Search for T-violation effects in compound neutron resonance at J-PARC

Masaaki Kitaguchi

Center for experimental studies, KMI, Nagoya University

Laboratory for Particle Properties (Φ-Lab.)

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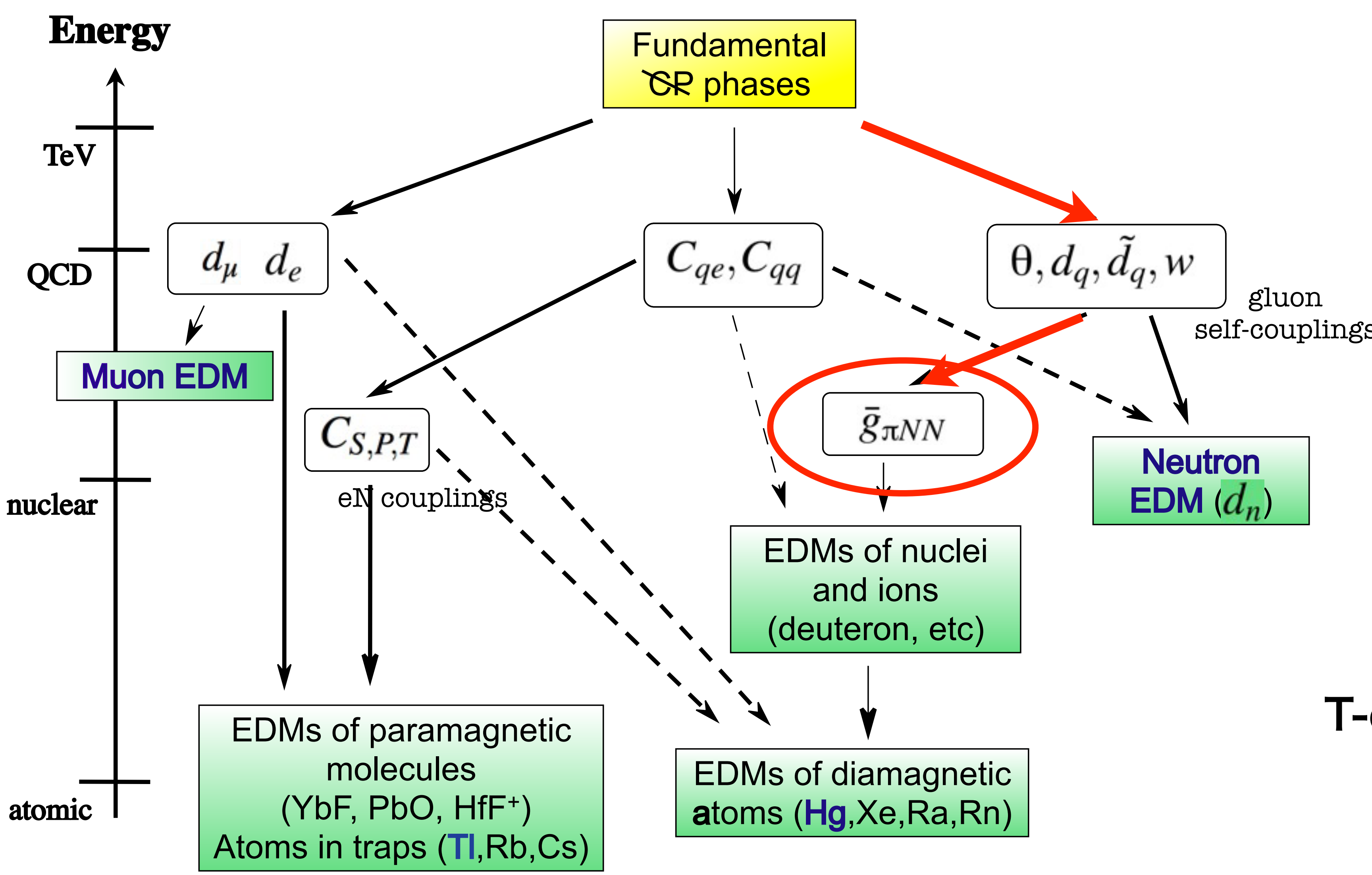
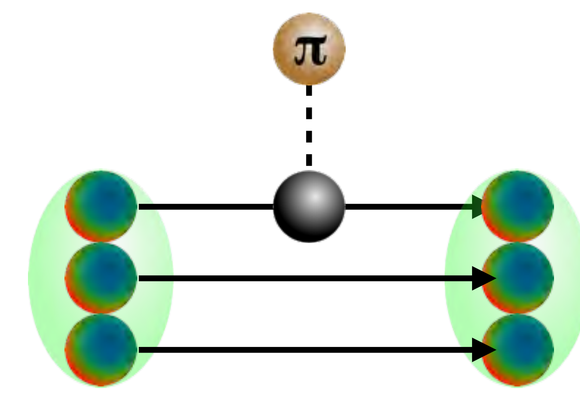
T-odd correlation in compound nuclei

