T Violation in n-A Reactions

Neutron Optical Parity and Time-Reversal EXperiment

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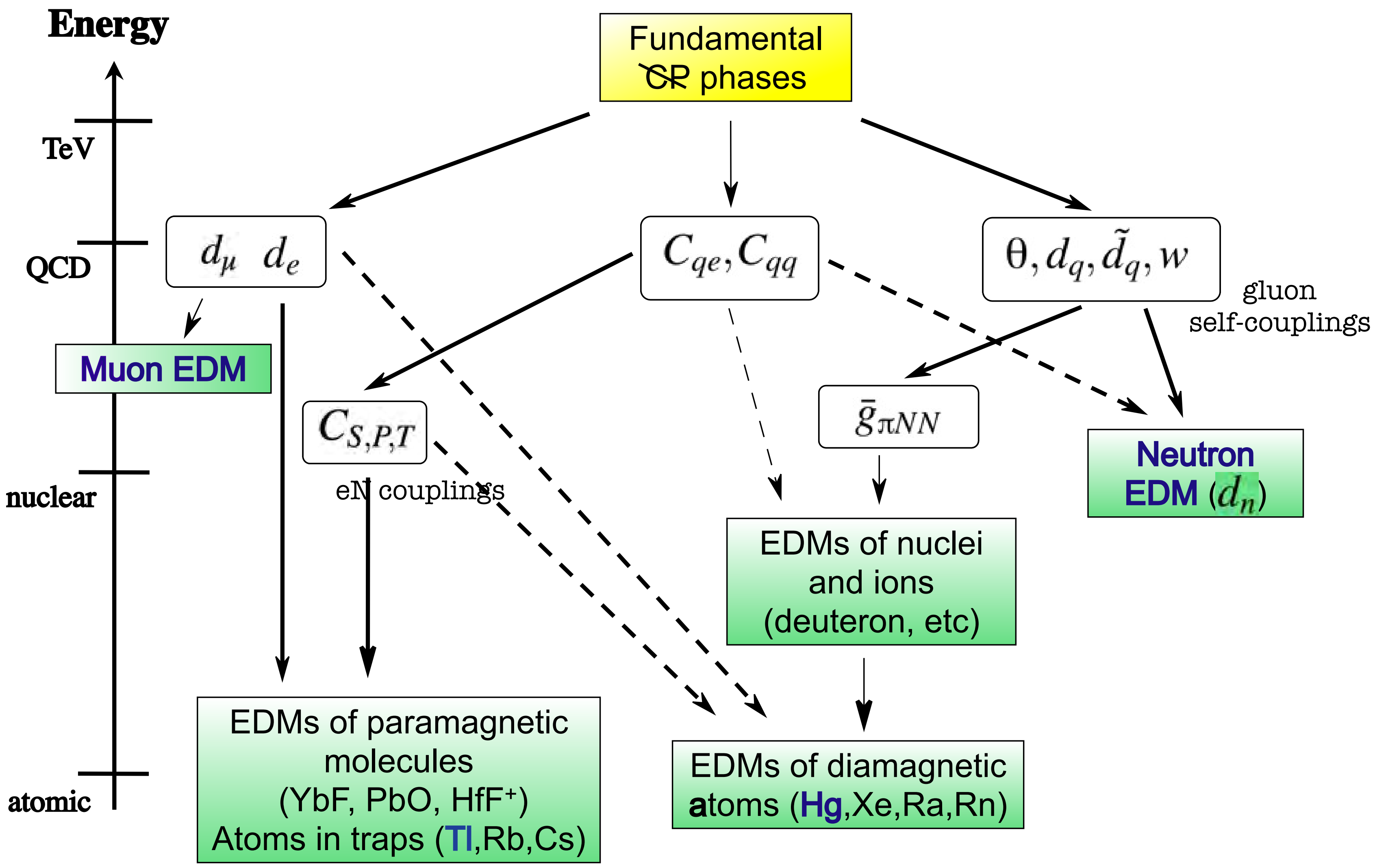
on behalf of the NOPTREX collaboration



Energy

TeV

QCD

nuclear

atomic

Fundamental ~~CP~~ phases

$d_\mu \ d_e$

C_{qe}, C_{qq}

$\theta, d_q, \tilde{d}_q, w$

gluon self-couplings

Muon EDM

$C_{S,P,T}$

eN couplings

$\bar{g}_{\pi NN}$

Neutron EDM (d_n)

EDMs of nuclei and ions (deuteron, etc)

EDMs of paramagnetic molecules (YbF, PbO, HfF⁺) Atoms in traps (**Tl**,Rb,Cs)

EDMs of diamagnetic atoms (**Hg**,Xe,Ra,Rn)

$$d_{\mathrm{n}} \sim 1.1 \times \mathrm{e}(\underbrace{0.5 d_{\mathrm{u}}^{\mathrm{c}} + d_{\mathrm{d}}^{\mathrm{c}}}_{\text{valence quark contribution}}) + 1.4 \times (\underline{-0.25 d_{\mathrm{u}} + d_{\mathrm{d}}})$$

$$|d_{\mathrm{n}}| < 2.9 \times 10^{-26}\,\mathrm{e} \cdot \mathrm{cm} \leftrightarrow |d_{\mathrm{n}}^{\mathrm{SM}}| < 10^{-32}\,\mathrm{e} \cdot \mathrm{cm}$$

Pospelov Ritz, Ann Phys 318 (05) 119

$$d_{\mathrm{Tl}} \sim \underbrace{-585 d_{\mathrm{e}}}_{\text{relativistic effect}} \mathrm{e}\, 43\,\mathrm{GeV} \times (C_{\mathrm{S}}^{(0)} - 0.2 C_{\mathrm{s}}^{(1)})$$

$$|d_{\mathrm{e}}| < 1.7 \times 10^{-27}\,\mathrm{e} \cdot \mathrm{cm} \leftrightarrow |d_{\mathrm{e}}^{\mathrm{SM}}| < 10^{-40}\,\mathrm{e} \cdot \mathrm{cm}$$

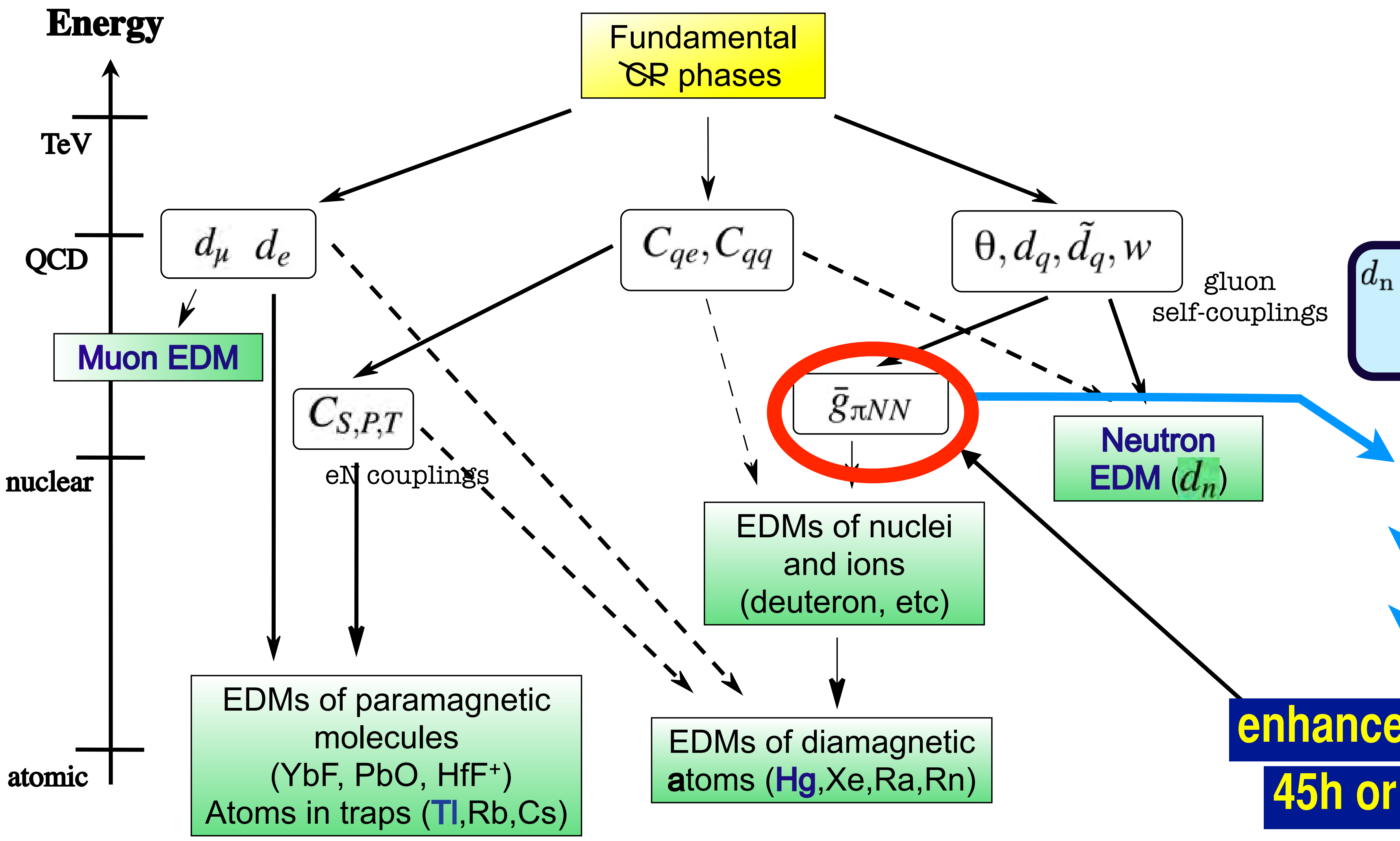
$$d_{\mathrm{Hg}} \sim 7 \times 10^{-3} \mathrm{e} (\underbrace{0.5 d_{\mathrm{u}}^{\mathrm{c}} + d_{\mathrm{d}}^{\mathrm{c}}}_{\text{via } \pi\text{–N interaction}})$$

$$d_{\mathrm{D}} \sim \underbrace{(d_{\mathrm{u}} + d_{\mathrm{d}}) - 0.2 \mathrm{e} (d_{\mathrm{u}}^{\mathrm{c}} + d_{\mathrm{d}}^{\mathrm{c}})}_{\text{constituent particle EDMs}} + \underbrace{6 \mathrm{e} (d_{\mathrm{d}}^{\mathrm{c}} - d_{\mathrm{u}}^{\mathrm{c}})}_{\pi \text{ exchange}}$$

KEK 2018S12

Neutron Optical Parity and Time Reversal EXperiment

NOPTREX Collaboration



Pospelov Ritz, Ann Phys 318 (05) 119

$$d_{\rm n} \sim 1.1 \times {\rm e}(\underbrace{0.5 d^{\rm c}_{\rm u} + d^{\rm c}_{\rm d}}_{\text{valence quark contribution}}) + 1.4 \times (\underline{-0.25 d_{\rm u} + d_{\rm d}})$$

$$|d_{\rm n}| < 2.9 \times 10^{-26}\,{\rm e \cdot cm} \leftrightarrow |d^{\rm SM}_{\rm n}| < 10^{-32}\,{\rm e \cdot cm}$$

nucleon $\langle W_{\rm T} \rangle$

compound state $\left\langle I + \frac{1}{2} \middle| W_{\rm T} \middle| I - \frac{1}{2} \right\rangle$

experiment $\langle {\rm s} | W_{\rm T} | {\rm p} \rangle$

enhanced sensitivity in compound nuclei

45h or 2h to reach nEDM “upper limit”

(30d or 1d with existing technologies)

$$d_{\rm Tl} \sim \underbrace{-585 d_{\rm e}}_{\text{relativistic effect}} {\rm e}\, 43\,{\rm GeV} \times (C^{(0)}_{\rm S} - 0.2 C^{(1)}_{\rm s})$$

$$|d_{\rm e}| < 1.7 \times 10^{-27}\,{\rm e \cdot cm} \leftrightarrow |d^{\rm SM}_{\rm e}| < 10^{-40}\,{\rm e \cdot cm}$$

$$d_{\rm Hg} \sim 7 \times 10^{-3} {\rm e} \underbrace{(0.5 d^{\rm c}_{\rm u} + d^{\rm c}_{\rm d})}_{\text{via } \pi-{\rm N} \text{ interaction}}$$

$$d_{\rm D} \sim \underbrace{(d_{\rm u} + d_{\rm d}) - 0.2{\rm e}(d^{\rm c}_{\rm u} + d^{\rm c}_{\rm d})}_{\text{constituent particle EDMs}} + \underbrace{6{\rm e}(d^{\rm c}_{\rm d} - d^{\rm c}_{\rm u})}_{\pi \text{ exchange}}$$

KEK 2018S12

Neutron Optical Parity and Time Reversal EXperiment

NOPTREX Collaboration

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A.S.Tremsin

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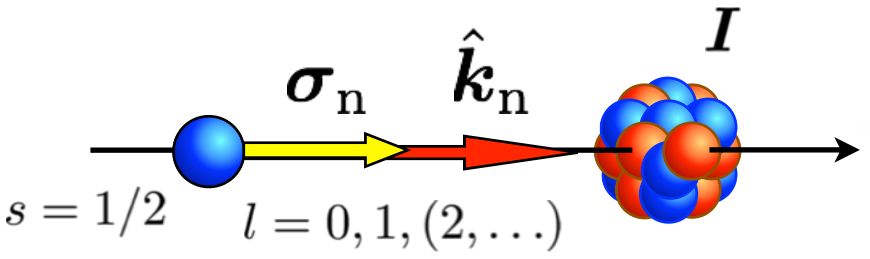
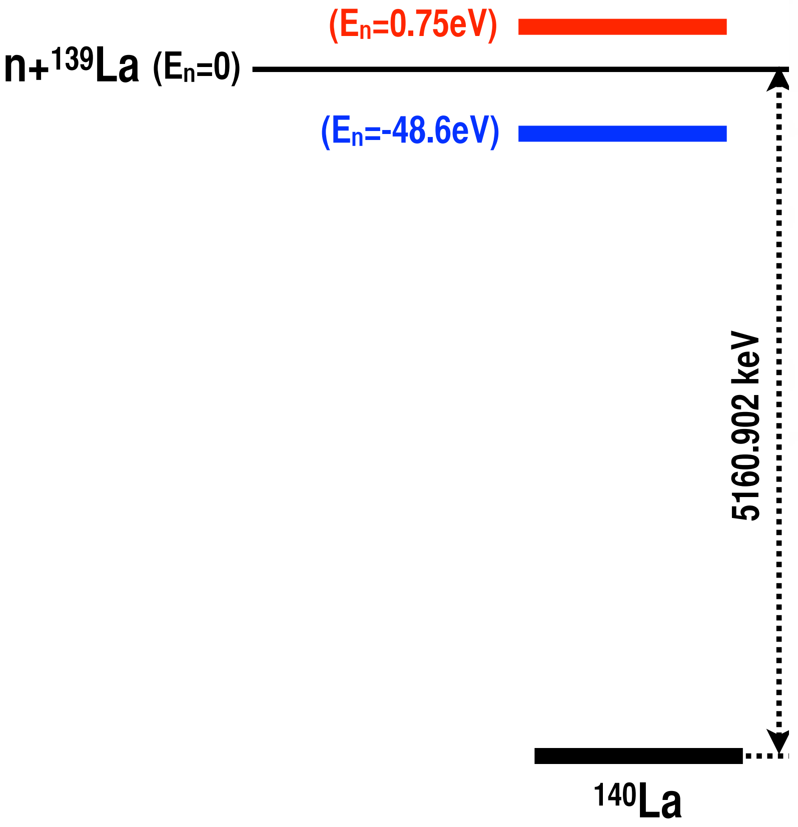
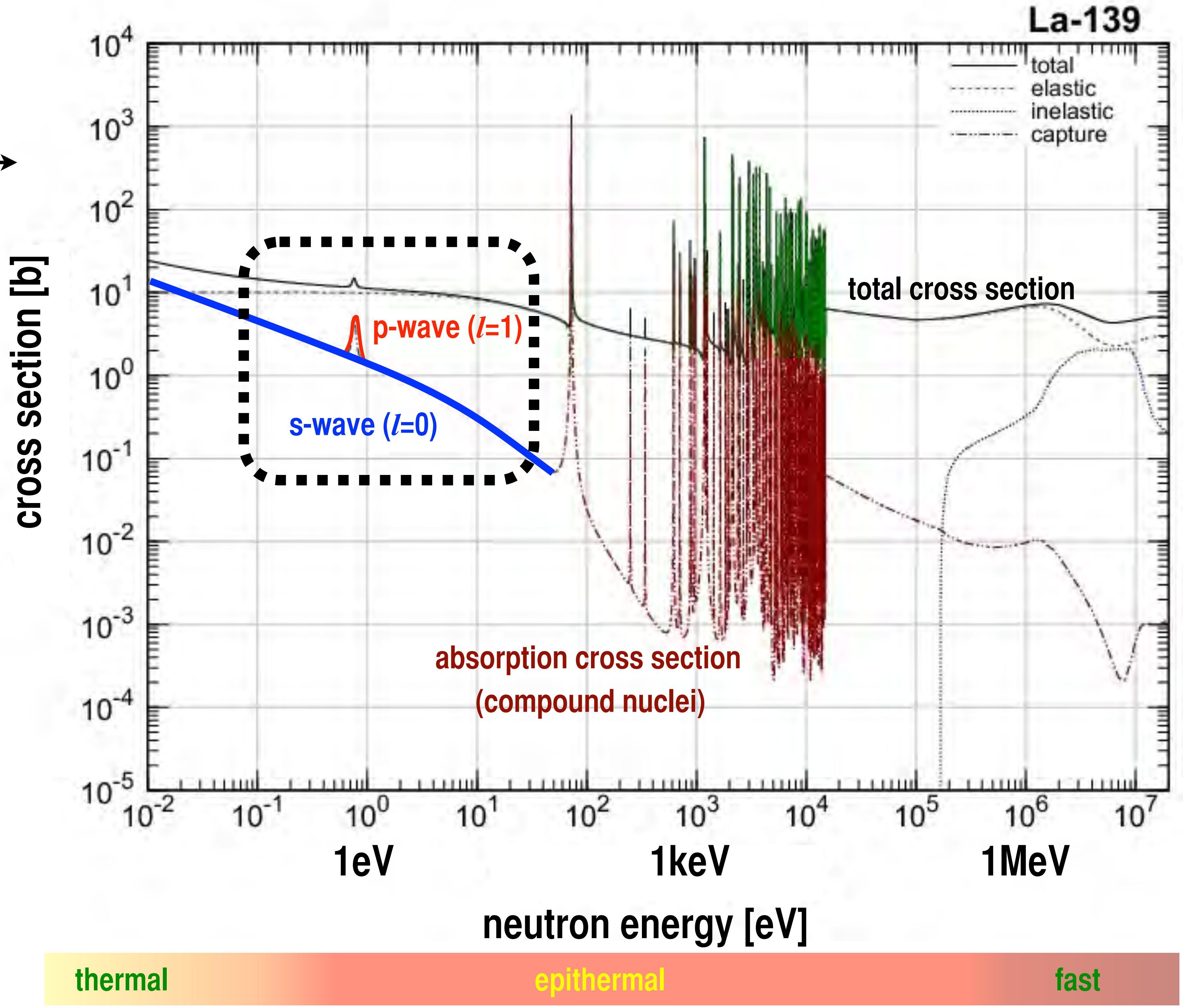
Compound States

