0.1eV ≤ E_n ≤ MeV (in this presentation, E_n ~1 eV)

Discrete symmetry in epithermal neutron optics

2018S12/ J-PARC P76 NOPTREX

(Neutron Optical Parity and Time-Reversal EXperiment)

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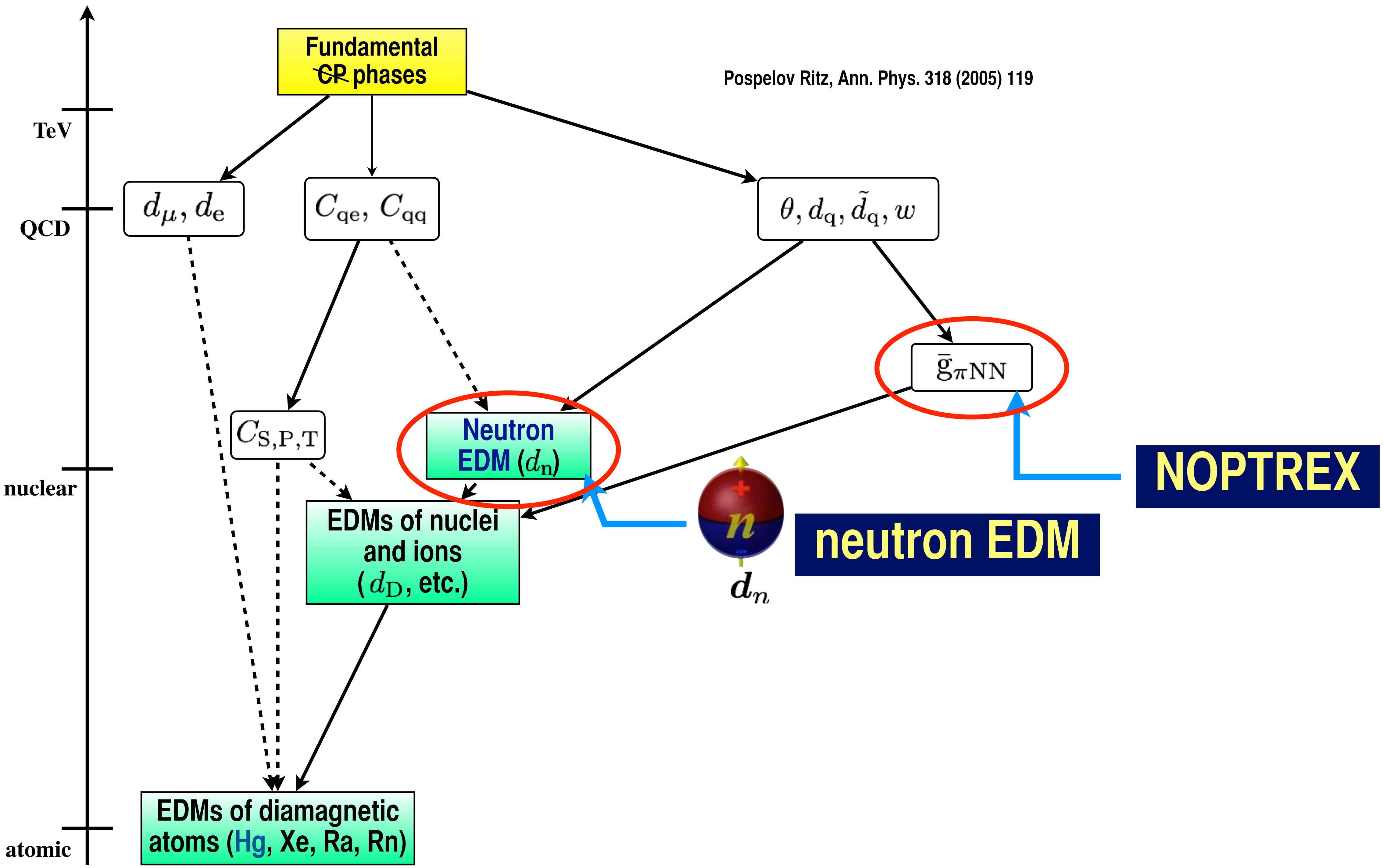
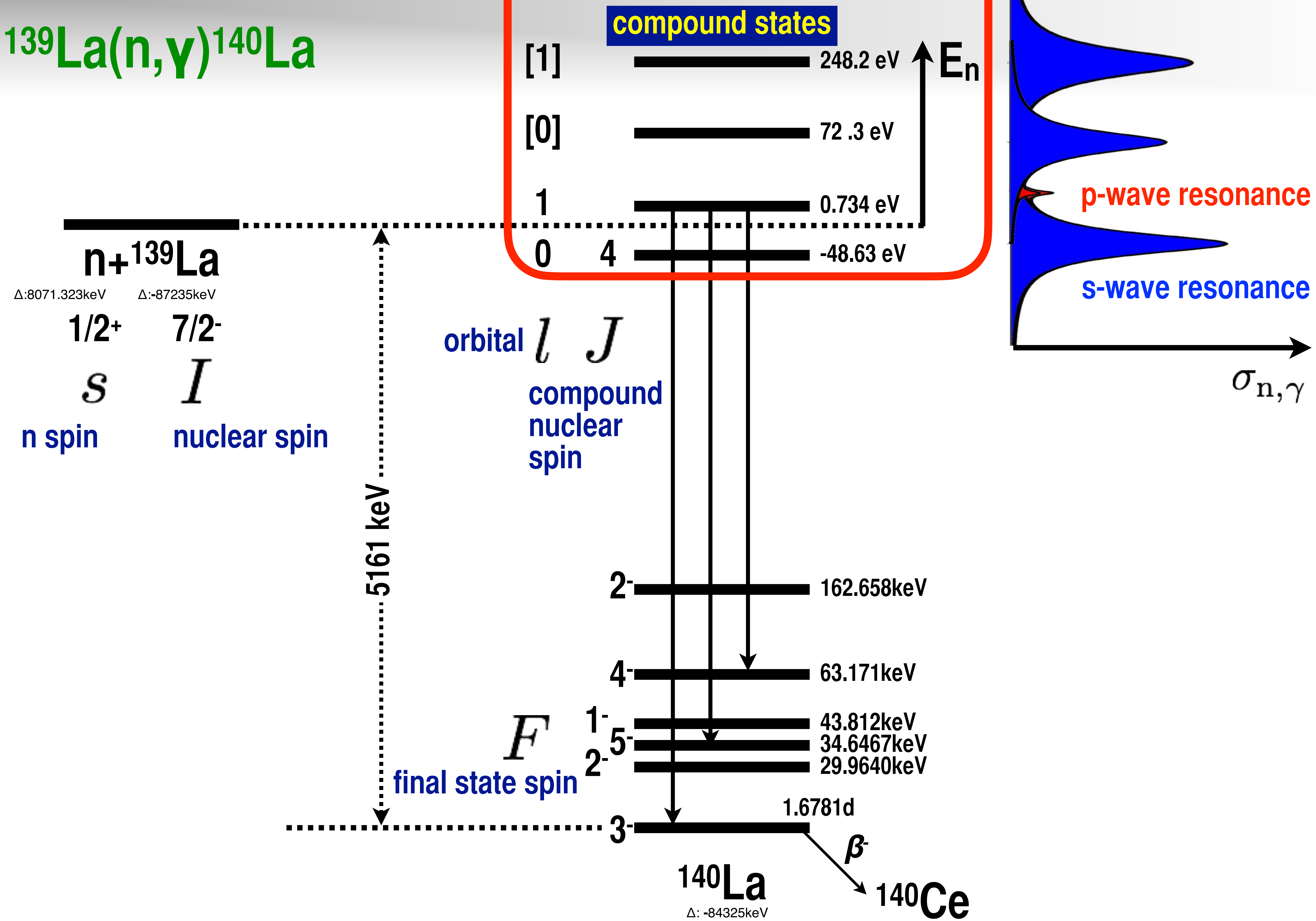
CP-violation in Low Energy Phenomena

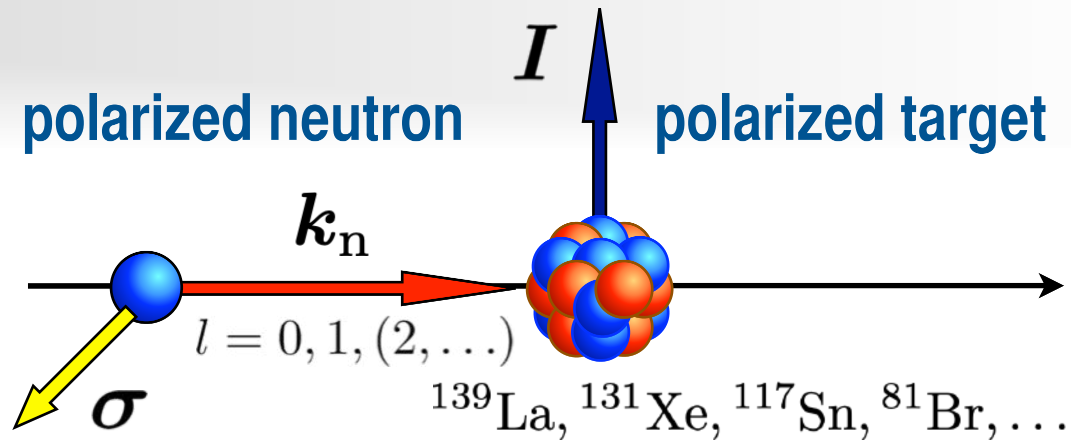


$^{139}La(n,\gamma)^{140}La$



Forward Scattering Amplitude

no fake T-violation

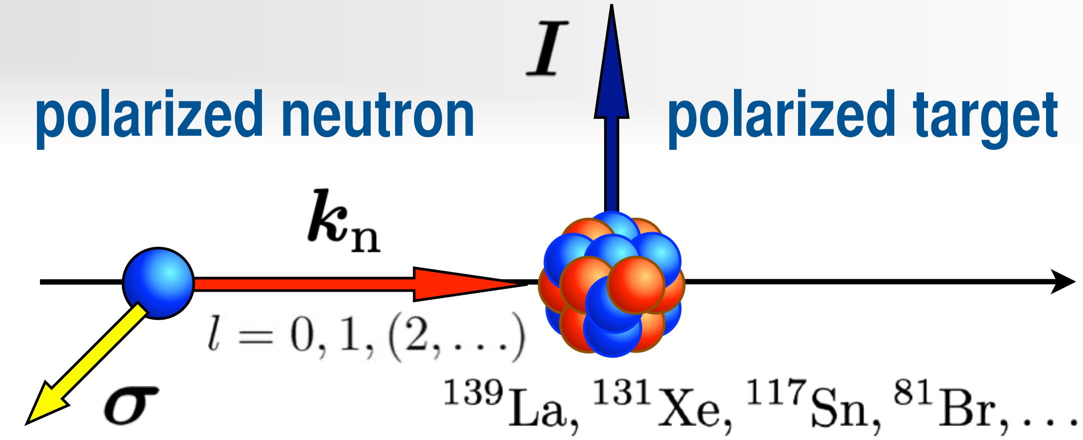


$$f(0) \rightarrow f = A' + B'\boldsymbol{\sigma} \cdot \hat{\boldsymbol{I}} + C'\boldsymbol{\sigma} \cdot \hat{\boldsymbol{k}} + D'\boldsymbol{\sigma} \cdot (\hat{\boldsymbol{I}} \times \hat{\boldsymbol{k}})$$

- A': Spin Independent, P-even T-even
- B': Spin Dependent, P-even T-even
- C': P-violation, P-odd T-even
- D': T-violation, P-odd T-odd

Forward Scattering Amplitude

no fake T-violation



$$f(0) \rightarrow f = A' + B'\boldsymbol{\sigma}\cdot\hat{\boldsymbol{I}} + C'\boldsymbol{\sigma}\cdot\hat{\boldsymbol{k}} + D'\boldsymbol{\sigma}\cdot(\hat{\boldsymbol{I}}\times\hat{\boldsymbol{k}})$$

- A': Spin Independent, P-even T-even
- B': Spin Dependent, P-even T-even
- C': P-violation, P-odd T-even
- D': T-violation, P-odd T-odd

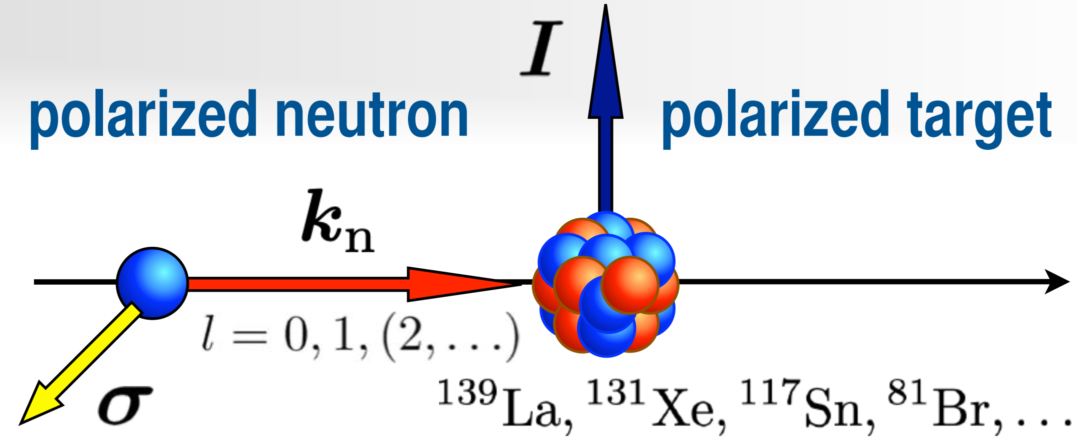
$$f = A' + P_1 H'(\hat{\boldsymbol{k}}_n\cdot\hat{\boldsymbol{I}}) + P_2 E'\left((\hat{\boldsymbol{k}}_n\cdot\hat{\boldsymbol{I}})^2 - \frac{1}{3}\right)$$

$$+(\boldsymbol{\sigma}\cdot\hat{\boldsymbol{I}})\left\{P_1 B' + P_2 F'(\hat{\boldsymbol{k}}_n\cdot\hat{\boldsymbol{I}}) + P_3\frac{B'_3}{3}\left((\hat{\boldsymbol{k}}_n\cdot\hat{\boldsymbol{I}})^2 - 1\right)\right\}$$

$$+(\boldsymbol{\sigma}\cdot\hat{\boldsymbol{k}}_n)\left\{C' + P_1 K'(\hat{\boldsymbol{k}}_n\cdot\hat{\boldsymbol{I}}) - P_2\frac{F'}{3} + P_3\frac{2B'_3}{3}(\hat{\boldsymbol{k}}_n\cdot\hat{\boldsymbol{I}})\right\}$$

$$+(\boldsymbol{\sigma}\cdot(\hat{\boldsymbol{k}}_n\times\hat{\boldsymbol{I}}))\left(P_1 D' + P_2 G'(\hat{\boldsymbol{k}}_n\cdot\hat{\boldsymbol{I}})\right)$$

- A': P-even T-even
- H': P-odd T-even
- E': P-even T-even
- B': P-even T-even
- F': P-odd T-even
- $B'_3/3$: P-even T-even
- C': P-odd T-even
- K': P-even T-even
- $F'/3$: P-odd T-even
- $2B'_3/3$: P-even T-even
- D': P-odd T-odd
- G': P-even T-odd



P-even T-even

$$f(0) \rightarrow f = A' + B'\boldsymbol{\sigma}\cdot\hat{\boldsymbol{I}} + C'\boldsymbol{\sigma}\cdot\hat{\boldsymbol{k}} + D'\boldsymbol{\sigma}\cdot(\hat{\boldsymbol{I}}\times\hat{\boldsymbol{k}})$$

P-odd T-even

Spin Independent
P-even T-even

Spin Dependent
P-even T-even

P-violation
P-odd T-even

T-violation
P-odd T-odd

$$f = A' + P_1 H'(\hat{\boldsymbol{k}}_n\cdot\hat{\boldsymbol{I}}) + P_2 E'\left((\hat{\boldsymbol{k}}_n\cdot\hat{\boldsymbol{I}})^2 - \frac{1}{3}\right)$$

P-even T-even | P-odd T-even | P-even T-even

P-even T-even

$$+(\boldsymbol{\sigma}\cdot\hat{\boldsymbol{I}})\left\{P_1 B' + P_2 F'(\hat{\boldsymbol{k}}_n\cdot\hat{\boldsymbol{I}}) + P_3\frac{B_3'}{3}\left((\hat{\boldsymbol{k}}_n\cdot\hat{\boldsymbol{I}})^2 - 1\right)\right\}$$

P-even T-even | P-odd T-even | P-even T-even

P-odd T-odd

$$+(\boldsymbol{\sigma}\cdot\hat{\boldsymbol{k}}_n)\left\{C' + P_1 K'(\hat{\boldsymbol{k}}_n\cdot\hat{\boldsymbol{I}}) - P_2\frac{F'}{3} + P_3\frac{2B_3'}{3}(\hat{\boldsymbol{k}}_n\cdot\hat{\boldsymbol{I}})\right\}$$

P-odd T-even | P-even T-even | P-odd T-even | P-even T-even

$$+(\boldsymbol{\sigma}\cdot(\hat{\boldsymbol{k}}_n\times\hat{\boldsymbol{I}}))\left(P_1 D' + P_2 G'(\hat{\boldsymbol{k}}_n\cdot\hat{\boldsymbol{I}})\right)$$

P-odd T-odd | P-even T-odd

T-violation in Compound Nuclear States

A'

P-even T-even

$$\frac{d\sigma_{n\gamma}}{d\Omega_\gamma}(E_n)$$

C' $(\boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{k}}_n)$

P-odd T-even

$$(\vec{n},\gamma)(n,\vec{\gamma})(\vec{n},\vec{\gamma})$$

$$\frac{d\sigma_{\vec{n}\gamma}}{d\Omega_\gamma}(E_n)$$

10^6 enhancement in compound nuclear state

B' $(\boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{I}})$

P-even T-even

D' $\boldsymbol{\sigma}_n \cdot (\hat{\boldsymbol{k}}_n \times \hat{\boldsymbol{I}})$

P-odd T-odd

10^6 enhancement in compound nuclear state

T-violation in Compound Nuclear States

A' P-even T-even $\frac{d\sigma_{n\gamma}}{d\Omega_\gamma}(E_n)$

polarized neutron

C' $(\boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{k}}_n)$ P-odd T-even

$(\vec{n},\gamma)(n,\vec{\gamma})(\vec{n},\vec{\gamma})$

$\frac{d\sigma_{\vec{n}\gamma}}{d\Omega_\gamma}(E_n)$

10^6 enhancement
in compound nuclear state

polarized target

B' $(\boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{I}})$ P-even T-even

D' $\boldsymbol{\sigma}_n \cdot (\hat{\boldsymbol{k}}_n \times \hat{\boldsymbol{I}})$ P-odd T-odd

10^6 enhancement
in compound nuclear state

T-violation in Compound Nuclear States

A'

P-even T-even

$$\frac{d\sigma_{n\gamma}}{d\Omega_\gamma}(E_n)$$

polarized neutron

C' $(\boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{k}}_n)$

P-odd T-even

$(\vec{n},\gamma)(n,\vec{\gamma})(\vec{n},\vec{\gamma})$

$$\frac{d\sigma_{\vec{n}\gamma}}{d\Omega_\gamma}(E_n)$$

polarized target

B' $(\boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{I}})$

P-even T-even

D' $\boldsymbol{\sigma}_n \cdot (\hat{\boldsymbol{k}}_n \times \hat{\boldsymbol{I}})$

P-odd T-odd

(1) P- and T-violation in Compound Nuclear States

(2) Neutron Optics

(3) Phenomenological Estimation of T-violation Sensitivity

(4) Determination of Angular Momentum Factor

→κ~1

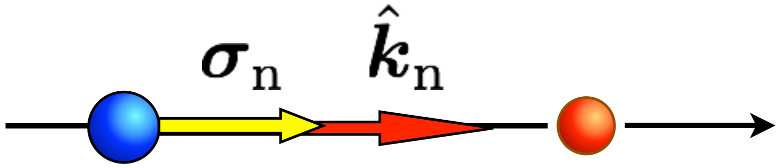
(1) P- and T-violation in Compound Nuclear States

