Status of NOPTREX work toward searches for P-odd/T-odd and P-even/T-odd NN interactions in polarized neutron optics

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(1) Introduction
(2) P-odd/T-odd search: progress toward experiment in ^{139}La
(3) P-even/T-odd search: progress toward experiment in ^{127}I

NSF PHY-2209481

Thanks for slides: H. Shimizu, T. Okudaira, V. Gudkov, D. Bowman,…

NOPTREX Collaboration List November 2022

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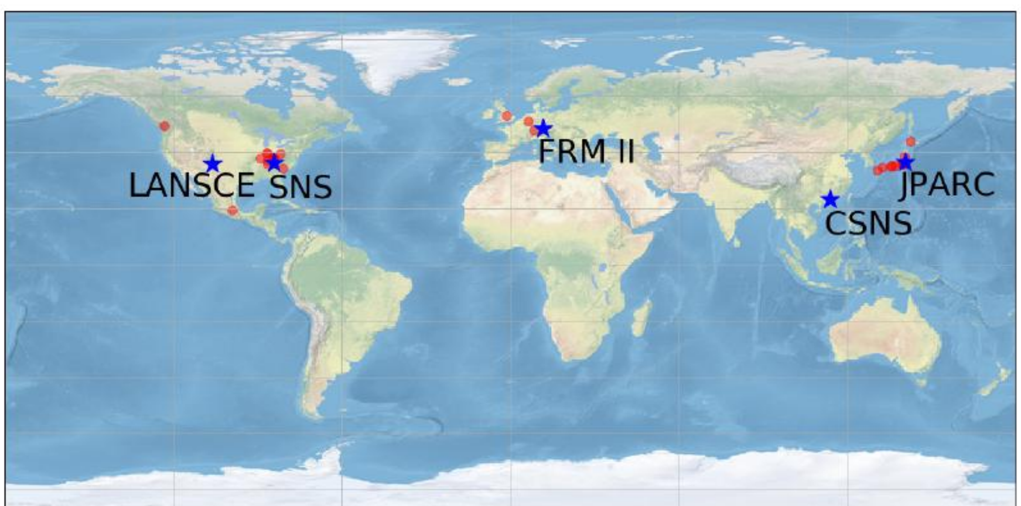


NOPTREX

Neutron Optical Parity and Time-Reversal EXperiment

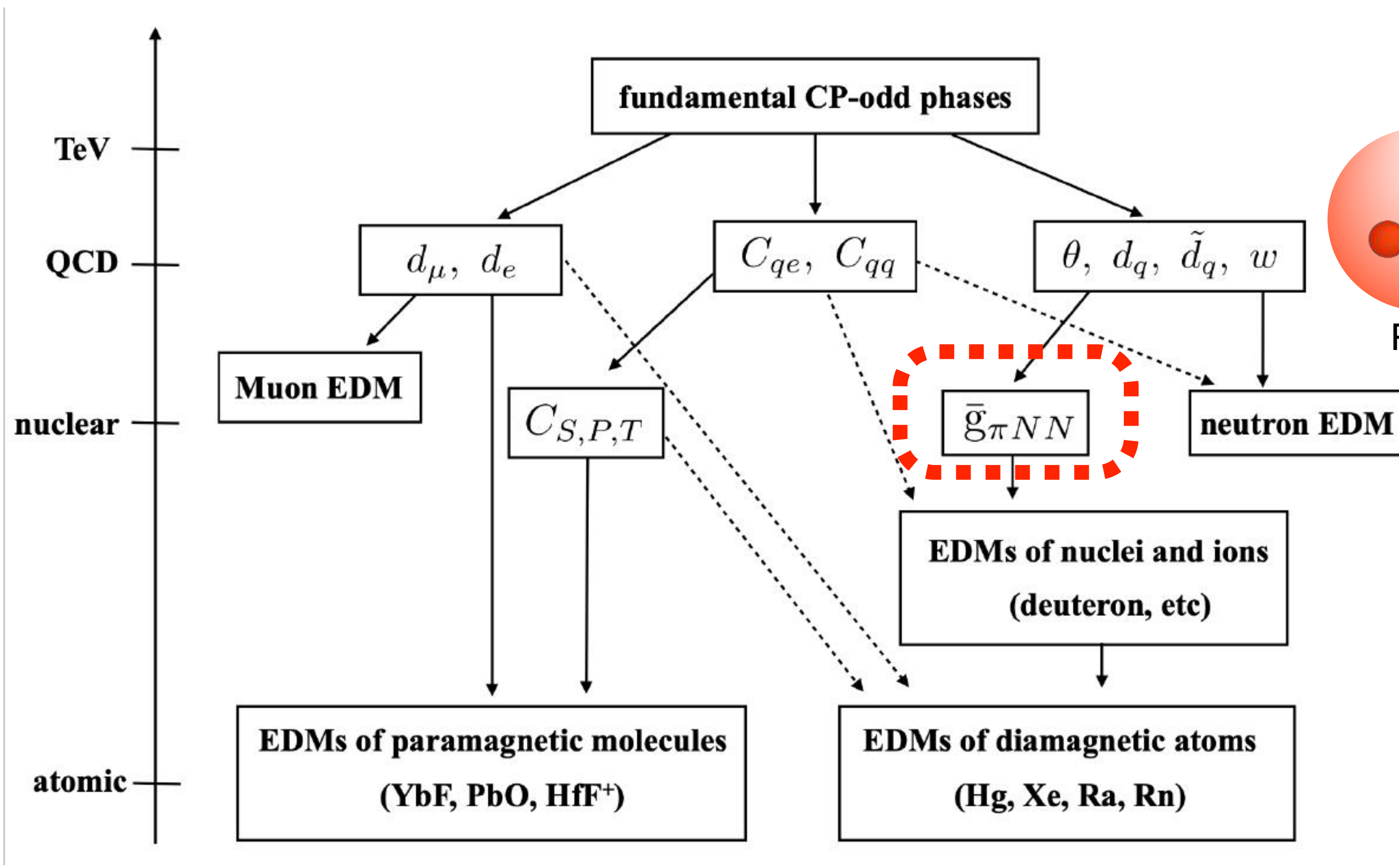
Unique global, "many-source" neutron science collaboration

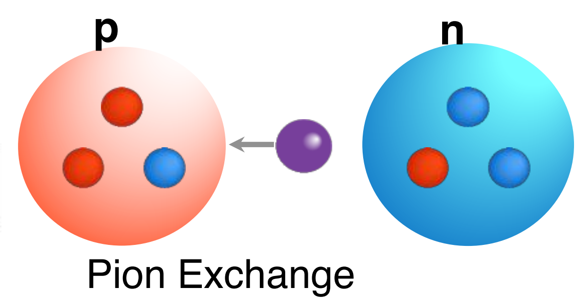
T-violation search in Polarized Neutron Optics

(NOT an EDM)

NOPTREX

Neutron Optical Parity and Time-Reversal EXperiment

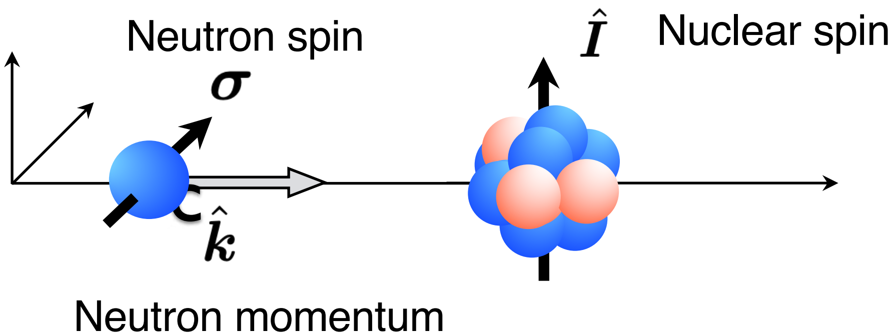




Search for T-violation in NN interaction (pion exchange+...)

Search for P-odd/T-odd in Forward Transmission

→Polarized neutron transmission through polarized nuclear target



KEY POINT: this is a NULL TEST for T, no “final state interactions” to fake T (Ryudin ~1964, 1969,…, Bowman/Gudkov 2014)

Forward scattering amplitude

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

Spin-independent cross section

Spin dependence

P-violation

T-violating cross section

t→-t

opposite signs upon P and T

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

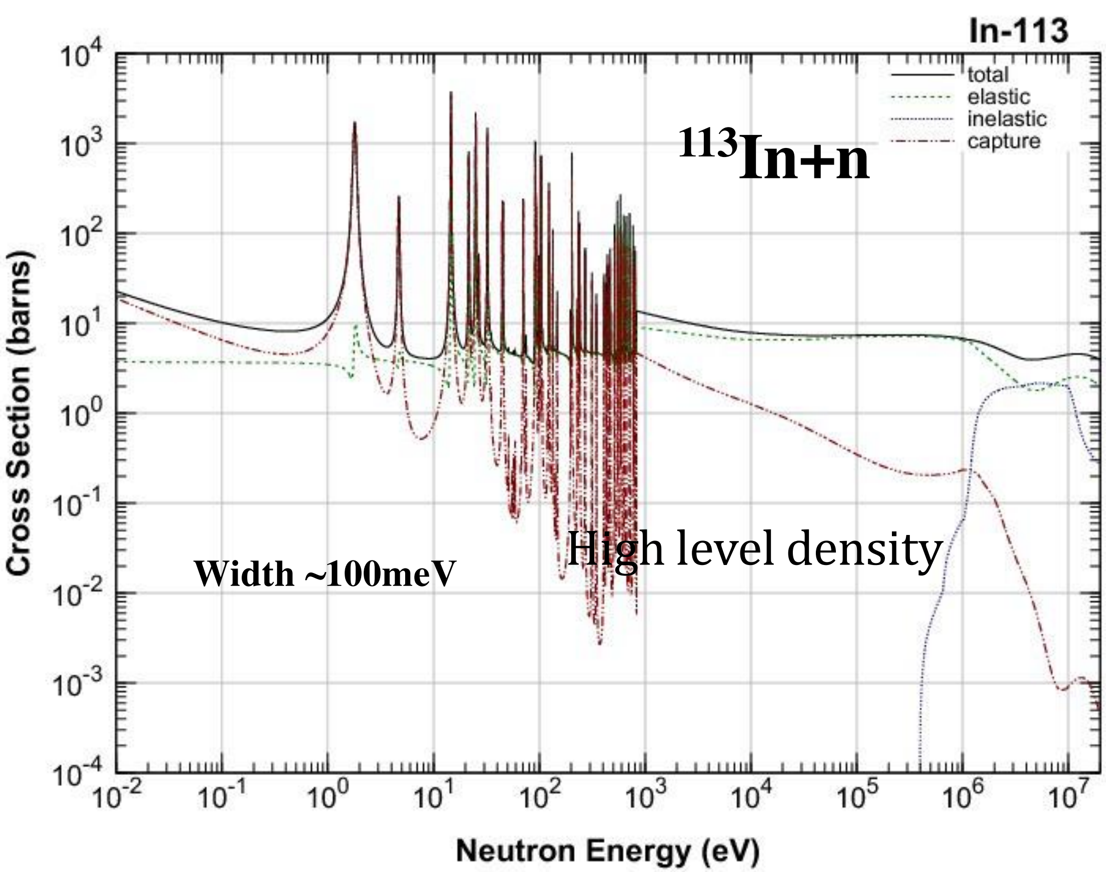
Neutron-Nucleus Resonances

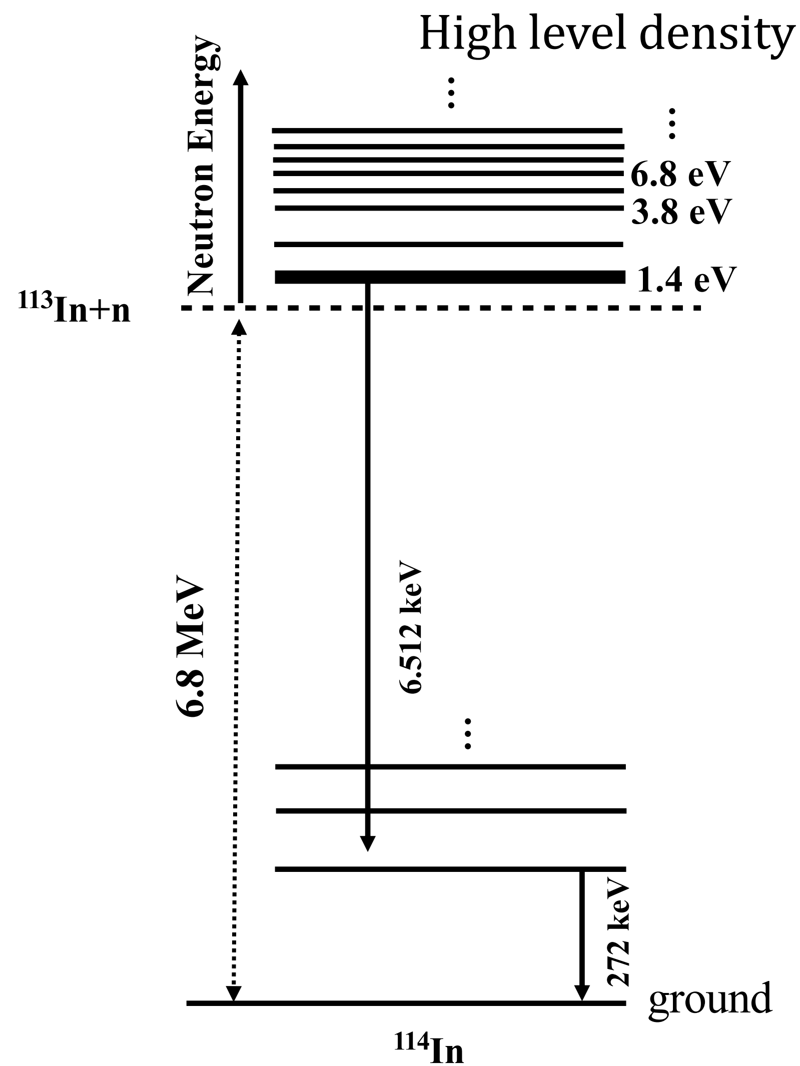
dense set of resonances just above neutron separation energy

mainly L=0 resonances, but lots of L=1 resonances

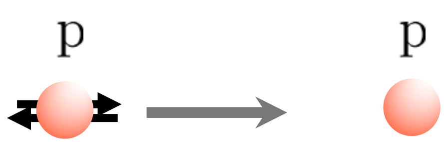
P-odd/T-odd mix L=0 and L=1 states

P-even/T-odd mix pairs of L=1states





Amplification of P-odd asymmetry in p-wave n-A resonance

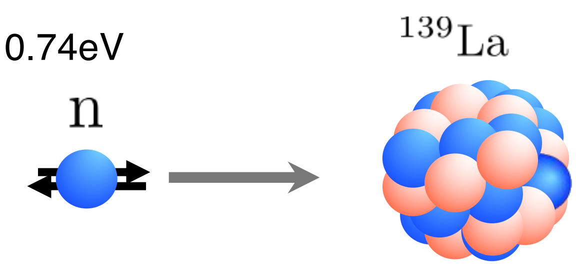


Helicity dependence of the p-p scattering cross section

-(1.7±0.8)×10^{-7} @E=15MeV

$$A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

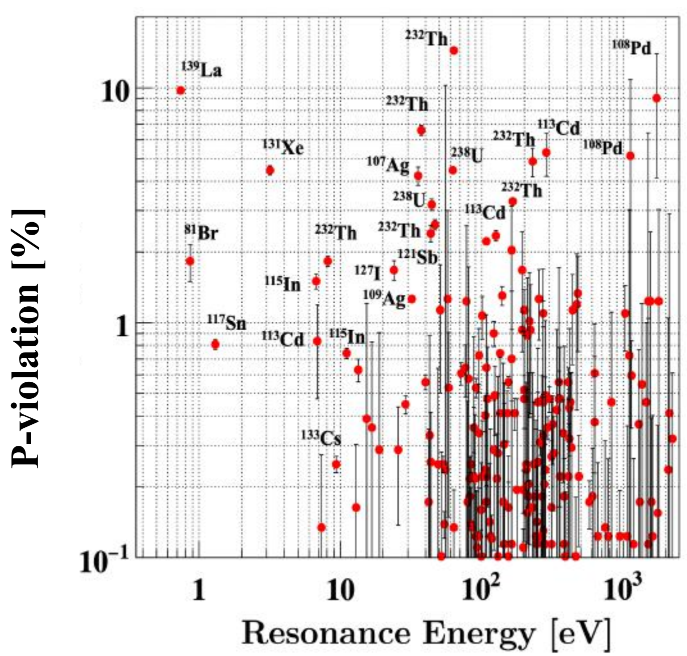
Interaction between nucleons: 10^{-7} P-violation



Helicity dependence of cross section in neutron transmission ^{139}La (Dubna, Alfimenkov 1982)

0.097±0.003 @E_n=0.74eV

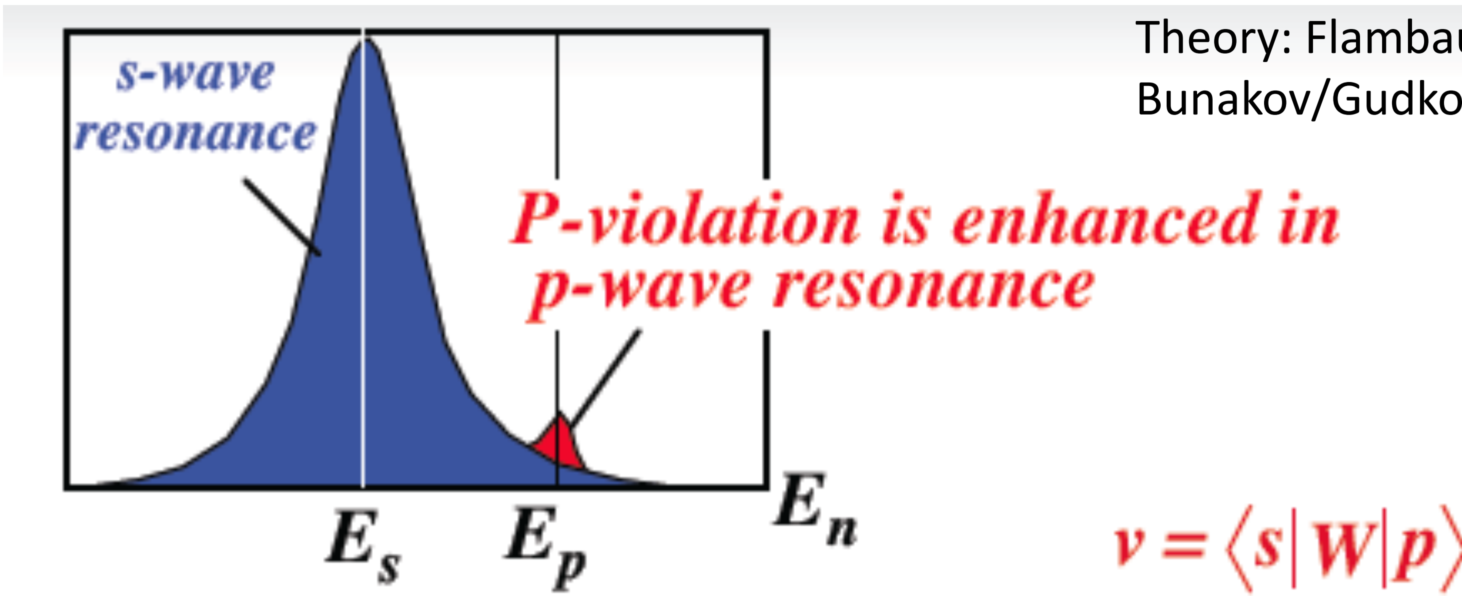
Compound nucleus: 10^{-1} P-violation



P-odd amplitude can be enhanced by ~10^6 in compound nucleus

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

Theory: Flambaum/Sushkov/ Bunakov/Gudkov 1982

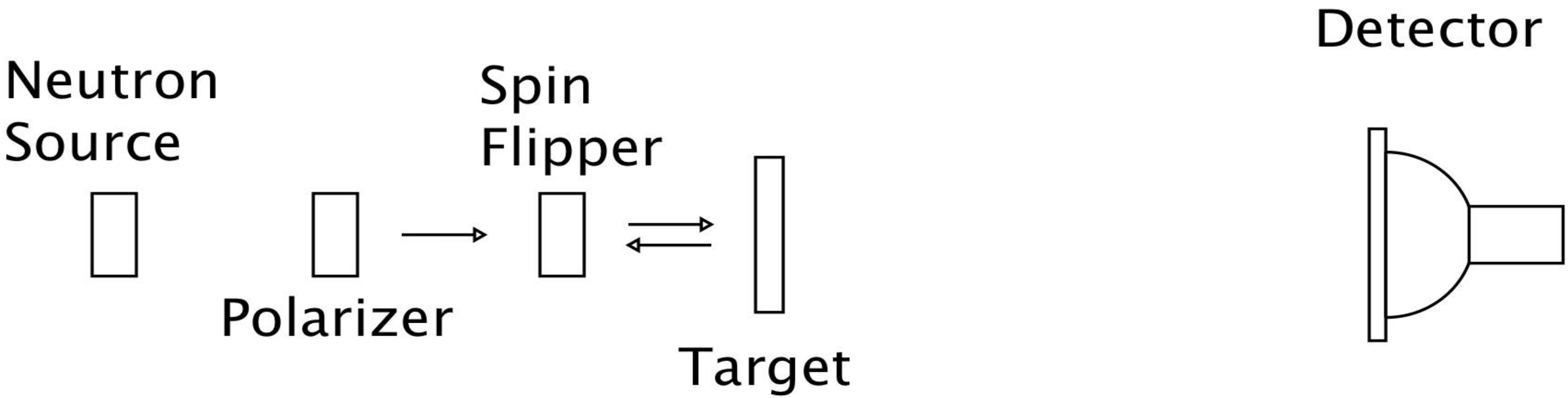


Neutron in a narrow p-wave resonance in a heavy nucleus with energy just above threshold (~eV-keV) lasts ~ 10^6 times longer inside nucleus compared to a direct reaction from potential scattering

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 PV/TV asymmetry. Kinematic nature of enhancement->amplification works for any PV/TV interaction.