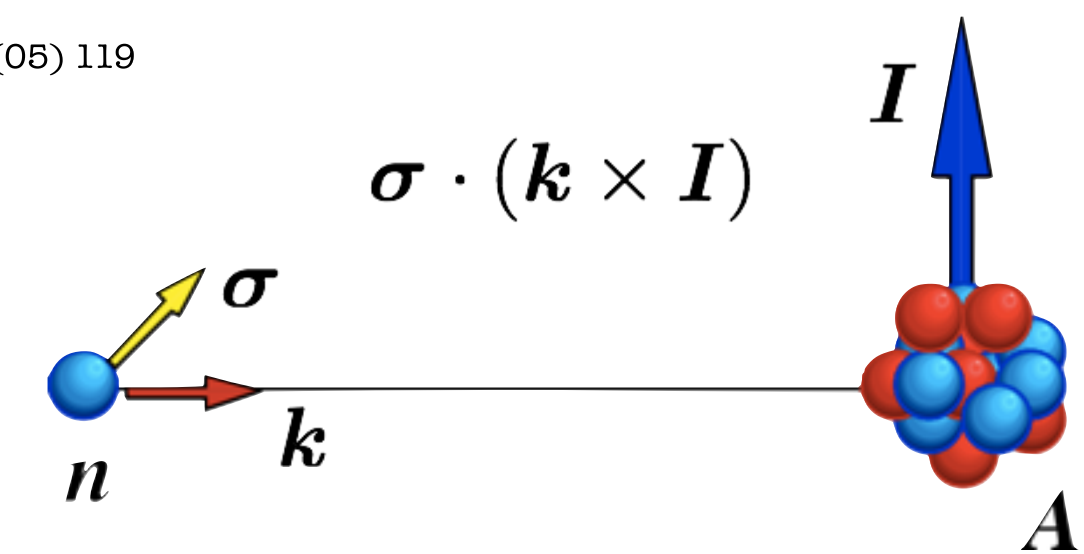
T-odd Correlation in Compound Nuclei



Pospelov Ritz, Ann Phys 318 (05) 119

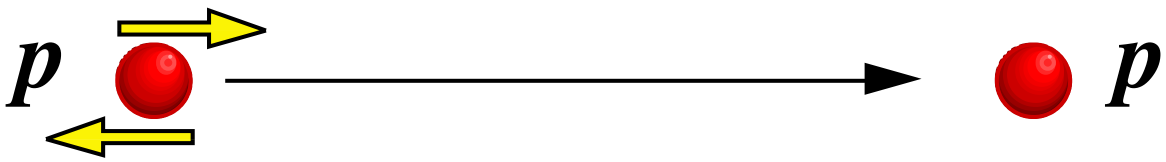


T-odd P-odd pion-nucleon coupling



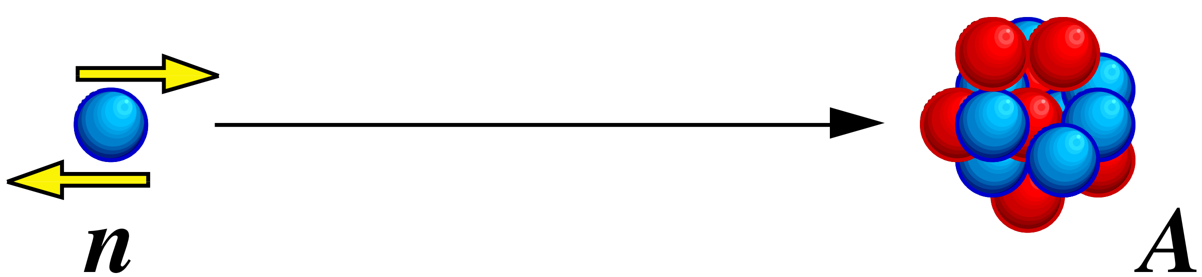
P-violation in compound nuclei

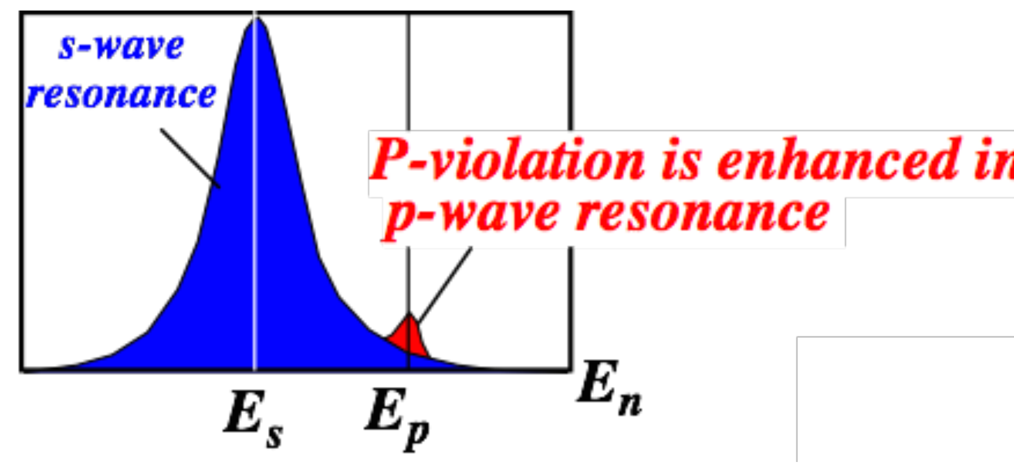
P-violation in nucleon



15MeV	$-(1.7\pm0.8)\times10^{-7}$
45MeV	$-(2.3\pm0.8)\times10^{-7}$
800MeV	$-(2.4\pm1.1\pm0.1)\times10^{-7}$

P-violation in neutron-nuclei reaction



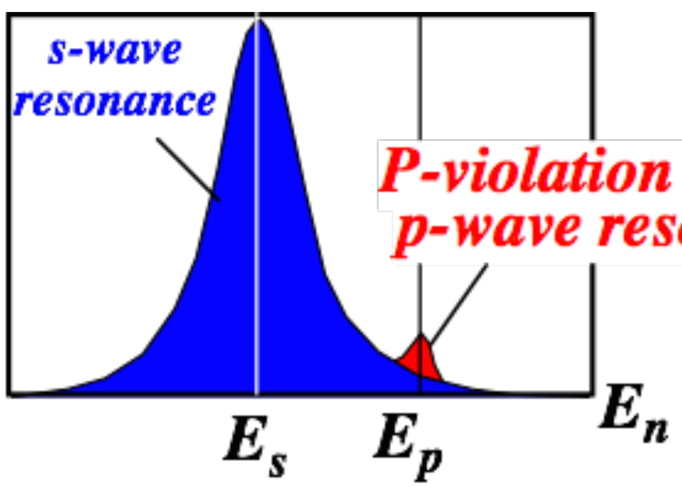


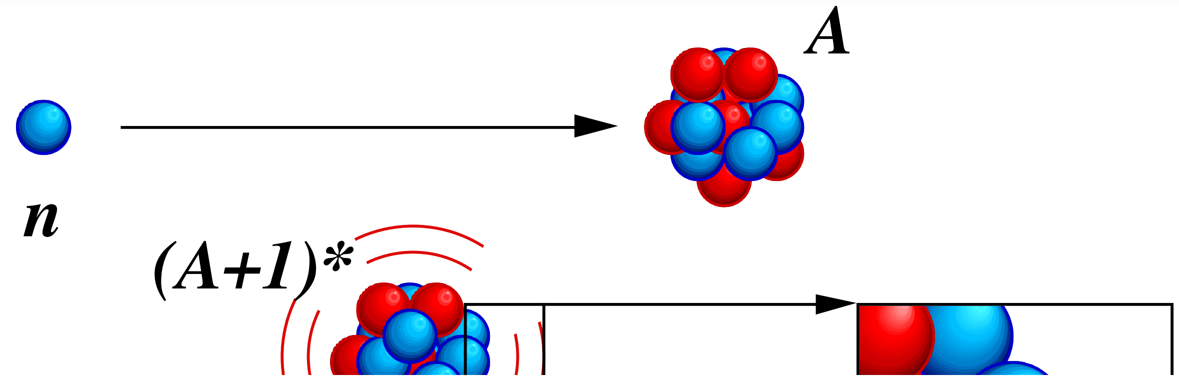
^{139}La	$E_n = 0.734$ eV	0.097 ± 0.003
^{81}Br	$E_n = 0.734$ eV	0.021 ± 0.001
^{111}Cd	$E_n = 4.53$ eV	$-(0.013^{+0.007}_{-0.004})$

2% of p-wave total cross section

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

P-violation in compound nuclei





$$J = I + j \qquad j = l + s$$

- J: Resonance spin
- I: target spin
- j: neutron total angular momentum

$l = 0$ **s-wave resonance** s

$1/kR \sim 10^{-3}$

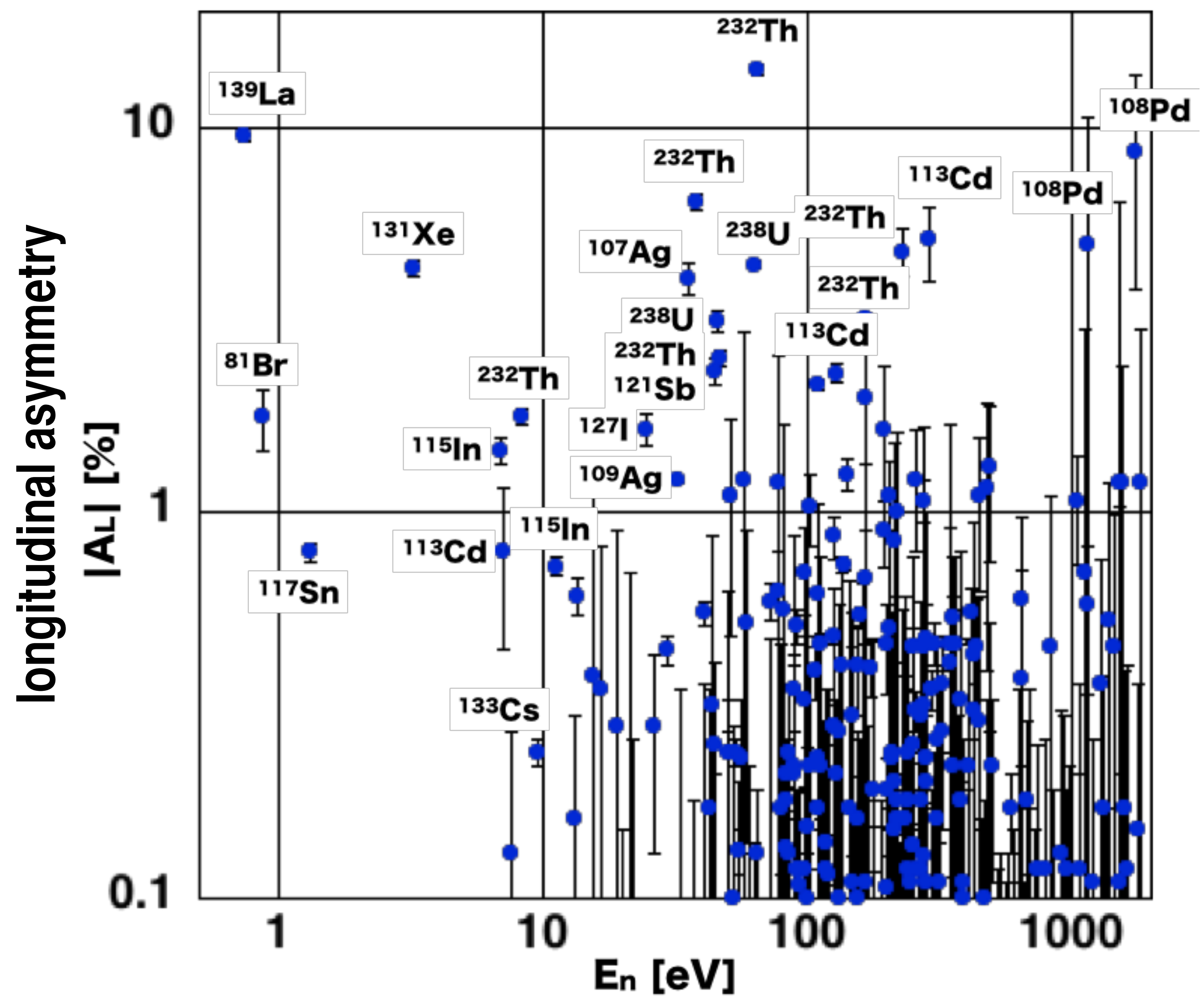
interference

J is good quantum number

$l = 1$ **p-wave resonance**

$j = 1/2 \quad p_{1/2}$

$j = 3/2 \quad p_{3/2}$



T-violation in compound nuclei

The interference between s-wave and p-wave results in the interference between partial waves with different channel spin.