10^6 enhancement of P-violation in compound nuclear state

P-violation in nucleon-nucleon interaction

P-violation

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



$$A_{\mathrm{L}} = \frac{\Delta\sigma}{\sigma_0}$$

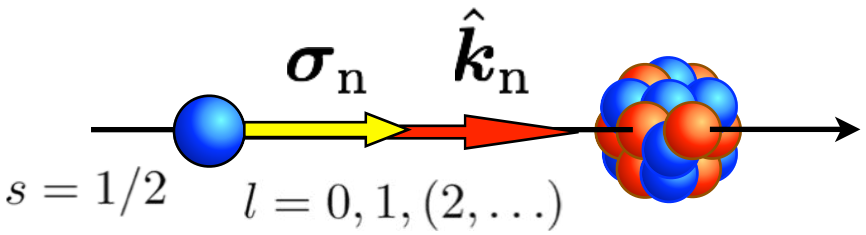
10^{-7} for NN

admixture of weak interaction

P-violation in Compound State

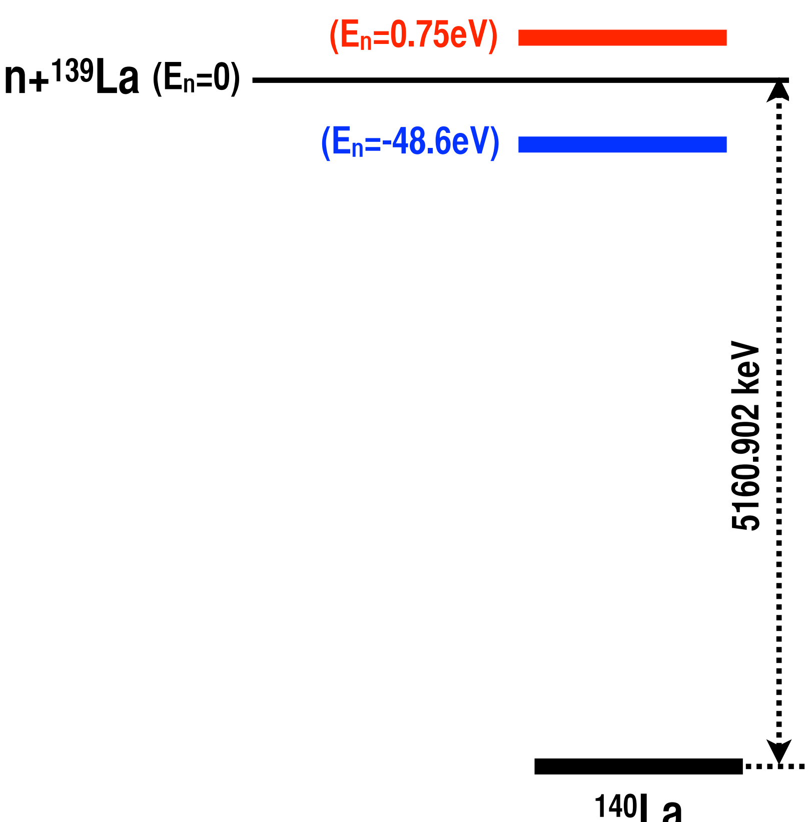
P-violation

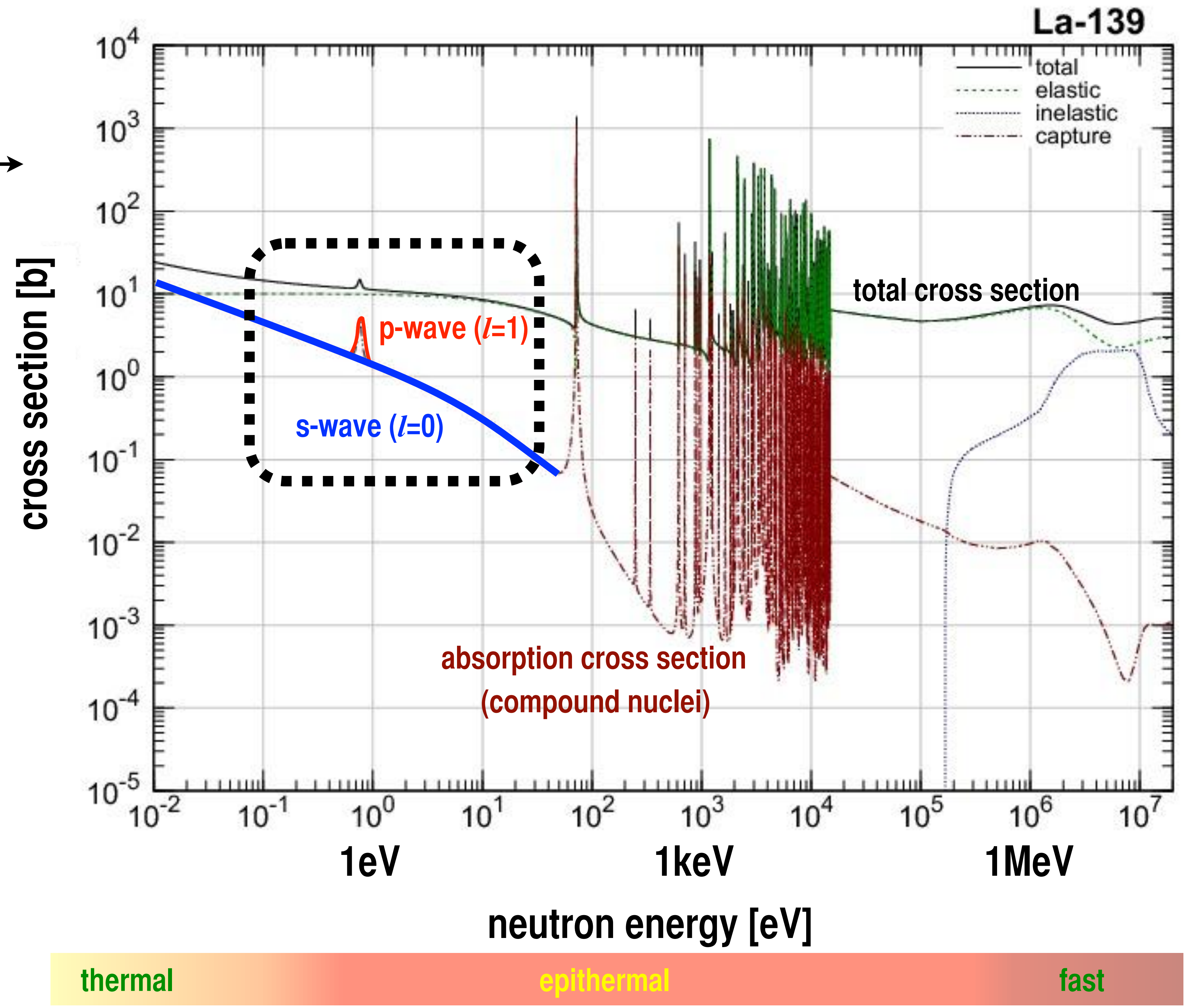
$$\sigma = \sigma_0 + \Delta\sigma(\boldsymbol{\sigma}_\mathrm{n} \cdot \hat{\boldsymbol{k}}_\mathrm{n})$$



$$A_\mathrm{L} = \frac{\Delta\sigma}{\sigma_0} \times \frac{\sigma_0}{\sigma_\mathrm{p}}$$

10^{-7} for NN



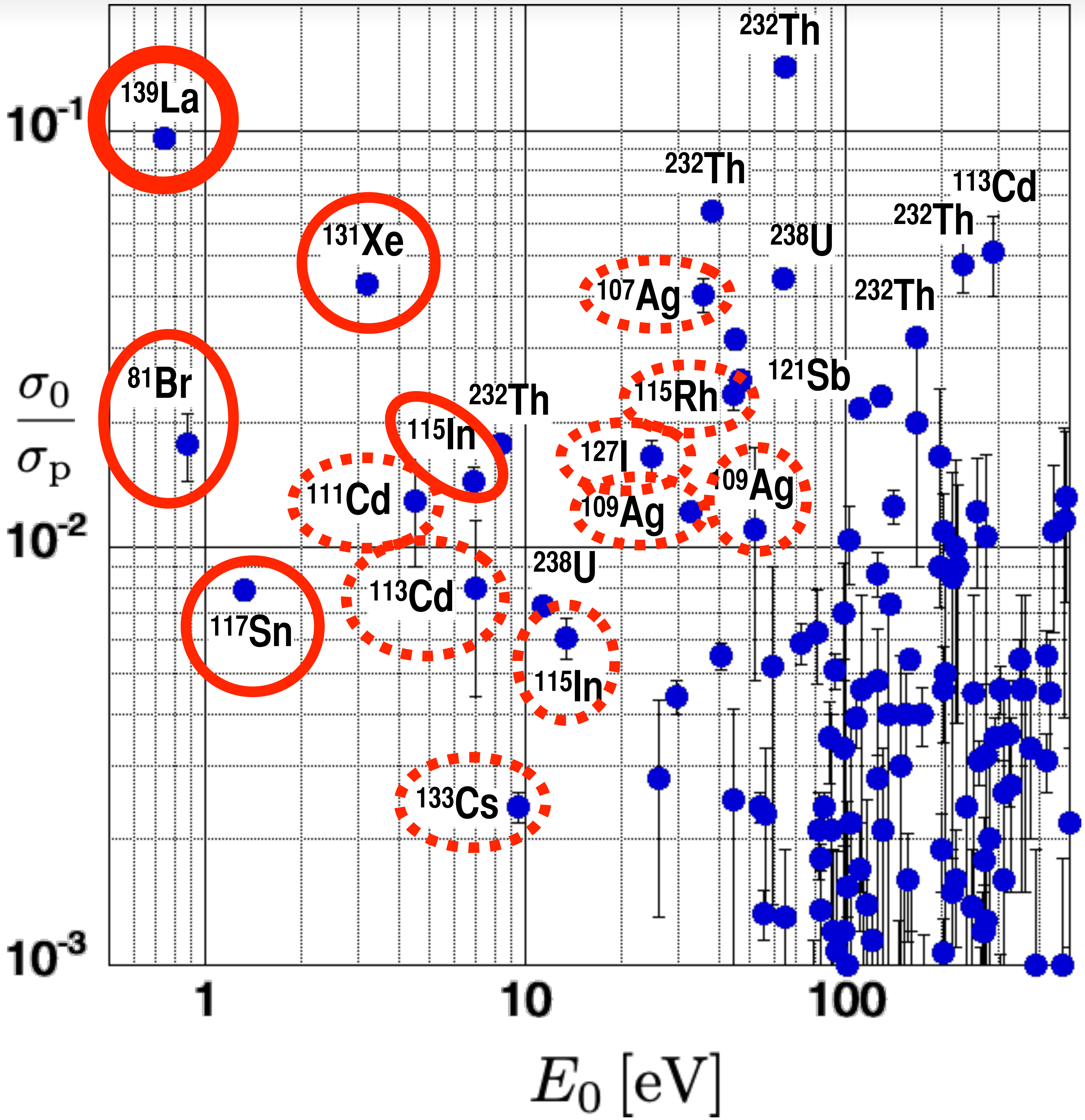


Enhancement of P-violation in Compound Resonances

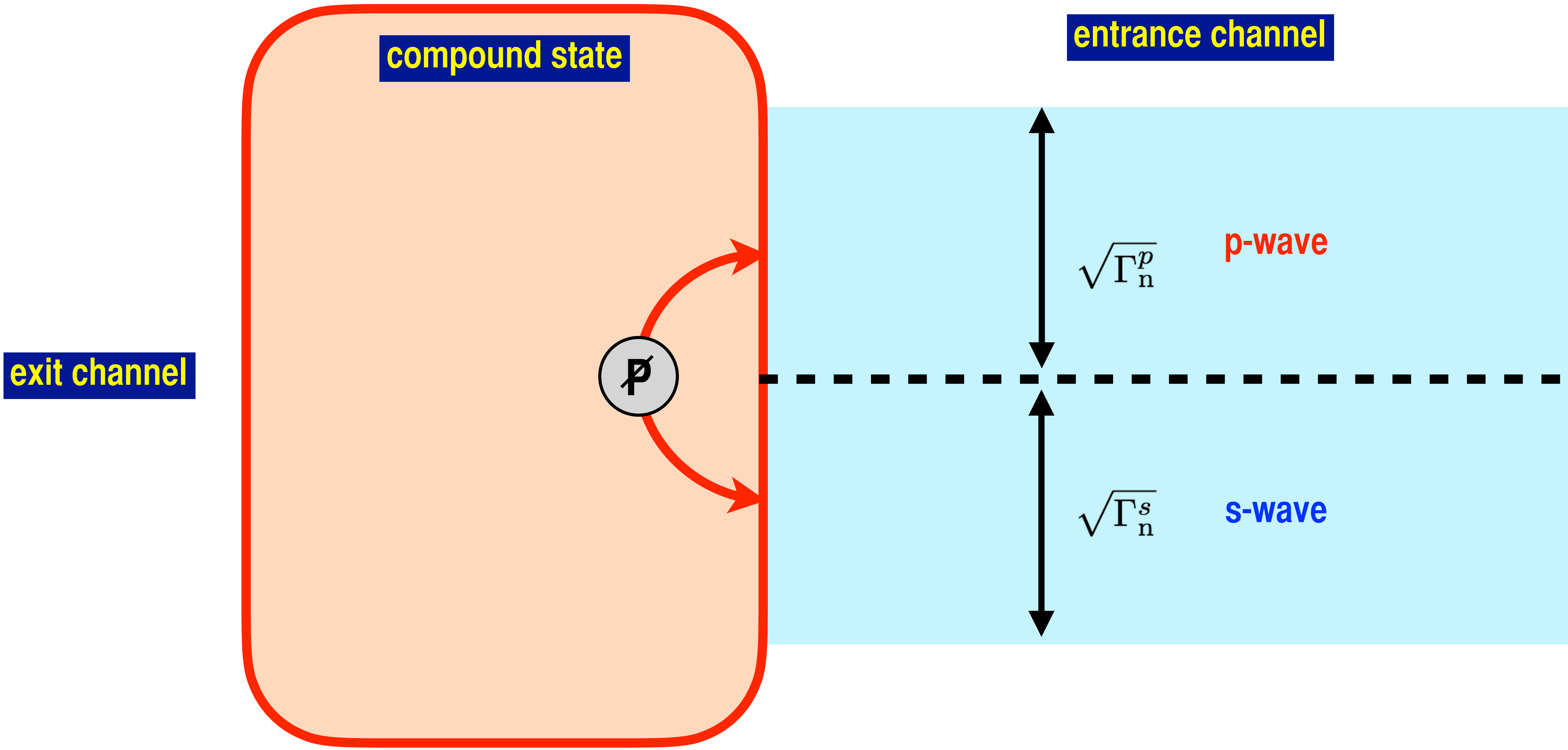
Mitchell, Phys. Rep. 354 (2001) 157
Shimizu, Nucl. Phys. A552 (1993) 293

$$A_L = \frac{\Delta\sigma}{\sigma_0} \times \frac{\sigma_0}{\sigma_p}$$

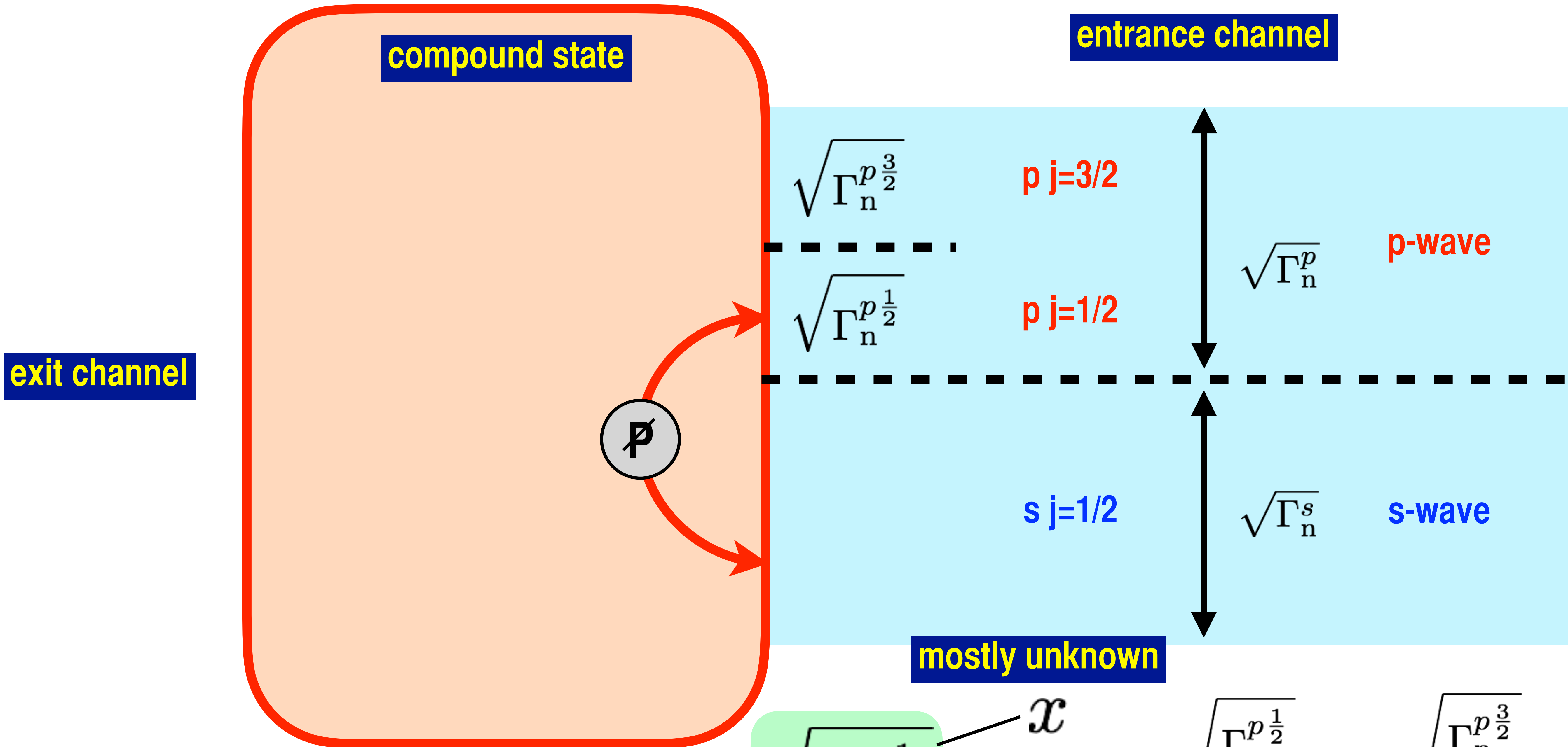
10^{-7} for NN



Dynamical Enhancement



Dynamical Enhancement



$$\sqrt{\Gamma_{\rm n}^{p\frac{3}{2}}} \quad \sqrt{\Gamma_{\rm n}^{p\frac{1}{2}}} \quad \sqrt{\Gamma_{\rm n}^{p}} \quad \sqrt{\Gamma_{\rm n}^{s}}$$

$$A_{\rm L} = -\frac{2W}{E_{\rm p} - E_{\rm s}} \sqrt{\frac{\Gamma_{\rm n}^{s}}{\Gamma_{\rm n}^{p}}} \sqrt{\frac{\Gamma_{\rm n}^{p\frac{1}{2}}}{\Gamma_{\rm n}^{p}}}$$

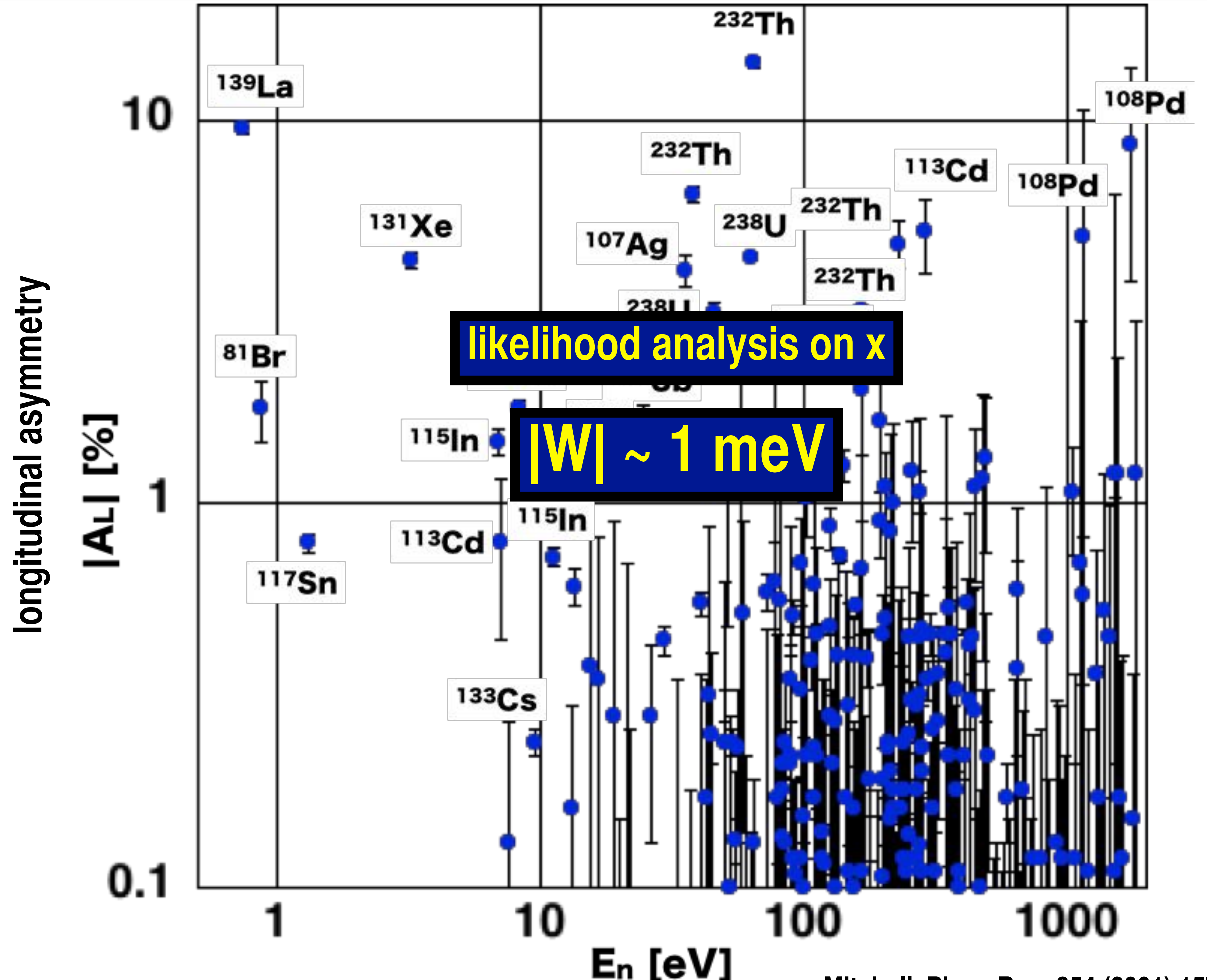
x

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

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

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

Universality Check



Mitchell, Phys. Rep. 354 (2001) 157

compound nuclear spin orbital n spin nuclear spin

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

n entrance spin $\boldsymbol{j}$ ($\boldsymbol{l} + \boldsymbol{s}$) $\boldsymbol{S}$ ($\boldsymbol{s} + \boldsymbol{I}$) channel spin