TRIPLE $\sigma \cdot k$ P violation work in heavy nuclei



Measure P-odd neutron helicity dependence of total cross section $\Delta\sigma/\sigma$

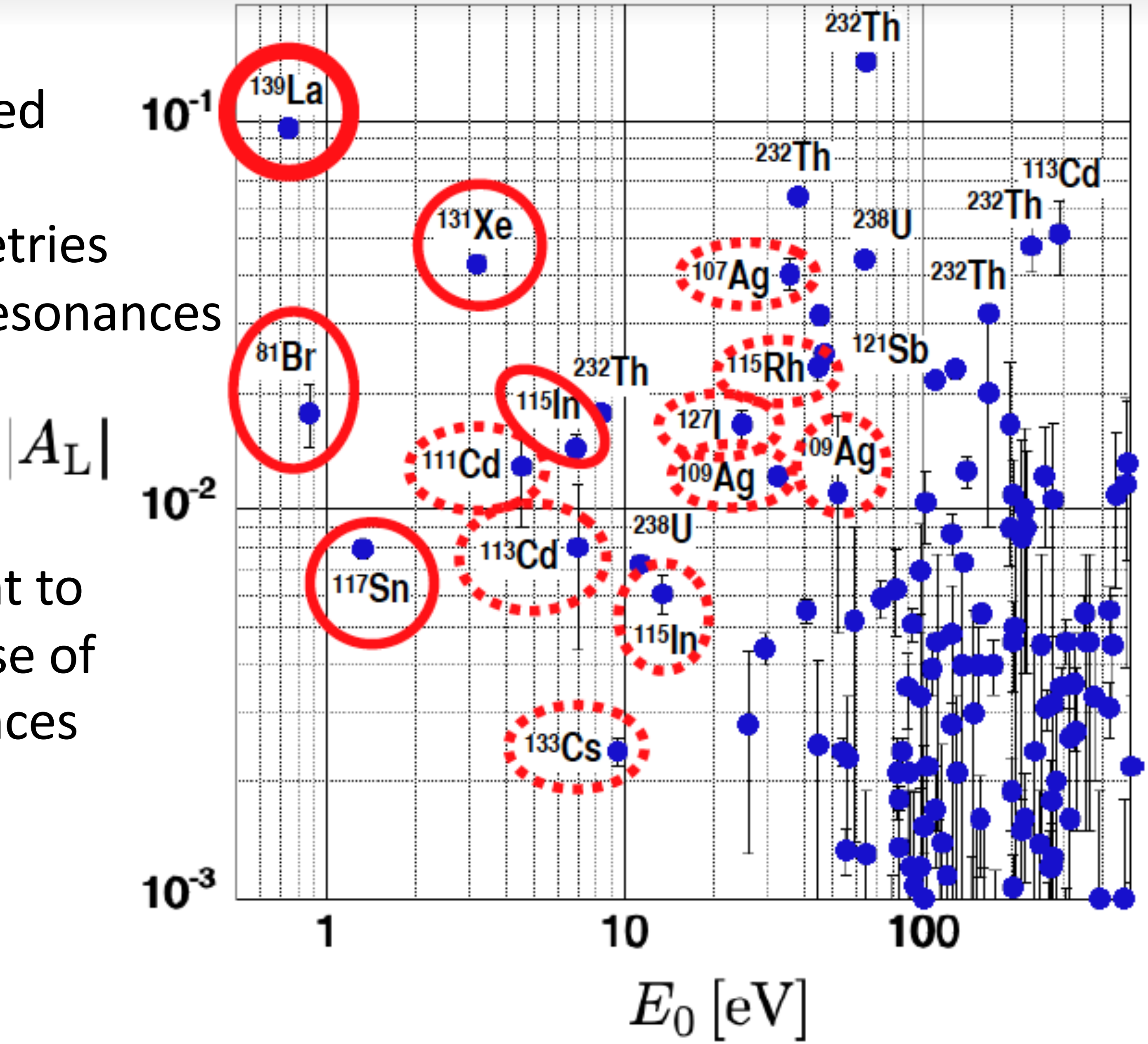
TRIPLE collaboration measured ~75 parity-odd asymmetries in p-wave resonances in heavy nuclei in eV-keV energies G. M. Mitchell, J. D. Bowman, S. I. Penttila, and E. I. Sharapov, Phys. Rep. 354, 157 (2001).

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).

D. Bowman

Mitchell, Phys. Rep. 354 (2001) 157
Shimizu, Nucl. Phys. A552 (1993) 293

Measured P-odd asymmetries in n-A resonances



We want to make use of resonances for T

T-violating observable: ratio of PT to P amplitudes (Gudkov, Physics Reports)

Optical theorem relating forward scattering cross section to spin dependent part of cross section:

$$\Delta\sigma_p = \frac{4\pi}{k} Im(f_- - f_+)$$

Optical theorem relating forward scattering cross section to spin dependent part with a polarized target:

$$\Delta\sigma_{PT} = \frac{4\pi}{k} Im(f_\uparrow - f_\downarrow)$$

Ratio is simple for case of 2-resonance mixing:

$$\frac{\Delta\sigma_{PT}}{\Delta\sigma_P} = \kappa(J)\frac{w}{v}$$

For a forward scattering amplitude of the form

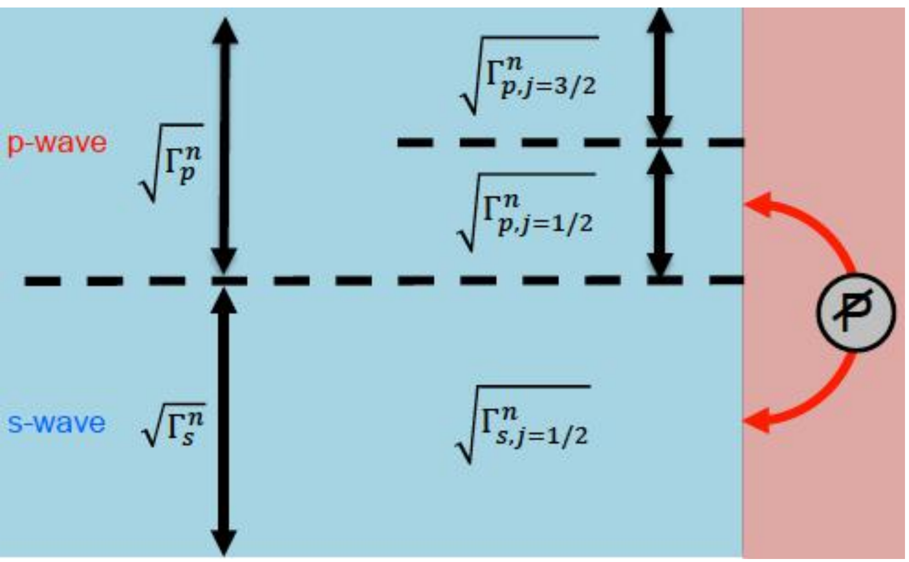
$$f = < f\left|V_p + V_{PT}\right|i > = \frac{(v+iw)\sqrt{\Gamma_{\mathrm{p}}^{\mathrm{n}}\Gamma_s^n}}{(E - E_s + \frac{i\Gamma_s}{2})(E - E_p + \frac{i\Gamma_p}{2})}$$

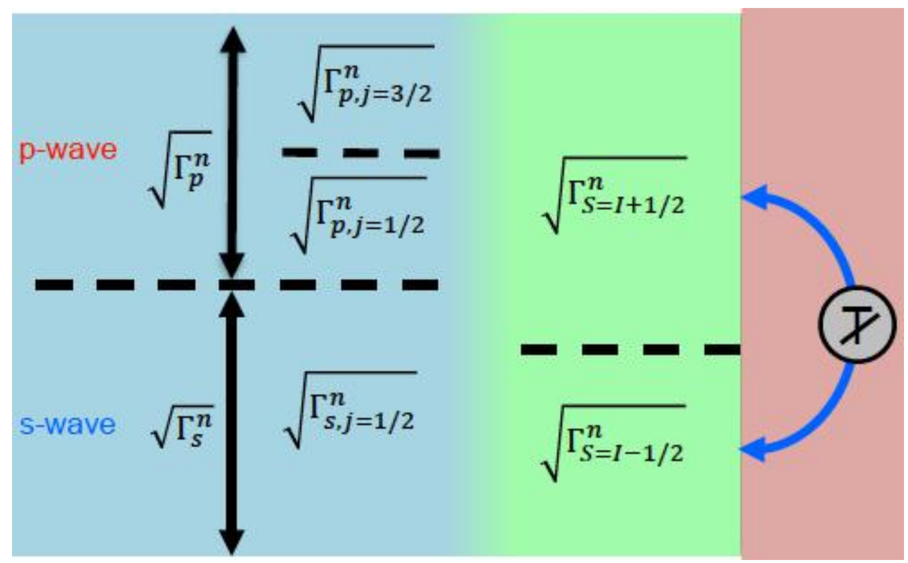
κ(J) "Spectroscopy" Factor

P transformation acts on L=0,1 T transformation acts on S=I +/- 1/2

$$P : |\ell s I\rangle \rightarrow (-1)^{\ell} |\ell s I\rangle$$
$$\ell = 0{,}1$$

$$T : |\ell s I\rangle \rightarrow (-1)^{i\pi S} K |\ell s I\rangle$$
$$S = I \pm 1/2$$





$$\kappa(J = I + 1/2) = \left[\frac{\sqrt{I}}{2I+1)}\right]\left(-2\sqrt{I} + \sqrt{2I+3}\frac{y}{x}\right)$$

$$\kappa(J = I - 1/2) = \left[\frac{1}{2\sqrt{2I+1}}\right]\left(2\sqrt{I+1} + \sqrt{2I-1}\frac{y}{x}\right)$$

Spin-weighted linear combination of p-wave resonance widths in the two j=1/2 and j=3/2 channels

Must be measured

Forward Scattering Amplilitude

$$\sigma_{tot} = \frac{4\pi}{k}\mathrm{Im}[f(0)]$$

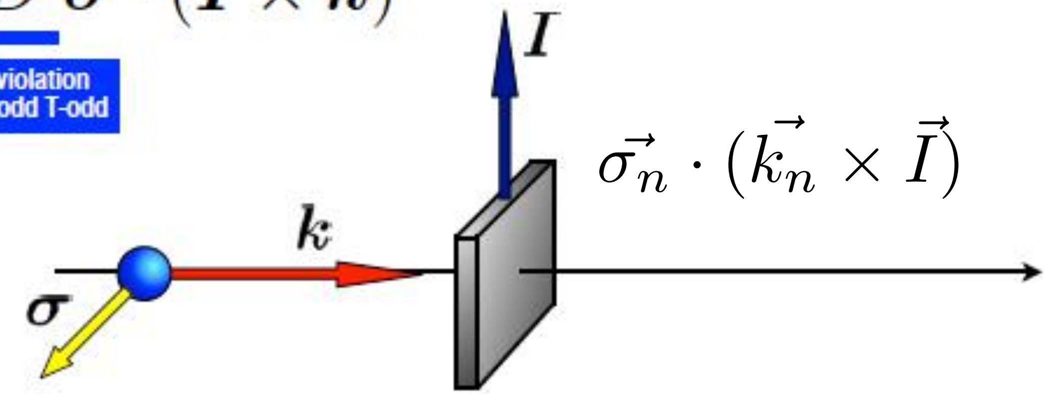
$$f = A' + B'\boldsymbol{\sigma}\cdot\hat{\boldsymbol{I}} + C'\boldsymbol{\sigma}\cdot\hat{\boldsymbol{k}} + D'\boldsymbol{\sigma}\cdot(\hat{\boldsymbol{I}}\times\hat{\boldsymbol{k}})$$

Spin Independent P-even T-even

Spin Dependent P-even T-even

P-violation P-odd T-even

T-violation P-odd T-odd



$$\vec{\sigma_n}\cdot(\vec{k_n}\times\vec{I})$$

$$|s\rangle \quad |p\rangle \quad |p_{1/2}\rangle \quad |p_{3/2}\rangle$$

$$J_s E_s \Gamma_s \Gamma_s^n \quad J_p E_p \Gamma_p \Gamma_p^n \quad \Gamma_{p,1/2}^n \quad \Gamma_{p,3/2}^n \quad \langle W\rangle$$

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

λ can be measured with a statistical uncertainty of ~10^{-6} in 10^7 sec at MW-class spallation neutron sources. ~X10 better than present limits from N/nuclei EDM limits

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

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

Expressions for λ_{PT} from different sources

$$\frac{W_{TP}}{W} = 0.12|\eta_n| = |(-1.2 g_s \bar{g}_0 + 6.0 g_s \bar{g}_1 + 2.4 g_s \bar{g}_2) 10^5|.$$

where g_s=(strong) pion coupling,
g_0, g_1, g_2 are P-odd/T-odd pion couplings for I=0,1,2

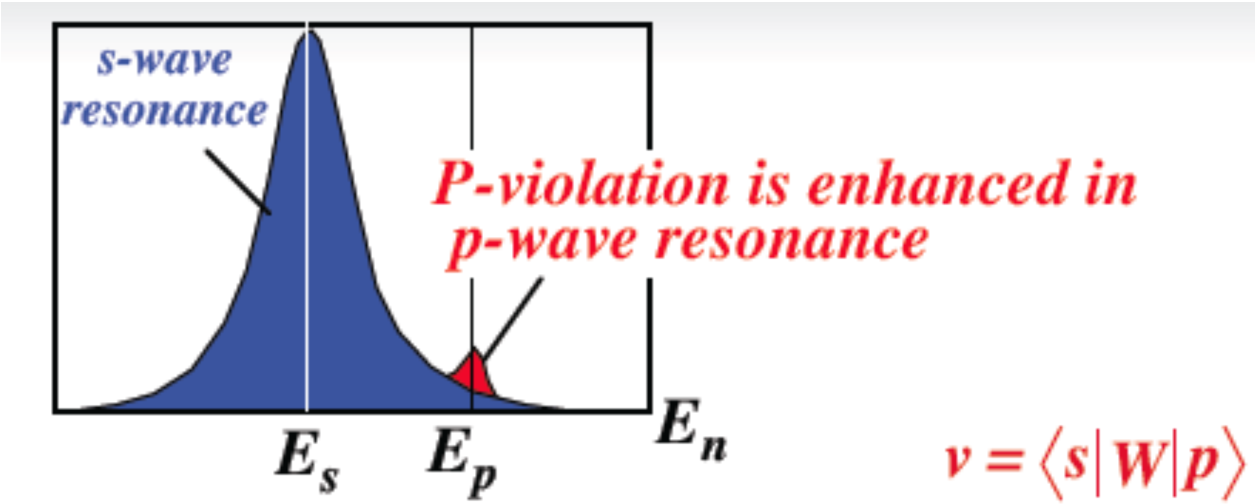
$$\frac{W_{TP}}{W} = 5.3 \times 10^4 |\theta|$$ in terms of θ_{QCD}

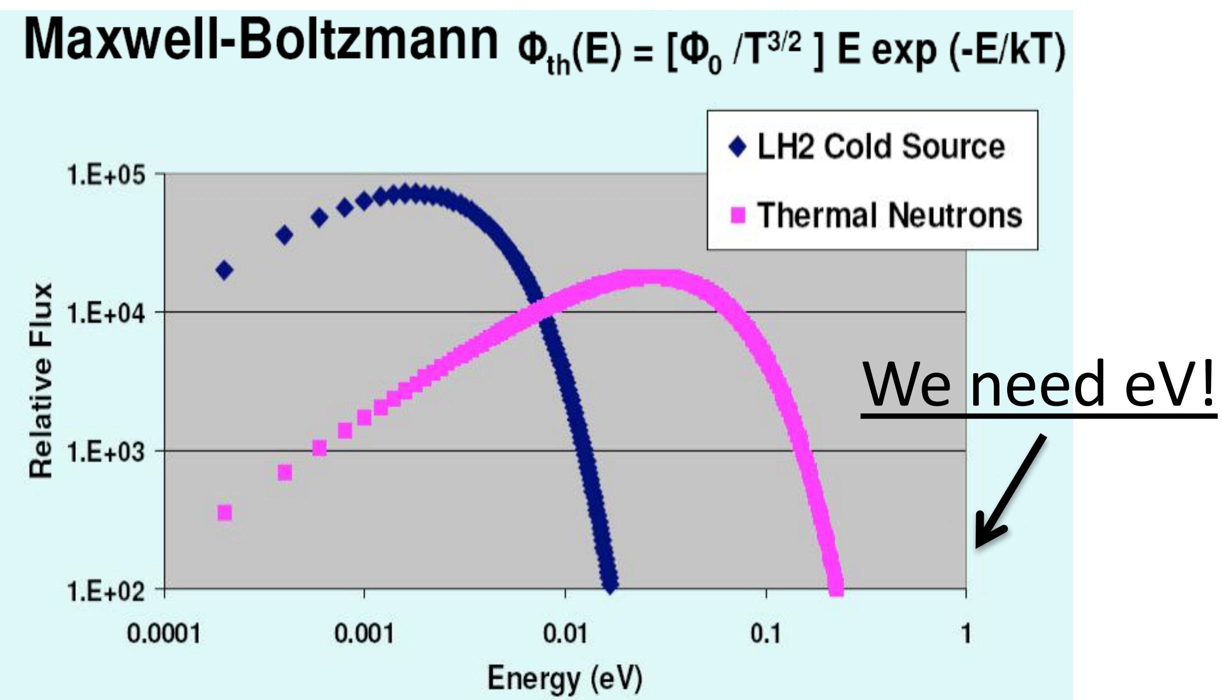
$$\frac{W_{TP}}{W} = |(-1.0(\tilde{d}_u + \tilde{d}_d) + 24(\tilde{d}_u - \tilde{d}_d))10^{20}|/\mathrm{cm}$$ in terms of quark chromo-EDMs

$$\frac{W_{TP}}{W} < 10^{-5}$$ present limit from EDM experiments (NOTE axion-like particle limits are X100 worse!)

V. V. Flambaum and A. J. Mansour, Phys. Rev. C 105, 015501 (2022).
P. Fadeev and V. V. Flambaum, Phys. Rev. C 100 (2019).
N. Yamanaka, B. K. Sahoo, N. Yoshinaga, T. Sato, K. Asahi, and B. P. Das, Eur. Phys. J. A 53, 54 (2017).
S. Mantry, M. Pitschmann, and M. J. Ramsey-Musolf, Phys. Rev. D 90, 054016 (2014).
Y. V. Stadnik, V. A. Dzuba, and V. V. Flambaum, Phys. Rev. Lett. 120, 013202 (2018).

Why is a pulsed, spallation neutron source important for NOPTREX?





