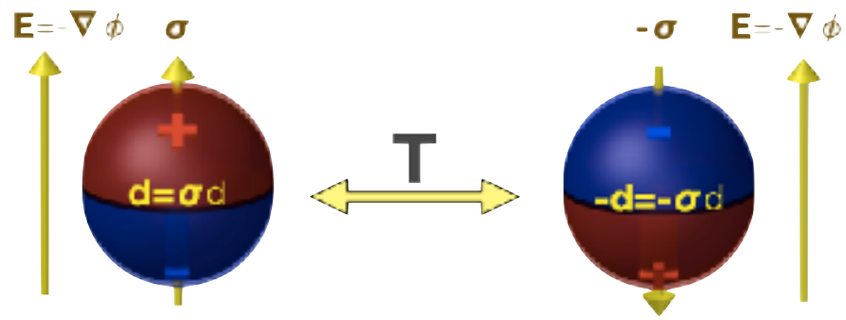
Search for T-violation using polarized neutron beam and polarized target : NOPTREX (J-PARC E99)

Takuya Okudaira (Phi lab, Nagoya Univ.)
On behalf of NOPTREX collaboration

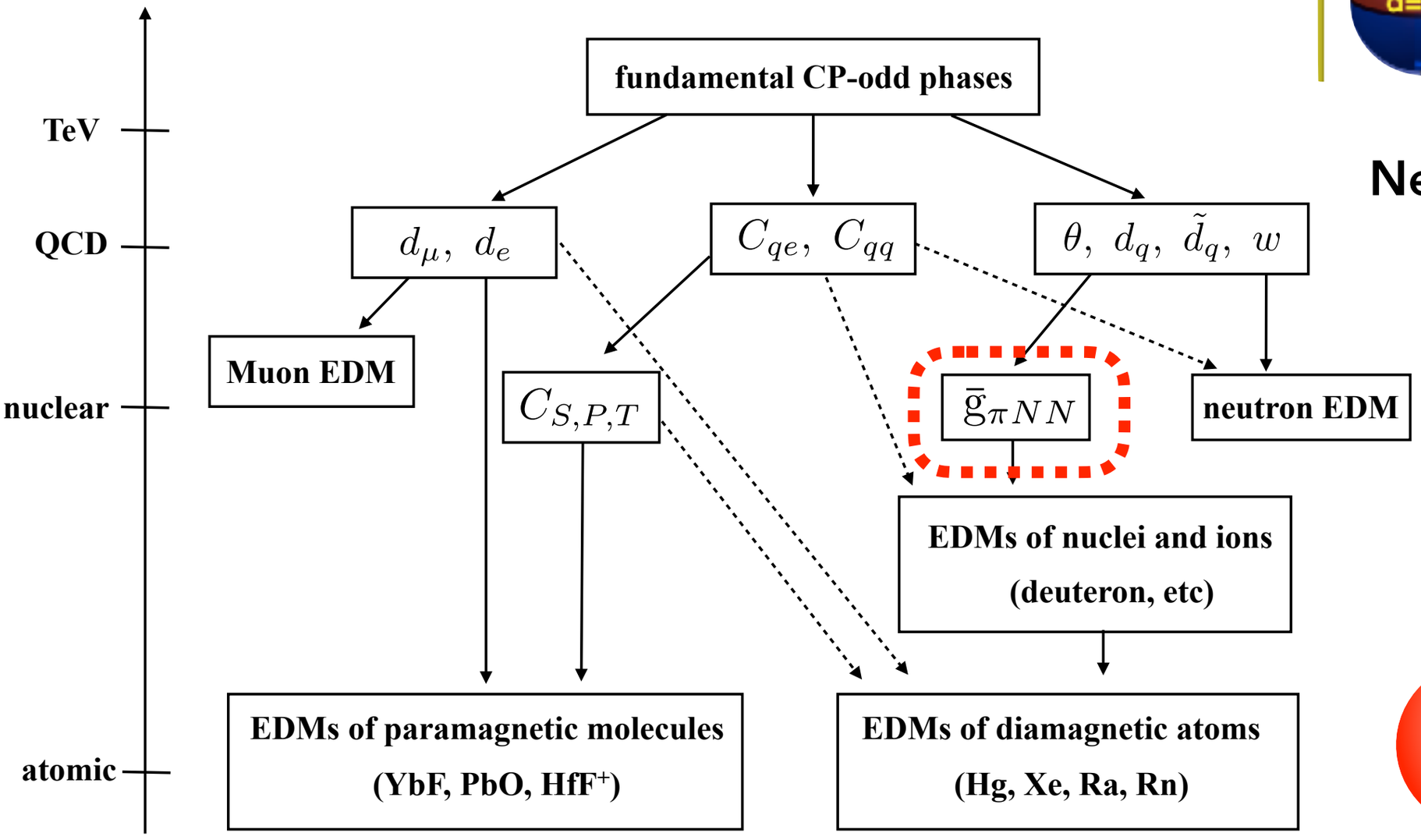
KMI symposium 2025

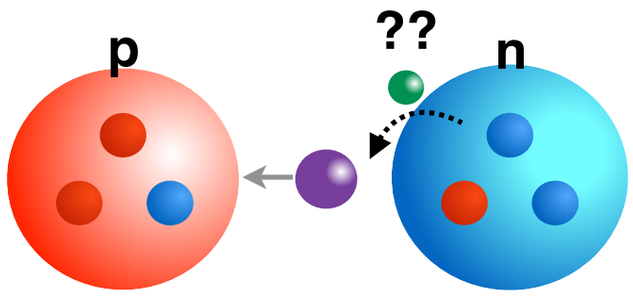
NOPTREX : J-PARC E99 experiment

T-violation search in nucleon interaction

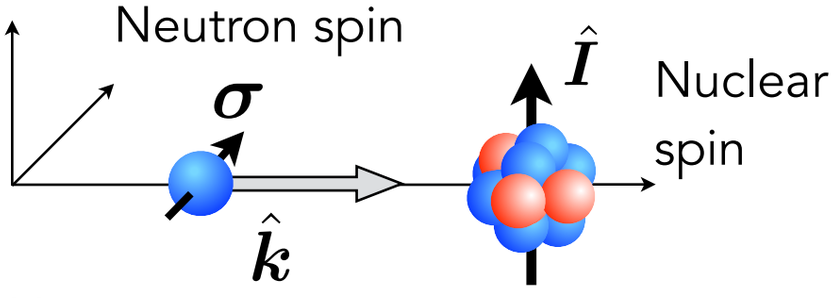


Neutron Electric dipole memoment(EDM)





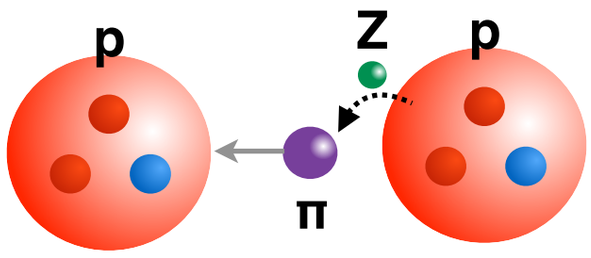
Pion Exchange



NOPTREX

Neutron Optical Parity and Time-Reversal EXperiment

Parity violating effect in nucleon-nucleon system



Weak interaction in nucleon-nucleon interaction

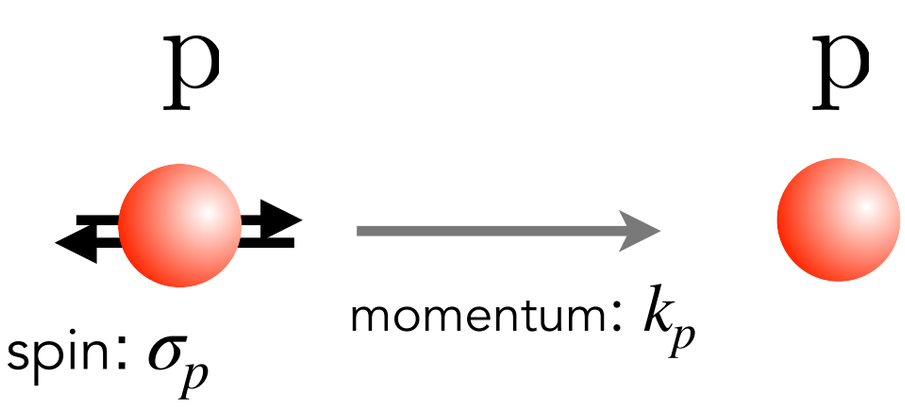
→ Extracts weak interaction via P-odd observable