P-violation

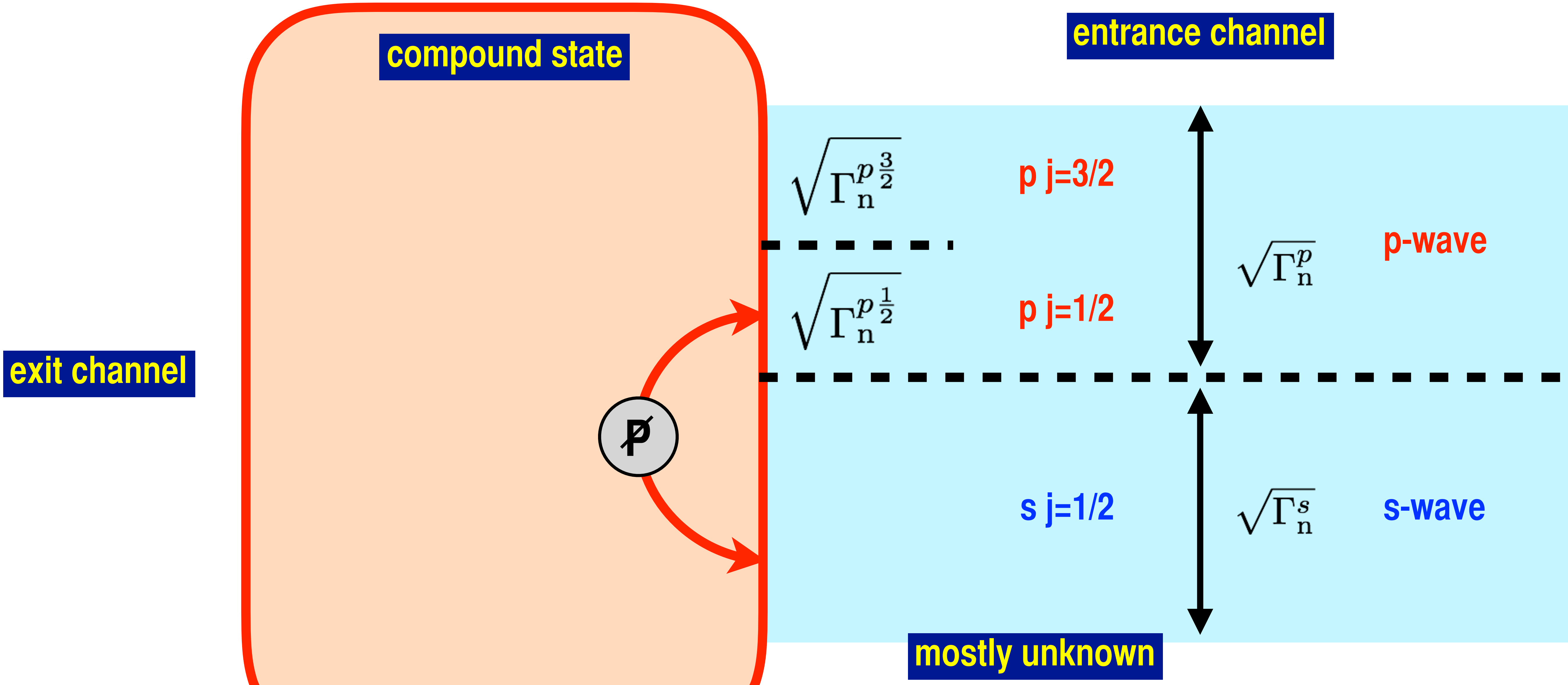
$$\sigma = \sigma_0 + \boxed{\Delta\sigma}(\boldsymbol{\sigma}_{\rm n} \cdot \hat{\boldsymbol{k}}_{\rm n})$$







Universality Check



compound state

entrance channel

exit channel

$\not{P}$

$\sqrt{\Gamma_{\mathrm{n}}^{p\frac{3}{2}}}$ p j=3/2

$\sqrt{\Gamma_{\mathrm{n}}^{p\frac{1}{2}}}$ p j=1/2

$\sqrt{\Gamma_{\mathrm{n}}^{p}}$ p-wave

s j=1/2

$\sqrt{\Gamma_{\mathrm{n}}^{s}}$ s-wave

mostly unknown

$$A_{\mathrm{L}} = -\frac{2W}{E_{\mathrm{p}} - E_{\mathrm{s}}}\sqrt{\frac{\Gamma_{\mathrm{n}}^{s}}{\Gamma_{\mathrm{n}}^{p}}}\underbrace{\sqrt{\frac{\Gamma_{\mathrm{n}}^{p\frac{1}{2}}}{\Gamma_{\mathrm{n}}^{p}}}}_{x}$$

$$x = \sqrt{\frac{\Gamma_{\mathrm{n}}^{p\frac{1}{2}}}{\Gamma_{\mathrm{n}}^{p}}} \quad y = \sqrt{\frac{\Gamma_{\mathrm{n}}^{p\frac{3}{2}}}{\Gamma_{\mathrm{n}}^{p}}}$$

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

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

compound nuclear spin **orbital** **n spin** **nuclear spin**

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

n entrance spin $\boldsymbol{j}$ $\boldsymbol{S}$ **channel spin**

$$|((Is)S, l)J\rangle = \sum_j \langle (I, (sl)j)J|((Is)S, l)J\rangle \, |(I, (sl)j)J\rangle$$

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

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

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

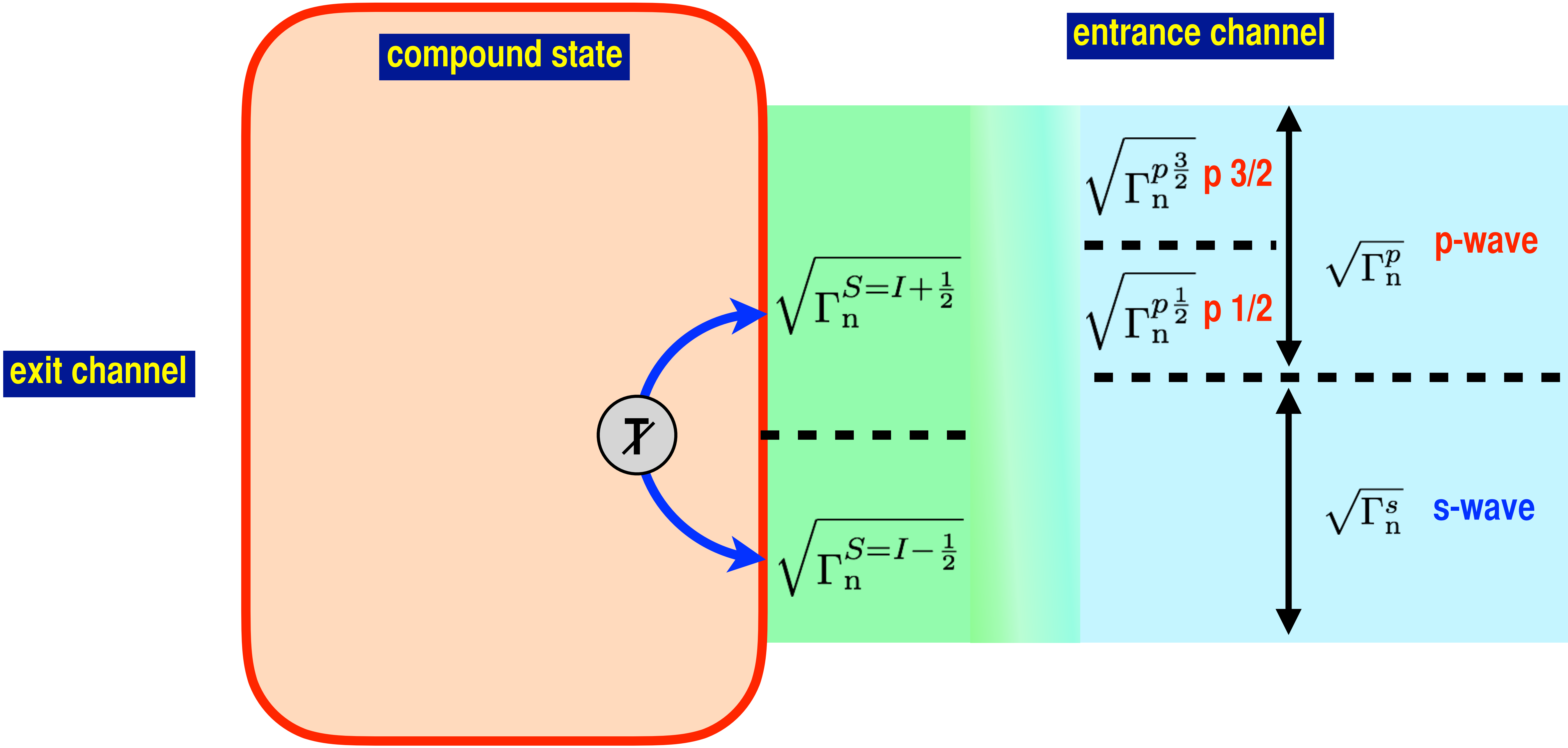
s-p interference ⇔ channel-spin interference

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

$$l = 0, 1$$ **P-odd**

$$S = I \pm 1/2$$ **T-odd**

T-odd ➡ Channel-spin Interference



compound state

entrance channel

exit channel

$\not{T}$

$\sqrt{\Gamma_{\rm n}^{S=I+\frac{1}{2}}}$

$\sqrt{\Gamma_{\rm n}^{S=I-\frac{1}{2}}}$

$\sqrt{\Gamma_{\rm n}^{p\frac{3}{2}}}$ p 3/2

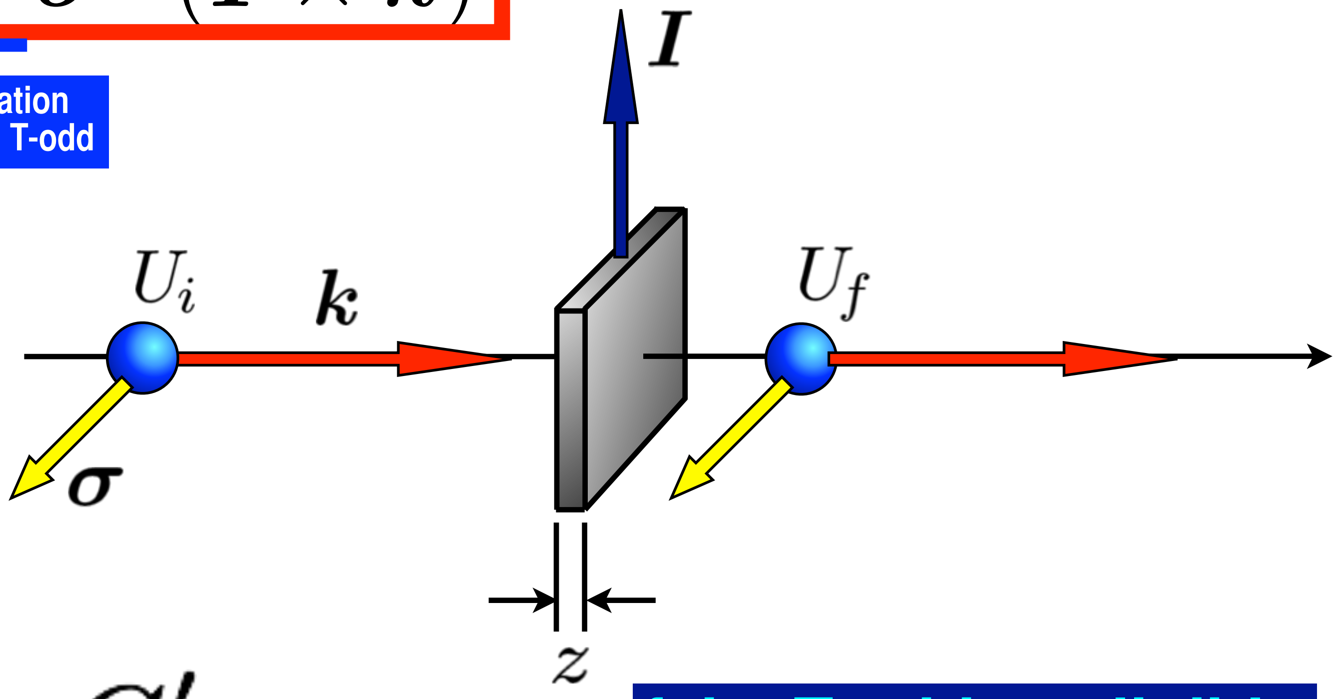
$\sqrt{\Gamma_{\rm n}^{p\frac{1}{2}}}$ p 1/2

$\sqrt{\Gamma_{\rm n}^{p}}$ p-wave

$\sqrt{\Gamma_{\rm n}^{s}}$ s-wave

T-violation in Neutron Optics

$$f = \underbrace{A'}_{\substack{\text{Spin Independent}\\ \text{P-even T-even}}} + \underbrace{B'}_{\substack{\text{Spin Dependent}\\ \text{P-even T-even}}}\boldsymbol{\sigma}\cdot\hat{\boldsymbol{I}} + \underbrace{C'}_{\substack{\text{P-violation}\\ \text{P-odd T-even}}}\boldsymbol{\sigma}\cdot\hat{\boldsymbol{k}} + \boxed{\underbrace{D'}_{\substack{\text{T-violation}\\ \text{P-odd T-odd}}}\boldsymbol{\sigma}\cdot(\hat{\boldsymbol{I}}\times\hat{\boldsymbol{k}})}$$



fake T-odd negligible

T-violating matrix element

$$\overset{D'}{\ }\quad \boxed{\Delta\sigma_{\mathrm{CP}} = \kappa(J)\frac{W_{\mathrm{T}}}{W}\overset{C'}{\Delta\sigma_{\mathrm{P}}}}$$

Gudkov, Phys. Rep. 212 (1992) 77

T-violation **angular momentum factor** **P-violation**

P-violating matrix element

T-violation in Neutron Optics

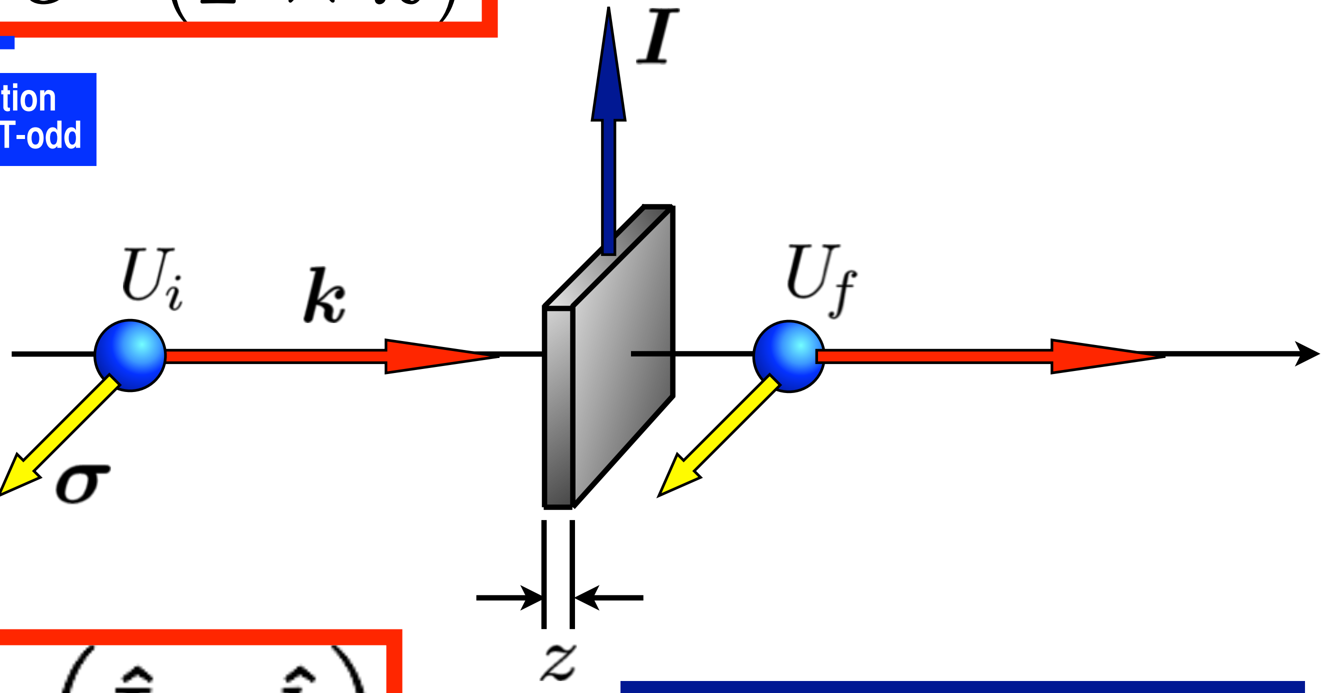
$$f = \underbrace{A'}_{} + \underbrace{B'}_{}\boldsymbol{\sigma}\cdot\hat{\boldsymbol{I}} + \underbrace{C'}_{}\boldsymbol{\sigma}\cdot\hat{\boldsymbol{k}} + \boxed{\underbrace{D'}_{}\boldsymbol{\sigma}\cdot(\hat{\boldsymbol{I}}\times\hat{\boldsymbol{k}})}$$

Spin Independent
P-even T-even

Spin Dependent
P-even T-even

P-violation
P-odd T-even

T-violation
P-odd T-odd



$$U_f = \delta U_i$$

$$\delta = e^{i(n-1)kz} \qquad n = 1 + \frac{2\pi\rho}{k^2} f$$

$$\delta = \underbrace{A}_{} + \underbrace{B}_{}\boldsymbol{\sigma}\cdot\hat{\boldsymbol{I}} + \underbrace{C}_{}\boldsymbol{\sigma}\cdot\hat{\boldsymbol{k}} + \boxed{\underbrace{D}_{}\boldsymbol{\sigma}\cdot\left(\hat{\boldsymbol{I}}\times\hat{\boldsymbol{k}}\right)}$$

Spin Independent
P-even T-even

Spin Dependent
P-even T-even

P-violation
P-odd T-even

T-violation
P-odd T-odd

fake T-odd negligible

$$A = e^{iZA'}\cos b \qquad B = ie^{iZA'}\frac{\sin b}{b}ZB'$$

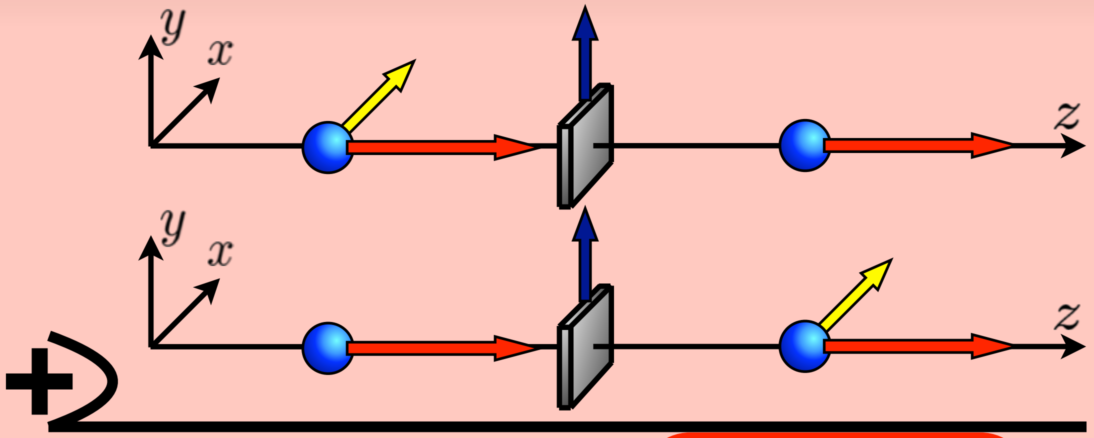
$$Z = \frac{2\pi\rho}{k}z \qquad C = ie^{iZA'}\frac{\sin b}{b}ZC'$$

