Spin in Fundamental Physics

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Spin in Symmetry

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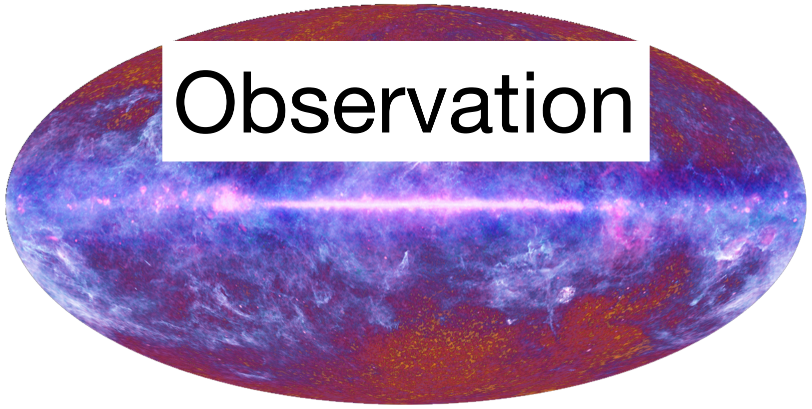
Why is there far more matter than antimatter?

Sakharov conditions

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

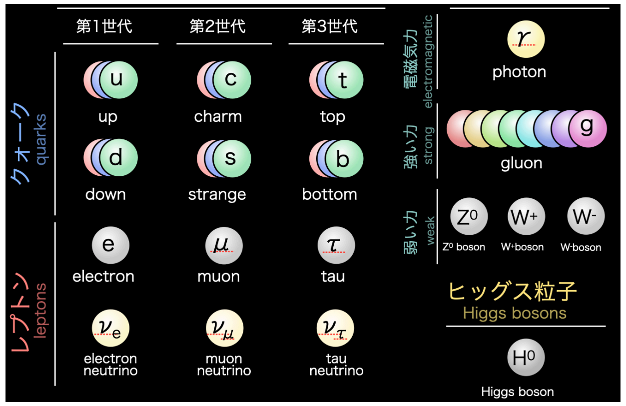


$$n_b/n_\gamma = (0.61\pm0.02)\times\mathbf{10^{-9}}$$

More CP-violation

(from unknown source) is required !

Standard Model



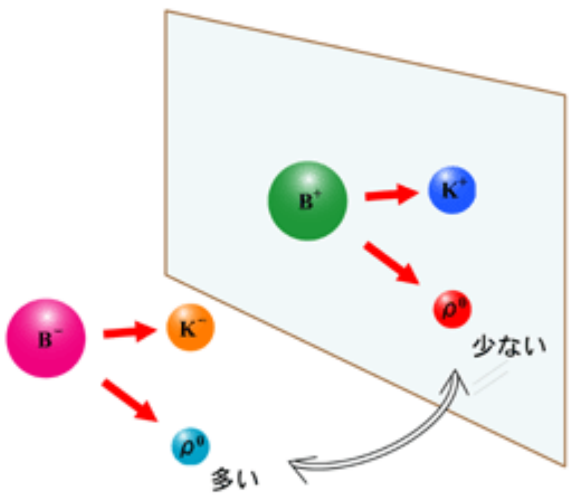
$$n_b/n_\gamma = \mathbf{10^{-18}}$$

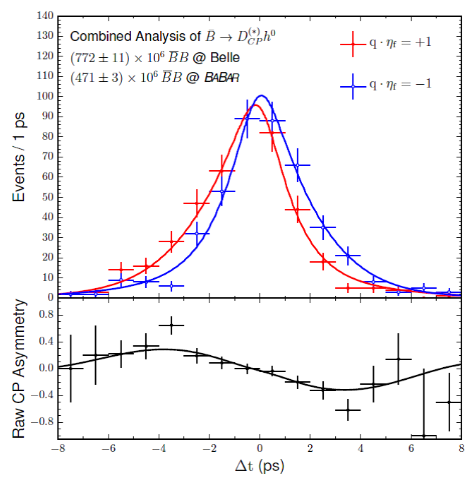
Spin for CP-violation search

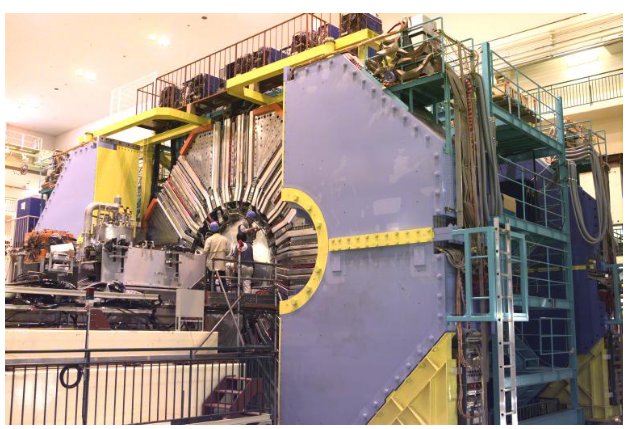
Time reversal symmetry violation
is equivalent to CP violation using CPT theorem.

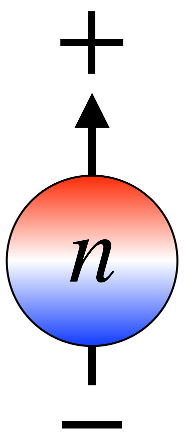
matter-antimatter asymmetry ↔ Time reversal asymmetry

CPT theorem







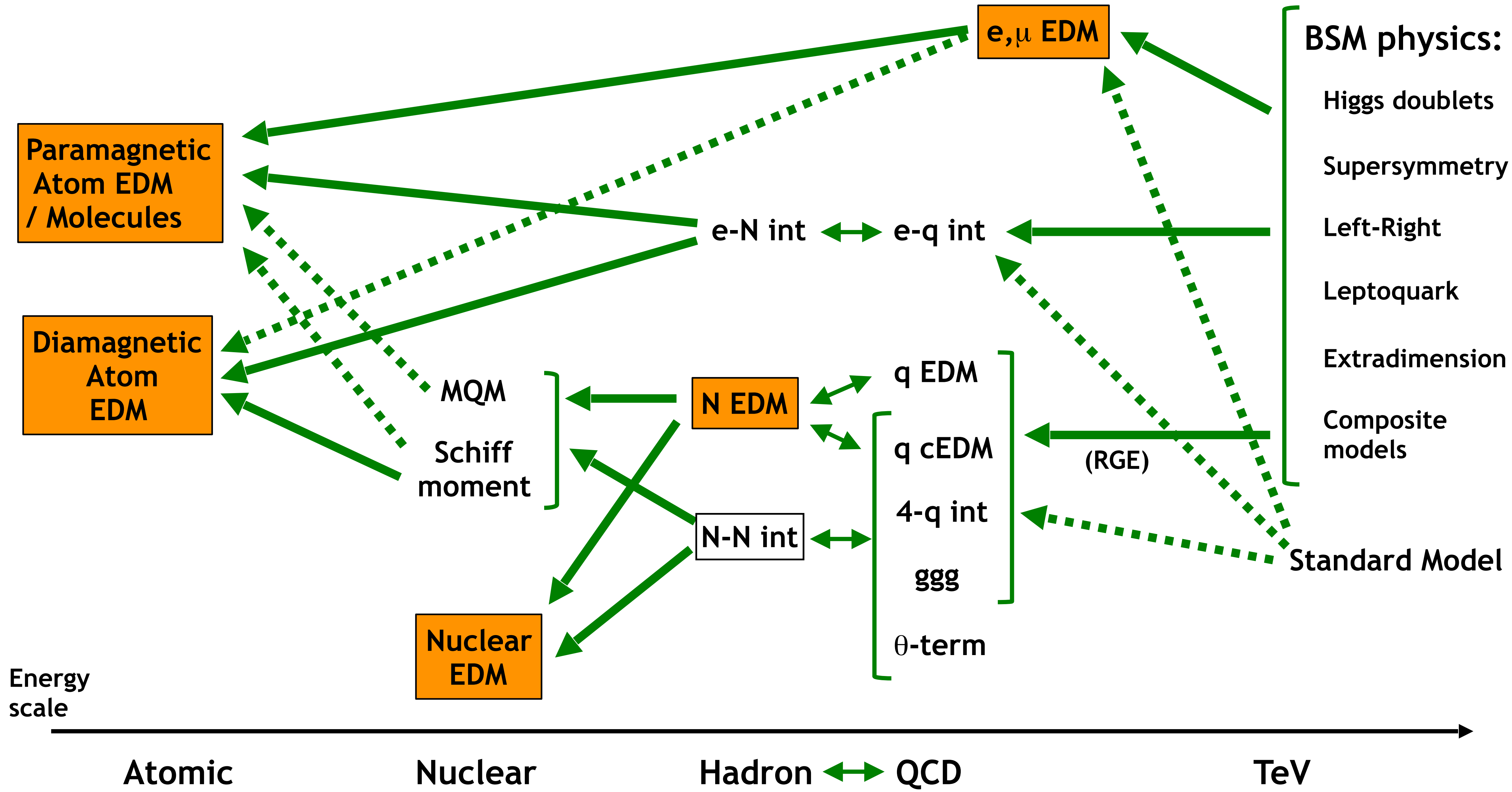


No antimatter needed.

➡ **"Spin" experiment**

Final state interaction can
be negligible (in some case).

T-violation search experiments (EDM)



observable : Observable available at experiment

: Sizable dependence

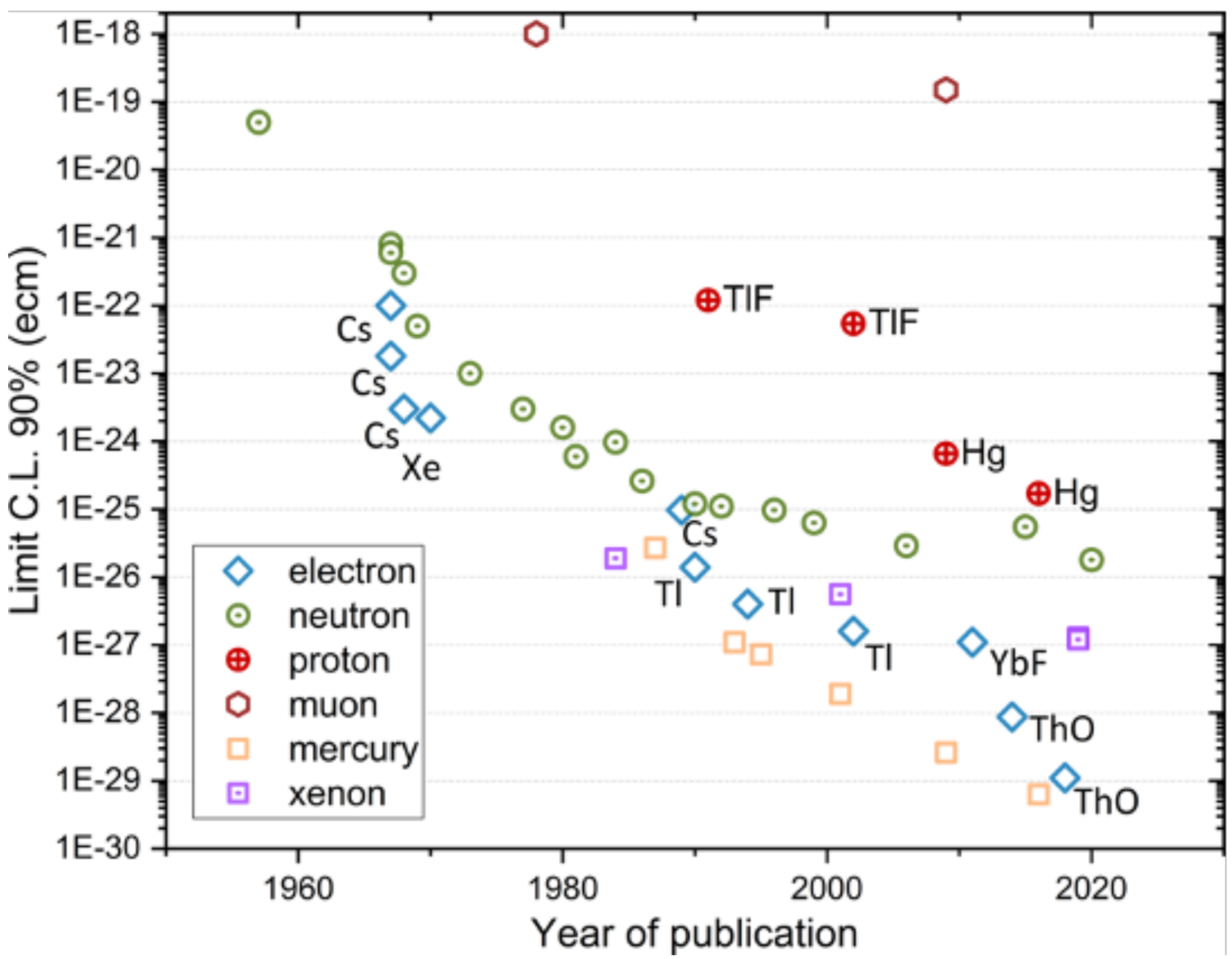
: Weak dependence

: Matching

Illustrated by N. Yamanaka

Various EDM search experiments

No finite value of EDM detected in various systems



K. Kirch and P. Schmidt-Wellenburg
EPJ Web of Conferences 234, 01007 (2020)

Upper limits :

electron EDM

$|d_e| < 1.6\times10^{-27}$ ecm Tl

$|d_e| < 1.1\times10^{-29}$ ecm ThO

$|d_e| < 4.1\times10^{-30}$ ecm HfF^{+}

muon EDM

$|d_\mu| < 1.5\times10^{-19}$ ecm g-2

neutron EDM

$|d_n| < 1.8 \times 10^{-26}$ ecm UCN

atomic EDM

$|d_{Xe}| < 1.2\times10^{-27}$ ecm ^{129}Xe

$|d_{Hg}| < 6.3\times10^{-30}$ ecm ^{199}Hg

Standard Model prediction

neutron : $d_n \simeq 10^{-32}$ ecm

electron : $d_e \simeq 10^{-38}$ ecm

-> If finite EDMs are found,
it is due to the physics
beyond the standard model !!

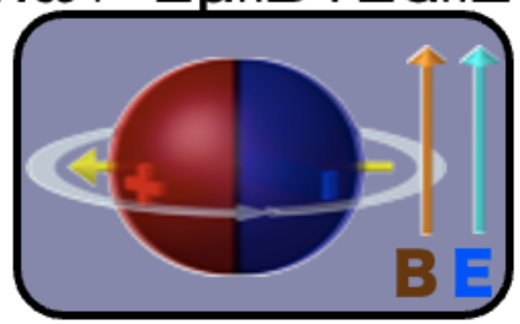
Neutron EDM

Ultra cold neutron

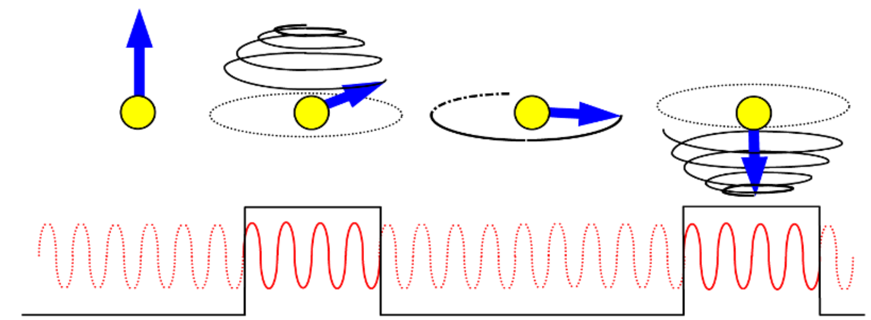
is very slow neutron with

Energy	~200 neV
Velocity	~5 m/s

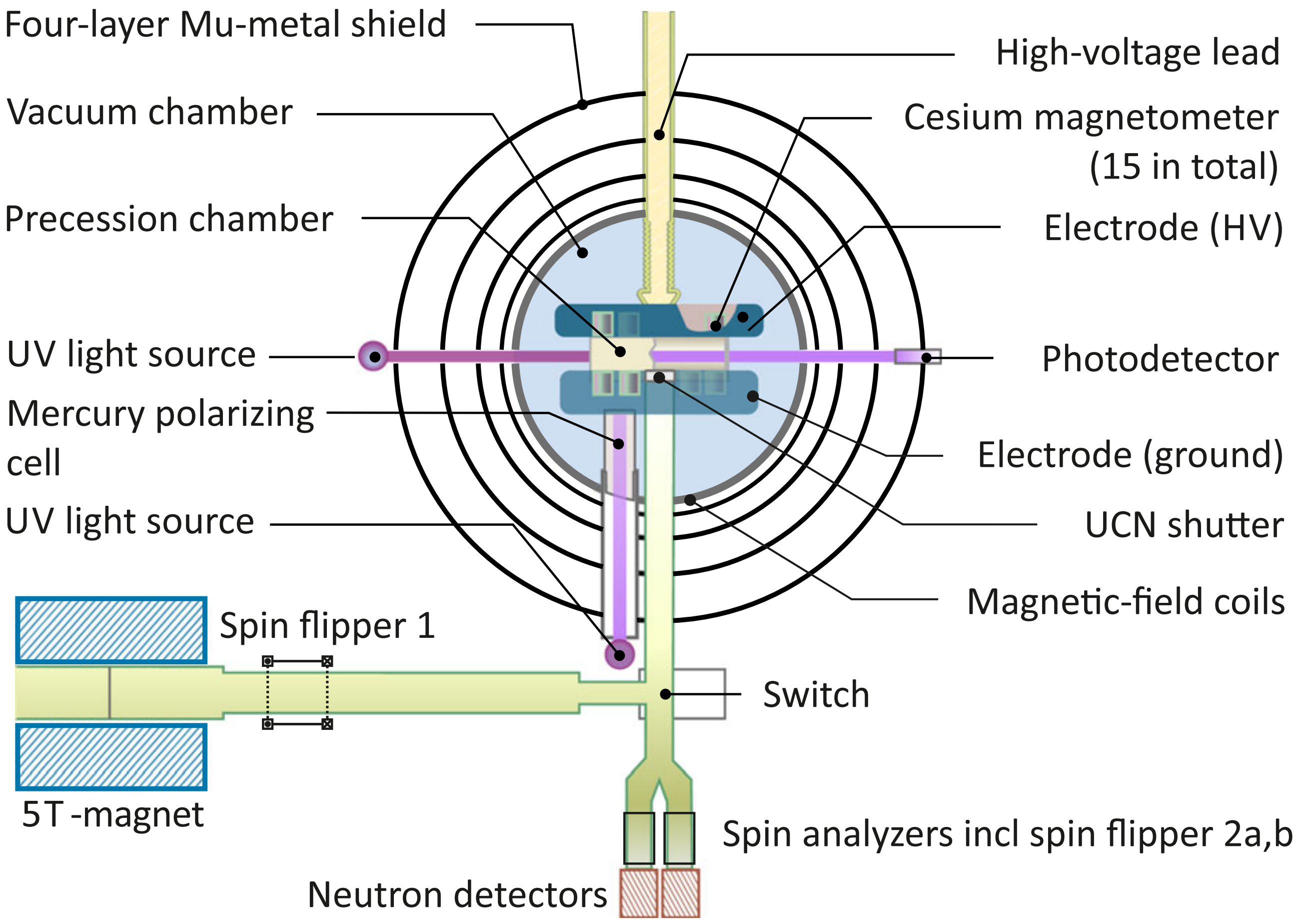
$$\hbar\omega_{+} = 2\mu_n B + 2d_n E$$

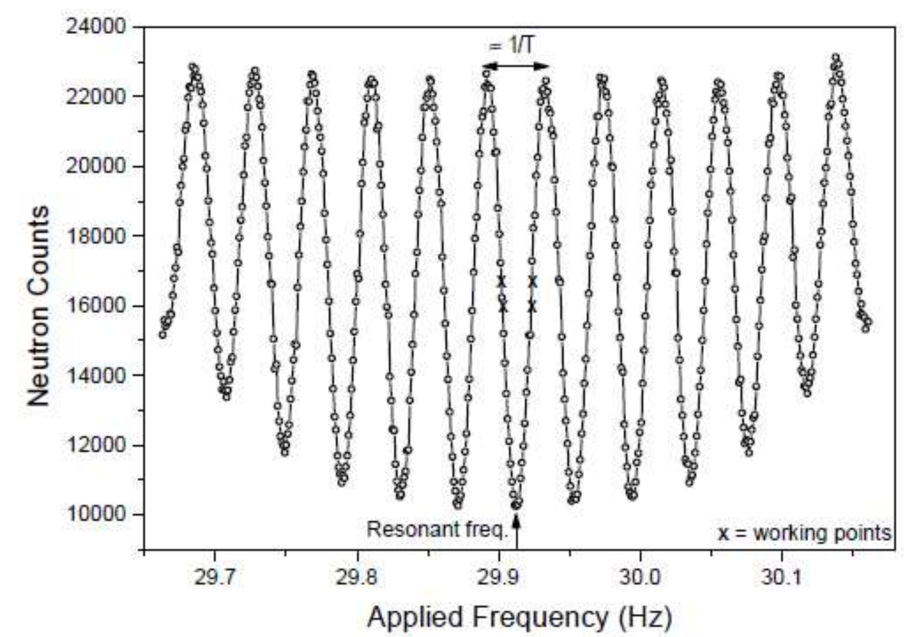


Spin flip by separated oscillating magnetic field (Ramsey resonance)



$$\hbar\omega = \begin{cases} -2\mu_n B_0 - 2d_n E \ (E\uparrow) \\ -2\mu_n B_0 + 2d_n E \ (E\downarrow) \end{cases} \rightarrow \Delta\omega = -\frac{4d_n E}{\hbar}$$





