



Parity Violation with Neutrons

— Enhanced Discrete Symmetry Breaking in Compound Nuclear States —

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Small admixture of the weak interaction induces parity-violating effects in the nuclear interactions at the level of 10^{-7} relative to the strong interaction. On the other hand, extremely large P-violating effects are observed in helicity-dependent neutron capture reactions. The largely enhanced P-violation effects are observed in p-wave resonances located on tails of neighboring s-wave resonances, which are currently explained as the results of the small energy spacing between partial amplitudes into parity-unfavored compound nuclear states. The reaction mechanism of the neutron capture reactions with large P-violation enhancement, such as $^{139}\text{La}(n,\gamma)^{140}\text{La}$, $^{117}\text{Sn}(n,\gamma)^{118}\text{Sn}$, $^{131}\text{Xe}(n,\gamma)^{132}\text{Xe}$, etc., is being studied by measuring spin-angular correlation terms of emitted gamma-rays, which is, so far, consistent with statistical treatment in compound nuclear states. In this paper, present status and plans of the study of the entrance channel in progress using the pulsed epithermal neutron at the Japan Proton Accelerator Research Complex (J-PARC). The large enhancement is also expected to be applicable to the breaking of time-reversal-invariance, which introduces a new possibility to search for new physics beyond the standard model of elementary particles. An estimation of possible experimental sensitivity to the CP-violation will be also discussed in comparison with the search for the electric dipole moment of neutrons, which are intensively in progress.



Parity Violation with Neutrons

— Enhanced Discrete Symmetry Breaking in Compound Nuclear States —

Experimental Fact

Enhanced P-violating Effects in Compound Nuclear States induced by Epithermal Neutron Absorption