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

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

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

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

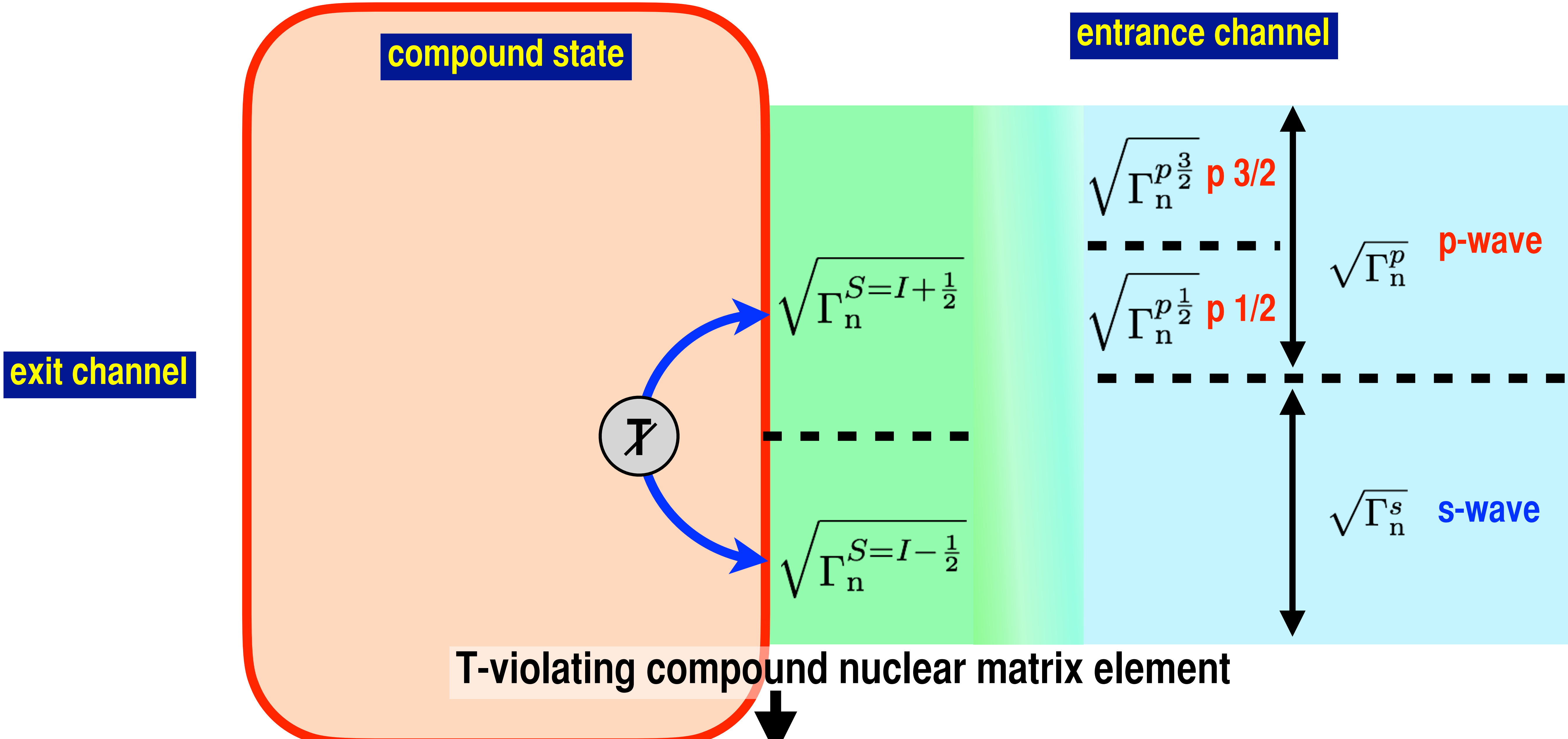
s-p interference ⇔ channel-spin interference

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

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

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

T-odd ➡ Channel-spin Interference



T-violating compound nuclear matrix element

$$D' \;—\; \Delta\sigma_{CP} = \kappa(J)\frac{\langle s|W_T|p\rangle}{\langle s|W|p\rangle}\Delta\sigma_P \;—\; C'$$

P-odd T-odd (D') | T-violation ($\Delta\sigma_{CP}$) | angular momentum factor ($\kappa(J)$) | P-violation ($\Delta\sigma_P$) | P-odd T-even (C')

Gudkov, Phys. Rep. 212 (1992) 77

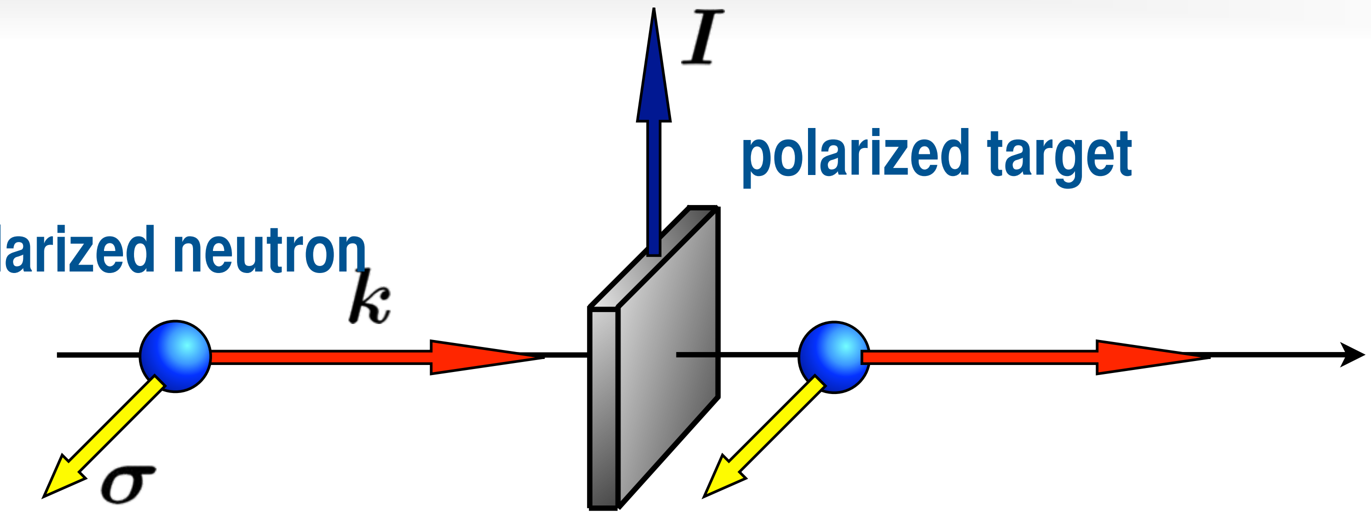
P-violating compound nuclear matrix element

(2) Neutron Optics

description via forward scattering amplitude

T-violation in Neutron Optics

no fake T-violation



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

- A': Spin Independent, P-even T-even
- B': Spin Dependent, P-even T-even
- C': P-violation, P-odd T-even
- D': T-violation, P-odd T-odd

$$U_{\mathrm{f}} = \mathfrak{S}U_{\mathrm{i}}$$

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

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

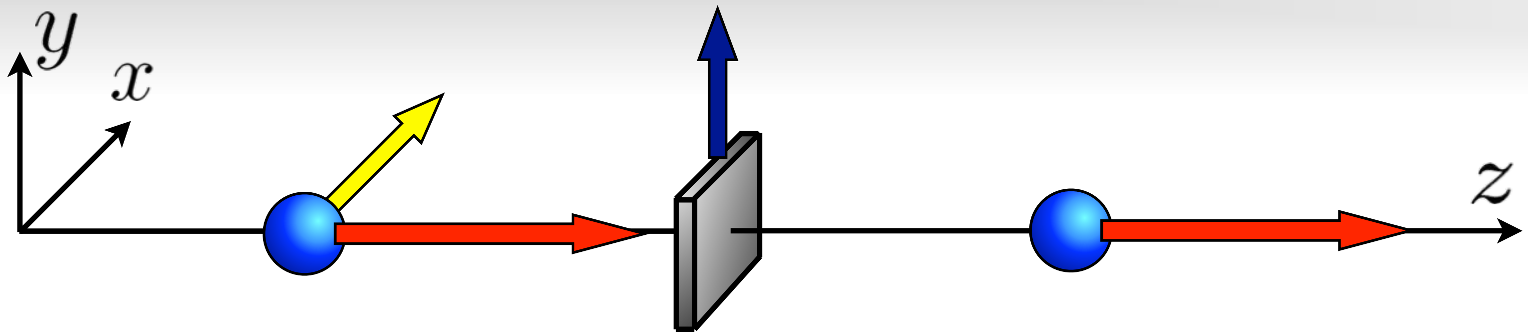
$$Z = \frac{2\pi\rho}{k}z \qquad C = ie^{iZA'}\frac{\sin b}{b}ZC'$$

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

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

- A: Spin Independent, P-even T-even
- B: Spin Dependent, P-even T-even
- C: P-violation, P-odd T-even
- D: T-violation, P-odd T-odd

fake T-odd due to non-forward scattering correctable or negligible



$$A_x \equiv \mathrm{Tr}\left[\mathfrak{S}^\dagger \sigma_x \mathfrak{S}\right] = 4\left(\mathrm{Re}\,\underline{A^*}\,\underline{D} + \mathrm{Im}\,\underline{B^*}\,\underline{C}\right)$$

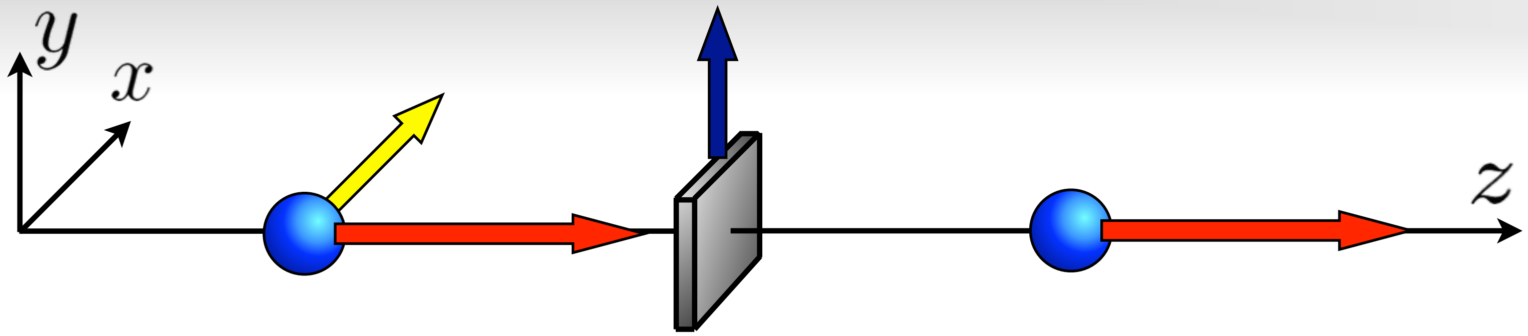
Spin Independent P-even T-even

T-violation P-odd T-odd

Spin Dependent P-even T-even

P-violation P-odd T-even

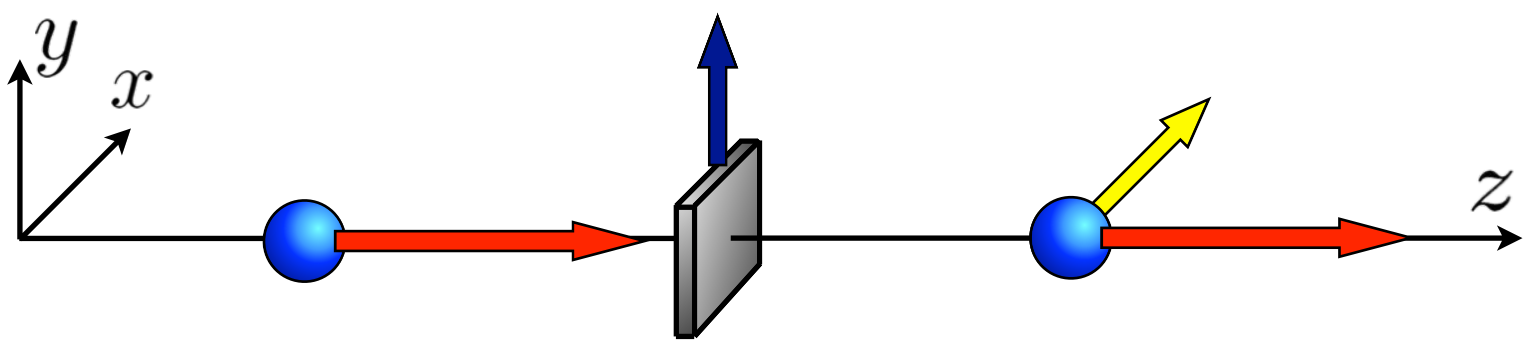
Analyzing Power



$$A_x \equiv \mathrm{Tr}\left[\mathfrak{S}^\dagger \sigma_x \mathfrak{S}\right] = 4\left(\mathrm{Re}\, A^* D + \mathrm{Im}\, B^* C\right)$$

A^*: Spin Independent, P-even T-even
D: T-violation, P-odd T-odd
B^*: Spin Dependent, P-even T-even
C: P-violation, P-odd T-even

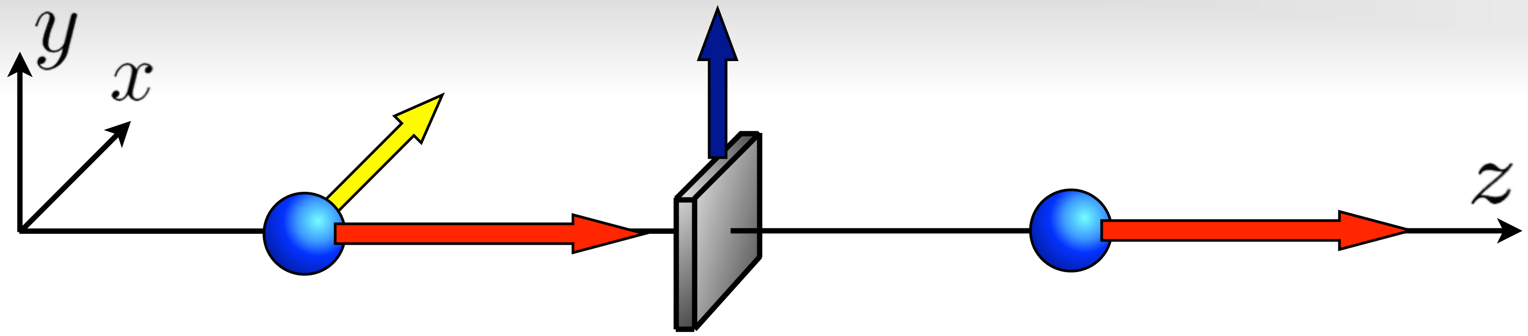
Analyzing Power



$$P_x \equiv \mathrm{Tr}\left[\sigma_x \mathfrak{S}^\dagger \mathfrak{S}\right] = 4\left(\mathrm{Re}\, A^* D - \mathrm{Im}\, B^* C\right)$$

A^*: Spin Independent, P-even T-even
D: T-violation, P-odd T-odd
B^*: Spin Dependent, P-even T-even
C: P-violation, P-odd T-even

Polarization



$$A_x \equiv \mathrm{Tr}\left[\mathfrak{S}^\dagger \sigma_x \mathfrak{S}\right] = 4\left(\mathrm{Re}\,A^* D + \mathrm{Im}\,B^* C\right)$$

- A: Spin Independent, P-even T-even
- D: T-violation, P-odd T-odd
- B: Spin Dependent, P-even T-even
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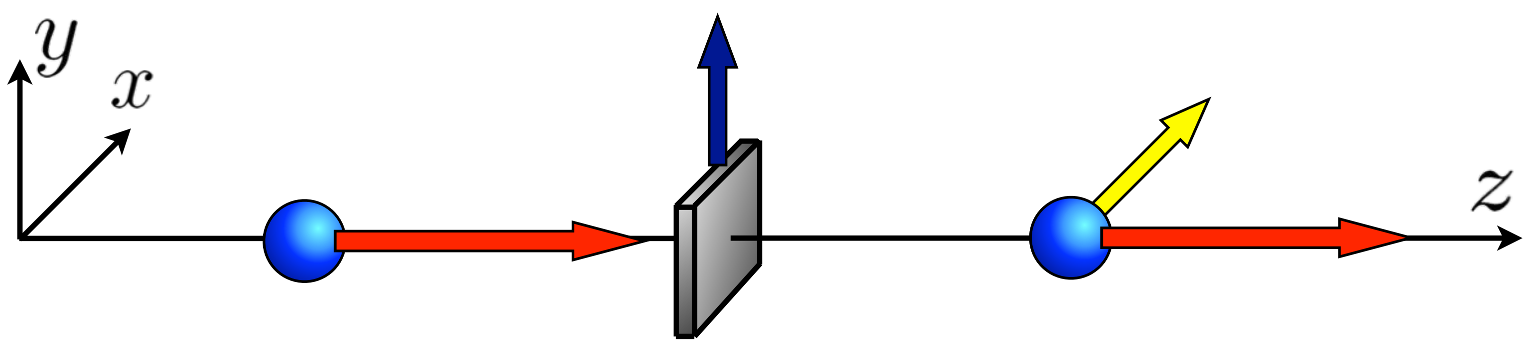
Analyzing Power



$$P_x \equiv \mathrm{Tr}\left[\sigma_x \mathfrak{S}^\dagger \mathfrak{S}\right] = 4\left(\mathrm{Re}\,A^* D - \mathrm{Im}\,B^* C\right)$$

- A: Spin Independent, P-even T-even
- D: T-violation, P-odd T-odd
- B: Spin Dependent, P-even T-even
- C: P-violation, P-odd T-even

Polarization

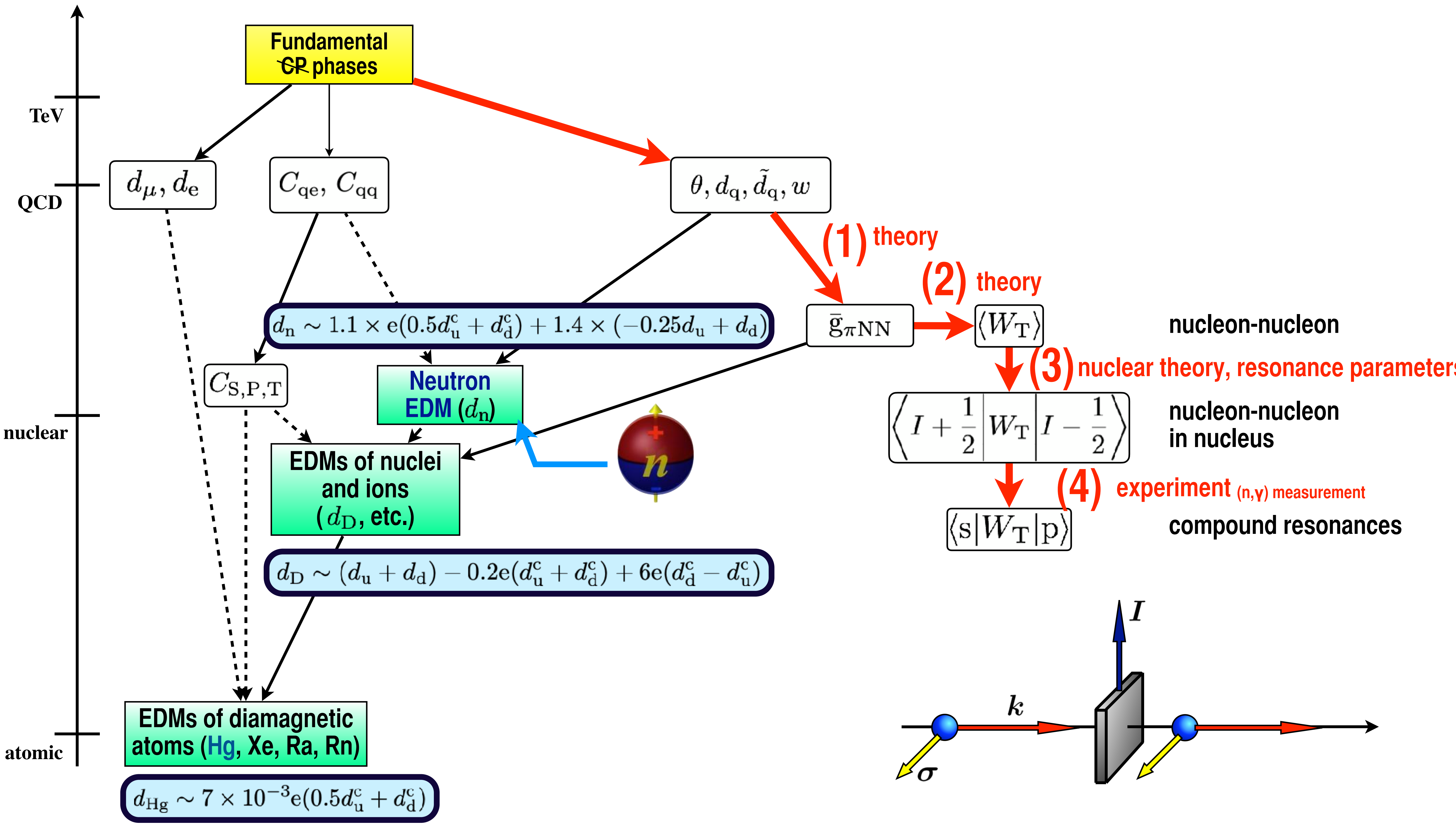
+)