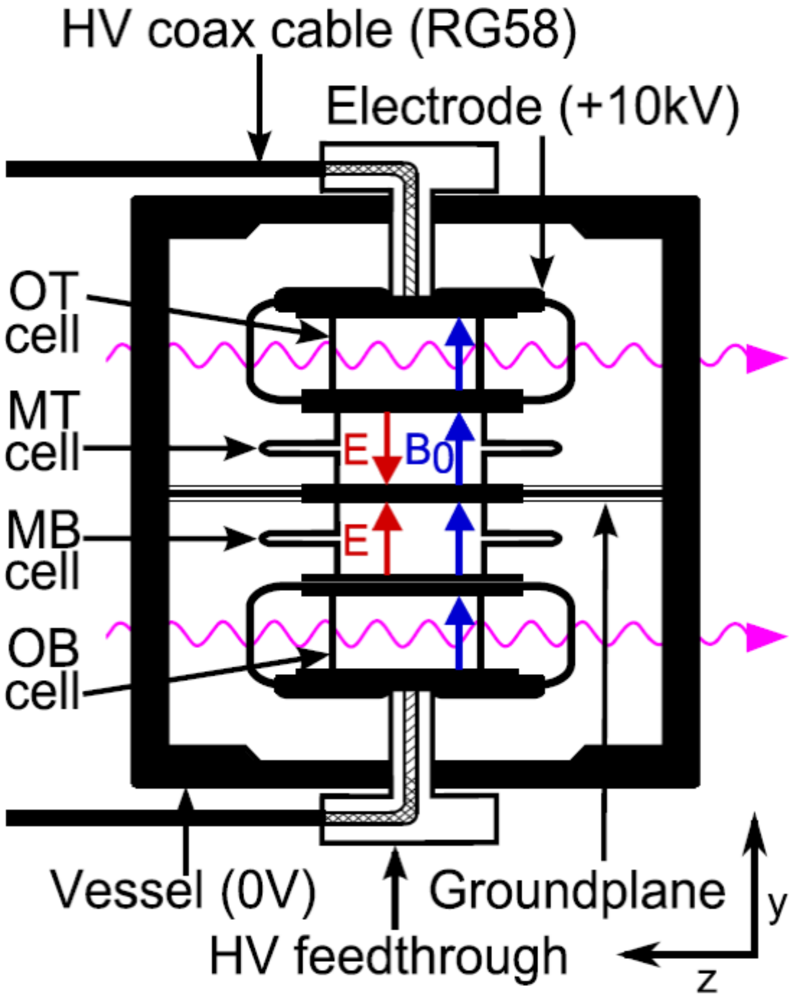
$$|d_n| < 1.5 \times 10^{-27}\ e\text{cm}$$

PSI (Switzerland)

C. Abel et al., Phys. Rev. Lett124, 081803 (2020)

Atomic EDM (diamagnetic)

^{199}Hg

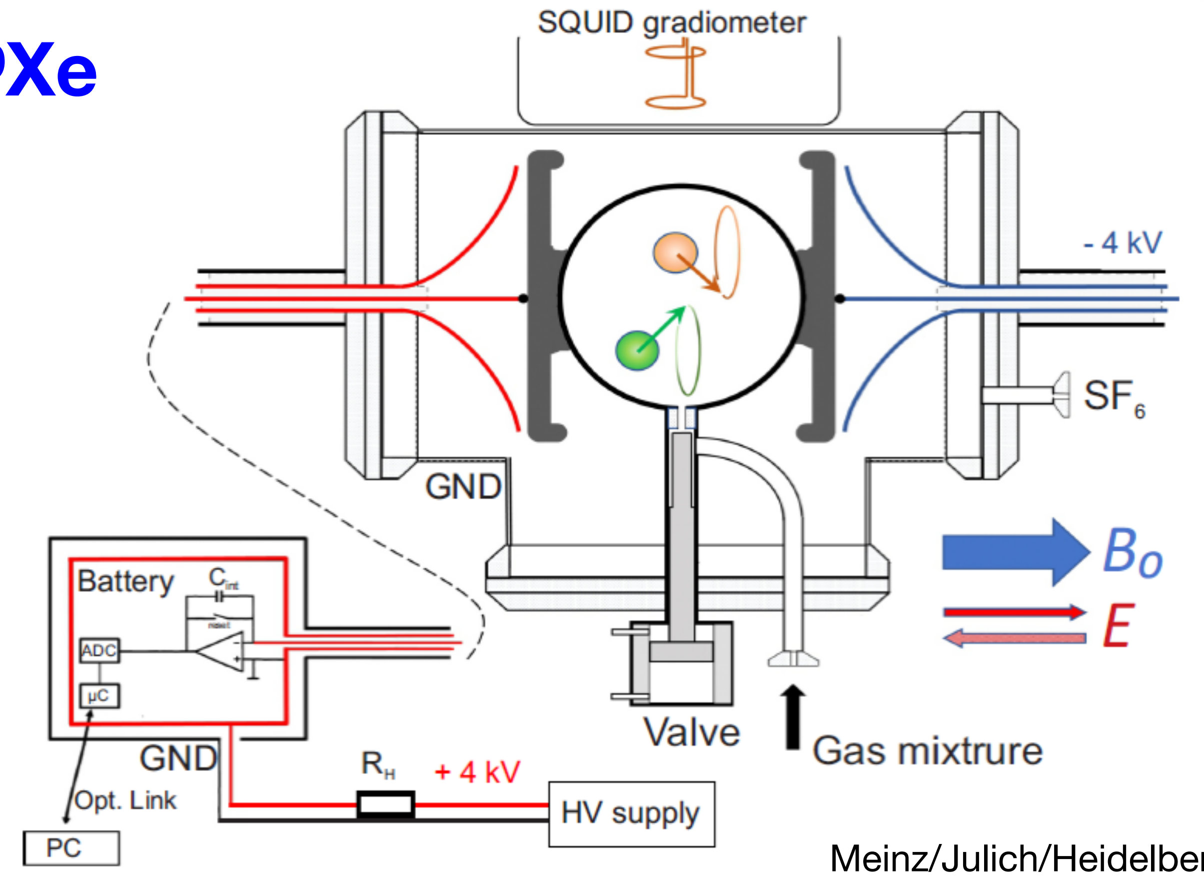


$$|d_{Hg}| < 7.4 \times 10^{-30}\ e\text{cm}$$

Seattle (USA)

Graner et al., Phys. Rev. Lett. 116,161601 (2016) .

^{129}Xe



Meinz/Julich/Heidelberg

Munchen/Michigan/Berlin/Julich

$$|d_{Xe}| < 4.8 \times 10^{-27}\ e\text{cm}$$

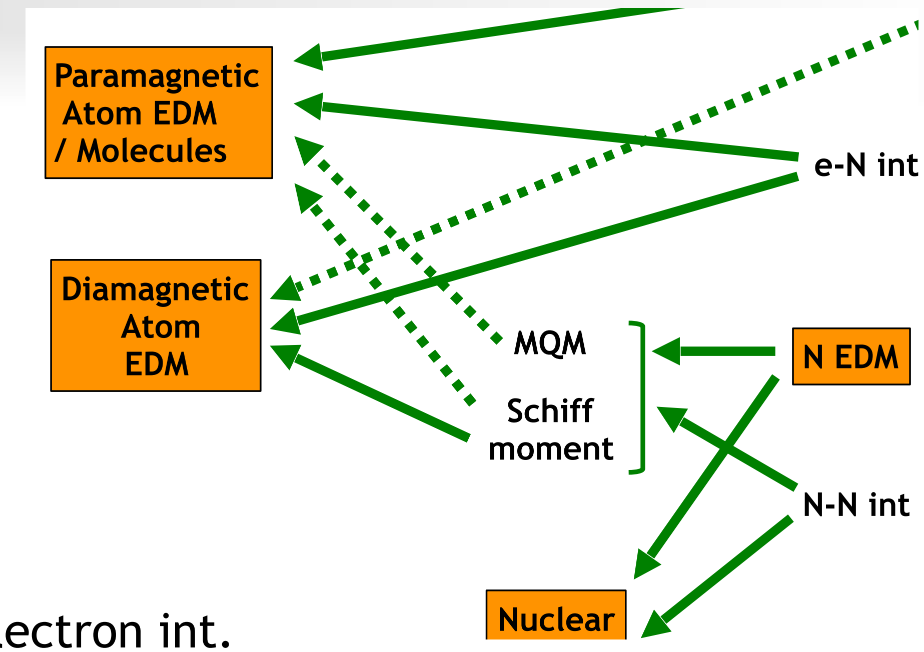
Sachdeva et al., arXiv 1902.02864

Meinz/Julich/Heidelberg

$$|d_{Xe}| < 1.5 \times 10^{-27}\ e\text{cm}$$

Allmendinger et al., arXiv 1904.12295

T violating coupling constants in nucleus



EDM measurements with various system (nucleon, nuclei, atom, molecules) are needed to deconvolute the couplings.

nucleon EDMs　　Nucleon-electron int.

$$d_{\rm dia} = \boxed{\alpha_{\rm Sch} S_{\rm Sch}} + \alpha_{d_{\rm p}} d_{\rm p} + \alpha_{d_{\rm n}} d_{\rm n} + \alpha_{C_{\rm T}^{(0)}} C_{\rm T}^{(0)} + \boxed{\alpha_{C_{\rm T}^{(1)}} C_{\rm T}^{(1)}}$$

$d_{\rm Hg}$: Vanishingly small contribution from $\bar{g}_{\pi NN}^{(1)}$

Coefficient values, from the compilation of: [J. Engel *et al.*, *Prog. Part. Nucl. Phys.* **71** (2013) 21]

$$d_{\rm Hg} = -\left(0.38^{+2.3}_{-0.19} \times 10^{-17}\right) \cdot \bar{g}_{\pi NN}^{(0)} + \left(0^{+1.6}_{-4.9} \times 10^{-17}\right) \cdot \bar{g}_{\pi NN}^{(1)} - \left(2.0^{+3.9}_{-0.0} \times 10^{-20}\right) \cdot C_{\rm T}$$

$$d_{\rm Xe} = -\left(0.29^{+2.3}_{-0.11} \times 10^{-18}\right) \cdot \bar{g}_{\pi NN}^{(0)} - \left(0.22^{+1.7}_{-0.11} \times 10^{-18}\right) \cdot \bar{g}_{\pi NN}^{(1)} + \left(4^{+2}_{-0} \times 10^{-21}\right) \cdot C_{\rm T}$$

$$d_{\rm n} = -\left(1.5 \times 10^{-14}\right) \cdot \bar{g}_{\pi NN}^{(0)} + \left(1.4 \times 10^{-16}\right) \cdot \bar{g}_{\pi NN}^{(1)}$$

$d_{\rm n}$: No contribution from $C_{\rm T}$

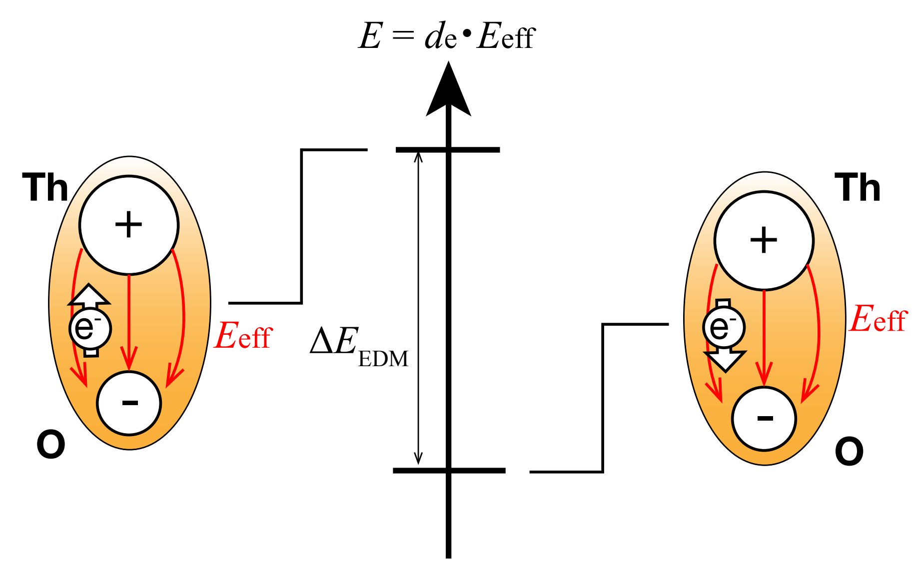
Atomic and molecular EDM

EDM measurement with polar molecules has been realized since 2010. Measurement sensitivity has been greatly improved by using the large effective electric field inside molecules.

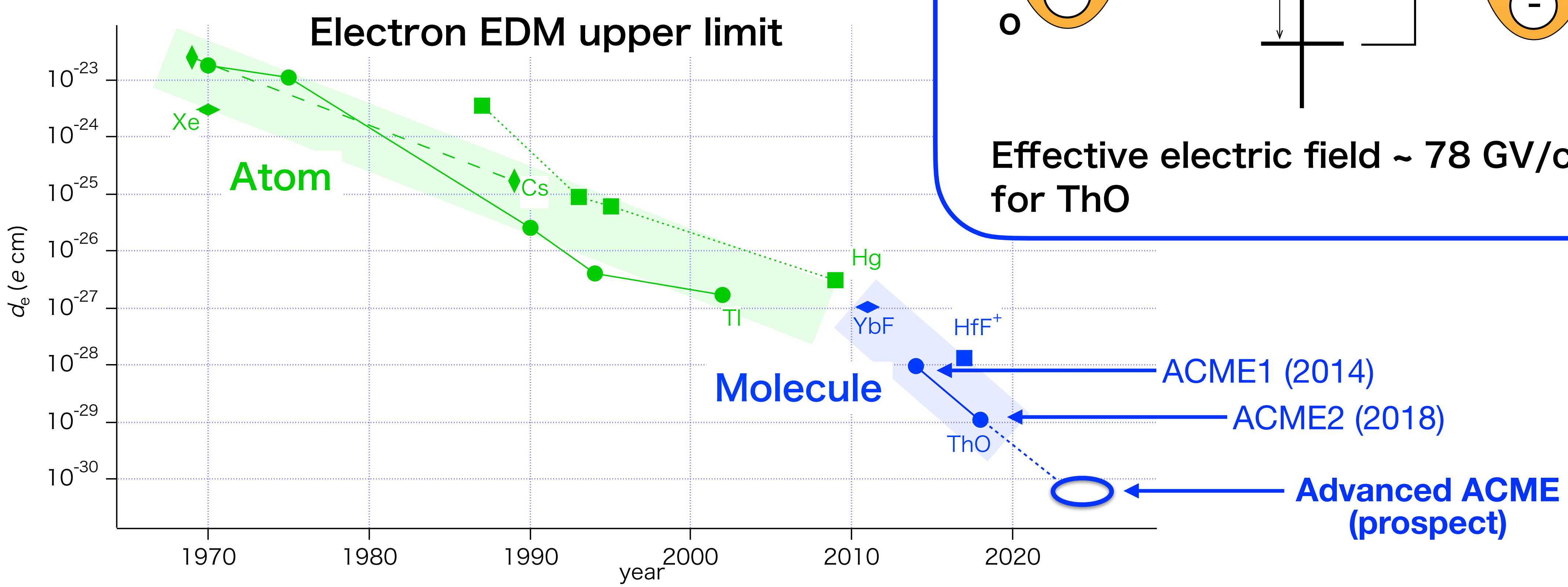
YbF : Hinds2011(Imperial College), $|d_e|<10^{-27}$ e cm

ThO : ACME2 Collaboration 2018, $|d_e|<1.1 \times 10^{-29}$ e cm

PbO, PbF, HfF+, HgF/BaF, RaF, TlF, YbHg, …



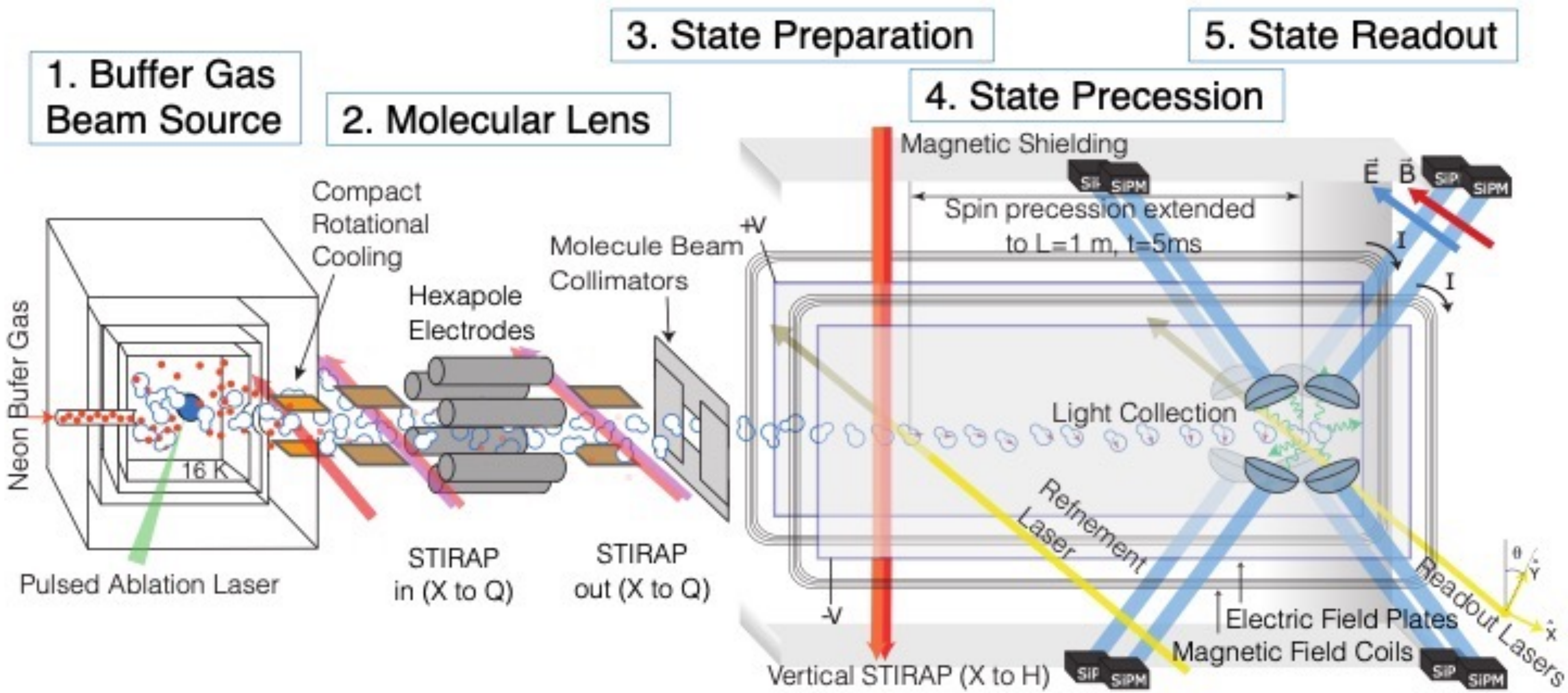
Effective electric field ~ 78 GV/cm for ThO



molecular EDM

ACME III experiment

ThO



x30 improvement

$$\Delta d_e \sim \frac{\hbar}{E_{\mathrm{eff}}\tau}\frac{1}{\sqrt{\dot{n}_{\mathrm{mol}}T}}\sqrt{\frac{F}{\varepsilon_{\mathrm{det}}}}$$

Projected Improvement	Signal gain	EDM sensitivity
Longer precession time	0.27	2.6
Molecular lens	12.0	3.4
Photon detector upgrade	2.7	1.6
Improved collection optics	1.6	1.3
Timing jitter noise	1.0	1.7
Total	14.0	31.2

Atomic EDM (isotope)

^{210}Fr Electron EDM enhanced

$T_{1/2}$~3min

	Rb	Cs	Fr
enhanced factor	27.5	114	**799**

Shitara, N., *et al.*, J. High Energ. Phys. **2021**(2021)124.