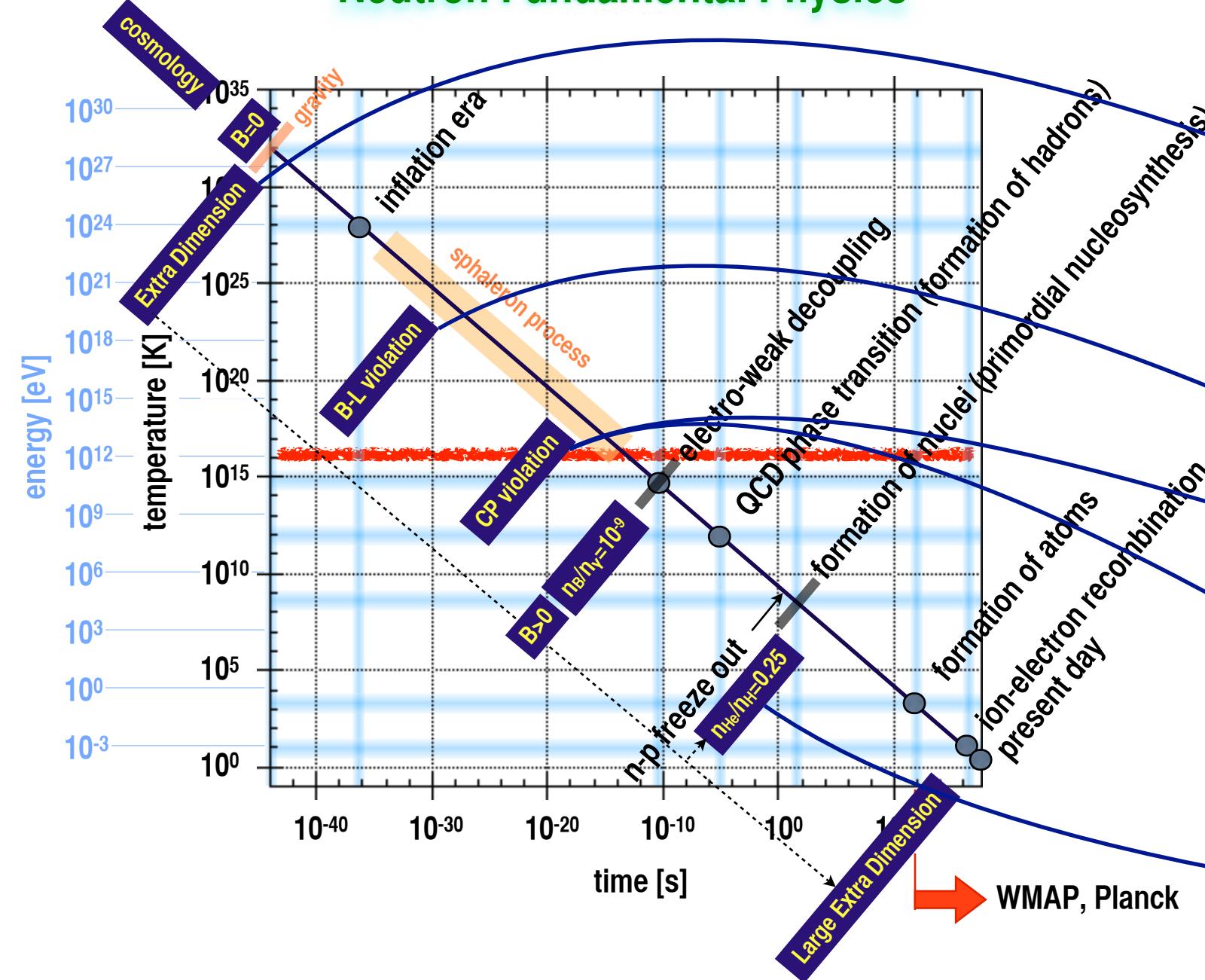


Applicability of the Enhancement Mechanism to T-violation \leftrightarrow CP-violation
to deliver new physics searches in T-violation, complementary to EDM searches
(mostly in P-odd T-odd interactions)

Introduction of Neutron Fundamental Physics in Japan

Neutron Fundamental Physics

searches for new physics
beyond the standard model



new-force search
 (α, λ)

neutron scattering
neutron interferometry