Gudkov, Phys. Rep. 212 (1992) 77.

$$\boldsymbol{J} = \boldsymbol{l} + \boldsymbol{s} + \boldsymbol{I}$$
$$\boldsymbol{j} = \boldsymbol{l} + \boldsymbol{s}$$
$$\boldsymbol{S} = \boldsymbol{s} + \boldsymbol{I}$$

$$P : |lsI\rangle \to (-1)^l |lsI\rangle$$

$$T : |lsI\rangle \to (-1)^{i\pi S_y} K |lsI\rangle$$

$$|((Is)S,l)J\rangle = \sum_j \langle (I,(sl)j)J|((Is)S,l)J\rangle \, |(I,(sl)j)J\rangle$$
$$= \sum_j (-1)^{l+s+I+J} \sqrt{(2j+1)(2S+1)} \left\{ \begin{array}{ccc} I & s & l \\ J & S & j \end{array} \right\} |(I,(sl)j)J\rangle$$

$$x = \sqrt{\frac{\Gamma_p^n(j=1/2)}{\Gamma_p^n}} \qquad y = \sqrt{\frac{\Gamma_p^n(j=3/2)}{\Gamma_p^n}} \qquad x_S = \sqrt{\frac{\Gamma_p^n(S=I-1/2)}{\Gamma_p^n}} \qquad y_S = \sqrt{\frac{\Gamma_p^n(S=I+1/2)}{\Gamma_p^n}}$$

$$z_j = \left\{ \begin{array}{cc} x & (j=1/2) \\ y & (j=3/2) \end{array} \right. , \quad \tilde{z}_S = \left\{ \begin{array}{cc} x_S & (S=I-1/2) \\ y_S & (S=I+1/2) \end{array} \right. \qquad \tilde{z}_S = \sum_j (-1)^{l+I+j+S} \sqrt{(2j+1)(2S+1)} \left\{ \begin{array}{ccc} l & s & j \\ I & J & S \end{array} \right\} z_j$$

T-violation in compound nuclei

The interference between s-wave and p-wave results in the interference between partial waves with different channel spin.

Gudkov, Phys. Rep. 212 (1992) 77.

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

T-violation P-violation

$$\kappa(I-\frac{1}{2}) = (-1)^{2I}\left(1+\frac{1}{2}\sqrt{\frac{2I-1}{I+1}}\frac{y}{x}\right)$$

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

$$x^2 = \frac{\Gamma^n_{p,1/2}}{\Gamma^n_p} \qquad y^2 = \frac{\Gamma^n_{p,3/2}}{\Gamma^n_p}$$

$$x^2+y^2=1$$

Unknown parameter

$$x = \cos\phi \qquad y = \sin\phi$$

T-odd Correlation in Compound Nuclei

Gudkov, Phys. Rep. 212 (1992) 77.

T-violation is also enhanced?

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

T-violation

g_{CP}/g_{P} P-violation

compare with EDM 

Estimation in effective field theory

Y.-H.Song et al., Phys. Rev. C83 (2011) 065503

$$\frac{W_{\mathrm{T}}}{W} = \frac{\Delta\sigma^{\not{T}\not{P}}}{\Delta\sigma^{\not{P}}} \simeq (-0.47)\left(\frac{\bar{g}_{\pi}^{(0)}}{h_{\pi}^{1}} + (0.26)\frac{\bar{g}_{\pi}^{(1)}}{h_{\pi}^{1}}\right)$$

$$\kappa(J) \sim 1$$

from upper limit of nEDM

$$|d_n| < 2.9 \times 10^{-26}\,\mathrm{e\,cm}$$

$$\bar{g}_{\pi}^{(0)} < 2.5 \times 10^{-10}$$

from upper limit of Hg EDM

$$|d_{\mathrm{Hg}}| < 3.1 \times 10^{-29}\mathrm{e \cdot cm}$$

$$\bar{g}_{\pi}^{(1)} < 0.5 \times 10^{-11}$$

$$|\Delta\sigma_{\mathrm{T}}| < \ 1.0 \times 10^{-4} \ \mathrm{barn}$$

T-odd Correlation in Compound Nuclei

NOP-T

	^{139}La	^{81}Br	^{117}Sn	^{131}Xe	^{115}In
large $\Delta\sigma_P$	◎	○	◎	◎	◎
low E_p [eV]	◎	◎	○	○	△
small nonzero I	7/2 △	3/2 ○	1/2 ◎	3/2 ○	9/2 △
isotopic abn	◎	○	×	△	◎
large |κ(J)|	○?	?	?	◎?	?
method of pol.	DNP	—	—	OP	—

T.Okudaira (Nagoya Univ.)

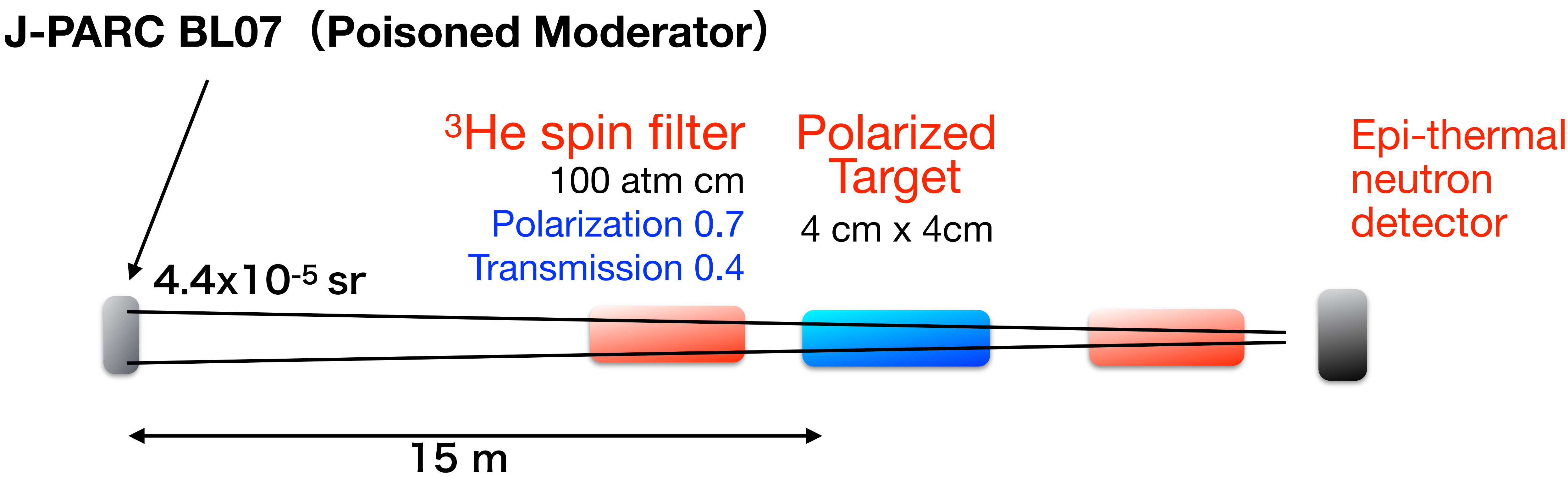
I. Itoh (Nagoya Univ.)

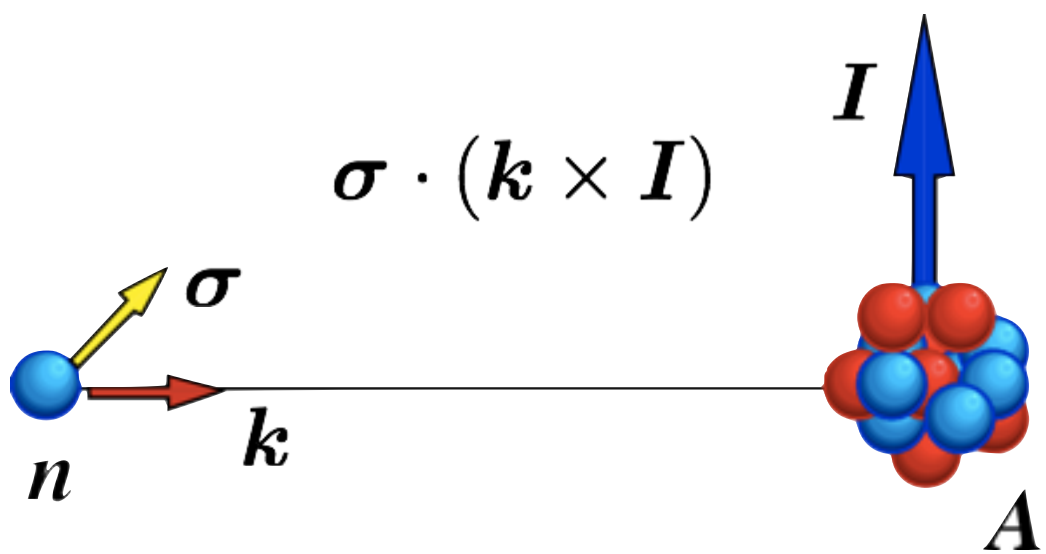
J. Koga (Kyushu Univ.)

S. Takada (Kyushu Univ.)

T-odd Correlation in Compound Nuclei

Experimental plan





Asymmetry of 10^{-6} can be measured in a few days.