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

(3) Phenomenological Estimation of T-violation Sensitivity

factorization of nuclear properties

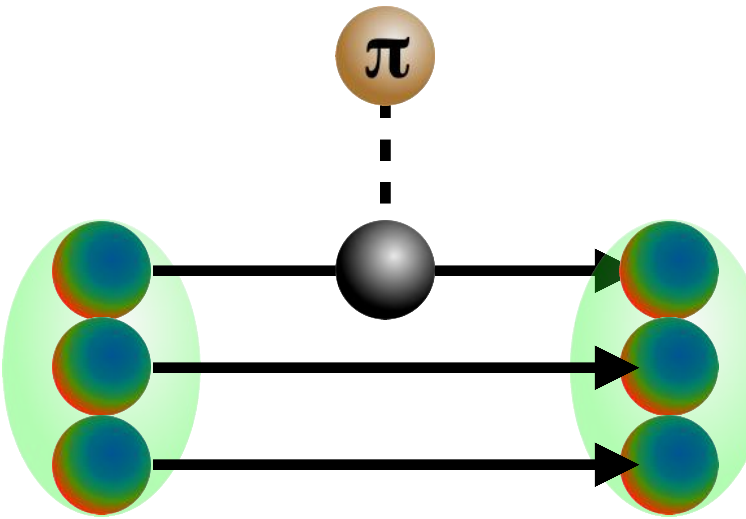
CP-violation in Low Energy Phenomena



Estimation in Effective Field Theory

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

T-odd P-odd meson couplings



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

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

$$T_{12}^z = 3\tau_1^z \tau_2^z - \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 \qquad Y_1(x) = \left(1 + \frac{1}{x}\right) \frac{e^{-x}}{x}$$

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

Estimation in Effective Field Theory

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

$$d_{\rm n} \sim 0.14(\bar{g}_\pi^{(0)} - \bar{g}_\pi^{(2)})$$

$$d_{\rm p} \sim -0.14(\bar{g}_\pi^{(0)} - \bar{g}_\pi^{(2)})$$

$$d_{^3{\rm He}} \sim (-0.0542 d_{\rm p} + 0.868 d_{\rm n}) + 0.072 \left[\bar{g}_\pi^{(0)} + 1.92\bar{g}_\pi^{(1)} + 1.2\right.$$

$$d_{\rm d} \sim 0.19\bar{g}_\pi^{(1)} + 0.0035\bar{g}_\eta^{(1)} + 0.0017\bar{g}_\rho^{(1)} - 0.0049\bar{g}_\omega^{(1)}$$

$$d_{^3{\rm H}} \sim (0.868 d_{\rm p} - 0.0552 d_{\rm n}) - 0.072 \left[\bar{g}_\pi^{(0)} - 1.97\bar{g}_\pi^{(1)} + 1.26\bar{g}_\pi^{(2)} - 0.\right.$$

$$\frac{\Delta\sigma_{\rm CP}}{2\sigma_{\rm tot}} = \frac{-0.185{\rm b}}{\sigma_{\rm tot}} \left[\bar{g}_\pi^{(0)} + 0.26\bar{g}_\pi^{(1)} + 0.0012\bar{g}_\eta^{(0)} + 0.0034\bar{g}_\eta^{(1)} - 0.\right.$$

$$\frac{1}{N}\frac{{\rm d}\phi_{\rm CP}}{{\rm d}z} = (-65{\rm rad}\cdot{\rm fm}^2) \left[\bar{g}_\pi^{(0)} + 0.12\bar{g}_\pi^{(1)} + 0.0072\bar{g}_\eta^{(0)} + 0.\right.$$

Estimation in Effective Field Theory

nuclear — nuclear effect — nucleon

$$\frac{\langle s|W_{\rm T}|p\rangle}{\langle s|W|p\rangle} = Q\frac{\langle W_{\rm T}\rangle}{\langle W\rangle}$$

Gudkov, Phys. Rep. 212 (1992) 77
(Koonin, Phys. Rev. Lett. 69 (1992)1163)

$$Q \simeq 1 - 0.2$$

Flambaum, Phys. Rev. C51 (1995) 2914

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

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

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

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

↓

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

↕

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

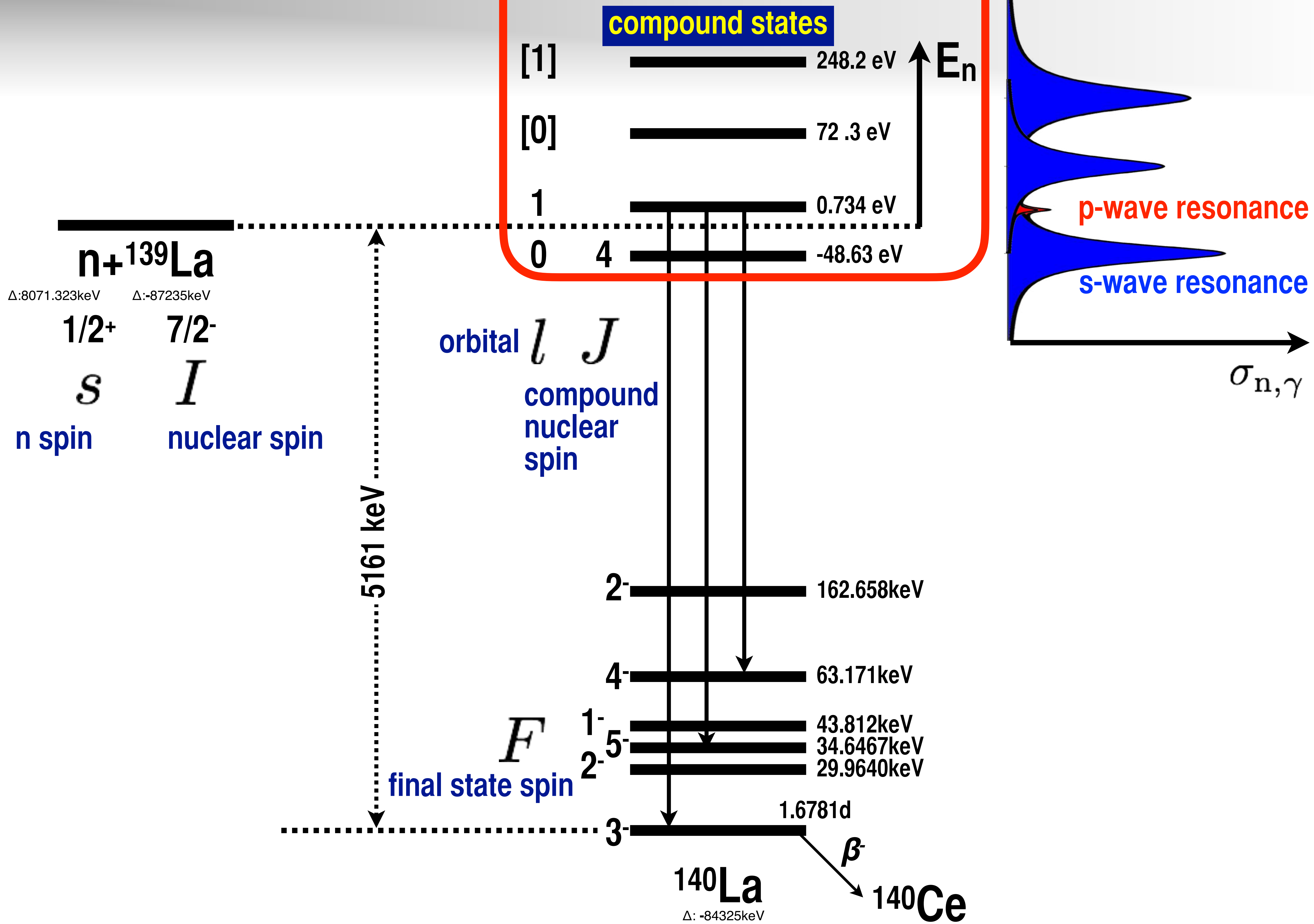
←**discovery potential corresponding to the present nEDM upper limit**

(4) Determination of Angular Momentum Factor

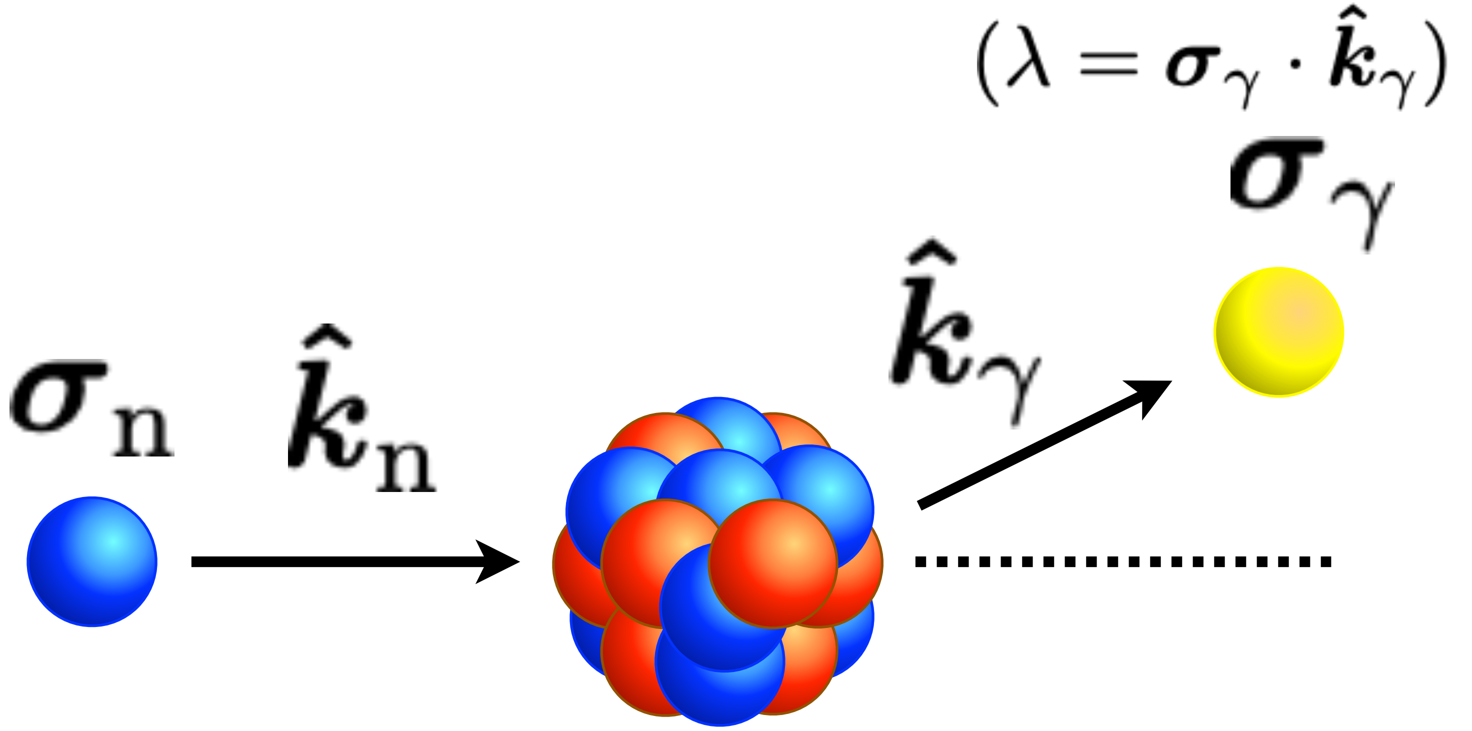
Energy dependent angular distribution of individual γ-rays
$^{139}La(n,\gamma)^{140}La$ for the complete determination of partial amplitudes of s-wave and p-wave incident neutrons

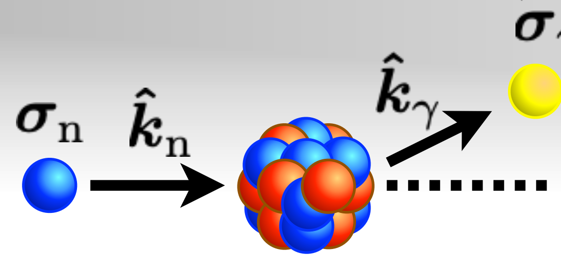
$$\kappa(J) = 4.84^{+5.58}_{-1.69}, \quad 0.99^{+0.08}_{-0.07}$$

Okudaira et al., PRC97(2018)034622


compound states
[1]
248.2 eV
[0]
72 .3 eV
1
0.734 eV
0
4
-48.63 eV
E_n
p-wave resonance
s-wave resonance
$\sigma_{n,\gamma}$
n+^{139}La
Δ:8071.323keV
Δ:-87235keV
1/2+
7/2-
s
I
n spin
nuclear spin
orbital l J
compound nuclear spin
5161 keV
2^-
162.658keV
4^-
63.171keV
1^-
43.812keV
5^-
34.6467keV
2^-
29.9640keV
F
final state spin
1.6781d
3^-
β^-
^{140}La
Δ: -84325keV
^{140}Ce

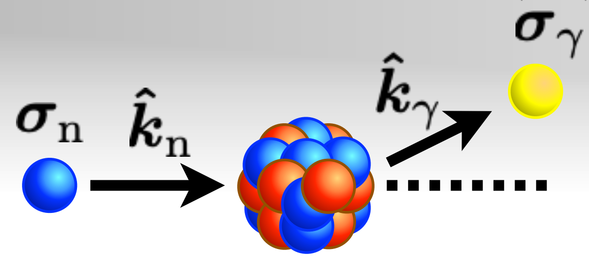
Details of Entrance Channel





$$
\begin{aligned}
2\frac{d\sigma}{d\Omega} = \; & a_0 \\
& + a_1\left[\hat{\boldsymbol{k}}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\gamma\right] \\
& + a_2\left[\boldsymbol{\sigma}_\mathrm{n}\cdot(\hat{\boldsymbol{k}}_\mathrm{n}\times\hat{\boldsymbol{k}}_\gamma)\right] \\
& + a_3\left[(\hat{\boldsymbol{k}}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\gamma)^2-\frac{1}{3}\right] \\
& + a_4\left[(\hat{\boldsymbol{k}}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\gamma)(\boldsymbol{\sigma}_\mathrm{n}\cdot(\hat{\boldsymbol{k}}_\mathrm{n}\times\hat{\boldsymbol{k}}_\gamma))\right] \\
& + a_5\left[(\boldsymbol{\sigma}_\gamma\cdot\hat{\boldsymbol{k}}_\gamma)(\boldsymbol{\sigma}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\gamma)\right] \\
& + a_6\left[(\boldsymbol{\sigma}_\gamma\cdot\hat{\boldsymbol{k}}_\gamma)(\boldsymbol{\sigma}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\mathrm{n})\right] \\
& + a_7\left[(\boldsymbol{\sigma}_\gamma\cdot\hat{\boldsymbol{k}}_\gamma)((\boldsymbol{\sigma}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\gamma)(\hat{\boldsymbol{k}}_\gamma\cdot\hat{\boldsymbol{k}}_\mathrm{n})-\frac{1}{3}(\boldsymbol{\sigma}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\mathrm{n}))\right] \\
& + a_8\left[(\boldsymbol{\sigma}_\gamma\cdot\hat{\boldsymbol{k}}_\gamma)((\boldsymbol{\sigma}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\mathrm{n})(\hat{\boldsymbol{k}}_\gamma\cdot\hat{\boldsymbol{k}}_\mathrm{n})-\frac{1}{3}(\boldsymbol{\sigma}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\gamma))\right] \\
& + a_9\left[\boldsymbol{\sigma}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\gamma\right] \\
& + a_{10}\left[\boldsymbol{\sigma}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\mathrm{n}\right] \\
& + a_{11}\left[(\boldsymbol{\sigma}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\gamma)(\hat{\boldsymbol{k}}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\gamma)-\frac{1}{3}(\boldsymbol{\sigma}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\mathrm{n})\right] \\
& + a_{12}\left[(\boldsymbol{\sigma}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\mathrm{n})(\hat{\boldsymbol{k}}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\gamma)-\frac{1}{3}(\boldsymbol{\sigma}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\gamma)\right] \\
& + a_{13}\left[(\boldsymbol{\sigma}_\gamma\cdot\hat{\boldsymbol{k}}_\gamma)\right] \\
& + a_{14}\left[(\boldsymbol{\sigma}_\gamma\cdot\hat{\boldsymbol{k}}_\gamma)(\hat{\boldsymbol{k}}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\gamma)\right] \\
& + a_{15}\left[(\boldsymbol{\sigma}_\gamma\cdot\hat{\boldsymbol{k}}_\gamma)(\boldsymbol{\sigma}_\mathrm{n}\cdot(\hat{\boldsymbol{k}}_\mathrm{n}\times\hat{\boldsymbol{k}}_\gamma))\right] \\
& + a_{16}\left[(\boldsymbol{\sigma}_\gamma\cdot\hat{\boldsymbol{k}}_\gamma)((\hat{\boldsymbol{k}}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\gamma)^2-\frac{1}{3})\right] \\
& + a_{17}\left[(\boldsymbol{\sigma}_\gamma\cdot\hat{\boldsymbol{k}}_\gamma)(\hat{\boldsymbol{k}}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\gamma)(\boldsymbol{\sigma}_\mathrm{n}\cdot(\hat{\boldsymbol{k}}_\mathrm{n}\times\hat{\boldsymbol{k}}_\gamma))\right]
\end{aligned}
$$

	$\boldsymbol{\sigma}_\mathrm{n}$−dep.	$\boldsymbol{\sigma}_\gamma$−dep.	P	T	
a_0	no	no	even	even	1
a_1	no	no	even	even	$\hat{\boldsymbol{k}}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\gamma$
a_2	yes	no	even	odd	$\boldsymbol{\sigma}_\mathrm{n}\cdot(\hat{\boldsymbol{k}}_\mathrm{n}\times\hat{\boldsymbol{k}}_\gamma)$
a_3	no	no	even	even	$(\hat{\boldsymbol{k}}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\gamma)^2-\frac{1}{3}$
a_4	yes	no	even	odd	$(\hat{\boldsymbol{k}}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\gamma)(\boldsymbol{\sigma}_\mathrm{n}\cdot(\hat{\boldsymbol{k}}_\mathrm{n}\times\hat{\boldsymbol{k}}_\gamma))$
a_5	yes	yes	even	even	$(\boldsymbol{\sigma}_\gamma\cdot\hat{\boldsymbol{k}}_\gamma)(\boldsymbol{\sigma}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\gamma)$
a_6	yes	yes	even	even	$(\boldsymbol{\sigma}_\gamma\cdot\hat{\boldsymbol{k}}_\gamma)(\boldsymbol{\sigma}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\mathrm{n})$
a_7	yes	yes	even	even	$(\boldsymbol{\sigma}_\gamma\cdot\hat{\boldsymbol{k}}_\gamma)((\boldsymbol{\sigma}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\gamma)(\hat{\boldsymbol{k}}_\gamma\cdot\hat{\boldsymbol{k}}_\mathrm{n})-\frac{1}{3}(\boldsymbol{\sigma}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\mathrm{n}))$
a_8	yes	yes	even	even	$(\boldsymbol{\sigma}_\gamma\cdot\hat{\boldsymbol{k}}_\gamma)((\boldsymbol{\sigma}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\mathrm{n})(\hat{\boldsymbol{k}}_\gamma\cdot\hat{\boldsymbol{k}}_\mathrm{n})-\frac{1}{3}(\boldsymbol{\sigma}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\gamma))$
a_9	yes	no	odd	even	$\boldsymbol{\sigma}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\gamma$
a_{10}	yes	no	odd	even	$\boldsymbol{\sigma}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\mathrm{n}$
a_{11}	yes	no	odd	even	$(\boldsymbol{\sigma}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\gamma)(\hat{\boldsymbol{k}}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\gamma)-\frac{1}{3}(\boldsymbol{\sigma}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\mathrm{n})$
a_{12}	yes	no	odd	even	$(\boldsymbol{\sigma}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\mathrm{n})(\hat{\boldsymbol{k}}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\gamma)-\frac{1}{3}(\boldsymbol{\sigma}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\gamma)$
a_{13}	no	yes	odd	even	$(\boldsymbol{\sigma}_\gamma\cdot\hat{\boldsymbol{k}}_\gamma)$
a_{14}	no	yes	odd	even	$(\boldsymbol{\sigma}_\gamma\cdot\hat{\boldsymbol{k}}_\gamma)(\hat{\boldsymbol{k}}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\gamma)$
a_{15}	yes	yes	odd	odd	$(\boldsymbol{\sigma}_\gamma\cdot\hat{\boldsymbol{k}}_\gamma)(\boldsymbol{\sigma}_\mathrm{n}\cdot(\hat{\boldsymbol{k}}_\mathrm{n}\times\hat{\boldsymbol{k}}_\gamma))$
a_{16}	no	yes	odd	even	$(\boldsymbol{\sigma}_\gamma\cdot\hat{\boldsymbol{k}}_\gamma)((\hat{\boldsymbol{k}}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\gamma)^2-\frac{1}{3})$
a_{17}	yes	yes	odd	odd	$(\boldsymbol{\sigma}_\gamma\cdot\hat{\boldsymbol{k}}_\gamma)(\hat{\boldsymbol{k}}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\gamma)(\boldsymbol{\sigma}_\mathrm{n}\cdot(\hat{\boldsymbol{k}}_\mathrm{n}\times\hat{\boldsymbol{k}}_\gamma))$