$$b = Z(B'^2 + C'^2 + D'^2)^{1/2} \qquad D = ie^{iZA'}\frac{\sin b}{b}ZD'$$

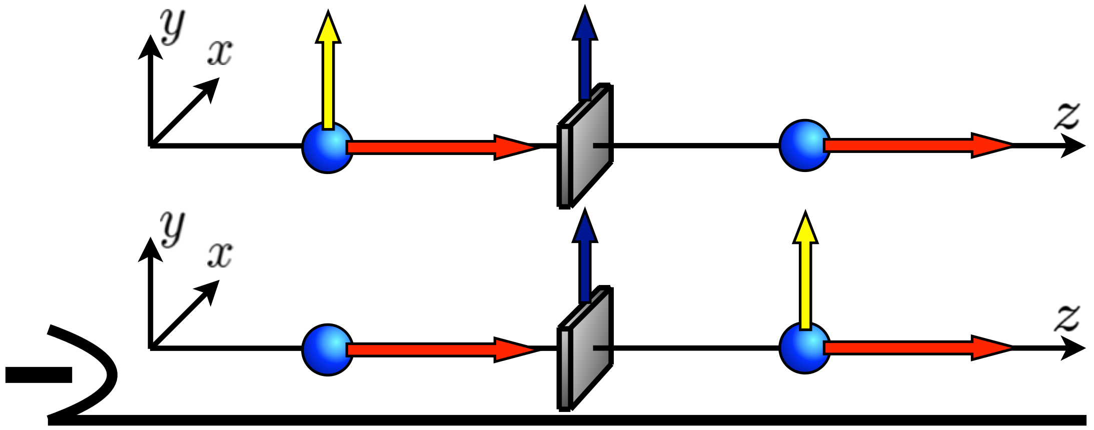
D≠0 ➡ D'≠0

validity of this description can be checked via the consistency among A, B, C

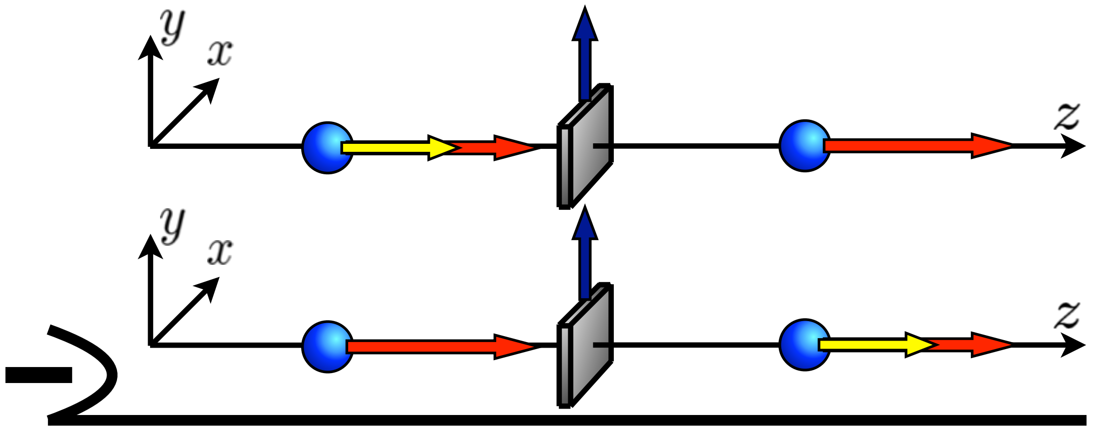
Analyzing Power and Polarization



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

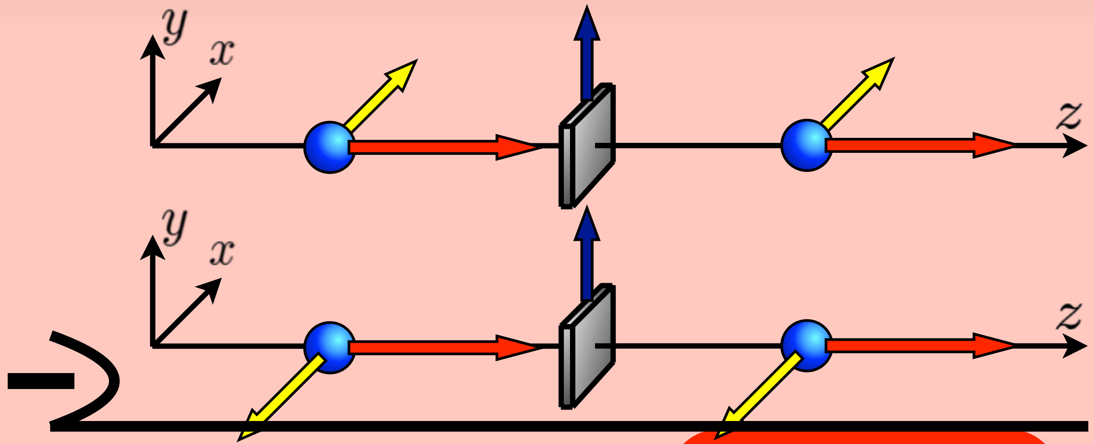


$$A_y - P_y = 8\mathrm{Im}\,C^* D$$

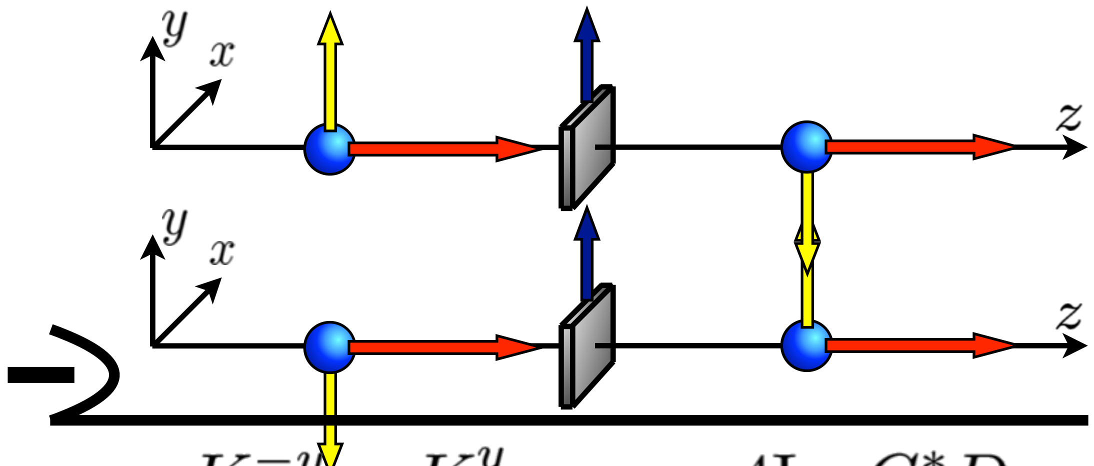


$$A_z - P_z = 8\mathrm{Im}\,D^* B$$

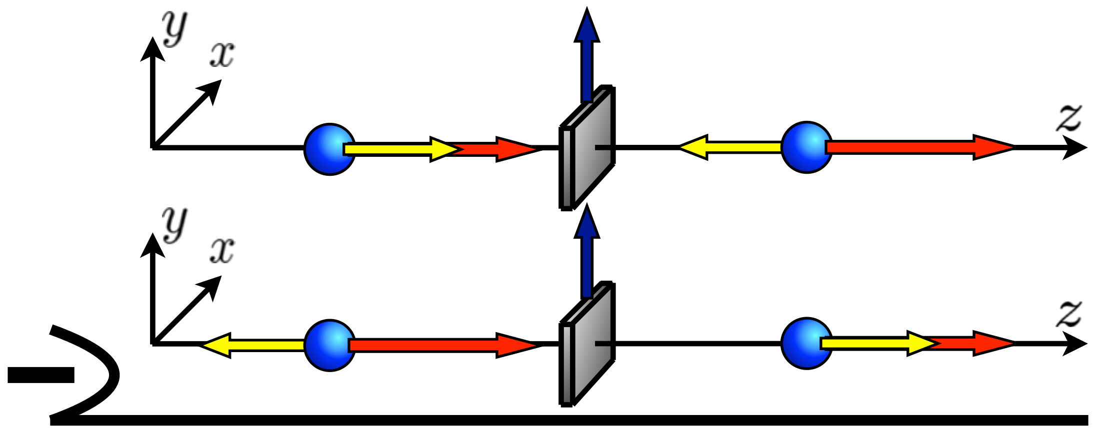
Polarization Transfer Coefficient



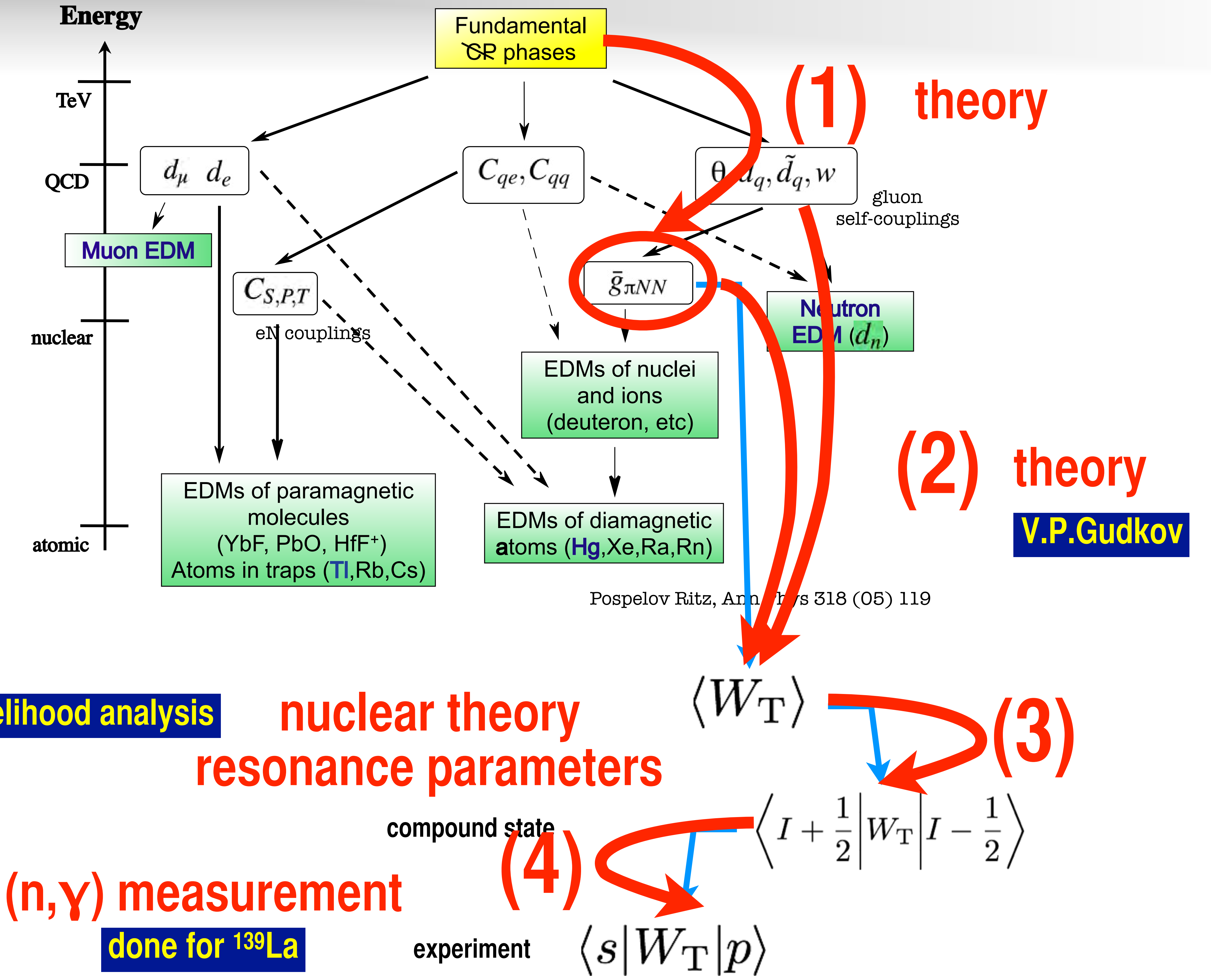
$$K_x^x - K_{-x}^{-x} = \boxed{4\mathrm{Re}\,A^* D}$$



$$K_y^{-y} - K_{-y}^{y} = 4\mathrm{Im}\,C^* D$$



$$K_z^{-z} - K_{-z}^{z} = 4\mathrm{Im}\,D^* B$$



Energy

TeV

QCD

nuclear

atomic

Fundamental ~~CP~~ phases

(1) theory

$d_\mu \quad d_e$

C_{qe}, C_{qq}

$\theta, d_q, \tilde{d}_q, w$

gluon self-couplings

Muon EDM

$C_{S,P,T}$

eN couplings

$\bar{g}_{\pi NN}$

Neutron EDM (d_n)

EDMs of nuclei and ions (deuteron, etc)

(2) theory

V.P.Gudkov

EDMs of paramagnetic molecules (YbF, PbO, HfF^+) Atoms in traps (Tl,Rb,Cs)

EDMs of diamagnetic atoms (Hg,Xe,Ra,Rn)

Pospelov Ritz, Ann Phys 318 (05) 119

$\langle W_T \rangle$

done via likelihood analysis

nuclear theory

resonance parameters

(3)

compound state

$\left\langle I+\frac{1}{2}\middle|W_T\middle|I-\frac{1}{2}\right\rangle$

(4)

(n,γ) measurement

done for ^{139}La

experiment

$\langle s|W_T|p\rangle$

(1), (2) Estimation in Effective Field Theory

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

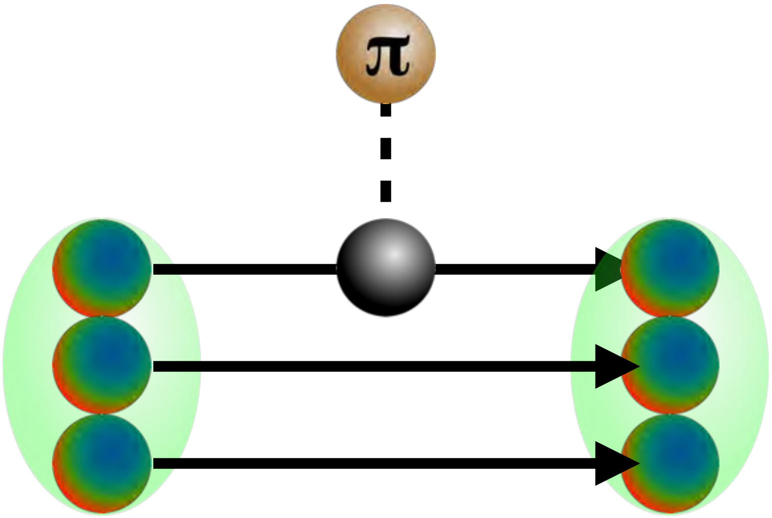
$$\boldsymbol{\sigma}_\pm = \boldsymbol{\sigma}_1 \pm \boldsymbol{\sigma}_2 \qquad \boldsymbol{r} = \boldsymbol{r}_1 - \boldsymbol{r}_2 \qquad x_a = m_a r$$

$$T^z_{12} = 3\tau^z_1\tau^z_2 - \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 \qquad Y_1(x) = \left(1 + \frac{1}{x}\right)\frac{e^{-x}}{x}$$

$$g_\pi = 13.07, \quad g_\eta = 2.24, \quad g_\rho = 2.75, \quad g_\omega = 8.25$$

$$\begin{aligned}
V_{\mathrm{CP}} = & \left[-\frac{\bar{g}^{(0)}_\eta g_\eta}{2m_N}\frac{m^2_\eta}{4\pi}Y_1(x_\eta) + \frac{\bar{g}^{(0)}_\omega g_\omega}{2m_N}\frac{m^2_\omega}{4\pi}Y_1(x_\omega)\right]\boldsymbol{\sigma}_- \cdot \hat{\boldsymbol{r}} \\
& + \left[-\frac{\bar{g}^{(0)}_\pi g_\pi}{2m_N}\frac{m^2_\pi}{4\pi}Y_1(x_\pi) + \frac{\bar{g}^{(0)}_\rho g_\rho}{2m_N}\frac{m^2_\rho}{4\pi}Y_1(x_\rho)\right]\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 \boldsymbol{\sigma}_- \cdot \hat{\boldsymbol{r}} \\
& + \left[-\frac{\bar{g}^{(2)}_\pi g_\pi}{2m_N}\frac{m^2_\pi}{4\pi}Y_1(x_\pi) + \frac{\bar{g}^{(2)}_\rho g_\rho}{2m_N}\frac{m^2_\rho}{4\pi}Y_1(x_\rho)\right]T^z_{12}\boldsymbol{\sigma}_- \cdot \hat{\boldsymbol{r}} \\
& + \left[-\frac{\bar{g}^{(1)}_\pi g_\pi}{2m_N}\frac{m^2_\pi}{4\pi}Y_1(x_\pi) + \frac{\bar{g}^{(1)}_\eta g_\eta}{2m_N}\frac{m^2_\eta}{4\pi}Y_1(x_\eta) + \frac{\bar{g}^{(1)}_\rho g_\rho}{2m_N}\frac{m^2_\rho}{4\pi}Y_1(x_\rho) + \frac{\bar{g}^{(1)}_\omega g_\omega}{2m_N}\frac{m^2_\omega}{4\pi}Y_1(x_\omega)\right]\tau_+\boldsymbol{\sigma}_- \cdot \hat{\boldsymbol{r}} \\
& + \left[-\frac{\bar{g}^{(1)}_\pi g_\pi}{2m_N}\frac{m^2_\pi}{4\pi}Y_1(x_\pi) - \frac{\bar{g}^{(1)}_\eta g_\eta}{2m_N}\frac{m^2_\eta}{4\pi}Y_1(x_\eta) - \frac{\bar{g}^{(1)}_\rho g_\rho}{2m_N}\frac{m^2_\rho}{4\pi}Y_1(x_\rho) + \frac{\bar{g}^{(1)}_\omega g_\omega}{2m_N}\frac{m^2_\omega}{4\pi}Y_1(x_\omega)\right]\tau_+\boldsymbol{\sigma}_+ \cdot \hat{\boldsymbol{r}}
\end{aligned}$$

T-odd P-odd meson couplings



$$\Rightarrow \quad \tilde{d}_n \simeq 0.14\left(\bar{g}^{(0)}_\pi - \bar{g}^{(2)}_\pi\right)$$

$$\Rightarrow \quad \frac{\Delta\sigma_{\mathrm{CP}}}{2\sigma_{\mathrm{tot}}} = \frac{-0.185[\mathrm{b}]}{2\sigma_{\mathrm{tot}}}\left(\bar{g}^{(0)}_\pi + 0.26\bar{g}^{(1)}_\pi\right)$$

(1), (2) Estimation in Effective Field Theory

$$\frac{\langle s|W_{\mathrm{T}}|p\rangle}{\langle s|W|p\rangle} \simeq (1-0.1) \times \frac{\langle W_{\mathrm{T}}\rangle}{\langle W\rangle}$$

Gudkov, Phys. Rep. 212 (1992) 77

Flambaum, Phys. Rev. C51 (1995) 2914

$$\frac{W_{\mathrm{T}}}{W} \simeq -0.47\left(\frac{\bar{g}_\pi^{(0)}}{h_\pi^1} + 0.26\frac{\bar{g}_\pi^{(1)}}{h_\pi^1}\right)$$

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

$$\bar{g}_\pi^{(0)} < 2.5 \times 10^{-10} \qquad |d_{\mathrm{n}}| < 3 \times 10^{-26}\, e\,\mathrm{cm}$$

$$\bar{g}_\pi^{(1)} < 0.5 \times 10^{-11} \qquad \left|d(^{199}\mathrm{Hg})\right| < 3.1 \times 10^{-29}\, e\,\mathrm{cm}$$

$$h_\pi^1 \sim 3 \times 10^{-7} \qquad \mathrm{n} + \mathrm{p} \rightarrow \mathrm{d} + \gamma$$

$$\left|\frac{W_{\mathrm{T}}}{W}\right| < 3.9 \times 10^{-4}$$

←discovery potential corresponding to the present nEDM upper limit

(3,4) Details of Entrance Channel

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

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

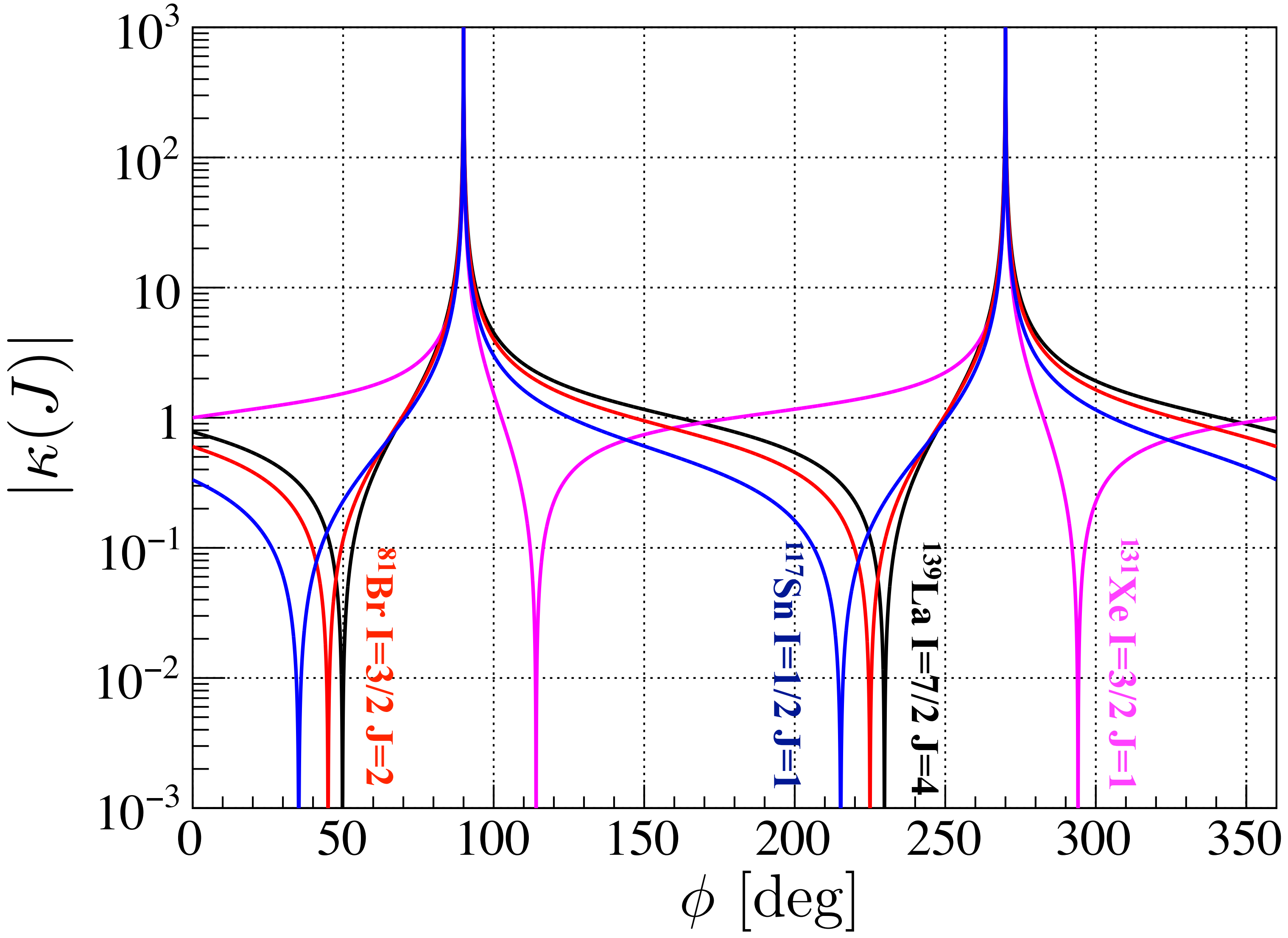
$$x^2 = \frac{\Gamma^{\mathrm{n}}_{\mathrm{p},j=\frac{1}{2}}}{\Gamma^{\mathrm{n}}_{\mathrm{p}}}, \quad y^2 = \frac{\Gamma^{\mathrm{n}}_{\mathrm{p},j=\frac{3}{2}}}{\Gamma^{\mathrm{n}}_{\mathrm{p}}}.$$