Feasibility studies and R&D

Target of NOP-T

Target nuclei

Large T-violating effect

Easy to polarize

Epithermal neutrons

High-intensity beamline

Polarized neutrons

Target of NOP-T

Nuclei with large $\kappa(J)$ is suitable.

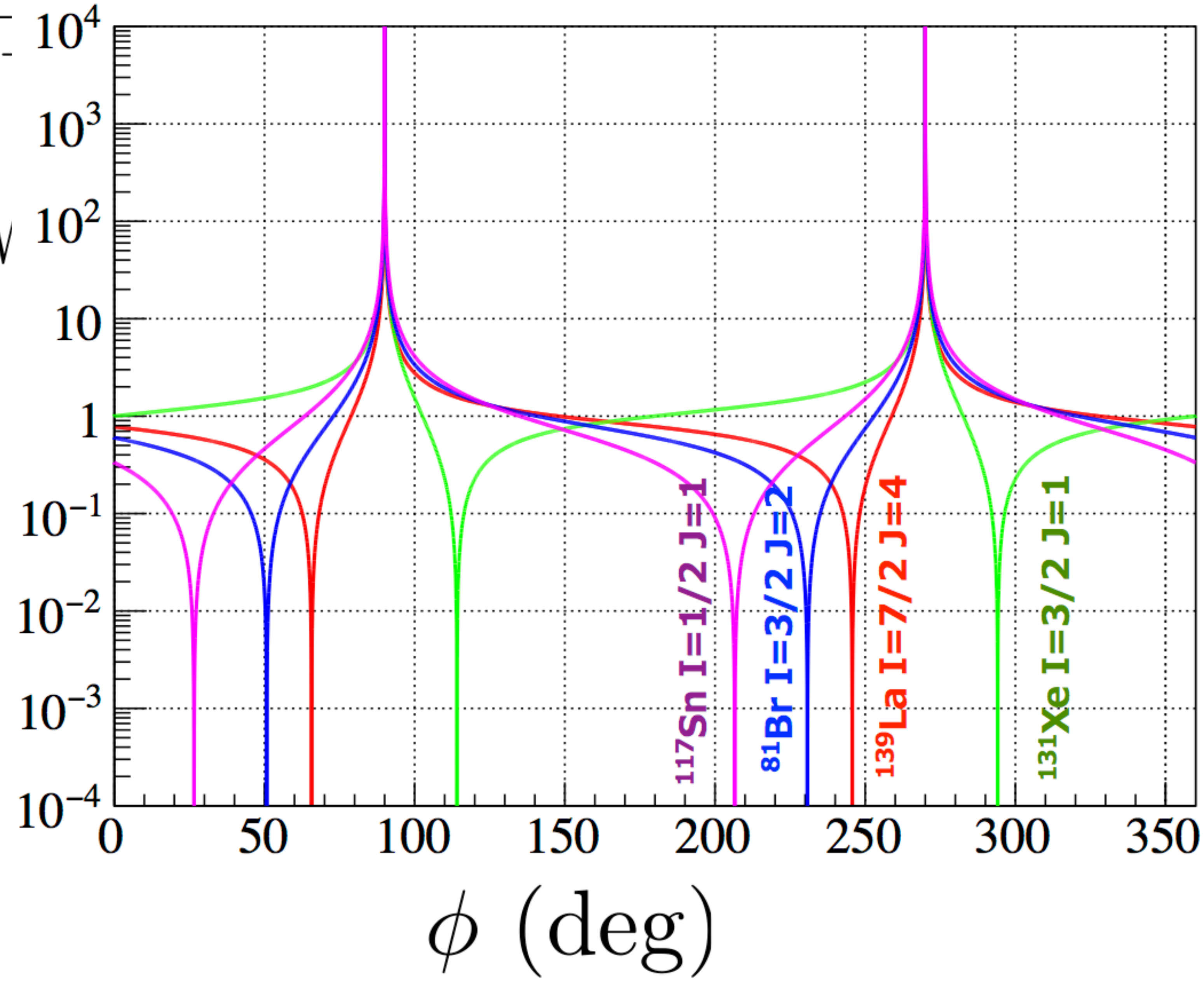
$$\kappa(I-\frac{1}{2}) = (-1)^{2I}\left(1+\frac{1}{2}\sqrt{\frac{2I-1}{I}}\,y\right)$$

$$\kappa(I-\frac{1}{2}) = (-1)^{2I+1}\frac{I}{I+1}\left(1-\frac{1}{2}\sqrt{}\right.$$

$$x^2 = \frac{\Gamma^n_{p,1/2}}{\Gamma^n_p} \qquad y^2 = \frac{\Gamma^n_{p,3/2}}{\Gamma^n_p}$$

$$x^2 + y^2 = 1$$

$$x = \cos\phi \qquad y = \sin\phi$$



Selection of target nuclei

(n, γ) reaction (for unpolarized case)

$$\frac{d\sigma}{d\Omega} = \frac{1}{2}\left(a_0 + \boxed{a_1}\boldsymbol{k}_n \cdot \boldsymbol{k}_\gamma + \boxed{a_3}\left((\boldsymbol{k}_n \cdot \boldsymbol{k}_\gamma)^2 - \frac{1}{3}\right)\right)$$

$$a_0 = \sum_{J_s} |V_1(J_s)|^2 + \sum_{J_s, j} |V_2(J_p j)|^2$$

Flambaum, Nucl. Phys. A435 (1985) 352

$$\boxed{a_1} = 2\mathrm{Re} \sum_{J_s, J_p, j} V_1(J_s) V_2^*(J_p j) P(J_s J_p \tfrac{1}{2} j 1 I F)$$

$$\boxed{a_3} = \mathrm{Re} \sum_{J_s, j, J'_p, j'} V_2(J_p j) V_2^*(J'_p j') P(J_p J'_p j j' 2 I F) 3\sqrt{10} \left\{ \begin{array}{ccc} 2 & 1 & 1 \\ 0 & \frac{1}{2} & \frac{1}{2} \\ 2 & j & j' \end{array} \right\}$$

$$V_1 = \frac{1}{2k_s}\sqrt{\frac{E_s}{E}} \frac{\sqrt{g\Gamma_s^n \Gamma_\gamma}}{E - E_s + i\Gamma_s/2}$$

$$V_2(j) = \frac{1}{2k_p}\sqrt{\frac{E_p}{E}} \sqrt{\frac{\Gamma_{pj}^n}{\Gamma_p^n}} \frac{\sqrt{g\Gamma_p^n \Gamma_\gamma}}{E - E_p + i\Gamma_p/2}$$

$V_2(j=1/2) = xV_2 = V_2 \cos\boxed{\phi}$

$V_2(j=3/2) = yV_2 = V_2 \sin\boxed{\phi}$

$$P(JJ'jj'kIF) = (-1)^{J+J'+j'+I+F} \frac{3}{2} \sqrt{(2J+1)(2J'+1)(2j+1)(2j'+1)} \left\{ \begin{array}{ccc} j & j & j' \\ I & J' & J \end{array} \right\} \left\{ \begin{array}{ccc} k & 1 & 1 \\ F & J & J' \end{array} \right\}$$