Strong interaction : Parity conserving
Weak interaction : Parity violating

e.g. Helicity dependence of cross section

Scattering experiment between polarized proton beam and unpolarized protons

$$\sigma_p \cdot k_p \xrightarrow{x \to -x} -\sigma_p \cdot k_p$$



Asymmetry of cross section depending on spin direction

-(1.7±0.8)×10^{-7}

$$A_{\mathrm{L}} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

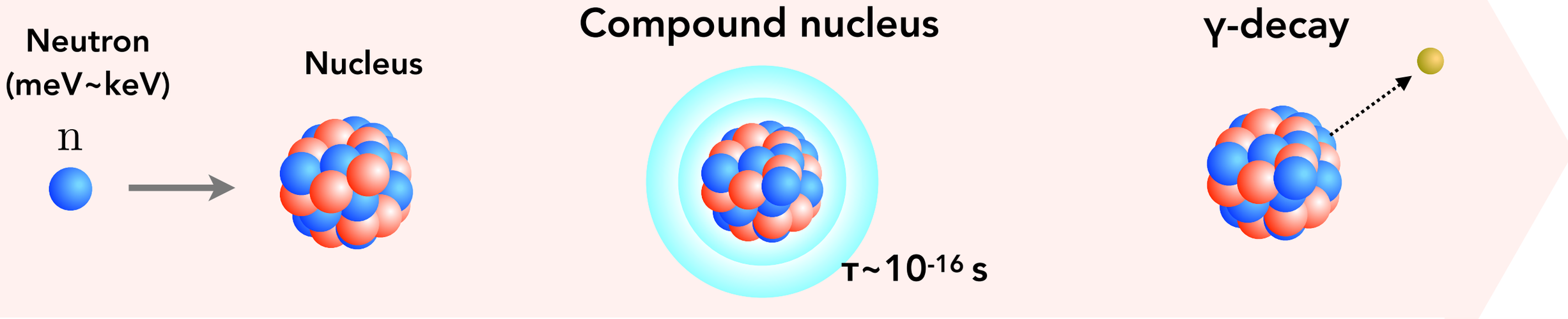
Phys. Rev. Lett 33:1307, (1974)

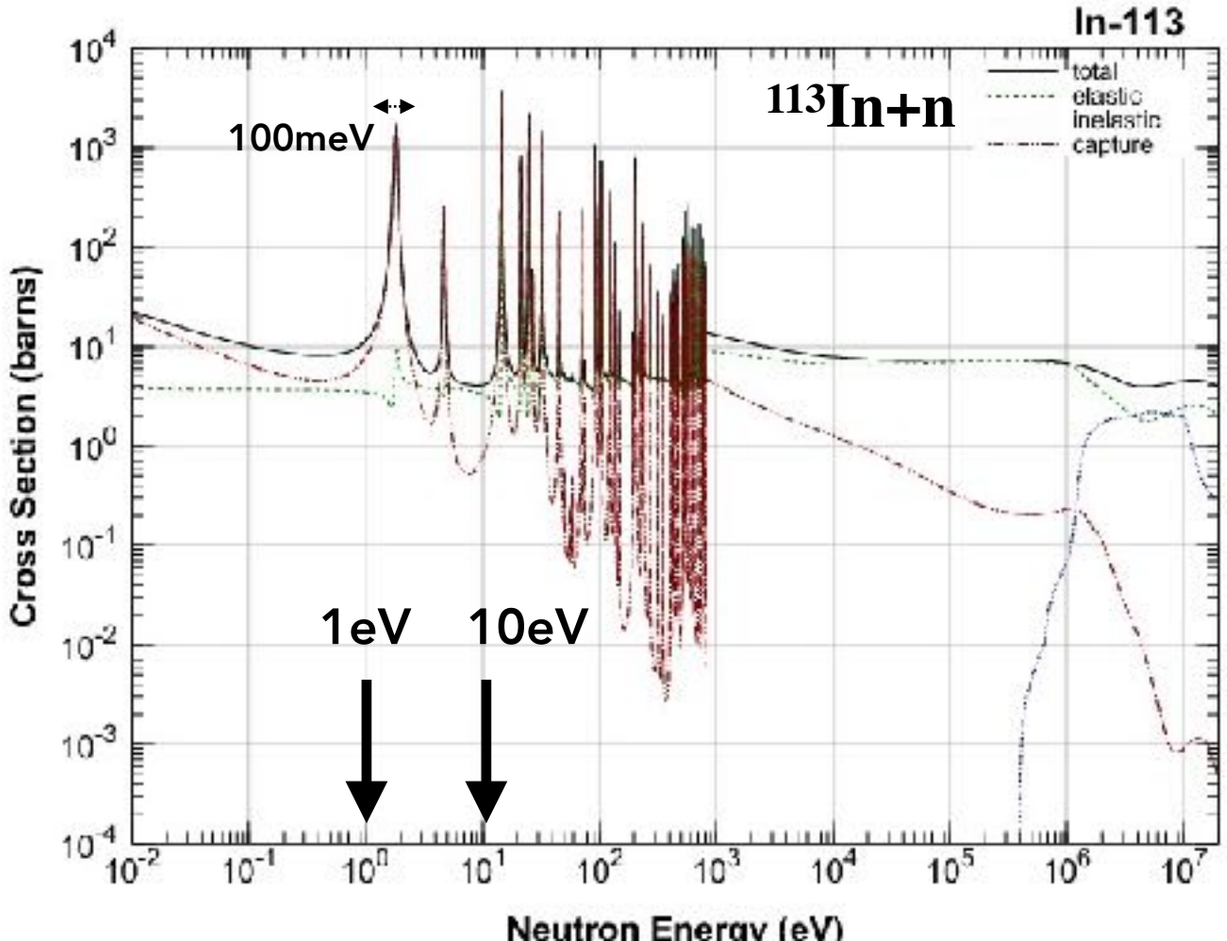
$$A_{\mathrm{L}} \simeq \frac{V_{\mathrm{weak}}}{V_{\mathrm{strong}}} \simeq G_{\mathrm{F}} m_\pi^2 \simeq 10^{-7}$$