Fr isotopes are produced by beam, laser-cooled, and trapped in optical lattice.
The spin of the trapped Fr atom can be precisely measured.

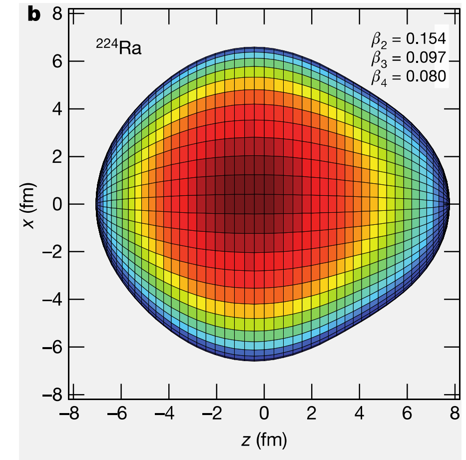
High intensity $^{18}O^{6+}$ beam from RIKEN AVF cyclotron

Fr^{+} beam production

^{211}Fr Nuclear EDM enhanced

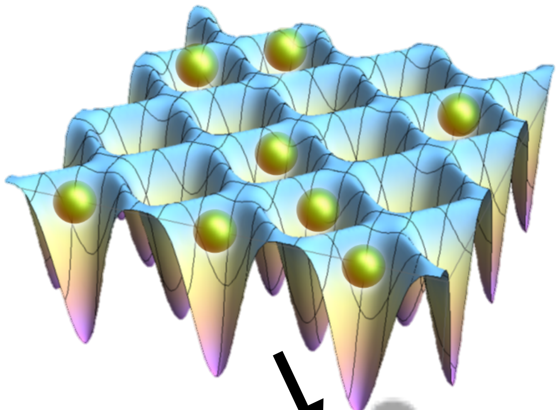
$T_{1/2}$~5min

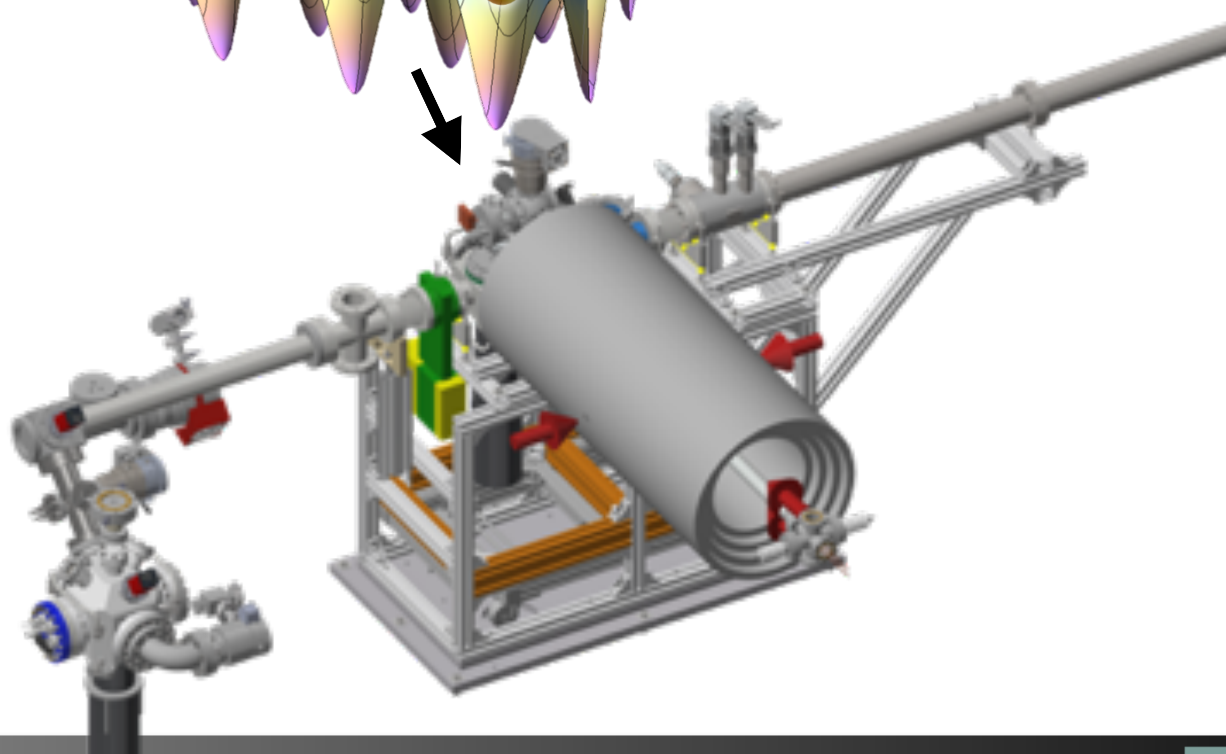
with Octupole deformation



Spevak, V., N. Auerbach, and V. V. Flambaum.. Physical Review C 56.3 (1997): 1357.

Fr MOT/LO
Optical lattice





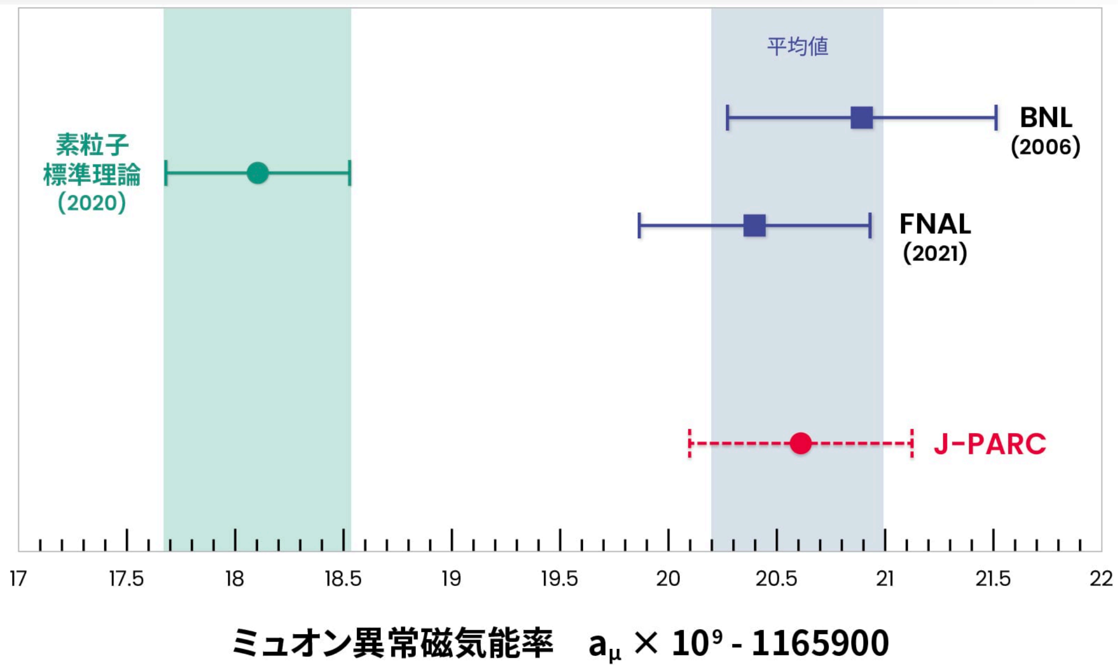
Muon g-2/EDM

μ g-2

FNAL confirmed BNL result.

4.1 σ discrepancy from SM

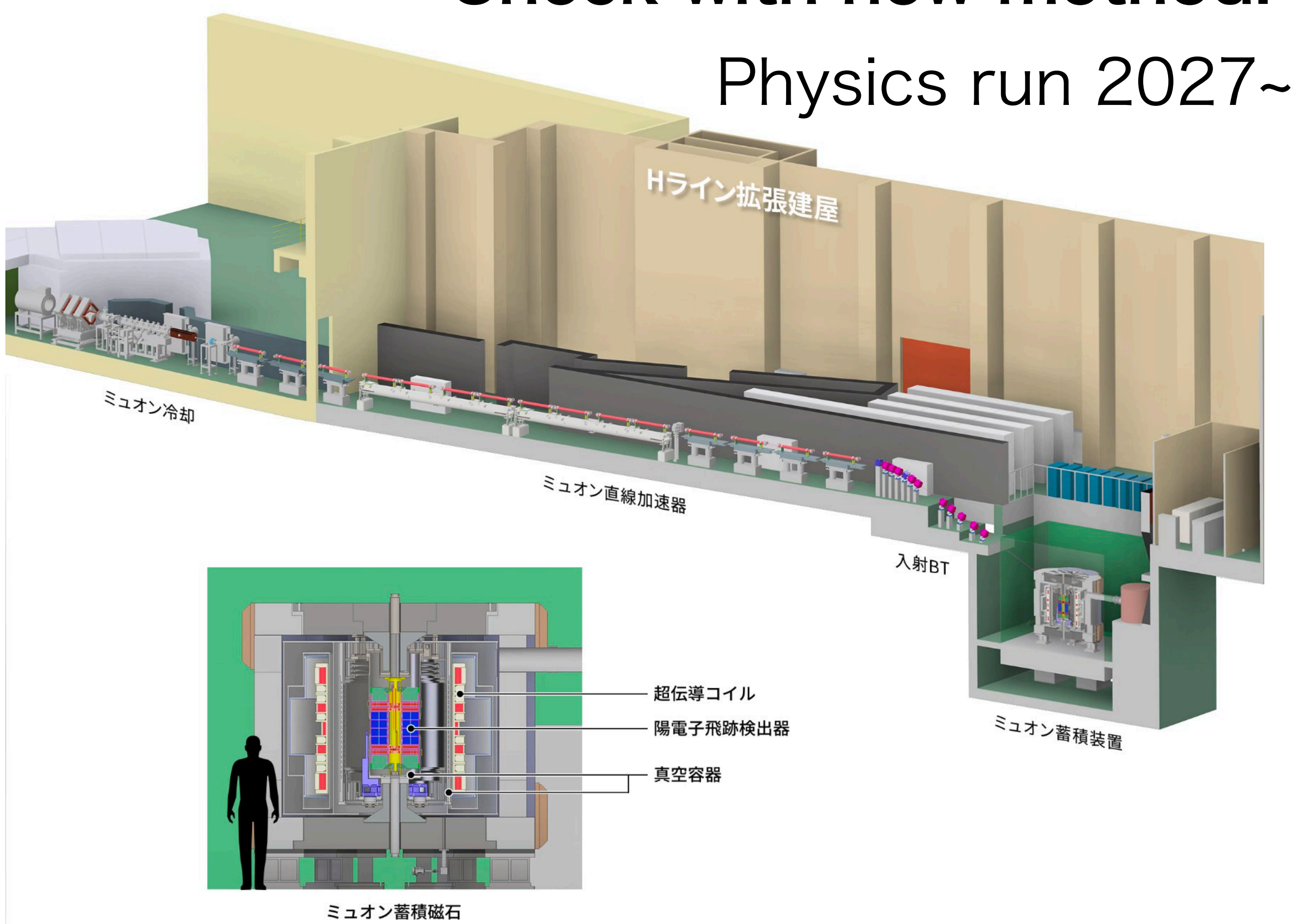
→ New physics?

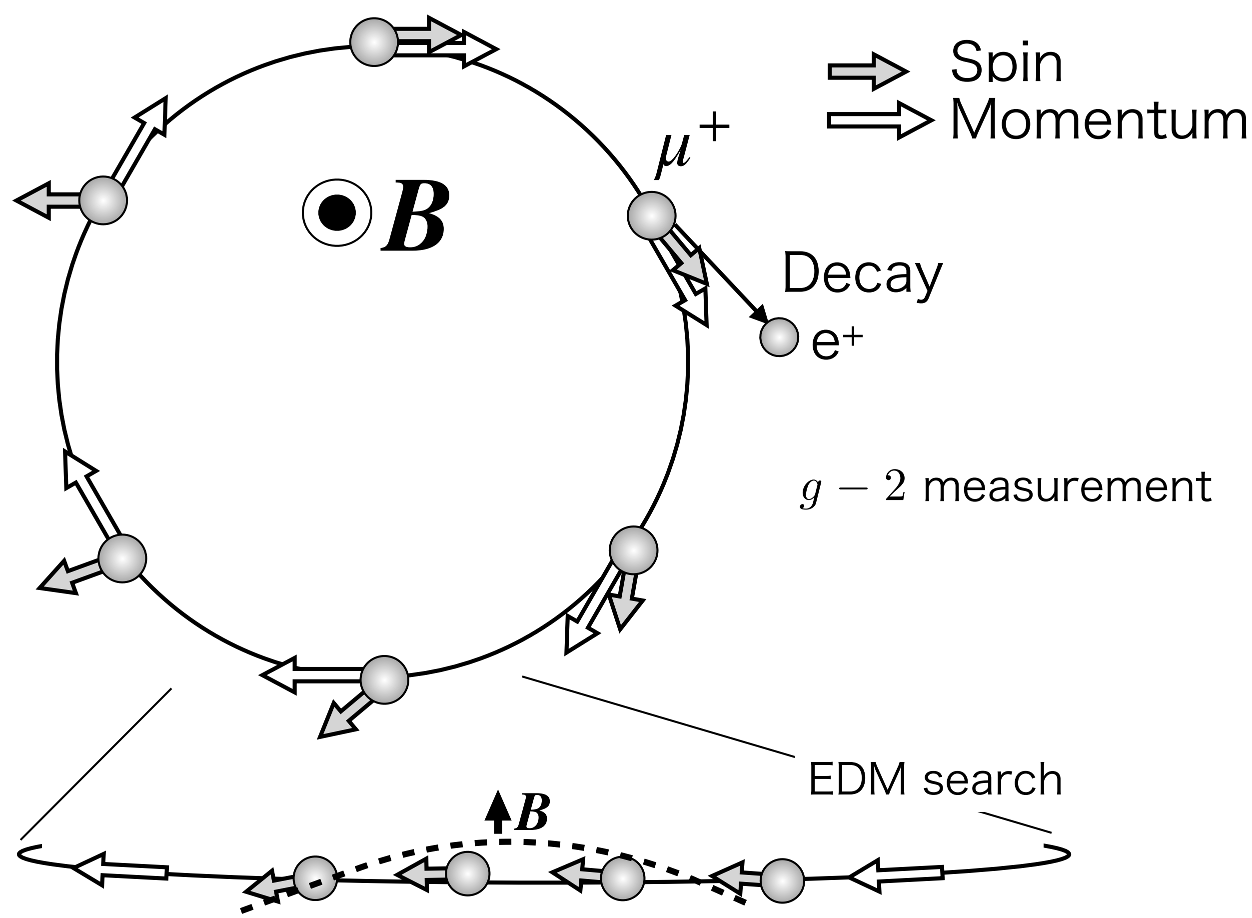


μ g-2/EDM at J-PARC

Check with new method.

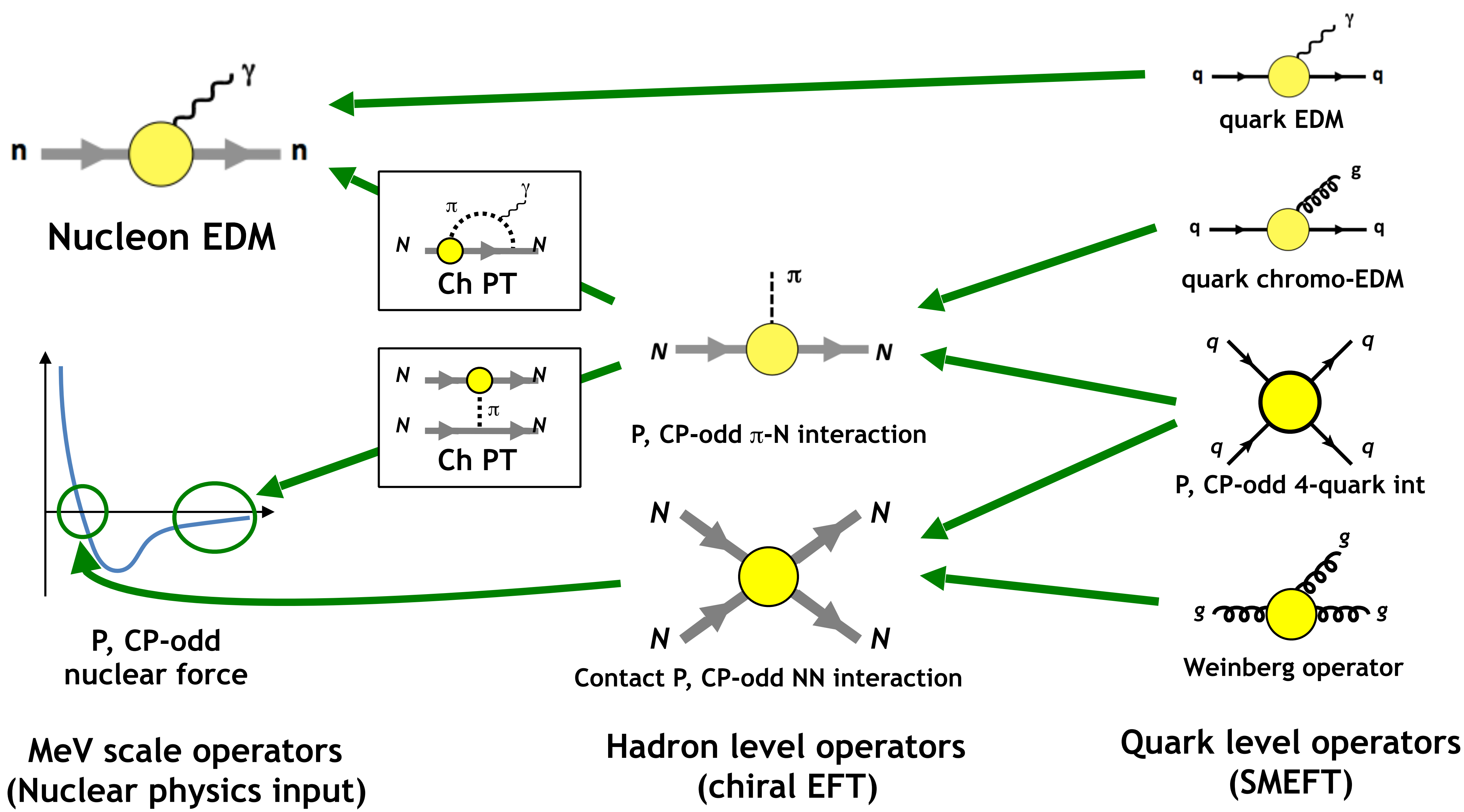
Physics run 2027~





T-violating nuclear interaction

CP-odd in nuclear interaction is also good probe.