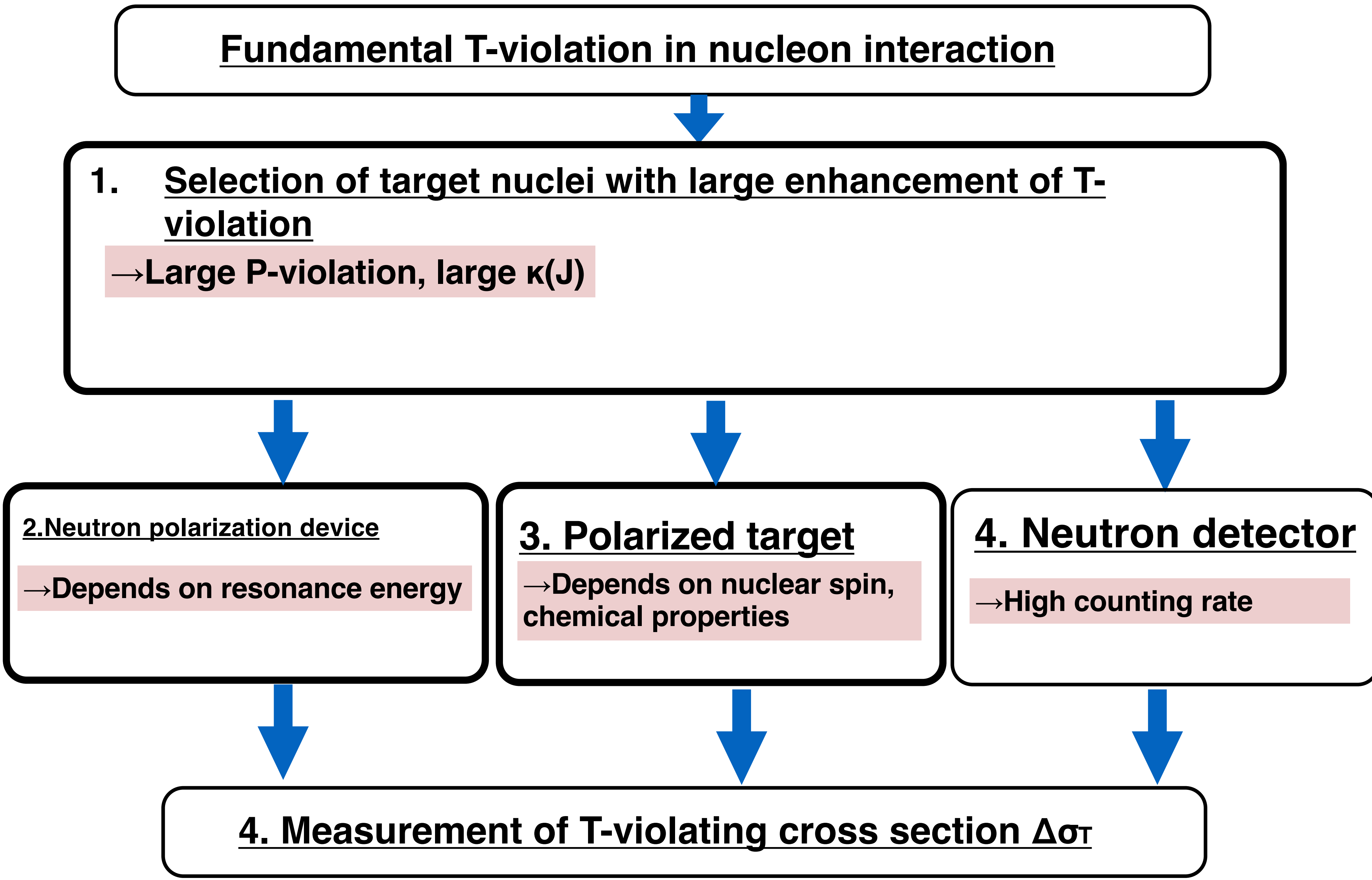
resonance energy ~eV, resonance width ~meVs

Short pulse-> resonance can be resolved using neutron time-of-flight

>~10^4 more “off-resonance” neutrons can be used to characterize possible systematic effects !

Few eV neutrons at reactors. Spallation neutron source make much more eV neutrons

Plan for T-violation search



Plan for T-violation search

Fundamental T-violation in nucleon interaction

1. Selection of target nuclei with large enhancement of T-violation

→First candidate : ^{139}La 0.74eV resonance

T. Okudaira *et. al.* , Phys. Rev. C. 97 034622 (2018) ^{139}La
T. Yamamoto *et al.* Phys. Rev. C. 101, 064624 (2020)
T. Okudaira *et. al.* , Phys. Rev. C. 104, 014601(2021)

J. Koga *et. al.*, Phys. Rev. C. **105**, 05461 (2022) ^{117}Sn
S. Endo *et al.*, Phys. Rev. C.106 064601 (2022)
T.Okudaira et al. arXiv:2212.10889 (2022) ^{131}Xe

2.Neutron polarization device

→^{3}He spin filter for ~0.74eV

85% ^{3}He polarization!!

T. Okudaira *et. al.* , NIM A 977, 164301 (2020)

3. Polarized La target

→Dynamic nuclear polarization

30% ^{139}La polarization!

K. Ishizaki *et al.*, NIM A1020, 165845 (2021)

4. Neutron detector

D. Schaper *et. al.*, NIM A 969, 163961 (2020)

U.S. NOPTREX
RCNP

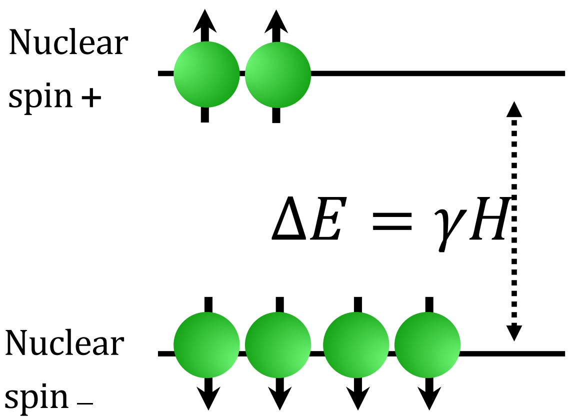
Key technique : Nuclear polarization

Nuclear polarization method

Static Nuclear Polarization
(Brute-Force Method)

Strong Magnetic field,

extremely low temperature



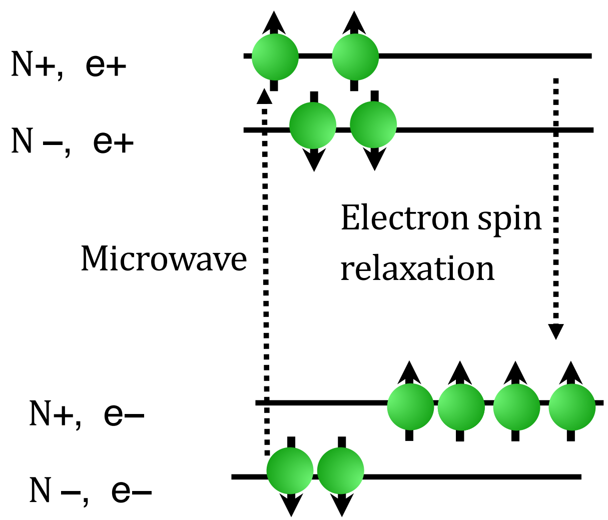
7T, 70mK,

→ ^{139}La polarization ~ 4%

Dynamic Nuclear Polarization(DNP)

Magnetic field, low temperature, microwave

Electron spin→nuclear spin



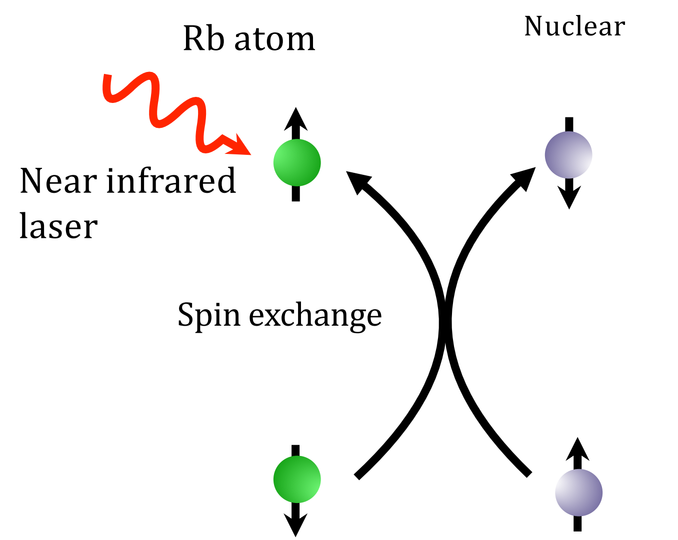
2~3 T, ~1 K

→^{139}La polarization >10 %

Spin exchange optical pumping(SEOP)

Low magnetic field, laser

Rb spin→nuclear spin



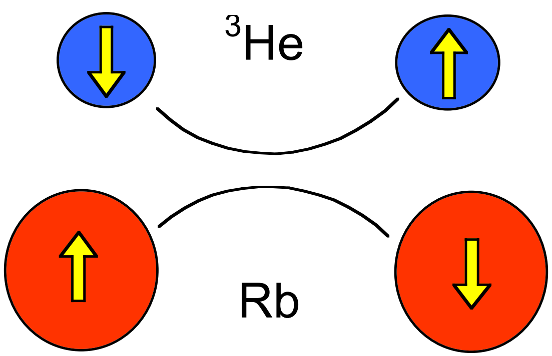
Noble gas (^{3}He, $^{129,\ 131}$Xe)

$1{\times}10^{-3}$ T, ~200°C

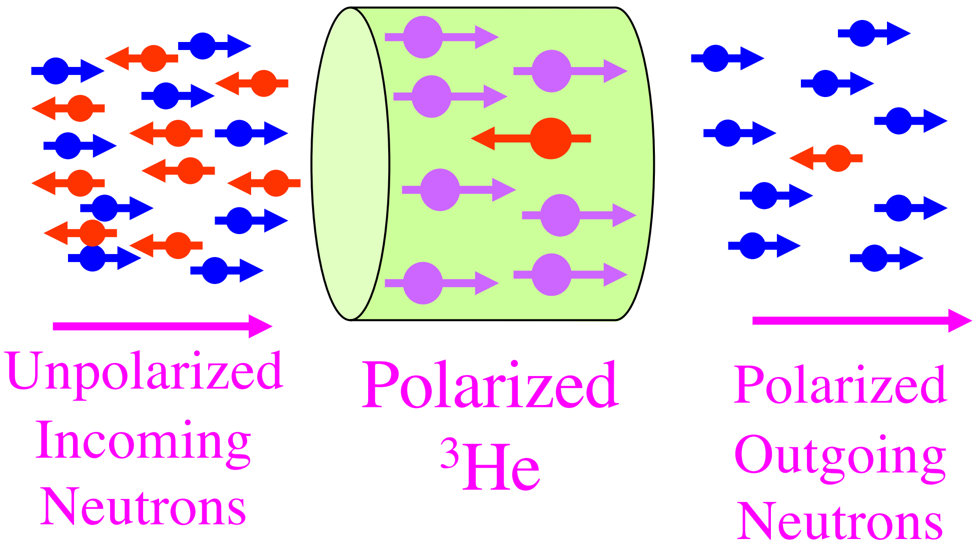
→^{3}He polarization >50 %

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

Polarized ^{3}He Neutron Spin Filters for eV



Laser-polarized Rb⇒^{3}He nucleus



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

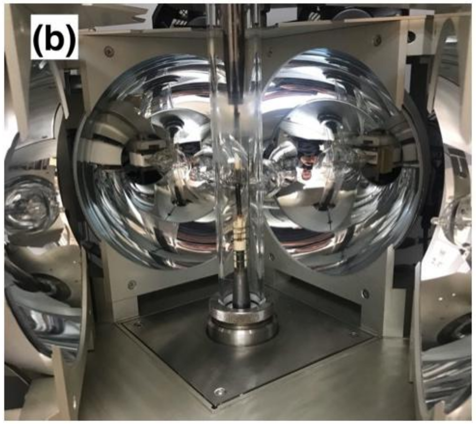
Spin flip by NMR on ^{3}He. By far the best choice for NOPTREX

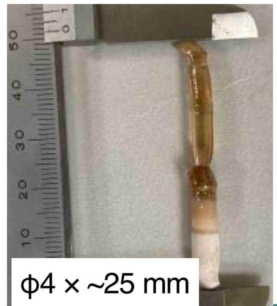
Need more polarized ^{3}He to polarize eV neutrons ($\sigma_a \sim 1/v_n$)

Development of polarized nuclear target

^{139}La polarized target by Dynamic Nuclear Polarization (DNP)

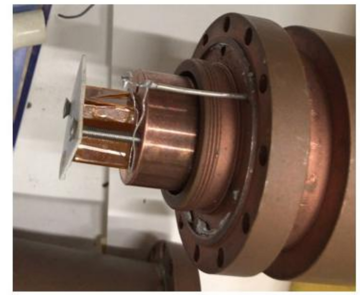
Crystal growth at Tohoku Univ.





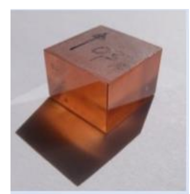
Tohoku Univ.,
Hiroshima Univ.,
Nagoya Univ.

Nuclear polarization at RCNP, Osaka Univ.



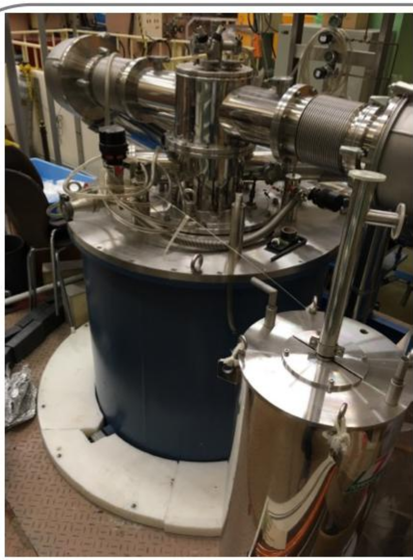
RCNP, Osaka Univ.
Hiroshima Univ., Nagoya Univ. ,Yamagata Univ.

Polarized La target



$LaAlO_3$ single crystal

Refrigerator



Nagoya Univ.,
RIKEN,
Japan Women's Univ.
Ashikaga Univ.
Hiroshima Univ.

Control for relaxation time

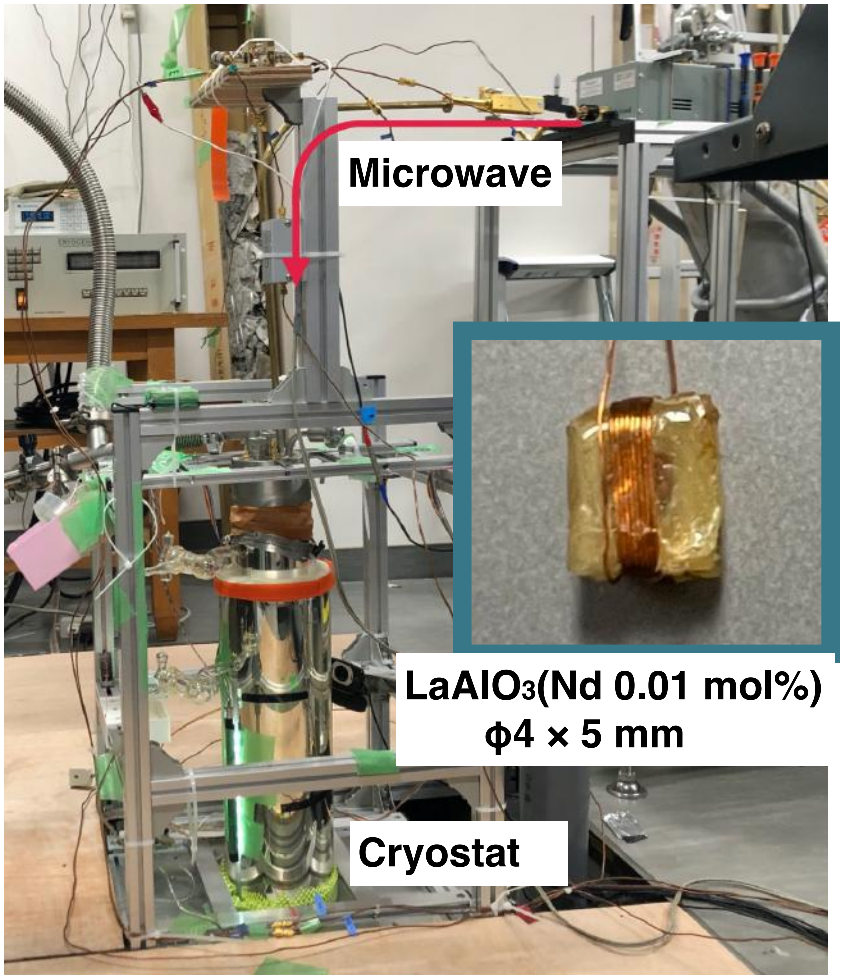
Hiroshima Univ.
Nagoya Univ.

Relaxation time control with aromatic molecule

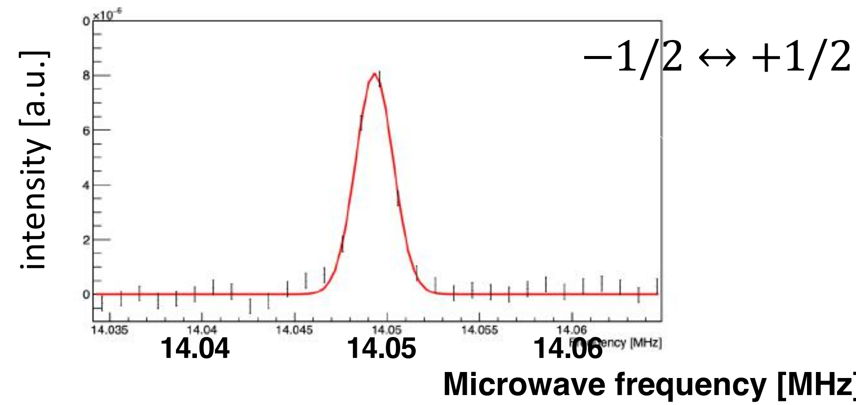
K. Ishizaki *et al.*, NIM A1020, 165845 (2021)

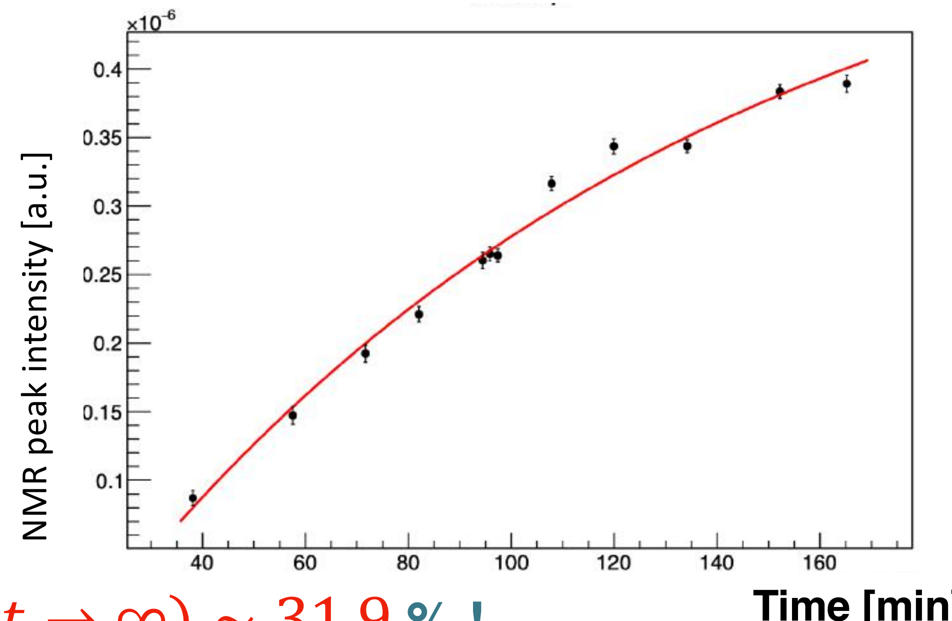
Development of polarized nuclear target

DNP experiment using $LaAlO_3$ crystal fabricated in Tohoku Univ.



Temperature ~1.5 K
Magnetic field ~ 2.3T at Yamagata Univ.





