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

Takuya Okudaira (Phi lab, Nagoya Univ.)

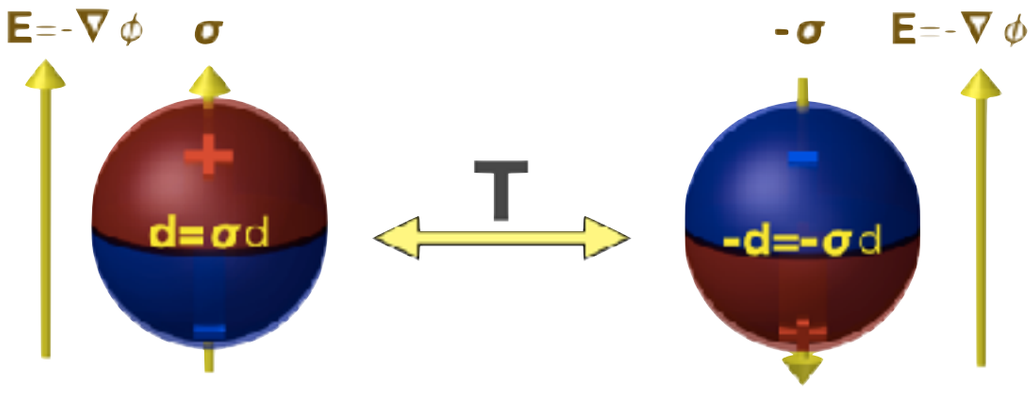
On behalf of NOPTREX collaboration

SSP2025

NOPTREX

Neutron Optical Parity and Time-Reversal EXperiment

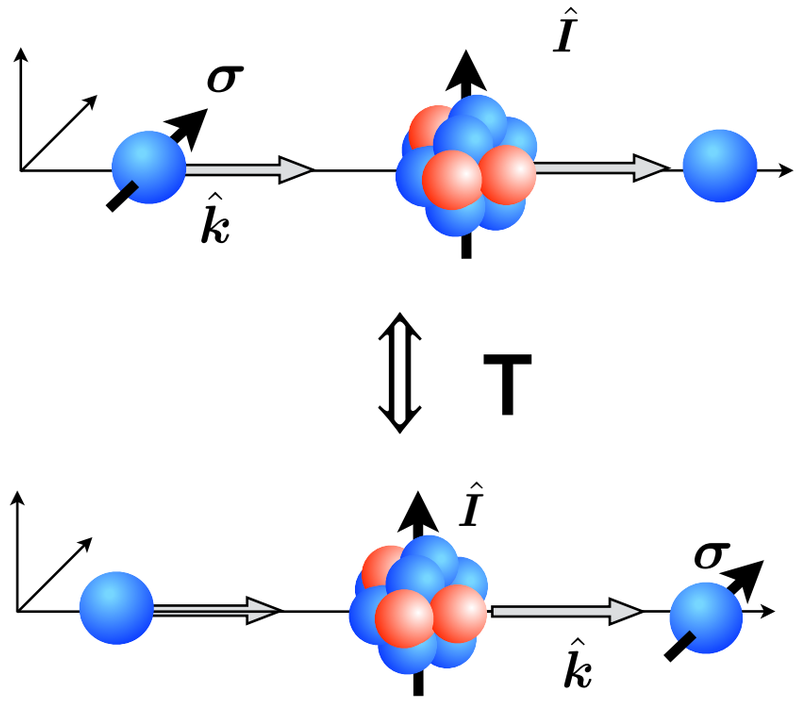
T-violation search in hadronic system using neutrons



n-EDM

T-violation of neutron

Ultra cold neutron(~100neV)



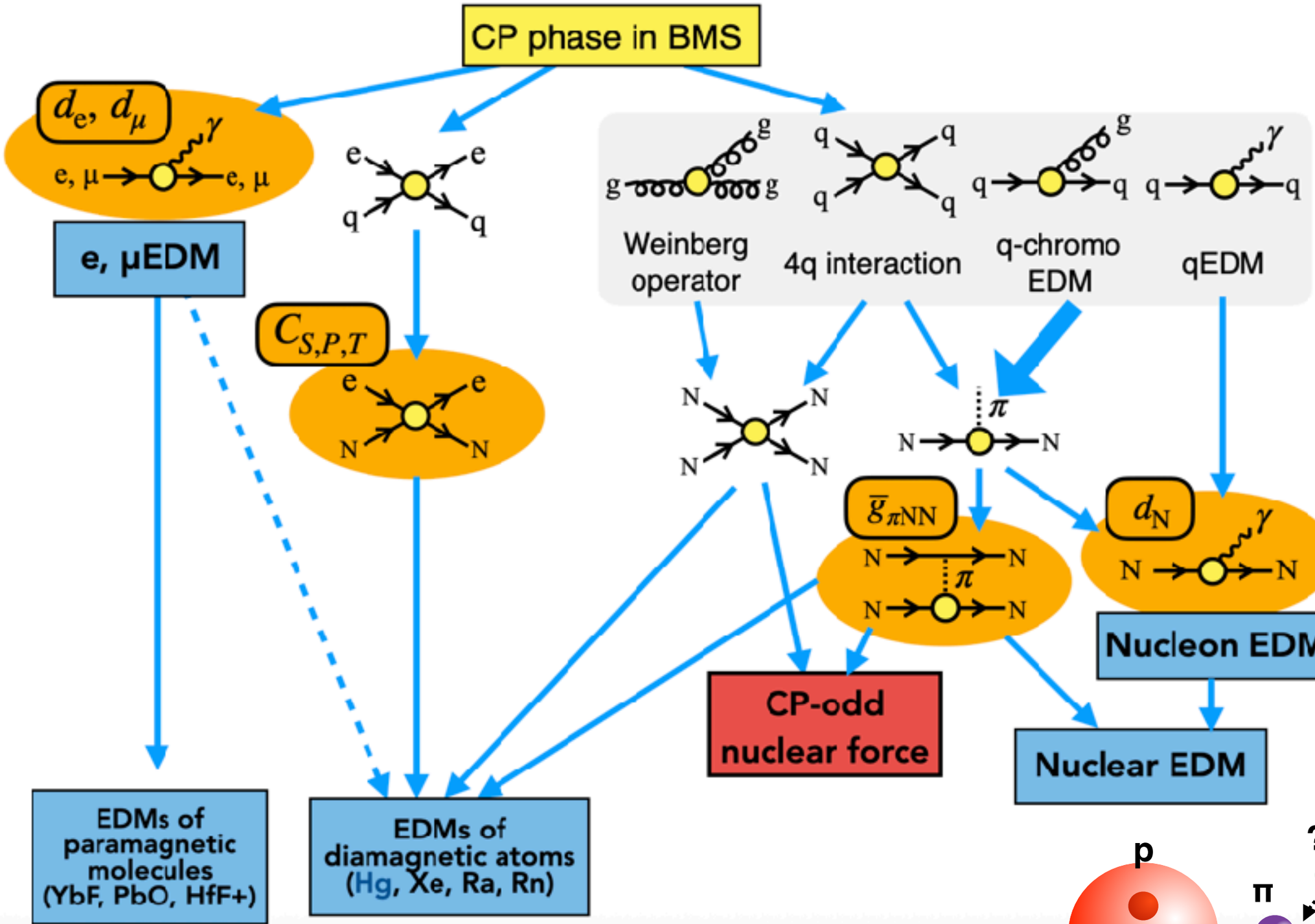
NOPTREX

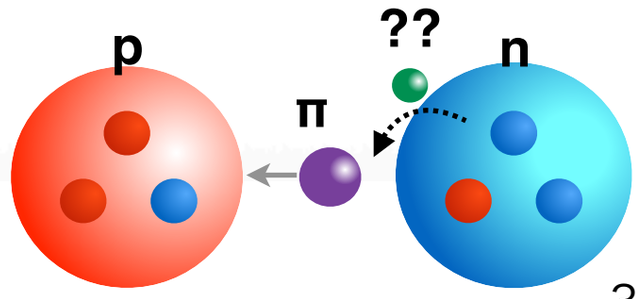
T-violation in nuclei

Epi-thermal neutron(~1eV)

NOPTREX : J-PARC E99 experiment

T-violation search in nucleon-nucleon interaction





Pion Exchange

NOPTREX Collaboration

J-PARC experiments

NOPTREX

Neutron Optical Parity and Time Reversal EXperiment

2025/07/17

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Juelich Center for Neutron Science K.Dickerson, E.Babcock

LANL A.Couture, D.Eigelbach, Z.Tang, J.Winkelbauer

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ORNL C.Jiang, S.Penttila

Ohio Univ. P.King

Paul Scherrer Institut P.Hautle, L.Zanini

Phase III Physics C.Haddock

South Dakota School of Mines and Tech. R.Shchepin

Southern Illinois Univ. B.M.Goodson

TRIUMF L.E.Charon-Garcia

Universidad Nacional Autonoma L.Barron-Palos, A.Perez-Martin

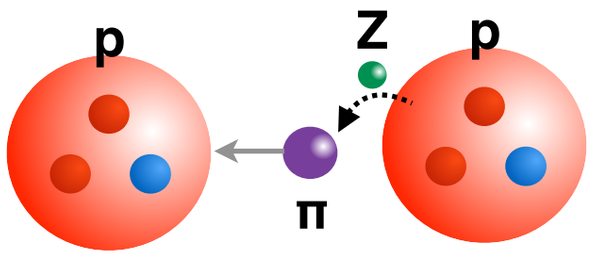
Univ. of Kentucky C.Crawford, J.O'Mahar, B.Plaster, J.Ratcliffe, M.Barlow

Univ. of South Carolina V.Gudkov

Wayne State Univ. E.Y.Chekmenev

Western Kentucky Univ. I.Novikov

Parity violating effect in nucleon-nucleon system



Weak interaction in nucleon-nucleon interaction

Strong interaction : Parity conserving

Weak interaction : Parity violating

→ **Extracts weak interaction via P-odd observable**

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

$-(1.7 \pm 0.8) \times 10^{-7}$

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

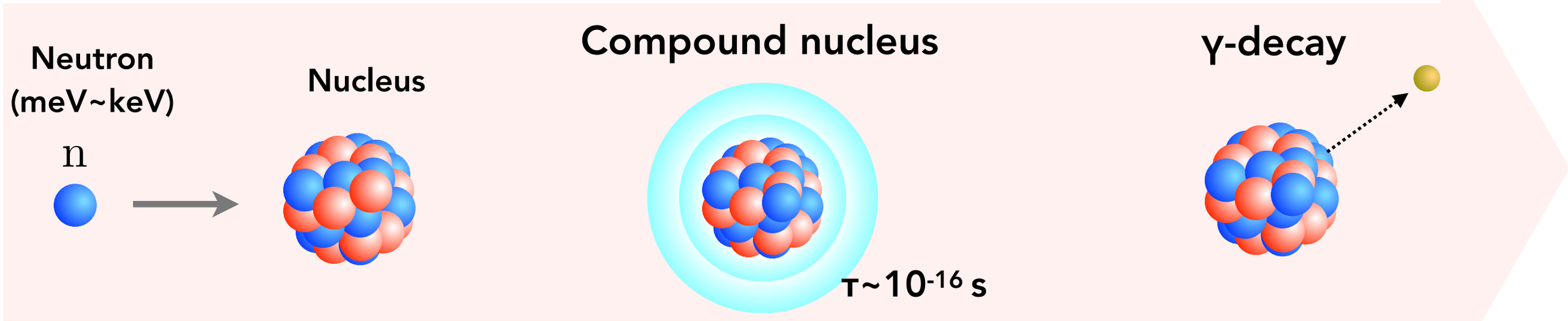
Phys. Rev. Lett 33:1307, (1974)