J. de Vries et al., PRC 84, 065501 (2011) Illustrated by N. Yamanaka

T-violating nuclear interaction

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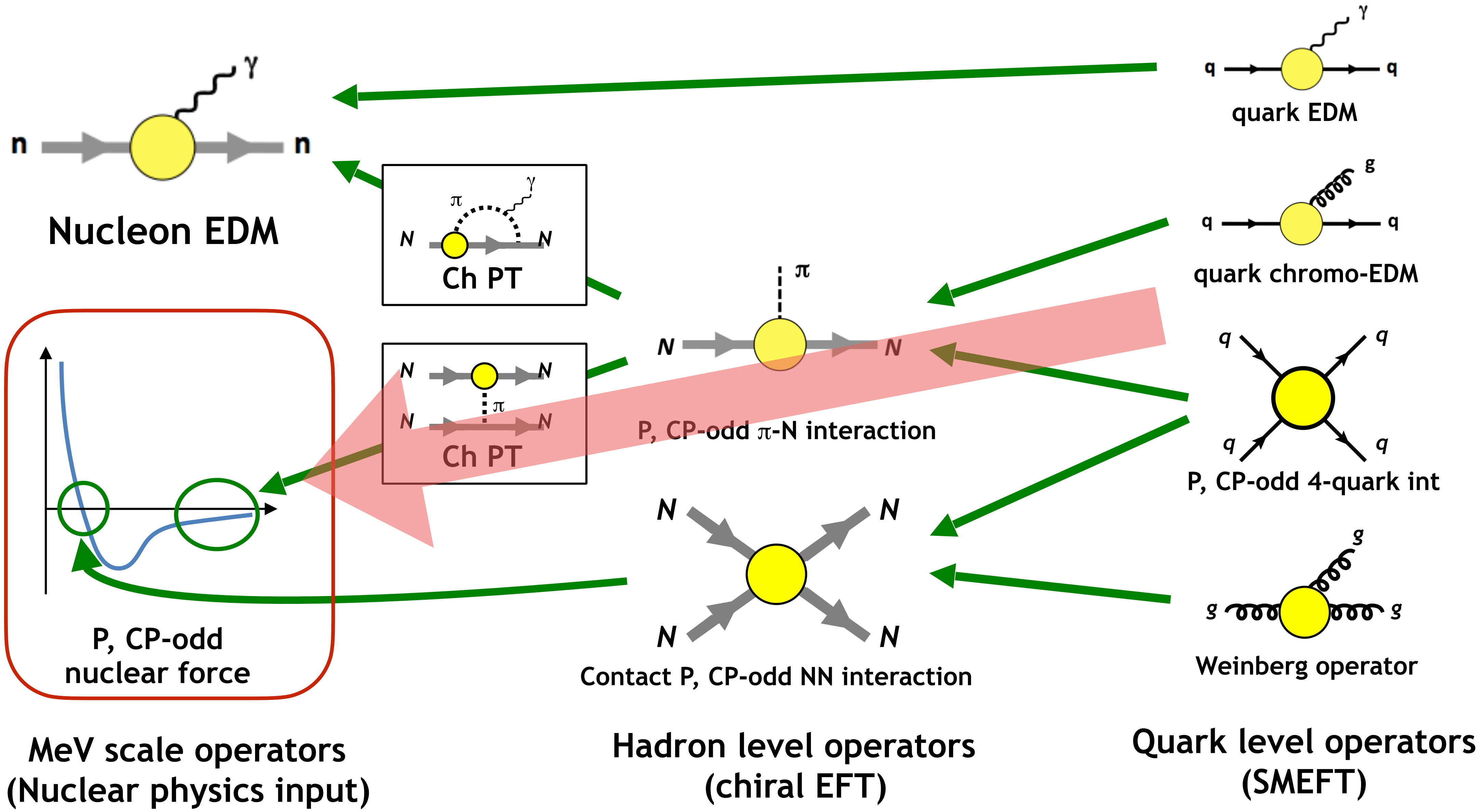


J. de Vries et al., PRC 84, 065501 (2011)   Illustrated by N. Yamanaka

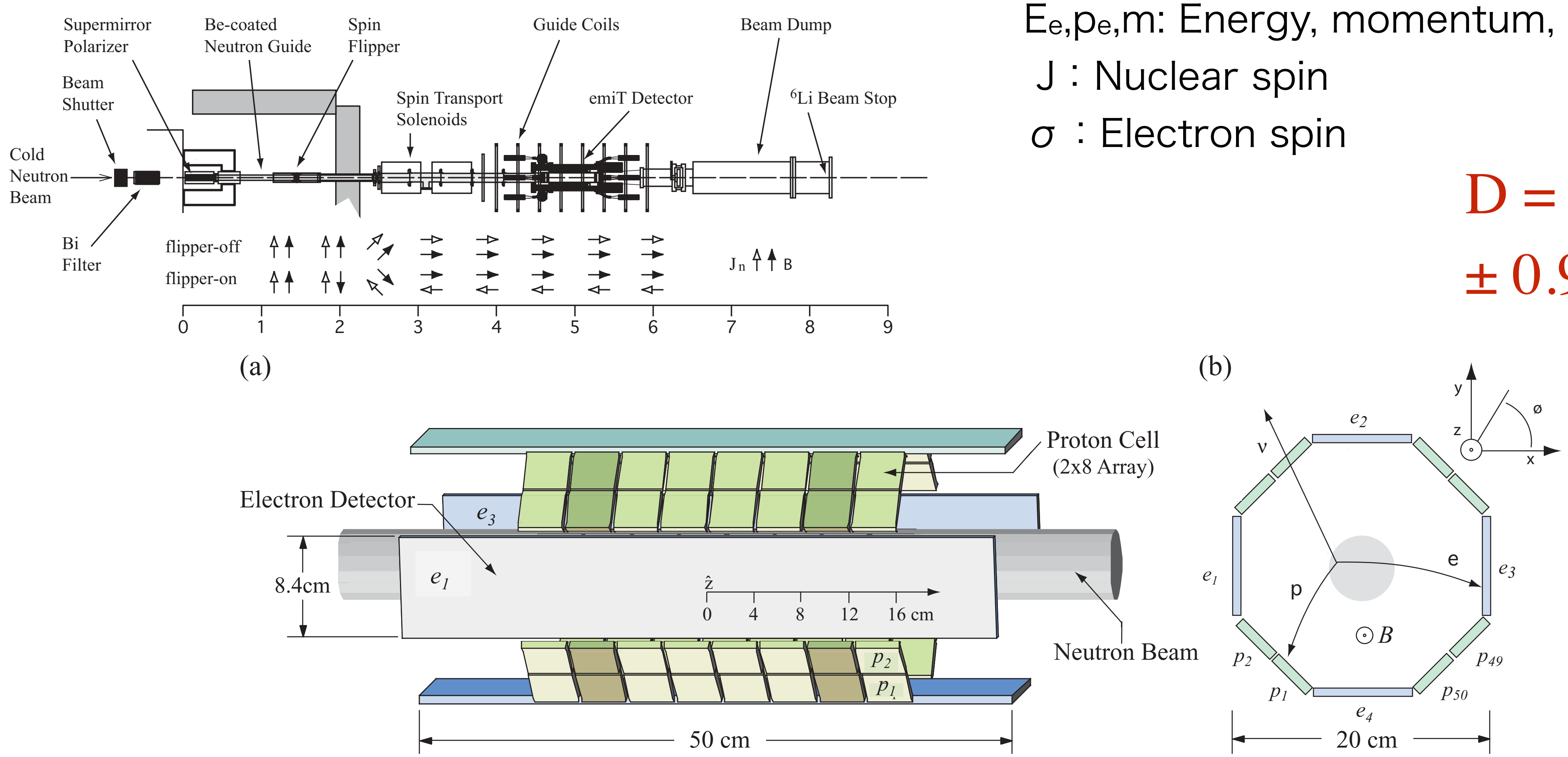
Triple correlation with neutron spin - electron - proton

Asymmetry of emitted electrons from polarized ^{8}Li.

$$\omega \propto 1 + A\frac{\vec{p_e}}{E_e}\cdot\frac{\langle\vec{J}\rangle}{J} + D\frac{\langle\vec{J}\rangle}{J}\cdot\left(\frac{\vec{p_e}}{E_e}\times\frac{\vec{p_\nu}}{E_\nu}\right) + R\vec{\sigma_e}\cdot\left(\frac{\langle\vec{J}\rangle}{J}\times\frac{\vec{p_e}}{E_e}\right) + \cdots$$

E_e,p_e,m: Energy, momentum, mass of electron
J : Nuclear spin
σ : Electron spin

D = [−0.94 ± 1.89(stat) ± 0.97(sys)] × 10^{-4}

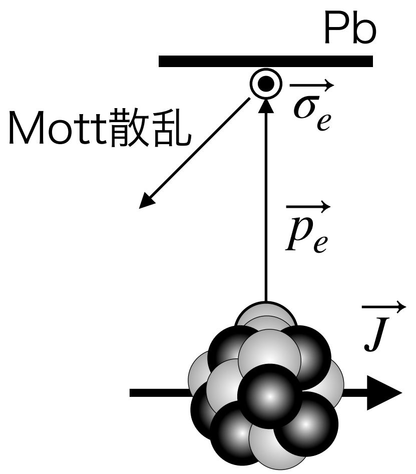


T. E. Chupp et al., PRC 86, 035505 (2012)

Triple correlation with ^{8}Li spin - p_e - σ_e

Asymmetry of momentum and polarization direction of emitted electrons from polarized ^{8}Li.

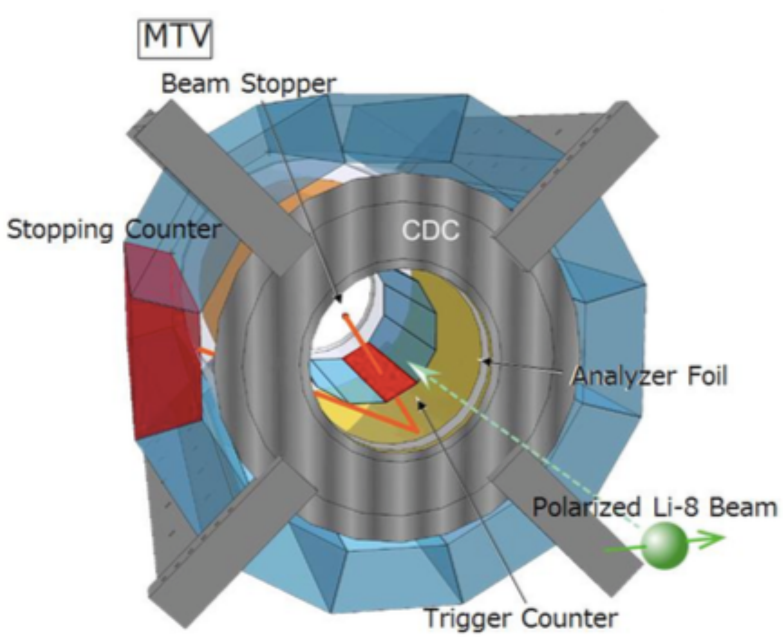
$$\omega \propto 1 + A\frac{\vec{p_e}}{E_e}\cdot\frac{\langle\vec{J}\rangle}{J} + D\frac{\langle\vec{J}\rangle}{J}\cdot\left(\frac{\vec{p_e}}{E_e}\times\frac{\vec{p_\nu}}{E_\nu}\right) + R\vec{\sigma_e}\cdot\left(\frac{\langle\vec{J}\rangle}{J}\times\frac{\vec{p_e}}{E_e}\right) + \cdots$$



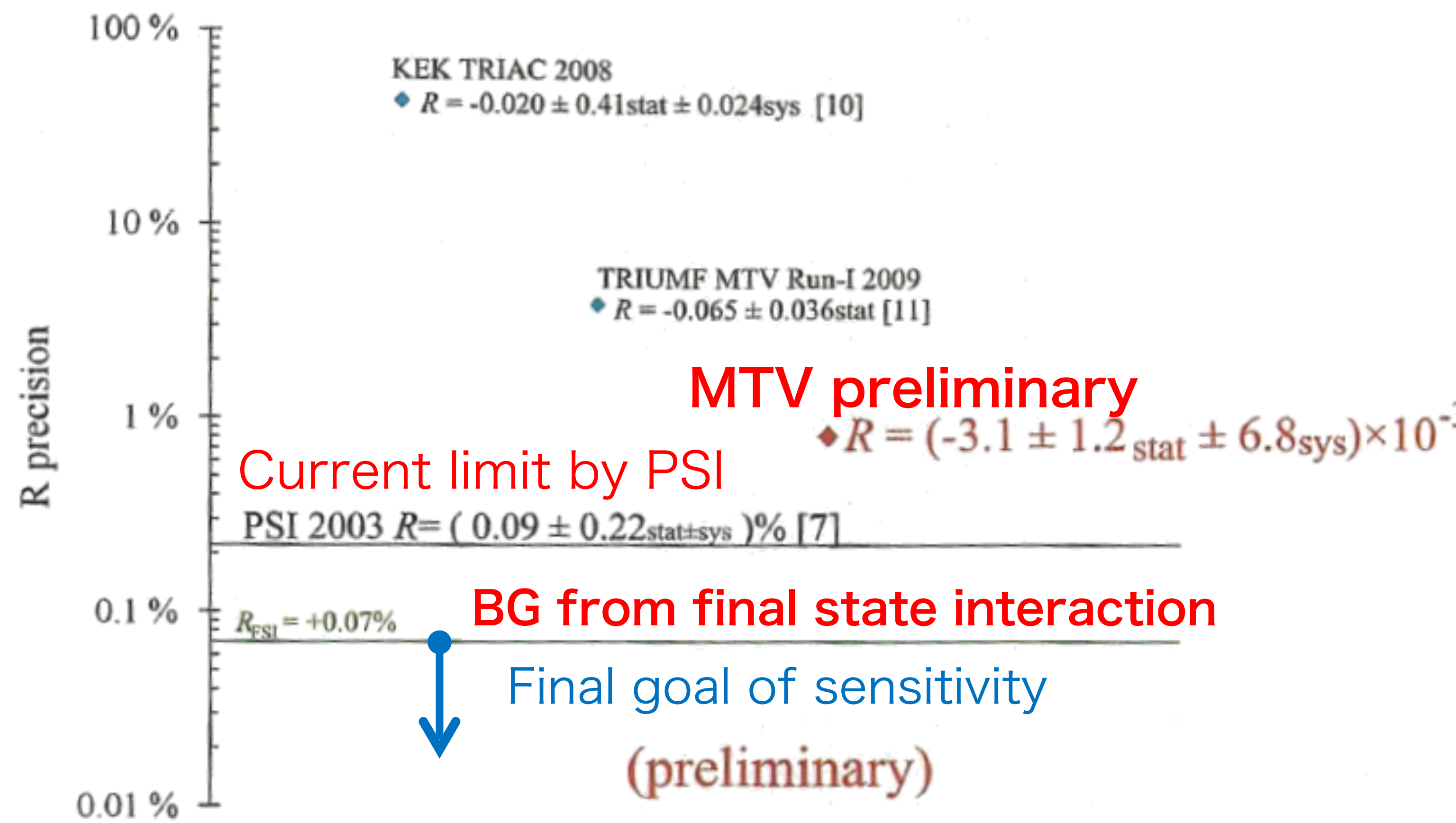
E_e, E_ν, p_e, p_ν : Energy and momentum of e and ν

J : Nuclear spin

σ : Electron spin

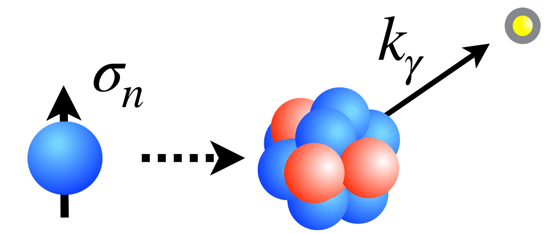


R. Tamiya, Master thesis (2014)



Parity violation in compound nucleus reactions

1974年 **Large party violation was found in angular distribution of $^{113}\mathrm{Cd}(\vec{\mathrm{n}},\gamma)^{114}\mathrm{Cd}$ for meV neutrons**



$$W(\theta) = \mathrm{const.}\,(1 + A_\gamma \vec{\sigma_n} \cdot \vec{k_\gamma})$$

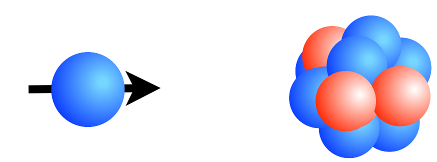
P-odd

$$A_\gamma = -(4.1 \pm 0.8) \times 10^{-4}$$

NPDγ : $A_\gamma \sim 10^{-8}$

1976年 **Angular distribution of $^{117}\mathrm{Sn}(\vec{\mathrm{n}},\gamma)^{118}\mathrm{Sn}$**

1981年 **Longitudinal asymmetry in neutron absorption reaction for meV neutrons**



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

$$^{139}\mathrm{La} + \vec{\mathrm{n}} \;:\; A_\mathrm{L} = (34.3 \pm 5.3) \times 10^{-5}\ \mathrm{barn}$$
$$^{117}\mathrm{Sn} + \vec{\mathrm{n}} \;:\; A_\mathrm{L} = (4.6 \pm 0.5) \times 10^{-5}\ \mathrm{barn}$$
$$^{81}\mathrm{Br} + \vec{\mathrm{n}} \;:\; A_\mathrm{L} = (60.6 \pm 6.2) \times 10^{-5}\ \mathrm{barn}$$

$$A_\mathrm{L} \sim 10^{-4}$$

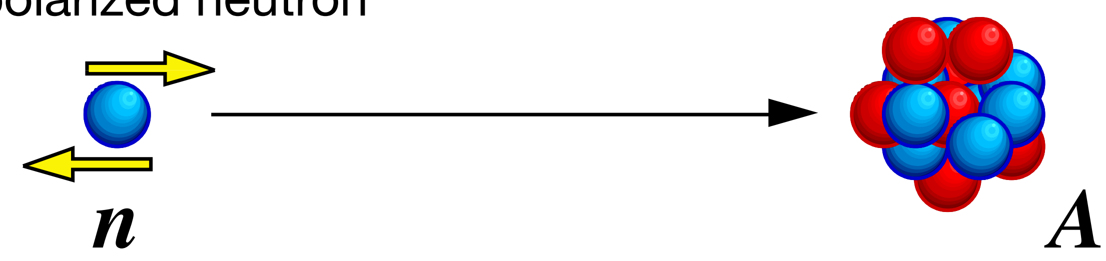
1981年 **Longitudinal asymmetry in neutron absorption reaction of $^{139}\mathrm{La} + \vec{\mathrm{n}}$ for 0.7eV neutrons**

$$A_\mathrm{L} = (9.56 \pm 0.35) \times 10^{-2}$$

1990年~ **Many isotopes** **TRIPLE collaboration at Los Alamos**

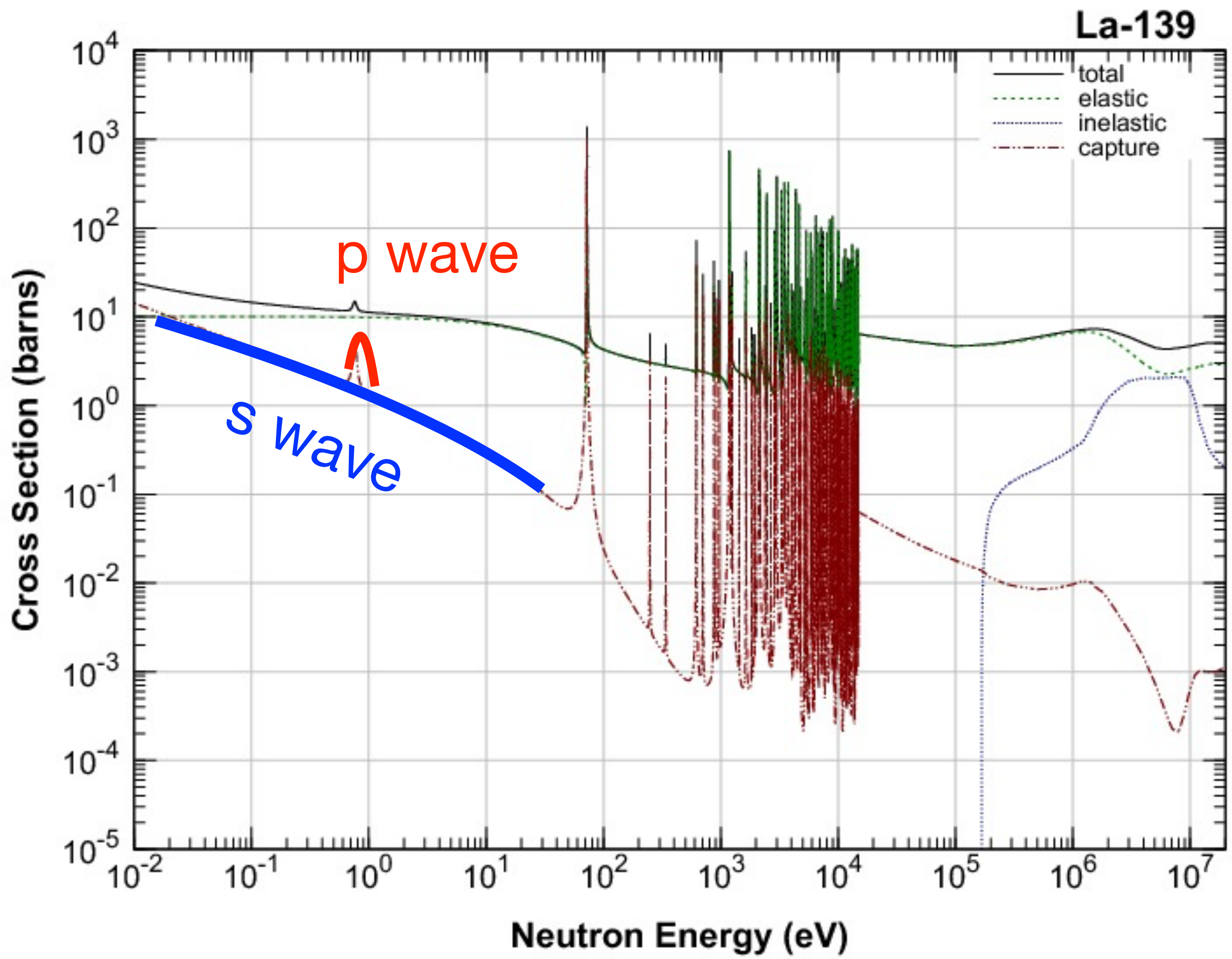
P-violation enhancement

neutron capture
around p-wave resonance



$$A_L = (9.56 \pm 0.35) \times 10^{-2}$$

^{139}**La** $\boldsymbol{E_n = 0.734}$ **eV**



P-violation is enhanced in
the interference between s-wave and p-wave
of compound nuclei.