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

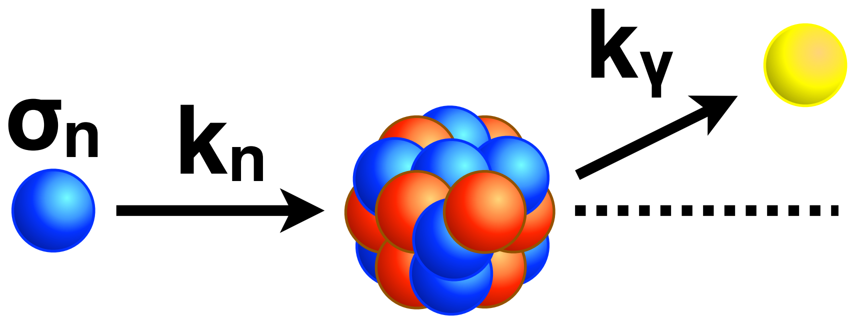
$$\boxed{x = \cos\phi, \quad y = \sin\phi}$$

↑

ϕ : necessary to estimate κ(J)



(3,4) Details of Entrance Channel



$$|s\rangle \quad J_s\, E_s\, \Gamma_s \Gamma^n_s$$

$$|p\rangle \quad J_p\, E_p\, \Gamma_p \Gamma^n_p$$

$$\boxed{\phi}$$

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

$$\Gamma^n_{p,1/2} \quad \Gamma^n_{p,3/2}$$

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

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

coeff.	$\boldsymbol{\sigma}_n$-dep.	$\boldsymbol{\sigma}_\gamma$-dep.	P	T	correlation
a_0	no	no	P-even	T-even	1
a_1	no	no	P-even	T-even	$\boldsymbol{k}_n \cdot \boldsymbol{k}_\gamma$
a_2	yes	no	P-even	T-odd	$\boldsymbol{\sigma}_n \cdot (\boldsymbol{k}_n \times \boldsymbol{k}_\gamma)$
a_3	no	no	P-even	T-even	$(\boldsymbol{k}_n \cdot \boldsymbol{k}_\gamma)^2 - \frac{1}{3}$
a_4	yes	no	P-even	T-odd	$(\boldsymbol{k}_n \cdot \boldsymbol{k}_\gamma)\, \boldsymbol{\sigma}_n \cdot (\boldsymbol{k}_n \times \boldsymbol{k}_\gamma)$
a_5	yes	yes	P-even	T-even	$(\boldsymbol{\sigma}_\gamma \cdot \boldsymbol{k}_\gamma)\, (\boldsymbol{\sigma}_n \cdot \boldsymbol{k}_\gamma)$
a_6	yes	yes	P-even	T-even	$(\boldsymbol{\sigma}_\gamma \cdot \boldsymbol{k}_\gamma)\, (\boldsymbol{\sigma}_n \cdot \boldsymbol{k}_\gamma)$
a_7	yes	yes	P-even	T-even	$(\boldsymbol{\sigma}_\gamma \cdot \boldsymbol{k}_\gamma) \left[(\boldsymbol{\sigma}_n \cdot \boldsymbol{k}_\gamma)\, (\boldsymbol{k}_\gamma \cdot \boldsymbol{k}_n) - \frac{1}{3}(\boldsymbol{\sigma}_n \cdot \boldsymbol{k}_n)\right]$
a_8	yes	yes	P-even	T-even	$(\boldsymbol{\sigma}_\gamma \cdot \boldsymbol{k}_\gamma) \left[(\boldsymbol{\sigma}_n \cdot \boldsymbol{k}_n)\, (\boldsymbol{k}_n \cdot \boldsymbol{k}_\gamma) - \frac{1}{3}(\boldsymbol{\sigma}_n \cdot \boldsymbol{k}_\gamma)\right]$
a_9	yes	no	P-odd	T-even	$(\boldsymbol{\sigma}_n \cdot \boldsymbol{k}_\gamma)$
a_{10}	yes	no	P-odd	T-even	$(\boldsymbol{\sigma}_n \cdot \boldsymbol{k}_n)$
a_{11}	yes	no	P-odd	T-even	$(\boldsymbol{\sigma}_n \cdot \boldsymbol{k}_\gamma)\, (\boldsymbol{k}_\gamma \cdot \boldsymbol{k}_n) - \frac{1}{3}(\boldsymbol{\sigma}_n \cdot \boldsymbol{k}_n)$
a_{12}	yes	no	P-odd	T-even	$(\boldsymbol{\sigma}_n \cdot \boldsymbol{k}_n)\, (\boldsymbol{k}_n \cdot \boldsymbol{k}_\gamma) - \frac{1}{3}(\boldsymbol{\sigma}_n \cdot \boldsymbol{k}_\gamma)$
a_{13}	no	yes	P-odd	T-even	$(\boldsymbol{\sigma}_\gamma \cdot \boldsymbol{k}_\gamma)$
a_{14}	no	yes	P-odd	T-even	$(\boldsymbol{\sigma}_\gamma \cdot \boldsymbol{k}_\gamma)\, (\boldsymbol{k}_n \cdot \boldsymbol{k}_\gamma)$
a_{15}	yes	yes	P-odd	T-odd	$(\boldsymbol{\sigma}_\gamma \cdot \boldsymbol{k}_\gamma)\, \boldsymbol{\sigma}_n \cdot (\boldsymbol{k}_n \times \boldsymbol{k}_\gamma)$
a_{16}	no	yes	P-odd	T-even	$(\boldsymbol{\sigma}_\gamma \cdot \boldsymbol{k}_\gamma) \left[(\boldsymbol{k}_n \cdot \boldsymbol{k}_\gamma)^2 - \frac{1}{3}\right]$
a_{17}	yes	yes	P-odd	T-odd	$(\boldsymbol{\sigma}_\gamma \cdot \boldsymbol{k}_\gamma)\, (\boldsymbol{k}_n \cdot \boldsymbol{k}_\gamma)\, \boldsymbol{\sigma}_n \cdot (\boldsymbol{k}_n \times \boldsymbol{k}_\gamma)$

(3,4) Details of Entrance Channel

Flambaum, Nucl. Phys. A435 (1985) 352

$$
\begin{aligned}
a_0 &= \textstyle\sum_{J_\mathrm{s}} |V_1(J_\mathrm{s})|^2 + \sum_{J_\mathrm{s},j} |V_2(J_\mathrm{p}j)|^2 \\
a_1 &= 2\mathrm{Re} \textstyle\sum_{J_\mathrm{s},J_\mathrm{p},j} V_1(J_\mathrm{s}) V_2^*(J_\mathrm{p}j) P(J_\mathrm{s}J_\mathrm{p}\frac{1}{2}j1IF) \\
a_2 &= -2\mathrm{Im} \textstyle\sum_{J_\mathrm{s},J_\mathrm{p},j} V_1(J_\mathrm{s}) V_2^*(J_\mathrm{p}j) \beta_j P(J_\mathrm{s}J_\mathrm{p}\frac{1}{2}j1IF) \\
a_3 &= \mathrm{Re} \textstyle\sum_{J_\mathrm{s},j,J'_\mathrm{p},j'} V_2(J_\mathrm{p}j) V_2^*(J'_\mathrm{p}j') P(J_\mathrm{p}J'_\mathrm{p}jj'2IF) 3\sqrt{10} \begin{Bmatrix} 2 & 1 & 1 \\ 0 & \frac{1}{2} & \frac{1}{2} \\ 2 & j & j' \end{Bmatrix} \\
a_4 &= -\mathrm{Im} \textstyle\sum_{J_\mathrm{s},j,J'_\mathrm{p},j'} V_2(J_\mathrm{p}j) V_2^*(J'_\mathrm{p}j') P(J_\mathrm{p}J'_\mathrm{p}jj'2IF) 6\sqrt{5} \begin{Bmatrix} 2 & 1 & 1 \\ 1 & \frac{1}{2} & \frac{1}{2} \\ 2 & j & j' \end{Bmatrix} \\
a_5 &= -\mathrm{Re} \Big[\textstyle\sum_{J_\mathrm{s},J'_\mathrm{s}} V_1(J_\mathrm{s}j) V_1^*(J'_\mathrm{s}j') P(J_\mathrm{s}J'_\mathrm{s}\frac{1}{2}\frac{1}{2}1IF) + \sum_{J_\mathrm{p},j,J'_\mathrm{p},j'} V_2(J_\mathrm{p}j) V_2^*(J'_\mathrm{p}j') P(J_\mathrm{p}J'_\mathrm{p}j. \\
a_6 &= -2\mathrm{Re} \textstyle\sum_{J_\mathrm{s}} V_1(J_\mathrm{s}j) V_2^*(J_\mathrm{p} = J_\mathrm{s}, \frac{1}{2}) \\
a_7 &= \mathrm{Re} \textstyle\sum_{J_\mathrm{s},J_\mathrm{p}} V_1(J_\mathrm{s}) V_2^*(J_\mathrm{p}\frac{3}{2}) P(J_\mathrm{s}J_\mathrm{p}\frac{1}{2}\frac{3}{2}2IF) \\
a_8 &= -\mathrm{Re} \textstyle\sum_{J_\mathrm{p},j,J'_\mathrm{p},j'} V_2(J_\mathrm{p}j) V_2^*(J'_\mathrm{p}j') P(J_\mathrm{p}J'_\mathrm{p}jj'1IF) 18 \begin{Bmatrix} 2 & 1 & 1 \\ 1 & \frac{1}{2} & \frac{1}{2} \\ 1 & j & j' \end{Bmatrix} \\
a_9 &= -2\mathrm{Re} \Big[\textstyle\sum_{J_\mathrm{s},J'_\mathrm{s}} V_1(J_\mathrm{s}j) V_3^*(J'_\mathrm{s}j') P(J_\mathrm{s}J'_\mathrm{s}\frac{1}{2}\frac{1}{2}1IF) + \sum_{J_\mathrm{p},j,J'_\mathrm{p},j'} V_2(J_\mathrm{p}j) V_4^*(J'_\mathrm{p}j') P(J_\mathrm{p}J'_\mathrm{p}. \\
a_{10} &= -2\mathrm{Re} \textstyle\sum_{J_\mathrm{s}} \left[V_2(J_\mathrm{p} = J_\mathrm{s}, \frac{1}{2}) V_3^*(J_\mathrm{s}) + V_1(J_\mathrm{s}) V_4^*(J_\mathrm{p} = J_\mathrm{s}, \frac{1}{2}) \right] \\
a_{11} &= 2\mathrm{Re} \textstyle\sum_{J_\mathrm{s},J_\mathrm{p}} \left[V_2(J_\mathrm{p}\frac{3}{2}) V_3^*(J_\mathrm{s}) + V_1(J_\mathrm{s}) V_4^*(J_\mathrm{p}\frac{3}{2}) \right] \sqrt{3} P(J_\mathrm{s}J_\mathrm{p}\frac{1}{2}\frac{1}{3}2IF) \\
a_{12} &= -\mathrm{Re} \textstyle\sum_{J_\mathrm{s},j,J'_\mathrm{p},j'} V_2(J_\mathrm{p}j) V_4^*(J'_\mathrm{p}j') P(J_\mathrm{p}J'_\mathrm{p}jj'1IF) 18 \begin{Bmatrix} 2 & 1 & 1 \\ 1 & \frac{1}{2} & \frac{1}{2} \\ 1 & j & j' \end{Bmatrix} \\
a_{13} &= 2\mathrm{Re} \left[\textstyle\sum_{J_\mathrm{s}} V_1(J_\mathrm{s}) V_3^*(J_\mathrm{s}) + \sum_{J_\mathrm{p}j} V_2(J_\mathrm{p}j) V_4^*(J_\mathrm{p}j) \right] \\
a_{14} &= 2\mathrm{Re} \textstyle\sum_{J_\mathrm{s}J_\mathrm{p}j} \left[V_2(J_\mathrm{p}j) V_3^*(J_\mathrm{s}) + V_1(J_\mathrm{s}) V_4^*(J_\mathrm{p}j) \right] P(J_\mathrm{s}J_\mathrm{p}\frac{1}{2}j1IF) \\
a_{15} &= 2\mathrm{Im} \textstyle\sum_{J_\mathrm{s}J_\mathrm{p}j} \left[V_2(J_\mathrm{p}j) V_3^*(J_\mathrm{s}) - V_1(J_\mathrm{s}) V_4^*(J_\mathrm{p}j) \right] \beta_j P(J_\mathrm{s}J_\mathrm{p}\frac{1}{2}j1IF) \\
a_{16} &= 2\mathrm{Re} \textstyle\sum_{J_\mathrm{p},j,J'_\mathrm{p},j'} V_2(J_\mathrm{p}j) V_4^*(J'_\mathrm{p}j') P(J_\mathrm{p}J'_\mathrm{p}jj'2IF) 3\sqrt{10} \begin{Bmatrix} 2 & 1 & 1 \\ 0 & \frac{1}{2} & \frac{1}{2} \\ 2 & j & j' \end{Bmatrix} \\
a_{17} &= -2\mathrm{Im} \textstyle\sum_{J_\mathrm{p},j,J'_\mathrm{p},j'} V_2(J_\mathrm{p}j) V_4^*(J'_\mathrm{p}j') P(J_\mathrm{p}J'_\mathrm{p}jj'2IF) 6\sqrt{5} \begin{Bmatrix} 2 & 1 & 1 \\ 1 & \frac{1}{2} & \frac{1}{2} \\ 2 & j & j' \end{Bmatrix}
\end{aligned}
$$

$|s\rangle$ $J_s \, E_s \, \Gamma_s \Gamma_s^n$

$|p\rangle$ $J_p \, E_p \, \Gamma_p \Gamma_p^n$

$\boxed{\phi}$

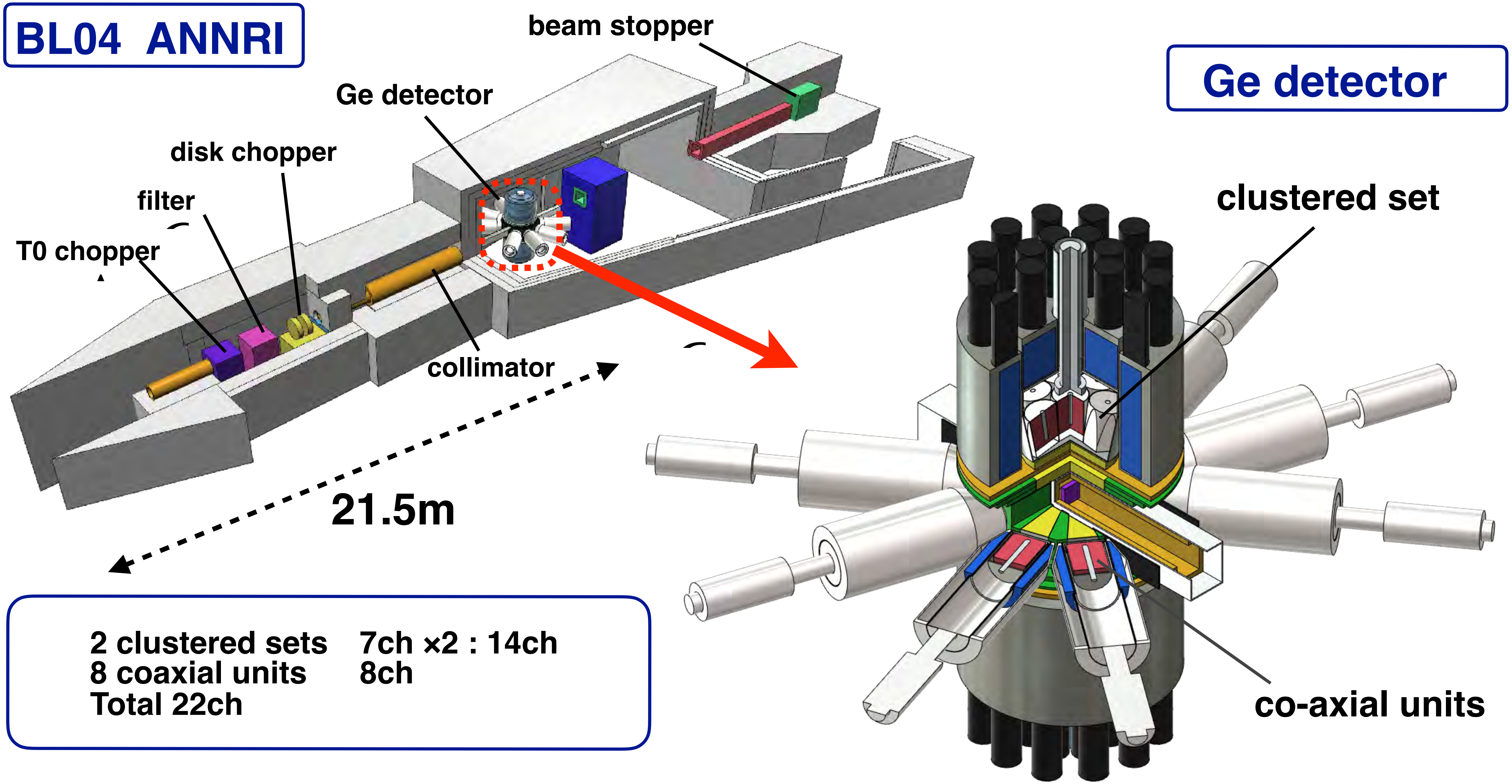
$|p_{1/2}\rangle$ $|p_{3/2}\rangle$

$\Gamma^n_{p,1/2}$ $\Gamma^n_{p,3/2}$

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

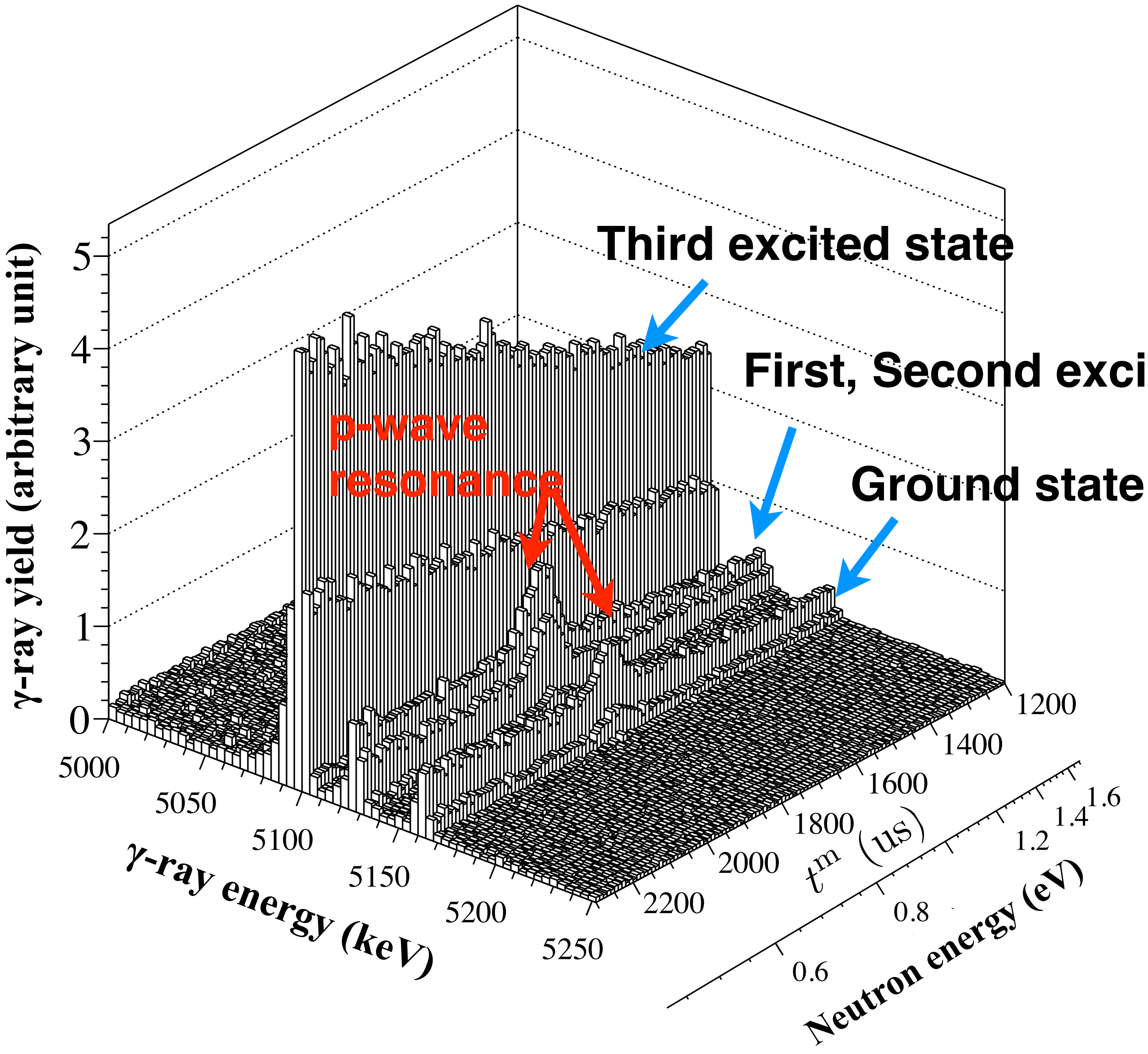
$$x = \sqrt{\frac{\Gamma_\mathrm{n}^{p\frac{1}{2}}}{\Gamma_\mathrm{n}^p}} \quad y = \sqrt{\frac{\Gamma_\mathrm{n}^{p\frac{3}{2}}}{\Gamma_\mathrm{n}^p}}$$