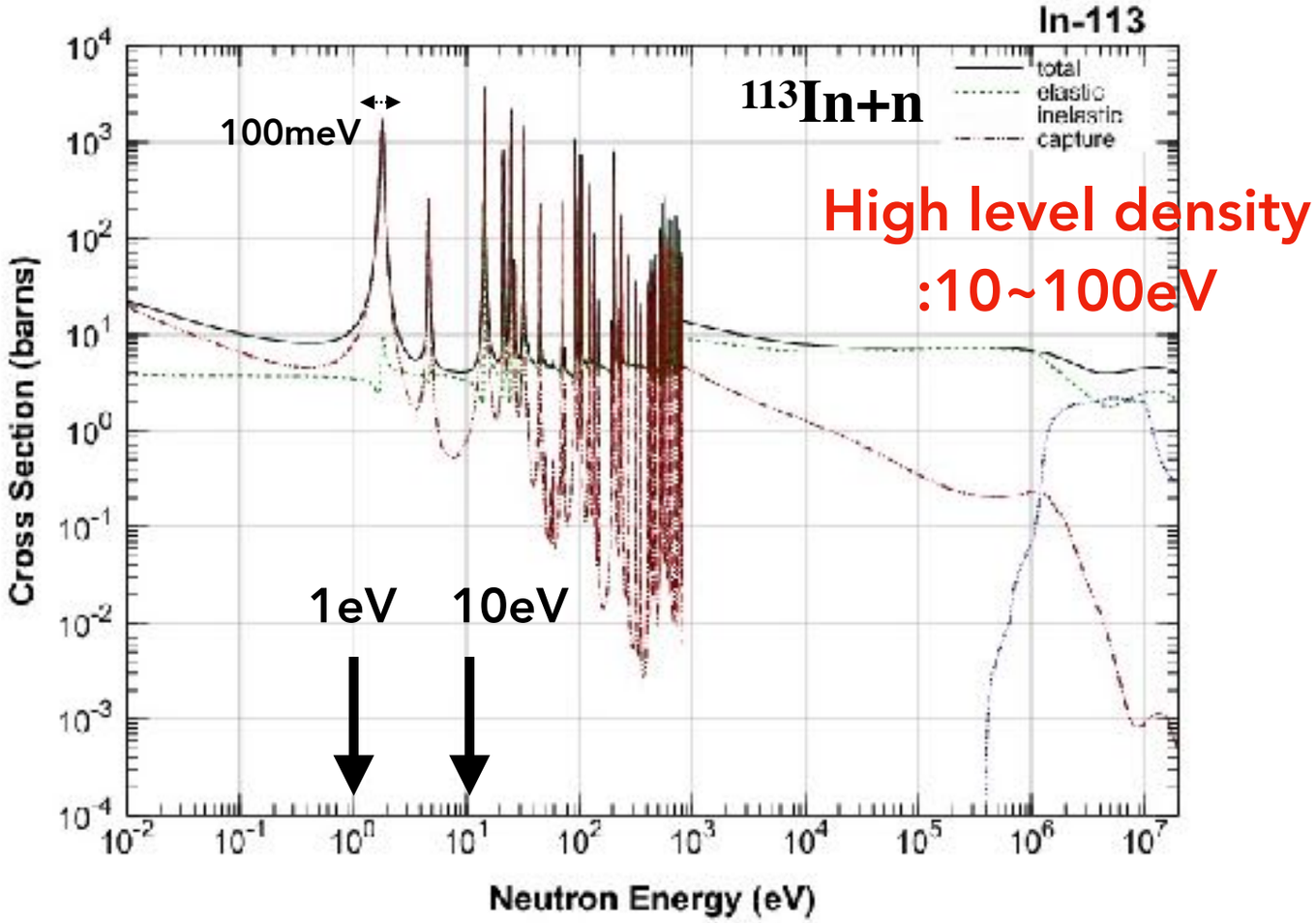
$$A_{\mathrm{L}} \simeq \frac{V_{\mathrm{weak}}}{V_{\mathrm{strong}}} \simeq G_{\mathrm{F}} m_\pi^2 \simeq 10^{-7}$$

Very small effect of weak interaction

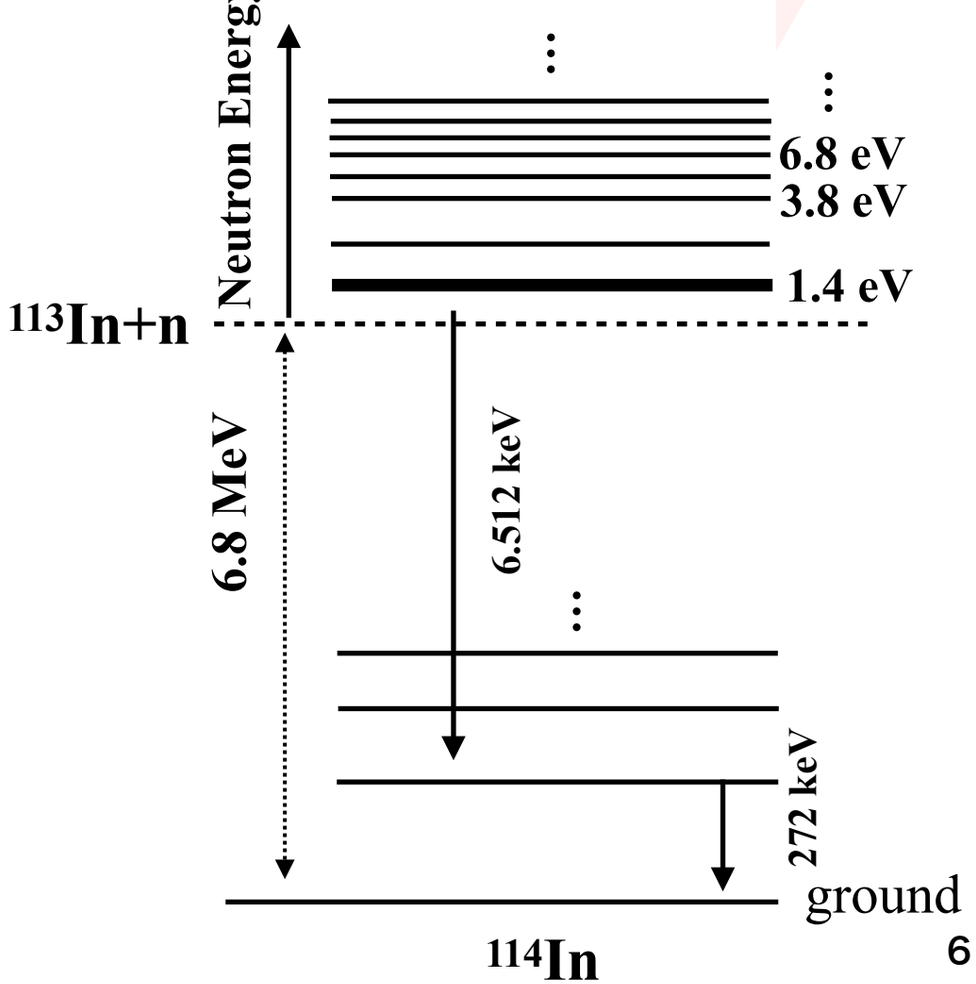
Neutron induced compound nuclei

Excited state formed after neutron capture with nucleus : Compound nucleus



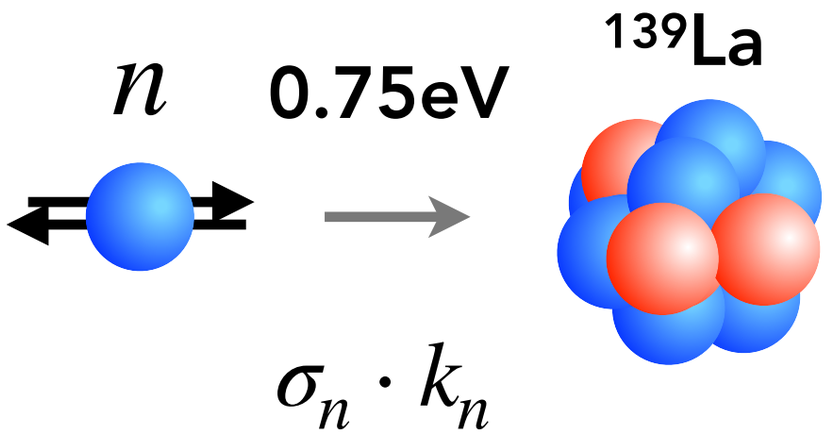


High level density
:10~100eV



Parity violating effect in neutron-nucleus system

Scattering between polarized neutron beam and unpolarized nuclei



helicity dependence in absorption cross section

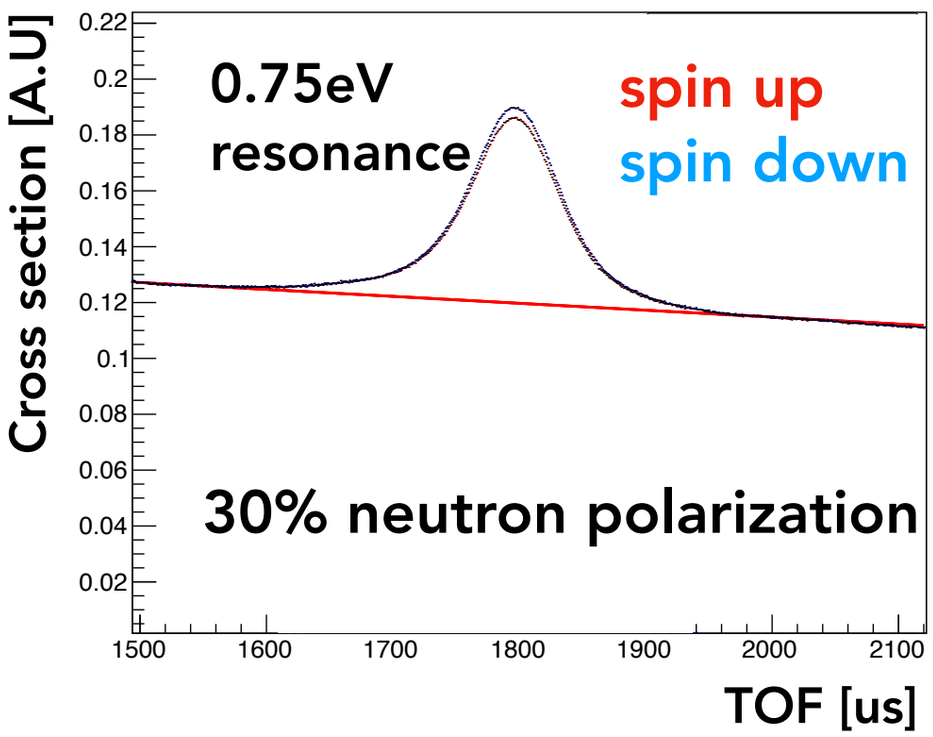
(0.97±0.03)x10^{-1} @E$_n$=0.75eV

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

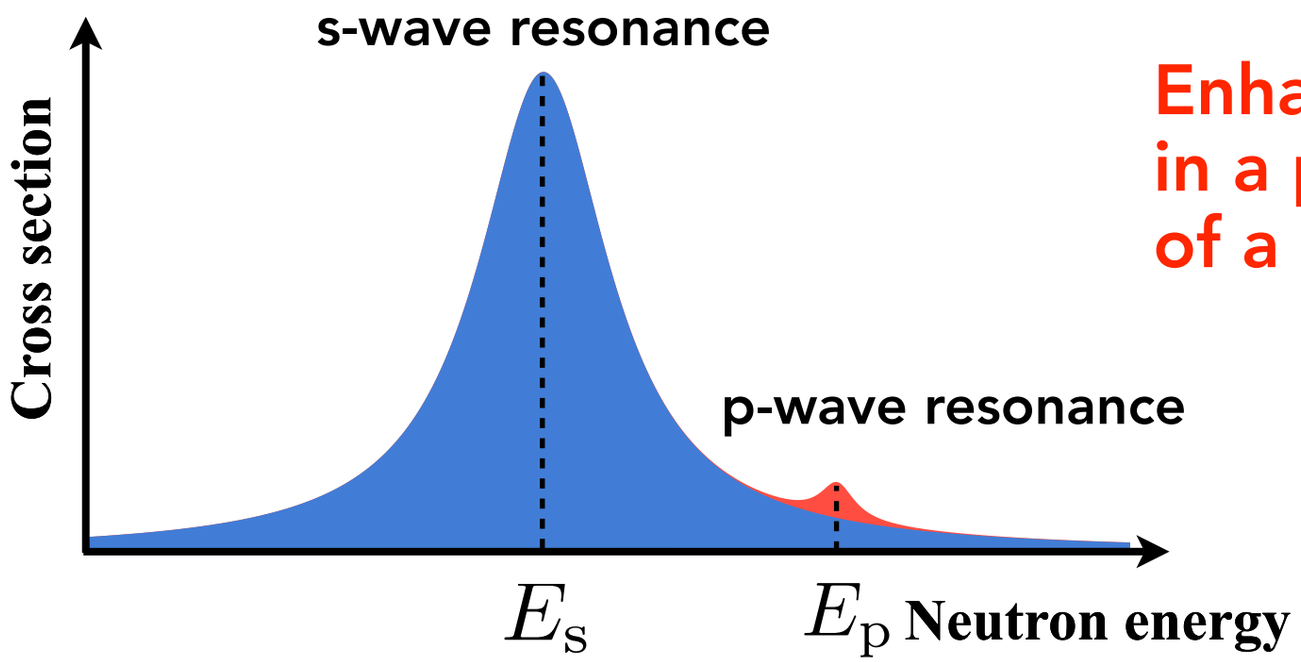
pp scattering :-(1.7±0.8)×10^{-7}

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

Compound nuclei is good amplifier for effect of weak interaction

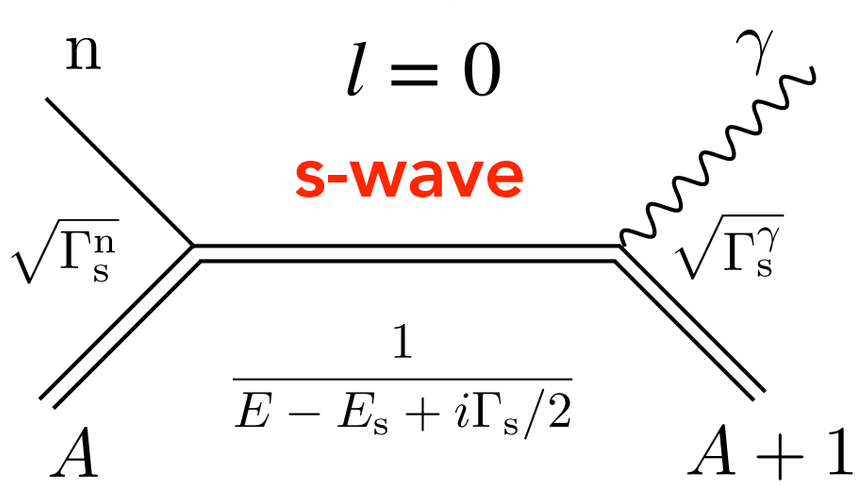


Enhancement of parity violation

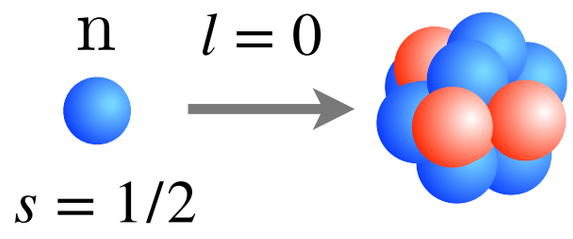


Enhancement of P-violation is observed in a p-wave resonance located in a tail of a s-wave resonance

