cell name</th>
<th>D (nm)</th>
<th>$V$ (cm$^3$)</th>
<th>$T_{up}$ (h)</th>
<th>$T_1$ (h)</th>
<th>X</th>
<th>$P_{He}$</th>
<th>nl, bar-cm</th>
<th>instrument</th>
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<td>4</td>
<td>895</td>
<td>4.76</td>
<td>NA</td>
<td>NA</td>
<td>0.853±0.012</td>
<td>8.507±0.060</td>
<td>ANDR</td>
</tr>
<tr>
<td>Maverick</td>
<td>615</td>
<td>4.33</td>
<td>NA</td>
<td>NA</td>
<td></td>
<td>0.821±0.011</td>
<td>8.878±0.060</td>
<td>ANDR</td>
</tr>
<tr>
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<td>0.851±0.007</td>
<td>8.507±0.071</td>
<td>NG6A</td>
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<tr>
<td>Maverick</td>
<td>4</td>
<td>615</td>
<td>5.76</td>
<td>208</td>
<td>0.177</td>
<td>0.826±0.007</td>
<td>8.878±0.071</td>
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</tr>
<tr>
<td>Syrah</td>
<td>6.2</td>
<td>790</td>
<td>4.03</td>
<td>NA</td>
<td>NA</td>
<td>0.835±0.023</td>
<td>13.16±0.16</td>
<td>BT-7 TAS</td>
</tr>
</tbody>
</table>

Confirmed with pol. n’s

Volume Bragg gratings are bulk slabs of photosensitive glass that contains Bragg planes with varying indices of refraction. They work as a frequency-selective feedback element. Chirped VBGs indicate variable grating periods.
$^3$He NSF: optimum thickness of $^3$He gas $\rho d$ at 0°C

$\rho d : 150 \sim 200$ atm-cm at 3.2 eV

$P_{He} = 0.75$
$^3$He cells & polarization

$^3$He cell at NIST
- $^3$He pressure $\sim 1$ atm
- $^3$He thickness $10 \sim 20$ atm-cm
- $P_{^3\text{He}} \sim 80\%$

$^3$He cell for JLab exp.
- Double chambers
- $^3$He pressure $\sim 7$ atm
- $^3$He thickness $\sim 280$ atm-cm
- $P_{^3\text{He}} \sim 70\%$
In-house cell fabrication

- $^3$He polarization ~80%
- Long lifetime 100 – 400 hrs, approaching dipole-dipole relaxation limit
- Dimensions / pressures:
  - 8 – 12 cm in length
  - 1 – 3 bars
  - Suitable for thermal/cold neutrons

Need longer cells for polarizing epi-thermal neutrons

Factors influencing choice of target and state for TR studies

- Large PV asymmetry
  - Barrier-penetration enhancement \( \sim \frac{1}{k} \sim E^{-1/2} \)
- Low energy resonance
  - Neutron flux at a spallation source \( \sim \frac{1}{E} \)
- \(^{139}\text{La}\)
  - 10% PV
  - \( E = 0.734 \text{ eV} \)
- Possibility to polarize
  - Several groups have reported 40% polarized La targets
Polarized target: the hardest part of the apparatus? Serious cryogenics for large volume

Dynamic Nuclear Polarization using microwaves

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</table>

Our nuclei are not so easy to polarize. All are $J\geq3/2 \rightarrow$ spin relaxation by quadrupolar fields etc.
DNP of La in Nd$^{3+}$ doped LaAlO$_3$

*it is not a new territory*: *it can be polarized via the Solid Effect*

[Maekawa et al., NIM A 366 (1995) 115]
- $P(^{139}\text{La}) \sim 20\%$
- $T \sim 1.5$ K $B \sim 2.3$ T

**last experiments**: at PSI in 1997!

[Hautle & Linuma, NIM A 440 (2000) 638]
- $P(^{139}\text{La}) \sim 50\%$ / $P(^{27}\text{Al}) \sim 65\%$
- Dilution refrigerator, $T < 300$ mK $B \sim 2.3$ T

**Crystals size**: $15 \times 15 \times 4$ mm

Nd$^{3+}$ doping: $0.03$ mol% $\sim 5 \times 10^{18}$ spins/ccm

(0.1 mol% / 0.3 mol%)

Nd$^{3+}$ ion replaces $^{139}\text{La}$ nucleus

two $g$-factors: $g_\parallel = 2.12$ $g_\perp = 2.68$
Conclusion from Nd$^{3+}$:LaAlO$_3$ experiments

**general**
- large polarization values can be achieved by known technique
- polarization was achieved in a dilution fridge
- crystal used so far were of not sufficient quality