Very small effect of weak interaction

Neutron induced compound nuclei

Excited state formed after neutron capture with nucleus : Compound nucleus



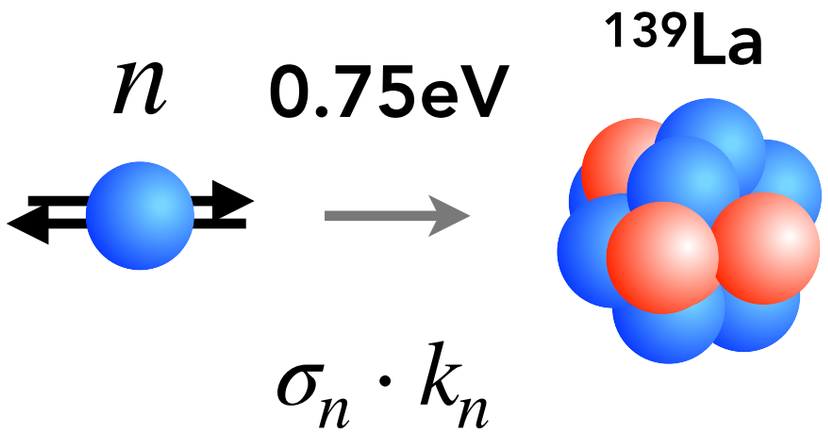


Narrow resonance width : 100meV

High level density :10~100eV

Parity violating effect in neutron-nucleus system

Scattering between polarized neutron beam and unpolarized nuclei



helicity dependence in absorption cross section

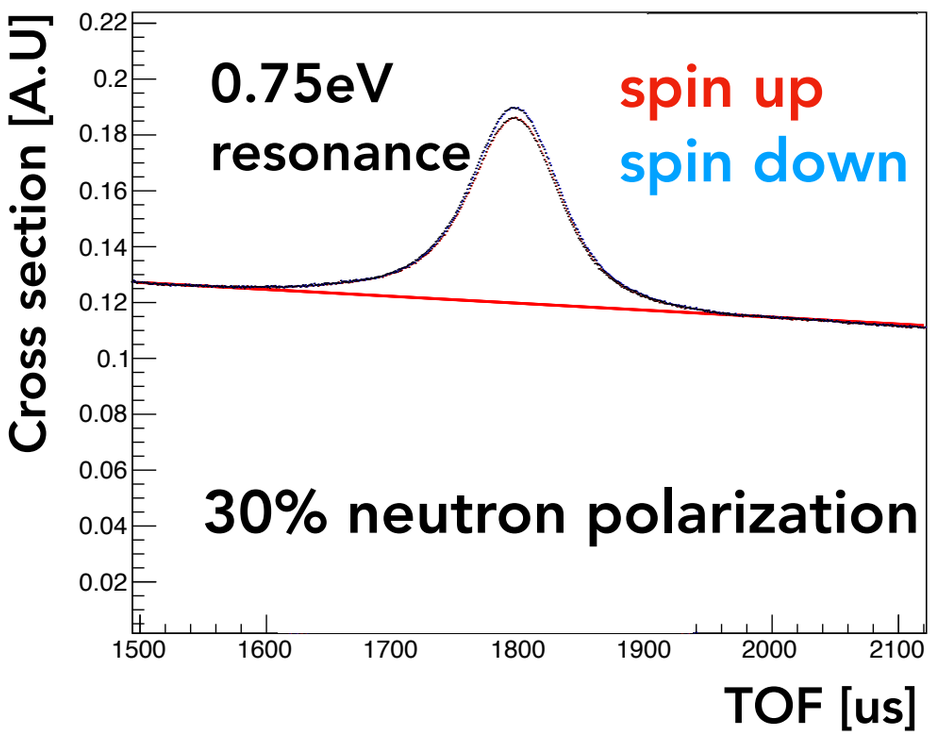
(0.97±0.03)x10^{-1} @E$_n$=0.75eV

$$A_{\mathrm{L}} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

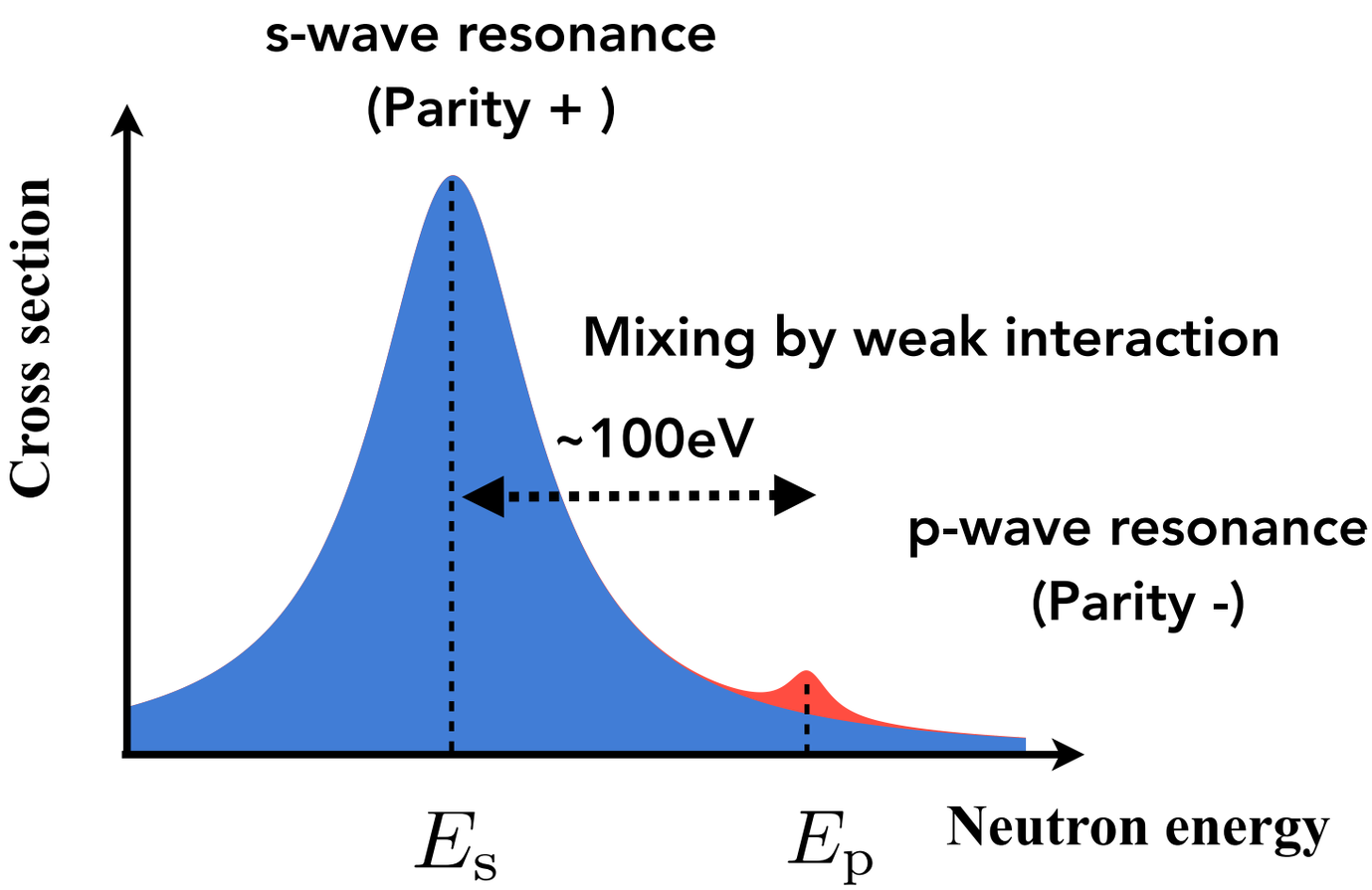
pp scattering :-(1.7±0.8)×10^{-7}

10^6 times larger P-violating effect
→ P-violating effect is largely enhance
in neutron absorption reaction
^{131}Xe, ^{117}Sn, ^{81}Br...

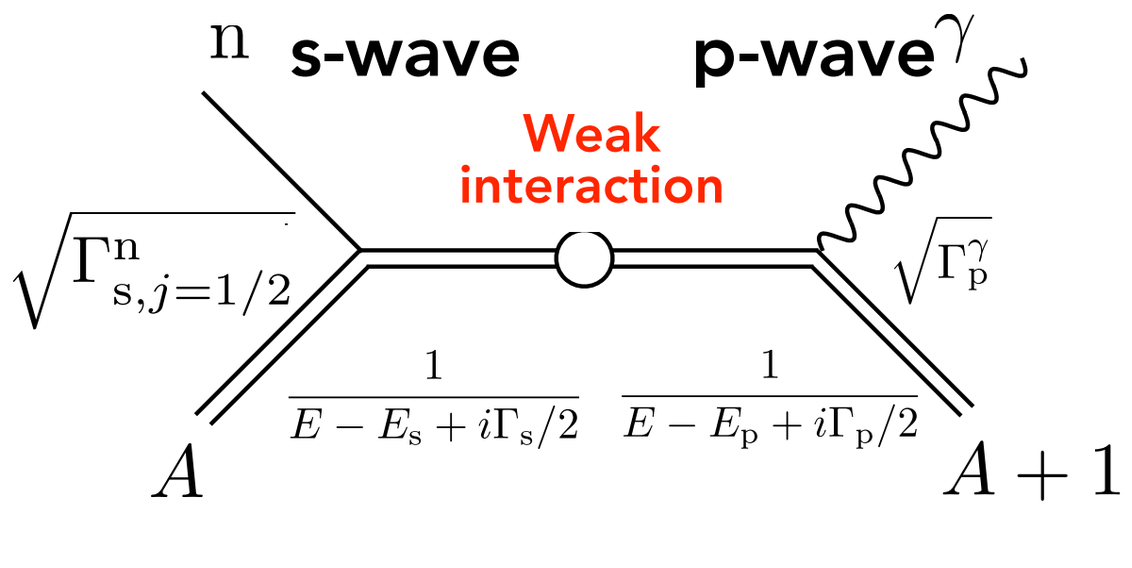
Compound nuclei is good amplifier for weak interaction



Enhancement of parity violation



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



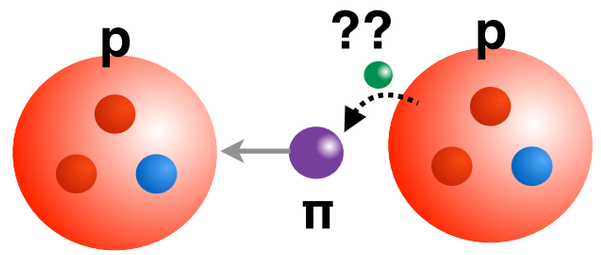
Weak matrix element

$$\frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{\Delta\sigma_{\mathrm{P}}}{2\sigma_p} = -\frac{2W}{E_{\mathrm{p}} - E_{\mathrm{s}}}\sqrt{\frac{\Gamma^{\mathrm{n}}_{\mathrm{s}}}{\Gamma^{\mathrm{n}}_{\mathrm{p}}}}\sqrt{\frac{\Gamma^{\mathrm{n}}_{\mathrm{p},j=\frac{1}{2}}}{\Gamma^{\mathrm{n}}_{\mathrm{p}}}}$$

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

Enhancement of T-violation

Compound nucleus is a good amplifier for weak interaction



If T-violating interaction exists….

T-violating effect can be largely enhanced as well as weak interaction

Size of T-violation in nucleon-nucleon interaction

T-violating cross section in neutron-nucleus

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

P-violating cross section in neutron-nucleus

Conversion factor from P-violation to T-violation
(Unknown: determined with (n,γ))