Parity +



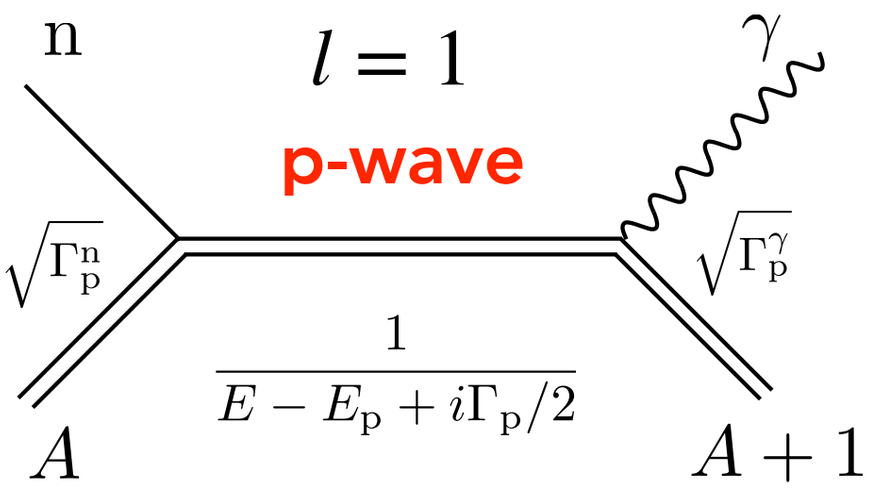
$j = l + s$

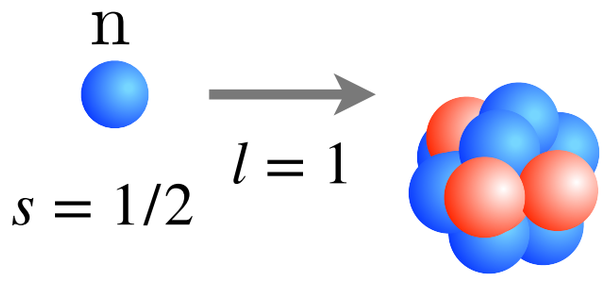


$j = 1/2$

Neutron total angular momentum

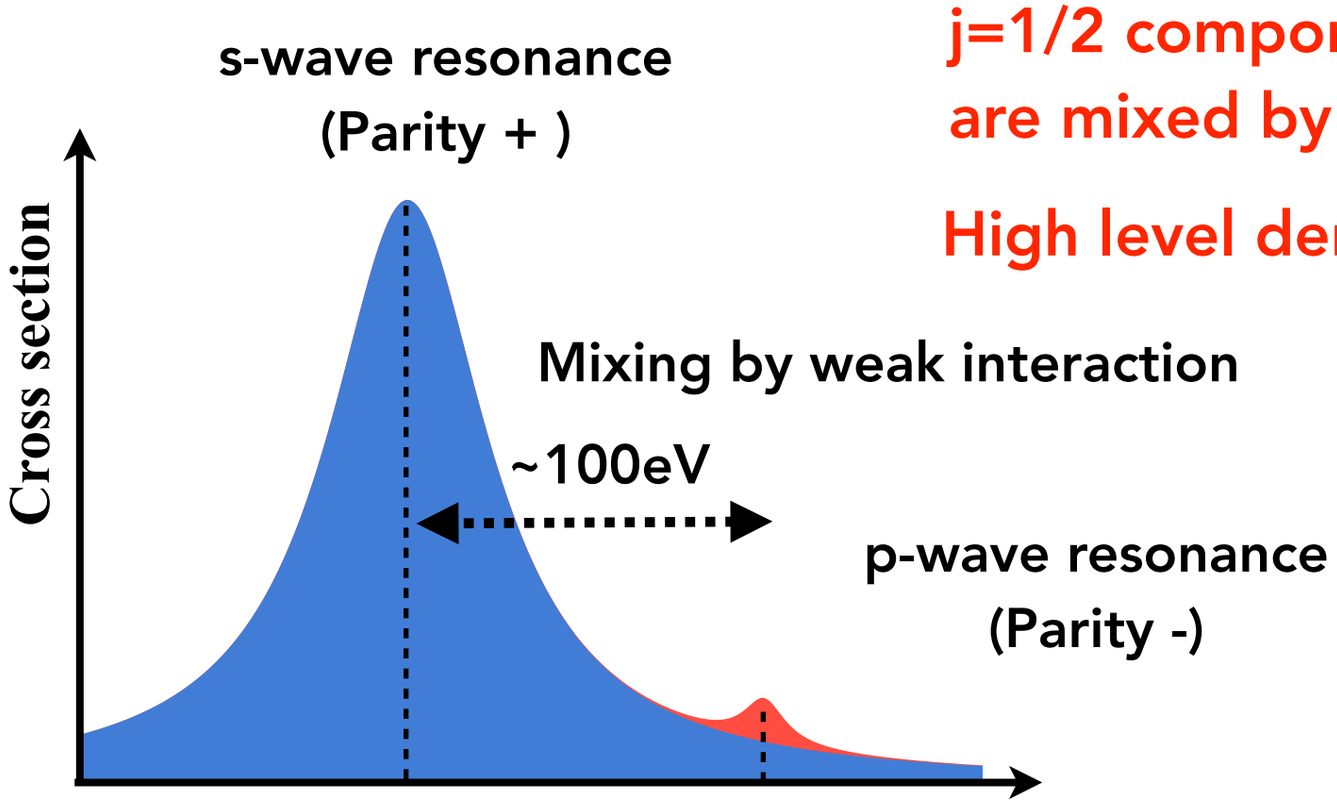
Parity -





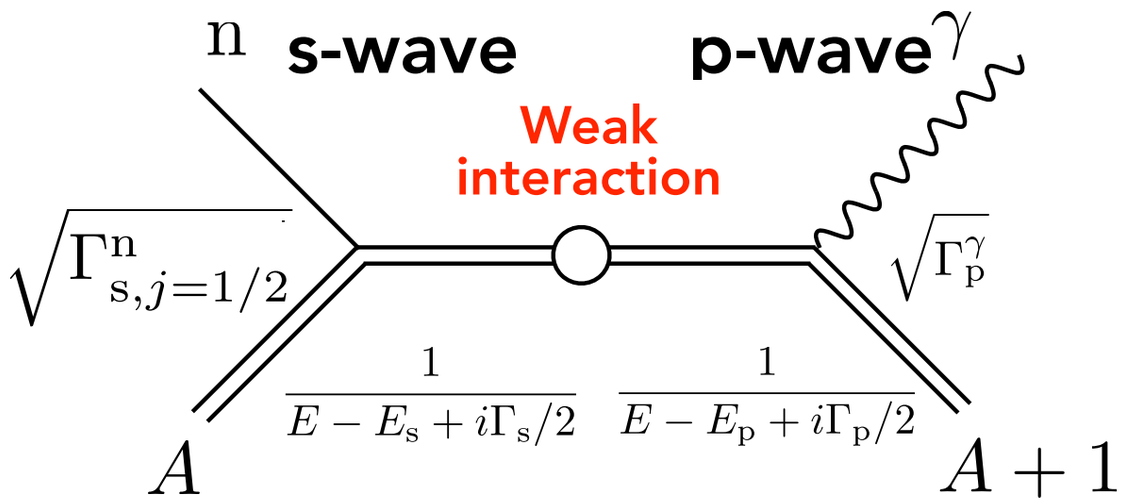
$j = 1/2$,3/2

Enhancement of parity violation



j=1/2 components of s-wave and p-wave amplitudes are mixed by weak interaction

High level density→Large enhancement



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

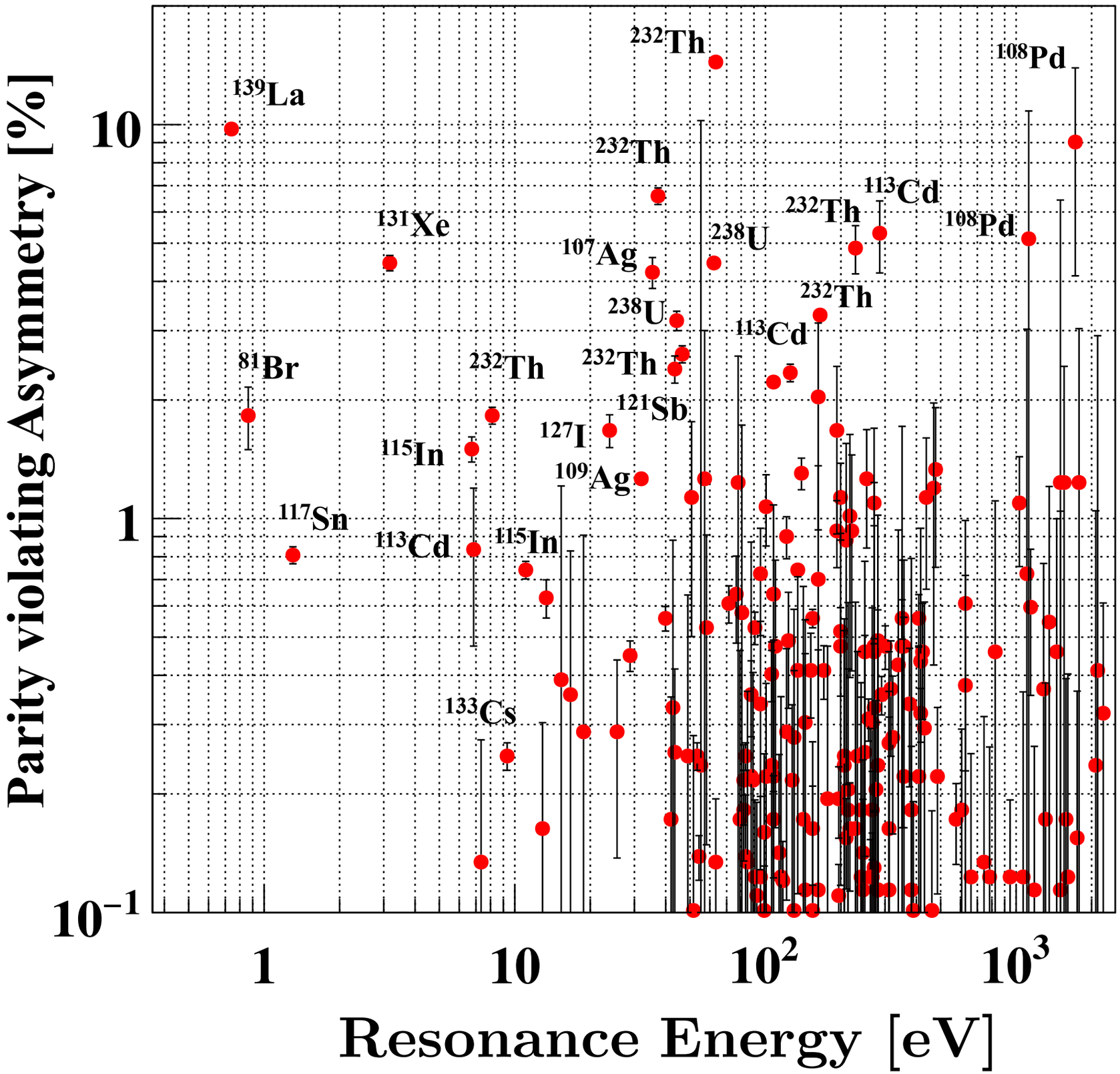
Weak matrix element

Dynamical Enhancement: 10^2 - 10^3

Structural Enhancement: ~ 10^3

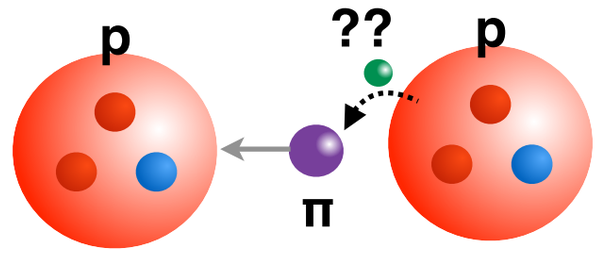
Partial neutron width j=1/2 component : x — Unmeasured