Achievable ^{139}La polarization : $P(t \to \infty) \sim 31.9$ **% !**

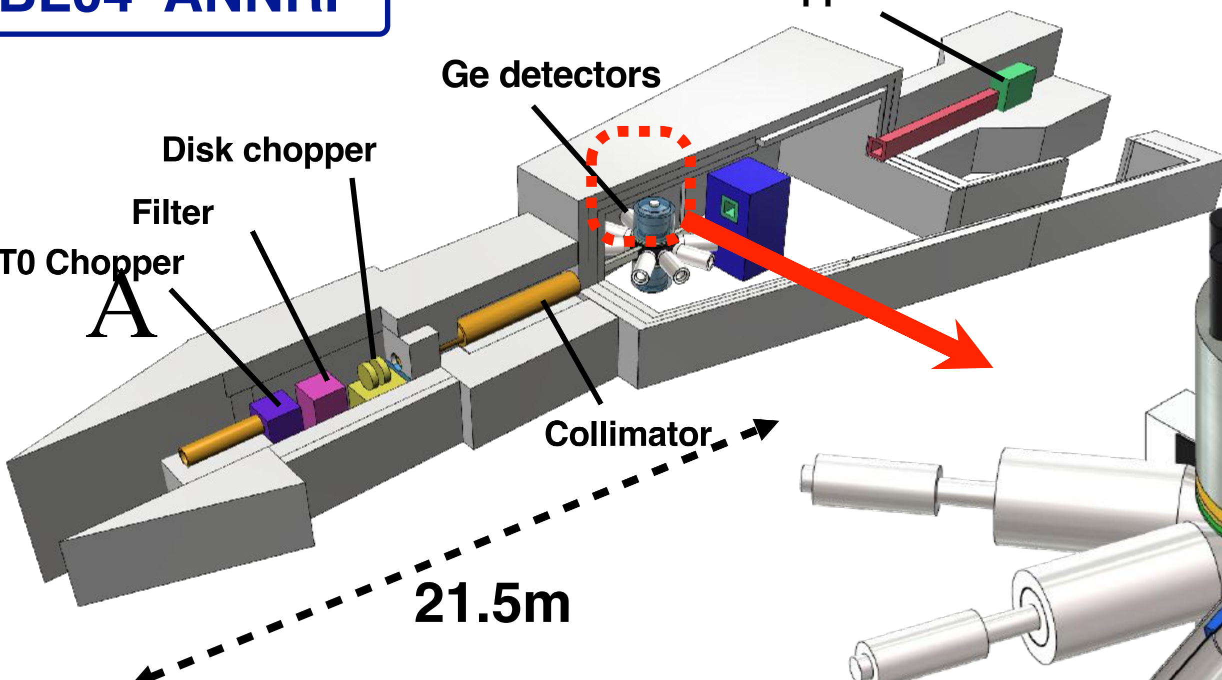
Confirm previous DNP work in $LaAlO_3$ (Hautle/Iinuma, NIM 2000)

Angular distribution of (n,γ) reactions

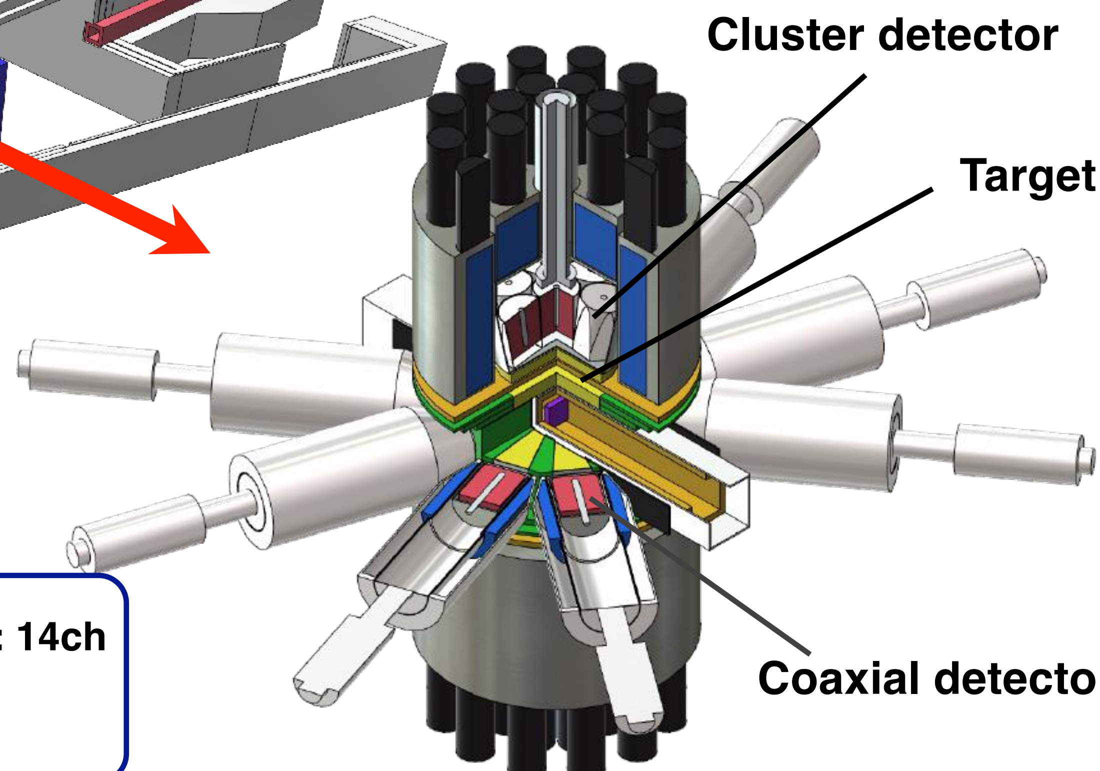
Experiments to determine κ(J) is ongoing at ANNRI (Accurate Neutron-Nucleus Reaction measurement Instrument) beam line in J-PARC

(n,γ)反応を測定

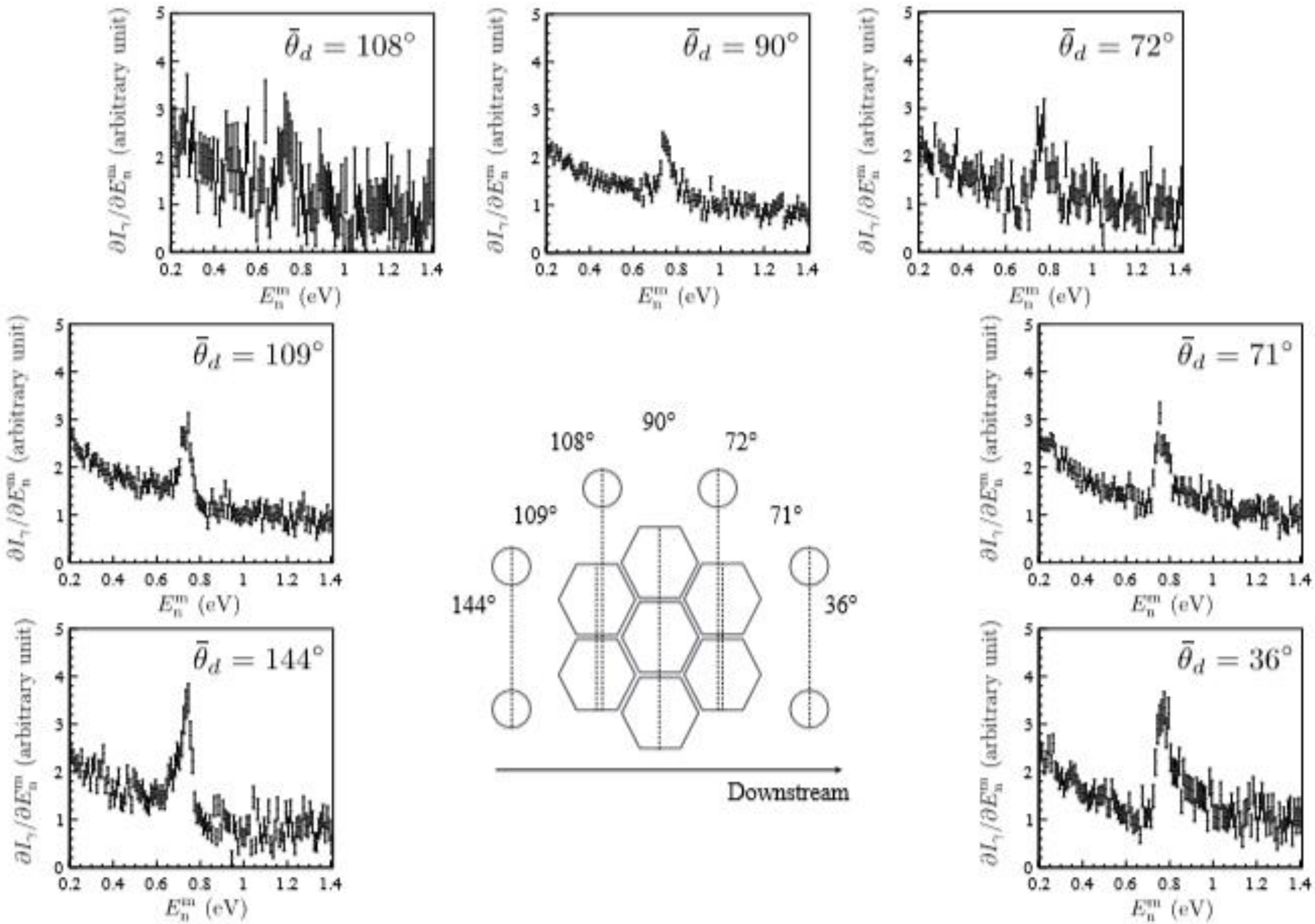
BL04 ANNRI



BL04 Ge Detectors



2 Cluster Detector (up・down) 7ch ×2 : 14ch
8 Coaxial Detector (side) 8ch
Total 22ch



κ ~0.9 was measured in ^{139}La at JPARC using (n, γ) angular distribution on 0.73 eV resonance using ANNRI Germanium array (Okudaira et al) More measurements check

Large κ makes T experiment in ^{139}La very sensitive!

Experiment using polarized La and neutrons

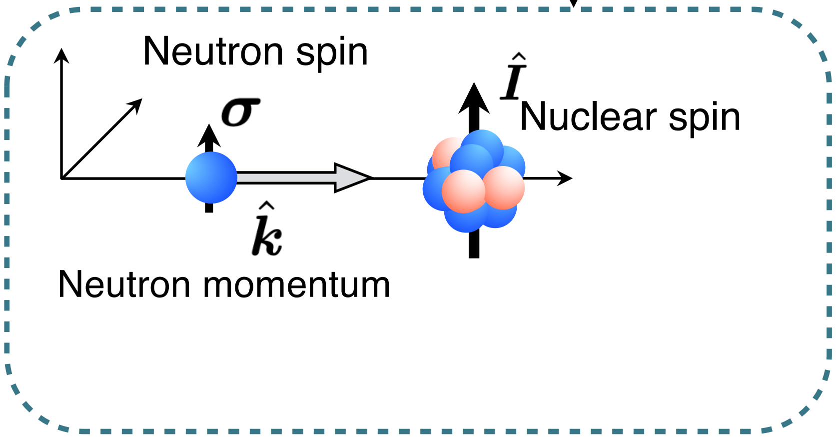
$$f = A' + B'\boldsymbol{\sigma}\cdot\hat{\boldsymbol{I}} + C'\boldsymbol{\sigma}\cdot\hat{\boldsymbol{k}} + D'\boldsymbol{\sigma}\cdot(\hat{\boldsymbol{I}}\times\hat{\boldsymbol{k}})$$

Normal cross section (Measured)

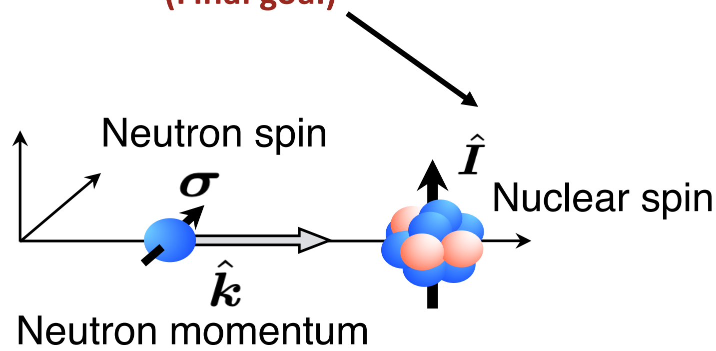
Spin dependence (Unmeasured)

P-violation (Measured)

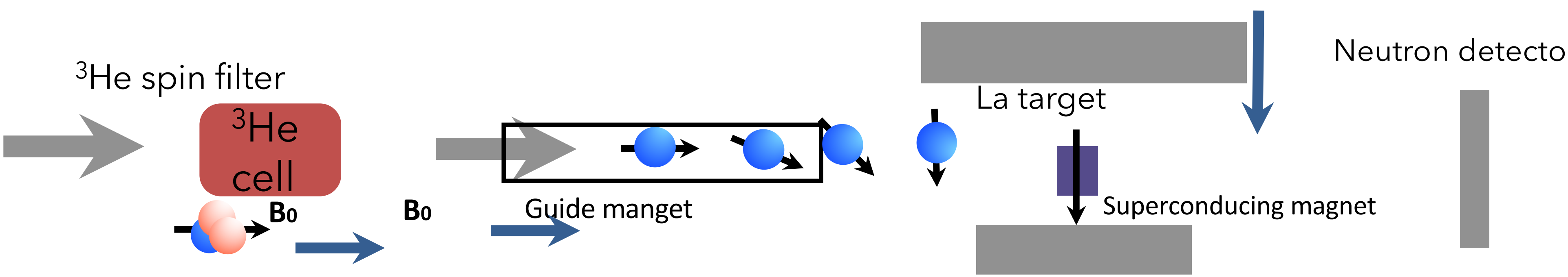
T-violation (Final goal)



Systematic error in T-violation

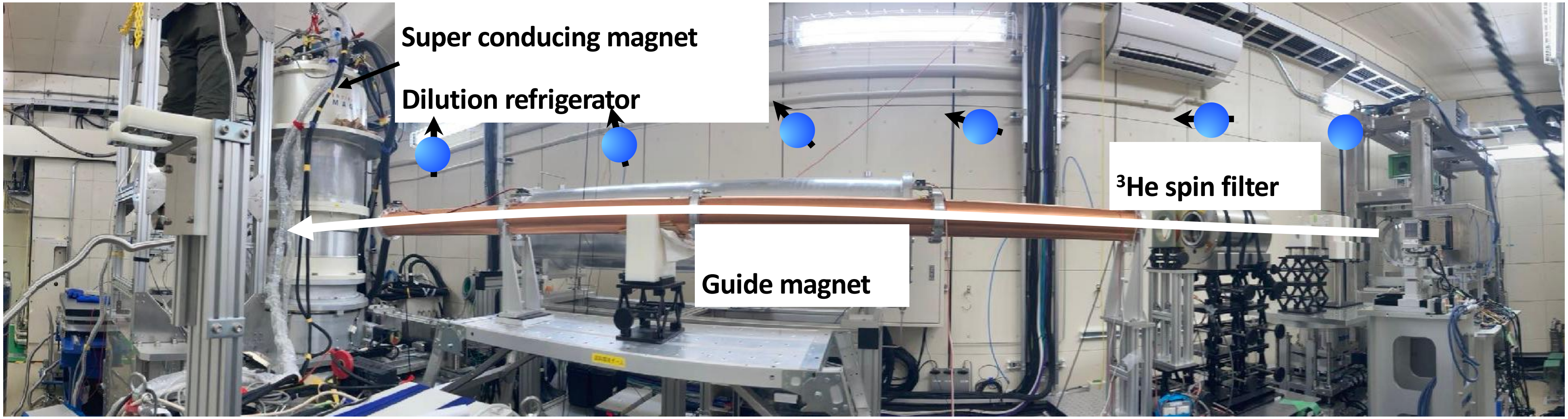


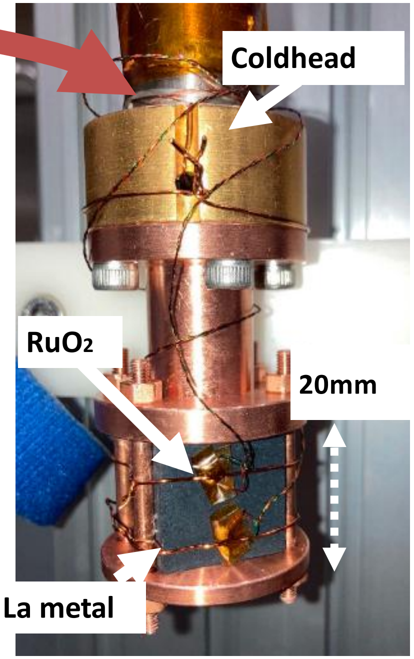
Spin dependent cross section measurement using static nuclear polarization

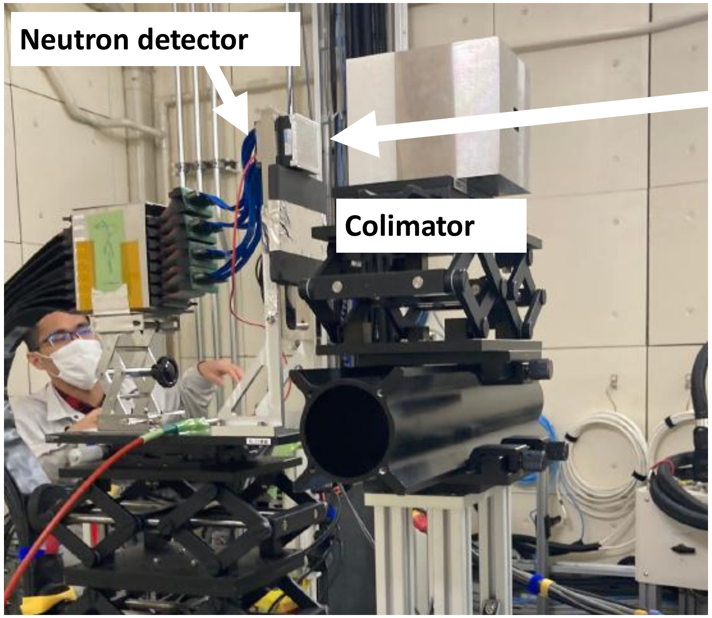


60mK dilution refrigerator, 7T super conducing magnet

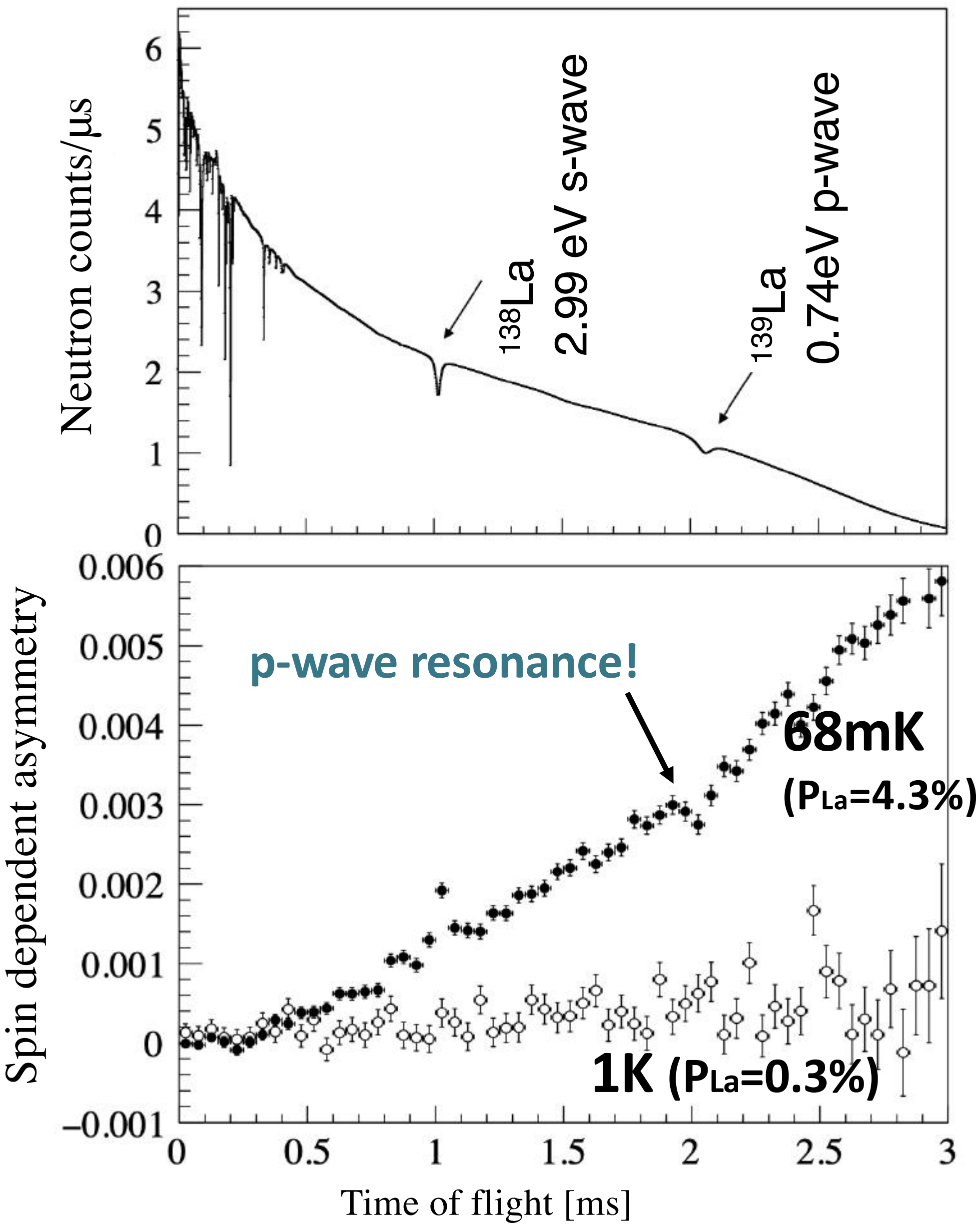
Experiment using polarized La and neutrons







Experiment using polarized La and neutrons

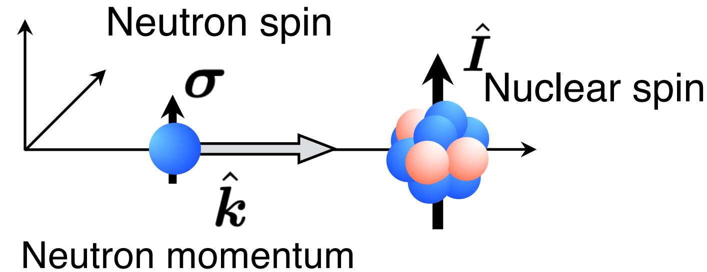


68mK, 6.7T

→^{139}La polarization : **4.3%**

Asymmetry of transmitted neutrons for parallel and anti-parallel spins

$$A_s = \frac{N_P - N_A}{N_P + N_A}$$

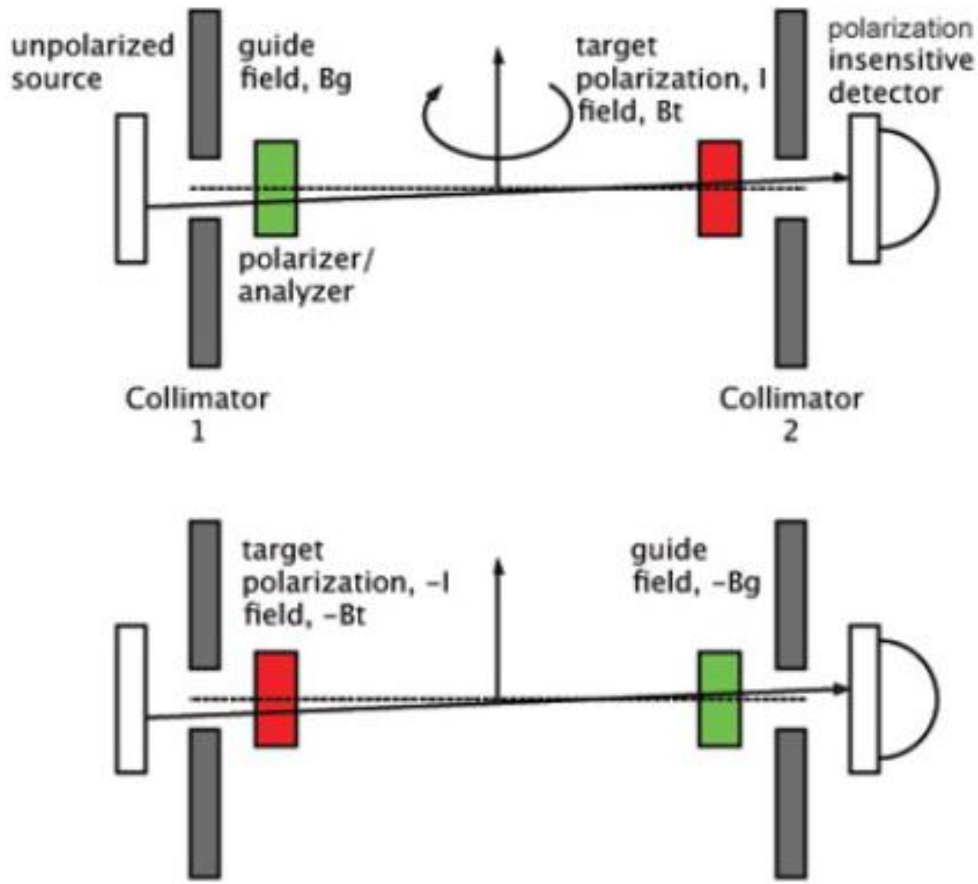


Successfully measured spin-dependent cross section!