(3,4) Details of Entrance Channel



2 clustered sets 7ch ×2 : 14ch
8 coaxial units 8ch
Total 22ch

(3,4) Details of Entrance Channel

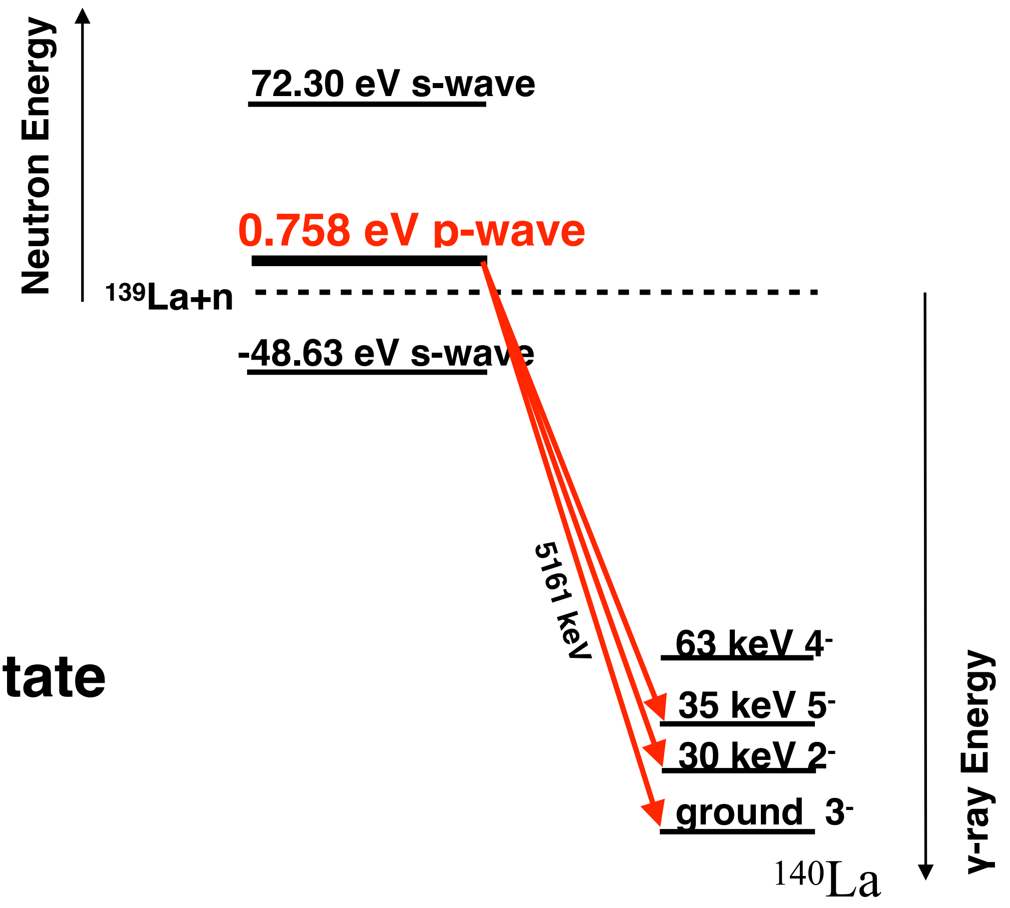


Third excited state

First, Second excited state

Ground state

p-wave resonance


Neutron Energy

72.30 eV s-wave

0.758 eV p-wave

^{139}La+n

-48.63 eV s-wave

5161 keV

63 keV 4^-

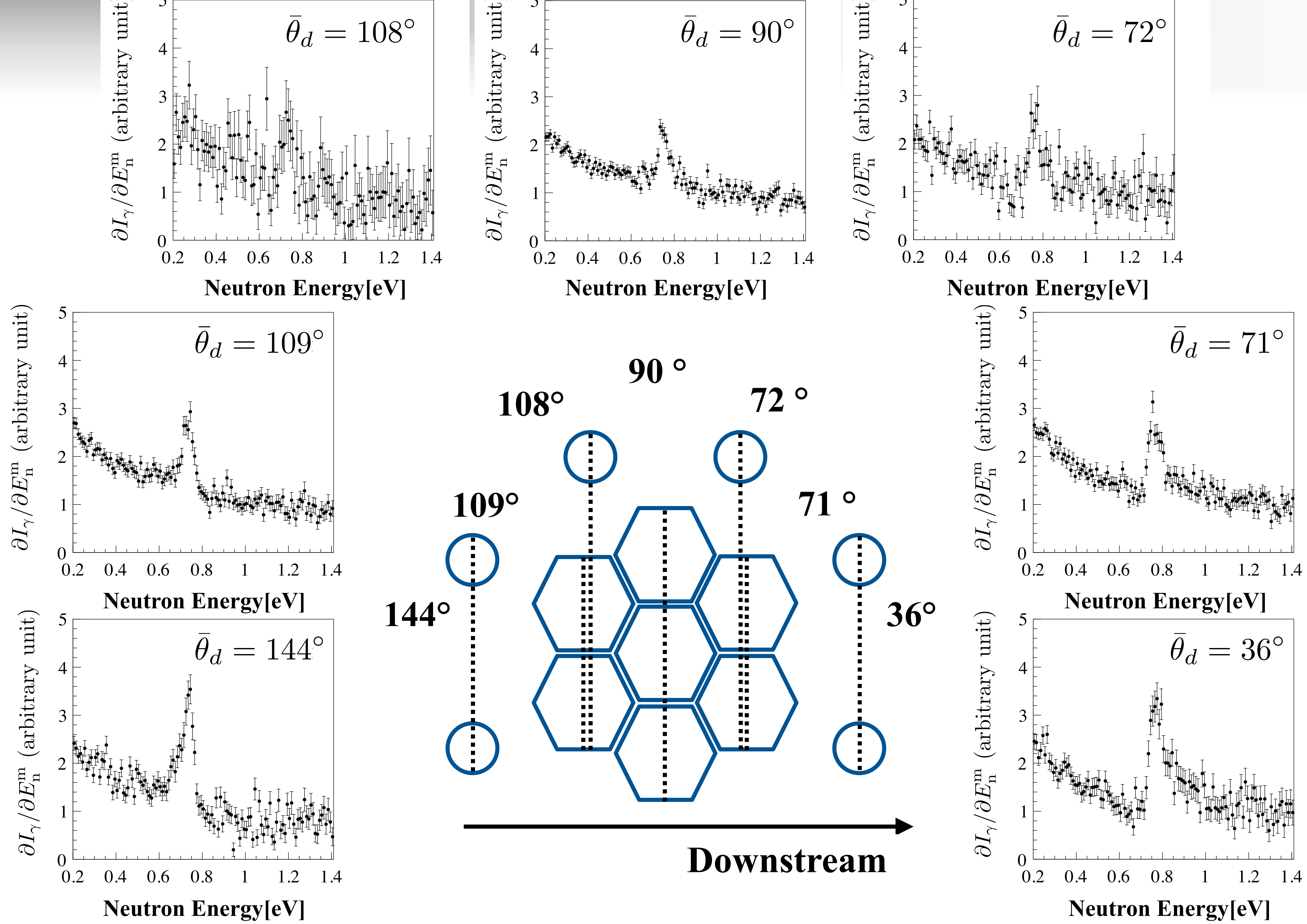
35 keV 5^-

30 keV 2^-

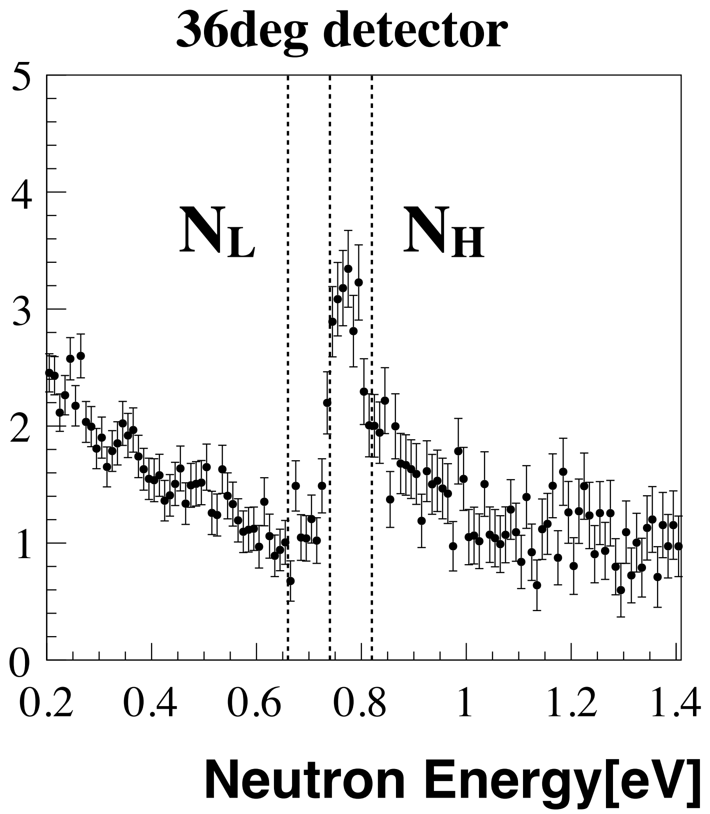
ground 3^-

^{140}La

γ-ray Energy

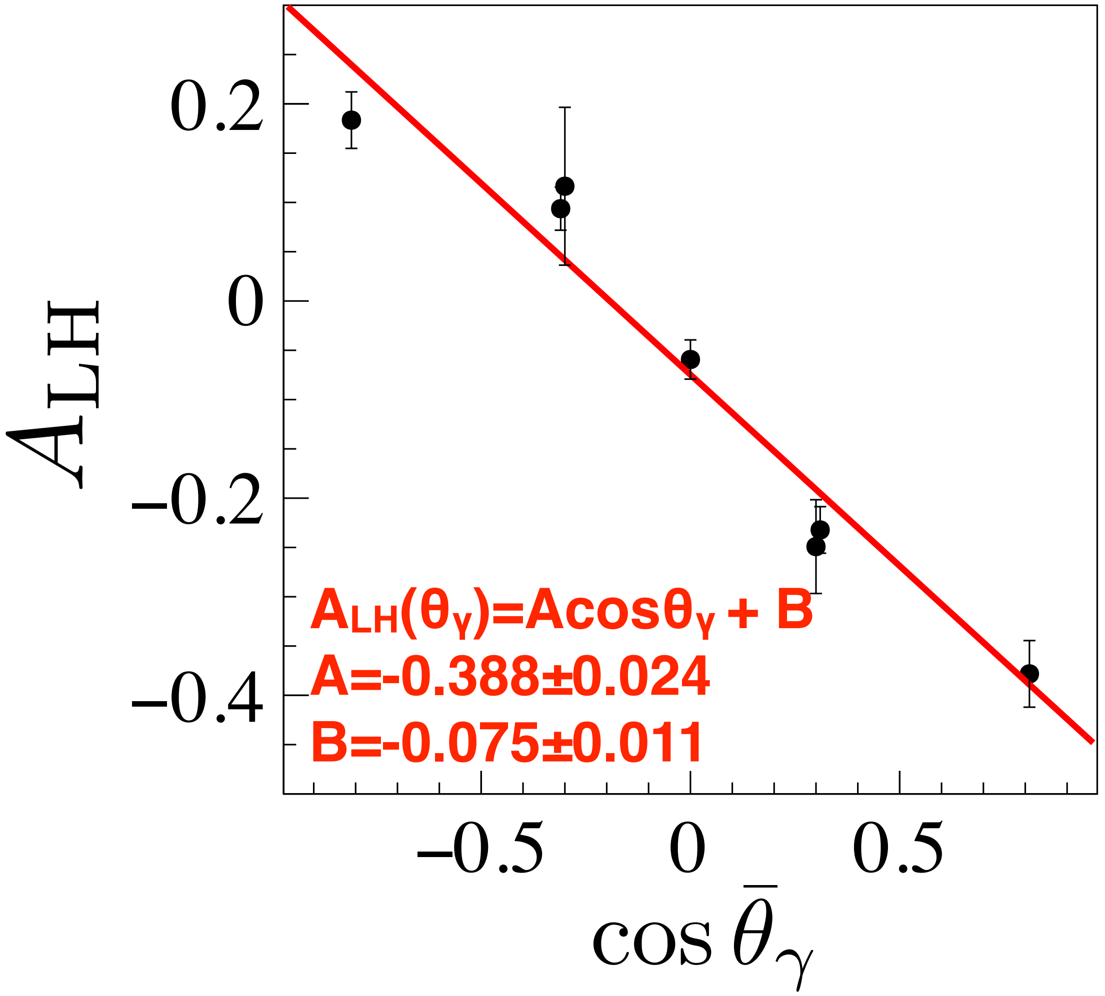
$\bar{\theta}_d = 108°$
$\bar{\theta}_d = 90°$
$\bar{\theta}_d = 72°$
$\bar{\theta}_d = 109°$
$\bar{\theta}_d = 71°$
$\bar{\theta}_d = 144°$
$\bar{\theta}_d = 36°$
$\partial I_\gamma / \partial E_n^m$ (arbitrary unit)
Neutron Energy[eV]
0
1
2
3
4
5
0.2
0.4
0.6
0.8
1
1.2
1.4
90 °
108°
72 °
109°
71 °
144°
36°
Downstream

(3,4) Details of Entrance Channel



$$A_{\mathrm{LH}} = \frac{N_{\mathrm{L}} - N_{\mathrm{H}}}{N_{\mathrm{L}} + N_{\mathrm{H}}}.$$

A_{LH} as a function of emission angle



Comparison with Flambaum's formalism

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

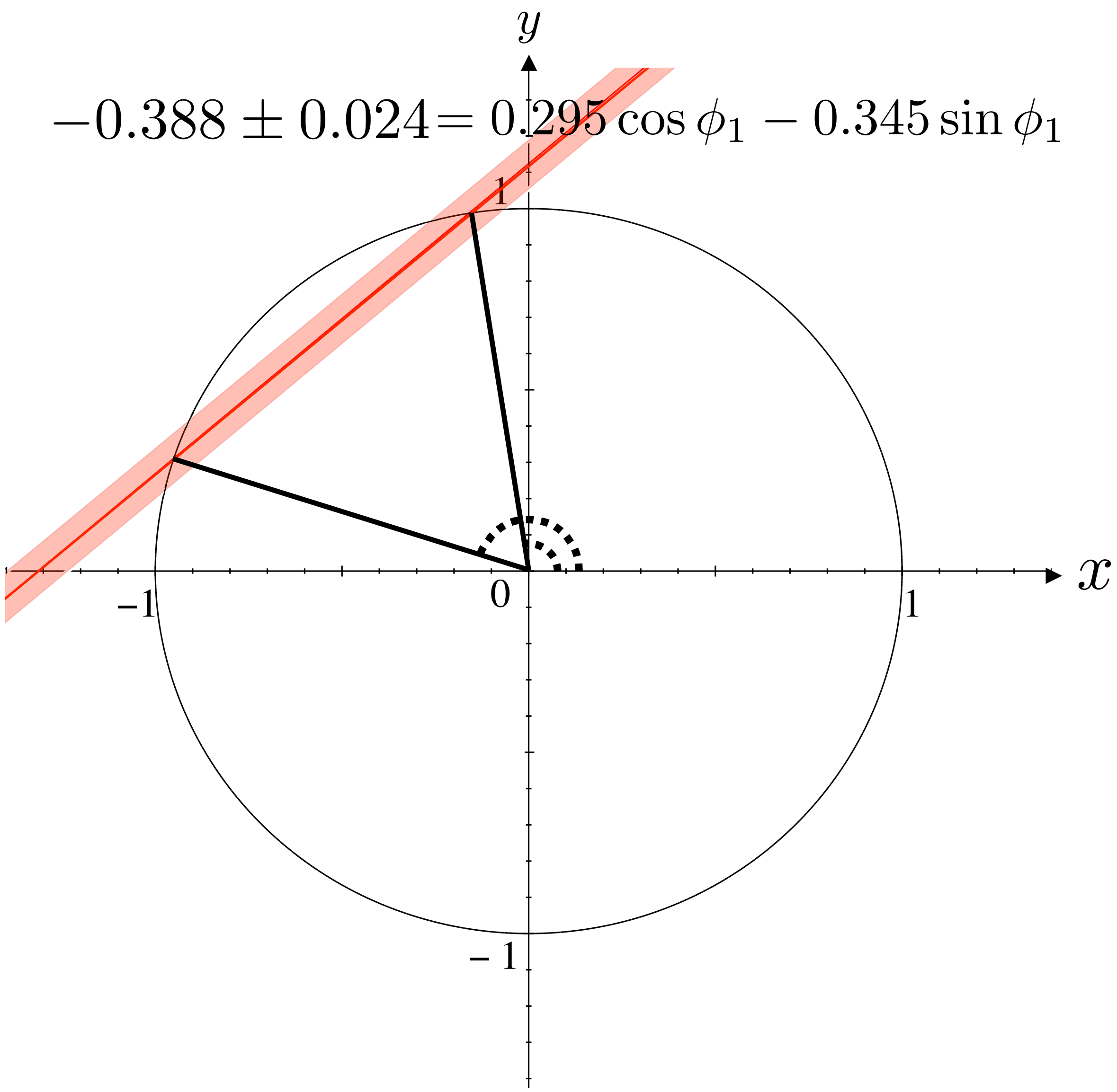
Measured angular dependence

Flambaum parametrization

(3,4) Details of Entrance Channel

$$\frac{\mathrm{d}\sigma_{\mathrm{n}\gamma}}{\mathrm{d}\Omega_\gamma} = \frac{1}{2}\left(a_0 + a_1 \cos\theta_\gamma + a_3(\cos^2\theta_\gamma - \frac{1}{3})\right)$$