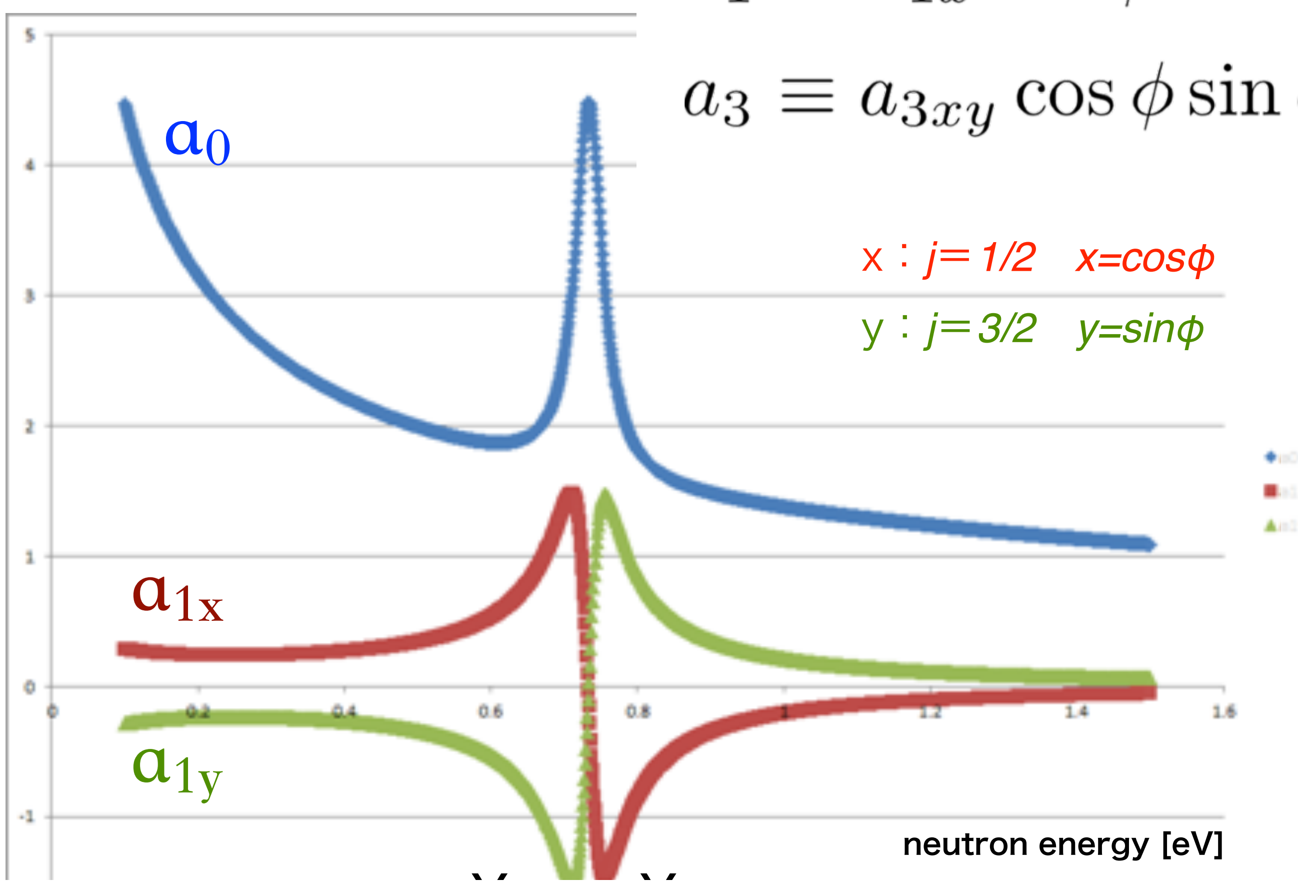
Selection of target nuclei

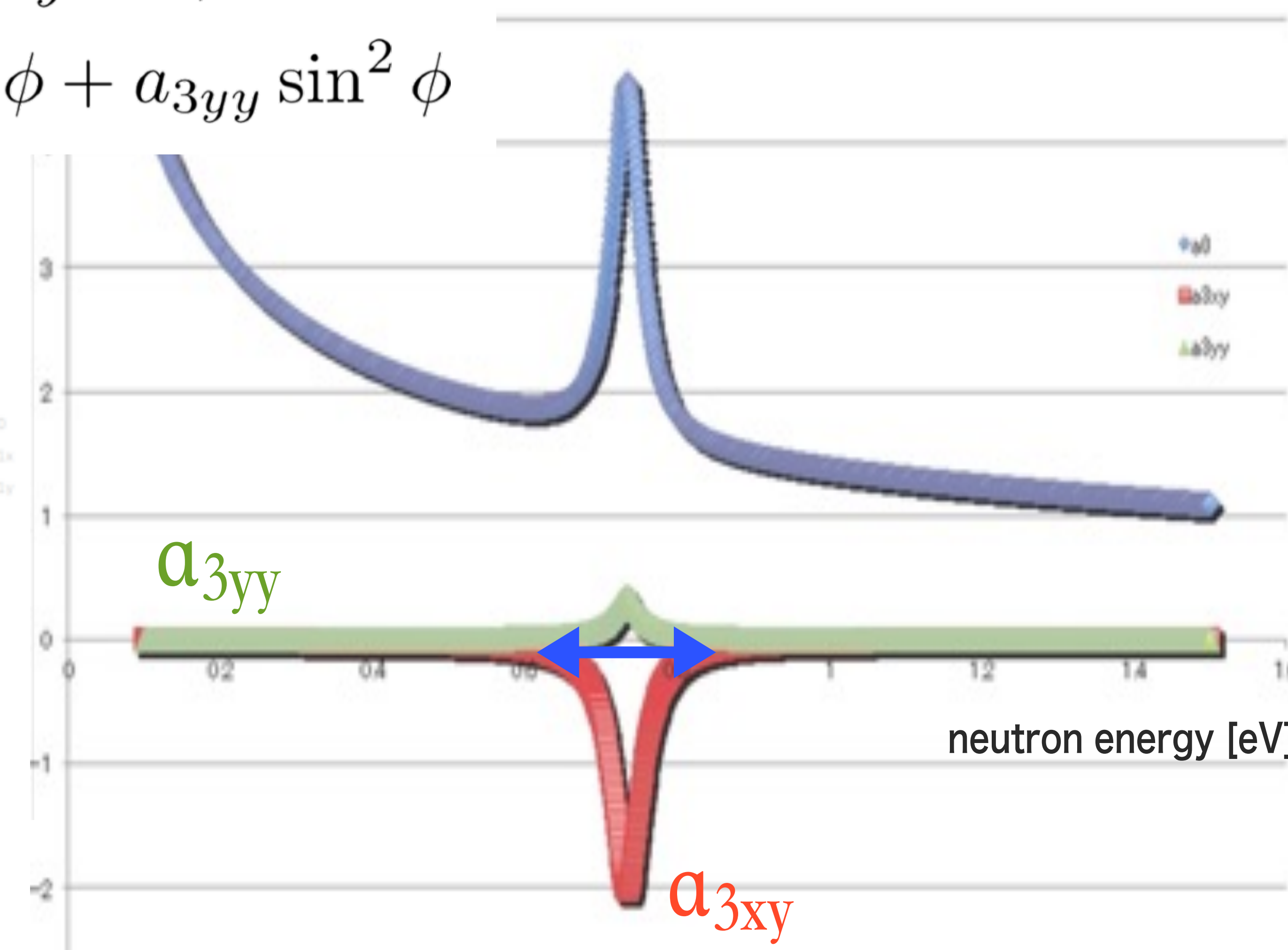
(n, γ) reaction (for unpolarized case)

$$\frac{d\sigma}{d\Omega} = \frac{1}{2}\left(a_0 + a_1 \boldsymbol{k}_n \cdot \boldsymbol{k}_\gamma + a_3\left((\boldsymbol{k}_n \cdot \boldsymbol{k}_\gamma)^2 - \frac{1}{3}\right)\right)$$

$$a_1 \equiv a_{1x}\cos\phi + a_{1y}\sin\phi$$

$$a_3 \equiv a_{3xy}\cos\phi\sin\phi + a_{3yy}\sin^2\phi$$





Selection of target nuclei

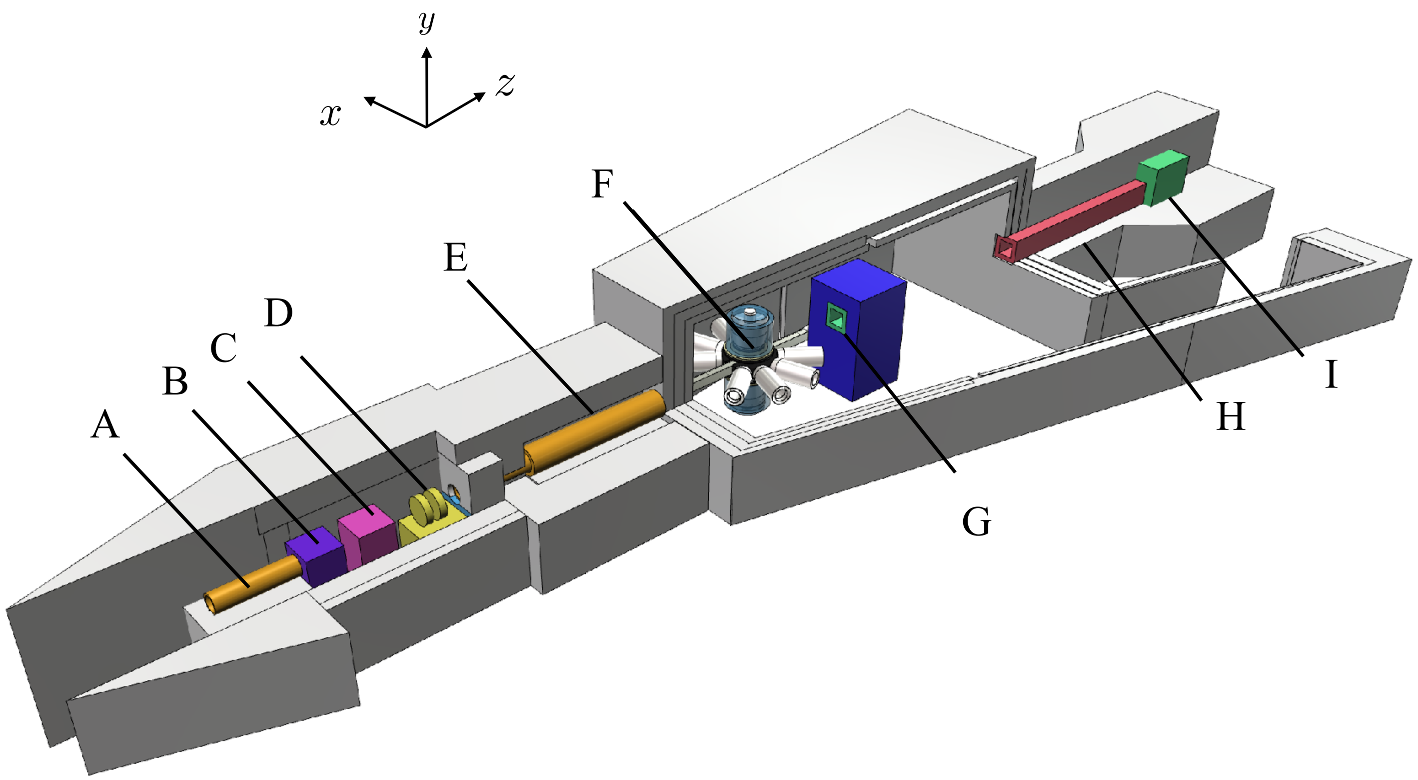
(n, γ) reaction measurement at J-PARC BL04 ANNRI