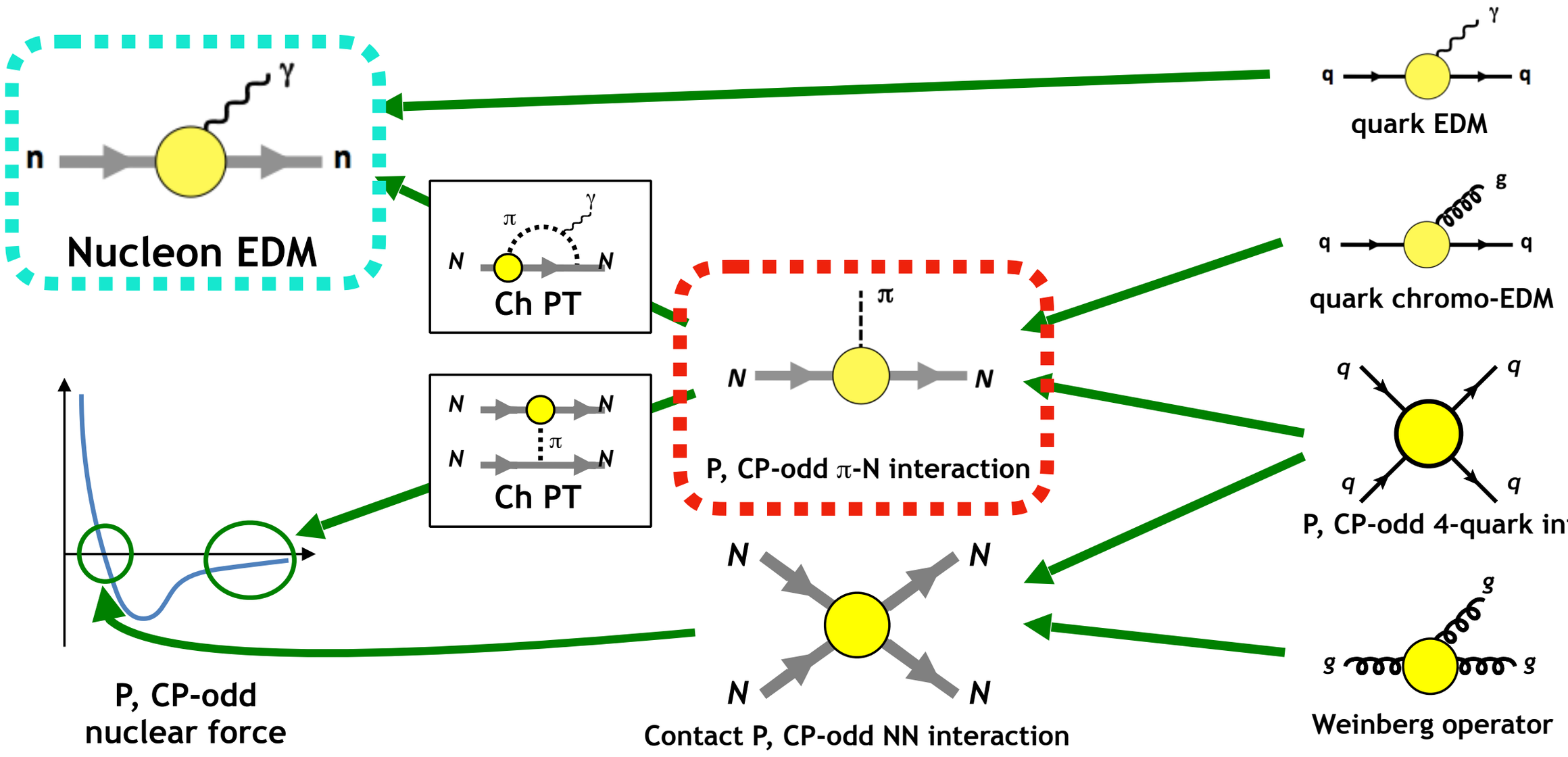
Size of P-violation in nucleon-nucleon interaction

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

Compound nuclei can also be a good amplifier for unknown interaction!

T-violating coupling

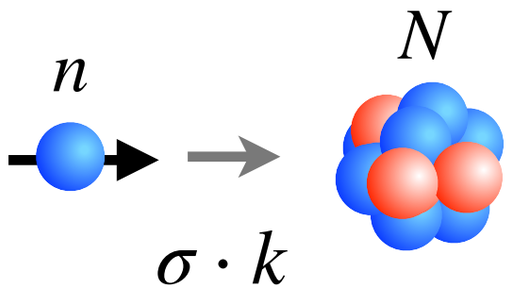
NOPTREX is sensitive for the T-odd pion coupling because we use the scattering process, not EDM



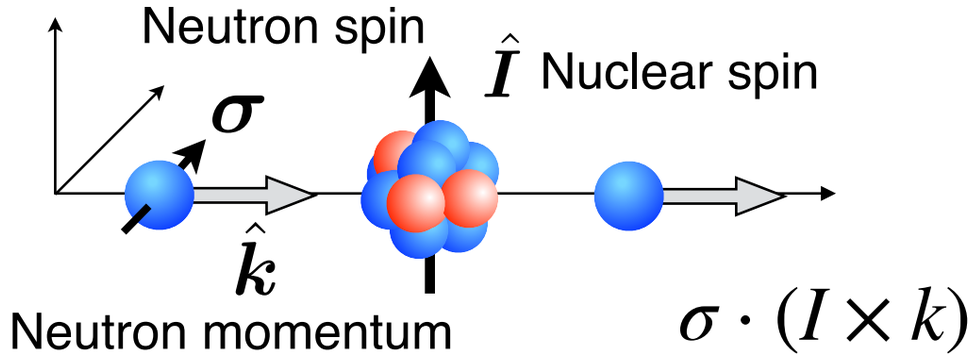
Dr. Nodoka Yamanaka's slide

How to search for T-violation

P-odd observable



T-odd observable



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

Spin independent cross section

Spin dependence (Strong interaction)

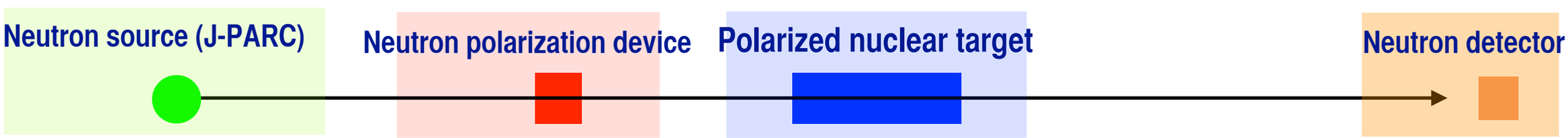
P-violation (Weak interaction)

T-violating cross section (Unknown interaction)

$t \rightarrow -t$

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

Reproduce T-transformation by controlling neutrons spin



~1eV Neutrons, Neutron polarization device, Polarized target

Plan for T-violation search

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

→Enhancement of T-violating effect in ^{139}La 0.75eV resonance : 6 x 10^5 times

T. Okudaira *et. al.* , Phys. Rev. C. 97 034622 (2018)
T. Yamamoto *et al.* Phys. Rev. C. 101, 064624 (2020)
T. Okudaira *et. al.* , Phys. Rev. C. 104, 014601(2021)
M. Okuizumi *et al.* Phys. Rev. C. accepted (2025)

^{139}La

J. Koga *et. al.*, Phys. Rev. C. **105**, 05461 (2022)
S. Endo *et al.*, Phys. Rev. C.106 064601 (2022)
T.Okudaira et al. Phys. Rev. C **107**, 054602 (2023)

^{117}Sn
^{131}Xe

2.Neutron polarization device

→^{3}He spin filter for ~0.75eV

40% neutron 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)
K. Ishizaki *et al.*, Rev. Sci. Instrum. 95, 063301 (2024)

4. Neutron detector

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

U.S. NOPTREX
RCNP

5. Neutron transmission experiment using polarized neutron beam and polarized target

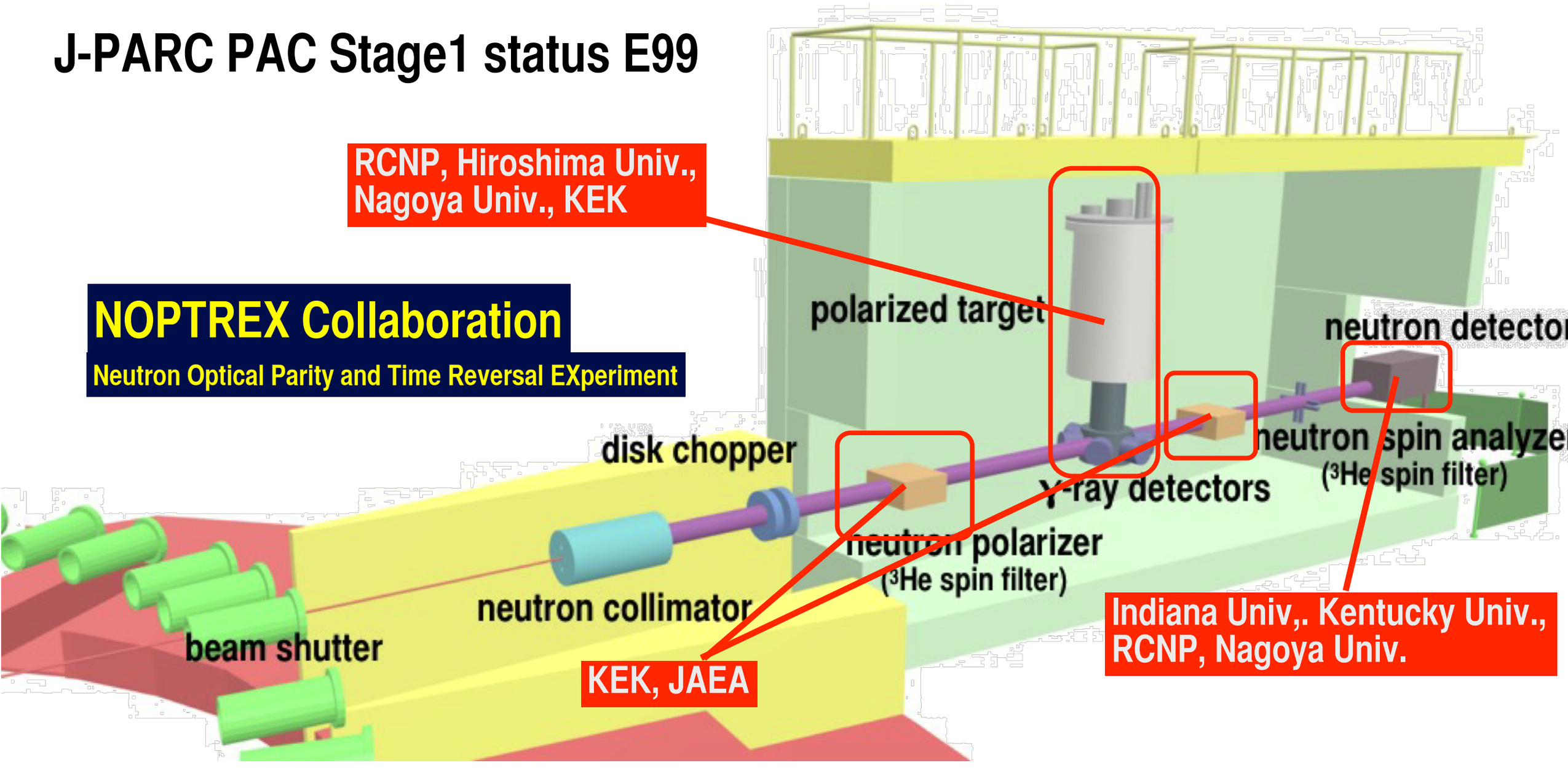
T. Okudaira *et al.*, Phys. Rev. C., 109, (2024) 044606
R. Nakabe *et al.*, Phys. Rev. C. (2024) L041602