Okudaira et al., PRC97(2018)034622

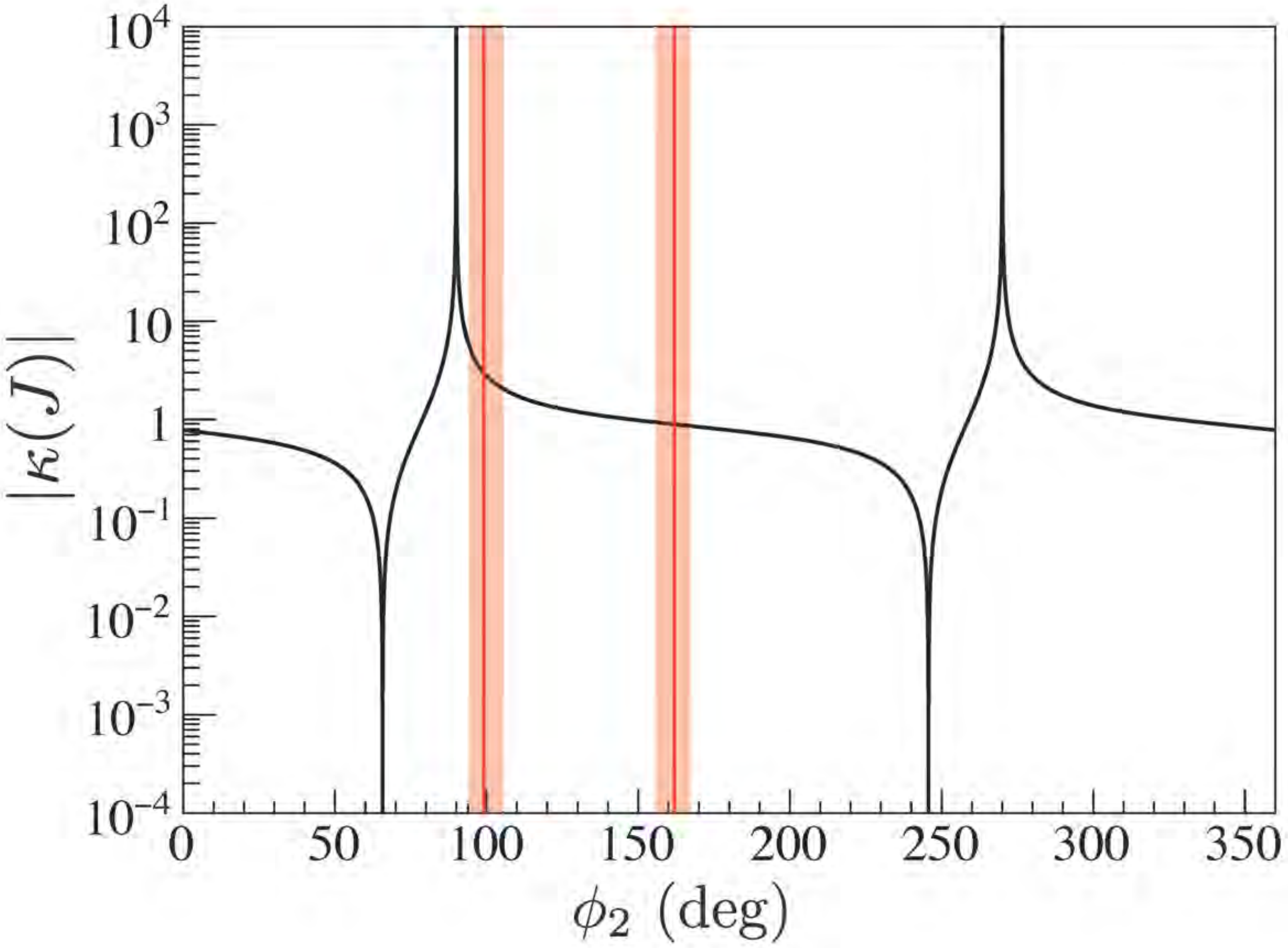


$$-0.388 \pm 0.024 = 0.295\cos\phi_1 - 0.345\sin\phi_1$$

$$\phi_2 = (99.2^{+6.3}_{-5.3})^\circ, \quad (161.9^{+5.3}_{-6.3})^\circ$$

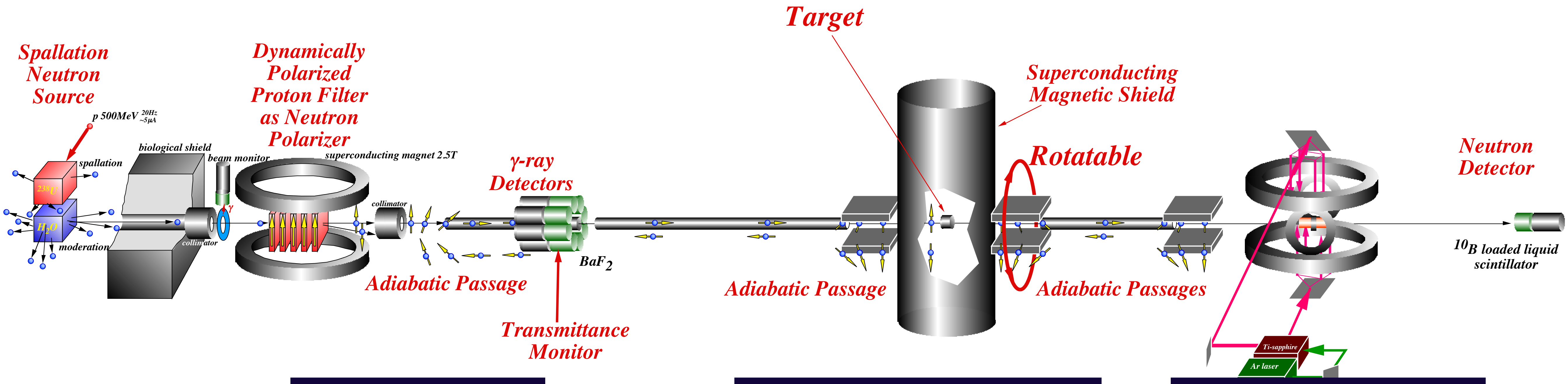
$$x = -0.16^{+0.09}_{-0.11}, \quad -0.95^{+0.03}_{-0.04}$$

$$\kappa(J) = 4.84^{+5.58}_{-1.69}, \quad 0.99^{+0.08}_{-0.07}$$



Neutron Optics for Parity and Time Reversal EXperiment

NOPTREX Collaboration



epithermal neutron polarizer

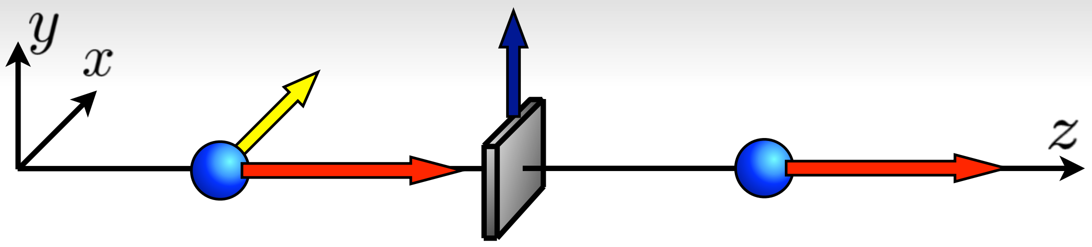
polarized target

spin control

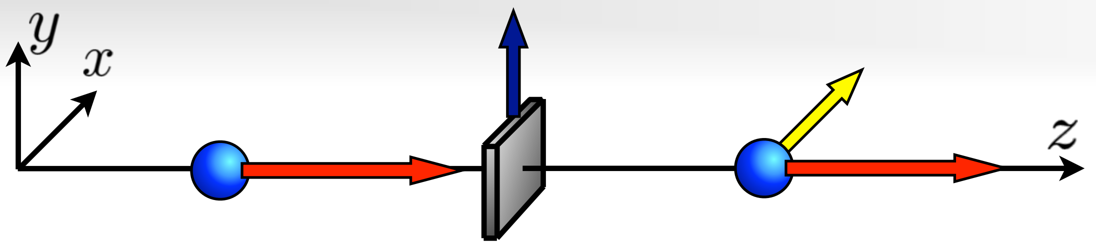
epithermal neutron spin analyzer

←*Polarized Neutron Source*→ ←*Target station*→ ←*Neutron Spin Analyzer*→

$\overrightarrow{{}^{3}\mathrm{He}}$ $\overrightarrow{{}^{139}\mathrm{La}}$ $\overrightarrow{{}^{3}\mathrm{He}}$

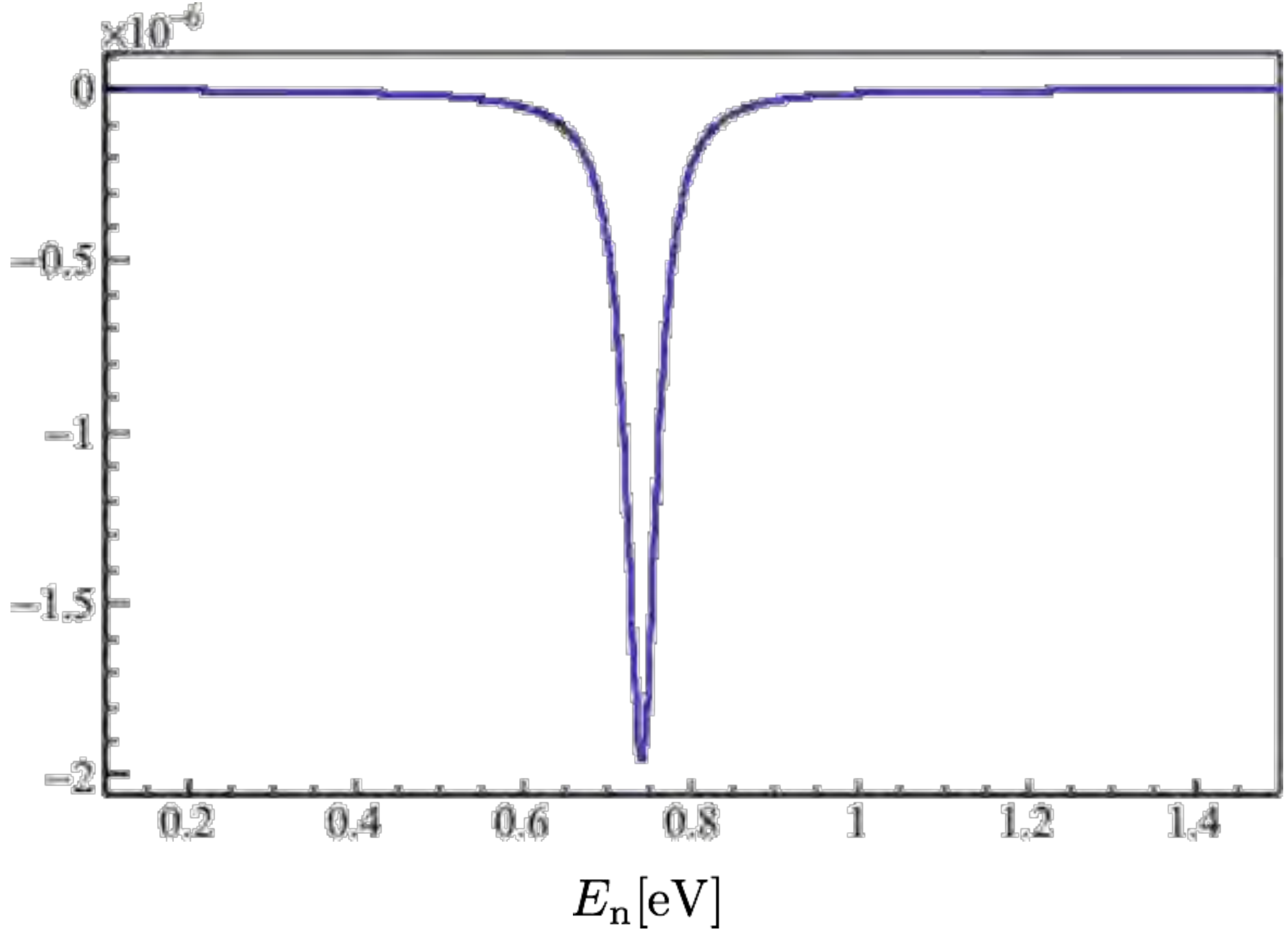


$$A_x = 4(\mathrm{Re}\underbrace{A^*}_{\substack{\text{Spin Independent}\\\text{P-even T-even}}}\underbrace{D}_{\substack{\text{T-violation}\\\text{P-odd T-odd}}} + \mathrm{Im}\underbrace{B^*}_{\substack{\text{Spin Dependent}\\\text{P-even T-even}}}\underbrace{C}_{\substack{\text{P-violation}\\\text{P-odd T-even}}})$$



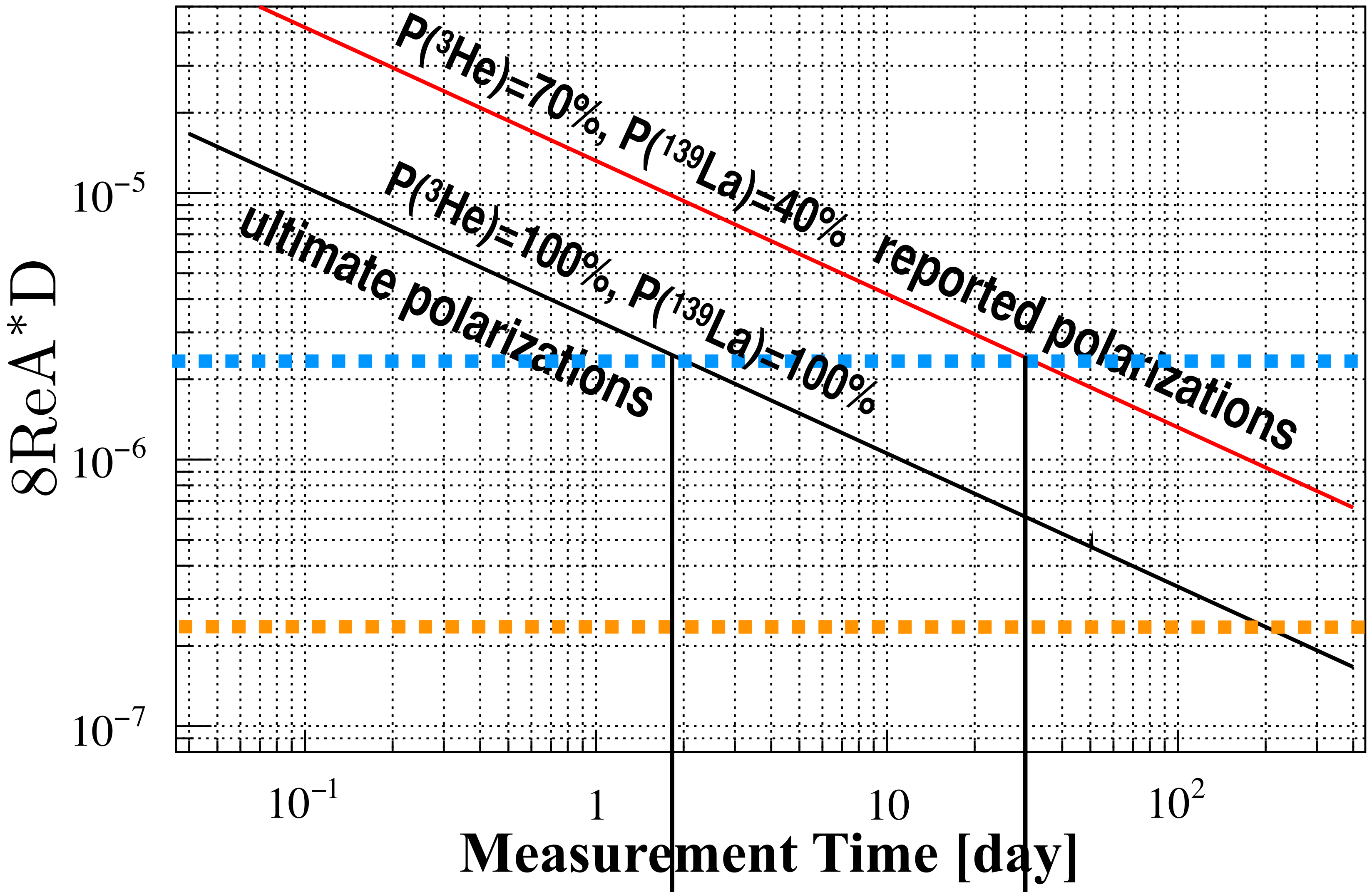
$$P_x = 4(\mathrm{Re}\underbrace{A^*}_{\substack{\text{Spin Independent}\\\text{P-even T-even}}}\underbrace{D}_{\substack{\text{T-violation}\\\text{P-odd T-odd}}} - \mathrm{Im}\underbrace{B^*}_{\substack{\text{Spin Dependent}\\\text{P-even T-even}}}\underbrace{C}_{\substack{\text{P-violation}\\\text{P-odd T-even}}})$$

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



$\overrightarrow{^{139}\mathrm{La}}$ $\mathrm{LaAlO_3}$

$P(^{139}\mathrm{La}) \geq 0.4$, $V \geq 4\mathrm{cm} \times 4\mathrm{cm} \times 6\mathrm{cm}$
$B_0 \leq 0.1\mathrm{T}$



corresponding to
$d_n = 3.0\times10^{-26}$ e cm

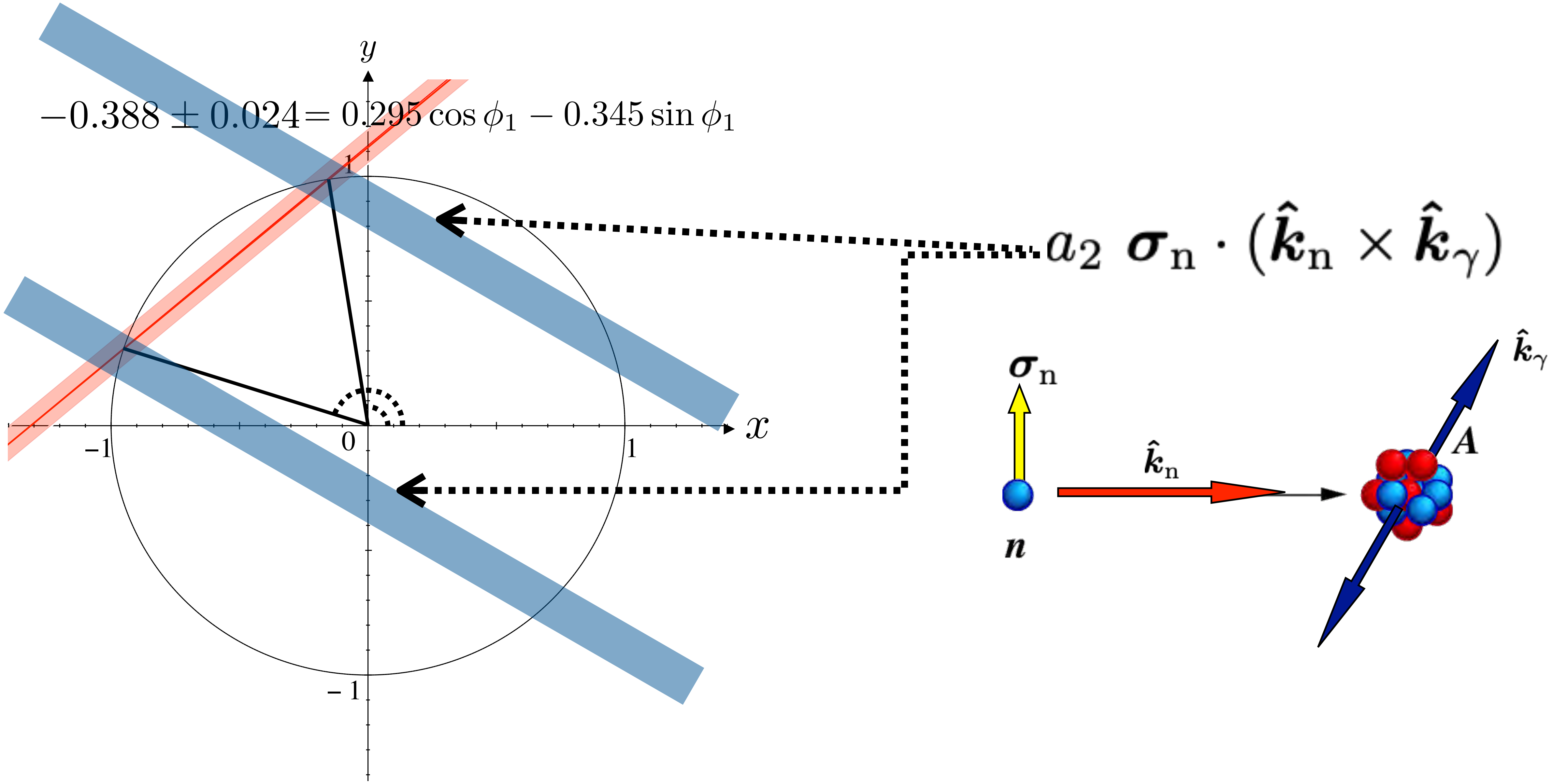
corresponding to
$d_n = 3.0\times10^{-27}$ e cm

with reported polarizations
reaches to the discovery potential in 30 days

with ultimate polarizations
reaches the discovery potential in 45 hours

(3,4) Details of Entrance Channel

$$\frac{d\sigma_{n\gamma}}{d\Omega_\gamma} = \frac{1}{2}\left(a_0 + a_1 \cos\theta_\gamma + a_3(\cos^2\theta_\gamma - \frac{1}{3})\right)$$



$$-0.388 \pm 0.024 = 0.295\cos\phi_1 - 0.345\sin\phi_1$$

$$a_2\ \boldsymbol{\sigma}_\mathrm{n}\cdot(\hat{\boldsymbol{k}}_\mathrm{n}\times\hat{\boldsymbol{k}}_\gamma)$$

$$\phi_2 = (99.2^{+6.3}_{-5.3})^\circ, \quad (161.9^{+5.3}_{-6.3})^\circ$$

$$x = -0.16^{+0.09}_{-0.11}, \quad -0.95^{+0.03}_{-0.04}$$

Higher-order Tensor Correlation Terms

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

$$+E'\left((\hat{\boldsymbol{k}}_\mathrm{n} \cdot \hat{\boldsymbol{I}})(\hat{\boldsymbol{k}}_\mathrm{n} \cdot \hat{\boldsymbol{I}}) - \frac{1}{3}(\hat{\boldsymbol{k}}_\mathrm{n} \cdot \hat{\boldsymbol{k}}_\mathrm{n})(\hat{\boldsymbol{I}} \cdot \hat{\boldsymbol{I}})\right)$$