To be published…

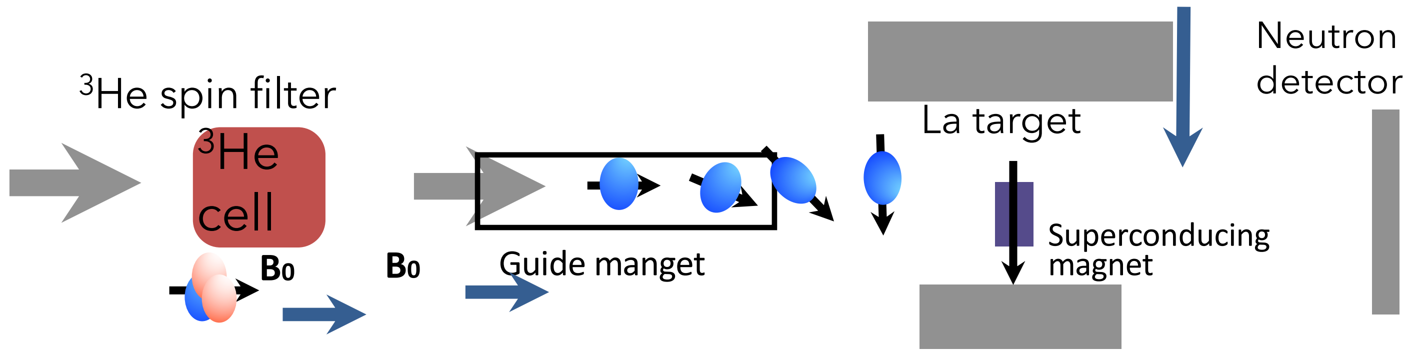
Big Milestone for T-violation search!

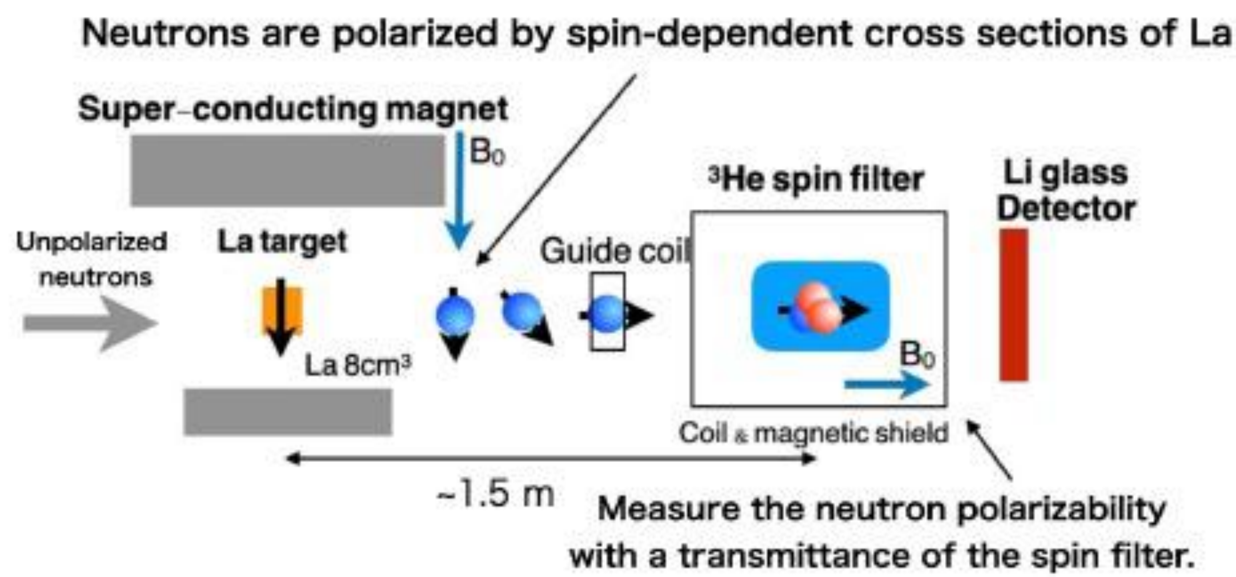
EDITORS' SUGGESTION Phys. Rev. C (2015)
Search for time reversal invariance violation in neutron transmission
J. David Bowman and Vladimir Gudkov



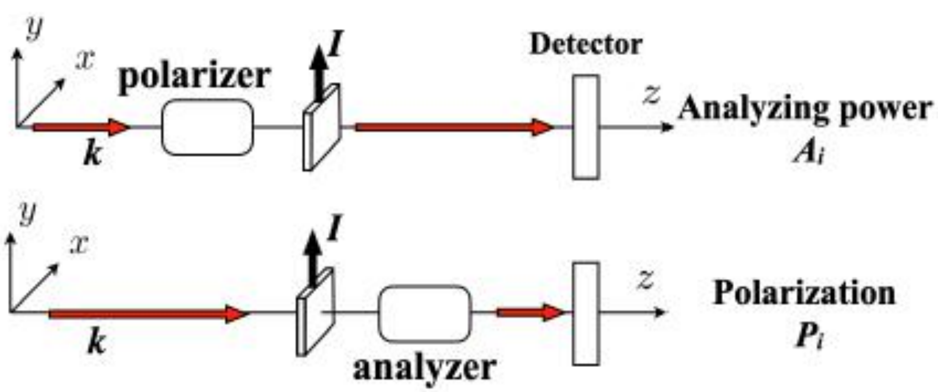
The authors analyze a novel null test to search for time reversal invariance in a model neutron transmission experiment. The proposed experimental procedure involves nuclear reactions and is sensitive to the neutron-nucleus interactions. The approach could significantly increase the discovery potential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

Recent Progress Toward a P-A test for T





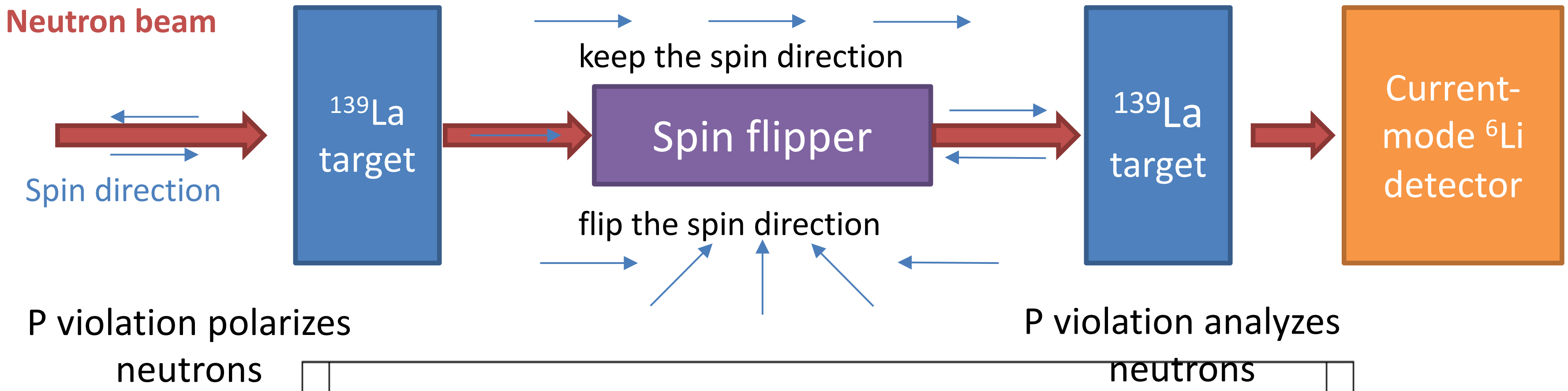
Recall textbook T symmetry condition: "polarizing power" P = "analyzing power" A



Soon we can do this at JPARC!

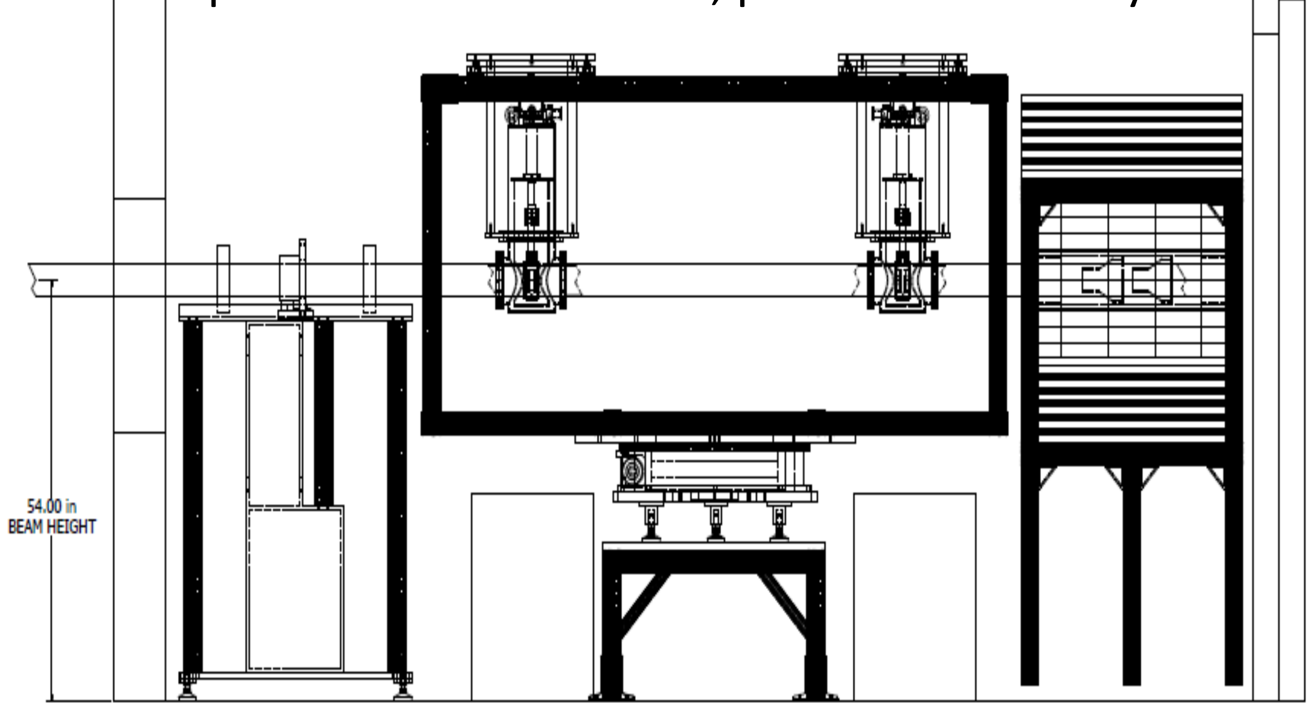
R. Nakabe

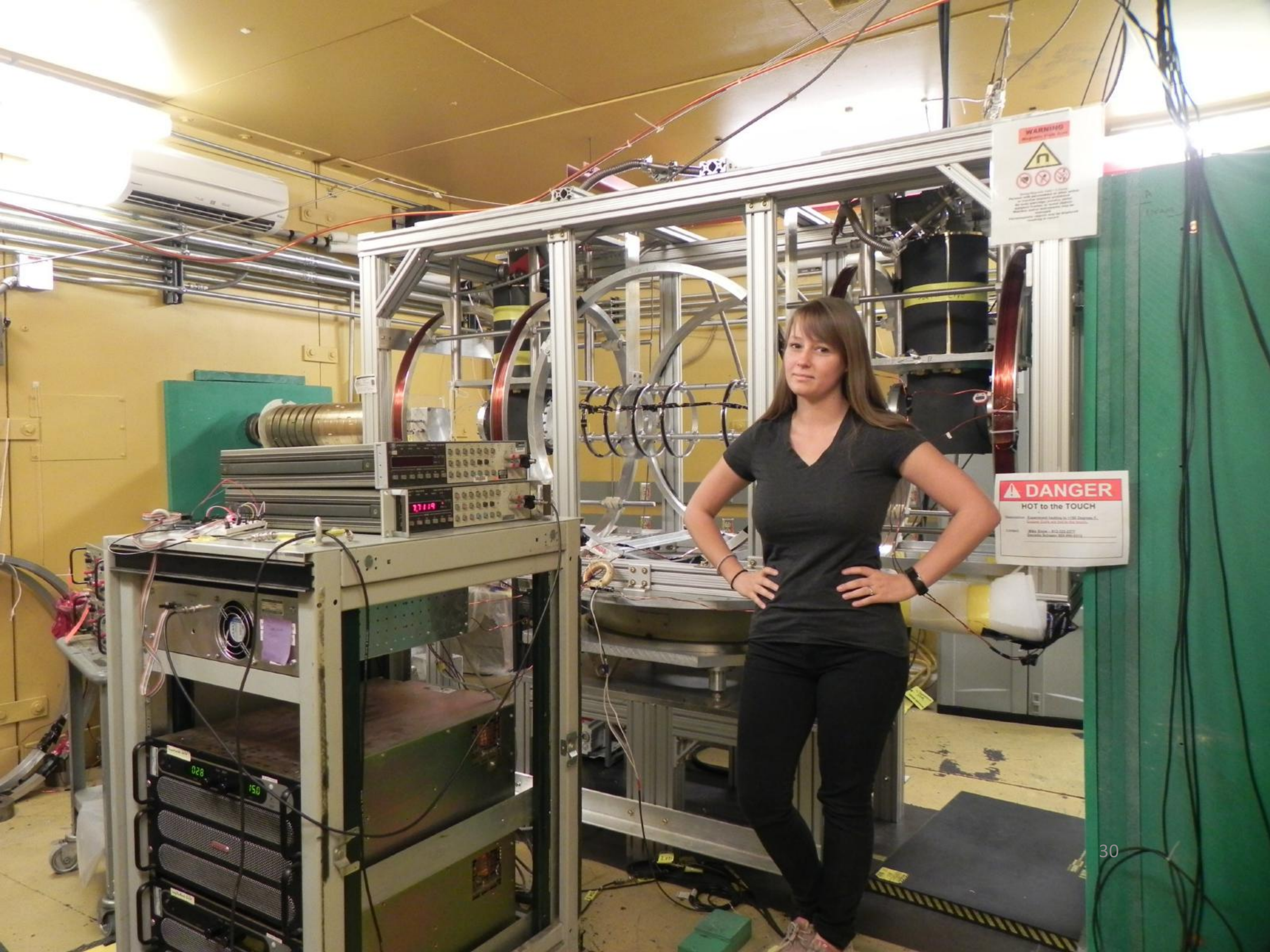
$$f = f_0 + f_1 \vec{\sigma_n} \cdot \vec{I} + f_2 \vec{\sigma_n} \cdot \vec{k_n} + f_3 \vec{\sigma_n} \cdot (\vec{k_n} \times \vec{I})$$



Parity violation measurements at LANSCE

^{139}La 0.7 eV resonance polarizes neutrons ~4%, polarizer and analyzer



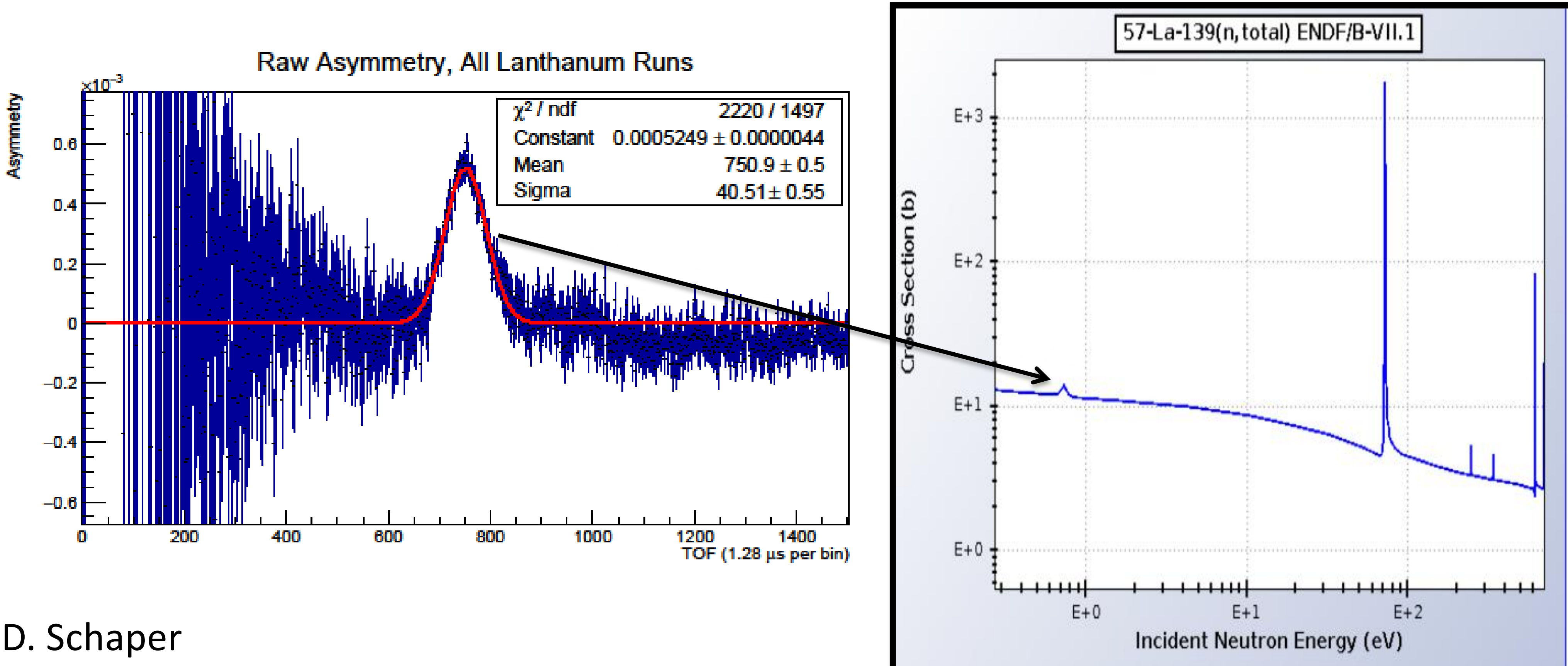

WARNING
DANGER
HOT to the TOUCH

Parity Violation in ^{139}La

Parity-odd asymmetry from neutron helicity dependence of neutron transmission

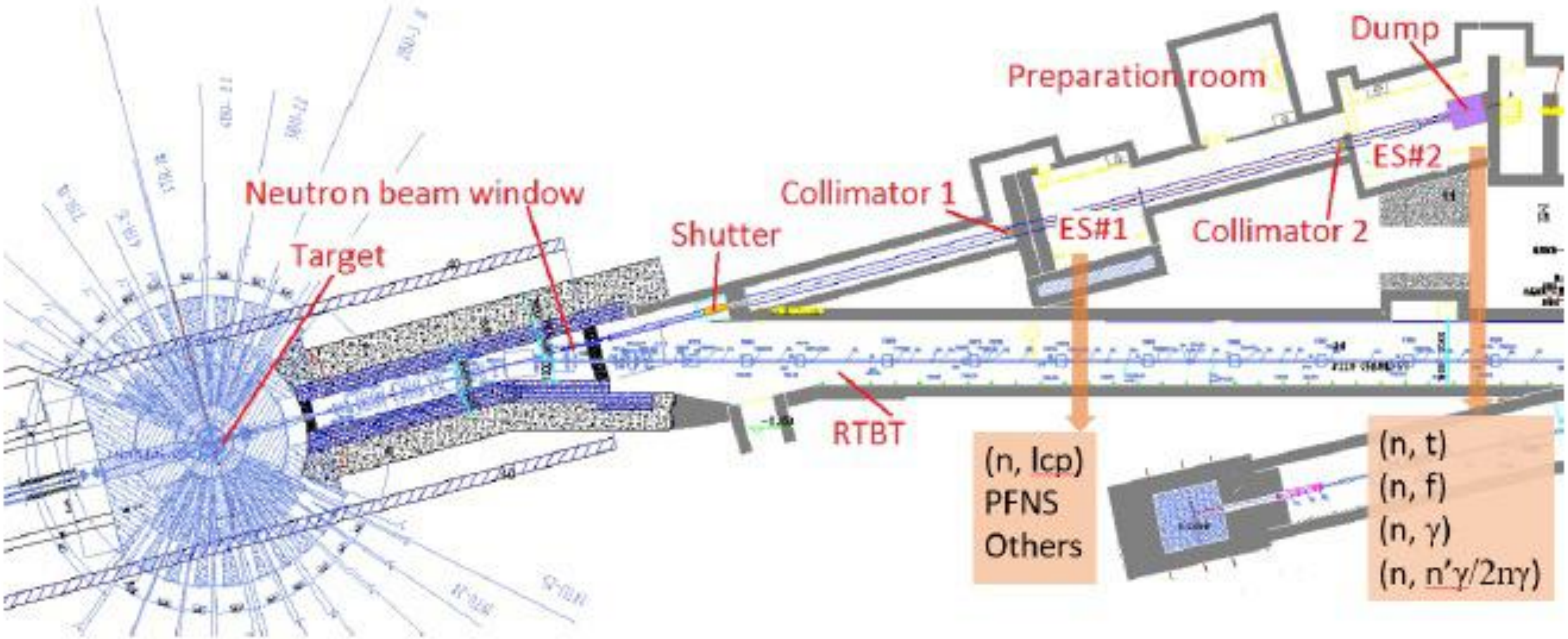
Asymmetries on all s-wave (L=0) n-A resonances are zero