**Questions that have to be answered before going on**
- how precise the polarization value needs to be known
- way to measure the polarization besides NMR (spin-dependent transmission, pseudomagnetic precession, Ramsey resonance)
- tolerable polarization inhomogeneity
- stability of polarization over time / frozen spin mode
- polarization cannot be easily flipped (like $^3$He) for the rotated configuration
- target size
- polarization level needed
- tolerable magnetic field (=> stray fields)
- overall size of PT apparatus
- $^3$He on beam (dilution refrigerator)
Conclusion from Nd\textsuperscript{3+}:LaAlO\textsubscript{3} experiments II

Answers to above questions could largely determine & constrain the requirements and layout of a polarized target system or make it even impossible??

what to do, suggestions

- define the possible options before start of further R&D
- get really good crystals (commercially available?)
- establish experimental data base to decide on the type of apparatus most suited for the experiment:

  check DNP performance & relaxation at different temperature / field combinations (1K / 5T or DR / 2.5T)
HXTC (XENA) “Open-Source” Xe Polarizer

Peter Nikolaou, SIUC / Vanderbilt

HXTC Goal: Make Human-Scale LPXe, easier, cheaper, and open-source
Best result to date:
Stupic et al. JMR 208 58-69, 2011
- $P=2.2\%$ for 5\% $^{131}$Xe in 1.5 bar
- (5000-fold at 9.4 T)
- Successful separation from Rb, SEOP Cell

How to do better?
- Use more powerful, narrowed laser (above was un-narrowed 40 W)
- Keep $^{131}$Xe partial pressure low during SEOP ($\Gamma > \gamma_{SE}$ at above ~1/3 bar); but would need to quickly re-pressurize for target somehow?
- Throw kitchen sink at it (try Cs, Rb/Cs hybrid, huge cells / low pressure, etc.?). $P=10\%$ “should” be possible; “More = Difficult”.
- May necessitate stopped-flow delivery of HP $^{131}$Xe to increase [Xe], but cont. flow w/o cryo-collection could allow much higher [AM]…
Xenon

DNP has been recently performed for Xenon doped at low temp.
a) Xe is liquid around 165K
b) TEMPO dissolved in iso-butanol
Mix them with a) 50% and b) 50% in weight.

[DNP result]
1.2K at 3.35T, \( \text{Pol(Xe129)} = 5.1\% \),
1.2K at 5T, \( \text{Pol(Xe129)} = 7.2\% \)

However, due to as much as 50% of iso-butanol, fraction of Xe is limited to 50%.
Mechanical Alloying (MA)

Using a ball mill, one crushes material into very fine power in nanometer scale and mixes them resulting in even chemical reactions.

Ten minutes of processing in a ball mill polymerizes a white monomer (left) into a bright red conducting polymer, poly(2-methoxy-5-2′-ethylhexyloxy phenylene vinylene) (right). Credit: ACS Macro Lett. http://cen.acs.org/articles/92/web/2014/03/Ball-Mill-Grinds-Monomers-Polymer.htm

It may be applicable to doping of most of “solid” material including solid Xeon.
MA with Xe and TEMPO

Xe (20g) + TEMPO (12.5 mg) → 2.4x10¹⁸ TEMPO/g
milling time: 60 min.
Temp.: around 93K

(0.52x10⁻³ TEMPO/Xe)

ESR (Xe+TEMPO) 103K

Symmetric and relatively narrow ESR spectrum suggesting uniform distribution of TEMPO

ESR (TEMPO) +50 deg. C.

ESR (TEMPO) 103K
How to Polarize Br: Triplet-DNP method?

• High electron polarization spontaneously produced in photo-excited aromatic molecule


Very weak dependence on B and T

Can bromine be polarized by substituting it into the aromatic molecules (pentacene/napththalene) used for this?
Polarization of Pentacene Molecule at High Temperature*

by M. Inuma et al.

$m_s \rightarrow m_l$

$|+1, +\frac{1}{2}\rangle \quad 12\%$

$|+1, -\frac{1}{2}\rangle$

$|0, +\frac{1}{2}\rangle \quad 76\%$

$|0, -\frac{1}{2}\rangle$

$|-1, +\frac{1}{2}\rangle \quad 12\%$

$|-1, -\frac{1}{2}\rangle$

$T_0$

$\sim 1\mu\text{sec}$

$\sim 20\text{nsec}$

$\sim 20\mu\text{sec}$

$S_0$

ground state

laser excitation

radiative process

non-radiative process

microwave irradiation
DNP at High Temperature and Low Field

Single crystal of naphthalene doped with pentacene

It can be polarized at 77 K / 270 K and 0.3 T, and held at 0.0007 T

1) laser irradiation  pentacene is excited to the triplet state.

2) microwave irradiation & sweep of the field within the lifetime of the triplet state  population transfer

3) transition from the triplet state to the diamagnetic ground state spontaneously, where no spin-spin interaction between e and p.

4) diffusion of proton spin from pentacene to naphthalene  proton polarization in naphthalene
Systematic Errors!