Experimental setup of T-violation search at J-PARC

J-PARC PAC Stage1 status E99

NOPTREX Collaboration

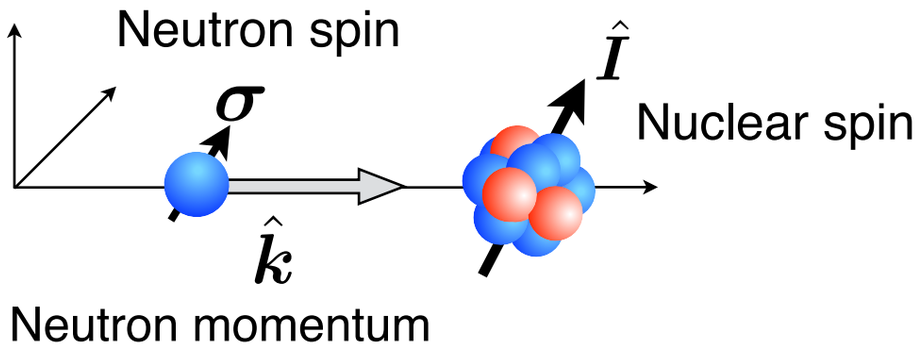
Neutron Optical Parity and Time Reversal EXperiment



Sensitivity corresponding to nEDM can be achieved by 1 month measurement with 70% neutron polarization and 40% ^{139}La polarization

Plan for T-violation search

● Phase 1 : T-violation search with low sensitivity

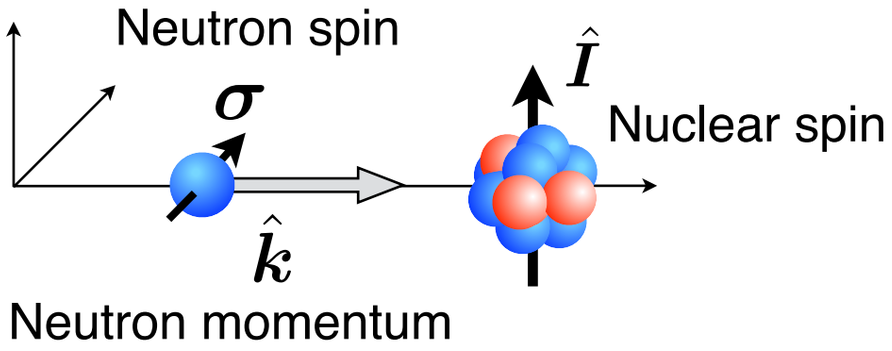


Neutron spin and nuclear spin : Parallel

- Existing beamline (BL04)
- 1x1x1cm^3 polarized target
- Easy neutron spin transport

→J-PARC Program Advisory Committee Stage1 status (2024)

● Phase 2 : T-violation search with high sensitivity



Neutron spin and nuclear spin : Perpendicular

※ With existing equipment, neutron spins rotate by applied magnetic fields

- Dedicated beam line
- 4x4x4cm^3 polarized target
- Intense neutron beam
- Difficult neutron spin transport

Recent updates (2024-2025)

- **Neutron transmission experiment using polarized ^{139}La and polarized neutrons**

T. Okudaira *et al*., Phys. Rev. C., 109, (2024) 044606

- **T-violation sensitivity of ^{139}La+n**
- **First T-violation limit in NOPTREX**

R. Nakabe *et al*., Phys. Rev. C. (2024) L041602

- **Development of neutron polarizer for the high neutron beam polarization**

S. Takahashi *et al*., NIMA. accepted (2025)

- **Development of Polarized La target**

K. Ishizaki *et al*., Rev. Sci. Instrum. 95, 063301 (2024)

→NOPTREX Phase-I experiment will be started from 2025

- **Study of enhancement mechanism**
  - γ-ray polarization measurement of (n,γ) reaction
  - Transverse asymmetry measurement of ^{139}La(n,γ)^{140}La* reaction

S. Endo *et. al*. Eur. Phys. J. A (2024) 60:166

M. Okuizumi *et al*. Phys. Rev. C. accepted (2025)

Experiment using polarized La and neutrons

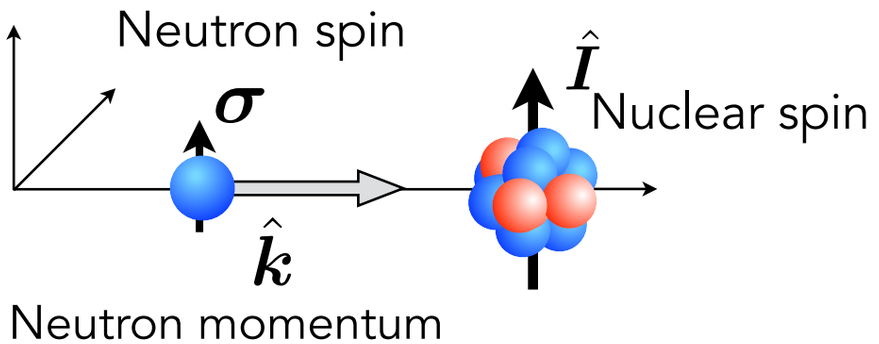
$$f = A' + B'\boldsymbol{\sigma}\cdot\hat{\boldsymbol{I}} + C'\boldsymbol{\sigma}\cdot\hat{\boldsymbol{k}} + D'\boldsymbol{\sigma}\cdot(\hat{\boldsymbol{I}}\times\hat{\boldsymbol{k}})$$

spin independent cross section

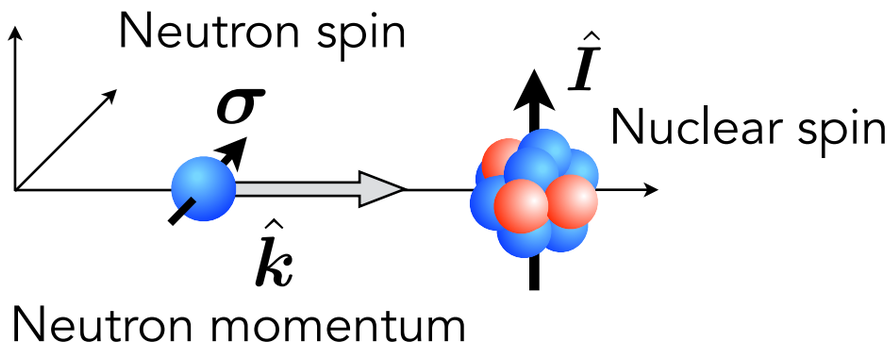
Spin dependence (strong interaction)

P-violation (Weak interaction)

T-violation (Unknown interaction)