Parity violation in neutron-nucleus system



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 by (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-violation search experiment (NOPTREX) is now ongoing at J-PARC

How to search for T-violation

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

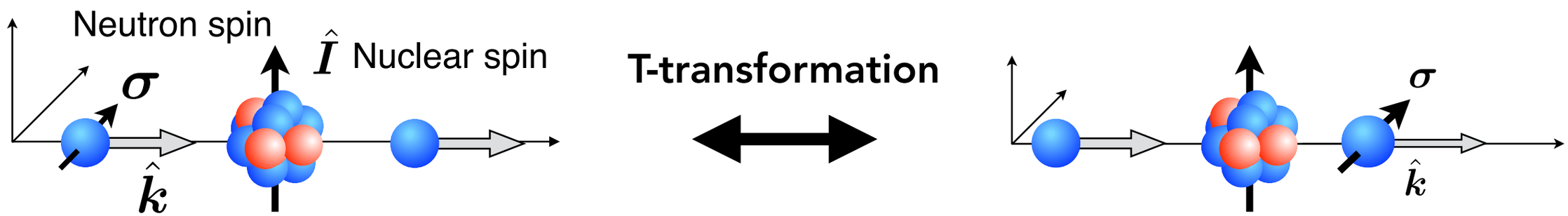
Spin independent cross section

Spin dependence (Strong interaction)

P-violation (Weak interaction)

T-violating cross section (Unknown interaction)

T-odd observable $\sigma\cdot(I\times k)$



Neutron momentum

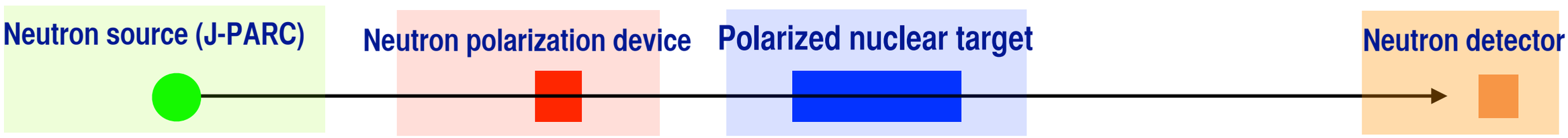
Analyzing power: A_x

Spin dependent transmission

Polarizing power: P_x

Neutron polarization

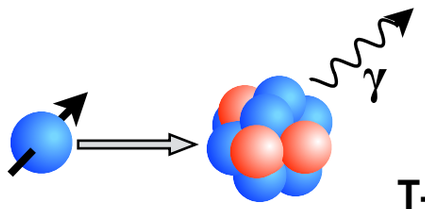
$$A_x + P_x = 8\mathrm{Re}A^*D$$



~1eV Neutrons, Neutron polarization device, Polarized target

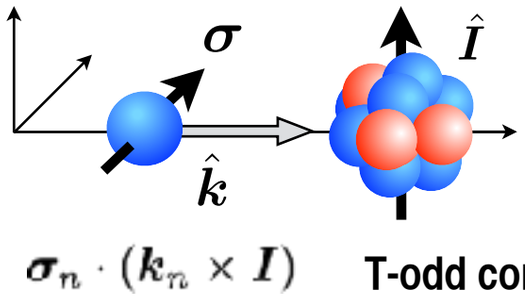
Features of NOPTREX

- Suppression of final state interaction



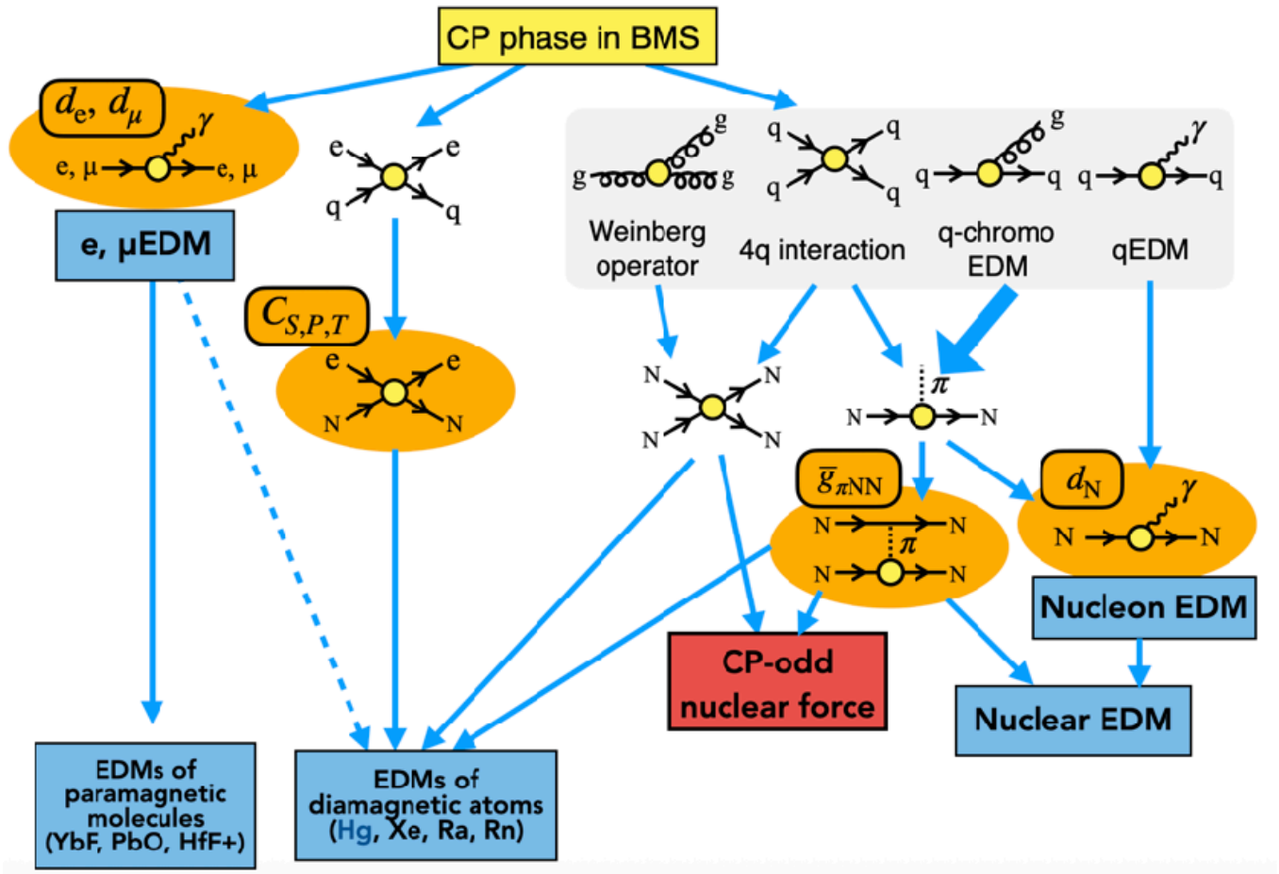
T-odd γ-ray angular correlation

Electric dipole moment



T-odd correlation in forward scattering amplitude

- Biased sensitivity of Chromo-EDM



Meson Exchange model

n-EDM

$$d_n \simeq 0.14(\bar{g}_\pi^{(0)} - \bar{g}_\pi^{(2)})$$

NOPTREX

$$|\Delta\sigma_T| \simeq 0.18(\bar{g}_\pi^{(0)} + 0.26\bar{g}_\pi^{(1)}) \text{ barn}$$

Different T-violating parameter space

V.V.Flambaum et al., Phys.Rev.C.105,015501 (2022)

Y.H.Song et al.,Phys. Rev. C., 83:065503, (2011.)

- Very large enhancement(~10^6) of T-violation

History of NOPTREX

1981 Discovery of very large parity violation $^{139}\mathrm{La} + \vec{\mathrm{n}}$ at Dubuna

1990~ Measurement of parity violation for many isotopes (~100) at Los Alamos

Parity violation measurement using (n,γ) reactions at KEK

Theoretical prediction of enhancement of T-violation

Discussion of T-violation search and fundamental study was started at KEK

→Discussion was suspended due to low neutron intensity,
(100 years measurement time was needed)

2010s Discussion of T-violation search was started again at J-PARC

Candidate nuclei for T-violation search

	^{139}La	^{81}Br	^{117}Sn	^{131}Xe
Large P-violation	9.8%	2.4%	0.8%	4.8%
Low resonance energy	0.75eV	0.88eV	1.3eV	3.3eV
Small Nuclear spin	7/2	3/2	1/2	3/2
Large natural abundance	100%	50%	8%	21%
|κ(J)|	0.6	?	0.4	1 or 0.3
Nuclear polarization	Dynamic Nuclear Polarization	–	–	Optical Pumping

Very good

Good

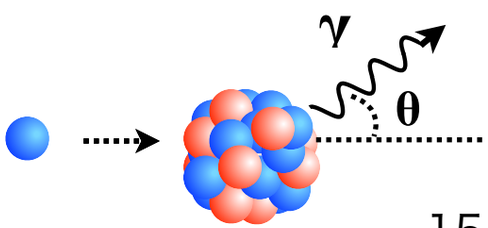
Acceptable

Bad

T. Okudaira *et. al.* , Phys. Rev. C. 97 034622 (2018)
T. Yamamoto *et al*. Phys. Rev. C. 101, 064624 (2020) ^{139}La
T. Okudaira *et. al.* , Phys. Rev. C. 104, 014601(2021)
M. Okuizumi *et al*. Phys. Rev. C. accepted (2025)

J. Koga *et. al.*, Phys. Rev. C. **105**, 05461 (2022) S. Endo *et al.*, Phys. Rev. C.106 064601 (2022) ^{117}Sn
T.Okudaira et al. Phys. Rev. C **107**, 054602 (2023) ^{131}Xe

Angular correlation by s-p mixing



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 : ~10^6 times

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.
M. Okuizumi *et al*. Phys. Rev.

J. Koga *et. al*., Phys. Rev. C. **105**, 05461 (2022) — ^{117}Sn
022)
023) — ^{131}Xe

(n,γ) measurement Poster : Mofan Zhang, Sodai Hayashi

2.Neutron polarization device

→^{3}He spin filter for ~0.75eV

Poster: Kanta Asai

3. Polarized La target

→Dynamic nuclear polarization

30% ^{139}La polarization!

Poster: Mao Okuizumi

4. Neutron detector

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

Poster: Sota Kudo

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

→Phase-0 : Statistically polarized target, First T-violation limit!

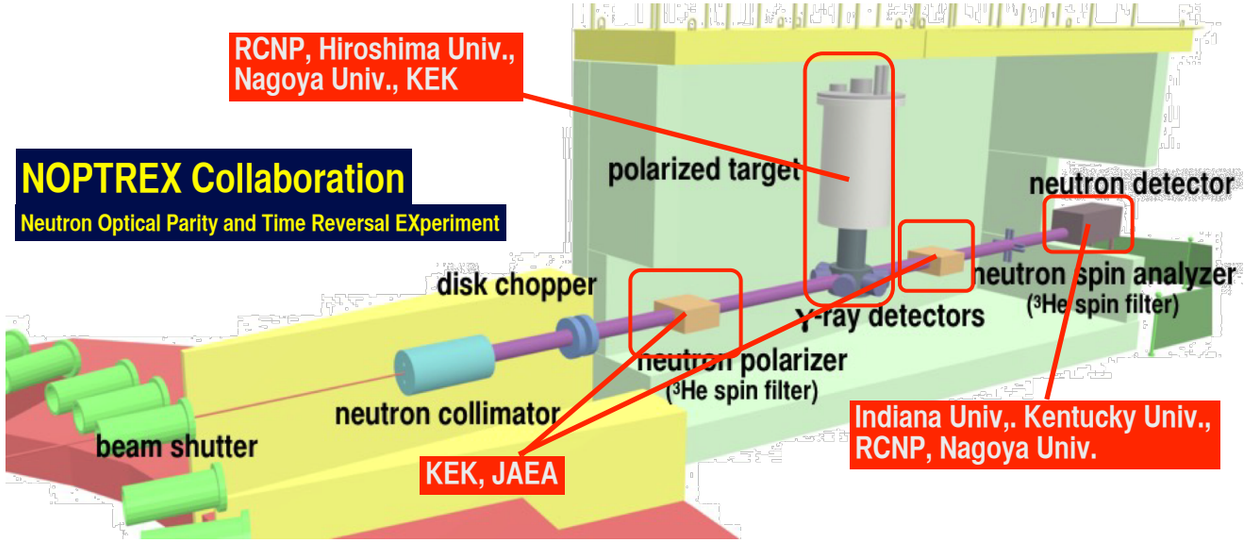
T. Okudaira *et al*., Phys. Rev. C., 109, (2024) 044606
R. Nakabe *et al*., Phys. Rev. C. (2024) L041602
R. Nakabe *et al*., arXiv:2509.06542v1 (2025)