$$\frac{d\sigma}{d\Omega} = \frac{1}{2}\left(a_0 + a_1 \boldsymbol{k}_n \cdot \boldsymbol{k}_\gamma + a_3\left((\boldsymbol{k}_n \cdot \boldsymbol{k})^2 - \frac{1}{3}\right)\right)$$

$$a_1 \equiv a_{1x}\cos\phi + a_{1y}\sin\phi$$

$$a_3 \equiv a_{3xy}\cos\phi\sin\phi + a_{3yy}\sin^2\phi$$

Single unknown parameter $\kappa(J)$ can be estimated by observing the shape of p-wave resonance peak.



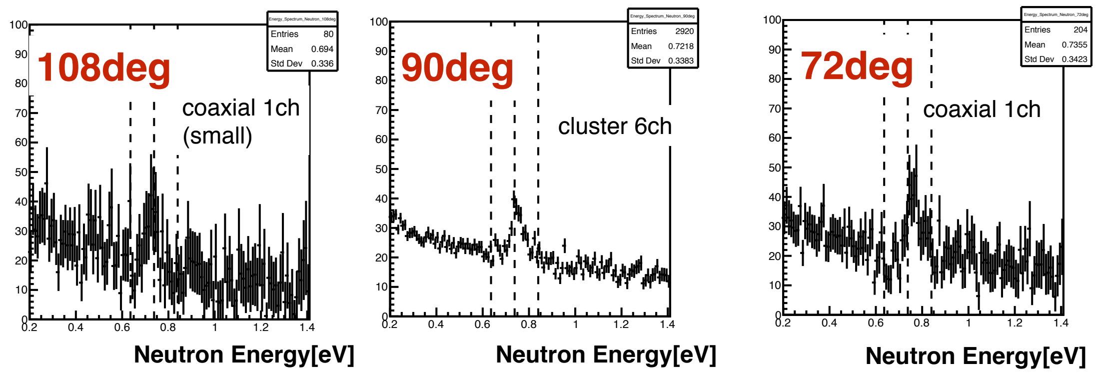
Sample Materials : ^{nat}La, La^{nat}Br$_3$, ^{nat}In

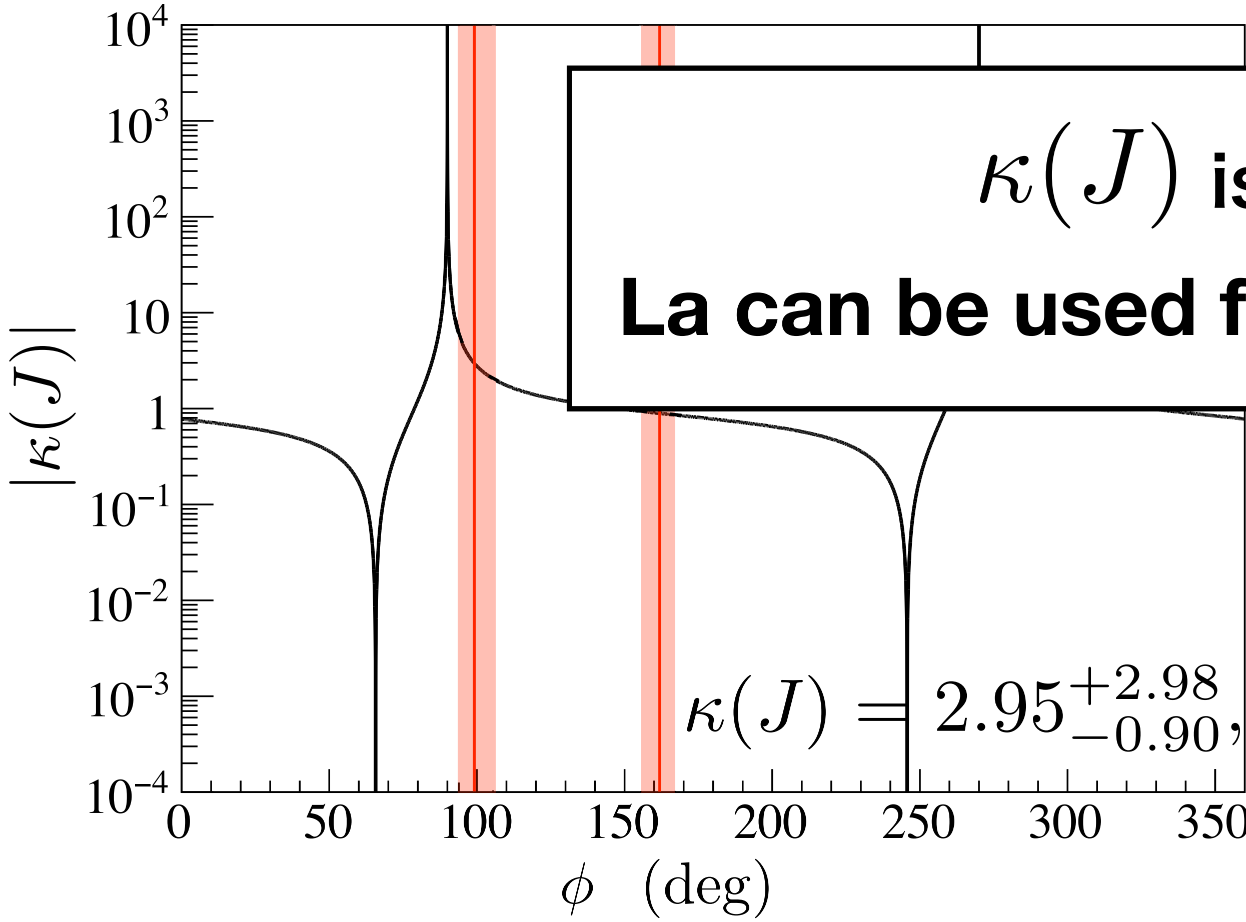
Intensity : ~ 3 x 10^5 n/cm^2/s : 0.9 eV < En < 1.1eV @300kW