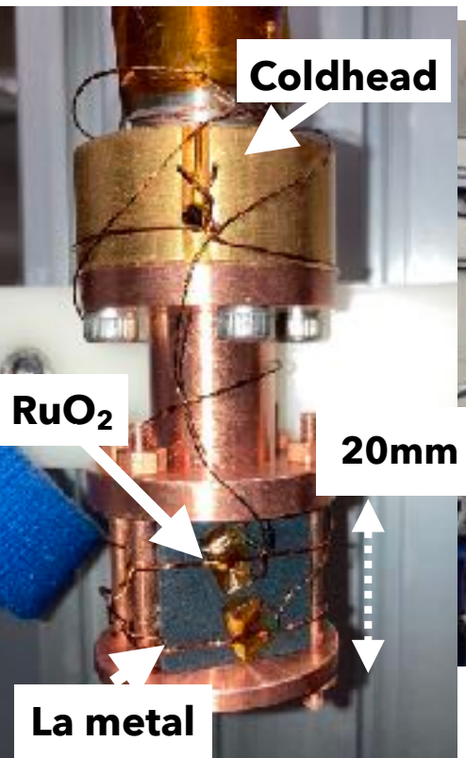


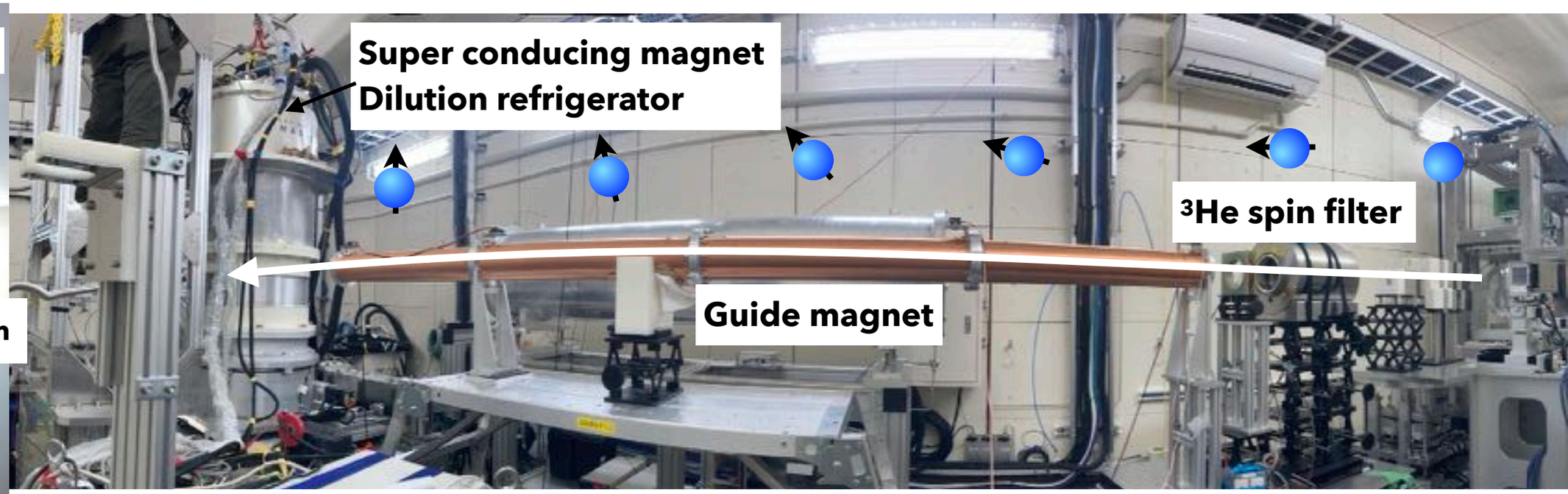
Neutron spin and nuclear spin : Parallel



Neutron spin and nuclear spin : Perpendicular

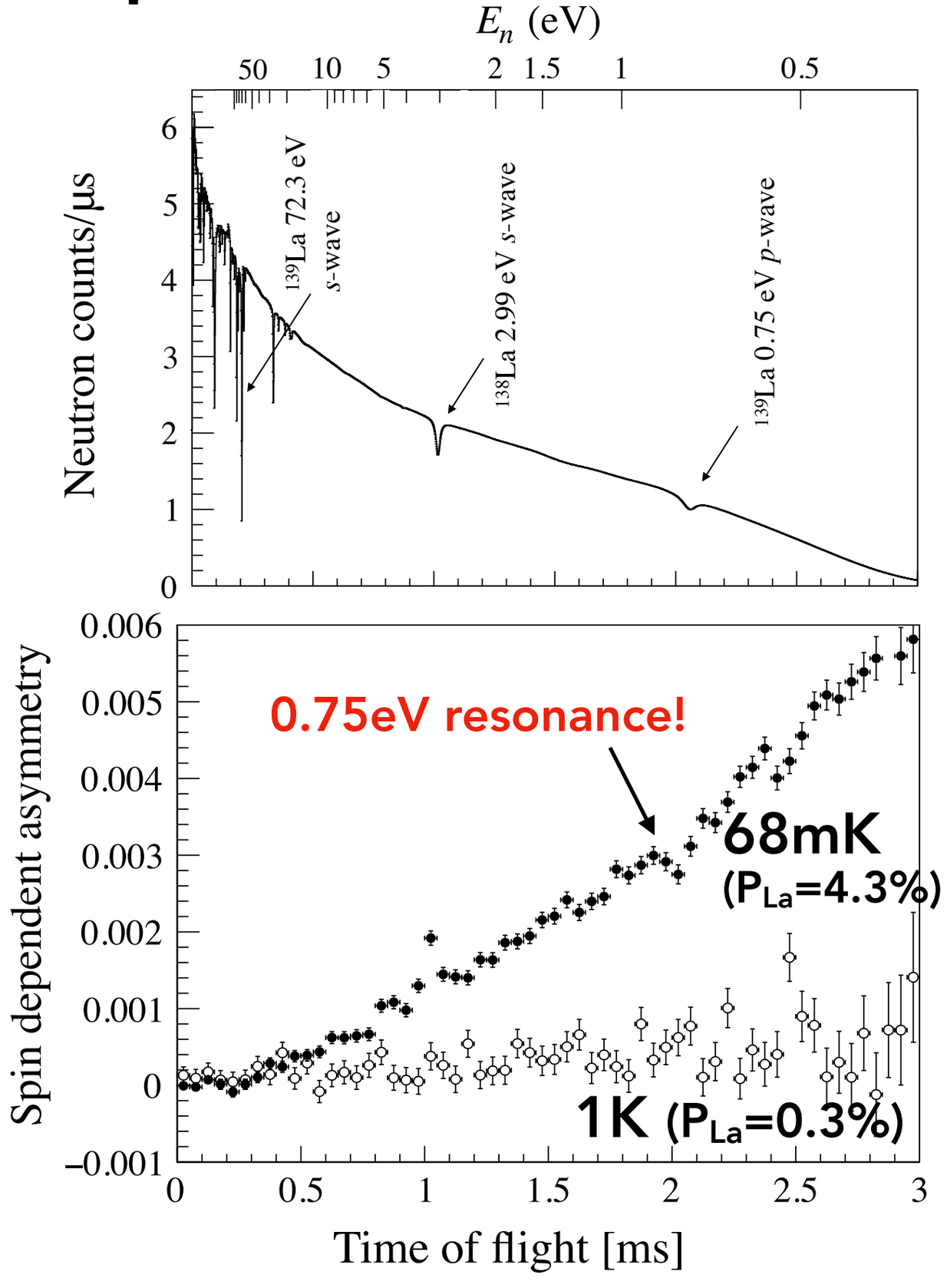
※ With existing equipment, neutron spins rotate by applied magnetic fields

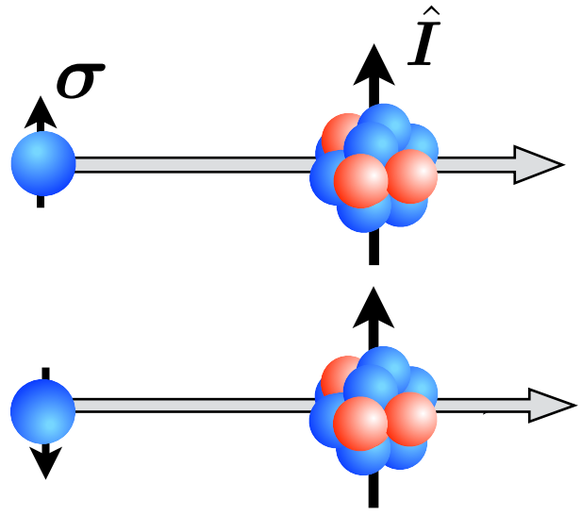




68mK, 68T→4% nuclear polarization

Experiment using polarized La and neutrons





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

Spin dependent cross section was observed!

Small spin dependence (0.1~0.01%) can be extracted!

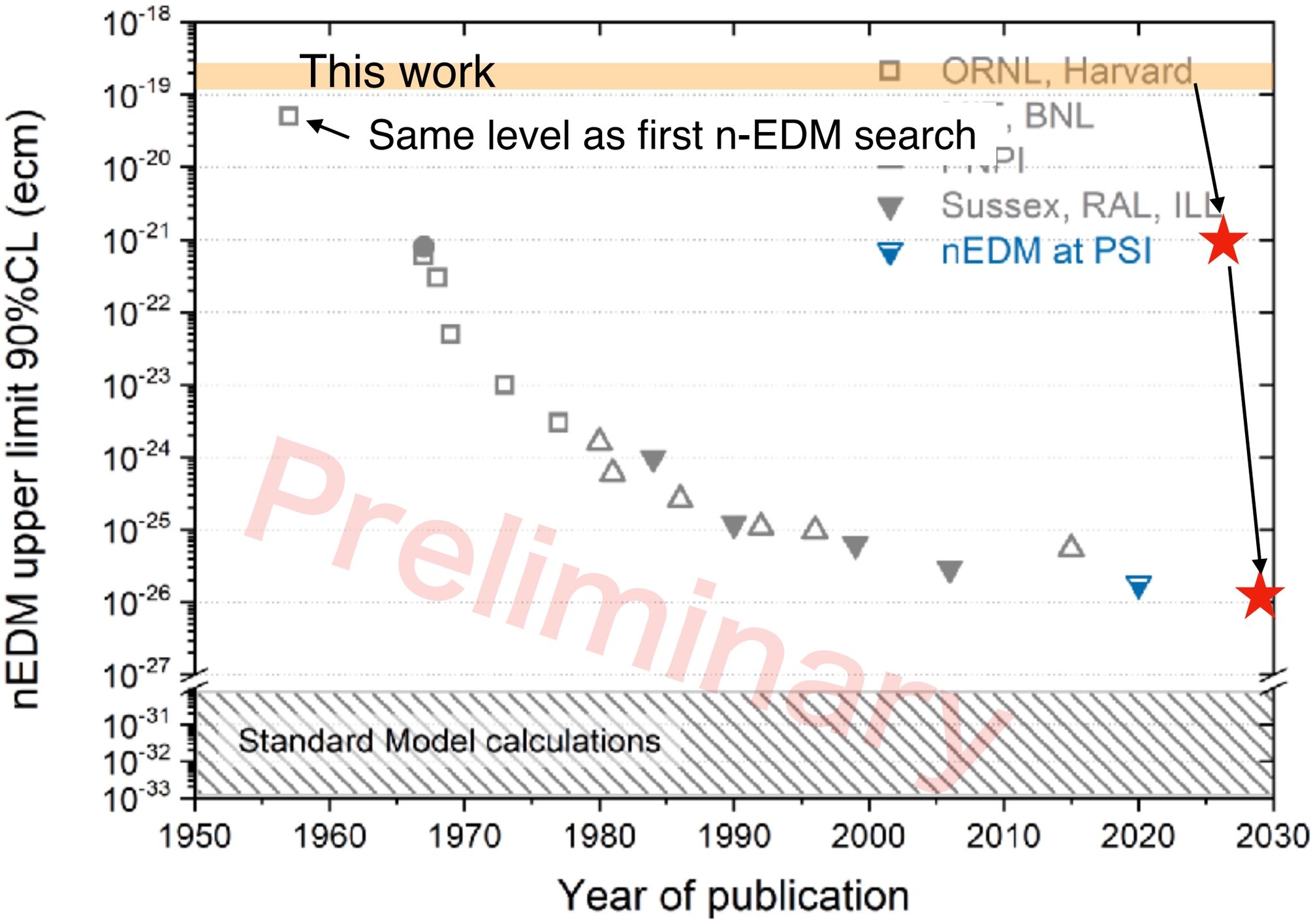
T. Okudaira *et al.*, Phys. Rev. C., 109, (2024) 044606