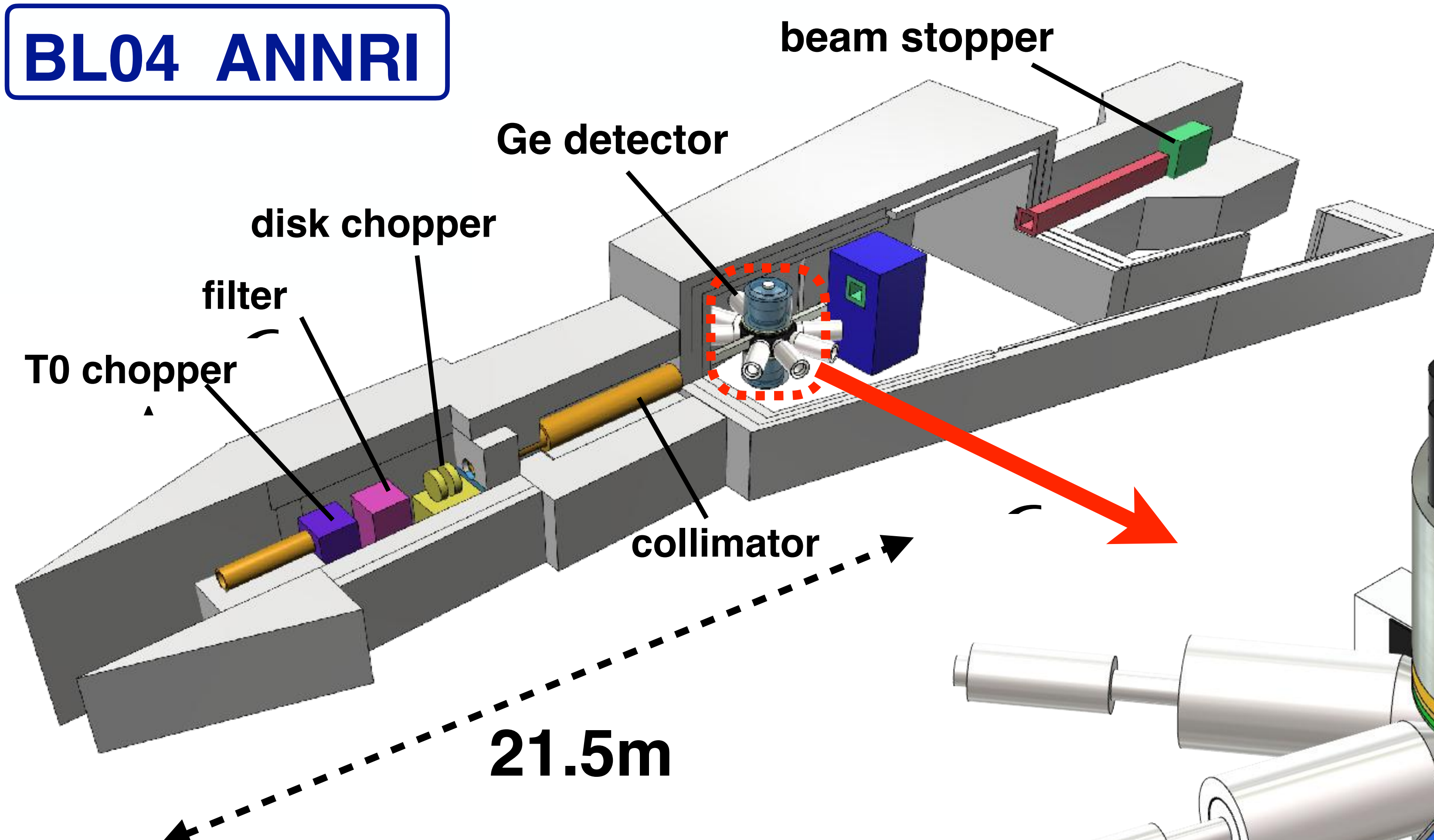


$$
\begin{aligned}
2\frac{d\sigma}{d\Omega} = \; & a_0 \\
& + a_1 \left[\hat{\boldsymbol{k}}_{\rm n}\cdot\hat{\boldsymbol{k}}_{\gamma}\right] \\
& + a_2 \left[\boldsymbol{\sigma}_{\rm n}\cdot(\hat{\boldsymbol{k}}_{\rm n}\times\hat{\boldsymbol{k}}_{\gamma})\right] \\
& + a_3 \left[(\hat{\boldsymbol{k}}_{\rm n}\cdot\hat{\boldsymbol{k}}_{\gamma})^2-\frac{1}{3}\right] \\
& + a_4 \left[(\hat{\boldsymbol{k}}_{\rm n}\cdot\hat{\boldsymbol{k}}_{\gamma})(\boldsymbol{\sigma}_{\rm n}\cdot(\hat{\boldsymbol{k}}_{\rm n}\times\hat{\boldsymbol{k}}_{\gamma}))\right] \\
& + a_5 \left[(\boldsymbol{\sigma}_{\gamma}\cdot\hat{\boldsymbol{k}}_{\gamma})(\boldsymbol{\sigma}_{\rm n}\cdot\hat{\boldsymbol{k}}_{\gamma})\right] \\
& + a_6 \left[(\boldsymbol{\sigma}_{\gamma}\cdot\hat{\boldsymbol{k}}_{\gamma})(\boldsymbol{\sigma}_{\rm n}\cdot\hat{\boldsymbol{k}}_{\rm n})\right] \\
& + a_7 \left[(\boldsymbol{\sigma}_{\gamma}\cdot\hat{\boldsymbol{k}}_{\gamma})((\boldsymbol{\sigma}_{\rm n}\cdot\hat{\boldsymbol{k}}_{\gamma})(\hat{\boldsymbol{k}}_{\gamma}\cdot\hat{\boldsymbol{k}}_{\rm n})-\frac{1}{3}(\boldsymbol{\sigma}_{\rm n}\cdot\hat{\boldsymbol{k}}_{\rm n}))\right] \\
& + a_8 \left[(\boldsymbol{\sigma}_{\gamma}\cdot\hat{\boldsymbol{k}}_{\gamma})((\boldsymbol{\sigma}_{\rm n}\cdot\hat{\boldsymbol{k}}_{\rm n})(\hat{\boldsymbol{k}}_{\gamma}\cdot\hat{\boldsymbol{k}}_{\rm n})-\frac{1}{3}(\boldsymbol{\sigma}_{\rm n}\cdot\hat{\boldsymbol{k}}_{\gamma}))\right] \\
& + a_9 \left[\boldsymbol{\sigma}_{\rm n}\cdot\hat{\boldsymbol{k}}_{\gamma}\right] \\
& + a_{10} \left[\boldsymbol{\sigma}_{\rm n}\cdot\hat{\boldsymbol{k}}_{\rm n}\right] \\
& + a_{11} \left[(\boldsymbol{\sigma}_{\rm n}\cdot\hat{\boldsymbol{k}}_{\gamma})(\hat{\boldsymbol{k}}_{\rm n}\cdot\hat{\boldsymbol{k}}_{\gamma})-\frac{1}{3}(\boldsymbol{\sigma}_{\rm n}\cdot\hat{\boldsymbol{k}}_{\rm n})\right] \\
& + a_{12} \left[(\boldsymbol{\sigma}_{\rm n}\cdot\hat{\boldsymbol{k}}_{\rm n})(\hat{\boldsymbol{k}}_{\rm n}\cdot\hat{\boldsymbol{k}}_{\gamma})-\frac{1}{3}(\boldsymbol{\sigma}_{\rm n}\cdot\hat{\boldsymbol{k}}_{\gamma})\right] \\
& + a_{13} \left[(\boldsymbol{\sigma}_{\gamma}\cdot\hat{\boldsymbol{k}}_{\gamma})\right] \\
& + a_{14} \left[(\boldsymbol{\sigma}_{\gamma}\cdot\hat{\boldsymbol{k}}_{\gamma})(\hat{\boldsymbol{k}}_{\rm n}\cdot\hat{\boldsymbol{k}}_{\gamma})\right] \\
& + a_{15} \left[(\boldsymbol{\sigma}_{\gamma}\cdot\hat{\boldsymbol{k}}_{\gamma})(\boldsymbol{\sigma}_{\rm n}\cdot(\hat{\boldsymbol{k}}_{\rm n}\times\hat{\boldsymbol{k}}_{\gamma}))\right] \\
& + a_{16} \left[(\boldsymbol{\sigma}_{\gamma}\cdot\hat{\boldsymbol{k}}_{\gamma})((\hat{\boldsymbol{k}}_{\rm n}\cdot\hat{\boldsymbol{k}}_{\gamma})^2-\frac{1}{3})\right] \\
& + a_{17} \left[(\boldsymbol{\sigma}_{\gamma}\cdot\hat{\boldsymbol{k}}_{\gamma})(\hat{\boldsymbol{k}}_{\rm n}\cdot\hat{\boldsymbol{k}}_{\gamma})(\boldsymbol{\sigma}_{\rm n}\cdot(\hat{\boldsymbol{k}}_{\rm n}\times\hat{\boldsymbol{k}}_{\gamma}))\right]
\end{aligned}
$$

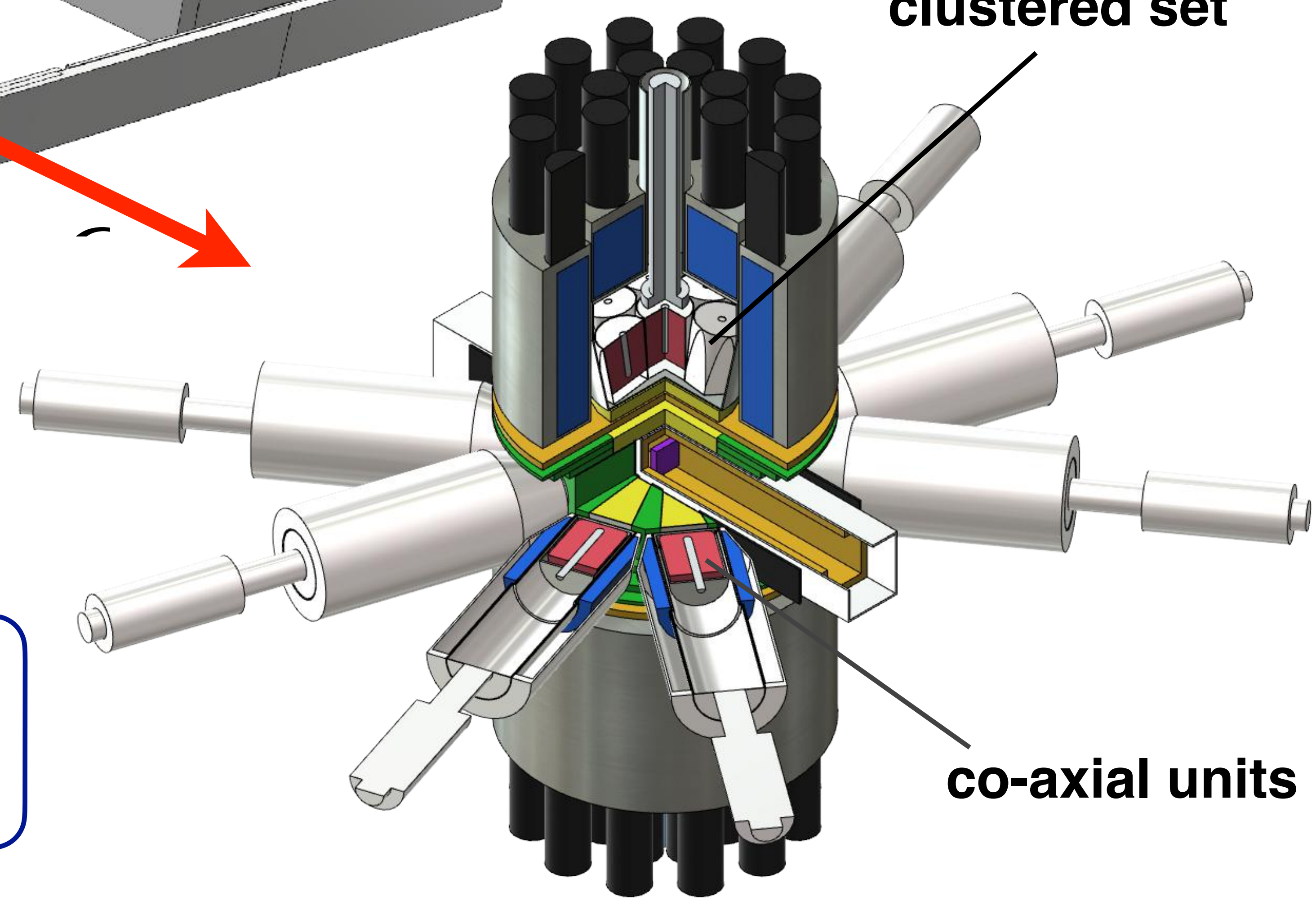
$$
\begin{aligned}
a_0 &= \sum_{J_{\rm s}}|V_1(J_{\rm s})|^2+\sum_{J_{\rm s},j}|V_2(J_{\rm p}j)|^2 \\
a_1 &= 2{\rm Re}\sum_{J_{\rm s},J_{\rm p},j}V_1(J_{\rm s})V_2^*(J_{\rm p}j)P(J_{\rm s}J_{\rm p}\tfrac{1}{2}j1IF) \\
a_2 &= -2{\rm Im}\sum_{J_{\rm s},J_{\rm p},j}V_1(J_{\rm s})V_2^*(J_{\rm p}j)\beta_jP(J_{\rm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