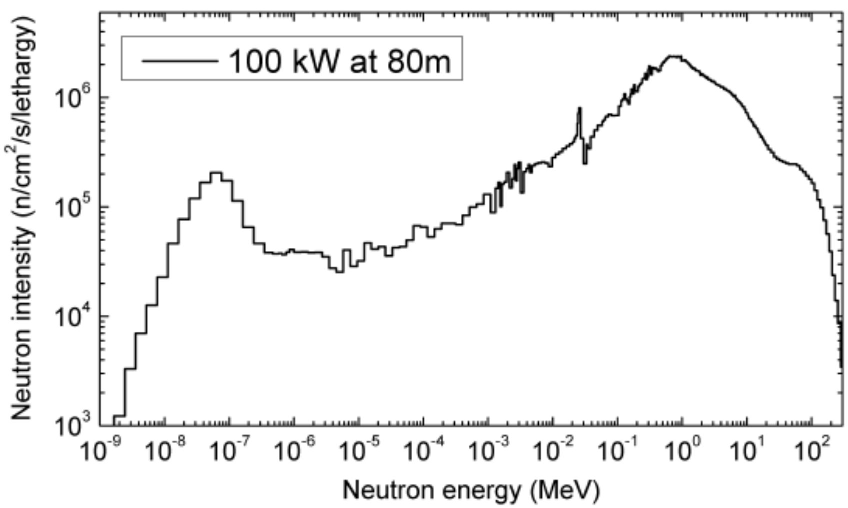
Goal: 1% precision measurement of A_L



D. Schaper

NOPTREX work started at CSNS

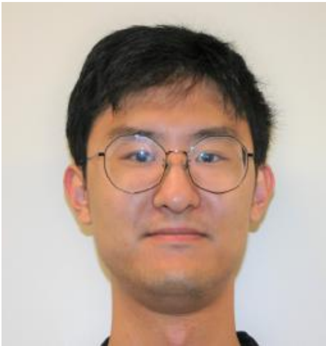




neutron CSNS Back-n beam @80m 1-10 eV, 1MW in future, same as SNS/JSNS

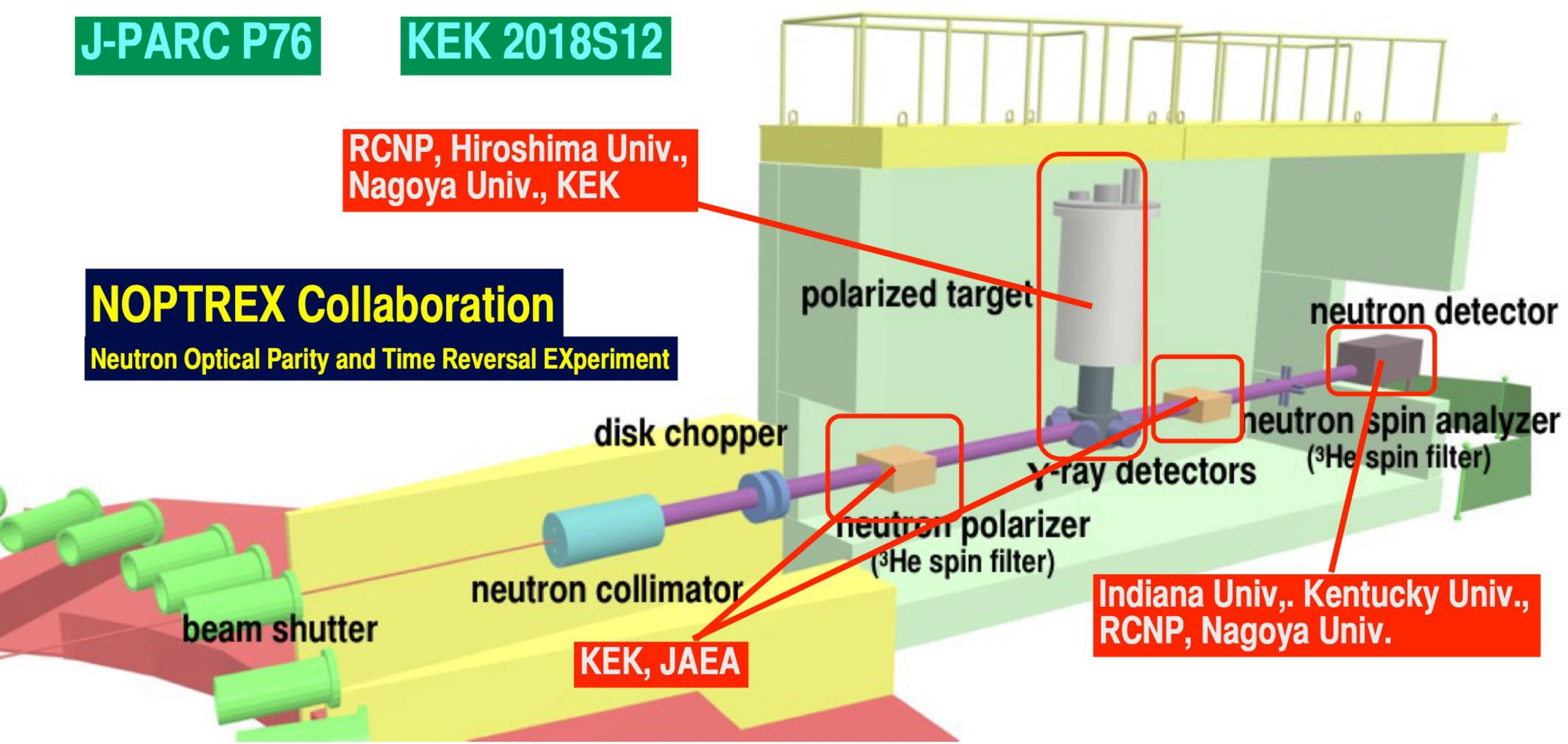
Mofan Zhang now at CSNS!

Approved experiment for 2023



(Proposed!) Experimental setup of T-violation search at J-PARC

Material Life science experimental Facility (MLF) at J-PARC



What About P-even/T-odd NN?

$$f = A' + B'(\vec{\sigma}\cdot\vec{I}) + C'(\vec{\sigma}\cdot\vec{k}) + D'(\vec{\sigma}\cdot[\vec{k}\times\vec{I}]) + H'(\vec{k}\cdot\vec{I}) + K'(\vec{\sigma}\cdot\vec{k})(\vec{k}\cdot\vec{I})$$
$$+ E'\left((\vec{k}\cdot\vec{I})(\vec{k}\cdot\vec{I}) - \frac{1}{3}(\vec{k}\cdot\vec{k})(\vec{I}\cdot\vec{I})\right) + F'\left((\vec{\sigma}\cdot\vec{I})(\vec{k}\cdot\vec{I}) - \frac{1}{3}(\vec{\sigma}\cdot\vec{k})(\vec{I}\cdot\vec{I})\right)$$
$$\boxed{+ G'(\vec{\sigma}\cdot[\vec{k}\times\vec{I}])(\vec{k}\cdot\vec{I})} + B_3'(\vec{\sigma}\cdot\vec{I})\left((\vec{k}\cdot\vec{I})(\vec{k}\cdot\vec{I}) - \frac{1}{3}(\vec{k}\cdot\vec{k})(\vec{I}\cdot\vec{I})\right) + \ldots,$$

V. Gudkov and H. M. Shimizu,
Phys. Rev. C 102, 015503 (2020).

P-even/T-odd term G can be present in forward amplitude resonance amplification of ~1000

~~(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

Direct constraints on P-even/T-odd NN interactions are poor

What About P-even/T-odd NN?

No P-even/T-odd effects in Standard Model: CKM, θ both P-odd/T-odd

Lowest mass meson exchange from $\rho^{+/-}$ [C-odd, J≥1]

[Herczeg Nucl. Phys. **75**, 655 (1966), Simonius PLB **58**, 147 (1975)]

VERY few experiments:

Detailed balance: [E. Blanke et al PRL **51**, 355 (1983); J. P. French et al PRL **54**, 2313 (1985)]: $g_\rho < 2x10^{-1}$

Charge symm. breaking [Simonius PRL **78**, 4161(1997)]: $g_\rho < 7x10^{-3}$

N transmission aligned Holmium (P. R. Huffman et al, PRC 55, 2684 (1997): $g_\rho < 6x10^{-2}$

Comparing with EDM P-odd/T-odd: $g_\pi < 10^{-11}$

Direct constraints on P-even/T-odd NN interactions are poor

Y. Uzikov

PHYSICAL REVIEW C VOLUME 55, NUMBER 5 MAY 1997

Test of parity-conserving time-reversal invariance using polarized neutrons and nuclear spin aligned holmium

P. R. Huffman,* N. R. Roberson, and W. S. Wilburn
Physics Department, Duke University, Durham, North Carolina 27708-0305
and Triangle Universities Nuclear Laboratory, Durham, North Carolina 27708-0308

C. R. Gould, D. G. Haase, C. D. Keith,† B. W. Raichle, M. L. Seely,‡ and J. R. Walston
Physics Department, North Carolina State University, Raleigh, North Carolina 27695-8202
and Triangle Universities Nuclear Laboratory, Durham, North Carolina 27708-0308
(Received 28 October 1996)

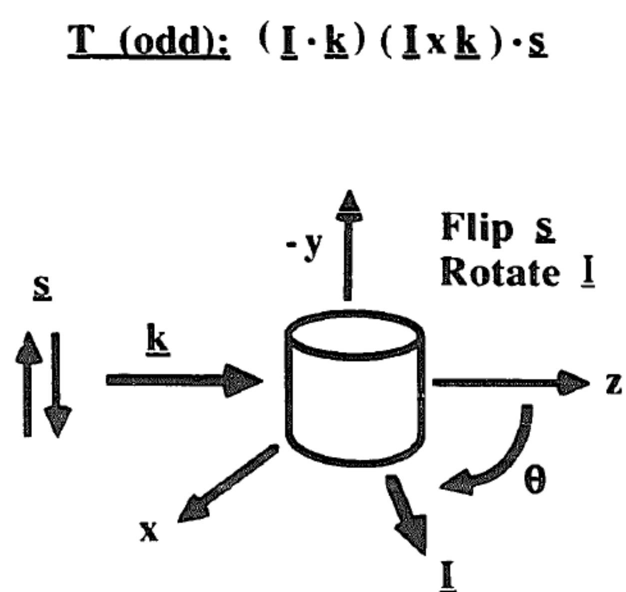


Fig. 1. Geometry for measurement of the $s\cdot(k\times I)(k\cdot I)$ term in neutron transmission through a cylindrical target.

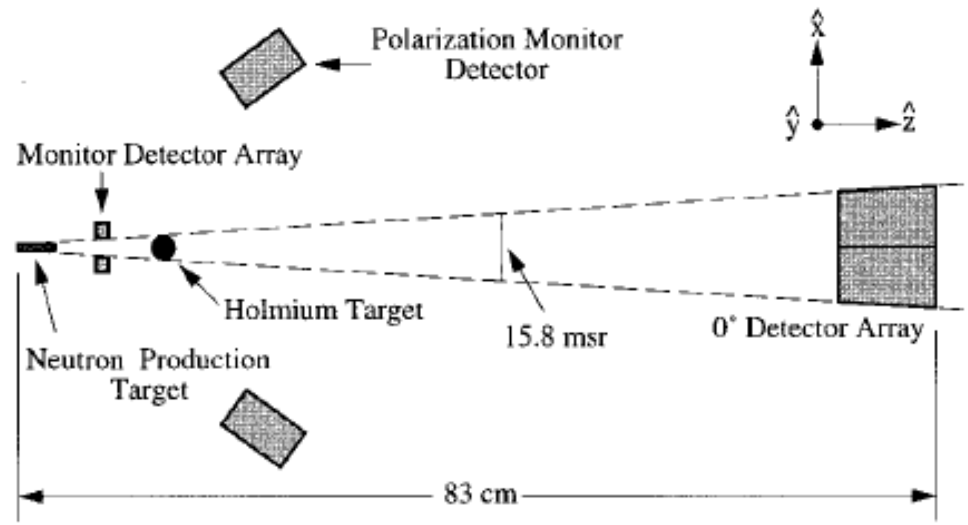


FIG. 1. The experimental setup for the fivefold correlation measurement. Vertically $(\pm\hat{\mathbf{y}})$ polarized neutrons with momentum $\hat{\mathbf{k}}$, directed along $\hat{\mathbf{z}}$, are transmitted through a nuclear-spin aligned holmium target and detected at 0°. The dashed lines depict the solid angle subtended by the neutron detectors. All components and distances are drawn to scale.

Uses polarized neutrons, tensor-aligned target

THEORY OF T-VIOLATING P-CONSERVING EFFECTS IN NEUTRON-INDUCED REACTIONS

V.P. GUDKOV

Leningrad Nuclear Physics Institute, Gatchina, Leningrad 188350, USSR

Received 10 January 1990
(Revised 25 July 1990)

Forward transmission ⇒ null test for T violation
Enhancement of asymmetry from high level density~10^3

P even-T-odd NN interactions can mix different p-wave resonances

$$\Delta\sigma_T = \frac{4\pi}{k}\,\mathrm{Im}\,\{\Delta f_T\}$$

$$\Delta\sigma_T \simeq \frac{4\pi}{k^2}\,\frac{\langle\tilde{\Gamma}^n_p\rangle v_T}{[p_1][p_2]}\{(E-E_{p1})\Gamma_{p2}+(E-E_{p2})\Gamma_{p1}\}$$

where $iv_T = \langle\varphi_{p2}|\hat{V}_T|\varphi_{p1}\rangle$;

$$\langle\tilde{\Gamma}^n_p\rangle = (\Gamma^n_{p1}(-)\Gamma^n_{p2}(+))^{1/2} - (\Gamma^n_{p1}(+)\Gamma^n_{p2}(-))^{1/2}$$

$\Gamma_p\,(+)$ and $\Gamma_p\,(-) = \Gamma_p\,(J=l\pm½)$

Current Status of Research on *T* Invariance in Neutron–Nuclear Reactions

A. G. Beda[a] and V. R. Skoy[b]

ISSN 1063-7796, Physics of Particles and Nuclei, 2007, Vol. 38, No. 6, pp. 775–794. © Pleiades Publishing, Ltd., 2007.
Original Russian Text © A.G. Beda, V.R. Skoy, 2007, published in Fizika Elementarnykh Chastits i Atomnogo Yadra, 2007, Vol. 38, No. 6.

$$f = A + pp_1B(\vec{s}\cdot\vec{I}) + pC(\vec{s}\cdot\vec{k}) + pp_1D(\vec{s}\cdot[\vec{k}\times\vec{I}]) + p_1E(\vec{k}\cdot\vec{I}) + \boxed{pp_2F(\vec{k}\cdot\vec{I})(\vec{s}\cdot[\vec{k}\times\vec{I}])} \quad (6)$$

F term is P-even/T-odd

$$p = \frac{\langle m_s\rangle}{s} \quad p_2 = \frac{3\langle m_I\rangle^2 - I(I+1)}{I(2I-1)}$$

Need polarized neutrons (p) and aligned nuclear target (p_2)

^{127}I has large electric quadrupole moment, good choice

Can be aligned by electric field gradients in crystals at low T

Need Γ_p (J=I±½) resonance parameters in ^{127}I , but not measured!

P-odd Asymmetries on p-wave Neutron Resonances

G. E. Mitchell, J. D. Bowman, S. I Penttila, E. I. Sharapov, Phys. Rep. **354**, 1 (2001).

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

(Some) P-even/T-odd Theory Work (flavor conserving)

$$\frac{G_F}{\sqrt{2}} \frac{q_1}{2m_p} \bar{\psi}_1 i\gamma_5 \sigma^{\mu\nu} (p_1' - p_1)_\nu \psi_1 \bar{\psi}_2 \gamma_\mu \gamma_5 \psi_2 \,,$$

$$C_7 \left(\frac{1}{\Lambda^3}\right) \bar{q}_1 \gamma_5 D^\mu q_2 \bar{q}_3 \gamma_5 \gamma_\mu q_4 + H.c.,$$

$$C_7' \left(\frac{1}{\Lambda^3}\right) \bar{q} \sigma_{\mu\nu} \lambda^A q G^{A\mu\rho} F^\nu_\rho \,,$$

$$C_7^{\gamma Z'} \bar{\psi} \sigma_{\mu\nu} \psi F^{\mu\alpha} Z^\nu_\alpha .$$

Some operators considered in previous work

Concentrated on using EDM limits to constrain P-even/T-odd interactions

Considered particular terms: not a general analysis

Later work (Kurylov et al PRD 2001, El Menoufi et al PLB 2017): loopholes in previous constraints

I. B. Khriplovich. What do we know about T odd but P even interaction? *Nucl. Phys.*, B352:385–401, 1991.

R. S. Conti and I. B. Khriplovich. New limits on T odd, P even interactions. *Phys. Rev. Lett.*, 68:3262–3265, 1992.

Jonathan Engel, Paul H. Frampton, and Roxanne P. Springer. Effective Lagrangians and parity conserving time reversal violation at low-energies. *Phys. Rev.*, D53:5112–5114, 1996.

M. J. Ramsey-Musolf. Electric dipole moments and the mass scale of new T violating, P conserving interactions. *Phys. Rev. Lett.*, 83:3997–4000, 1999. [Erratum: Phys. Rev. Lett.84,5681(2000)].