(1) Imperfect flipping of $\vec{k}_n, \vec{\sigma}_n, \vec{I}$ and B

$$f = f_0 + f_1 \vec{\sigma}_n \cdot \vec{I} + f_2 \vec{\sigma}_n \cdot \vec{k}_n + f_3 \vec{\sigma}_n \cdot (\vec{k}_n \times \vec{I})$$

Solution: (superconducting?) magnetic shielding? Implemented in neutron scattering instruments (CRYOPAD at ILL)

(2) Nonforward scattering: use neutron TOF+nonforward neutron detector?

(3) Polarized target nonuniformities/time dependence: polarized neutron imaging.

(4) Washout of signal from pseudomagnetic precession: how to minimize?
MLF 1\textsuperscript{st} Experimental Hall

- BL07
- BL05
- BL04
- BL10

Dimensions:
- 100 m
- 40 m
BL07/Poisoned (Thinner Side) / Not assigned
KEK-2015S12
NOP-T

Epithermal source:
J-PARC/MLF BL07
\[ \Omega = 4.4 \times 10^{-5} \text{sr} \]
\[ \Gamma = 0.1 \text{eV} \]

Spin polarizer:
\( ^3 \text{He} \) (100 atm cm)
\[ P_n = 0.7 \quad T_n = 0.4 \]

Polarized target:
4cm x 4cm (x 20cm)
\( ^{nat} \text{Xe} \) (9000 atm cm)
\[ P_{Xe} = 0.25 \]
\[ B_{ps} = 0.019 \text{T} \]

Spin analyzer:

15m

J-PARC/MLF

\( ^3 \text{He} \) Laser

ORNL/SNS

\( p \) DNP

MIONP (Triplet DNP)

\( ^{10} \text{B} \)-loaded Liq. Sci.

\( ^{nat} \text{Xe} \) (gas, liq, solid) Laser

\( \text{La (LaAlO}_3\text{)} \) DNP

\( \text{Br (?)} \) DNP

MIONP (Triplet DNP)
SNS beam #1 (Seppo Penttila)

ORNL statement:

If you can secure the resources for the experiment, you can have a beam at SNS
Present Activities

A Proposal to Test an eV Neutron Detector based on $^{10}$B/NaI(Tl) at LANSCE FP5 for future experiments on Time Reversal Violation in Neutron Resonances

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S. Vogel, Z. Tang
Los Alamos National Lab, Los Alamos, NM 87545 USA
(Dated: July 24, 2015)

LANSCE proposal successful: beamtime in Dec. 2015

Possibility at LANSCE: IU $^3$He polarizer+spin flipper+eV n detector, search for new large p–wave resonances. Soonest possible experiment ~fall 2016.
Current Activities: eV Current-Mode Neutron Detector Development

One of three large area (~50 cm x 50 cm) NaI(Tl) Xtal arrays at IU

$n^{10}\text{B} \rightarrow ^{11}\text{B} \rightarrow ^{4}\text{He} + ^{7}\text{Li}$ $^* \rightarrow 0.448$ MeV gamma $+ ^{7}\text{Li}$

Detect 0.488 MeV gamma in current mode using NaI(Tl)

NaI(Tl) scintillation light is fast enough that time response of this detector can resolve many neutron TOF bins across the p-wave resonance
T violation in Neutron Optics: TREX

- T – odd term in FORWARD scattering amplitude (a null test, like EDMs) with polarized n beam and polarized nuclear target
  \[ \bar{\sigma}_n \cdot (\vec{k}_n \times \vec{I}) \]
- P-odd/T-odd (most interesting)
- 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->\(\Delta \sigma_{PT}/\Delta \sigma_{P}\sim1E-5\). sensitivity can be \(~x100\) present n EDM limit
- The nuclei of interest, resonance energies, and P-odd asymmetry amplifications are measured. \(^{139}\)La can be polarized using DNP (LaAlO\(_3\)). \(^3\)He with SEOP can be used as a polarizer for eV neutrons
- **Can \(^{139}\)La, \(^{131}\)Xe, \(^{81}\)Br be polarized in large quantities for this experiment?**

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Resonance Energy</th>
<th>PV asymmetry</th>
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<tbody>
<tr>
<td>(^{131})Xe</td>
<td>3.2 eV</td>
<td>0.043</td>
</tr>
<tr>
<td>(^{139})La</td>
<td>0.748 eV</td>
<td>0.096</td>
</tr>
<tr>
<td>(^{81})Br</td>
<td>0.88 eV</td>
<td>0.02</td>
</tr>
</tbody>
</table>
Conclusions

On-resonance T violation in epithermal neutron resonances can now be measured with interesting sensitivity.

MW-class, short-pulsed spallation neutron sources (SNS, JPARC) are beautiful sources to use for the experiment: neutron time-of-flight can be used to great advantage to characterize possible systematic errors, especially to “dig out” any non-forward scattering in the transmitted beam.

Individual components OPERATION modes for the experiment have been realized: hardest part is the polarized target.