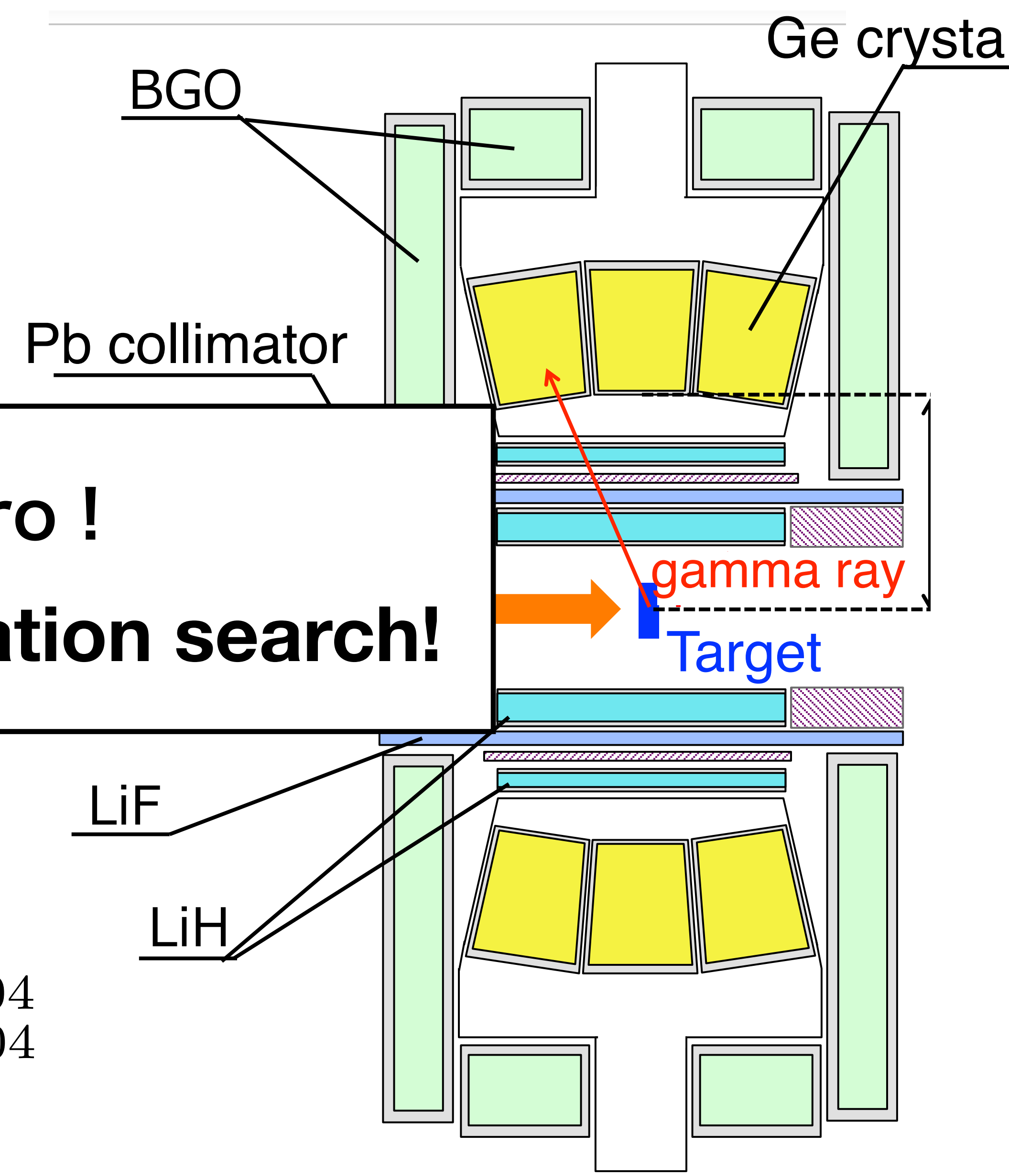
Selection of target nuclei

NOP-T

Shape of resonance peak changes according to the angle







$\kappa(J)$ is NOT zero !

La can be used for T-violation search!

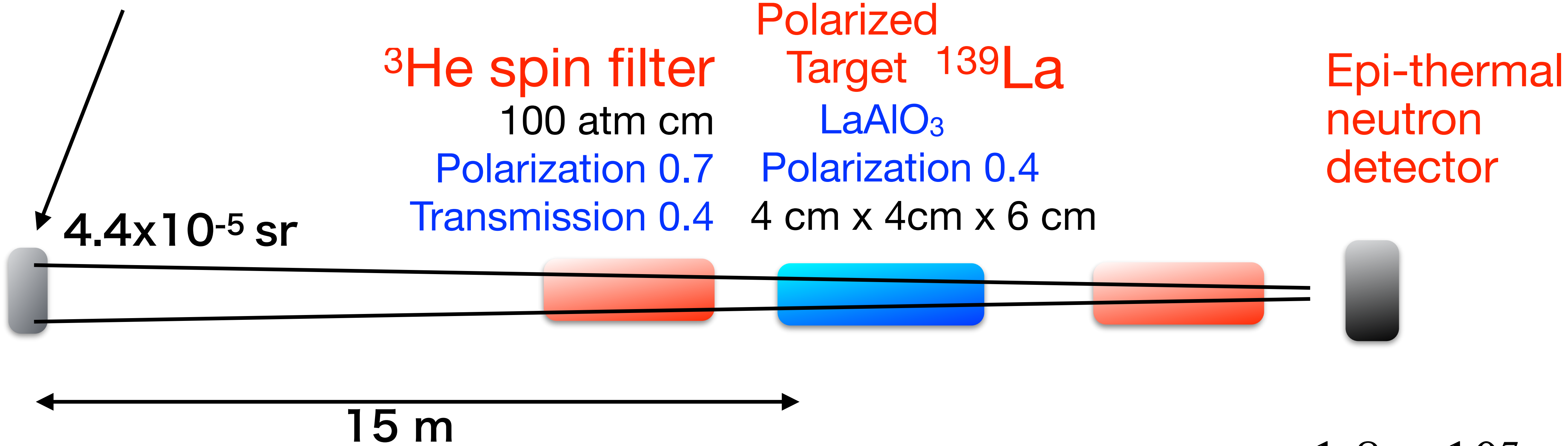
$$\kappa(J) = 2.95^{+2.98}_{-0.90}, \quad 0.89^{+0.04}_{-0.04}$$

T. Okudaira, et.al., https://arxiv.org/abs/1710.03065

T-odd Correlation in Compound Nuclei

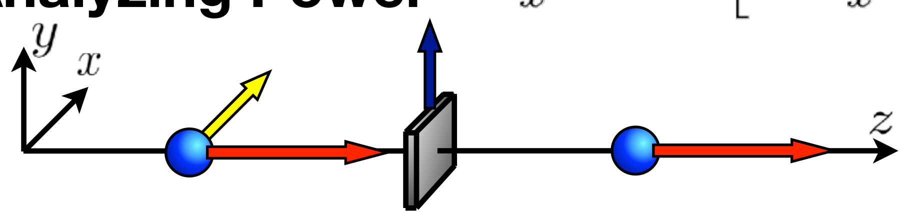
Experimental plan

J-PARC BL07 (Poisoned Moderator)

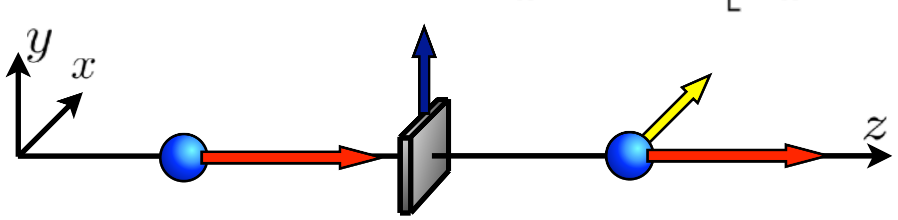


1.8×10^7 n/s

Analyzing Power $A_x \equiv \mathrm{Tr}\left[\delta^\dagger \sigma_x \delta\right]$



Polarization $P_x \equiv \mathrm{Tr}\left[\sigma_x \delta^\dagger \delta\right]$



$\kappa(J) = 0.89$

$8\mathrm{Re}\, A^* D \sim 4 \times 10^{-6}$

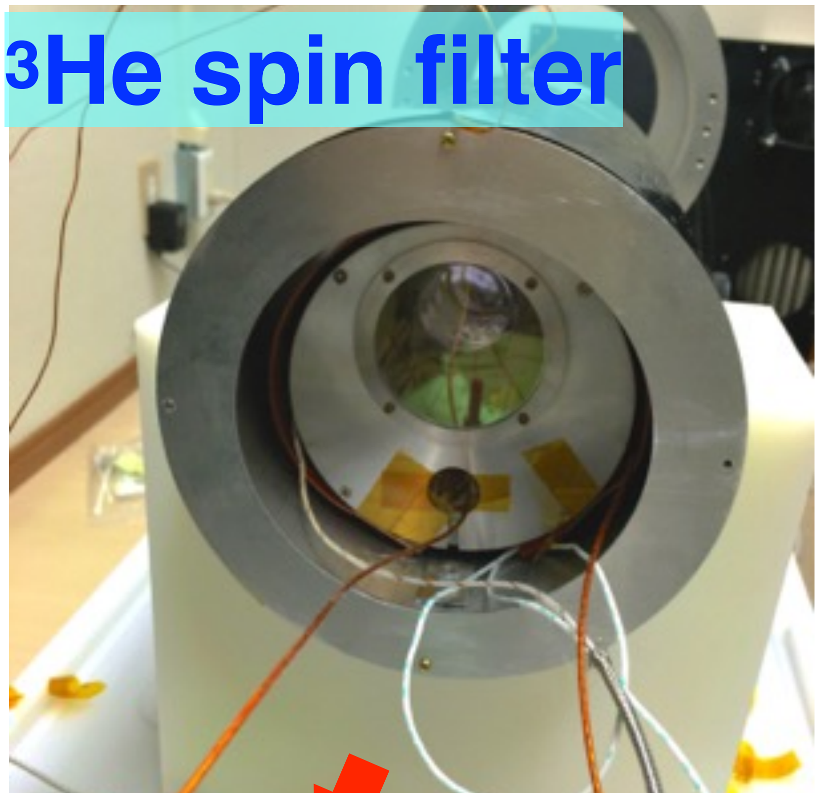
$$A_x + P_x = 8\mathrm{Re}\, A^* D$$

1.7 days

Feasible !