T-violation in Compound Nuclei

T-violating interaction in nucleon-nucleon 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-violating interaction in nucleon-nucleon interaction

Conversion factor from P-violation to T-violation

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

Enhanced P-violation $\Delta\sigma_P$ → Enhanced T-violation $\Delta\sigma_T$

Angular momentum (recombination) factor

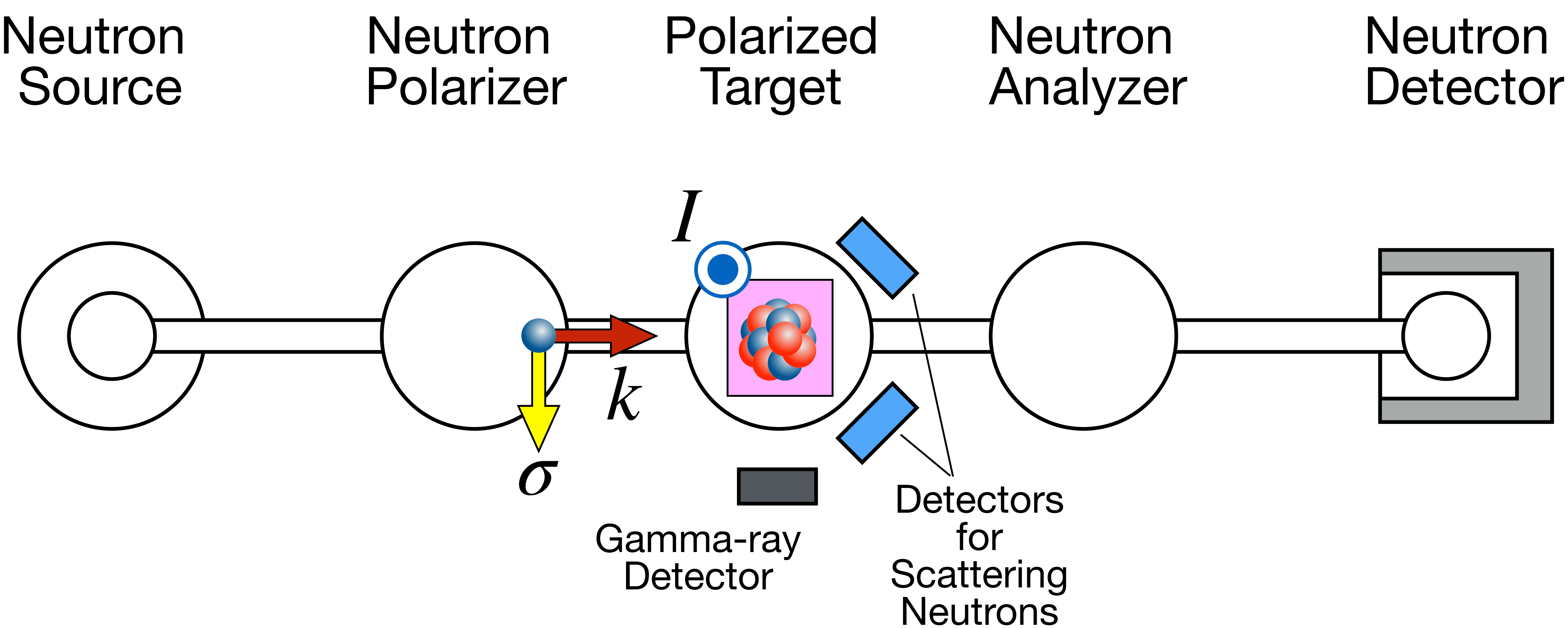
$$\kappa(J) = \begin{cases} (-1)^{2I}\left(1+\frac{1}{2}\sqrt{\frac{2I-1}{I+1}}\frac{y}{x}\right) & (J = I - \frac{1}{2}) \\ (-1)^{2I+1}\frac{I}{I+1}\left(1-\frac{1}{2}\sqrt{\frac{2I+3}{I}}\frac{y}{x}\right) & (J = I + \frac{1}{2}) \end{cases}$$

$$x = \sqrt{\frac{\Gamma_{\mathrm{n}}^{\mathrm{p},j=\frac{1}{2}}}{\Gamma_{\mathrm{n}}^{\mathrm{p}}}} \quad y = \sqrt{\frac{\Gamma_{\mathrm{n}}^{\mathrm{p},j=\frac{3}{2}}}{\Gamma_{\mathrm{n}}^{\mathrm{p}}}} \quad x^2 + y^2 = 1 \quad \begin{matrix} x = \cos\phi \\ y = \sin\phi \end{matrix}$$

Unknown parameter

Setup for T-violation experiment

Simple illustration of T-violation search experiment with polarized neutrons and target.



Forward scattering amplitude

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

spin independent cross section

Spin dependence

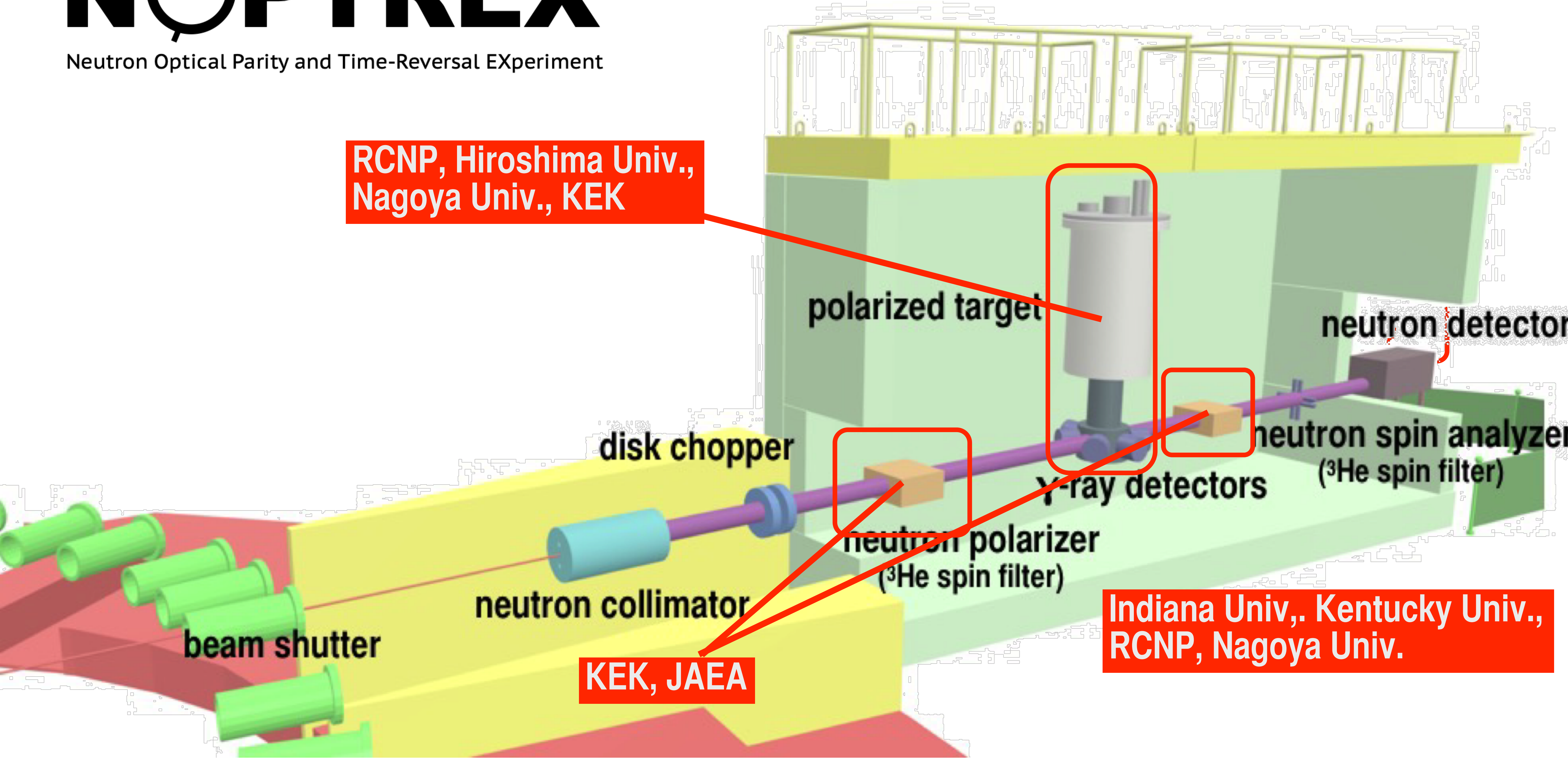
P-violation

T-violating cross section

T-violation experiment at J-PARC

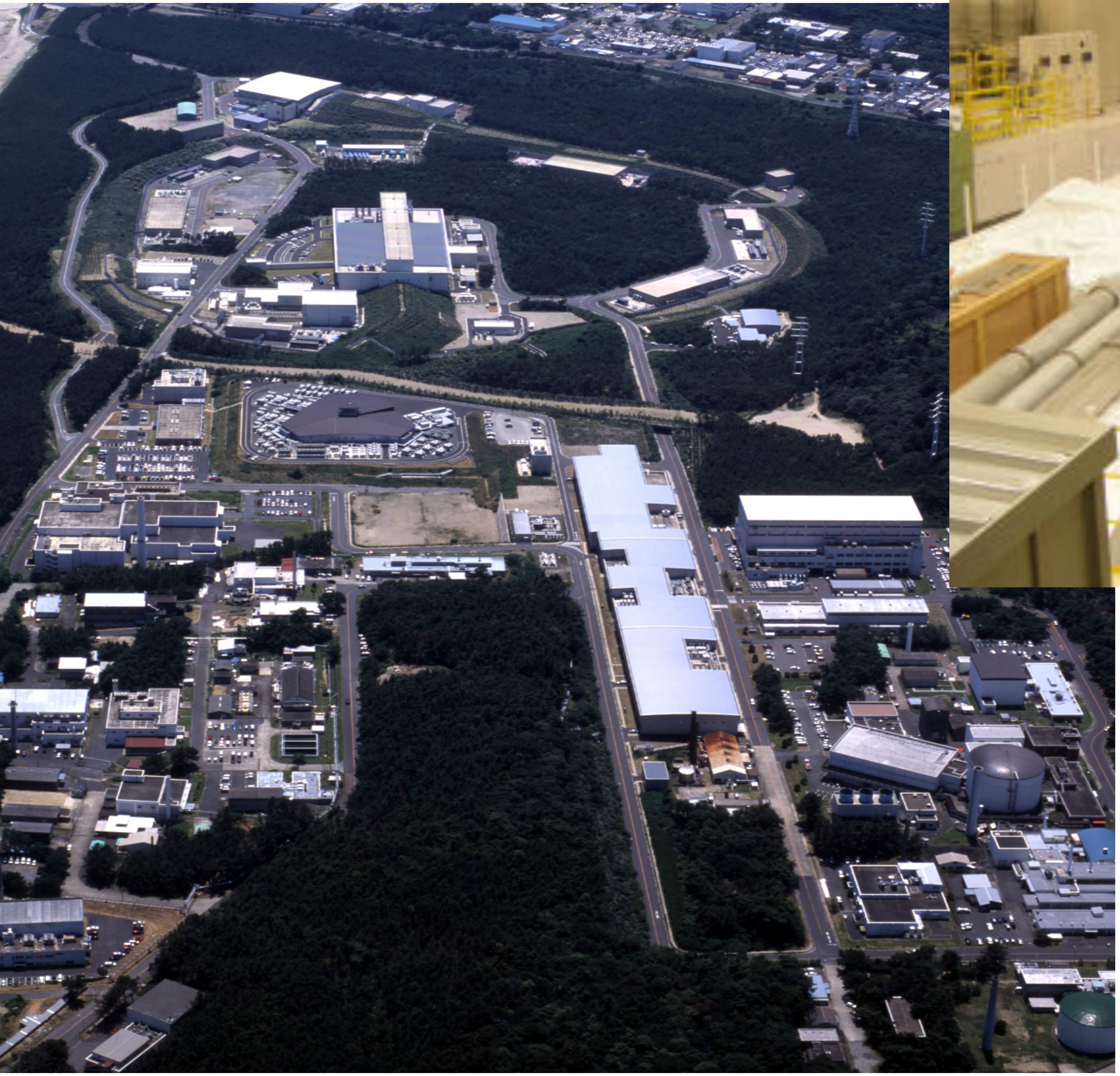
NOPTREX

Neutron Optical Parity and Time-Reversal EXperiment



J-PARC MLF

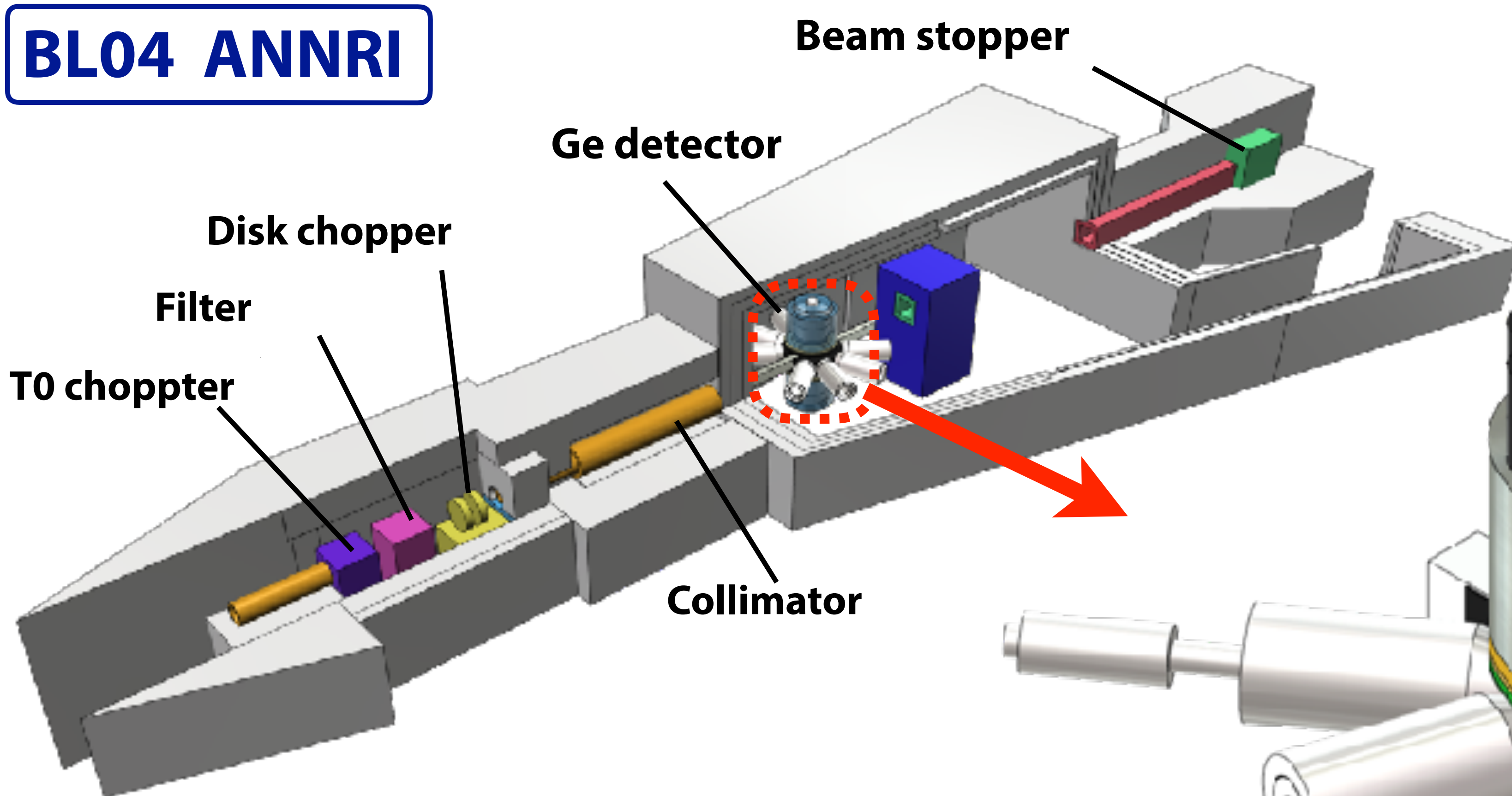
NOPTREX
Neutron Optical Parity and Time-Reversal EXperiment