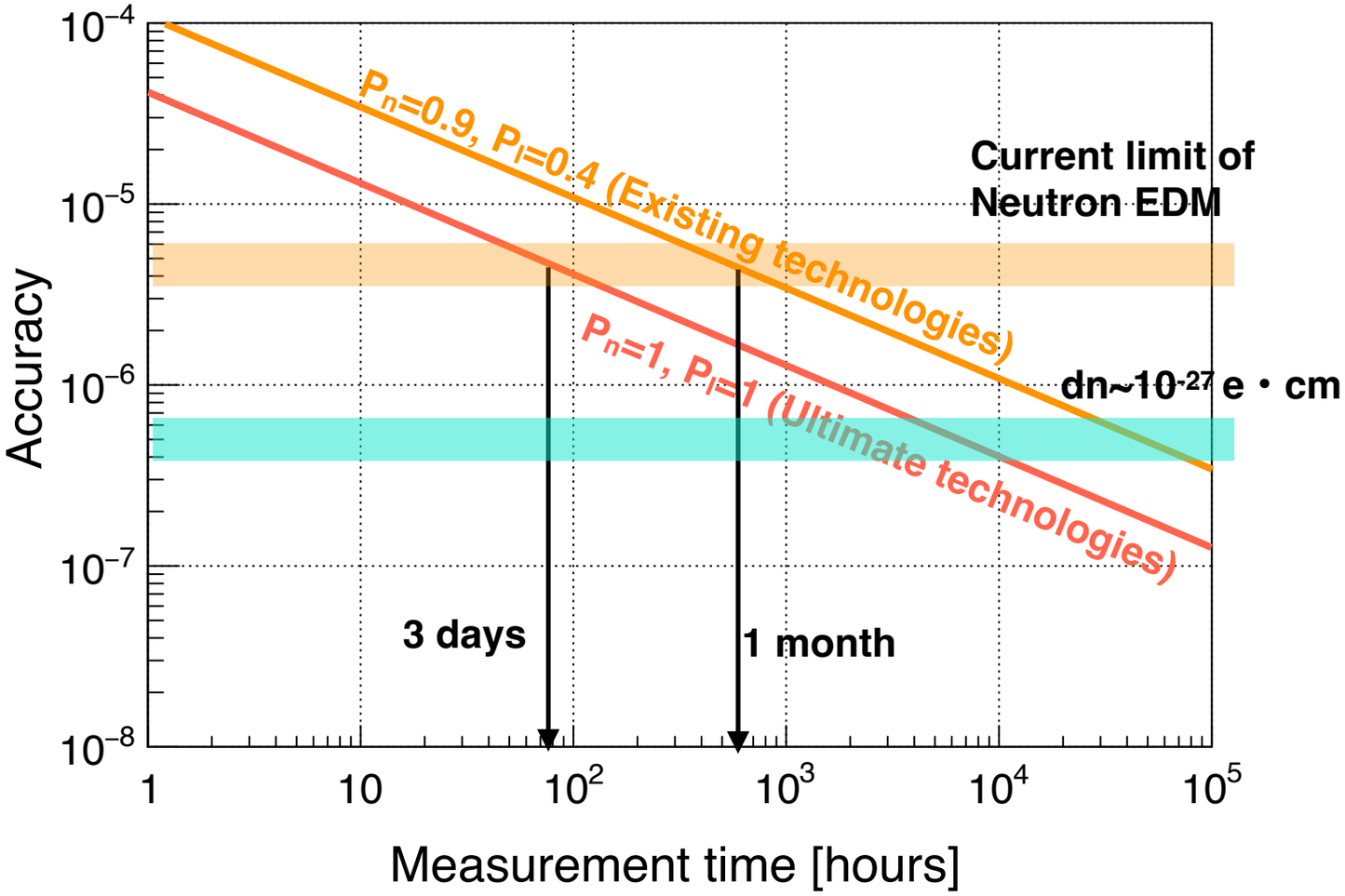
Phase-I : Scheduled on 2025-2026, Preparation is ongoing.

Phase-II : Fundamental development is going

Poster: Shiori Kawamura

T-violation sensitivity





Spin dependent asymmetry

$$\sim 5 \times 10^{-6}$$

⟷ **Current limit of nEDM**

Very rough comparison. T-violation parameters which can be searched for are different

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

(In 100% polarization case, 3days measurement)

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**

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

- **First T-violation limit in NOPTREX**

  R. Nakabe *et al*., arXiv:2509.06542v1 (2025)
  Submitted to PTEP

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

  S. Takahashi *et al*., NIMA. 1075 170410 (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 — S. Endo *et. al*. Eur. Phys. J. A (2024) 60:166
  - Transverse asymmetry measurement of ^{139}La(n,γ)^{140}La* reaction

M. Okuizumi *et al*., Phys. Rev. C. 111, 034611(2025)

Experiment using polarized La and neutrons

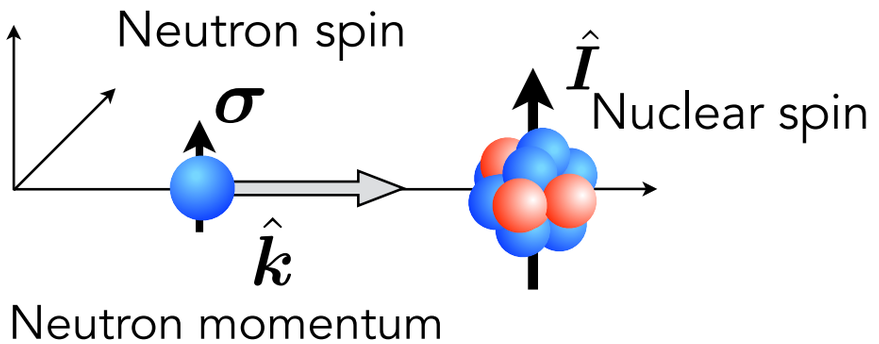
$$f = A' + B'\boldsymbol{\sigma}\cdot\hat{\boldsymbol{I}} + C'\boldsymbol{\sigma}\cdot\hat{\boldsymbol{k}} + D'\boldsymbol{\sigma}\cdot(\hat{\boldsymbol{I}}\times\hat{\boldsymbol{k}})$$

spin independent cross section

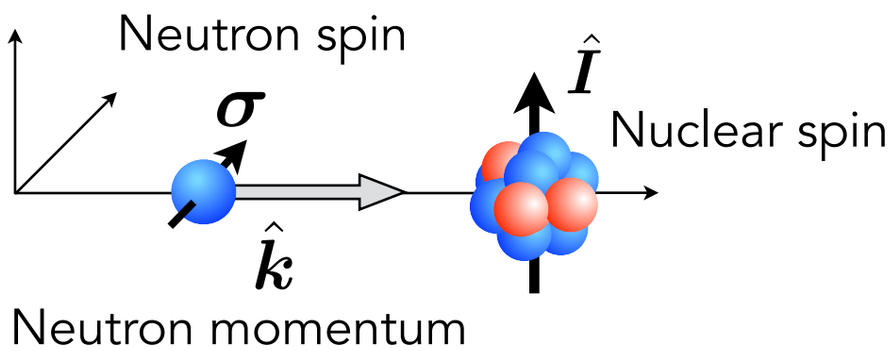
Spin dependence (strong interaction)

P-violation (Weak interaction)

T-violation (Unknown interaction)

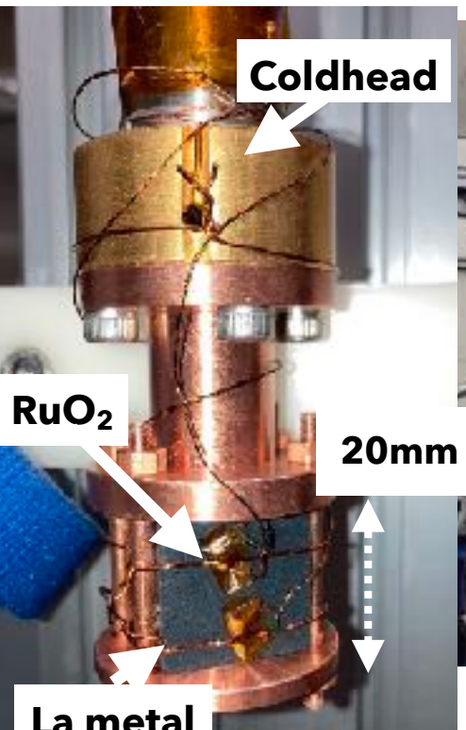


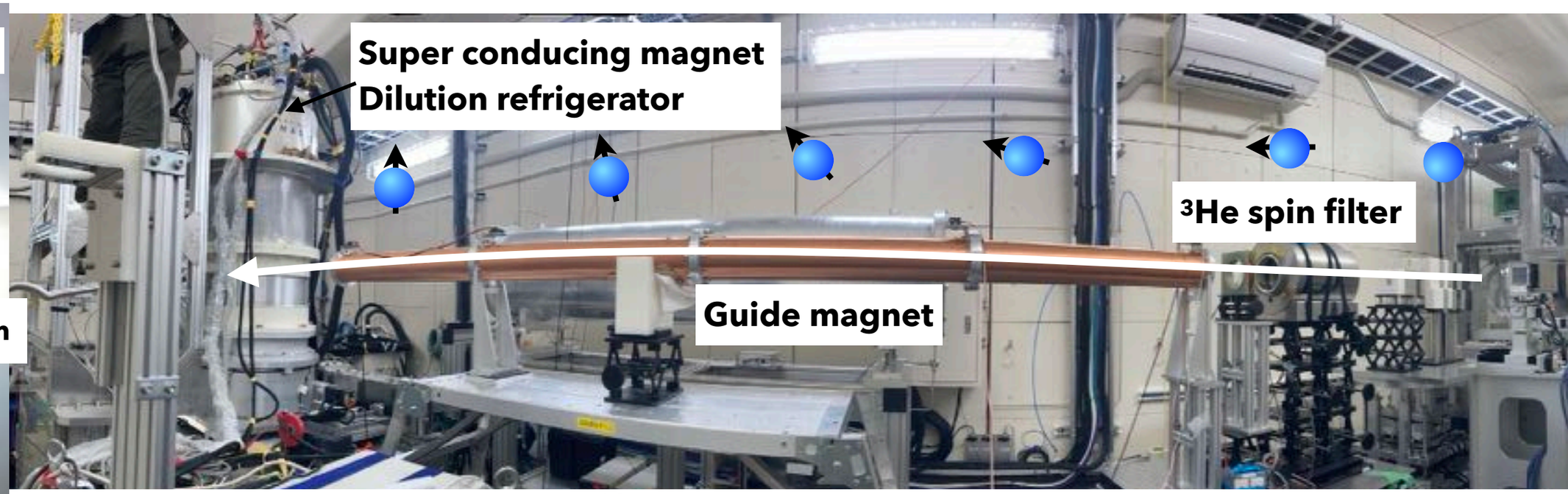
Neutron spin and nuclear spin : Parallel



Neutron spin and nuclear spin : Perpendicular

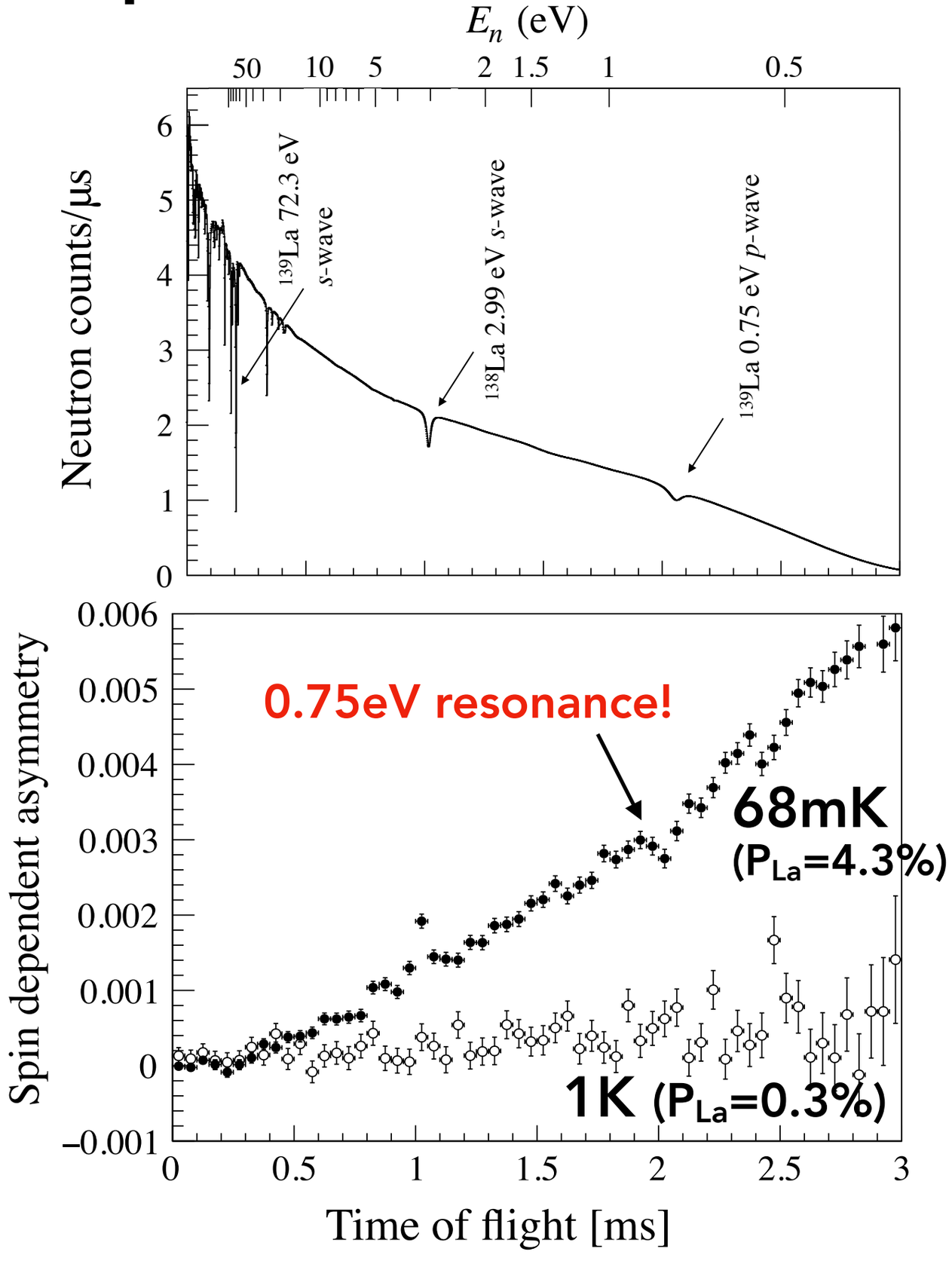
※ With existing equipment, neutron spins rotate by applied magnetic fields