P-even/T-odd in SMEFT (flavor conserving)

Table 7.3: Lowest mass-dimensional C-odd and CP-odd operators contributing to flavor-conserving interactions

1_a	$\frac{v^2}{2}\epsilon^{\mu\nu\alpha\beta}\partial_\alpha(\bar{u}_p\gamma_\beta\gamma_5 u_p)F_{\mu\nu}$	$-\frac{4G_F}{\sqrt{2}}[2c_w s_w(C_{W^2\varphi^2}-C_{B^2\varphi^2})-C_{WB\varphi^2}({c_w}^2-{s_w}^2)]$
1_b	$\frac{v^2}{2}\epsilon^{\mu\nu\alpha\beta}\partial_\alpha(\bar{d}_p\gamma_\beta\gamma_5 d_p)F_{\mu\nu}$	$\frac{4G_F}{\sqrt{2}}[2c_w s_w(C_{W^2\varphi^2}-C_{B^2\varphi^2})-C_{WB\varphi^2}({c_w}^2-{s_w}^2)]$
2_a	$\frac{v}{\sqrt{2}}(\bar{u}_p\sigma^{\mu\nu}\gamma_5 u_p)\partial_\mu(\bar{u}_r\gamma_\nu\gamma_5 u_r)$	$-G_F iC^{pr}_{quZ\varphi}$
2_b	$\frac{v}{\sqrt{2}}(\bar{u}_p\sigma^{\mu\nu}\gamma_5 u_p)\partial_\mu(\bar{d}_r\gamma_\nu\gamma_5 d_r)$	$G_F iC^{pr}_{qdZ\varphi}$
2_c	$\frac{v}{\sqrt{2}}(d_p\sigma^{\mu\nu}\gamma_5 d_p)\partial_\mu(\bar{u}_r\gamma_\nu\gamma_5 u_r)$	$-G_F iC^{pr}_{quZ\varphi}$
2_d	$\frac{v}{\sqrt{2}}(d_p\sigma^{\mu\nu}\gamma_5 d_p)\partial_\mu(d_r\gamma_\nu\gamma_5 d_r)$	$G_F iC^{pr}_{qdZ\varphi}$
3_a	$\frac{v}{\sqrt{2}}\big[V_{u_r d_p}(\bar{d}_p\sigma^{\mu\nu}u_r)\partial_\mu(\bar{u}_r\gamma_\nu d_p)$ $-V^*_{u_r d_p}(\bar{u}_r\sigma^{\mu\nu}d_p)\partial_\mu(\bar{d}_p\gamma_\nu u_r)\big]$	$2G_F i[\mathrm{Im}(C^{pr}_{quW\varphi})-\mathrm{Im}(C^{rp}_{qdW\varphi})]$
3_b	$\frac{v}{\sqrt{2}}\big[V_{u_r d_p}(d_p\sigma^{\mu\nu}\gamma_5 u_r)\partial_\mu(\bar{u}_r\gamma_\nu\gamma_5 d_p)$ $+V^*_{u_r d_p}(\bar{u}_r\sigma^{\mu\nu}\gamma_5 d_p)\partial_\mu(\bar{d}_p\gamma_\nu\gamma_5 u_r)\big]$	$-2G_F i[\mathrm{Im}(C^{pr}_{quW\varphi})+\mathrm{Im}(C^{rp}_{qdW\varphi})]$
4_a	$\frac{v}{\sqrt{2}}\big[V_{u_r d_p}(d_p\sigma^{\mu\nu}u_r)(\bar{u}_r\gamma_\mu d_p)A_\nu$ $+V^*_{u_r d_p}(\bar{u}_r\sigma^{\mu\nu}d_p)(\bar{d}_p\gamma_\mu u_r)A_\nu\big]$	$2G_F g s_w[\mathrm{Im}(C^{pr}_{quW\varphi})-\mathrm{Im}(C^{rp}_{qdW\varphi})]$
4_b	$\frac{v}{\sqrt{2}}\big[V_{u_r d_p}(\bar{d}_p\sigma^{\mu\nu}\gamma_5 u_r)(\bar{u}_r\gamma_\mu\gamma_5 d_p)A_\nu$ $-V^*_{u_r d_p}(\bar{u}_r\sigma^{\mu\nu}\gamma_5 d_p)(\bar{d}_p\gamma_\mu\gamma_5 u_r)A_\nu\big]$	$-2G_F g s_w[\mathrm{Im}(C^{pr}_{quW\varphi})+\mathrm{Im}(C^{rp}_{qdW\varphi})]$

New terms exist which have not been considered in the past

J. Shi. PhD thesis, U Kentucky (2020)
J. Shi and S. Gardner, in preparation

NOPTREX Experiment Status $\vec{\sigma_n} \cdot (\vec{k_n} \times \vec{I})$

- P-odd and T – odd term in FORWARD scattering amplitude (a null test, like EDMs) with polarized n beam and polarized nuclear target

- Amplified on select P-wave epithermal neutron resonances by ~5-6 orders of magnitude

- Estimates of stat sensitivity at JSNS/CSNS look very interesting:

$\Delta\sigma_{PT}/\Delta\sigma_P \sim 10^{-6}$,~x10 present EDM limits

- 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

- Present work: neutron spectroscopy on p-wave resonances to quantify sensitivity, polarized target development, first P-A T test at JPARC soon

P-even/T-odd NN interaction search

2 ways to violate T (+conserve CPT): P-odd/T-odd , P-even/T-odd

MANY search for P-odd/T-odd (EDMs,…), VERY few for P-even/T-odd

P-odd/T-odd effect can come from:

(1) BSM P-odd/T-odd, or (2) [BSM P-even/T-odd] + [SM P-odd]

Q: If you see a P-odd/T-odd effect in nucleus: is it (1) or (2)?

Experimental limits on P-even/T-odd NN interactions are quite poor

Neutron optics on n-A resonances can improve limits by ~10^3

NOPTREX Papers: Published Before 2020

D. Bowman and V. Gudkov, **On the Search for Time Reversal Invariance Violation in Neutron Transmission,** Phys. Rev. C **90**, 065503 (2014). arXiv:1407.7004

V. Gudkov and H. M. Shimizu, **Pseudomagnetic effects for resonance neutrons in the search for time reversal invariance violation**, Phys. Rev. C **95**, 045501 (2017). arXiv:1701.03521

V. Gudkov and H. M. Shimizu, **Nuclear spin dependence of time reversal invariance violating effects in neutron scattering,** Phys. Rev. C **97**, 065502 (2018), arXiv: 1710.02193

T. Okudaira, S. Takada, K. Hirota, A. Kimura, M. Kitaguchi, J. Koga, K. Nagamoto, T. Nakano, A. Okada, K. Sakai, H. M. Shimizu, T. Yamamoto, and T. Yoshioka, **Angular Distribution of γ-rays from Neutron-Induced Compound States of ^{140}La ,** Phys. Rev. C **97**, 034622 (2018). arXiv: 1710.03065

W. M. Snow, K. Dickerson, J. Devaney, and C. Haddock, **Calculations of the Theoretical Performance of Neutron Mirrors Based on Reflections from Neutron Resonances in Heavy Nuclei**, Phys. Rev. A **100**, 023612 (2019). arXiv:1810.11590

NOPTREX Papers: Published in 2020

V. Gudkov and H. M. Shimizu**, Neutron spin dynamics in polarized targets,** Phys. Rev. **C102**, 015503 (2020). arXiv: 1910.08598

D. Schaper, C. Auton, L. Barron-Palos, M. Borrego, A. Chavez, L. Cole, C. B. Crawford, J. Curole, H. Dhahri, J. Doskow, W. Fox, M.H. Gervais, B. M. Goodson, K. Knickerbocker, P. Jiang, P. M. King, H. Lu, M. Mocko, D. Olivera-Velarde, S.I. Penttila, A. Perez-Martin, W. M. Snow, K. Steffen, J. Vanderwerp, and G. Visser, **A modular apparatus for use in high-precision measurements of parity violation in polarized eV neutron transmission**, Nucl. Inst. Meth. A **969**, 163961 (2020). arXiv:2001.03432

T. Yamamoto, T. Okudaira, S. Endo, H. Fujioka, K. Hirota, T. Ino, K. Ishizaki, A. Kimura, M. Kitaguchi, J. Koga, S. Makise, Y. Niinomi, T. Oku, K. Sakai, T. Shima, H. M. Shimizu, S. Takada, Y. Tani, H. Yoshikawa, and T. Yoshioka, **Transverse asymmetry of gamma rays from neutron-induced compound states of ^{140}La,** Phys. Rev. C**101**, 064624 (2020). arXiv:2002.08655

T. Okudaira, T. Oku, T. Ino, H. Hayashida, H. Kira, K. Sakai, K. Hiroi, S. Takahashi, K. Aizawa, H. Endo, S. Endo, M. Hino, K. Hirota, T. Honda, K. Ikeda, K. Kakurai, W. Kambara, M. Kitaguchi, T. Oda, H. Ohshita, T. Otomo, H. M. Shimizu, T. Shinohara, J. Suzuki, T. Yamamoto, **Development and application of a ^{3}He Neutron Spin Filter at J-PARC**, Nucl. Inst. Meth. A **977,** 164301 (2020), arXiv: 2005.14399

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T. Okudaira, S. Endo, H. Fujioka, K. Hirota, K. Ishizaki, A. Kimura, M. Kitaguchi, J. Koga, Y. Ninomi, K. Sakai, T. Shima, H. M. Shimizu, S. Takada, Y. Tani, T. Yamamoto, H. Yoshikawa, and T. Yoshioka, **Energy dependent angular distribution of individual γ-rays in the 139La(n, γ)140La* reaction**, Phys. Rev. C **104**, 014601 (2021). arXiv: 2101.00262

K. Ishizaki, H. Hotta, I. Ide, M. Iinuma, T. Iwata, M. Kitaguchi, H. Kohri, D. Miura, Y. Miyachi, T. Ohta, H. M. Shimizu, H. Yoshikawa, and M. Yosoi, **Measurement of nuclear spin relaxation time in lanthanum aluminate for the development of polarized lanthanum target**, Nucl. Inst. Meth. A**1020**, 165845 (2021). arXiv:2105.06299

W. M. Snow, C. Haddock, and B. Heacock, **Searches for Exotic Interaction Using Neutrons**, invited paper, Special Issue: The Neutron Physics - Dark Matter Connection: Bridge Through the Baryon Symmetry Violation, Symmetry **14**, 10 (2021).

NOPTREX Papers Published/Submitted in 2022

J. Koga, S. Takada, S. Endo, H. Fujioka, K. Hirota, K. Ishizaki, A. Kimura, M. Kitaguchi, Y. Niinomi, T. Okudaira, K. Sakai, T. Shima, H. M. Shimizu, Y. Tani, T. Yamamoto, H. Yoshikawa, and T. Yoshioka, **Angular Distribution of γ-rays from the p-wave Resonance of ^{118}Sn,** Phys. Rev. C **105**, 054615 (2022). arXiv:2022.06222.

S. Endo, T. Okudaira, R. Abe, H. Fujioka, K. Hirota, A. Kimura, M. Kitaguchi, T. Oku, K. Sakai, T. Shima, H. M. Shimizu, S. Takada, S. Takahashi, T. Yamamoto, H. Yoshikawa, and T. Yoshioka, Measurement of the transverse asymmetry of γ-rays in the ^{117}Sn(n, γ)^{118}Sn reaction, Phys. Rev. C **106**, 064601 (2022). arXiv:2210.15807.

T. Okudaira et al, **Angular distribution of individual γ-rays from neutron induced p-wave resonance in the 131Xe(n, γ)132Xe* reaction,** submitted to Phys. Rev. C (2022). arXiv:2212.10889

H. Lu, W. M. Snow, D. Basler, B. M. Goodson, M. Barlow, and G. M. Schrank, Z. Salhi, O. Holderer, S. Passini, A. Ioffe, P. Gutfrunde, and E. Babcock, **The Nuclear Polarization Induced Neutron Birefringence of ^{129}Xe and ^{131}Xe Nuclei,** submitted to Phys. Rev. Lett. (2022). arXiv: 2301.00460

NOPTREX Papers to be Submitted (2023)

H. Lu, W. M. Snow, D. Basler, B. M. Goodson, Z. Salhi, O. Holderer, S. Passini, A. Ioffe, and E. Babcock, **Method for accurate determination of the ^{3}He neutron incoherent scattering length b_i ,** to be submitted to Phys. Rev. C (2023).

B. Goodson, E. Chekmenev, R. Shchepin, J. Curole, L. Charon-Garcia, W. M. Snow et al., **Progress Toward A Search for Time Reversal Violation in Polarized Neutron Transmission on the 1.33 eV P-Wave Resonance in Polarized ^{117}Sn Using SABRE,** to be submitted to Angewandte Chemie (2023).

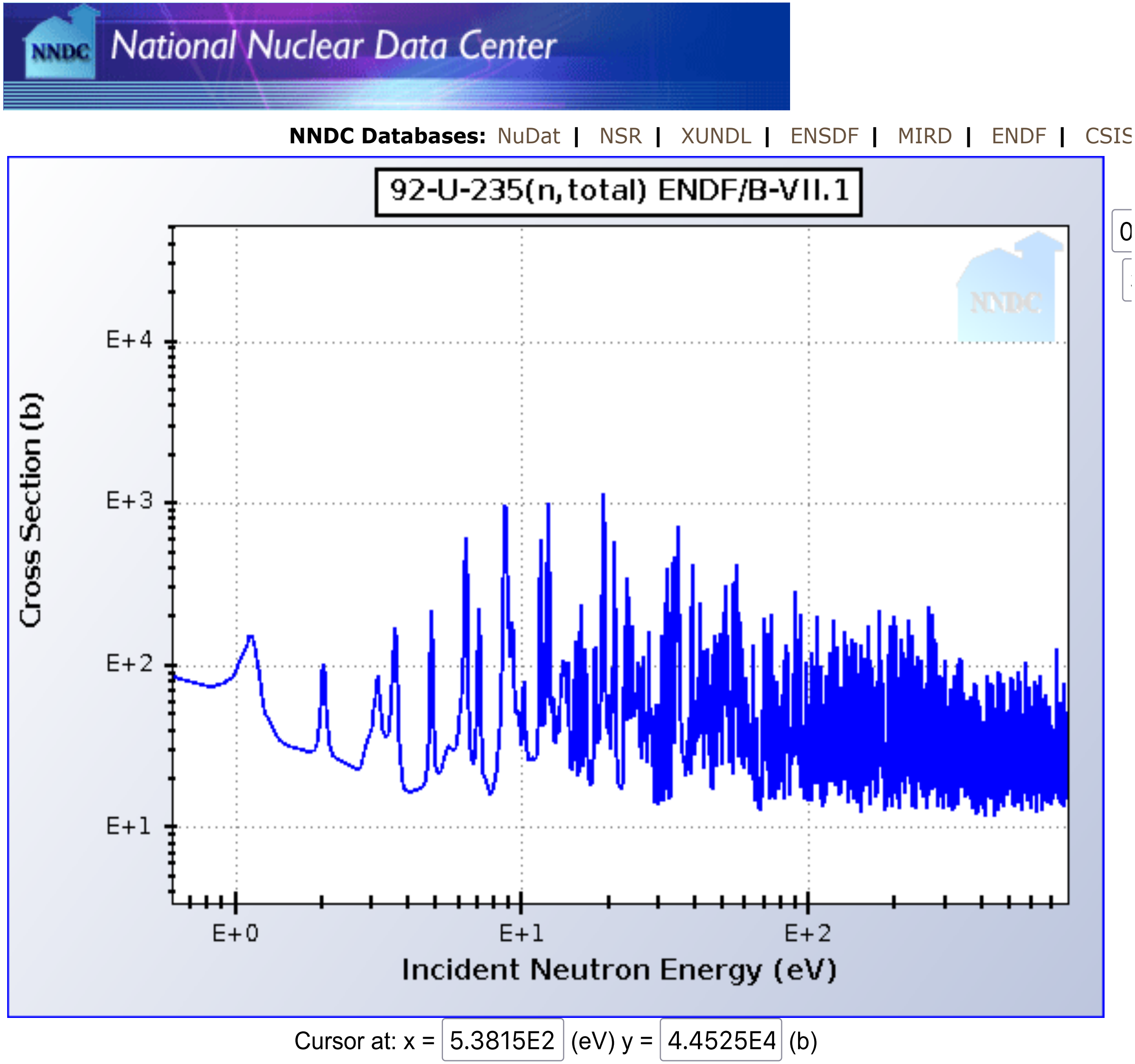
V. P. Gudkov and H. M. Shimizu, **Angular correlations in neutron-gamma reactions,** to be submitted to Phys. Rev. C (2023).

L. Charon-Garcia, J. Curole, V. P. Gudkov, W. M. Snow, and L. Barron-Palos **P-even and -odd asymmetries in n+ ^{117}Sn at the vicinity of the p resonance E_p=1.33 eV,** to be submitted to Phys. Rev. C (2023).

NOPTREX MS/PhD Theses 2018-present

Takuya Okudaira, PhD, Nagoya University (2018)
Tomoki Yamamoto, PhD, Nagoya University (2021)
Yuika Tani, MS, Tokyo Institute of Technology (2021)
Jun Koga, PhD, Kyushu University (2021)
Danielle Schaper, PhD, University of Kentucky (2021)
S Takada, PhD, Kyushu University (2022)
R Abe. MS, Nagoya University (2022)
Jonathan Curole, PhD, Indiana University (2023)
Hao Lu, PhD thesis, Indiana University (expected 2023)
Luis Charon-Garcia, PhD, UNAM (expected 2023)
Kento Kameda, MS, Tokyo Institute of Technology (2023)
Hiromoto Yoshikawa, PhD, RCNP/Osaka (???)
Rintaro Nakabe, PhD, Nagoya University (???)
Shunsuke Endo, PhD, JAEA (???)
Benjamín Salazar-Ángeles, MS, UNAM (???)
Kylie Dickerson, PhD, Indiana University (???)
Gabe Otero, PhD, Indiana University (???)
Clayton Auton, PhD, Indiana University (???)
Mofan Zhang, PhD, Indiana University (???)
Tobi Abdulgafar, PhD, Southern Illinois University (???)
Md Shahabuddin Alam, PhD, Southern Illinois University (???)

Neutron-Nucleus Resonances



Heavy nuclei possess a very dense set of resonances just above the neutron separation energy

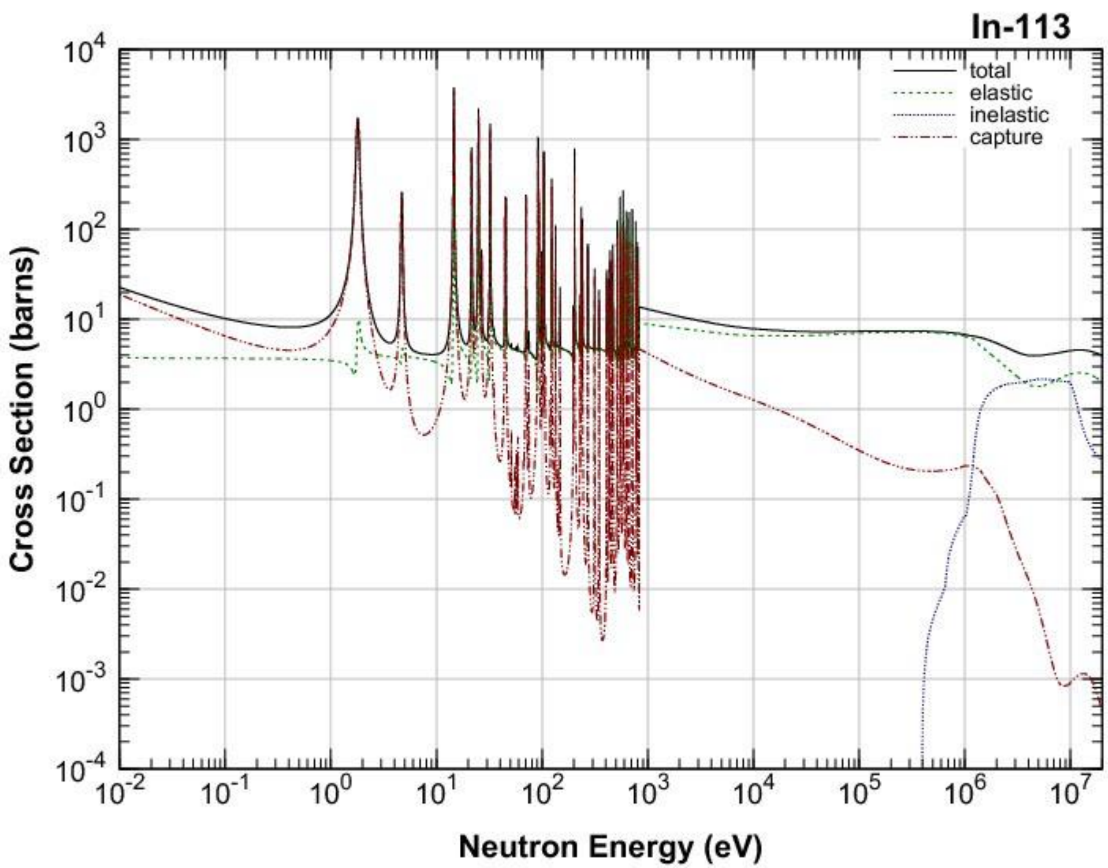
No Coulomb barrier -> neutrons can easily excite them

Mainly L=0 resonances, but lots of L=1 resonances

P-odd/T-odd mix L=0 and L=1 states

P-even/T-odd mix pairs of L=1states

Neutron-Nucleus Resonances



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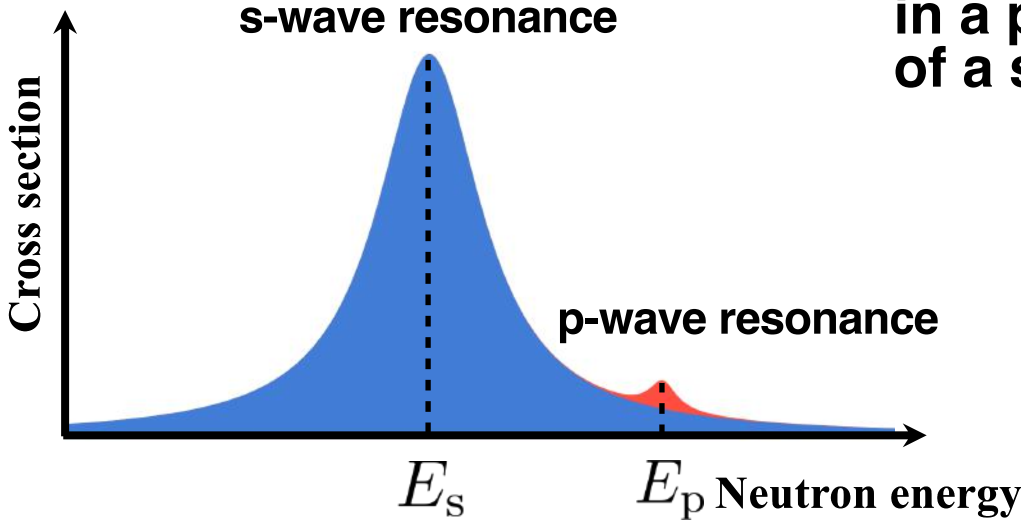
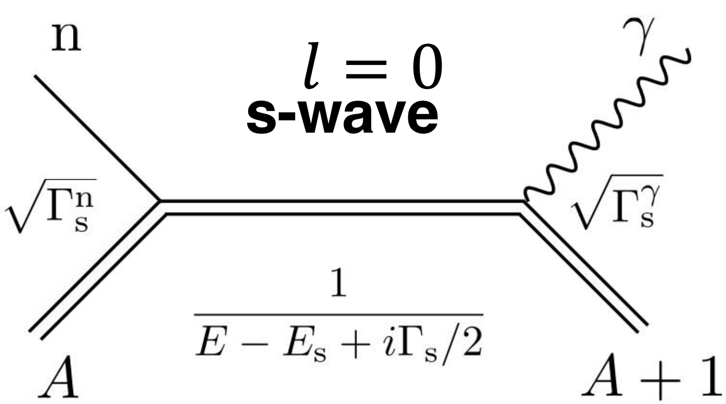
Enhancement of parity violation: mechanism