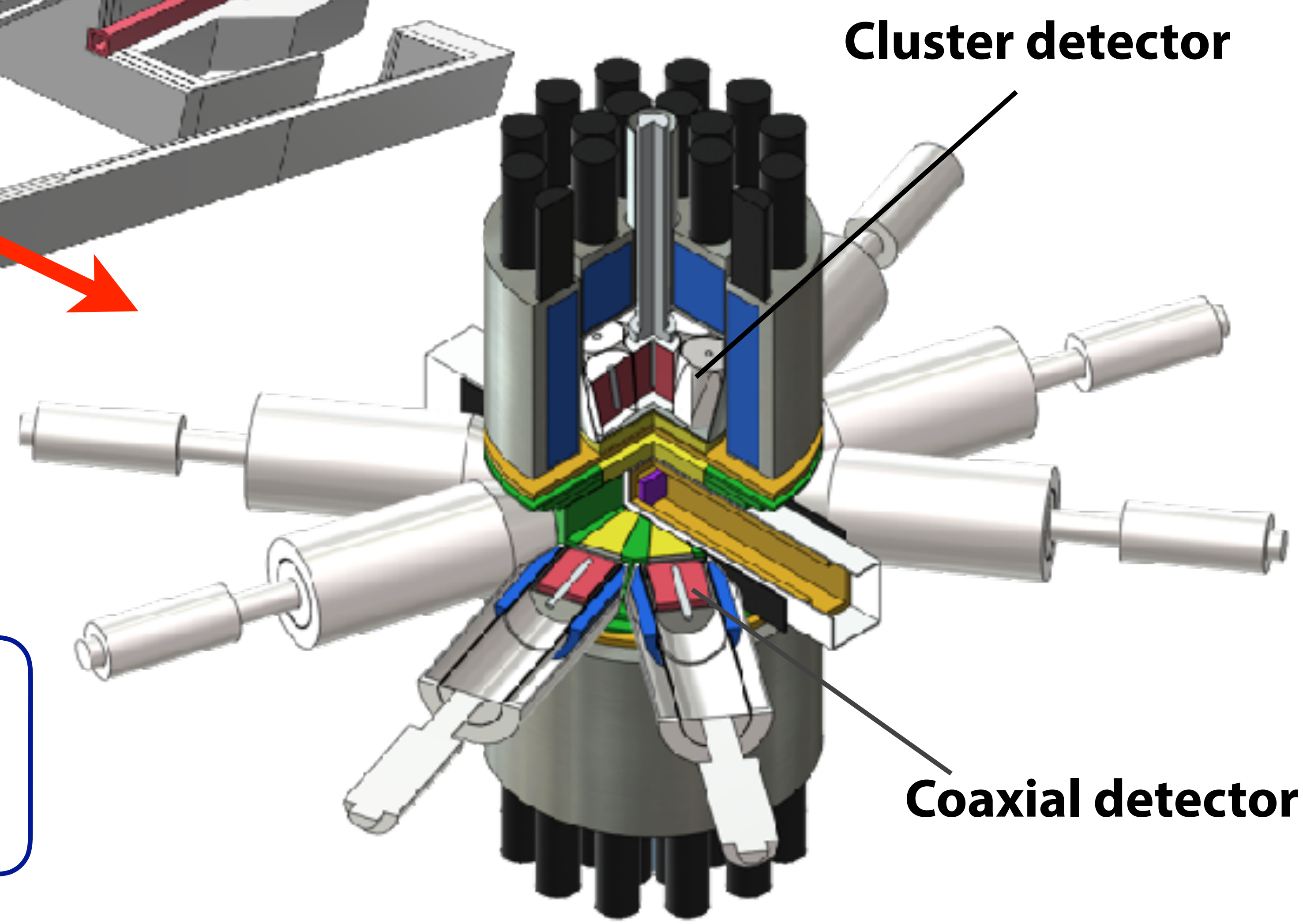
^{139}La (n, γ) measurement

NOPTREX
Neutron Optical Parity and Time-Reversal EXperiment

BL04 ANNRI



BL04 Ge Detector



2 Cluster Ge Detector 7ch ×2 : 14ch
8 Coaxial Ge Detector 8ch
22ch → 7 angles

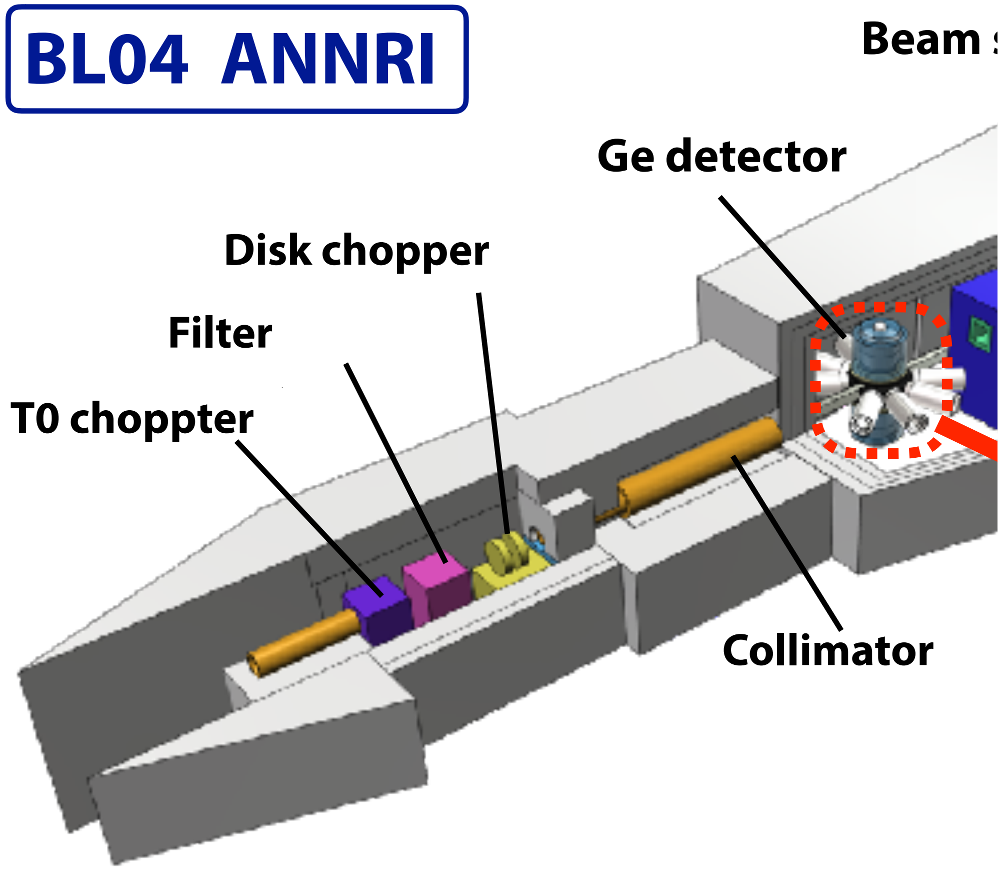
Targets : ^{nat}La 40mm x 40mm x 1mm

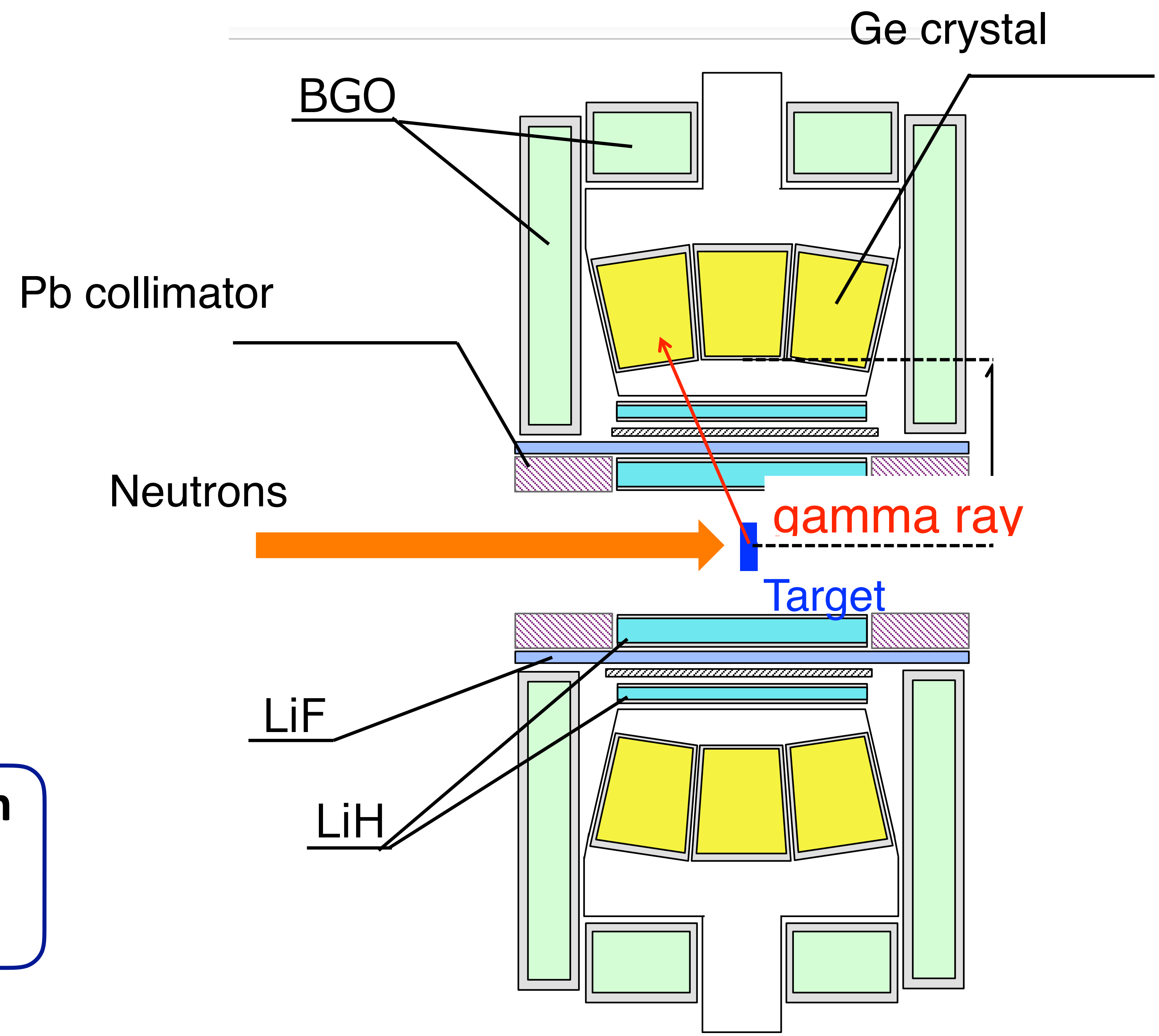
T. Okudaira et. al. , Phys. Rev. C97 (2018) 034622.

^{139}La (n, γ) measurement

NOPTREX
Neutron Optical Parity and Time-Reversal EXperiment

BL04 ANNRI





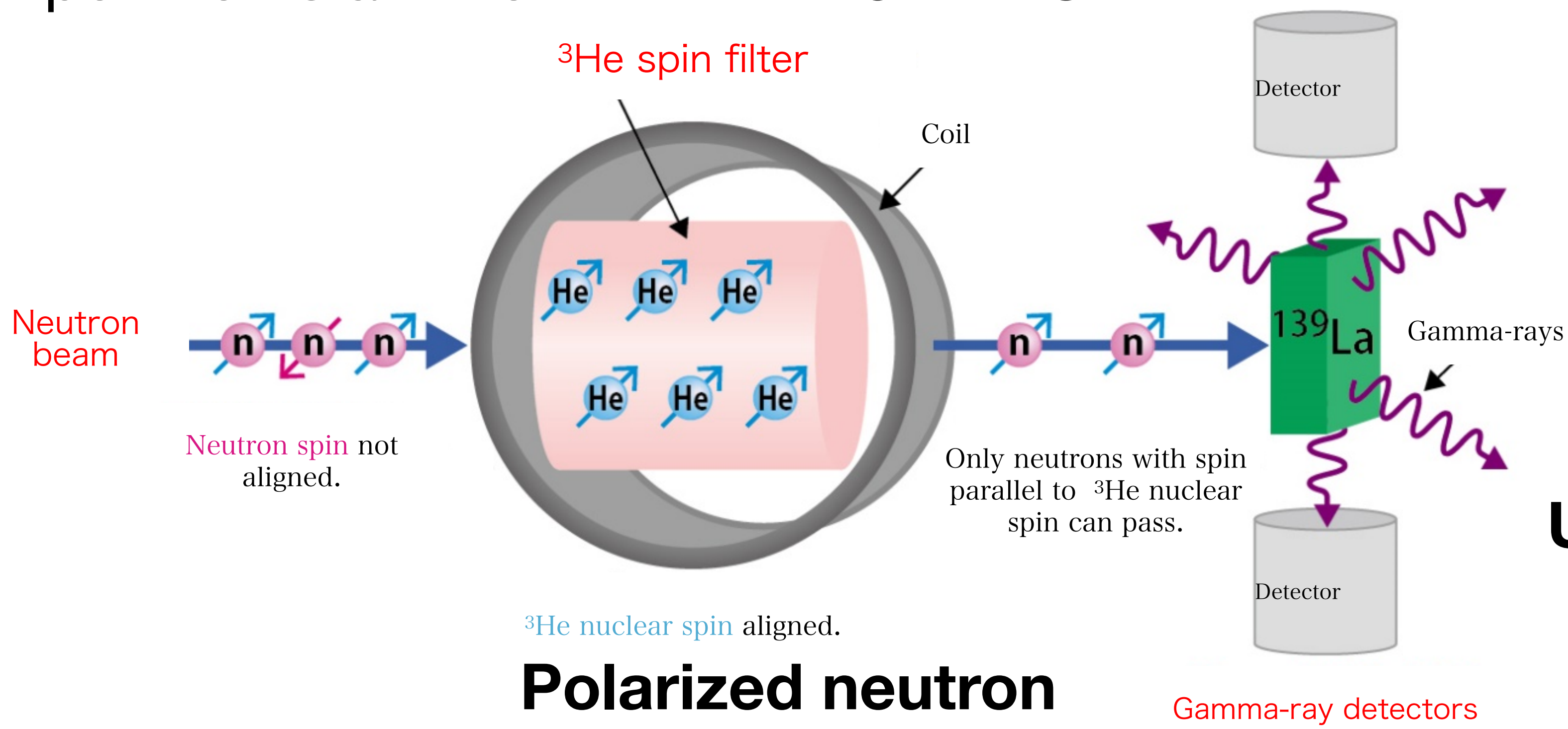
2 Cluster Ge Detector 7ch ×2 : 14ch
8 Coaxial Ge Detector 8ch
22ch → 7 angles

Targets : ^{nat}La 40mm x 40mm x 1mm

T. Okudaira et. al. , Phys. Rev. C97 (2018) 034622.

(n, γ) measurement with polarized neutrons

Pol. neutron experiments at BL04 ANNRI in J-PARC

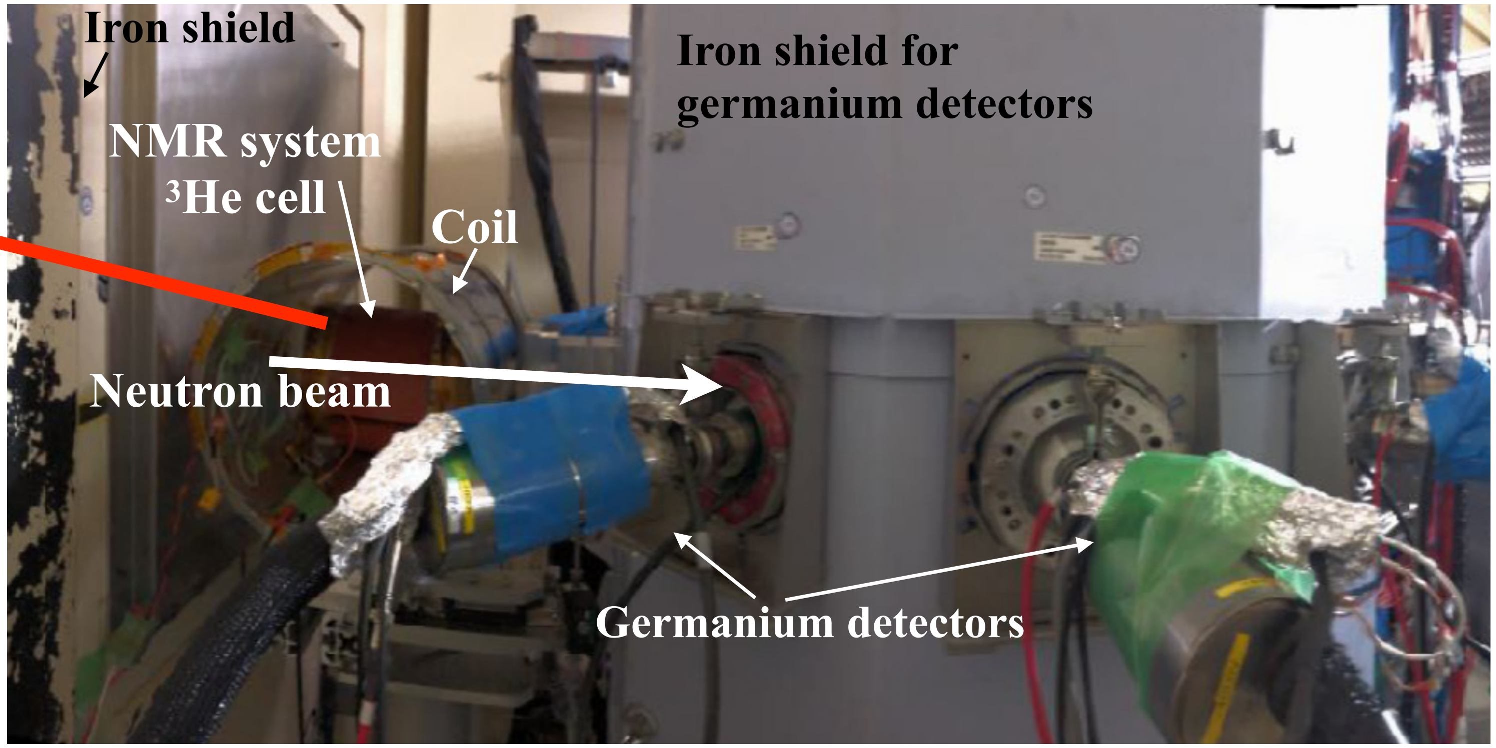


Polarized neutron

Unpolarized target

³He Cell

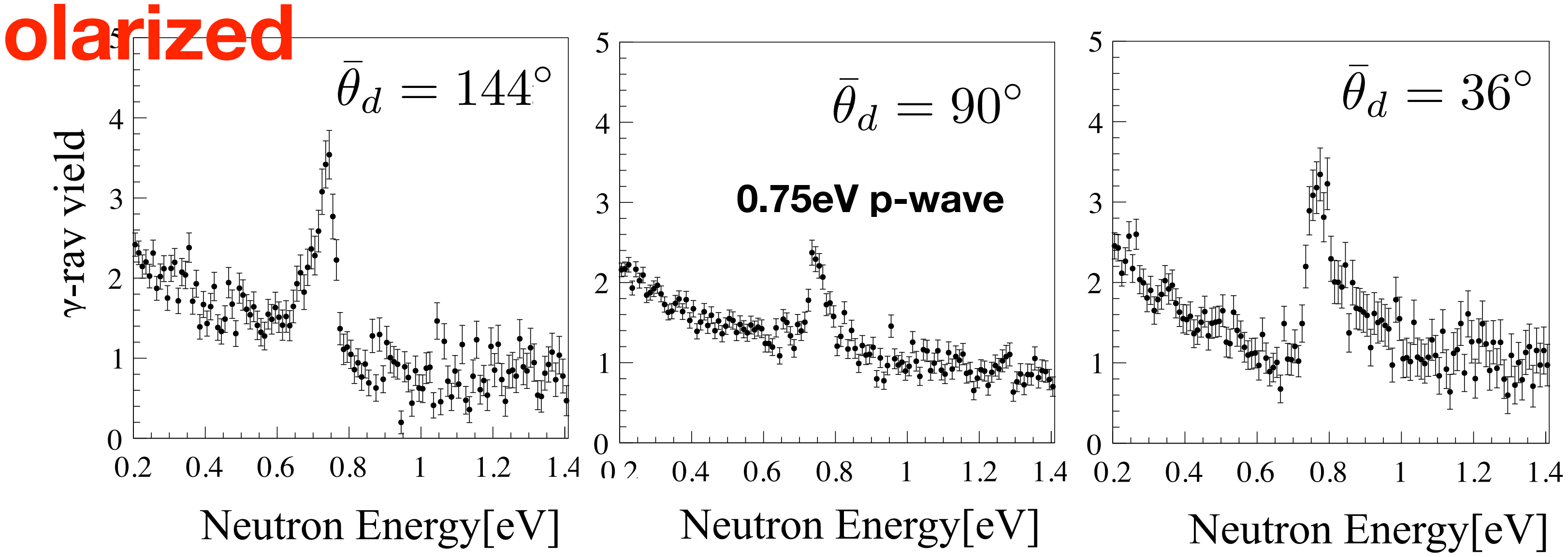
³He Polarization
> 0.8
Relaxation time
> 100 hours