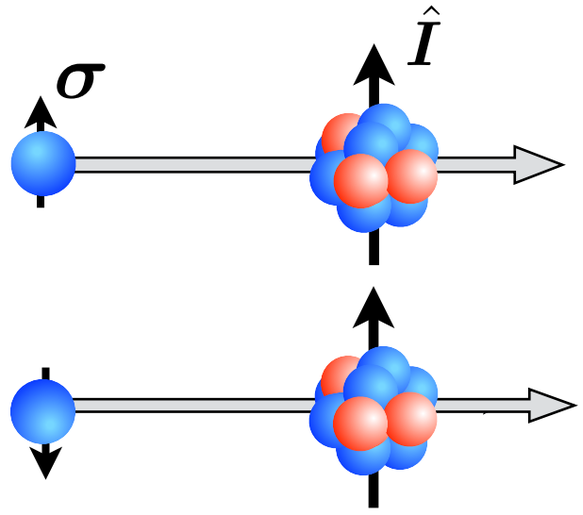




68mK, 6.8T→4% nuclear polarization

Experiment using polarized La and neutrons





$$A_y = \frac{N_- - N_+}{N_+ + N_-}$$

Spin dependent cross section was observed!

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

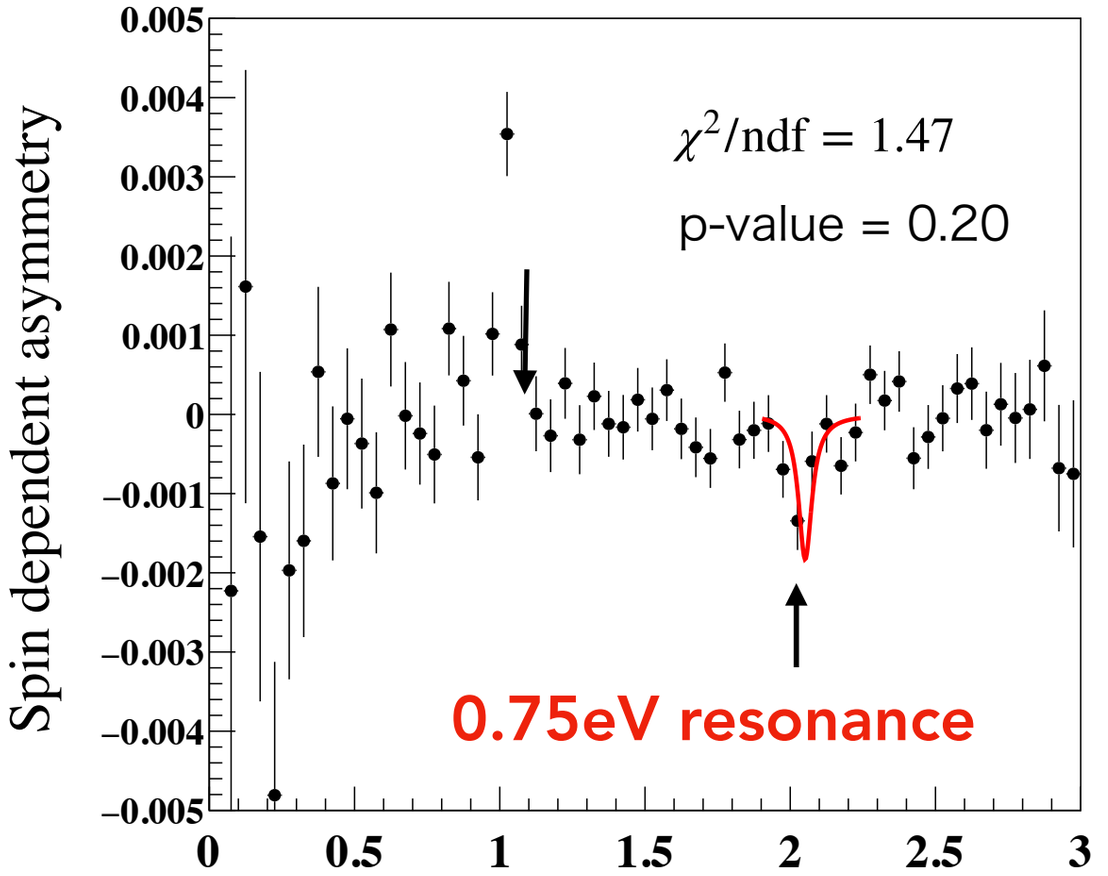
T. Okudaira *et al.*, Phys. Rev. C., 109, (2024) 044606

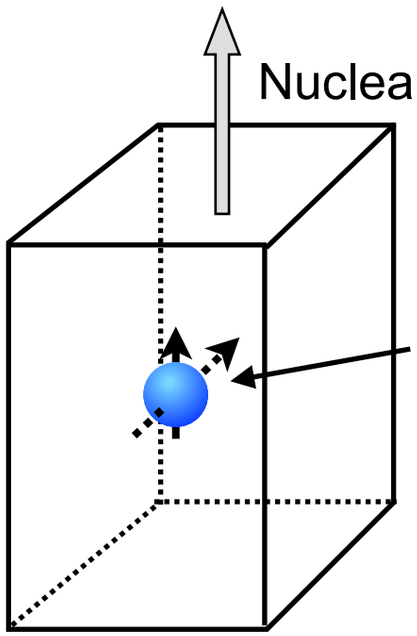
R. Nakabe *et al.*, Phys. Rev. C. (2024) L041602
Editor's suggestion

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

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

First constraint of T-violation by NOPTREX





Neutron is polarized with this direction and resonance curve is distorted if T-violating interaction exists
→ Second order of T-violating effect

$$A_y = \frac{N_- - N_+}{N_+ + N_-} = -\frac{2\mathrm{Re}A^*B}{|A|^2 + |B|^2 + |C|^2 + |D|^2}$$