P-even T-even

$$+F'\left((\boldsymbol{\sigma}_\mathrm{n} \cdot \hat{\boldsymbol{I}})(\hat{\boldsymbol{k}}_\mathrm{n} \cdot \hat{\boldsymbol{I}}) - \frac{1}{3}(\boldsymbol{\sigma}_\mathrm{n} \cdot \hat{\boldsymbol{k}}_\mathrm{n})(\hat{\boldsymbol{I}} \cdot \hat{\boldsymbol{I}})\right)$$

P-odd T-even

$$+G'(\boldsymbol{\sigma}_\mathrm{n} \cdot (\hat{\boldsymbol{k}}_\mathrm{n} \times \hat{\boldsymbol{I}}))(\hat{\boldsymbol{k}}_\mathrm{n} \cdot \hat{\boldsymbol{I}})$$

P-even T-odd

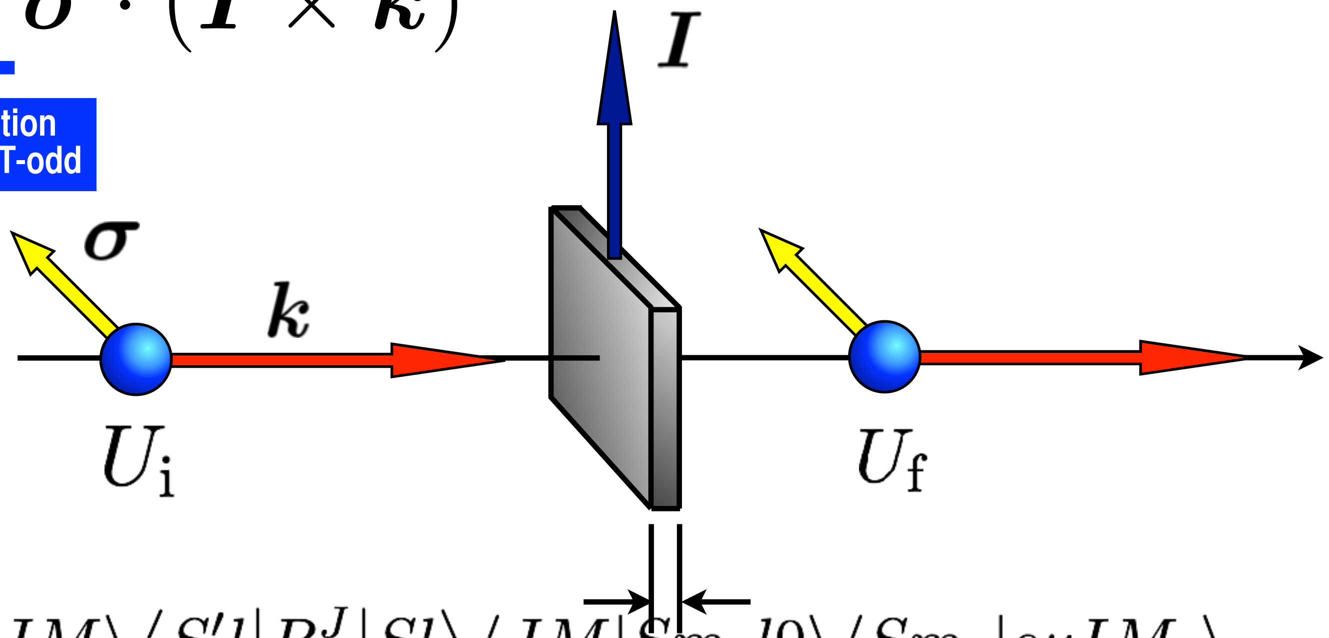
$$f = \left\{A' + E'\left((\hat{\boldsymbol{k}}_\mathrm{n} \cdot \hat{\boldsymbol{I}})(\hat{\boldsymbol{k}}_\mathrm{n} \cdot \hat{\boldsymbol{I}}) - \frac{1}{3}(\hat{\boldsymbol{k}}_\mathrm{n} \cdot \hat{\boldsymbol{k}}_\mathrm{n})(\hat{\boldsymbol{I}} \cdot \hat{\boldsymbol{I}})\right)\right\}$$

$$+\boldsymbol{\sigma}_\mathrm{n} \cdot \left\{\left(B' + F'(\hat{\boldsymbol{k}}_\mathrm{n} \cdot \hat{\boldsymbol{I}})\right)\hat{\boldsymbol{I}} + \left(C' - F'\frac{\hat{\boldsymbol{I}}^2}{3}\right)\hat{\boldsymbol{k}}_\mathrm{n} + \left(D' + G'(\hat{\boldsymbol{k}}_\mathrm{n} \cdot \hat{\boldsymbol{I}})\right)(\hat{\boldsymbol{k}}_\mathrm{n} \times \hat{\boldsymbol{I}})\right\}$$

$$F' = \frac{1}{\pi k}\frac{3}{16}\sqrt{\frac{3}{10}}\mathrm{Re}\left[\frac{\sqrt{\Gamma_\mathrm{s}^\mathrm{n}}}{E - E_\mathrm{s} - i\Gamma_\mathrm{s}} W \frac{\sqrt{\Gamma_\mathrm{p}^\mathrm{n}}}{E - E_\mathrm{p} + i\Gamma_\mathrm{p}}\right] y$$

Pseudomagnetism

$$f = \underbrace{A'}_{\substack{\text{Spin Independent}\\ \text{P-even T-even}}} + \underbrace{B'}_{\substack{\text{Spin Dependent}\\ \text{P-even T-even}}}\boldsymbol{\sigma}\cdot\hat{\boldsymbol{I}} + \underbrace{C'}_{\substack{\text{P-violation}\\ \text{P-odd T-even}}}\boldsymbol{\sigma}\cdot\hat{\boldsymbol{k}} + \underbrace{D'}_{\substack{\text{T-violation}\\ \text{P-odd T-odd}}}\boldsymbol{\sigma}\cdot(\hat{\boldsymbol{I}}\times\hat{\boldsymbol{k}})$$



pseudomagnetism

V.Gudkov and HMS, Phys. Rev. C95 045501 (2017)

$$f_\mu = \frac{i}{2k}\sum_{JlSS'M_I}(2l+1)\left\langle s\mu IM_I|S'm'_s\right\rangle\left\langle S'm'_s l0|JM\right\rangle\underline{\left\langle S'l\left|R^J\right|Sl\right\rangle}\left\langle JM|Sm_s l0\right\rangle\left\langle Sm_s|s\mu IM_I\right\rangle .$$

$$\left\langle S'_K l_K\left|R^{J_K}\right|S_K l_K\right\rangle = \underbrace{i\frac{\sqrt{\Gamma^{\mathrm{n}}_{l_K}(S'_K)}\sqrt{\Gamma^{\mathrm{n}}_{l_K}(S_K)}}{E-E_K+i\Gamma_K/2}e^{i(\delta_{l_K}(S'_K)+\delta_{l_K}(S_K))}}_{\text{compound resonance}} - \underbrace{2ie^{i\delta_{l_K}(S_K S'_K)}\sin\delta_{l_K}(S_K S'_K)}_{\text{potential scattering}}$$

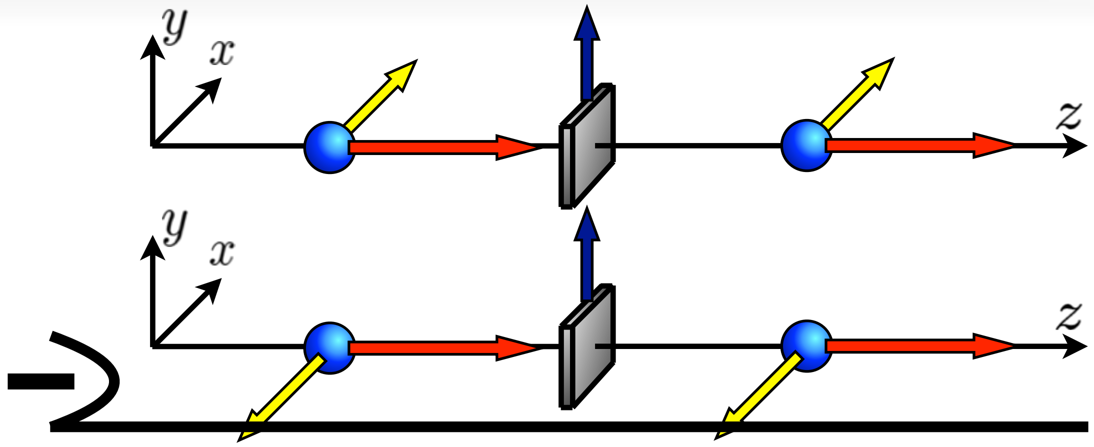
$$\omega^{\mathrm{s}}_{\mathrm{P}} = \frac{4\pi N\hbar}{M_{\mathrm{n}}}\frac{I}{(2I+1)}\left(a_+ - a_- - \sum_{K,\,l_K=0}\frac{\Gamma^{\mathrm{n}}_K}{2k}\frac{(E-E_K)}{(E-E_K)^2+(\Gamma_K/2)^2}\beta_K\right)$$

$$\beta_K = \begin{cases} 1 & (J_K = I+\frac{1}{2}) \\ -1 & (J_K = I-\frac{1}{2}) \end{cases}$$

$$\left\langle\left(I\pm\frac{1}{2}\right)0\left|R^{I\pm\frac{1}{2}}\right|\left(I\pm\frac{1}{2}\right)0\right\rangle = -2ika_\pm$$

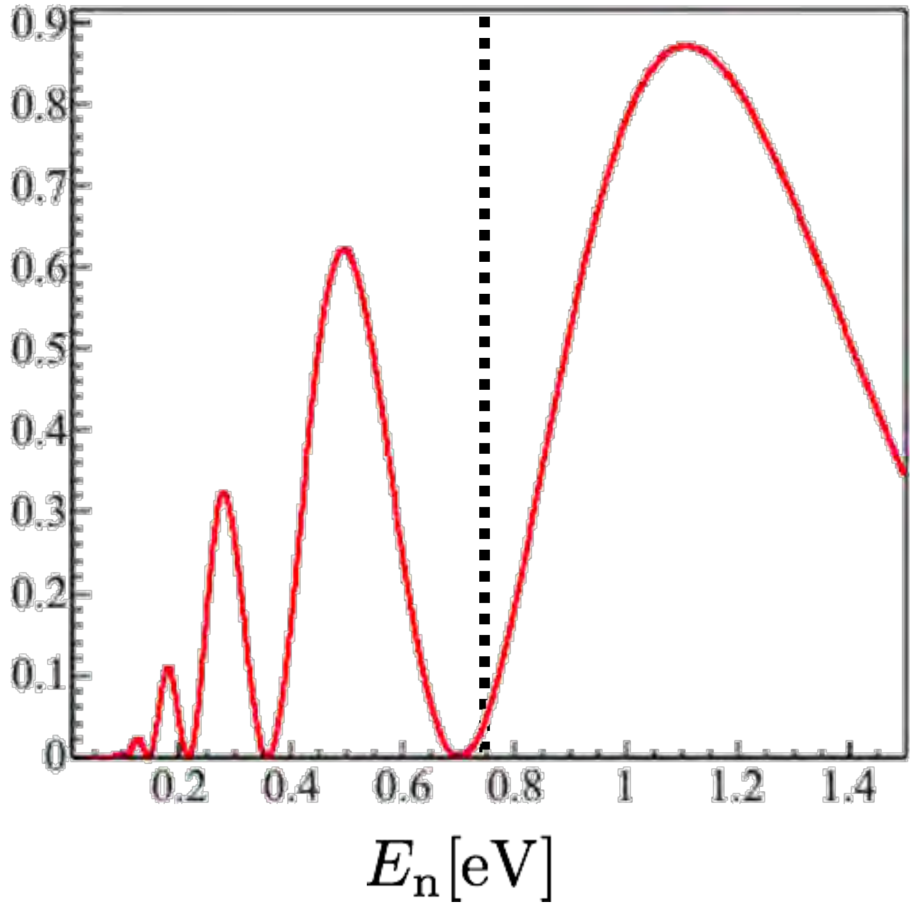
Polarization Transfer Coefficient

1. freeze target polarization
2. adjust magnetic field to cancel the pseudomagnetism (Re B’)

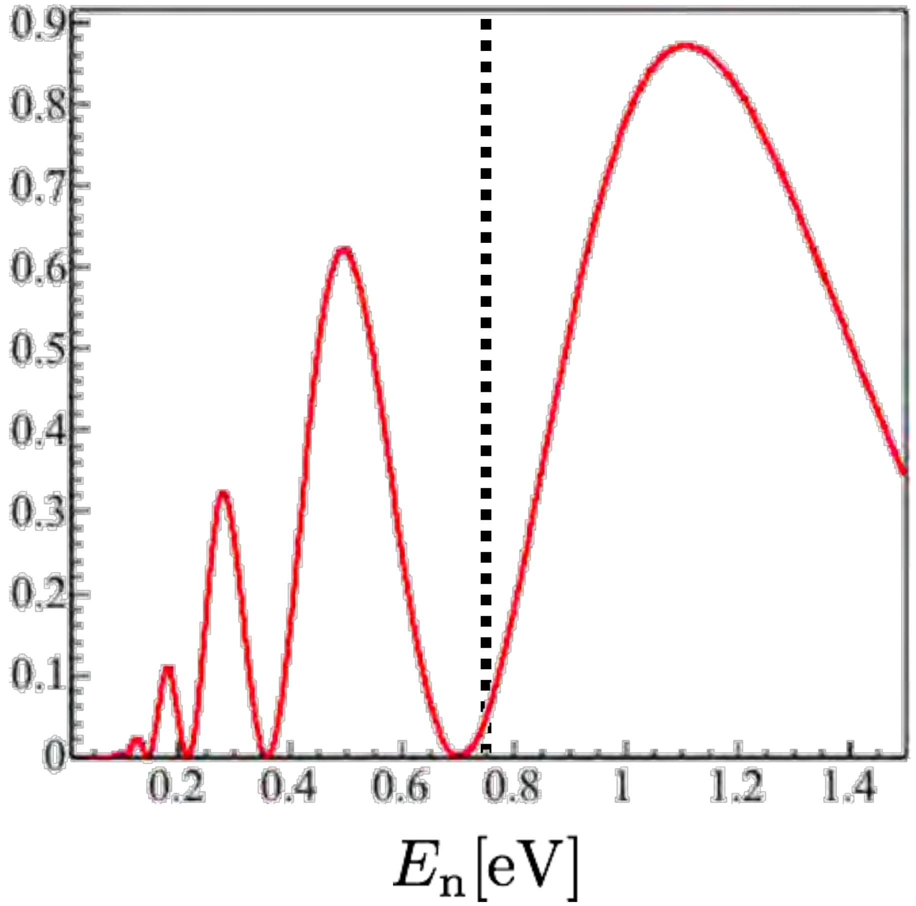


$$K^{x}_{x} - K^{-x}_{-x} = 4\mathrm{Re}\, A^* D$$

$$K^{+x}_{+x} = |A|^2 + |D|^2 + 2\mathrm{Re} A^* D$$



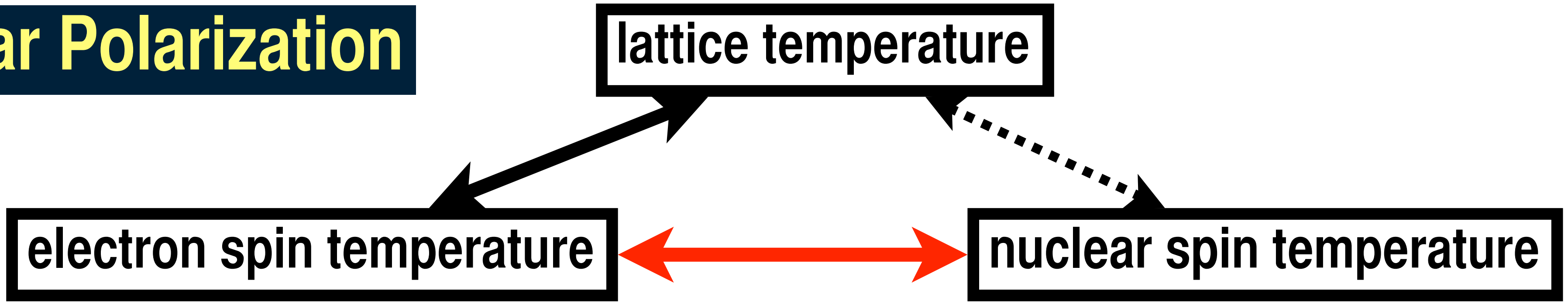
$$K^{-x}_{-x} = |A|^2 + |D|^2 - 2\mathrm{Re} A^* D$$



Alignment, adjustment of experimental apparatus can be measured through the function form of the energy dependence of neutron spin.

The polarized target is the key item.