Neutron Polarization

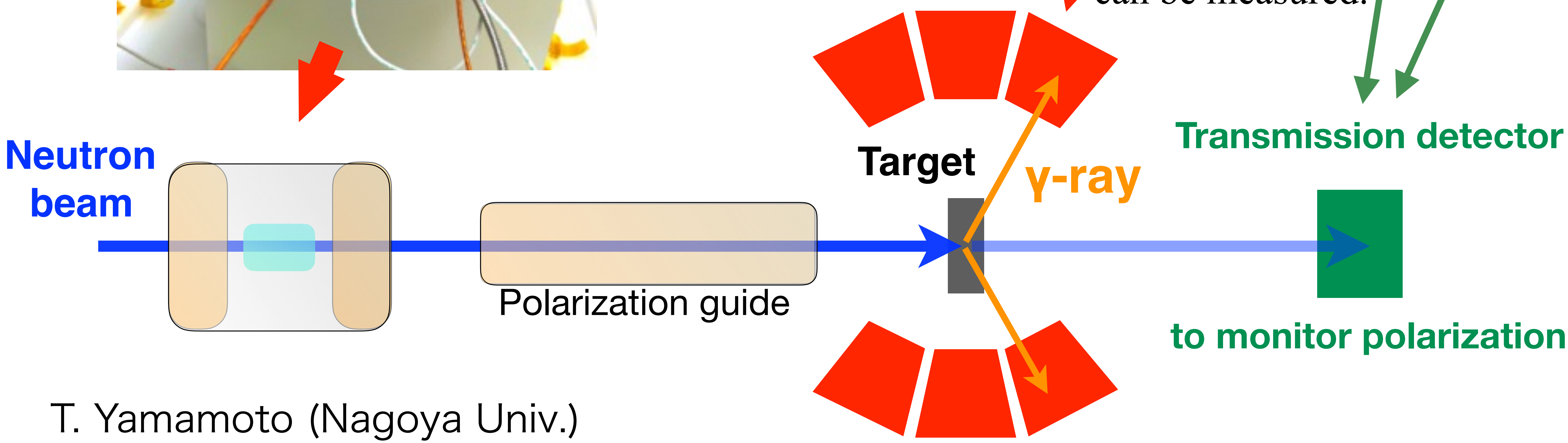
^{3}He neutron spin filter was installed to BL04



Flambaum, Nucl.Phys. A435(1985)352

$$\frac{d\sigma}{d\Omega} = \frac{1}{2}\left[a_0 - \frac{1}{3}a_3 + a_9(\sigma_n\cdot k_\gamma) + a_{10}(\sigma_n\cdot k_n) + a_{11}\left\{(\sigma_n\cdot k_\gamma)(k_\gamma\cdot k_n) - \frac{1}{3}(\sigma_n\cdot k_n)\right\}\right]$$

a_9, a_{10}, a_{11} can be measured.



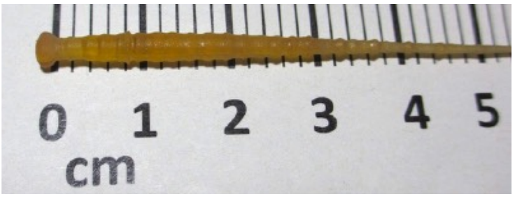
T. Yamamoto (Nagoya Univ.)

Target Polarization

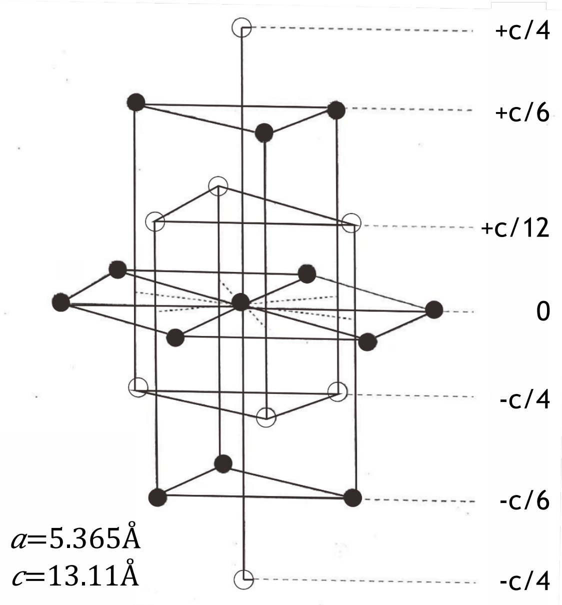
NOP-T

La DNP

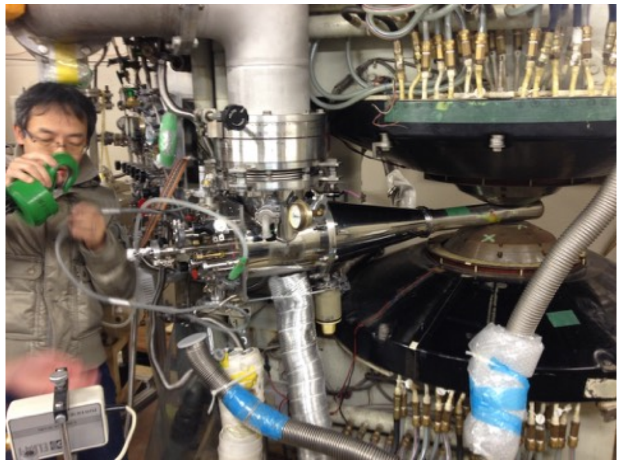
New crystal
by Tohoku univ.



$Nd^{3+}LaAlO_3$



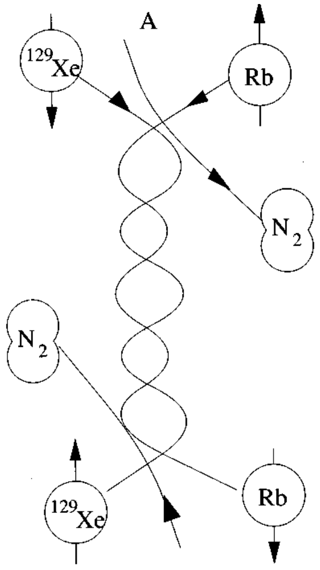
DNP in Yamagata Univ.



2.3T, 0.3K P~50% was reported (Kyoto Univ. PSI)

Xe SEOP UBC

Spin Exchange Optical Pumping

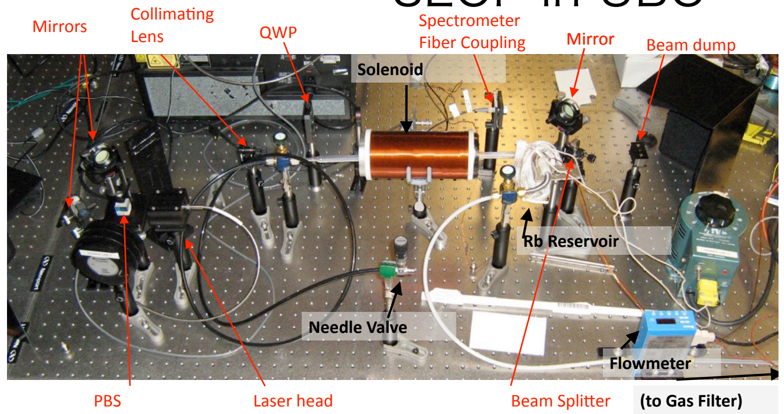


Rb polarized with laser

^{129}Xe was reported.

Try solid ^{131}Xe.

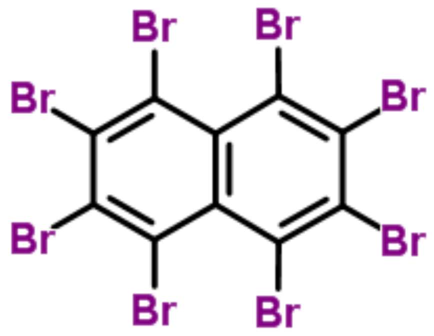
SEOP in UBC



Target polarization studies at RCNP, Osaka univ.

M. Iinuma (Hiroshima Univ.)

Br Triplet-DNP RIKEN



NOPTREX Collaboration

NOP-T

Nagoya University
H.M.Shimizu, M.Kitaguchi, K.Hirota, T.Okudaira, T.Yamamoto, I.Itoh, K.Ishizaki, S.Endoh, T.Satoh, C.C.Haddock, T.Morishima, G.Ichikawa, Y.Kiyanagi, T.Nakao, J.Hisano

Kyushu University
T.Yoshioka, S.Takada, J.Koga

JAEA
K.Sakai, A.Kimura,

Univ. British Colum
T.Momose

Hiroshima Univ.
M.Iinuma

Osaka Univ.
K.Ogata, H.Kohri, M.Yosoi, T.Shima

Tohoku Univ.
M.Fujita

Yamagata Univ.
T.Iwata, Y.Miyachi

RIKEN
N.Yamanaka, Y.Yamagata

KEK
T.Ino, S.Ishimoto, K.Taketani, K.Mishima

Kyoto Univ.
Y.I.Takahashi, M.Hino

TREX

Indiana University
W.M.Snow, J.Curole, J.Carini

Univ. South Carolina
V.Gudkov

Oak Ridge National Lab.
J.D.Bowman, S.Penttila, X.Tong

Univ.
D.Schaper, C.Crawford

rrer Institut

Southern Illinois University
B.M.Goodson

Univ. California Berkeley
A.S.Tremsin

Berea College
M.Veillette

US-Japan collaboration starts

Summary of T-violation search

T violation is enhanced in compound nuclei reaction.
(Sensitivity can be better than EDM experiment.)

T violation search in compound nuclei experiment requires complex system.

- Intense neutron source
- Epithermal neutron polarizer
- Target polarization
- Fast and efficient detector for epithermal neutrons
- Neutron spin control

We start US-Japan collaboration NOPTREX.