Second oder T-violating effect

$$|W_T| < 6.4 \text{ eV}$$

$$|\Delta\sigma_T| < 1.2 \times 10^2 \text{ barn}$$

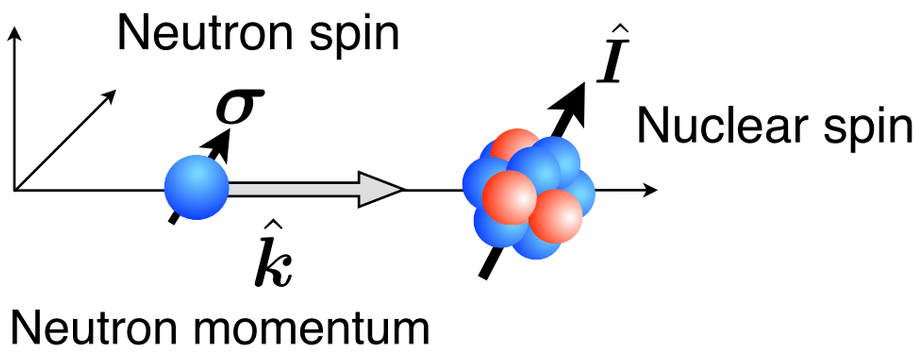
90% C.L. limits

Total cross section of ^{139}La+n : 15 barn

16hours measurement

Plan for T-violation search

● Phase 1 : T-violation search with low sensitivity

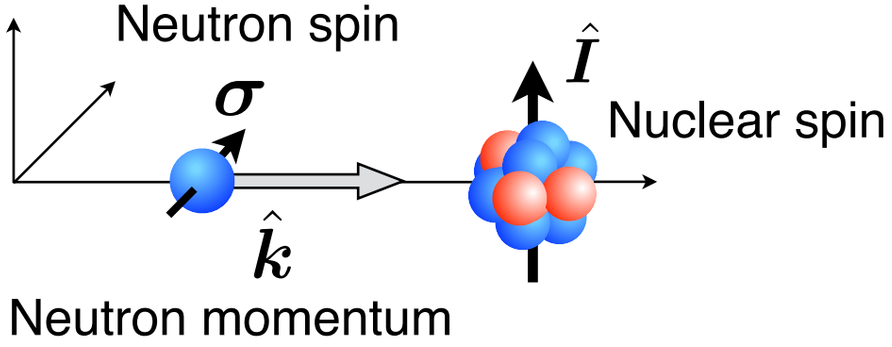


Neutron spin and nuclear spin : Parallel

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

→J-PARC E99 Stage1 status

● Phase 2 : T-violation search with high sensitivity

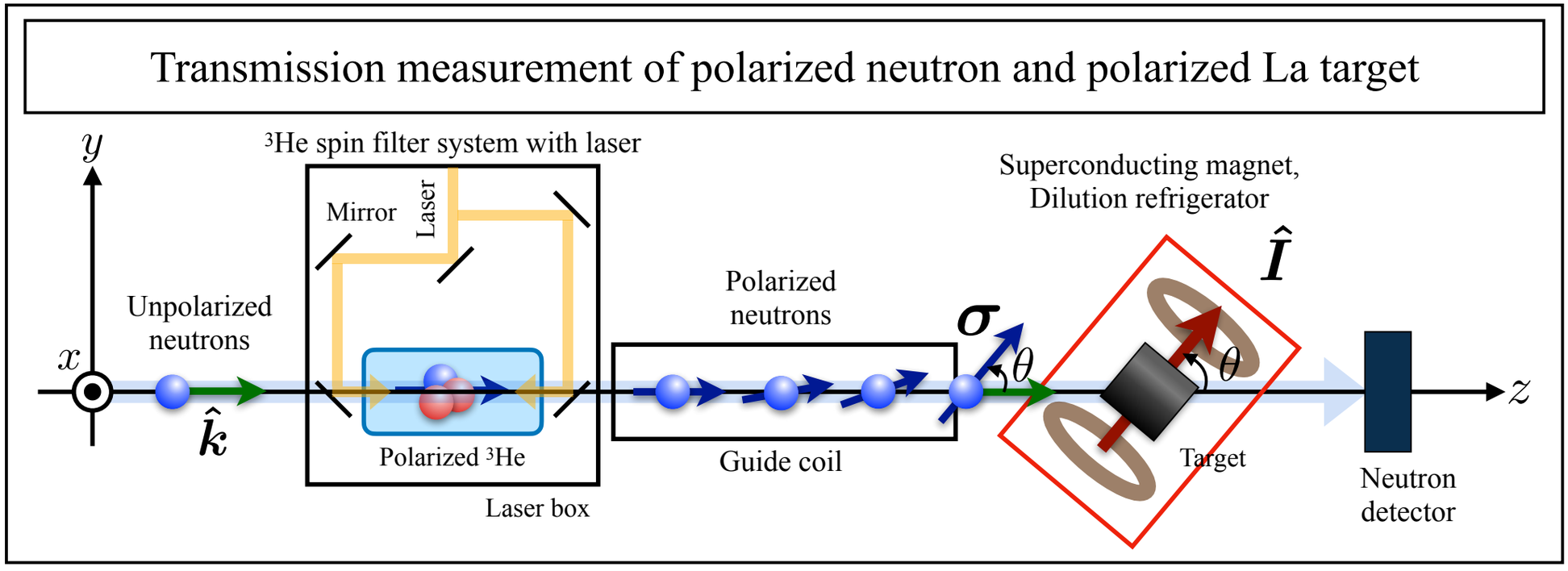


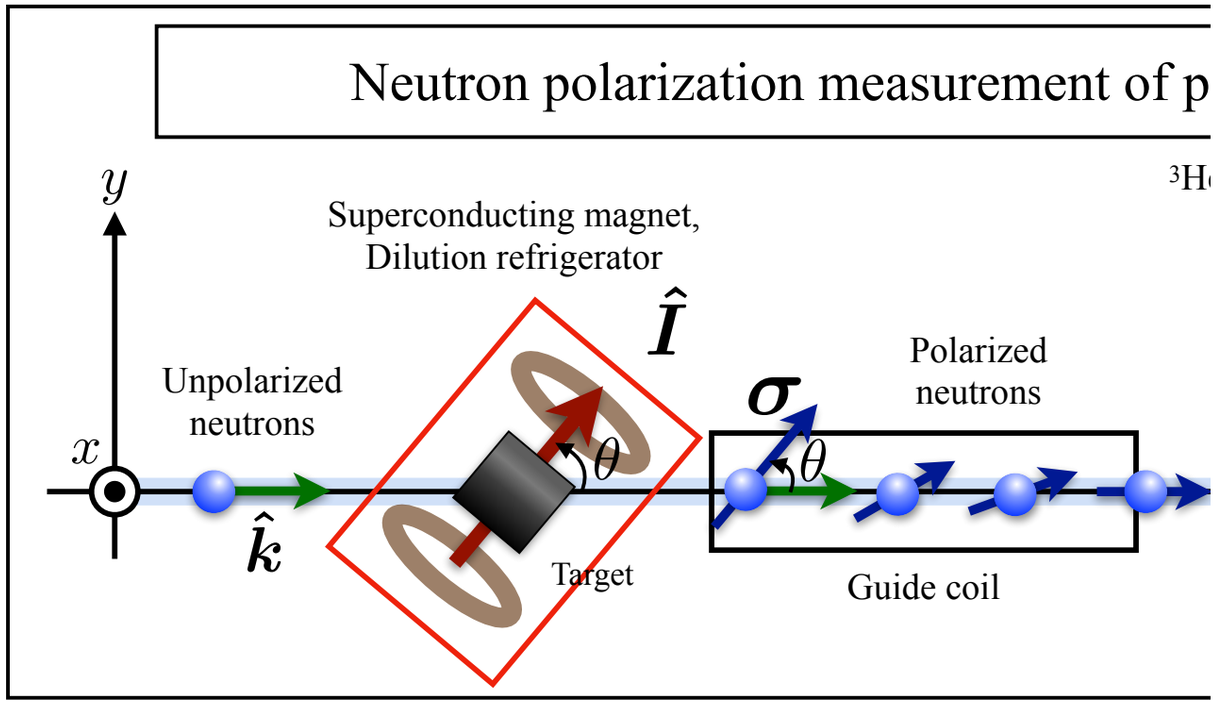
Neutron spin and nuclear spin : Perpendicular

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

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

Phase-I experiment at ANNRI beam line

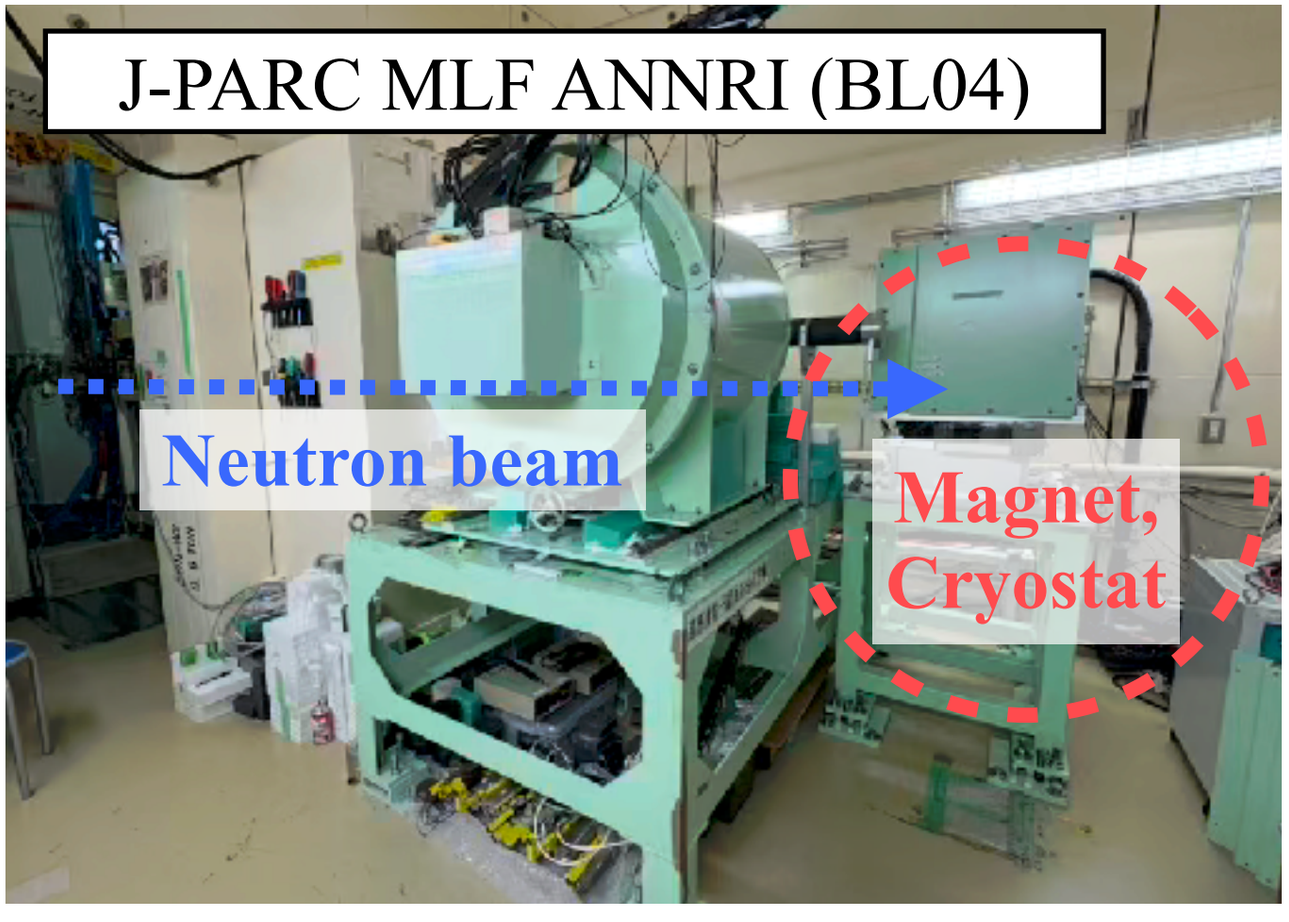




Spin dependent asymmetry

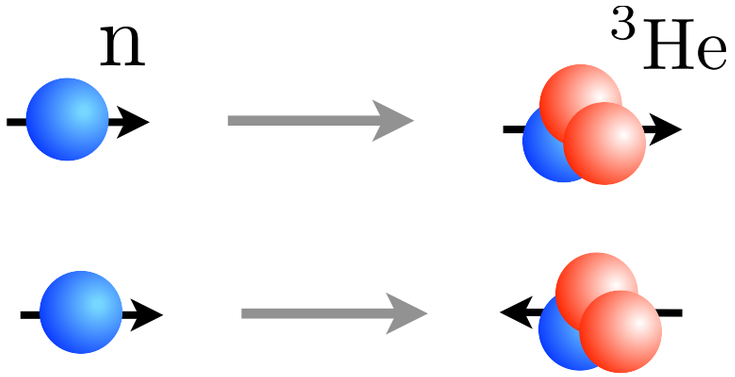
$$A = \frac{N_+^a - N_-^a}{N_+^a + N_-^a}$$

Time-reversal system

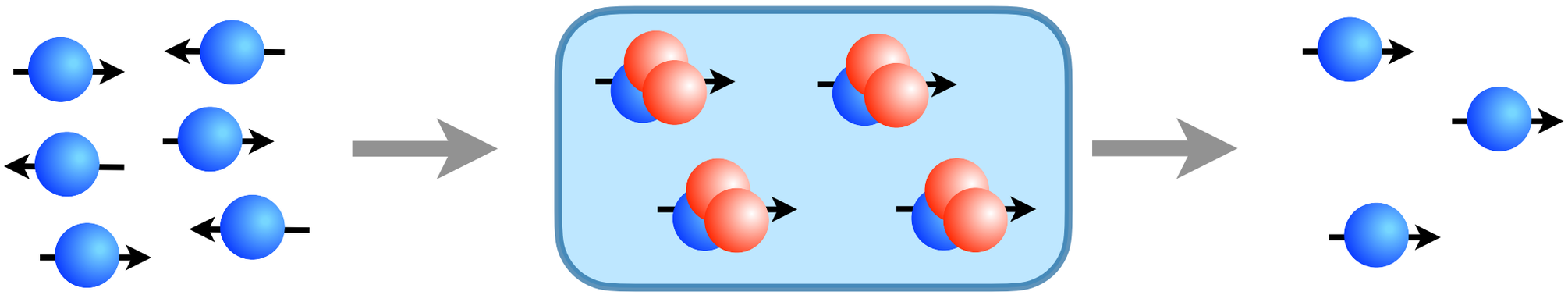


Neutron polarizer : ^{3}He Spin Filter

K. Asai, M. Okuizumi
Nagoya Univ.

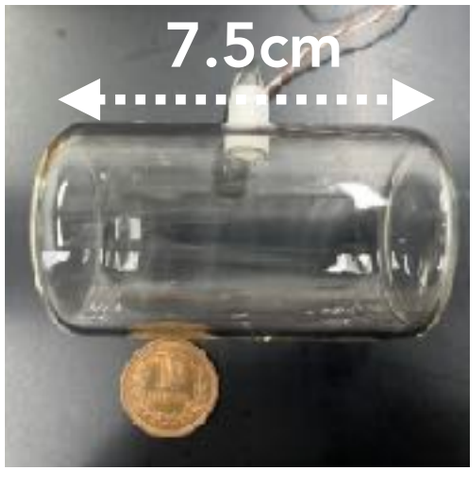


Large absorption cross section depending on spin direction



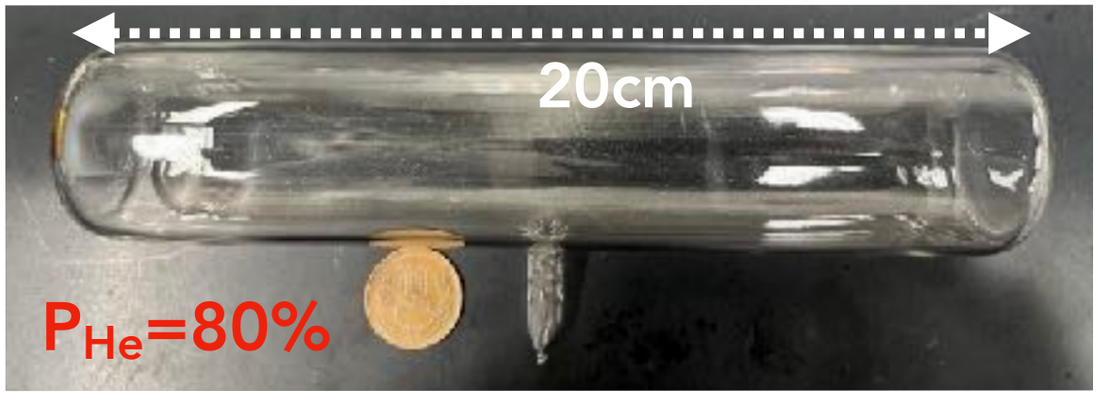
Unpolarized neutron | **Polarized ^{3}He gas** | **Polarized neutron**