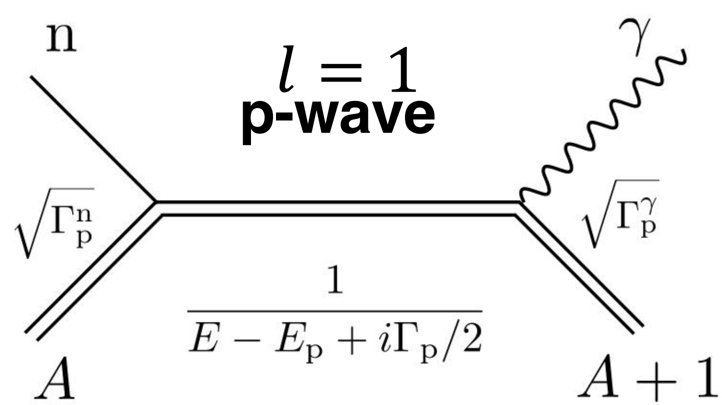


Enhancement of P-violation is observed in a p-wave resonance located in a tail of a s-wave resonance

s-wave resonance :
angular momentum of absorbed neutron 0
Parity +

p-wave resonance :
angular momentum of absorbed neutron 1
Parity -





$$j = l + s$$

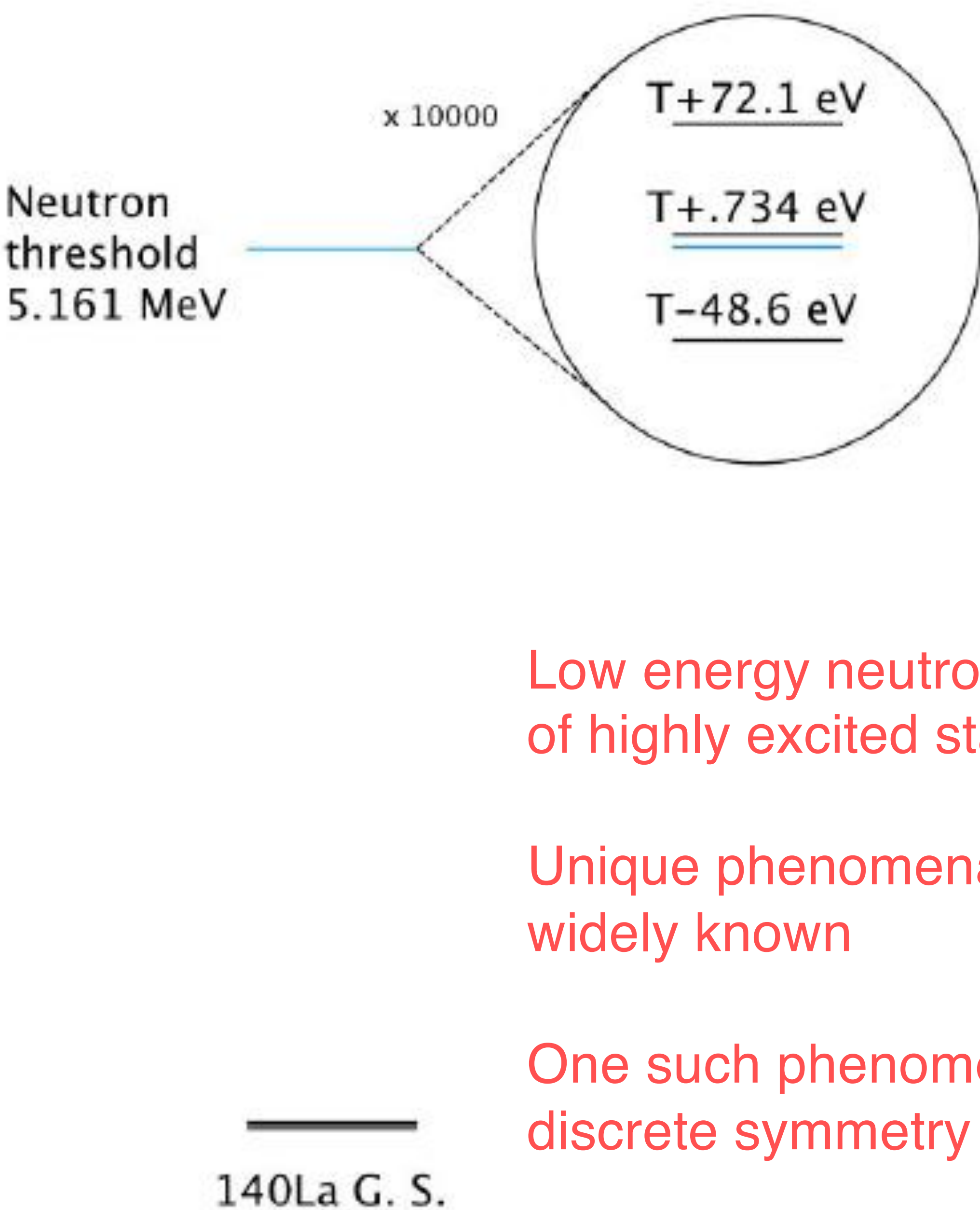
Total angular momentum of neutron

$$j = 1/2$$

Total angular momentum of neutron

$$j = 1/2,\ 3/2$$

139La+n System



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

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

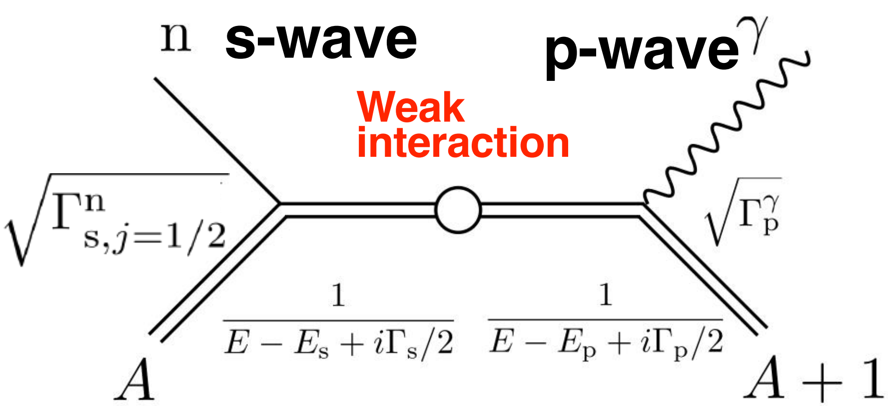
Unique phenomena occur in this regime which are not widely known

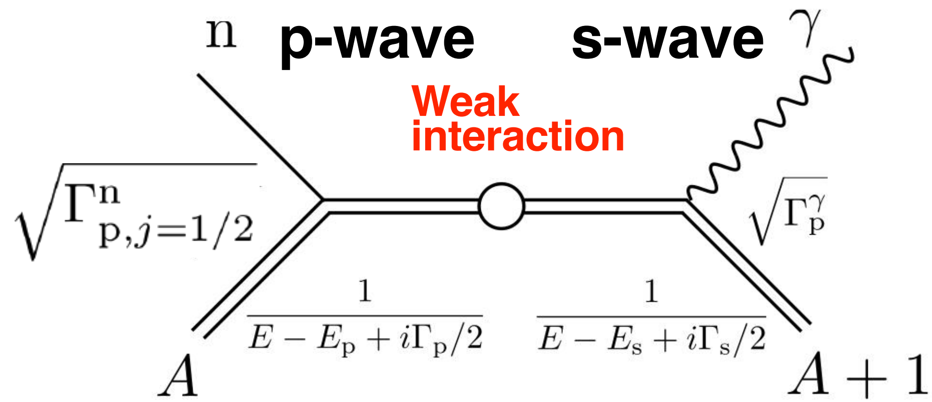
One such phenomenon is the large amplification of discrete symmetry breaking effects like P and T

D. Bowman

Enhancement of parity violation

This enhancement is caused by the mixture of j=1/2 component of s-wave and j=1/2 component of p-wave **→s-p mixing**





Theoretically, the enhancement is written as

$$\frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{\Delta\sigma_P}{2\sigma} = -\frac{2W}{E_p - E_s}\sqrt{\frac{\Gamma^n_s}{\Gamma^n_p}}\sqrt{\frac{\Gamma^n_{p,j=\frac{1}{2}}}{\Gamma^n_p}}$$

Dynamic Enhancement	Structural Enhancement	Partial neutron width j=1/2 component : x
10^2 - 10^3	~ 10^3	Unmeasured

Enhancement of T-violation

T-violation in fundamental interaction

T violation in a compound nucleus

$$\Delta\sigma_{\mathrm{T}} = \kappa(J)\frac{W_{\mathrm{T}}}{W}\Delta\sigma_{\mathrm{P}}$$

P violation in a compound nucleus

P-violation in fundamental interaction

Conversion factor from P-violation to T-violation

V. P. Gudkov. *Phys. Rep.*, 212:77, 1992.

Enhanced P-violation $\Delta\sigma_{\mathrm{P}}$ → Enhanced T-violation $\Delta\sigma_{\mathrm{T}}$

Large $\Delta\sigma_{\mathrm{P}}$ and κ(J) are better → Large T-violating cross section

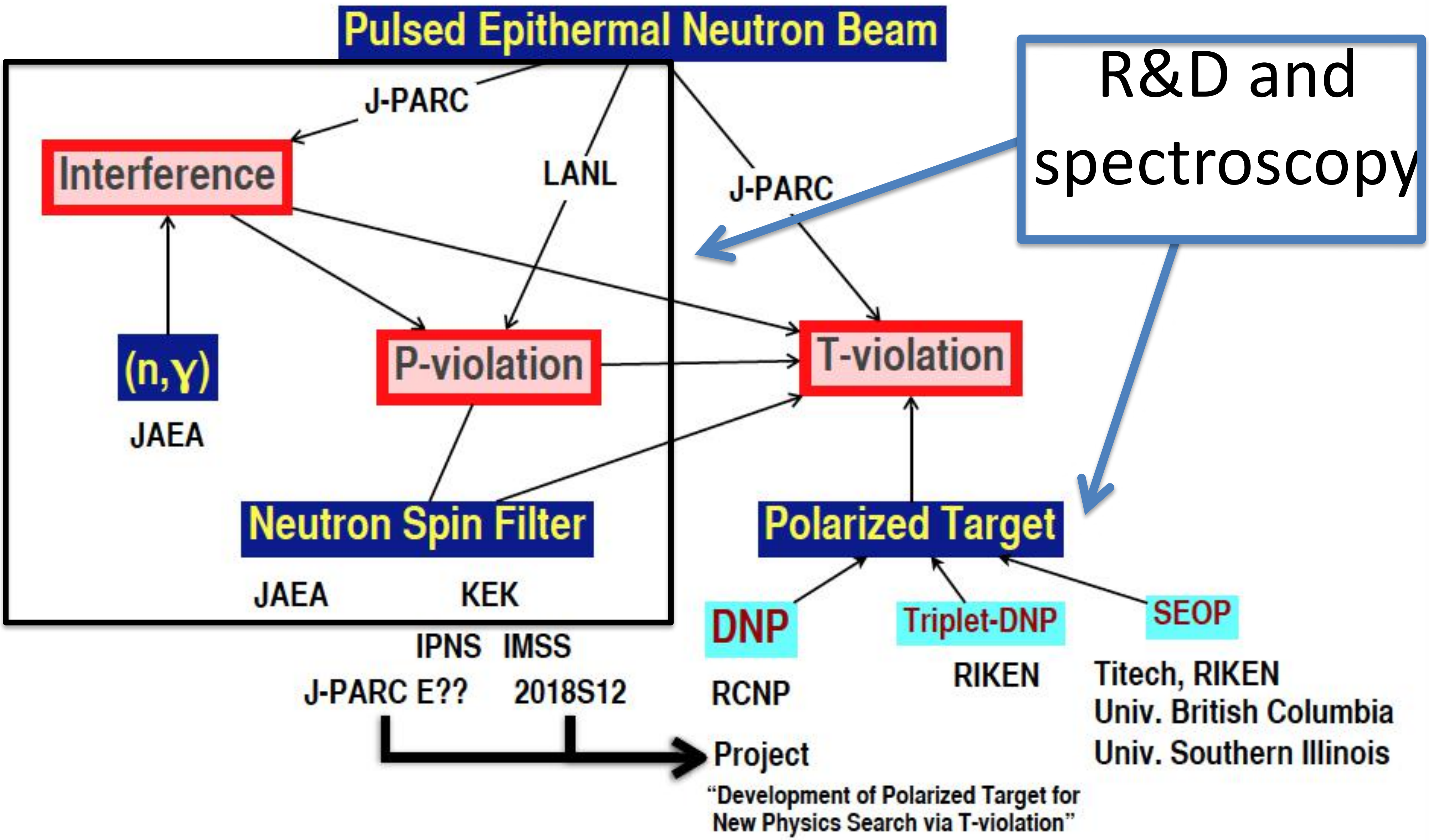
$$\kappa(J) = \begin{cases} (-1)^{2I}\left(1+\frac{1}{2}\sqrt{\frac{2I-1}{I+1}\frac{y}{x}}\right) & (J = I - \frac{1}{2}) \\ (-1)^{2I+1}\frac{I}{I+1}\left(1-\frac{1}{2}\sqrt{\frac{2I+3}{I}\frac{y}{x}}\right) & (J = I + \frac{1}{2}) \end{cases}$$

$$x^2 = \frac{\Gamma^{\mathrm{n}}_{\mathrm{p},j=\frac{1}{2}}}{\Gamma^{\mathrm{n}}_{\mathrm{p}}}, \quad y^2 = \frac{\Gamma^{\mathrm{n}}_{\mathrm{p},j=\frac{3}{2}}}{\Gamma^{\mathrm{n}}_{\mathrm{p}}}.$$

partial neutron width of p-wave resonance

κ(J) also depends on the partial neutron width

Map of Present NOPTREX Plan



P-odd/T-odd Reaction Theory

Optical Theorem allows us to relate the forward scattering amplitude to the total cross section

$$\sigma_{tot} = \frac{4\pi}{k}\mathrm{Im}[f(0)]$$

The forward scattering amplitude describes how initial and final states are connected by the weak interaction potential

$$f = \langle f|V_P + V_{PT}|i\rangle$$

v and w are our weak mixing matrix elements:

$$v + iw = \langle \phi_p|V_P + V_{PT}|\phi_s\rangle$$

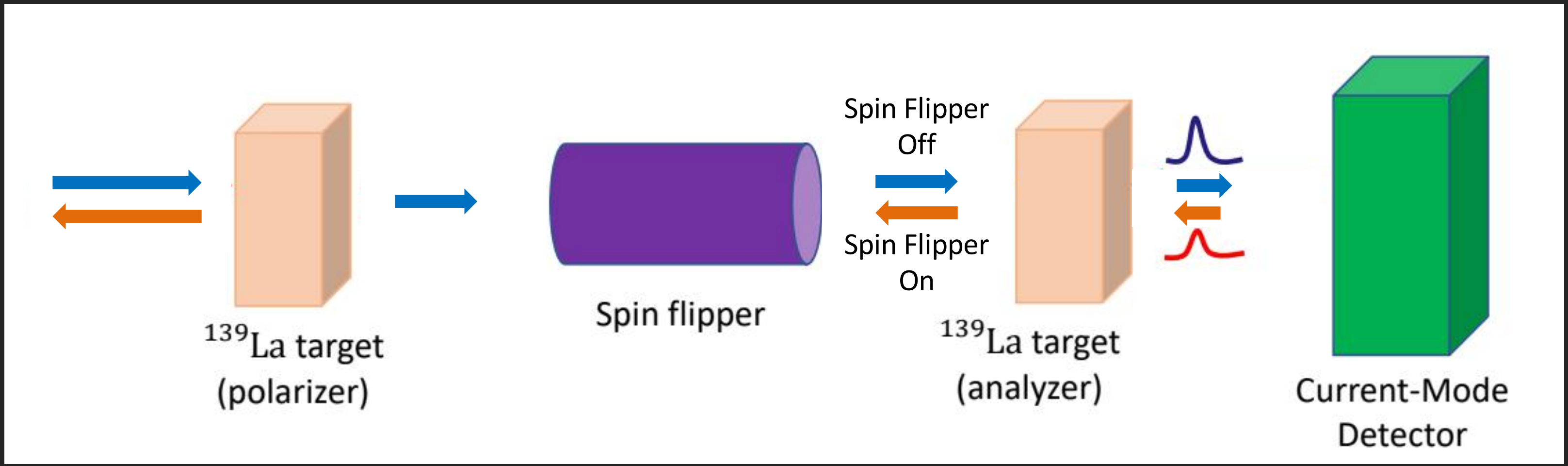
We can write:

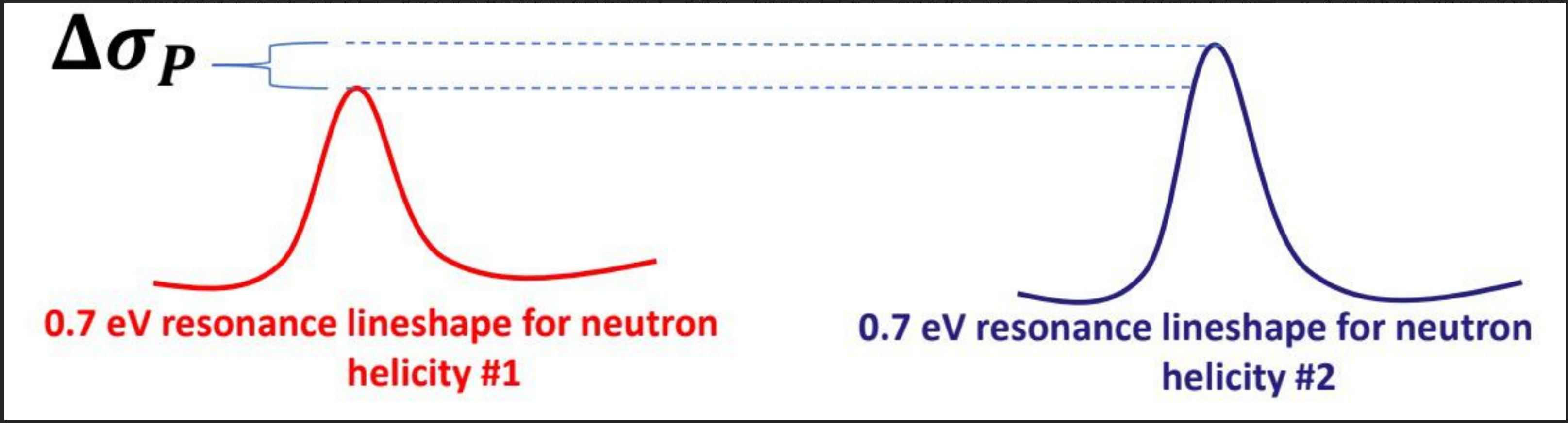
$$\Delta\sigma_{TP} = \kappa(J)\frac{w}{v}\Delta\sigma_P$$

Needed for NOPTREX nuclei to judge T violation sensitivity

See later talks

Double lanthanum experiment





P-odd/T-odd Reaction Theory

Optical theorem connects cross section difference to P-odd T-odd forward amplitude.

For mixing of one p-wave and one s-wave resonance (Gudkov, Physics Reports):

$$\Delta\sigma_{PT} = \frac{4\pi}{k}\,\mathrm{Im}(f_{\uparrow} - f_{\downarrow})$$

$$\Delta\sigma_{P} = \frac{4\pi}{k}\,\mathrm{Im}(f_{+} - f_{-})$$

$$f = \langle f \,|\, (V_P + V_{PT}) \,|\, i \rangle = \frac{(v + iw)\sqrt{\Gamma_p^n \Gamma_s^n}}{(E - E_s + \frac{i\Gamma_s}{2})(E - E_p + \frac{i\Gamma_p}{2})}$$

$$v + iw = \langle \phi_p \,|\, (V_P + V_{PT}) \,|\, \phi_s \rangle$$

Cross section ratio directly related to ratio of amplitudes between s and p resonances

$$\frac{\Delta\sigma_{PT}}{\Delta\sigma_{P}} = \kappa(J)\frac{w}{v}$$