R. Nakabe *et al.*, Phys. Rev. C. (2024) L041602
Editor's suggestion

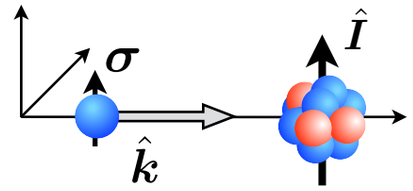
→Partial neutron width was determined
Big milestone for T-violation

R. Nakabe Ph.D thesis (2024)
Nagoya Univ.→JAEA

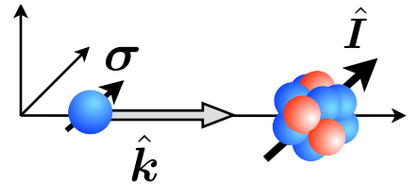
First limit of T-violation using compound nuclei



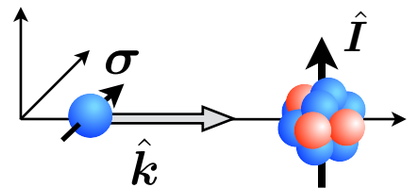
1day measurement



Phase-I experiment
1week measurement



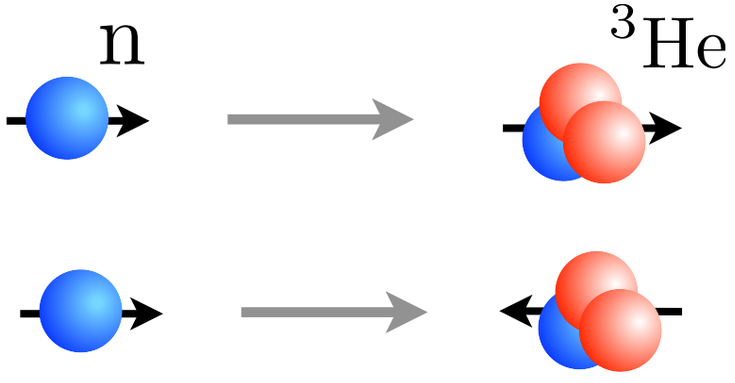
Phase-II experiment
1month measurement



We have a bright future!

Neutron polarizer : ^{3}He Spin Filter

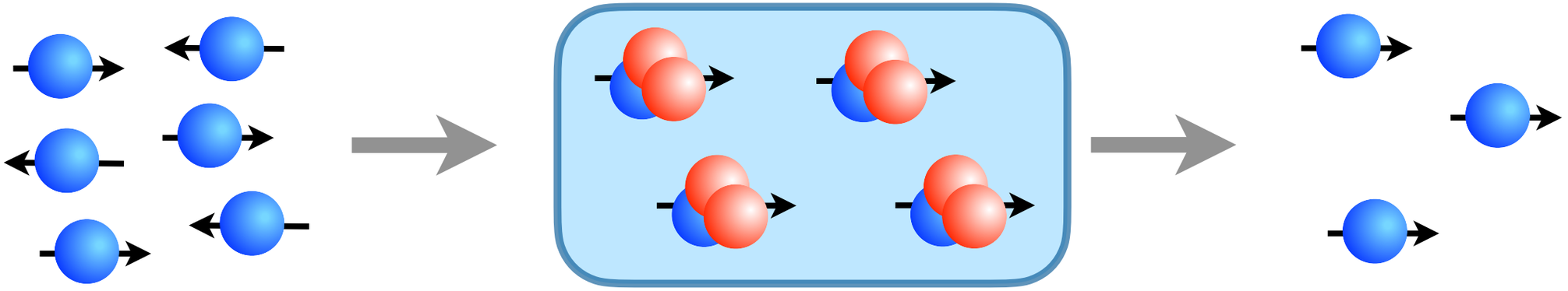
K. Asai, M. Okuizumi
Nagoya Univ.