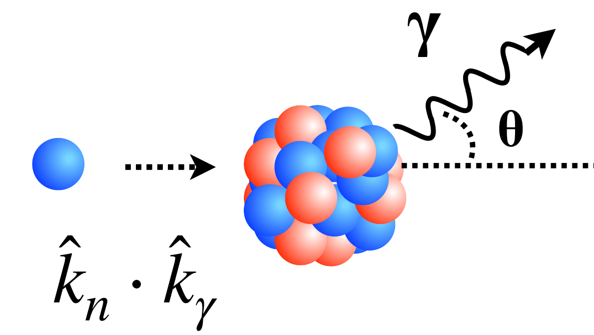


T. Okudaira et. al., Nucl. Instr. Meth. A977 (2020) 164301

^{139}La (n, γ) measurement

unpolarized





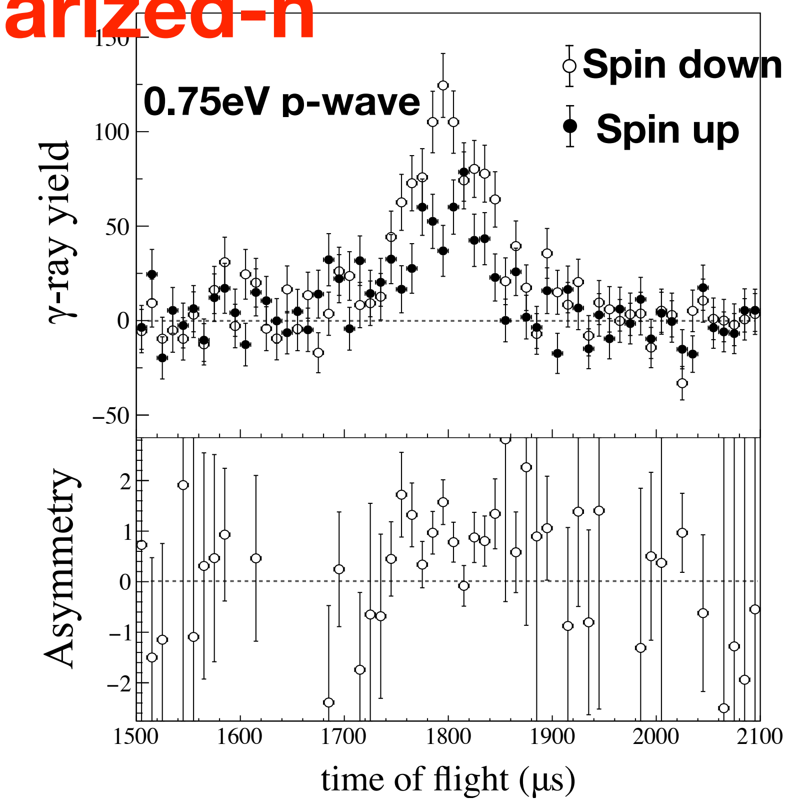
Angular distribution due to interference between s- and p-wave.

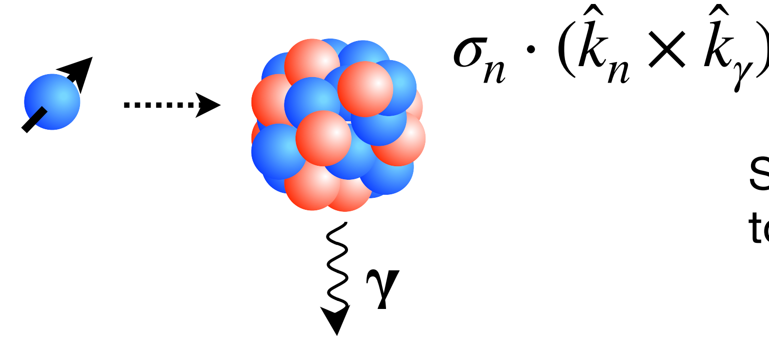
$$-0.388 \pm 0.024 = 0.295 \cos\phi \ \ - 0.345 \sin\phi$$

Experimental result — Theoretical calculation with s-p mixing

T. Okudaira et. al. ,
Phys. Rev. C97, 034622 (2018).

polarized-n





Spin dependent angular distribution due to interference between s- and p-wave.

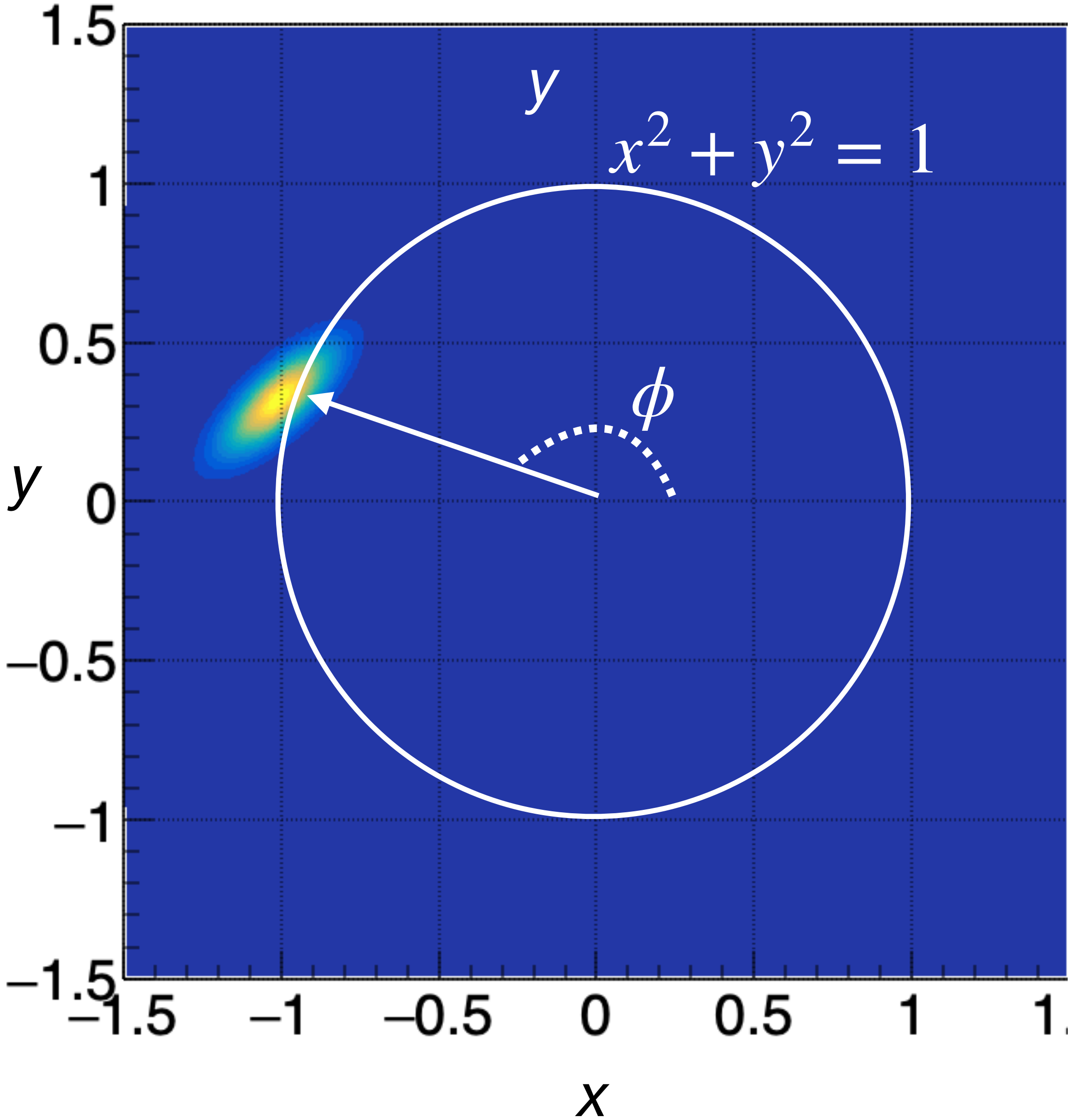
T. Yamamoto et. al. ,
Phys. Rev. C101, 064624 (2020).

$$-0.59 \pm 0.12 = 0.719 \cos\phi + 0.418 \sin\phi$$

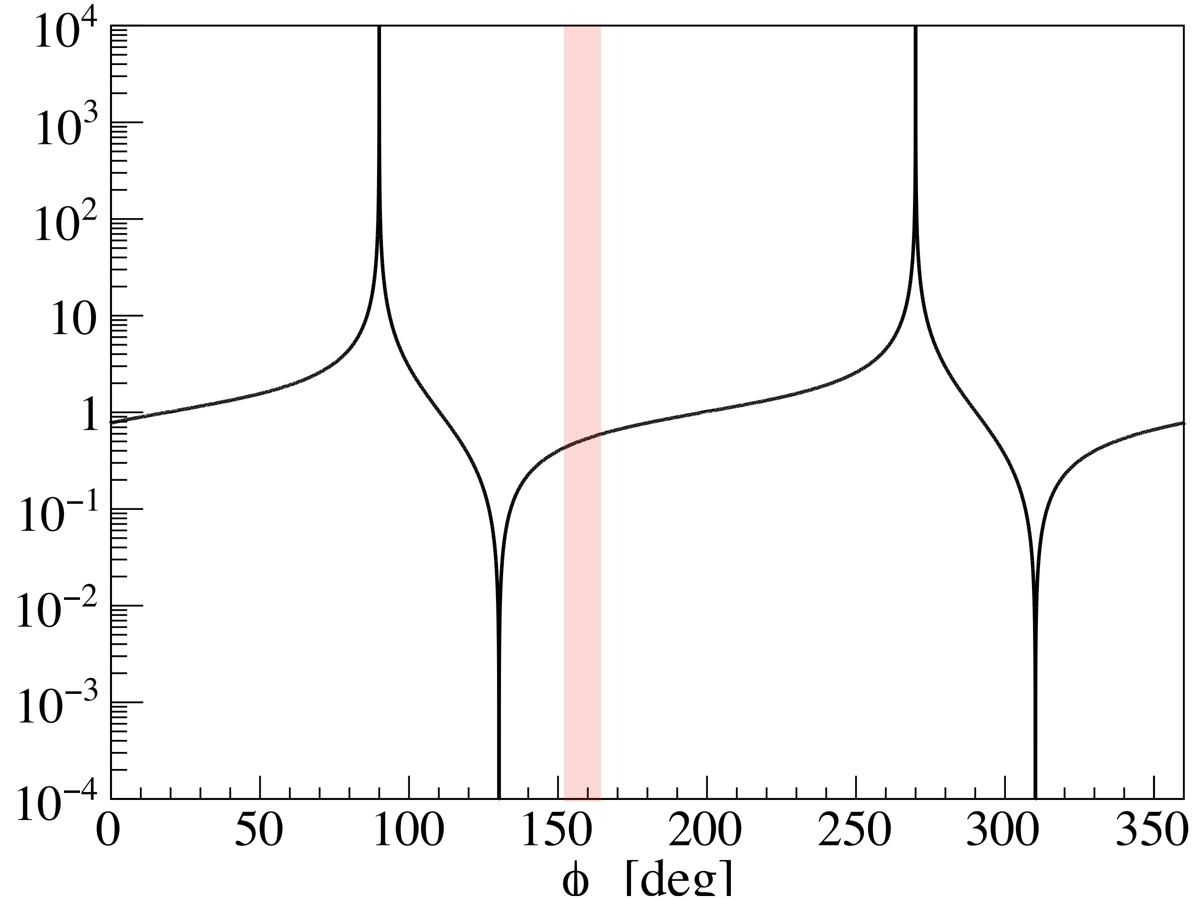
Experimental result — Theoretical calculation with s-p mixing

ϕ value by ^{139}La (n, γ) measurement

$x = \sqrt{\frac{\Gamma_n^{p,j=\frac{1}{2}}}{\Gamma_n^p}}$ ⟺ ϕ was estimated.



➡ Angular momentum (recombination) factor



$0.441 < \kappa(J) < 0.575$ (68 % C.L.)

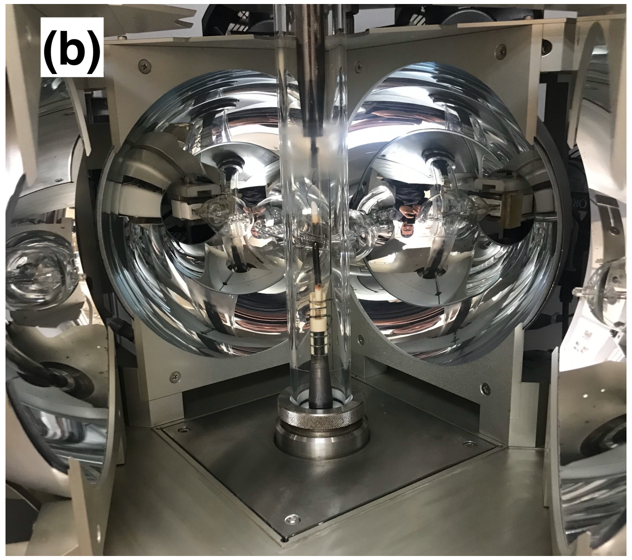
κ(J) was oder of 1

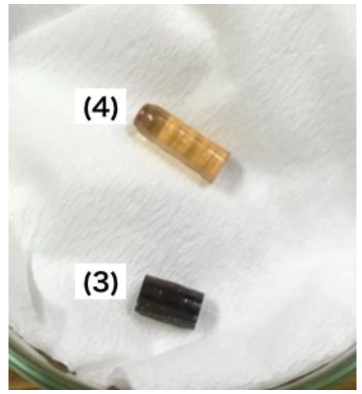
→ T-violation is also enhanced 10^6-fold !

$$\kappa(J) = 0.51 \pm 0.07$$

Polarized target R&D

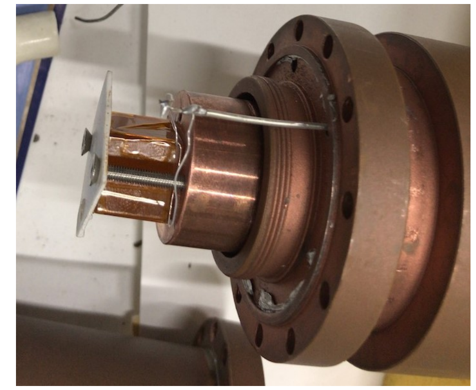
Crystal Growth at Tohoku Univ.





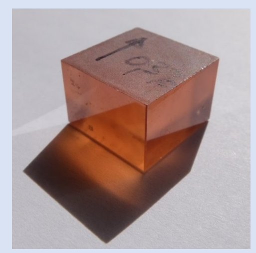
Tohoku Univ.,
Hiroshima Univ.
Nagoya Univ.

Target Polarization at RCNP, Osaka Univ.



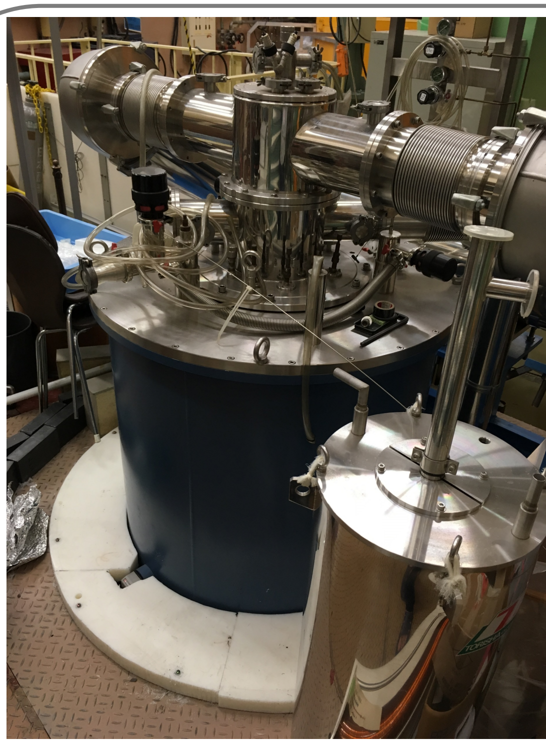
RCNP, Osaka Univ.
Hiroshima Univ., Nagoya Univ. ,Yamagata Univ.

Polarized La Target



$LaAlO_3$ (Nd^+) single crystal

Cryogenics



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

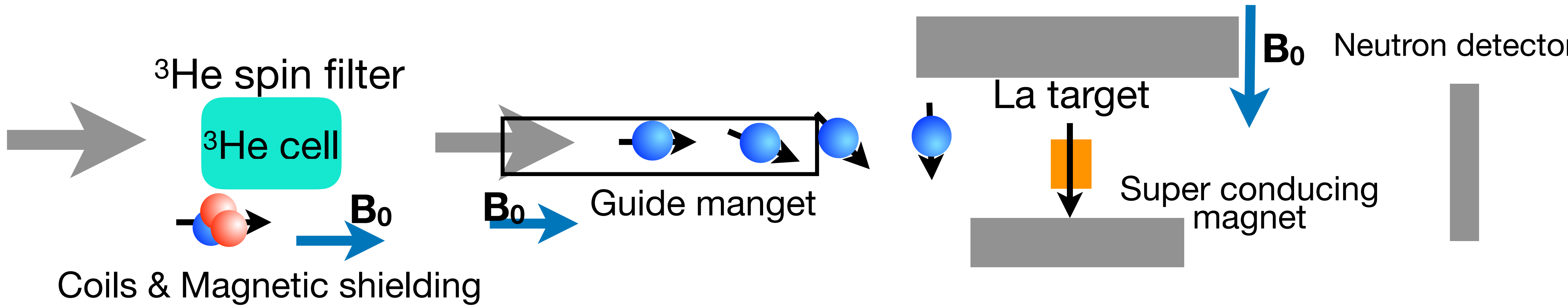
Relaxation Time Control

Hiroshima Univ.
Nagoya Univ.