Pendellosung interference
GRANIT

spontaneous transition from neutron to antineutron
 $\tau_{n\bar{n}}$

neutron antineutron oscillation

breaking of time reversal invariance
 d_n

neutron EDM
TUCAN

neutron β -decay
 τ_n

$\bar{g}_{\pi NN}$
epithermal neutron optics
NOPTREX

$$U(r) = \frac{U_0}{r} e^{-r/\lambda}$$

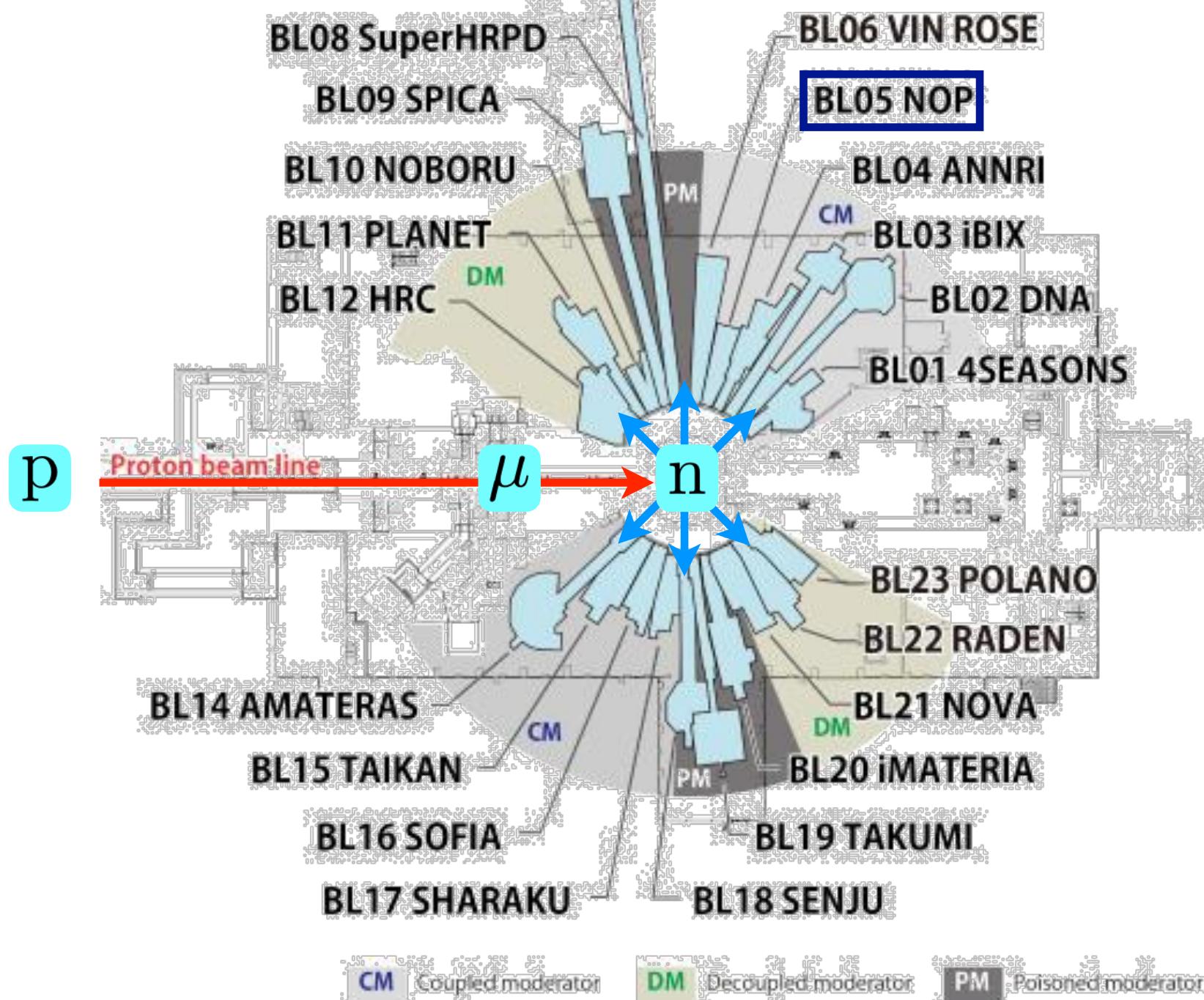
$$\text{Gravity} \quad U_g = \frac{GM}{r} \left(1 + \alpha e^{-r/\lambda} \right)$$