Neutron polarization 40%



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

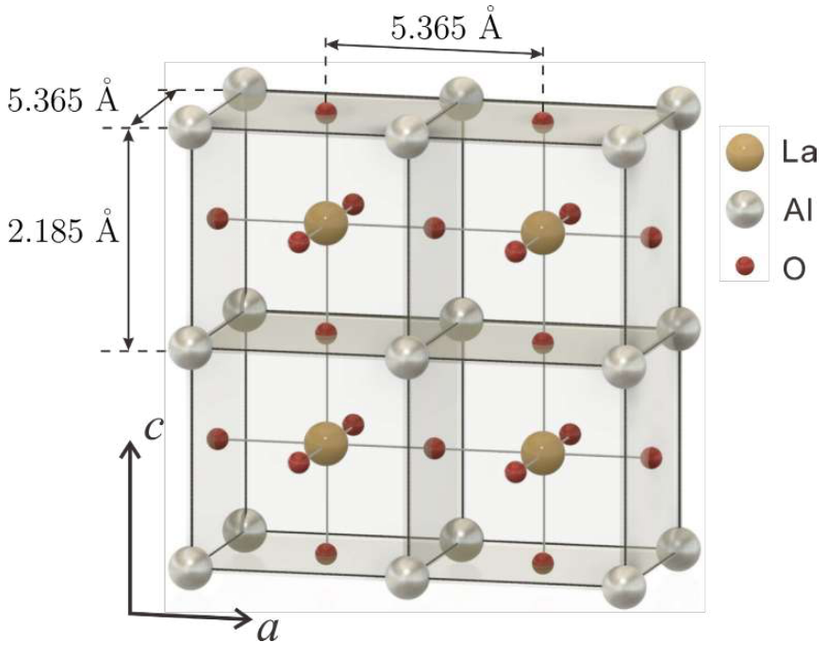
Neutron polarization 80% at 0.75eV



100W laser

Will be installed on beamline with laser system in 2025

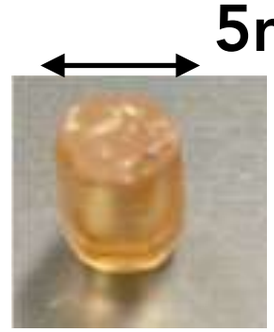
Polarized ^{139}La target



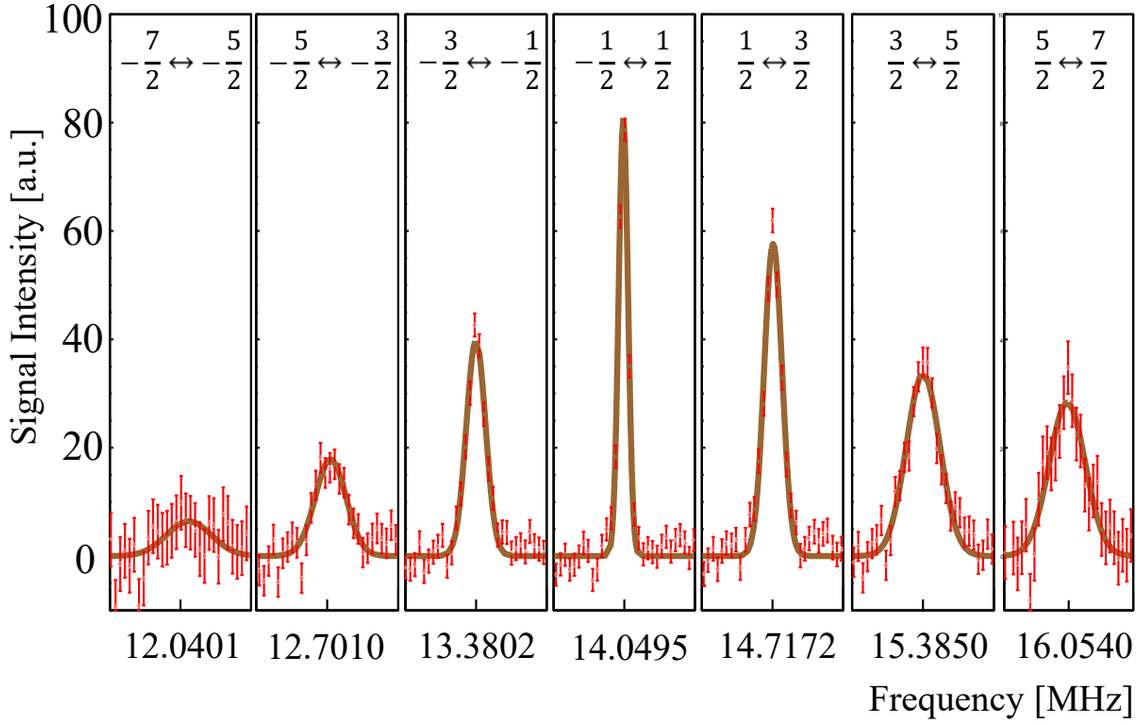
Polarization of nuclei with I>1 is very difficult
Electric quarto moment is coupled with electric field

Dynamic nuclear polarization using Perovskite crystal

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

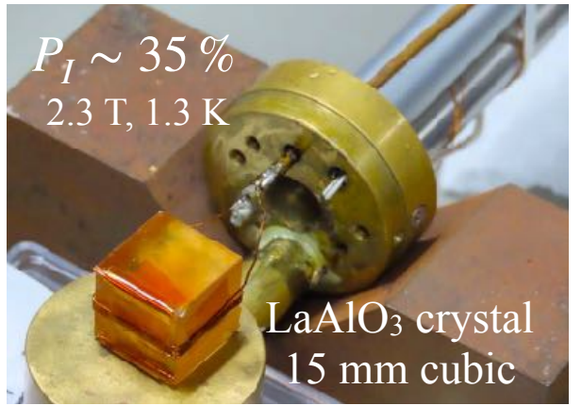


1.3K, 2.3T, Microwave irradiation at Yamagata Univ.



Achievable ^{139}La polarization :

$$P(t \to \infty) \sim 35\ \%$$



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

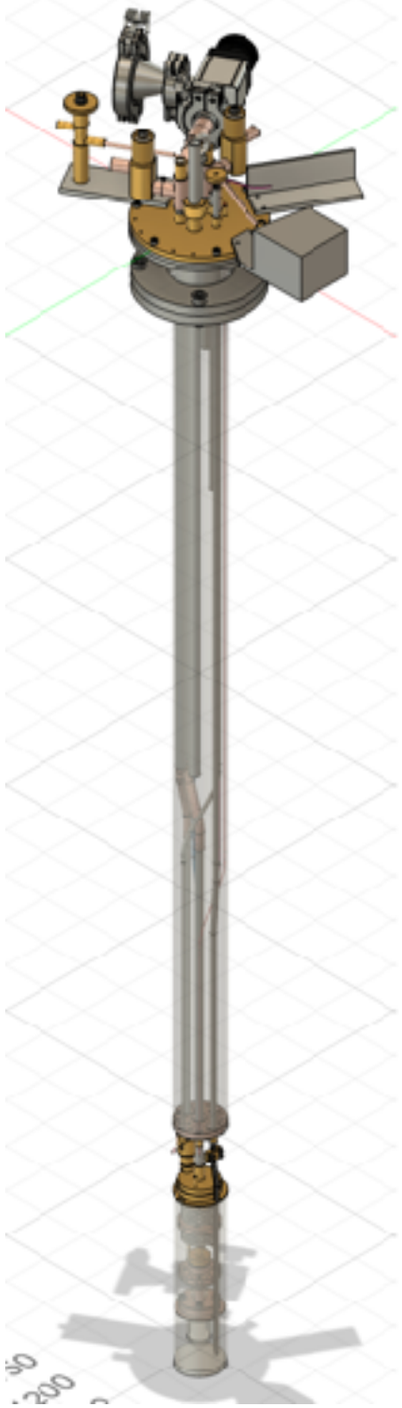
I.Ide, M.Okuizumi
Nagoya Univ. Ph.D student

Refrigerator development for polarized ^{139}La target

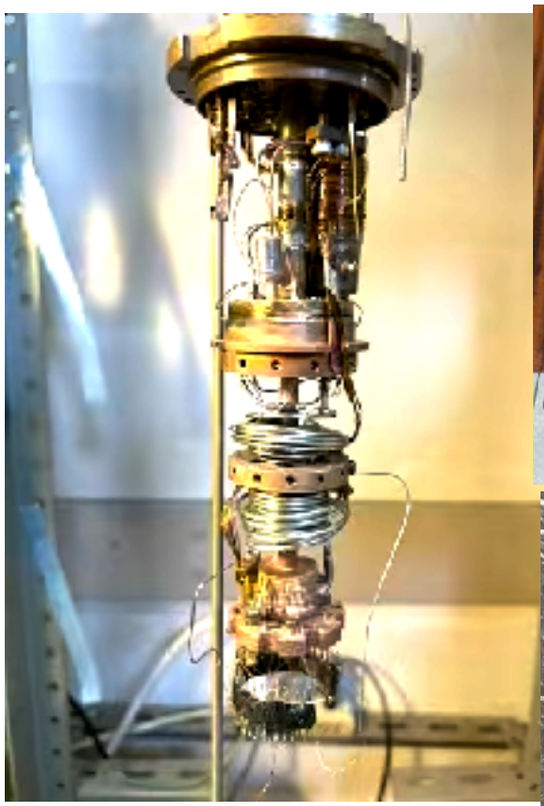
$LaAlO_3$ crystal will be installed on beamline under ~1K and 2T condition

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

4T superconducting maget



Collaboration with I-lab of Nagoya Univ.

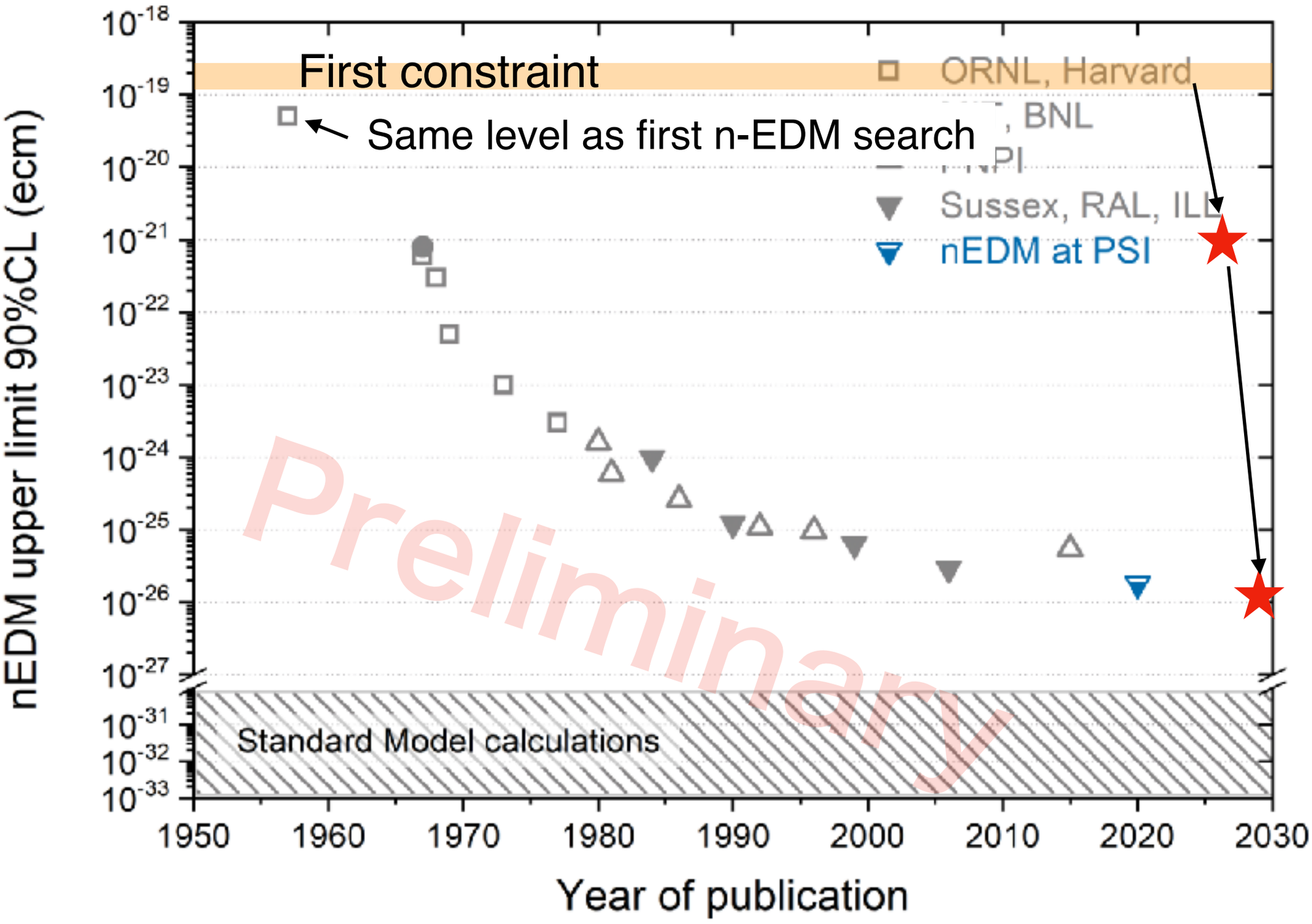


No leakage

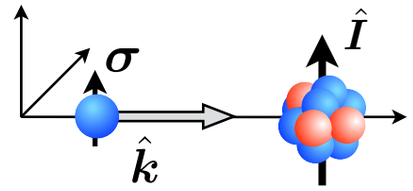
~50mK (Preliminary) was achieved

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

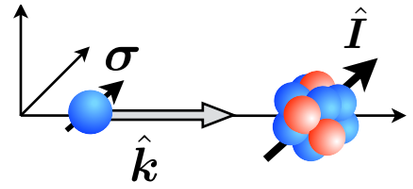
T-violation constraint by NOPTREX



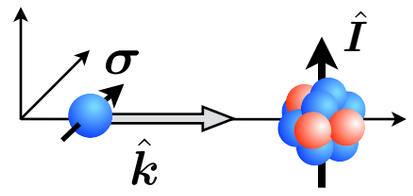
1day measurement



Phase-I experiment
1week measurement



Phase-II experiment
1month measurement



We have a bright future!