Detailed Study of Entrance Channel

BL04 ANNRI

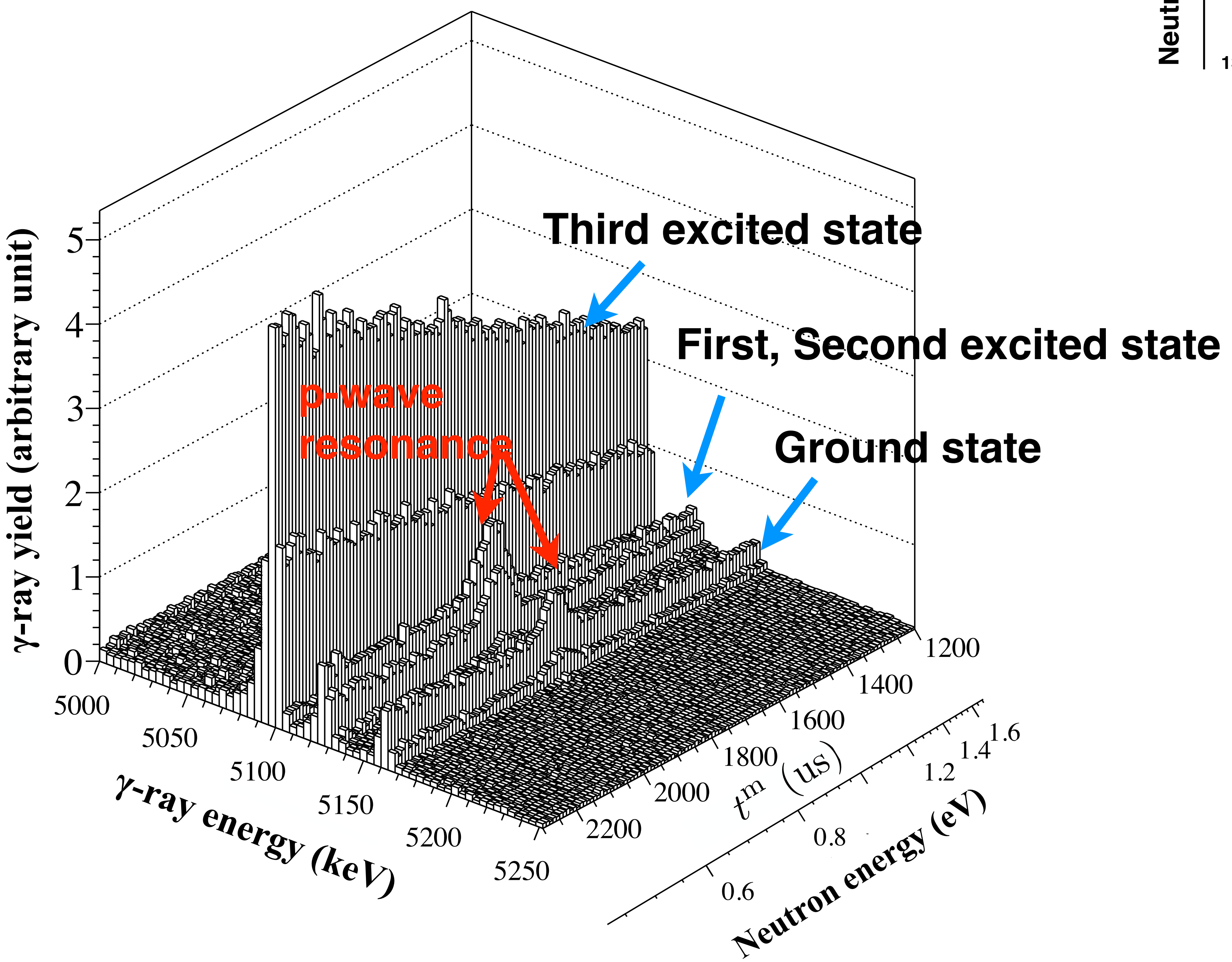


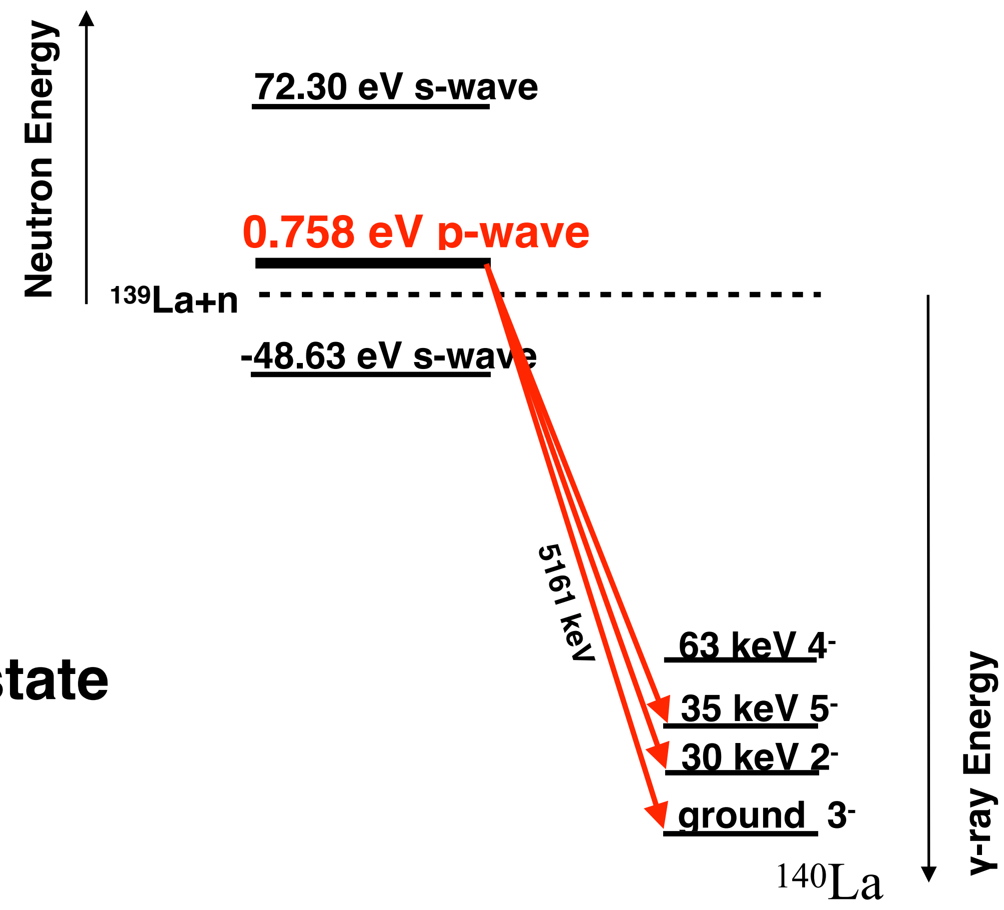
Ge detector

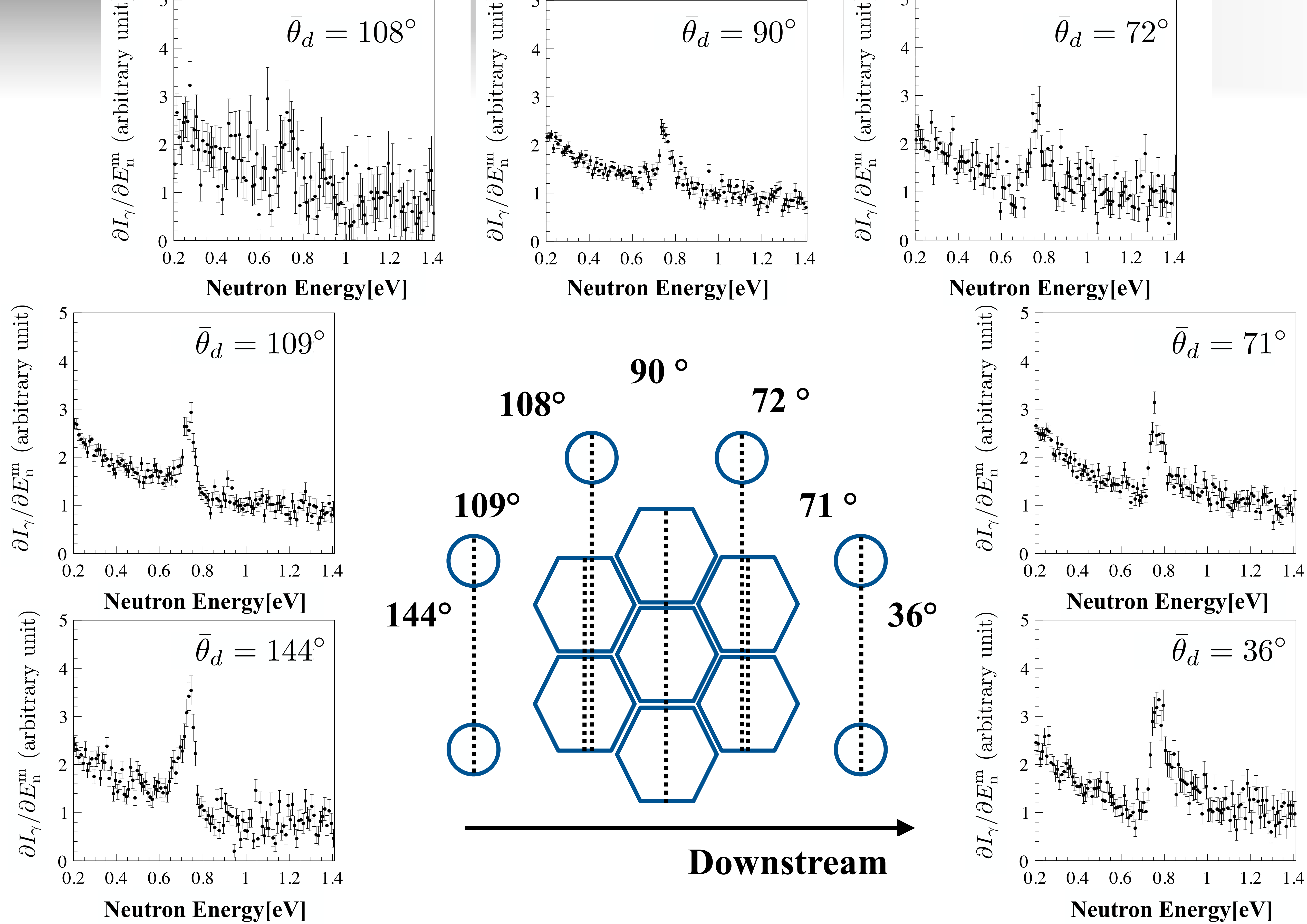


2 clustered sets	7ch ×2 : 14ch
8 coaxial units	8ch
Total 22ch	

Detailed Study of Entrance Channel





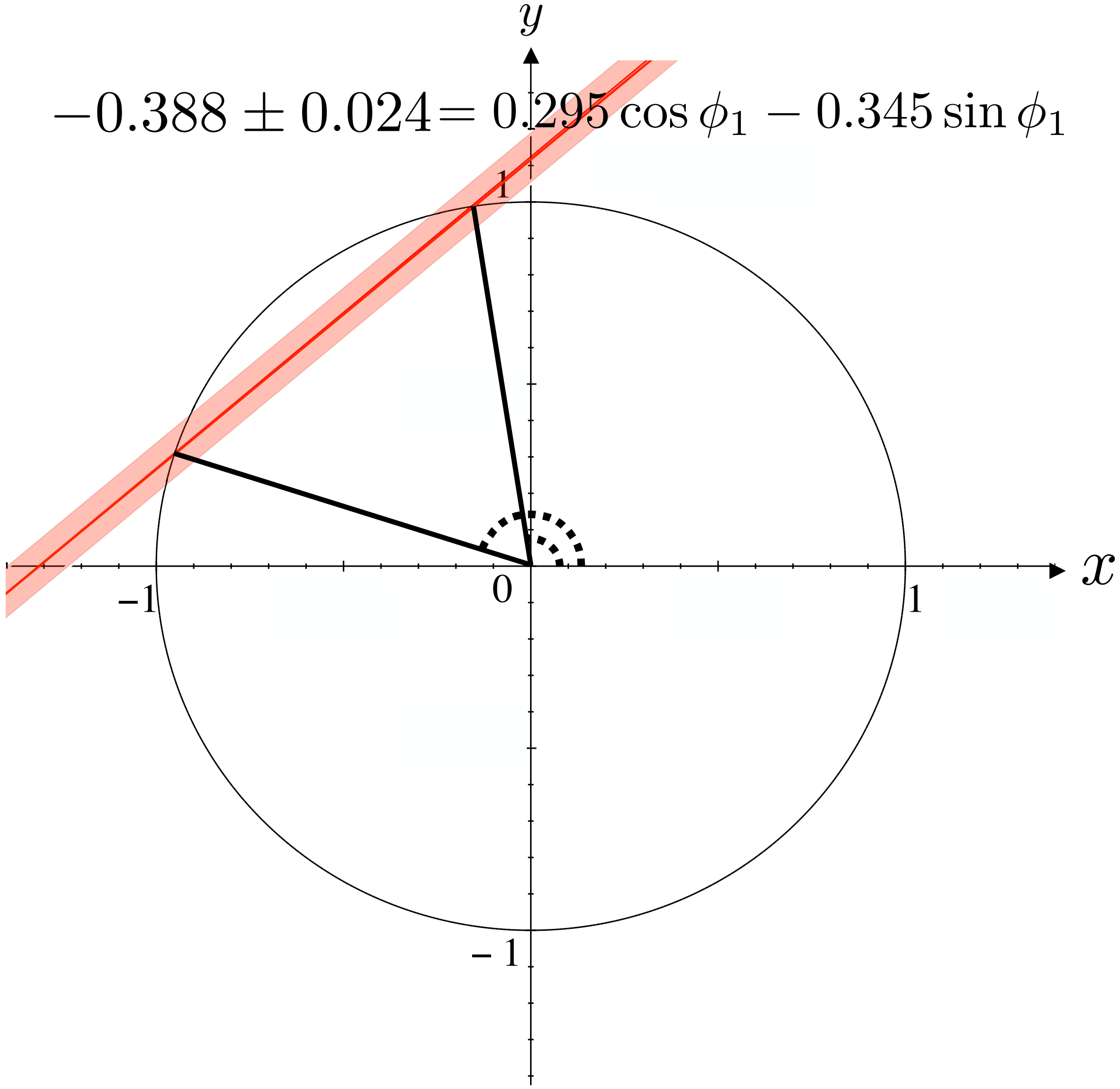

$\bar{\theta}_d = 108^\circ$
$\bar{\theta}_d = 90^\circ$
$\bar{\theta}_d = 72^\circ$
$\bar{\theta}_d = 109^\circ$
$\bar{\theta}_d = 71^\circ$
$\bar{\theta}_d = 144^\circ$
$\bar{\theta}_d = 36^\circ$
$\partial I_\gamma / \partial E_n^m$ (arbitrary unit)
Neutron Energy[eV]
90 °
108°
72 °
109°
71 °
144°
36°
Downstream

Detailed Study of Entrance Channel

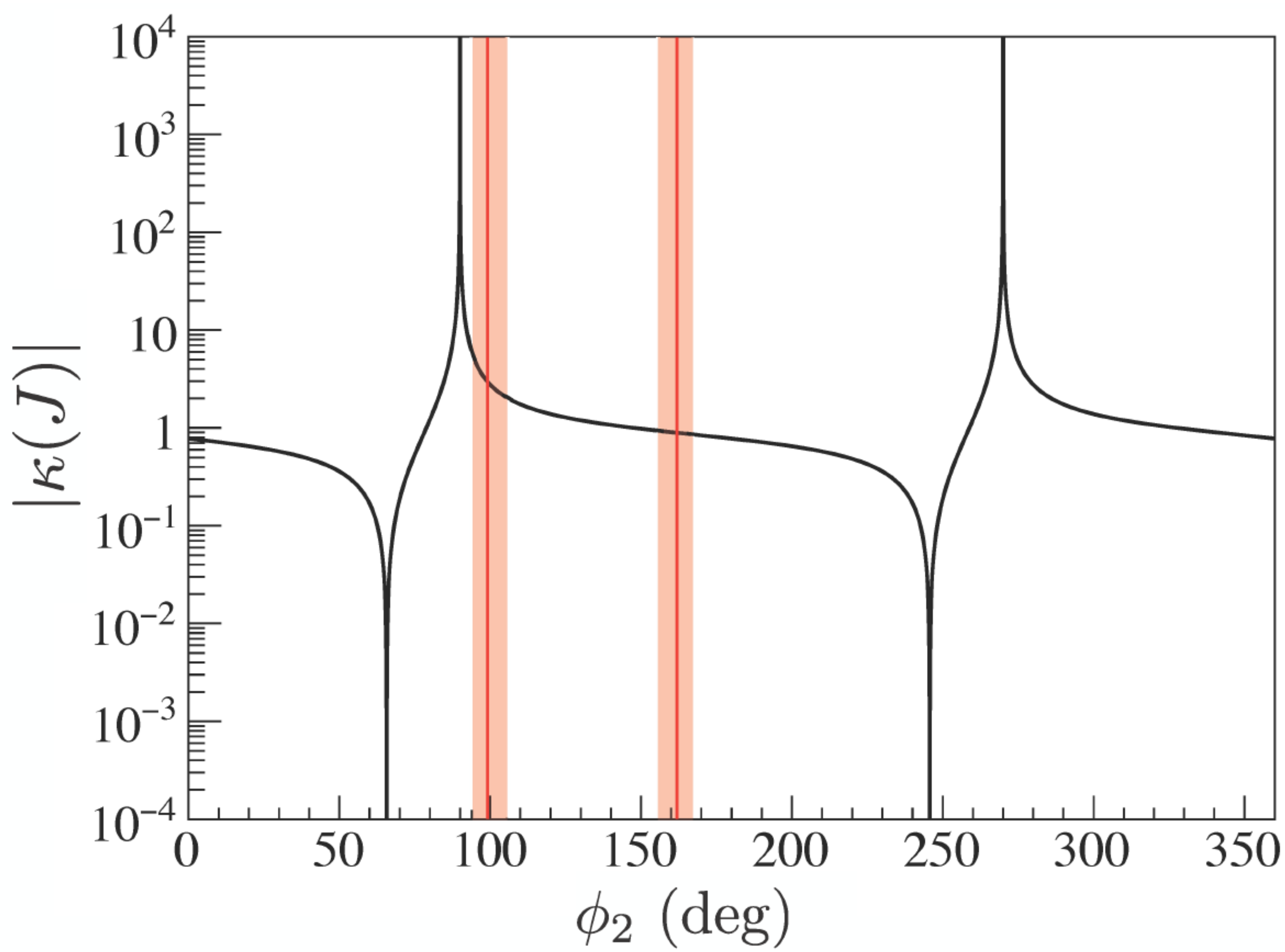
$$\frac{d\sigma_{n\gamma}}{d\Omega_\gamma} = \frac{1}{2}\left(a_0 + a_1 \cos\theta_\gamma + a_3(\cos^2\theta_\gamma - \frac{1}{3})\right)$$

Okudaira et al., PRC97(2018)034622

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



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

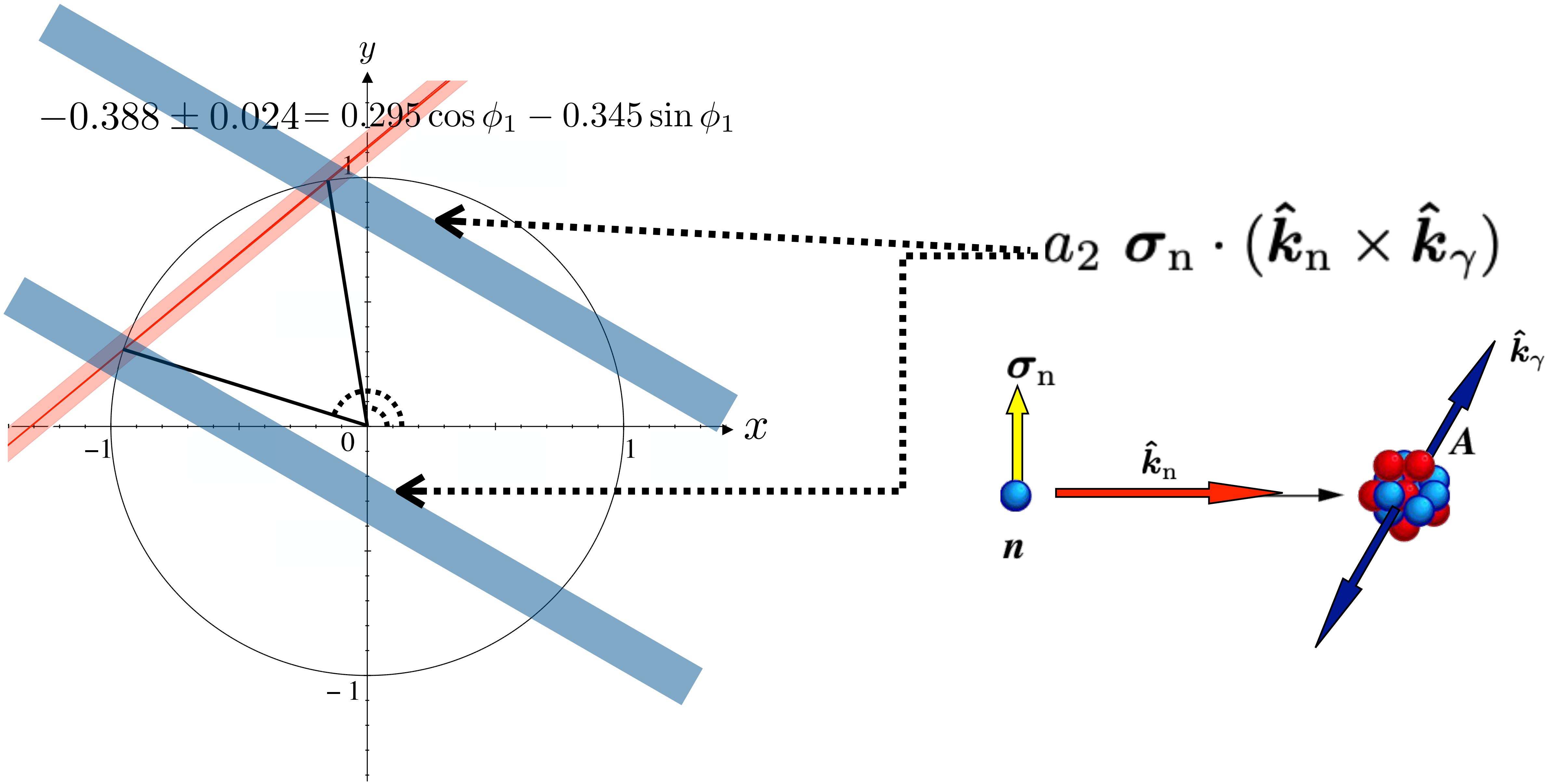


$$\phi_2 = (99.2^{+6.3}_{-5.3})^\circ, \quad (161.9^{+5.3}_{-6.3})^\circ$$

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

Detailed Study of Entrance Channel

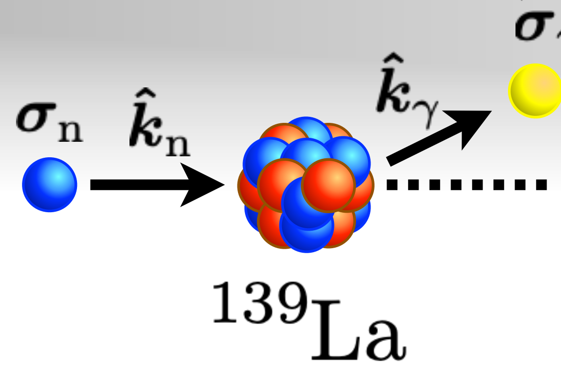
$$\frac{d\sigma_{n\gamma}}{d\Omega_\gamma} = \frac{1}{2}\left(a_0 + a_1\cos\theta_\gamma + a_3(\cos^2\theta_\gamma - \frac{1}{3})\right)$$

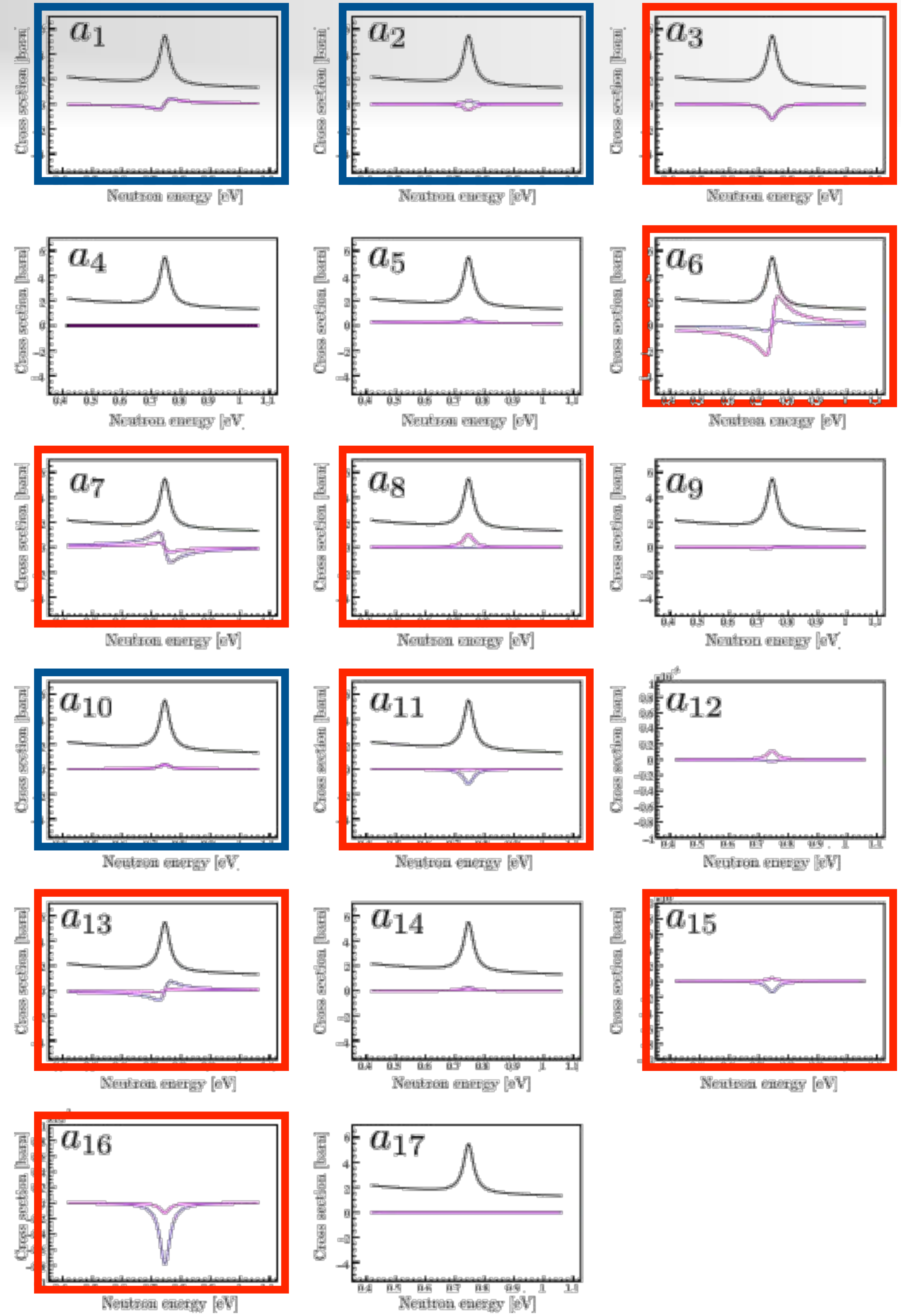


$$\phi_2 = (99.2^{+6.3}_{-5.3})^\circ, \quad (161.9^{+5.3}_{-6.3})^\circ$$

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

$$
\begin{aligned}
2\frac{d\sigma}{d\Omega} = \; & a_0 \\
& + a_1 \left[\hat{\boldsymbol{k}}_n \cdot \hat{\boldsymbol{k}}_\gamma\right] \\
& + a_2 \left[\boldsymbol{\sigma}_n \cdot (\hat{\boldsymbol{k}}_n \times \hat{\boldsymbol{k}}_\gamma)\right] \\
& + a_3 \left[(\hat{\boldsymbol{k}}_n \cdot \hat{\boldsymbol{k}}_\gamma)^2 - \frac{1}{3}\right] \\
& + a_4 \left[(\hat{\boldsymbol{k}}_n \cdot \hat{\boldsymbol{k}}_\gamma)(\boldsymbol{\sigma}_n \cdot (\hat{\boldsymbol{k}}_n \times \hat{\boldsymbol{k}}_\gamma))\right] \\
& + a_5 \left[(\boldsymbol{\sigma}_\gamma \cdot \hat{\boldsymbol{k}}_\gamma)(\boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{k}}_\gamma)\right] \\
& + a_6 \left[(\boldsymbol{\sigma}_\gamma \cdot \hat{\boldsymbol{k}}_\gamma)(\boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{k}}_n)\right] \\
& + a_7 \left[(\boldsymbol{\sigma}_\gamma \cdot \hat{\boldsymbol{k}}_\gamma)((\boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{k}}_\gamma)(\hat{\boldsymbol{k}}_\gamma \cdot \hat{\boldsymbol{k}}_n) - \frac{1}{3}(\boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{k}}_n))\right] \\
& + a_8 \left[(\boldsymbol{\sigma}_\gamma \cdot \hat{\boldsymbol{k}}_\gamma)((\boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{k}}_n)(\hat{\boldsymbol{k}}_\gamma \cdot \hat{\boldsymbol{k}}_n) - \frac{1}{3}(\boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{k}}_\gamma))\right] \\
& + a_9 \left[\boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{k}}_\gamma\right] \\
& + a_{10} \left[\boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{k}}_n\right] \\
& + a_{11} \left[(\boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{k}}_\gamma)(\hat{\boldsymbol{k}}_n \cdot \hat{\boldsymbol{k}}_\gamma) - \frac{1}{3}(\boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{k}}_n)\right] \\
& + a_{12} \left[(\boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{k}}_n)(\hat{\boldsymbol{k}}_n \cdot \hat{\boldsymbol{k}}_\gamma) - \frac{1}{3}(\boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{k}}_\gamma)\right] \\
& + a_{13} \left[(\boldsymbol{\sigma}_\gamma \cdot \hat{\boldsymbol{k}}_\gamma)\right] \\
& + a_{14} \left[(\boldsymbol{\sigma}_\gamma \cdot \hat{\boldsymbol{k}}_\gamma)(\hat{\boldsymbol{k}}_n \cdot \hat{\boldsymbol{k}}_\gamma)\right] \\
& + a_{15} \left[(\boldsymbol{\sigma}_\gamma \cdot \hat{\boldsymbol{k}}_\gamma)(\boldsymbol{\sigma}_n \cdot (\hat{\boldsymbol{k}}_n \times \hat{\boldsymbol{k}}_\gamma))\right] \\
& + a_{16} \left[(\boldsymbol{\sigma}_\gamma \cdot \hat{\boldsymbol{k}}_\gamma)((\hat{\boldsymbol{k}}_n \cdot \hat{\boldsymbol{k}}_\gamma)^2 - \frac{1}{3})\right] \\
& + a_{17} \left[(\boldsymbol{\sigma}_\gamma \cdot \hat{\boldsymbol{k}}_\gamma)(\hat{\boldsymbol{k}}_n \cdot \hat{\boldsymbol{k}}_\gamma)(\boldsymbol{\sigma}_n \cdot (\hat{\boldsymbol{k}}_n \times \hat{\boldsymbol{k}}_\gamma))\right]
\end{aligned}
$$