DNP: Dynamic Nuclear Polarization



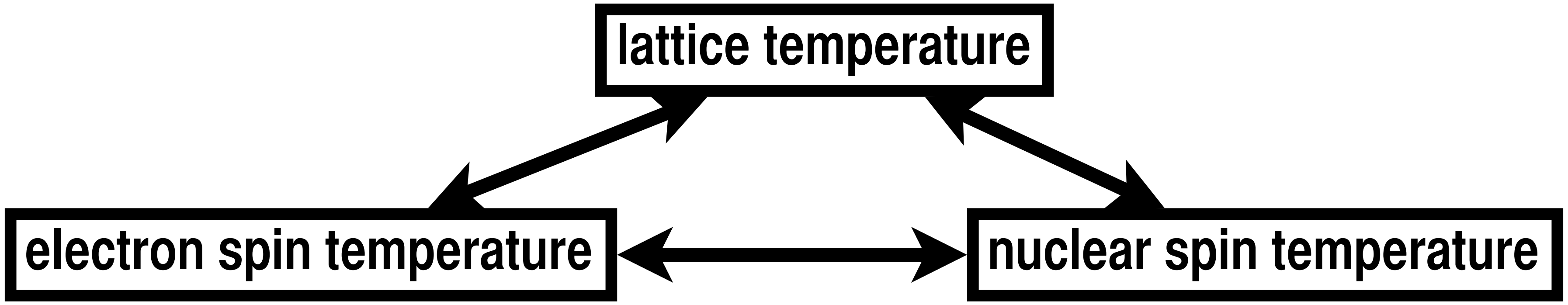
lattice temperature

electron spin temperature

nuclear spin temperature

Backup solution

Brute-force method



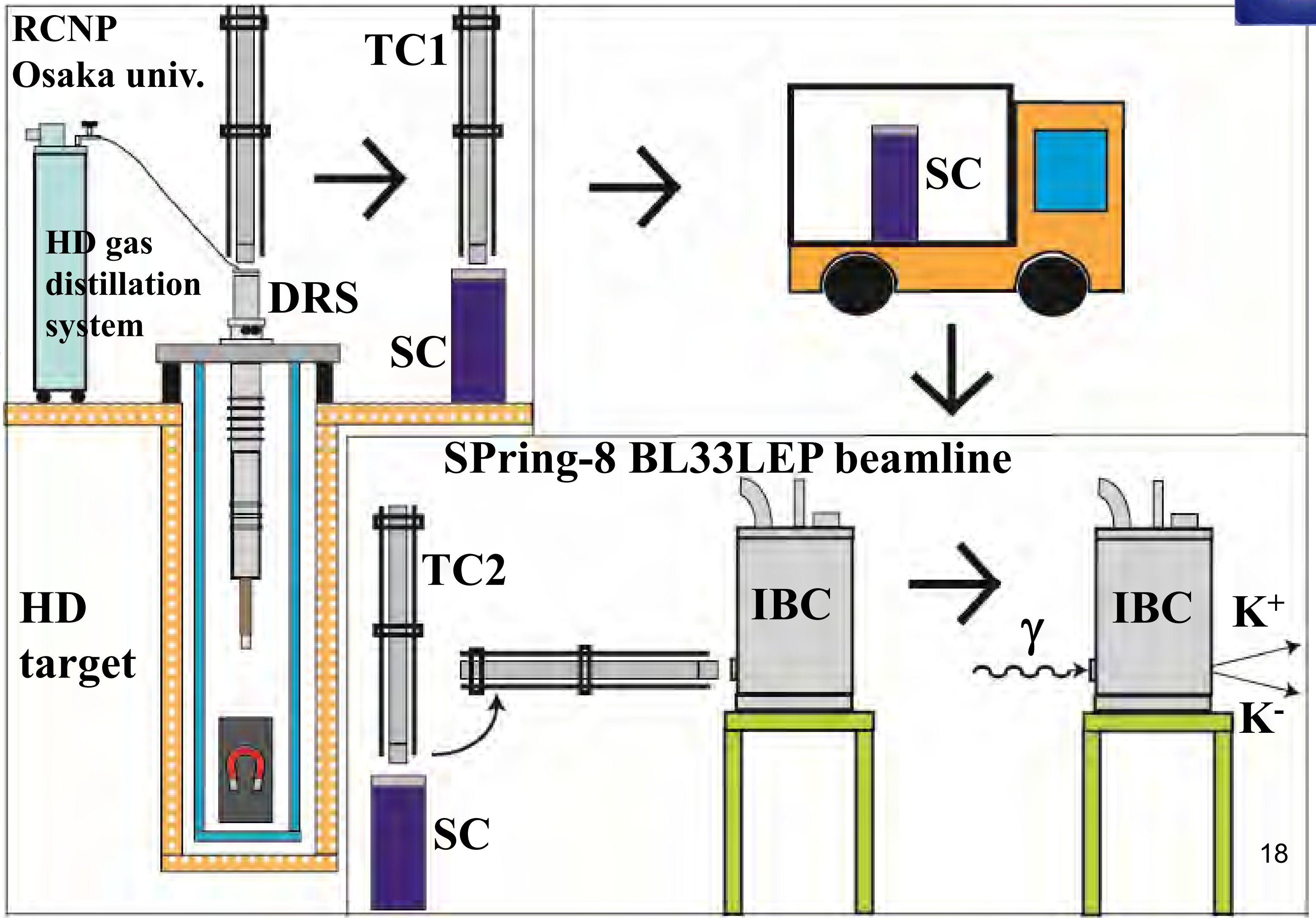
lattice temperature

electron spin temperature

nuclear spin temperature

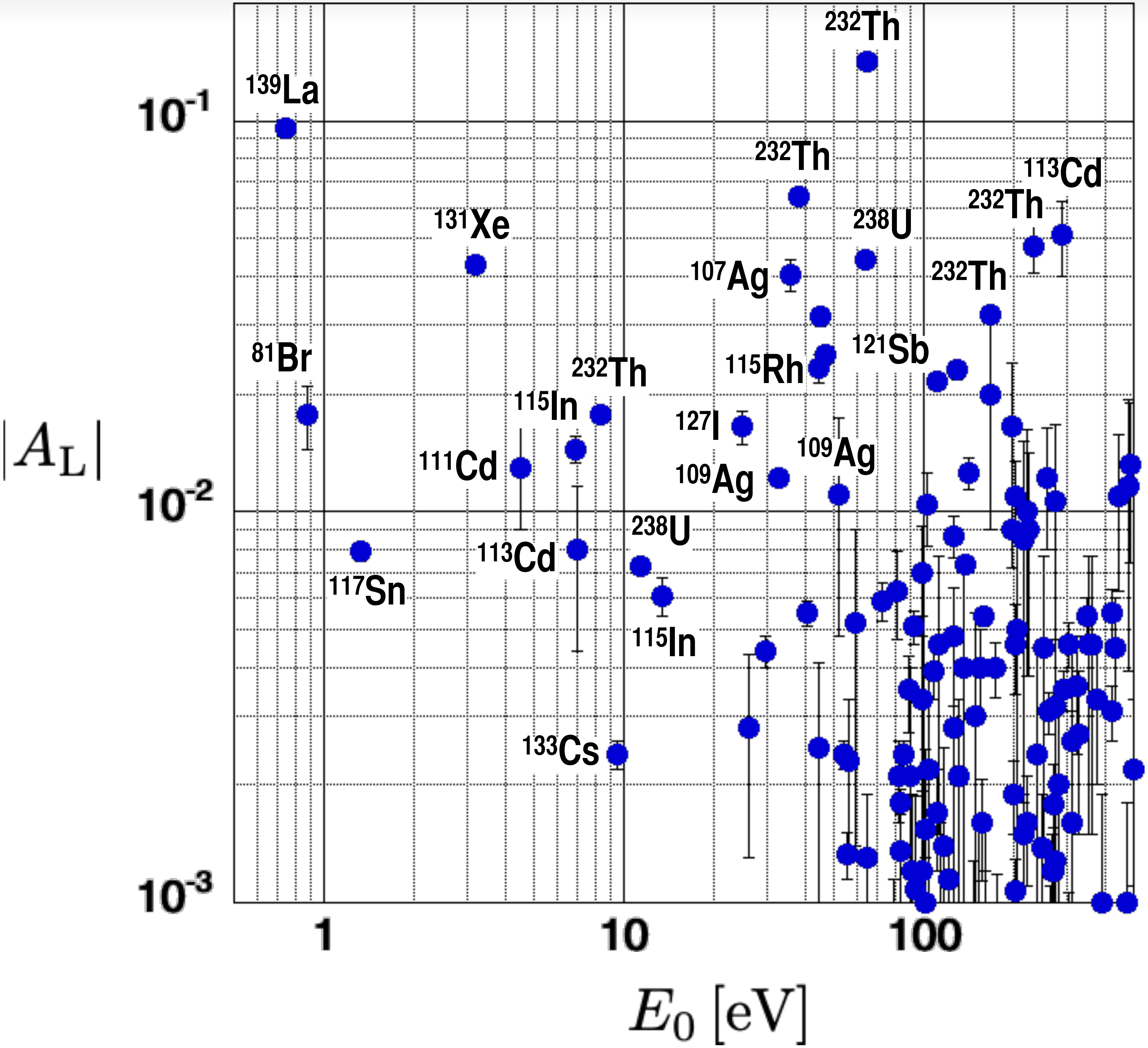
Brute-force Polarized Target to SPring8 → J-PARC

Transportation of polarized HD target

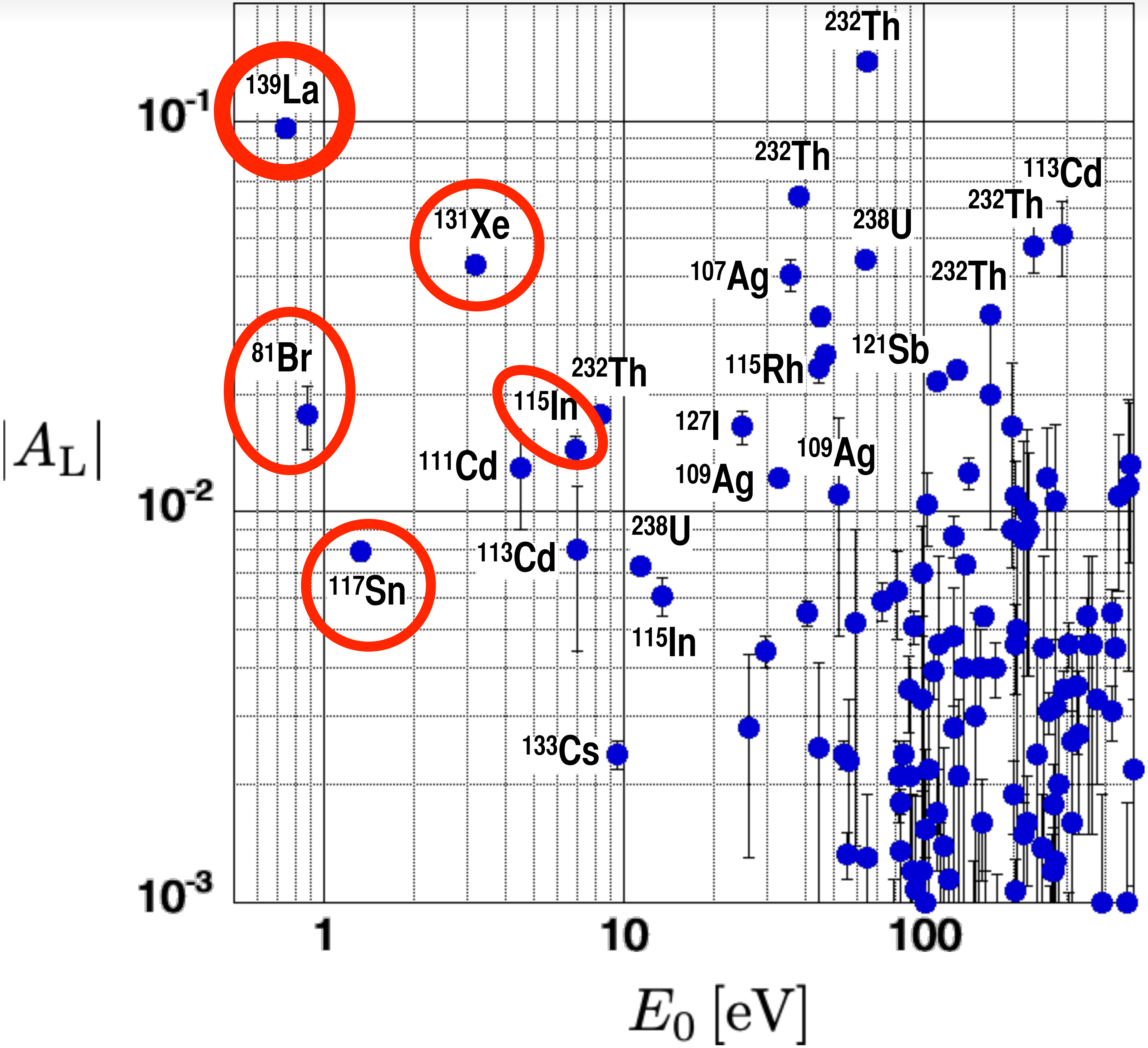


Survey other target nuclei

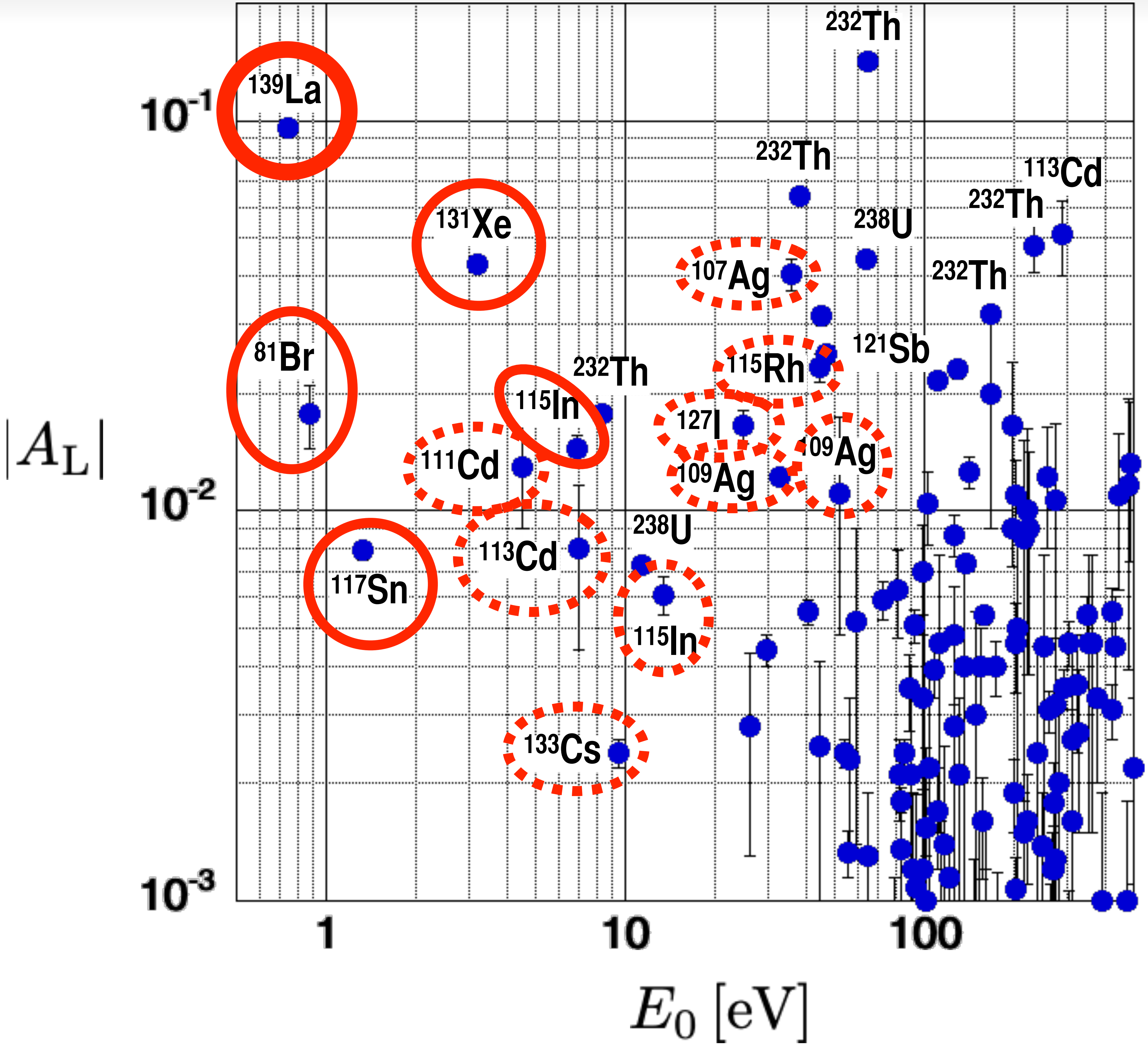
Mitchell, Phys. Rep. 354 (2001) 157
Shimizu, Nucl. Phys. A552 (1993) 293

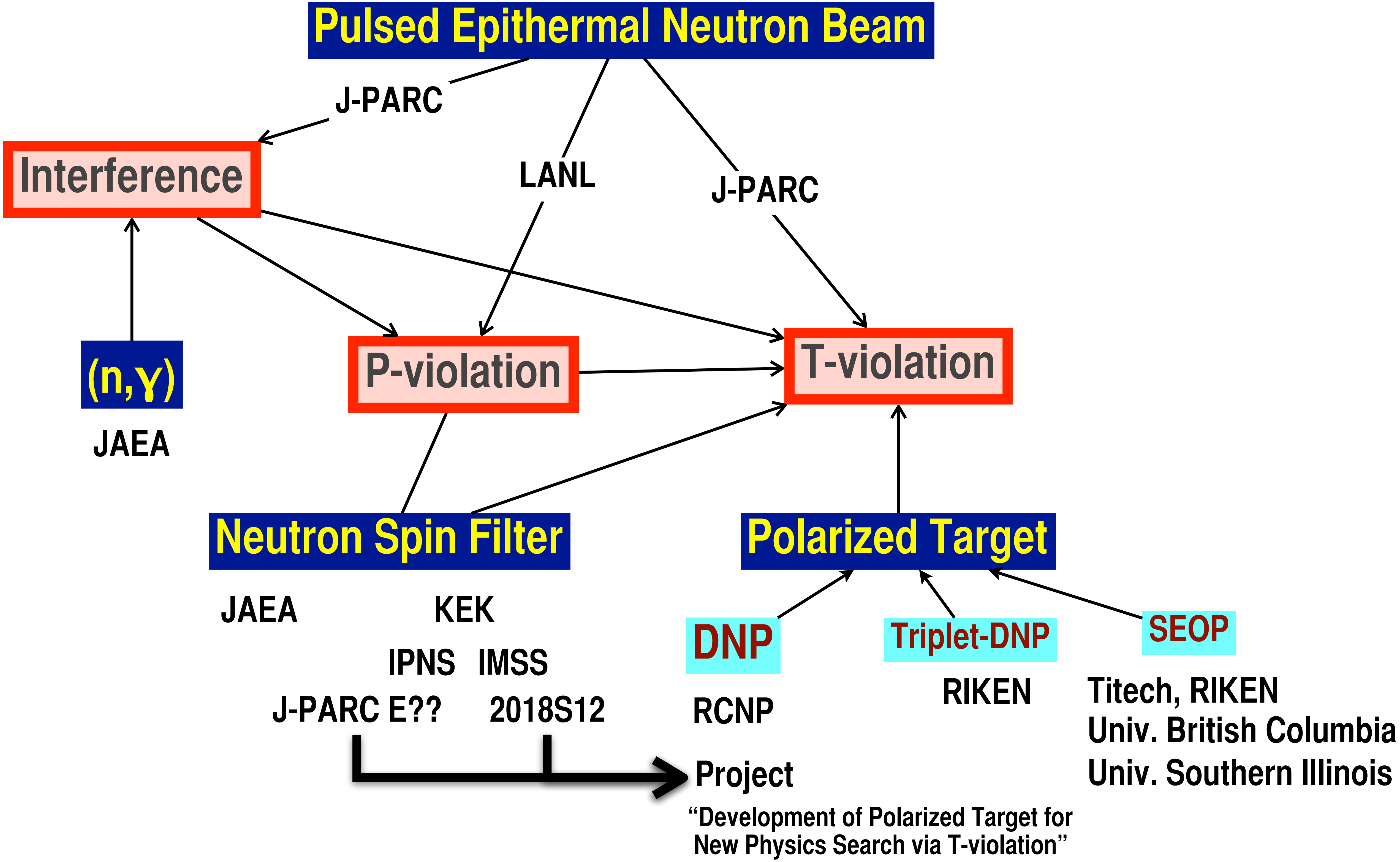


Mitchell, Phys. Rep. 354 (2001) 157
Shimizu, Nucl. Phys. A552 (1993) 293



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





Pulsed Epithermal Neutron Beam

J-PARC

LANL

J-PARC

Interference

(n,γ)

JAEA

P-violation

T-violation

Neutron Spin Filter

JAEA

KEK

IPNS IMSS

J-PARC E?? 2018S12

Polarized Target

DNP

RCNP

Triplet-DNP

RIKEN

SEOP

Titech, RIKEN
Univ. British Columbia
Univ. Southern Illinois

Project

“Development of Polarized Target for New Physics Search via T-violation”

KEK 2018S12

Neutron Optical Parity and Time Reversal EXperiment

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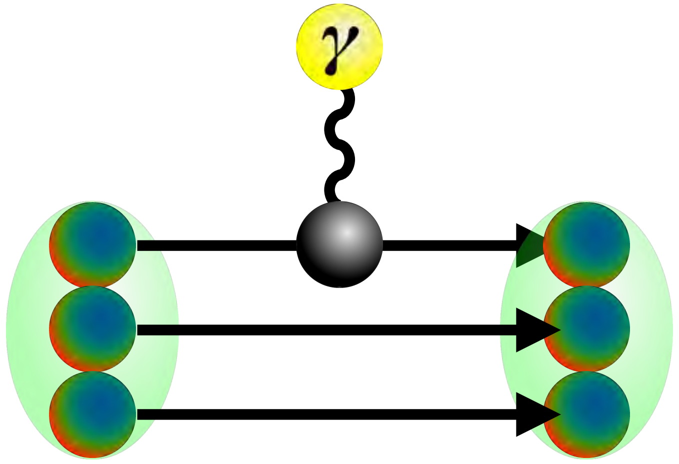
A.S.Tremsin

Berea College

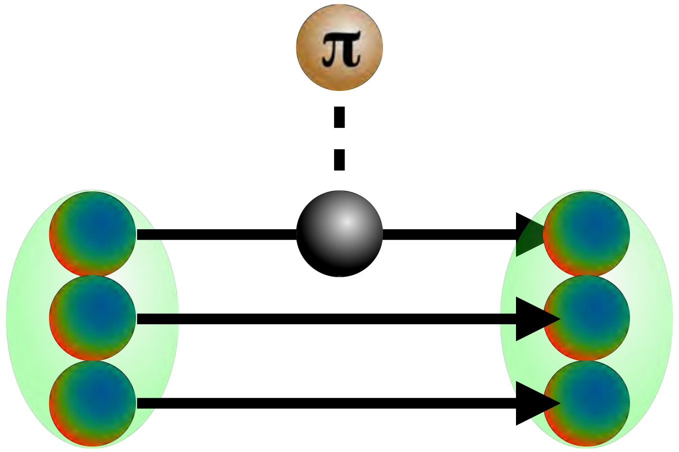
M.Veillette

leading nucleon-level P- and T-odd interaction

$$\mathcal{L}_{\mathrm{N,PTodd}} = -\frac{i}{2}\sum_{i=e,n,p} d_i \overline{\psi}_i \sigma_{\mu\nu}\gamma_5\psi_i F^{\mu\nu}$$
$$+\overline{N}\left[\underline{\bar{g}_\pi^{(0)}}\vec{\tau}\cdot\vec{\pi} + \underline{\bar{g}_\pi^{(1)}}\pi^0 + \underline{\bar{g}_\pi^{(2)}}\left(3\tau_3\pi^0 - \vec{\tau}\cdot\vec{\pi}\right)\right]N$$
$$-\frac{G_F}{\sqrt{2}}\bar{e}i\gamma_5 e\overline{N}\left[C_{\mathrm{S}}^{(0)} + C_{\mathrm{S}}^{(1)}\tau_3\right]N$$
$$-\frac{G_F}{\sqrt{2}}\epsilon^{\alpha\beta\mu\nu}\bar{e}\sigma_{\alpha\beta}e\overline{N}\sigma_{\mu\nu}\left[C_{\mathrm{T}}^{(0)} + C_{\mathrm{T}}^{(1)}\tau_3\right]N$$



nucleon EDM



T-odd P-odd pion-nucleon couplings