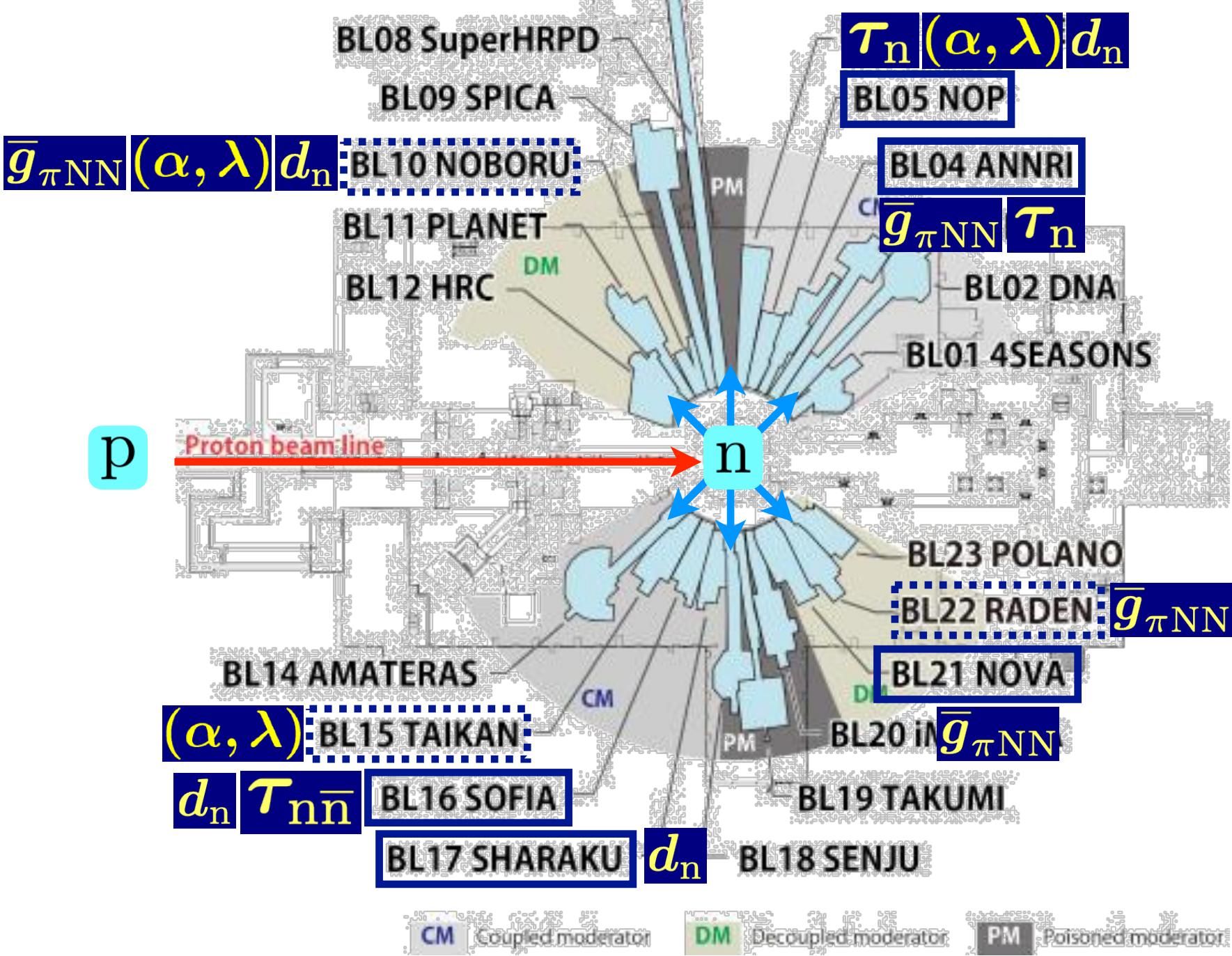
Dark Matter, Dark Energy

J-PARC

Japan Proton
Accelerator
Research
Complex

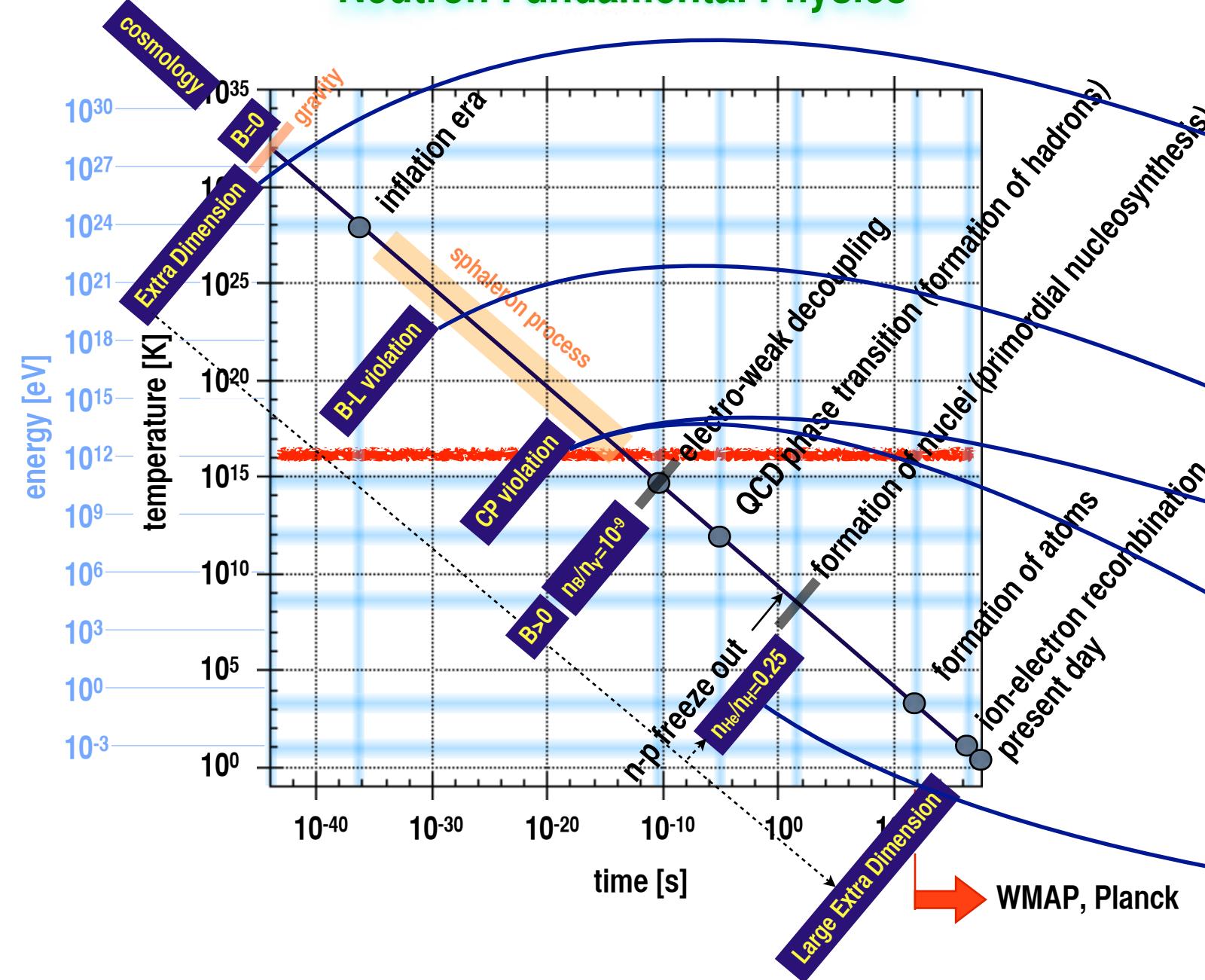




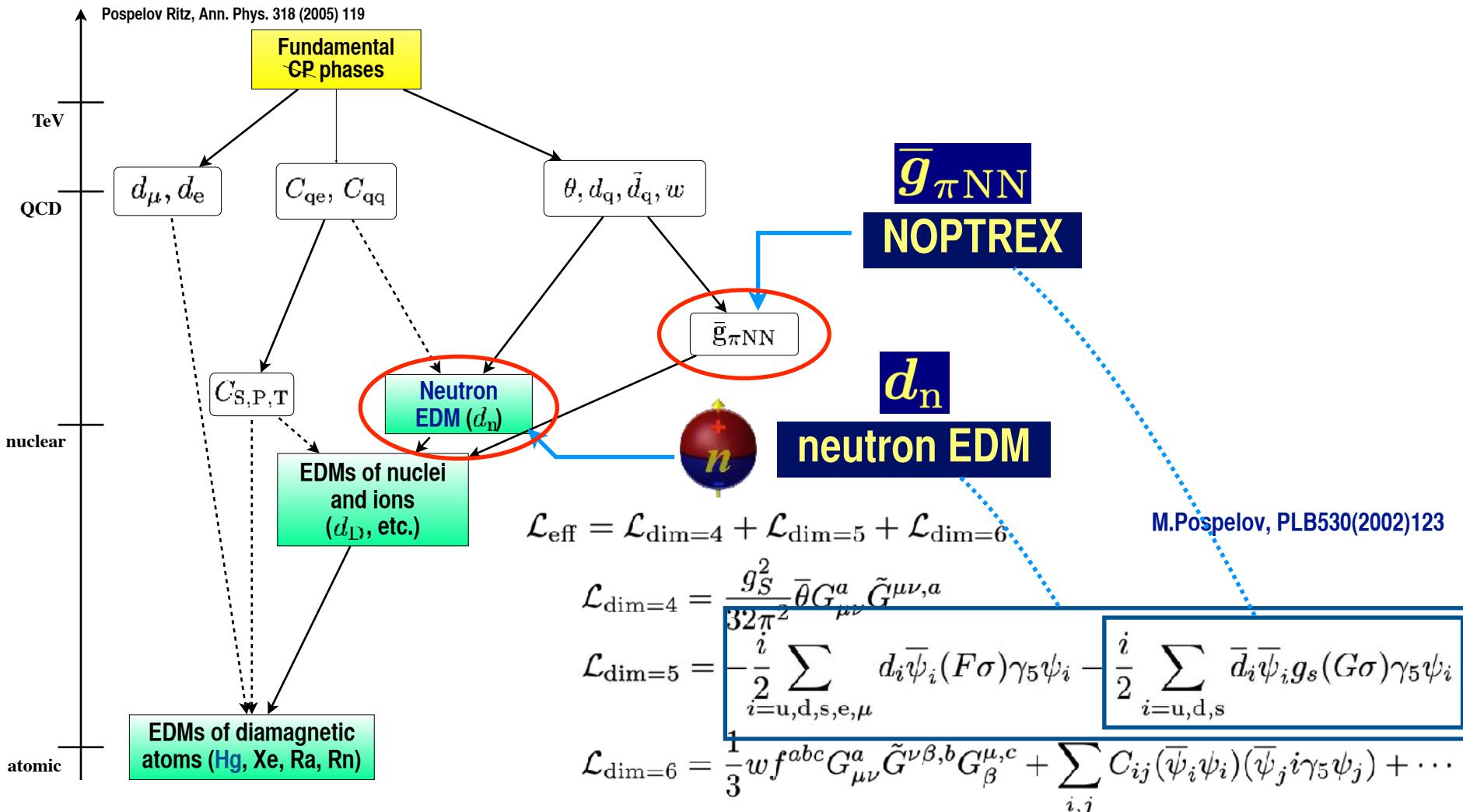


Neutron Fundamental Physics

searches for new physics
beyond the standard model



Propagation of CP-violation beyond the Standard Model into Low Energy Observables





Neutron Optical Parity and Time Reversal EXperiment

Enhanced Discrete Symmetry Breaking in Compound Nuclear States

Small admixture of the weak interaction induces parity-violating effects in the nuclear interactions at the level of 10^{-7} relative to the strong interaction. On the other hand, extremely large P-violating effects are observed in helicity-dependent neutron capture reactions. The largely enhanced P-violation effects are observed in p-wave resonances located on tails of neighboring s-wave resonances, which are currently explained as the results of the small energy spacing between partial amplitudes into parity-unfavored compound nuclear states. The reaction mechanism of the neutron capture reactions with large P-violation enhancement, such as $^{139}\text{La}(\text{n},\gamma)^{140}\text{La}$, $^{117}\text{Sn}(\text{n},\gamma)^{118}\text{Sn}$, $^{131}\text{Xe}(\text{n},\gamma)^{132}\text{Xe}$, etc., is being studied by measuring spin-angular correlation terms of emitted gamma-rays, which is, so far, consistent with statistical treatment in compound nuclear states. In this paper, present status and plans of the study of the entrance channel in progress using the pulsed epithermal neutron at the Japan Proton Accelerator Research Complex (J-PARC). The large enhancement is also expected to be applicable to the breaking of time-reversal-invariance, which introduces a new possibility to search for new physics beyond the standard model of elementary particles. An estimation of possible experimental sensitivity to the CP-violation will be also discussed in comparison with the search for the electric dipole moment of neutrons, which are intensively in progress.