Relaxation time control with aromatic molecule

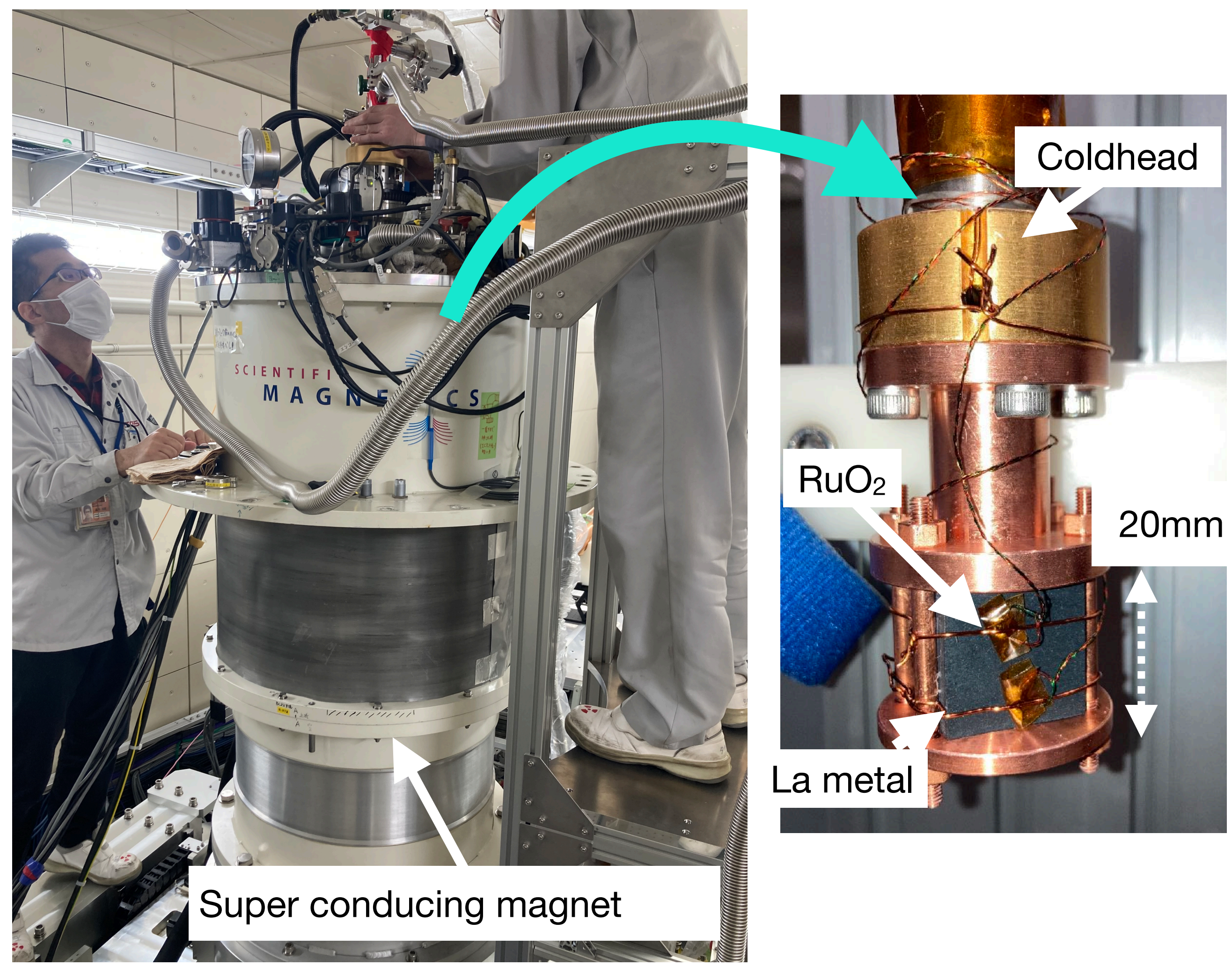
→ **La polarization(~30%) with large $LaAlO_3$**

Experiments with polarized target at J-PARC

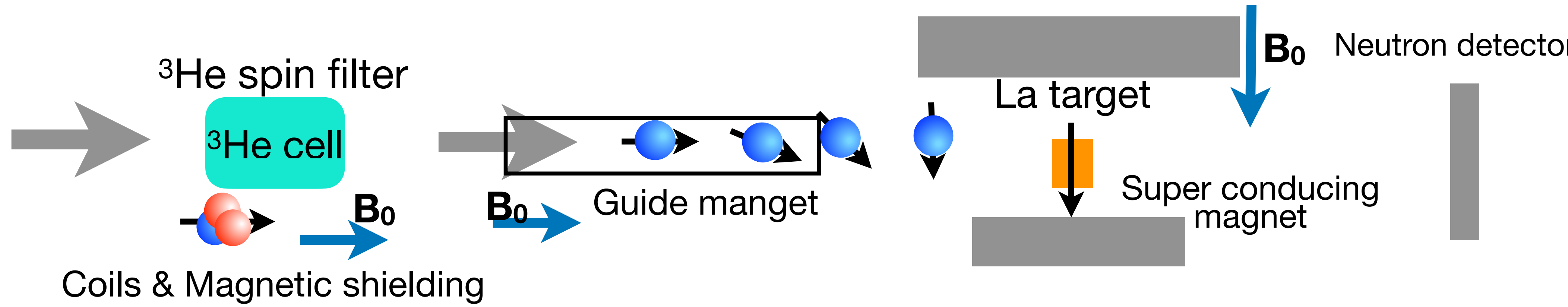


68mK, 6.7T →^{139}La polarization : 4.3%

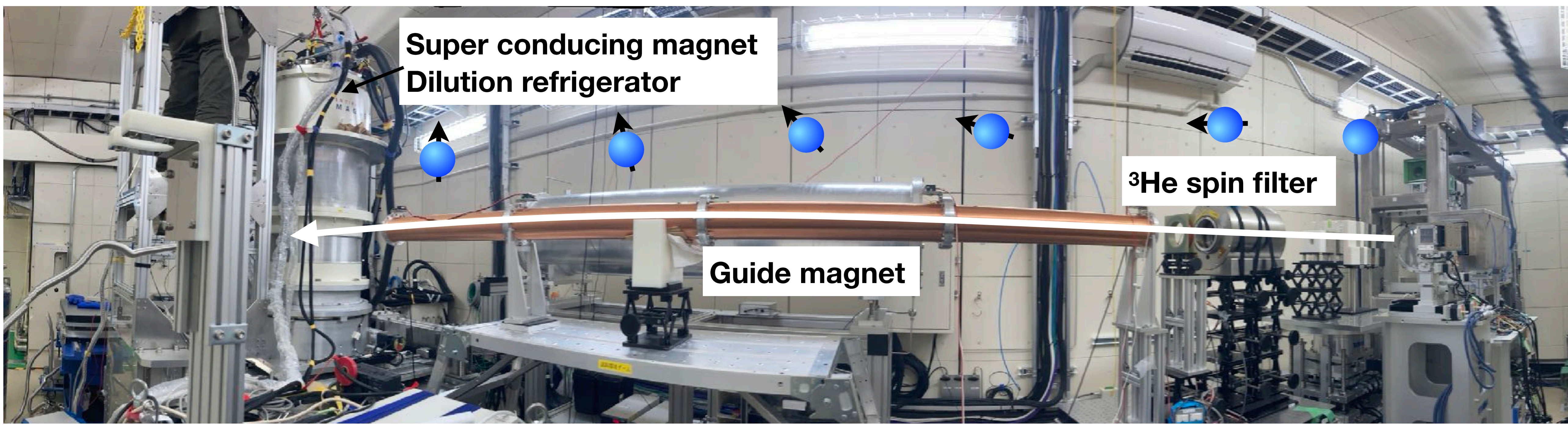
^{3}He polarization 85%
→Neutron polarization 40%



Experiments with polarized target at J-PARC



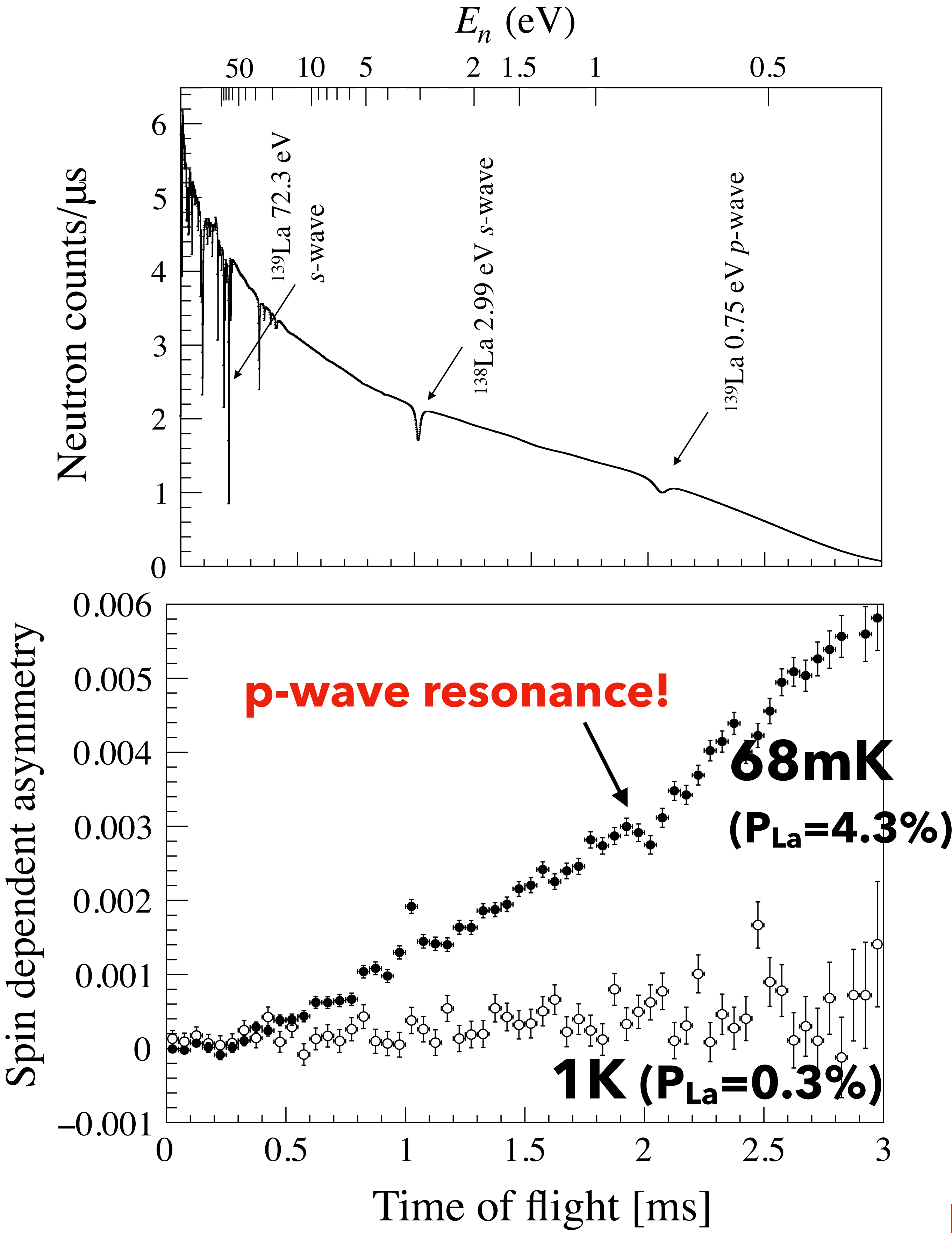
68mK, 6.7T **→^{139}La polarization : 4.3%**



Spin-dependent cross section was observed.

arXiv:2309.08905 (2023)
Submitted to PRC

Experiments with polarized target at J-PARC

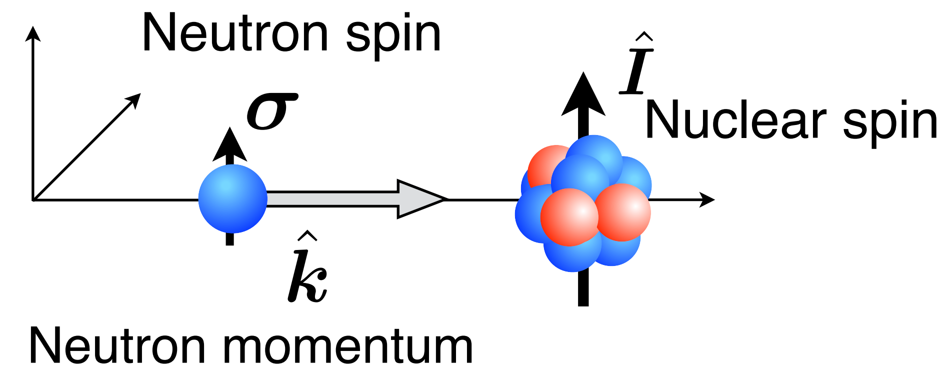


68mK, 6.7T

→ ^{139}La polarization : **4.3%**

Asymmetry of transmitted neutrons for parallel and anti-parallel spins

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

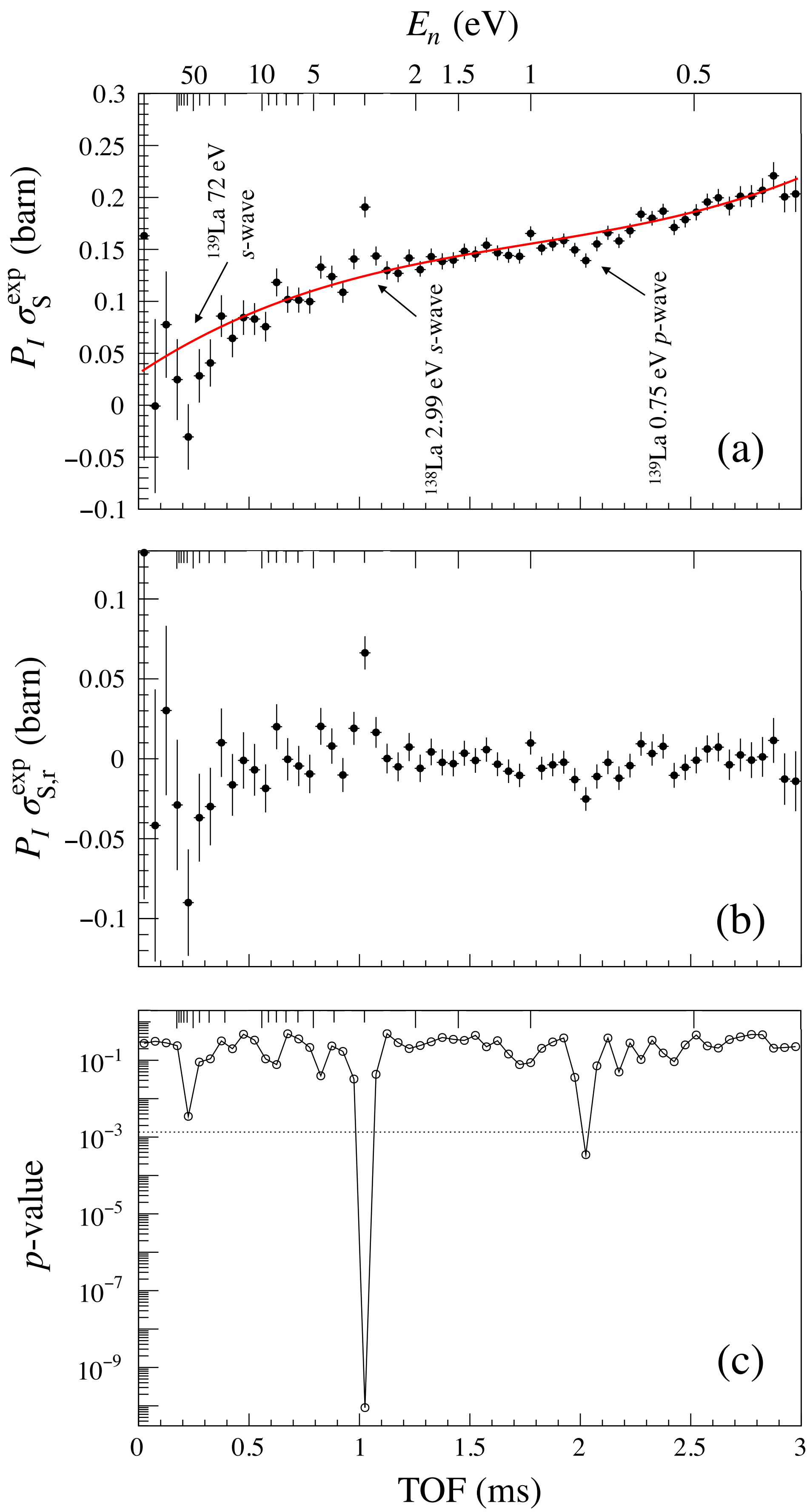


Successfully measured spin-dependent cross section!

arXiv:2309.08905 (2023)
Submitted to PRC

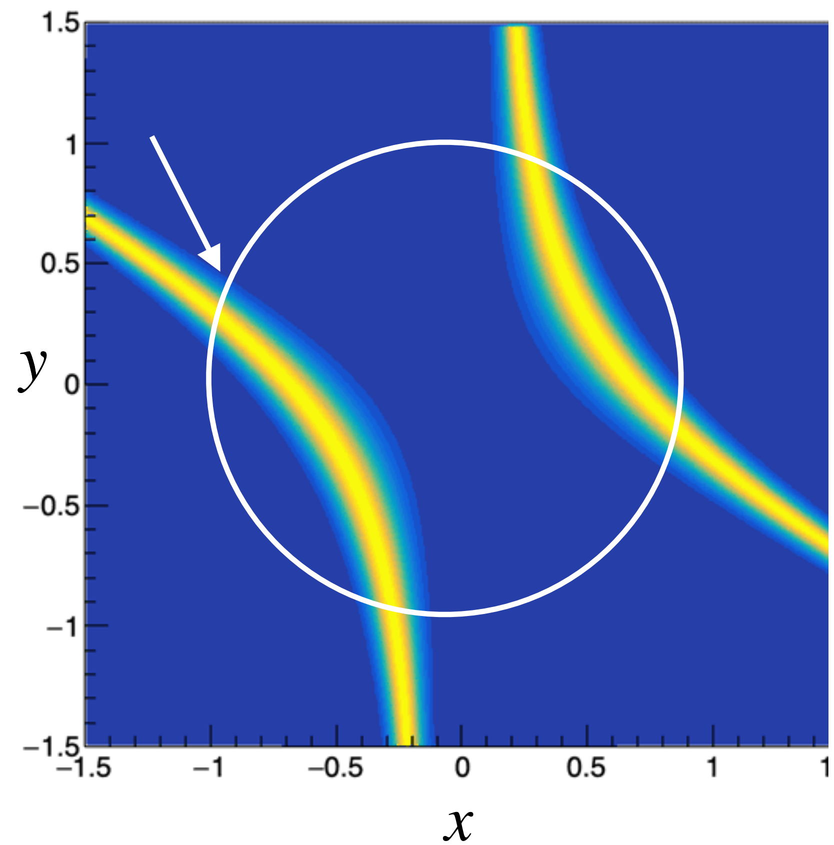
Big Milestone for T-violation search!

ϕ value

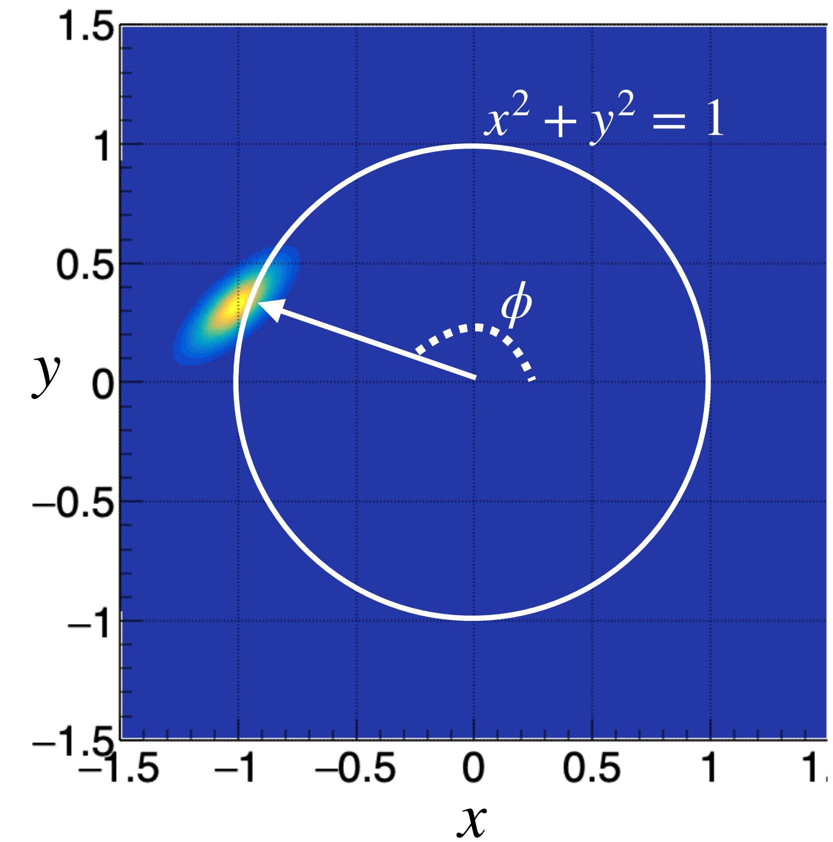


$$A_y = \frac{N_- - N_+}{N_+ + N_-} = -\frac{2\mathrm{Re}A^*B}{|A|^2 + |B|^2 + |C|^2 + |D|^2}$$

This work



(n,γ) reaction



Consistent solution of ϕ was obtained

In principle, T-violation limit can be obtained from this data (Second order effect of T-violation)

arXiv:2309.08905 (2023)
Submitted to PRC

Summary

CP-violation is one of the unsolved problems in particle physics.

EDMs of various systems are complementary and provide a strong limitation to CP violation.

nucleon, atom, molecule

NN interaction is good probe for T-violation search.

triple-vector correlation in beta-decay, resonance capture

Neutron is suitable for spin-experiment, easy to be polarized, controlled.

Discrete symmetry violation is enhanced in Compound States induced by Epithermal Neutron.

US-China-Japan collaboration NOPTREX was started.