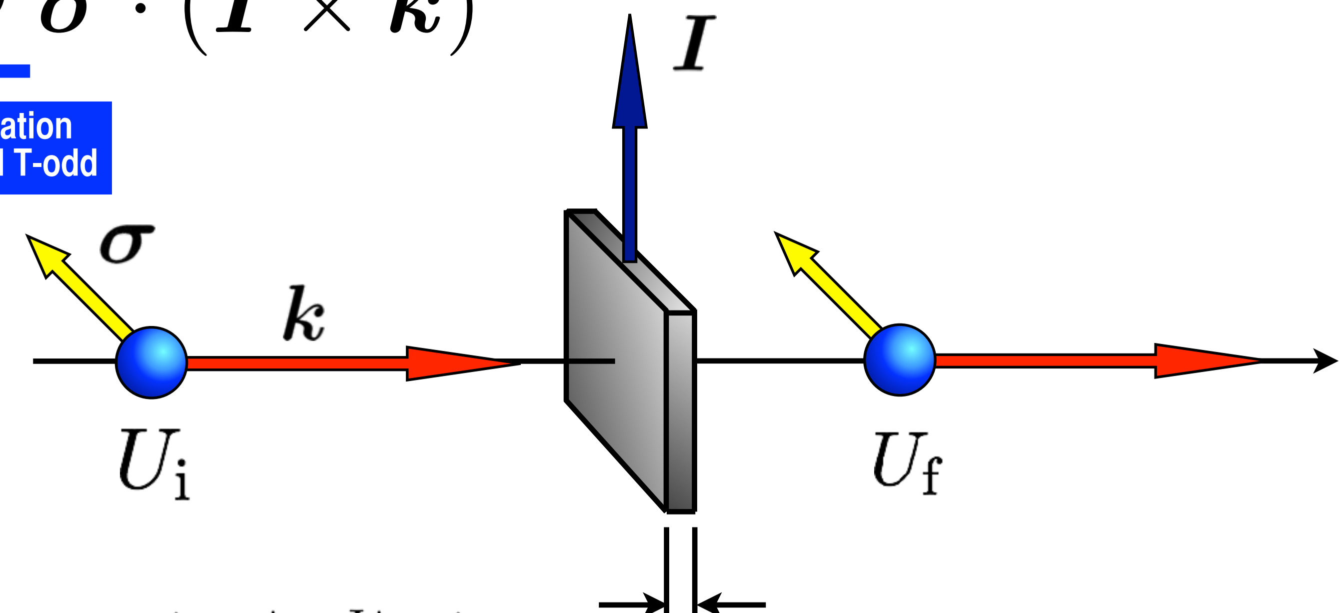




Pseudomagnetism

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

- A': Spin Independent, P-even T-even
- B': Spin Dependent, P-even T-even
- C': P-violation, P-odd T-even
- D': T-violation, P-odd T-odd



pseudomagnetism

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

$$f_\mu = \frac{i}{2k}\sum_{JlSS'M_I}(2l+1)\langle s\mu IM_I|S'm_s'\rangle\langle S'm_s'l0|JM\rangle\langle S'l|R^J|Sl\rangle\langle JM|Sm_sl0\rangle\langle Sm_s|s\mu IM_I\rangle\,.$$

$$\langle S_K'l_K|R^{J_K}|S_Kl_K\rangle = i\frac{\sqrt{\Gamma^{\rm n}_{l_K}(S_K')}\sqrt{\Gamma^{\rm n}_{l_K}(S_K)}}{E-E_K+i\Gamma_K/2}e^{i(\delta_{l_K}(S_K')+\delta_{l_K}(S_K))} - 2ie^{i\delta_{l_K}(S_KS_K')}\sin\delta_{l_K}(S_KS_K')$$

compound resonance — potential scattering

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

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

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

T-violation in Compound Nuclear States

A' — P-even T-even

$$\frac{d\sigma_{n\gamma}}{d\Omega_\gamma}(E_n)$$

polarized neutron

C' $(\boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{k}}_n)$ — P-odd T-even

$(\vec{n},\gamma)(n,\vec{\gamma})(\vec{n},\vec{\gamma})$

$$\frac{d\sigma_{\vec{n}\gamma}}{d\Omega_\gamma}(E_n)$$

10^6 enhancement in compound nuclear state

polarized target

B' $(\boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{I}})$ — P-even T-even

D' $\boldsymbol{\sigma}_n \cdot (\hat{\boldsymbol{k}}_n \times \hat{\boldsymbol{I}})$ — P-odd T-odd

10^6 enhancement in compound nuclear state

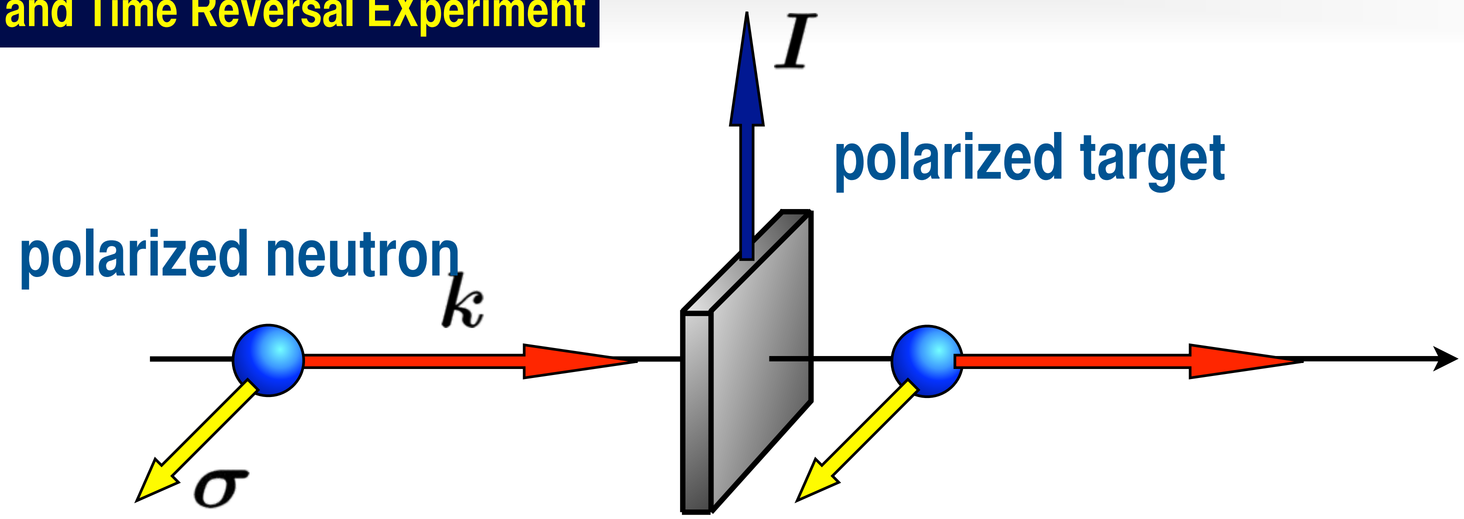
J-PARC P76

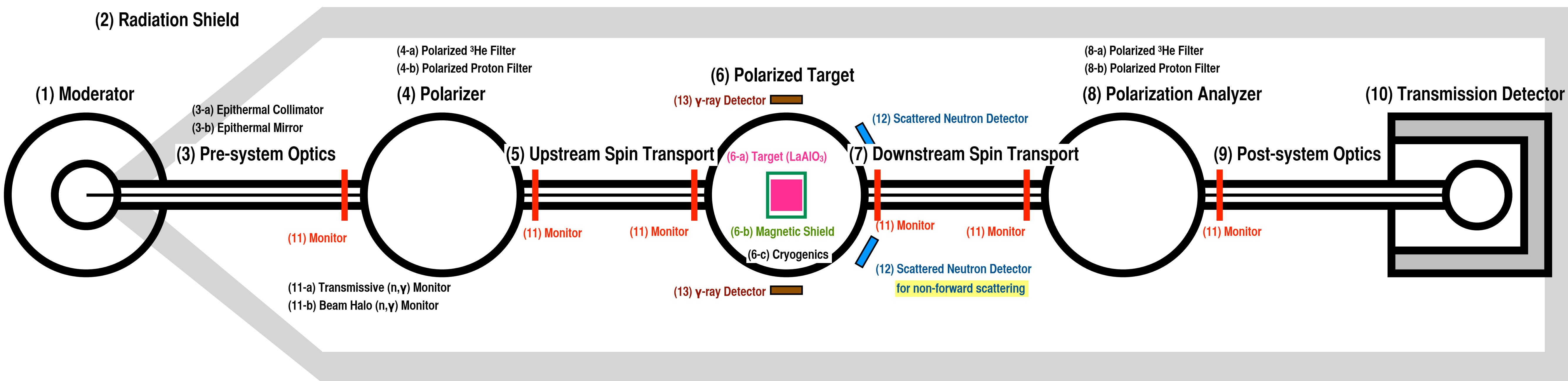
NOPTREX Collaboration

Neutron Optical Parity and Time Reversal EXperiment

BL07 (NOPTREX)

KEK 2018S12





J-PARC P76

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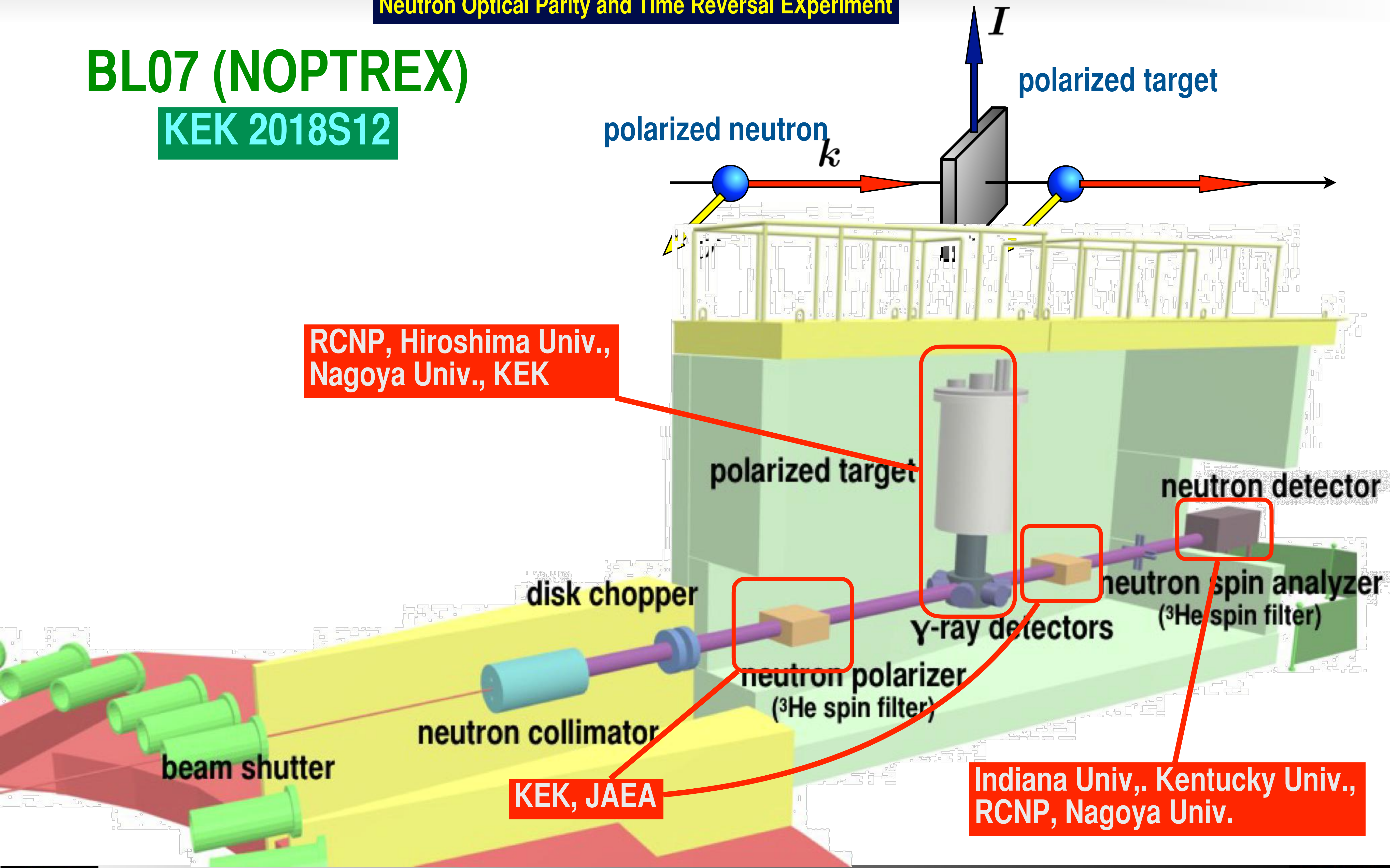
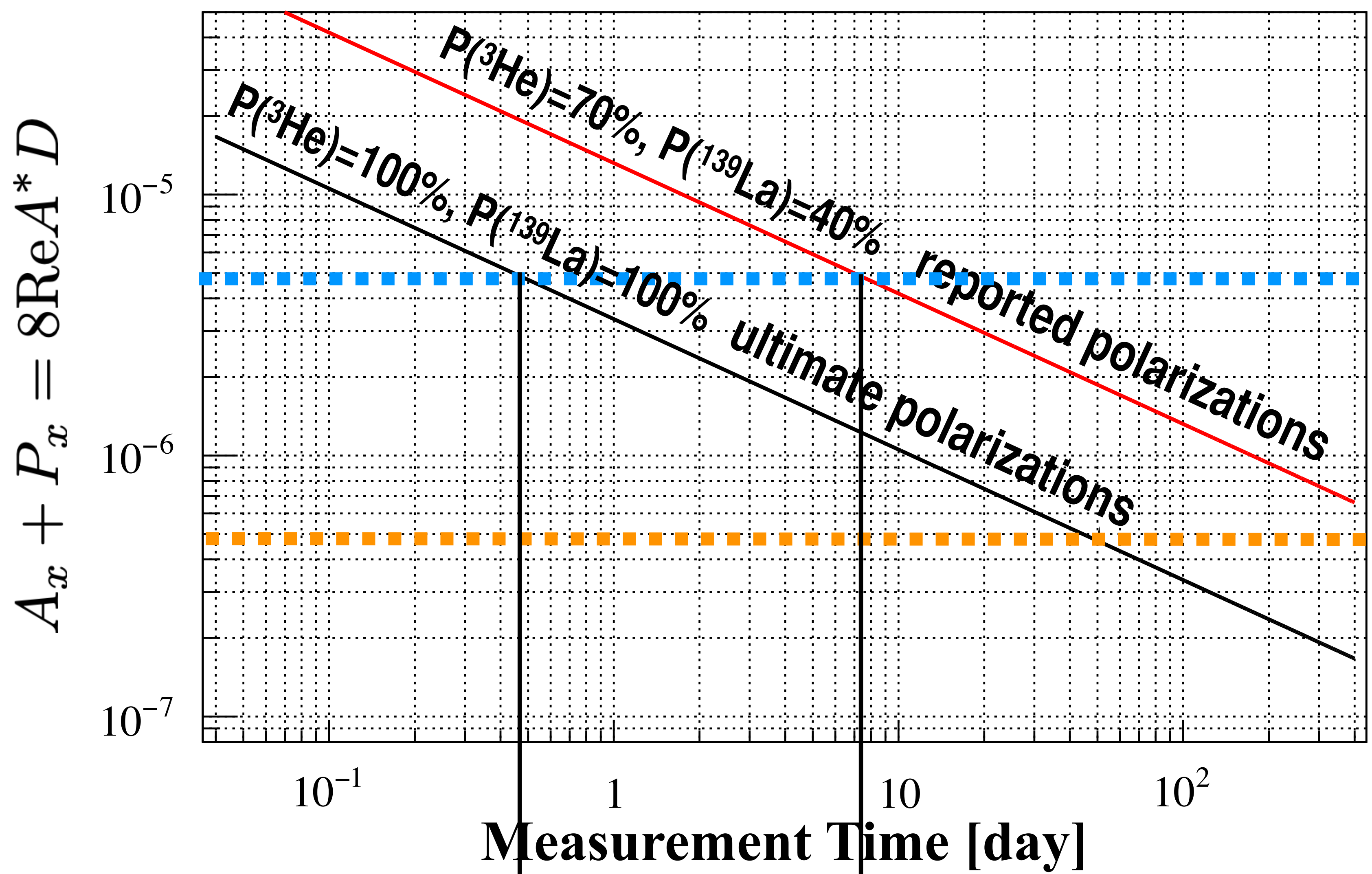


$\overrightarrow{^{139}\mathrm{La}}$ $\mathrm{LaAlO_3}$

P(^{139}La)≥0.4, V≥4cm×4cm×2.8cm
B_0≤0.1T

$$\left|\frac{\langle W_T \rangle}{\langle W \rangle}\right| < 3.9 \times 10^{-4}$$

$$8\mathrm{Re}A^* D = 5.3 \times 10^{-5}$$

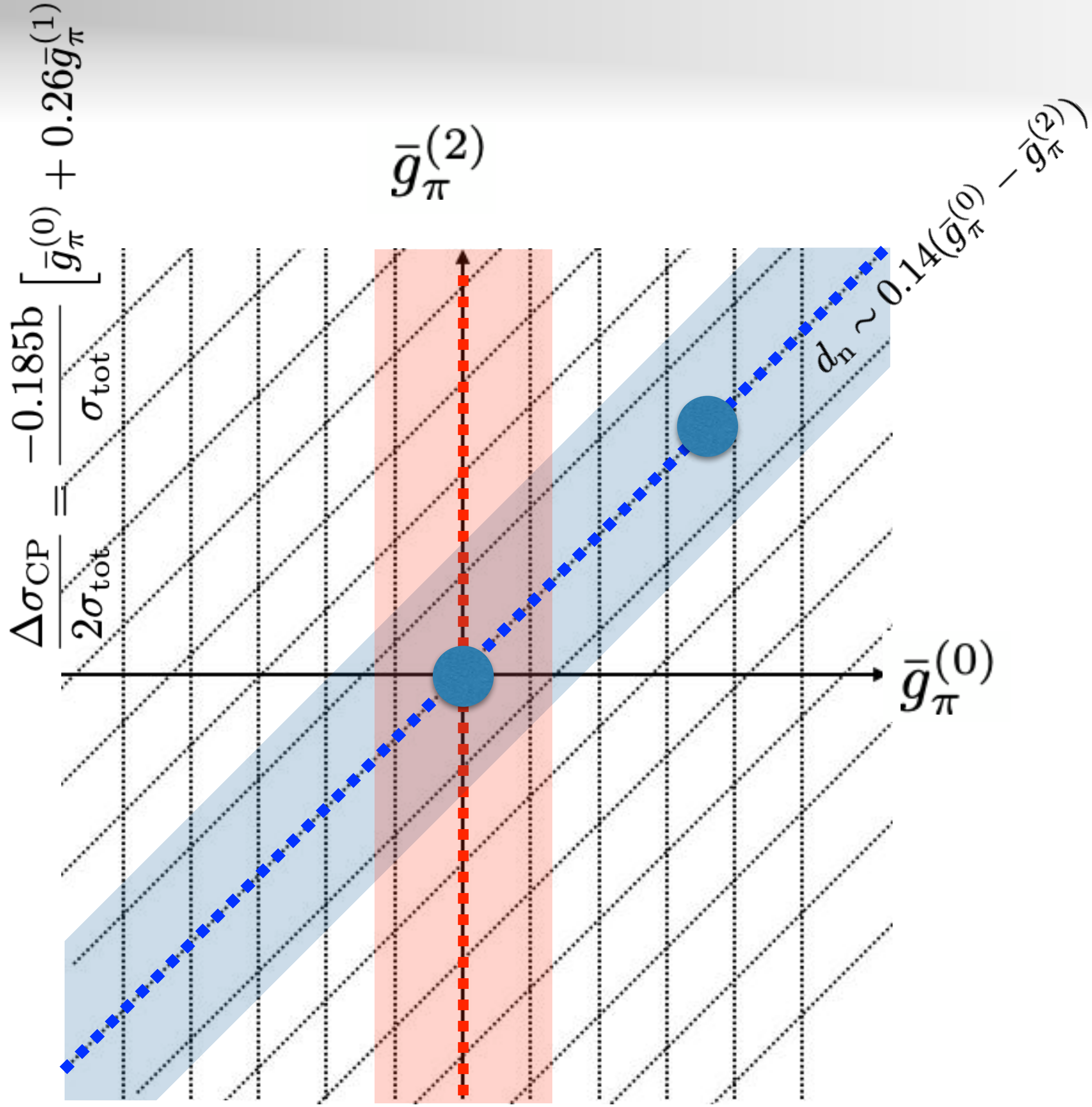


discovery potential corresponding to d_n =3.0×10^{-26} e cm

discovery potential corresponding to d_n =3.0×10^{-27} e cm

with reported polarizations reaches to the discovery potential in a week

with ultimate polarizations reaches the discovery potential in a day


$\frac{\Delta\sigma_{\mathrm{CP}}}{2\sigma_{\mathrm{tot}}} = \frac{-0.185\mathrm{b}}{\sigma_{\mathrm{tot}}}\left[\bar{g}_\pi^{(0)} + 0.26\bar{g}_\pi^{(1)}\right]$
$\bar{g}_\pi^{(2)}$
$d_{\mathrm{n}} \sim 0.14(\bar{g}_\pi^{(0)} - \bar{g}_\pi^{(2)})$
$\bar{g}_\pi^{(0)}$

Summary

10^6 Enhancement of P-violation

Interference between s- and p-waves in the entrance channel

Statistical nature of compound nuclear states

→ Reaction mechanism

direct process and compound process

(kinetic freedom dissipation → quantum decoherence?)