~0 barn

10666 barn

Large absorption cross section depending on spin direction

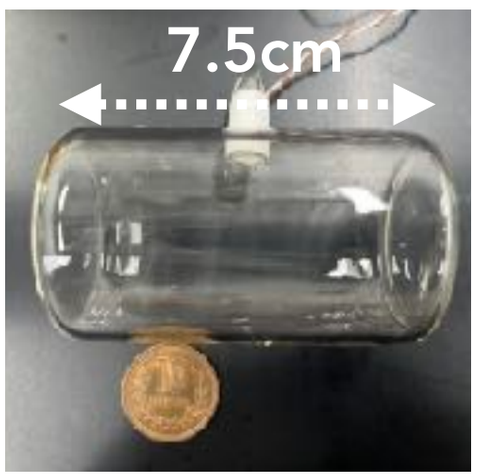


Unpolarized neutron

Polarized ^{3}He gas

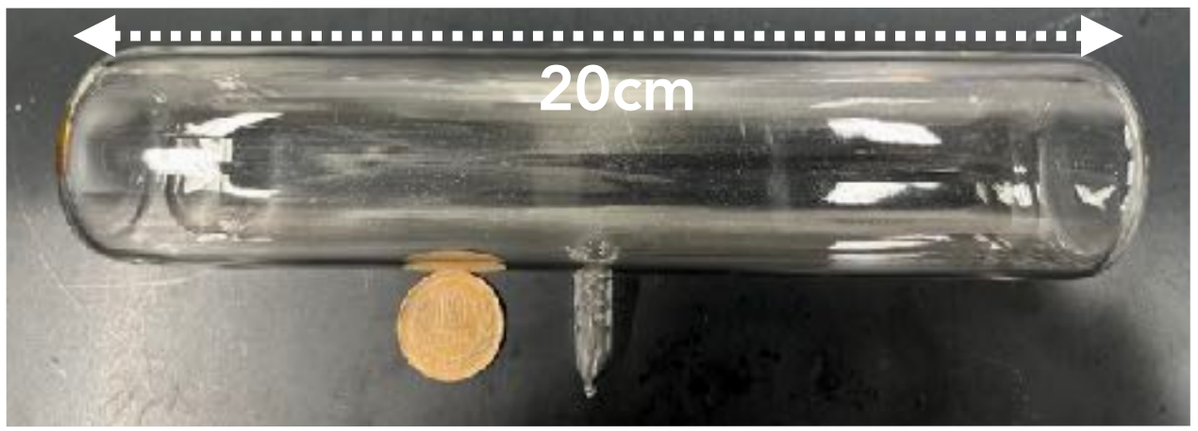
Polarized neutron

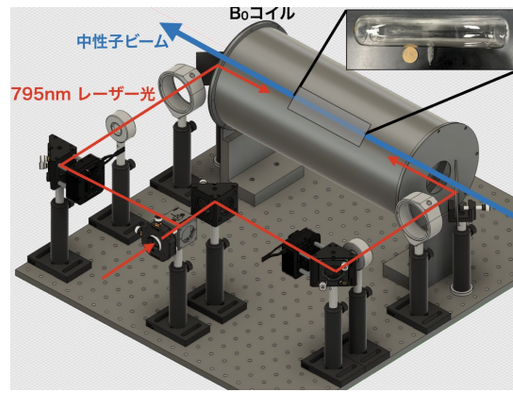
Neutron polarization 40%



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

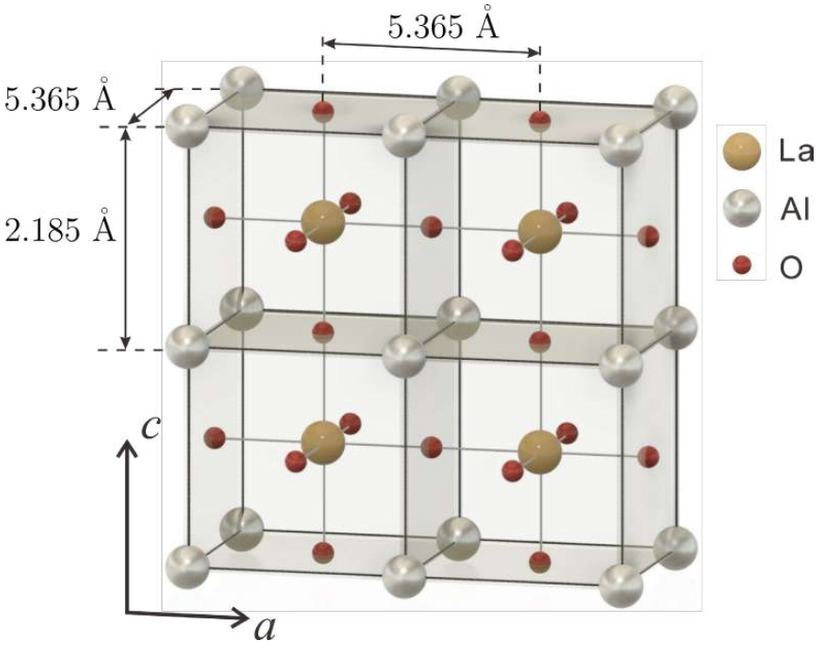
Neutron polarization 80% at 0.75eV





Will be installed on beamline with laser system in 2025

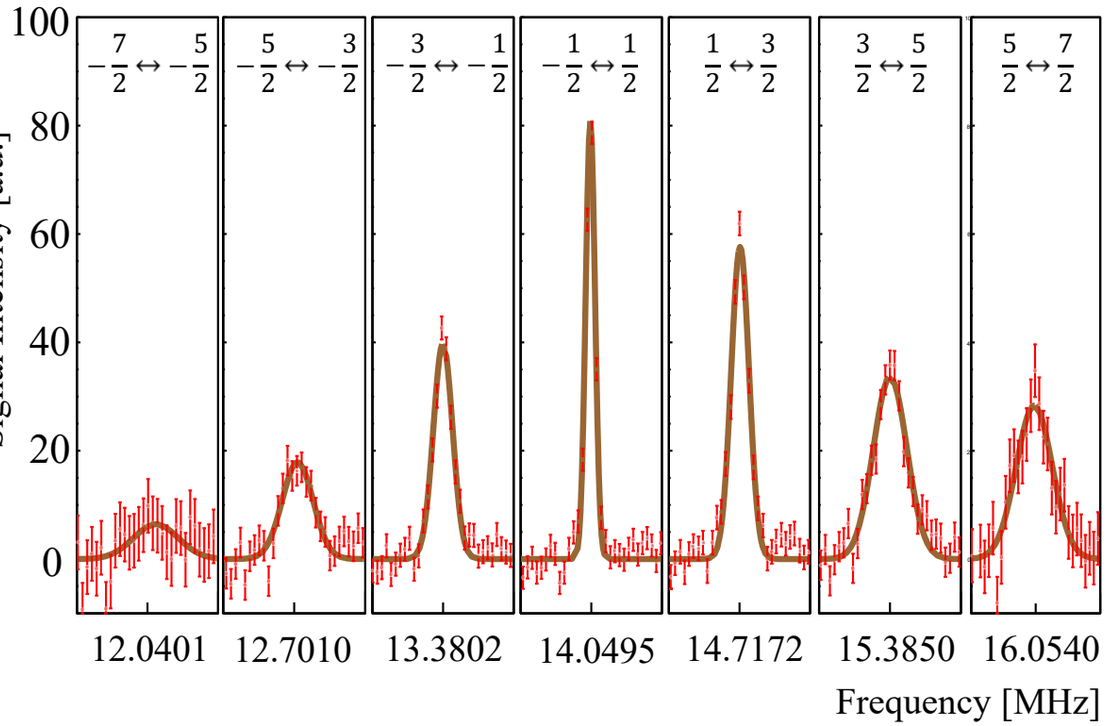
Polarized ^{139}La target



Polarization of nuclei with I>1 is very difficult
Electric quarto moment is coupled with electric field

Dynamic nuclear polarization using Perovskite crystal

Nd^{3+} $LaAlO_3$ single crystal target grown at Tohoku Univ.



1.3K, 2.3T, Microwave irradiation at Yamagata Univ.

Achievable ^{139}La polarization :
$P(t \to \infty) \sim 30\ \%$

I.Ide, Nagoya Univ.
Ph.D student

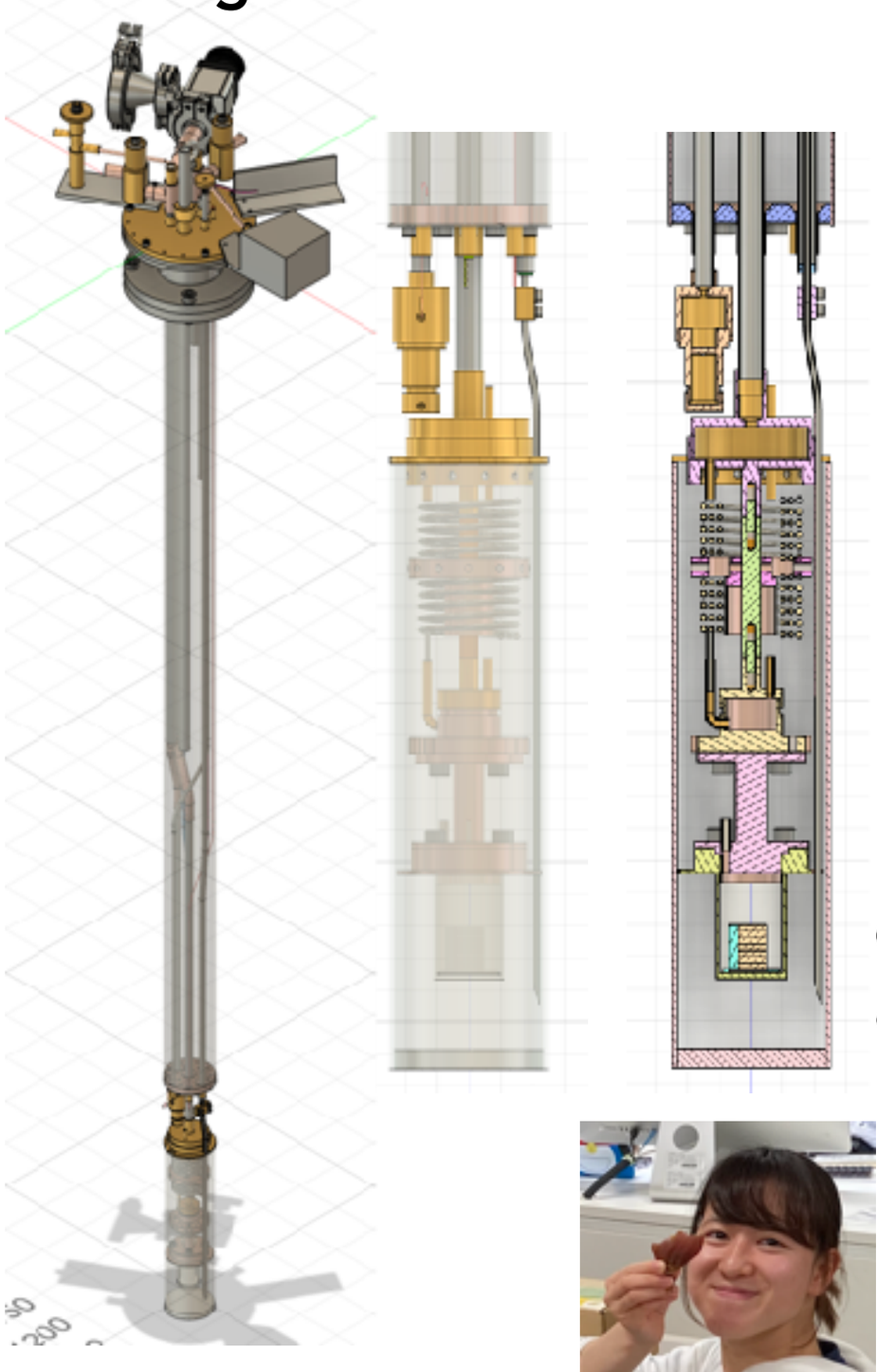
K. Ishizaki *et al*., Rev. Sci. Instrum. 95, 063301 (2024),
K. Ishizaki *et al*., NIM A1020, 165845 (2021)

Refrigerator development for polarized ^{139}La target

$LaAlO_3$ crystal will be installed on beamline under ~1K and 2T condition

Dilution refrigerator is now constructing for Phase-I T-violation search experiment

4T superconducting maget



Collaboration with I-lab of Nagoya Univ.

S. Kawamura &
M.Okuizumi
Nagoya Univ.
Ph.D student

Summary

- Search for T-violating effect using polarized neutrons and polarized ^{139}La

- Polarized neutron transmission experiment : NOPTREX phase1 at BL04 ANNRI beamline(from 2025)