Polarized target and spin control in it

↓

New physics search with enhanced sensitivity to T-violation

Summary

10^6 Enhancement of P-violation

Interference between s- and p-waves in the entrance channel

★ Statistical nature of compound nuclear states

→ Reaction mechanism

direct process and compound process

(kinetic freedom dissipation → quantum decoherence?)

★ Polarized target and spin control in it

↓

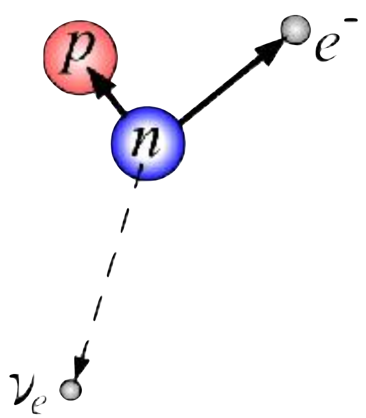
New physics search with enhanced sensitivity to T-violation

Physics using Slow Neutrons


M.Kitaguchi H.M.Shimizu

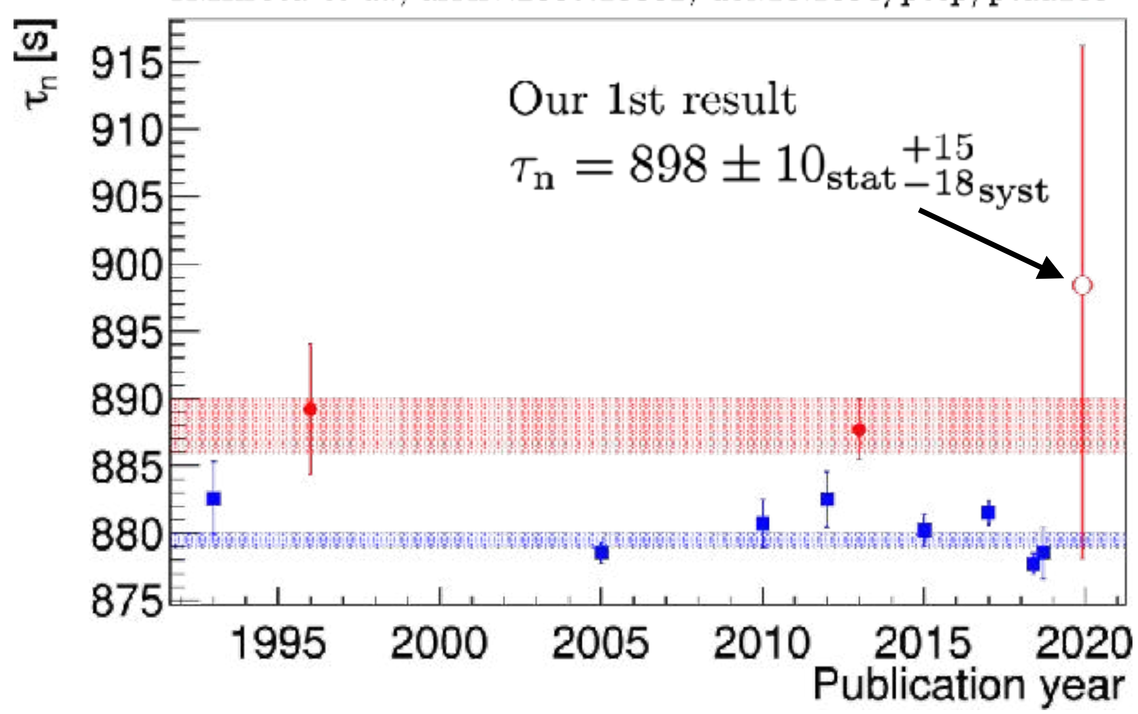
Neutron Lifetime

New type of in-beam measurement with pulsed neutrons



- CKM Unitarity check
- Big Bang Nucleosynthesis
- Decay to dark channel?

K.Hirota *et al.*, arXiv:2007.15302, doi:10.1093/ptep/ptaa169

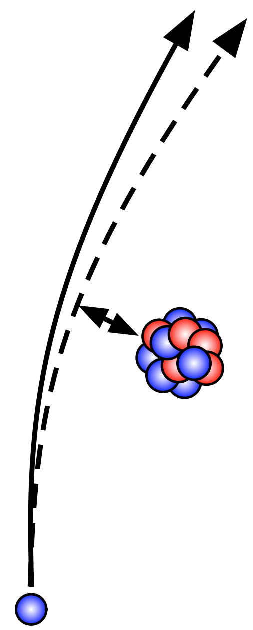


upgrade with enlarged acceptance is in progress

2021-: $\Delta\tau_n \leq 1$s

New Force Search

New limit on Yukawa-type medium-range force by scattering



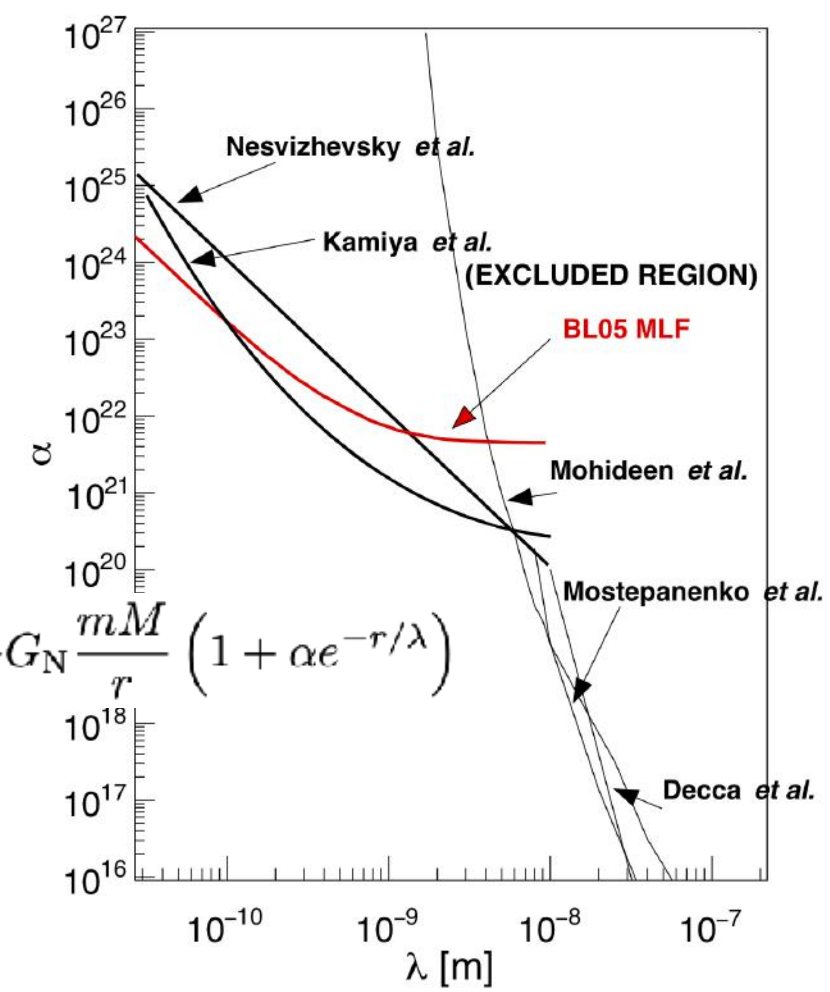
Extra-dimension?

New gauge boson coupled to mass?

C.C.Haddock *et al.*, Phys. Rev. D97, 062002 (2018)

Highlighted in APS

(https://physics.aps.org/synopsis-for/10.1103/PhysRevD.97.062002)



$$V(r) = -G_N \frac{mM}{r}\left(1 + \alpha e^{-r/\lambda}\right)$$

upgrade by new target of nano-particles
and large area detector is in progress

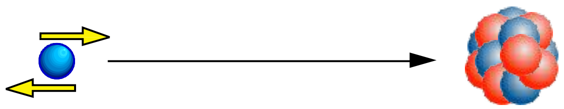
2021-: improve the upper limit of α

Physics using Slow Neutrons


M.Kitaguchi H.M.Shimizu

T-violation in Compound Nuclei

Enhanced symmetry violation in neutron resonance capture reactions



P-violation is 10^6 times enhanced in ^{139}La+n (E_n=0.74eV)

KEK 2018S12, J-PARC P76

NOPTREX Collaboration

Neutron Optical Parity and Time-Reversal EXperiment

suggesting discovery potential comparable with neutron EDM

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

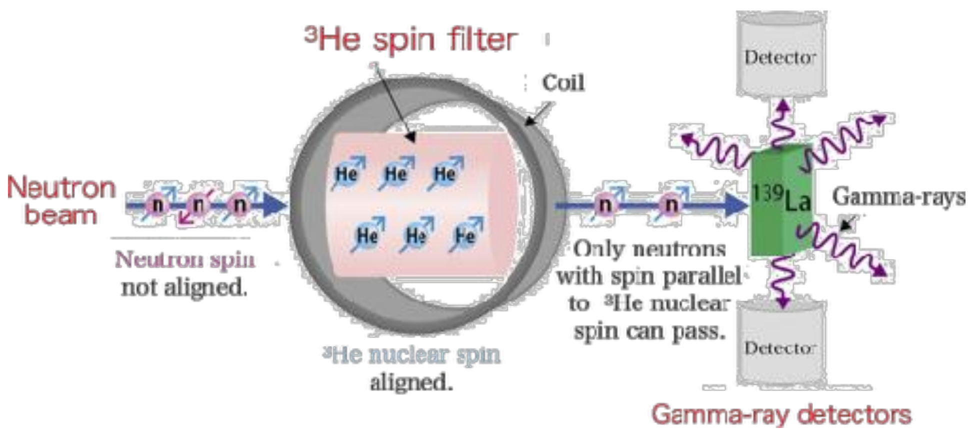
$$\Delta\sigma_{\mathrm{T}} = \kappa(J)\frac{W_{\mathrm{T}}}{W}\Delta\sigma_{\mathrm{P}}$$

$$\kappa(J) = 0.99^{+0.88}_{-0.07}, 4.84^{+5.58}_{1.69}$$

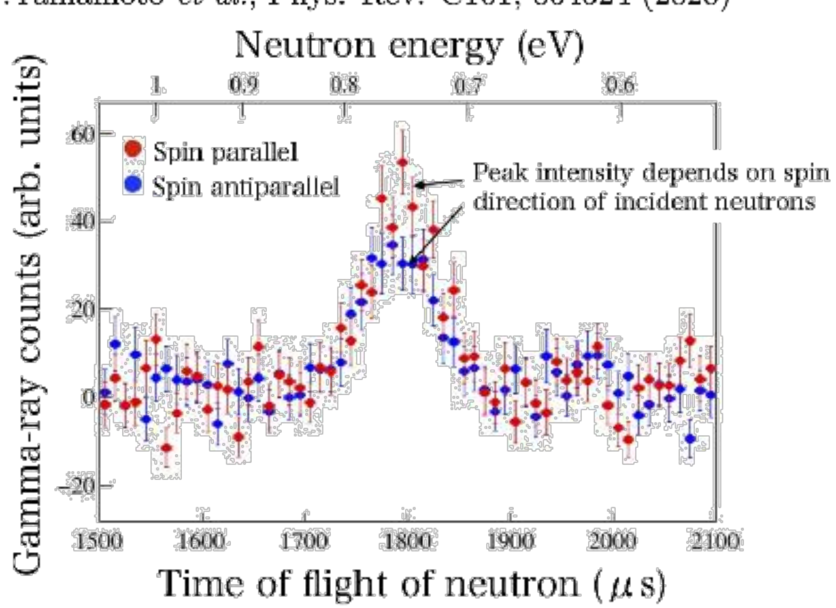
^{139}La resonance 30 days at J-PARC ⟷ Neutron EDM 10^{-26} e cm

NOPTREX Collaboration

Further study of reaction mechanism using polarized epithermal neutrons



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



Development of Polarized Nuclear Target

Crystal Growth IMR, Tohoku Univ.


Dynamical enhancement of lanthanum polarization has been identified in $LaAlO_3$. (Dec.2020)

IMR, Tohoku Univ.
Hiroshima Univ.
Nagoya Univ.

Enhancement of Nuclear Polarization
RCNP, Osaka Univ.


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

Polarized Lanthanum Target

$LaAlO_3$ single crystal doped with neodymium

Cryogenics

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

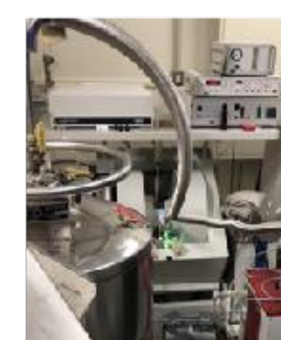
Development of very-low temperature and very-high cooling power cryostat

Control of Spin-lattice Relaxation Time

Natural Science Center for Basic Research and Development, Hiroshima Univ.

Hiroshima Univ.
Nagoya Univ.

Control of spin-lattice relaxation time using meta-stable state of aromatic molecules by laser irradiation

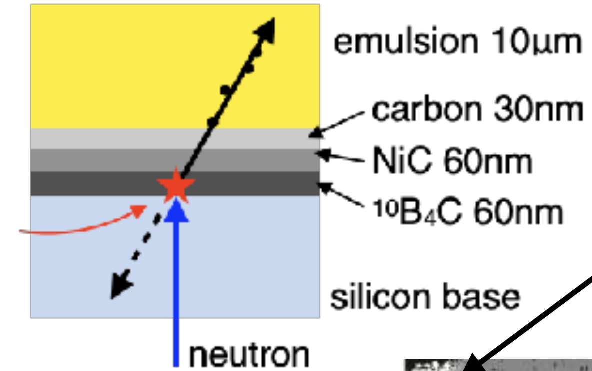


2021-: Polarized La target → Spin control technique → T-violation Search

Nuclear Emulsion for Neutron Detection

N.Naganawa *et al.*, Eur. Phys. J. C78, 959 (2018)

Fine-grained nuclear emulsion detector with ^{10}B neutron converter as a neutron imager with the position resolution less than **100 nm**.



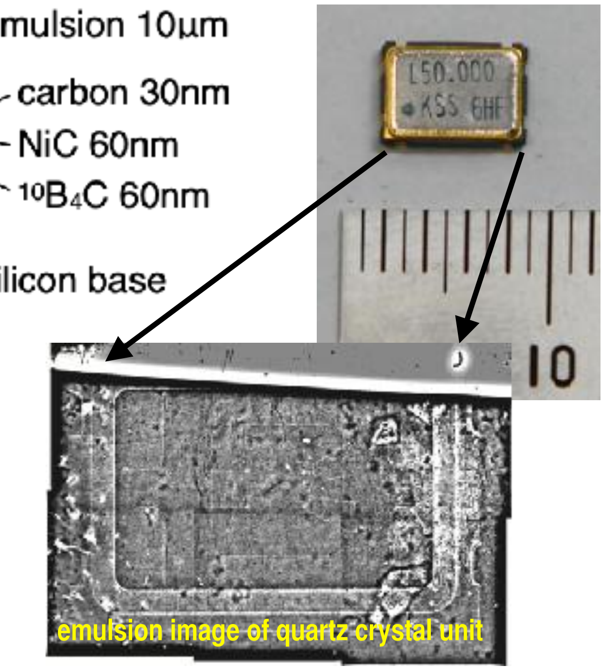
Neutron quantum states in gravitational potential

2021-: beam experiments

Industrial application to obtain neutron image with µm position resolution

K.Hirota *et al.*, submitted to J. Imaging

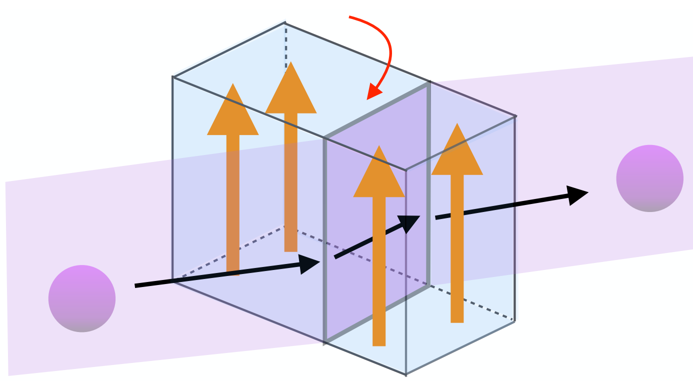
2021-: spread applications



nEDM Search using Extremely Strong Electric Field in Single Crystals

nEDM search of neutron dynamical diffraction in crystals

S.Itoh *et al.*, Nucl. Instrum. Methods A908, 78 (2018)

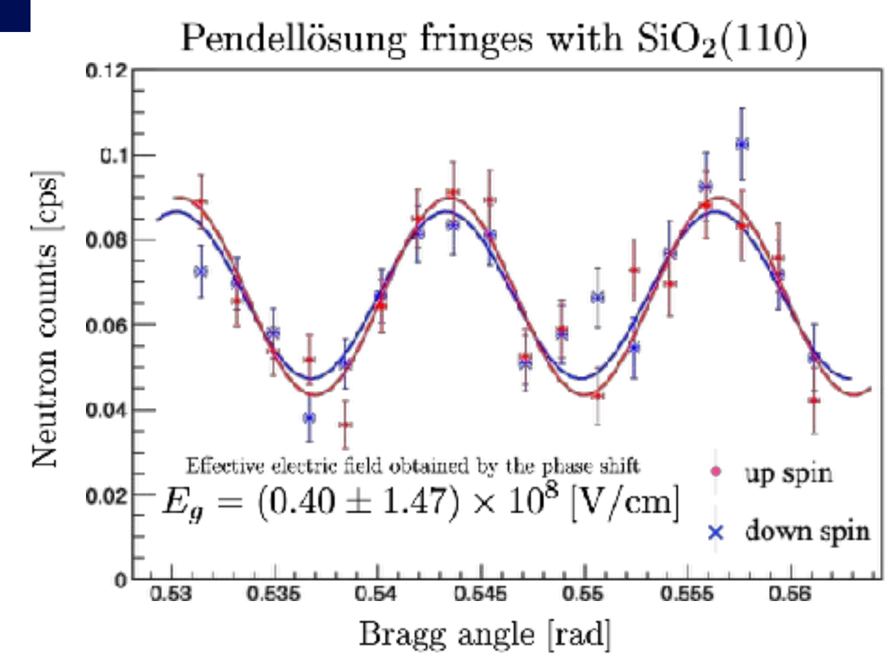


Pendellösung interference fringes

with pulsed neutrons was observed clearly

to be basis of **crystal-EDM technique**.

2021-: measurement of nEDM



Ultra High Precision Machining

Potential search in the vicinity of material surface (dark energy?)

B.Heacock *et al.*, Acta Cryst. A75, 833 (2019)

2021-: dark energy search

Contribution to EDM Search with Confined Ultracold Neutrons at TRIUMF

TUCAN Collaboration

TRIUMF Ultra-Cold Advanced Neutron source

E.Pierre *et al.*, J. Neutron Res. 20, 87 (2018)

S. Ahmed *et. al.* (TUCAN Collaboration), Phys. Rev. C 99, 025503 (2019)

Search for Neutron-Antineutron Oscillation

$$\mathrm{FOM} \equiv \langle NT^2 \rangle$$