NOPTREX

Neutron Optical Parity and Time Reversal EXperiment

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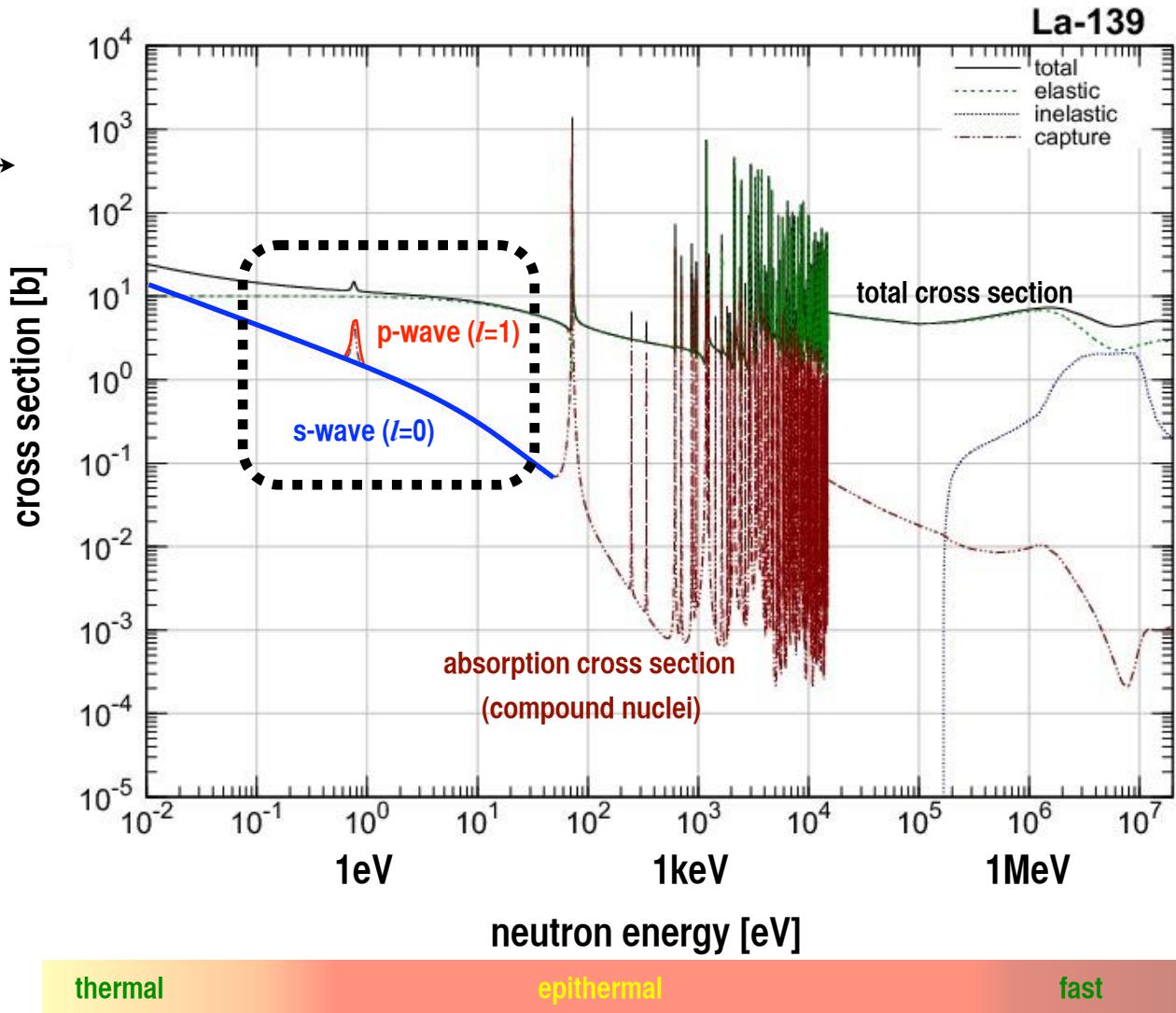
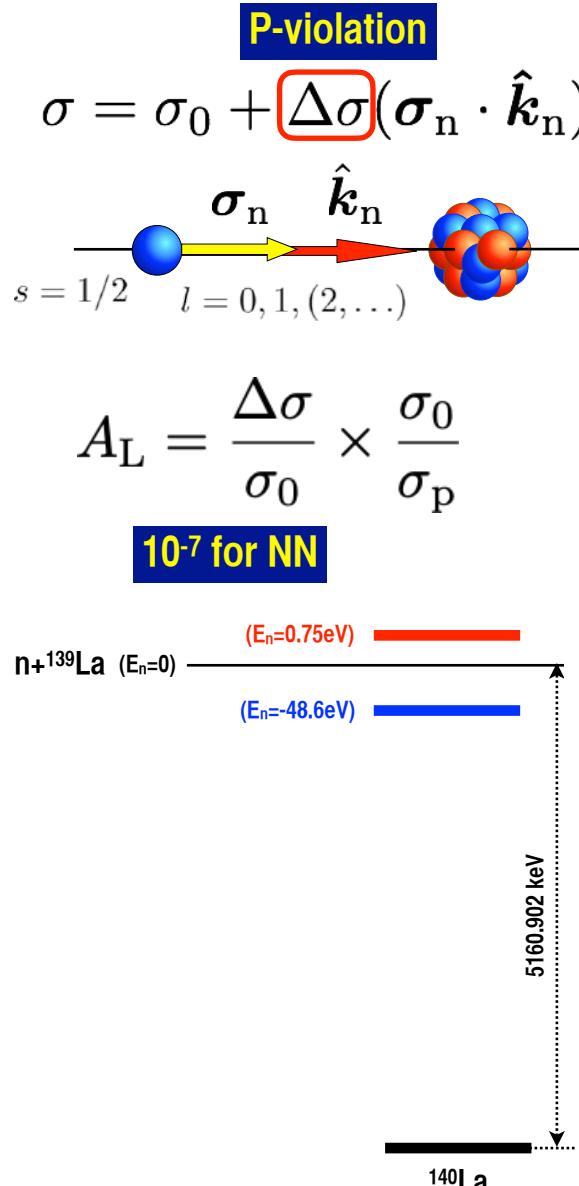
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M.Barlow

Depauw

A.Komives

P-violation in Compound State

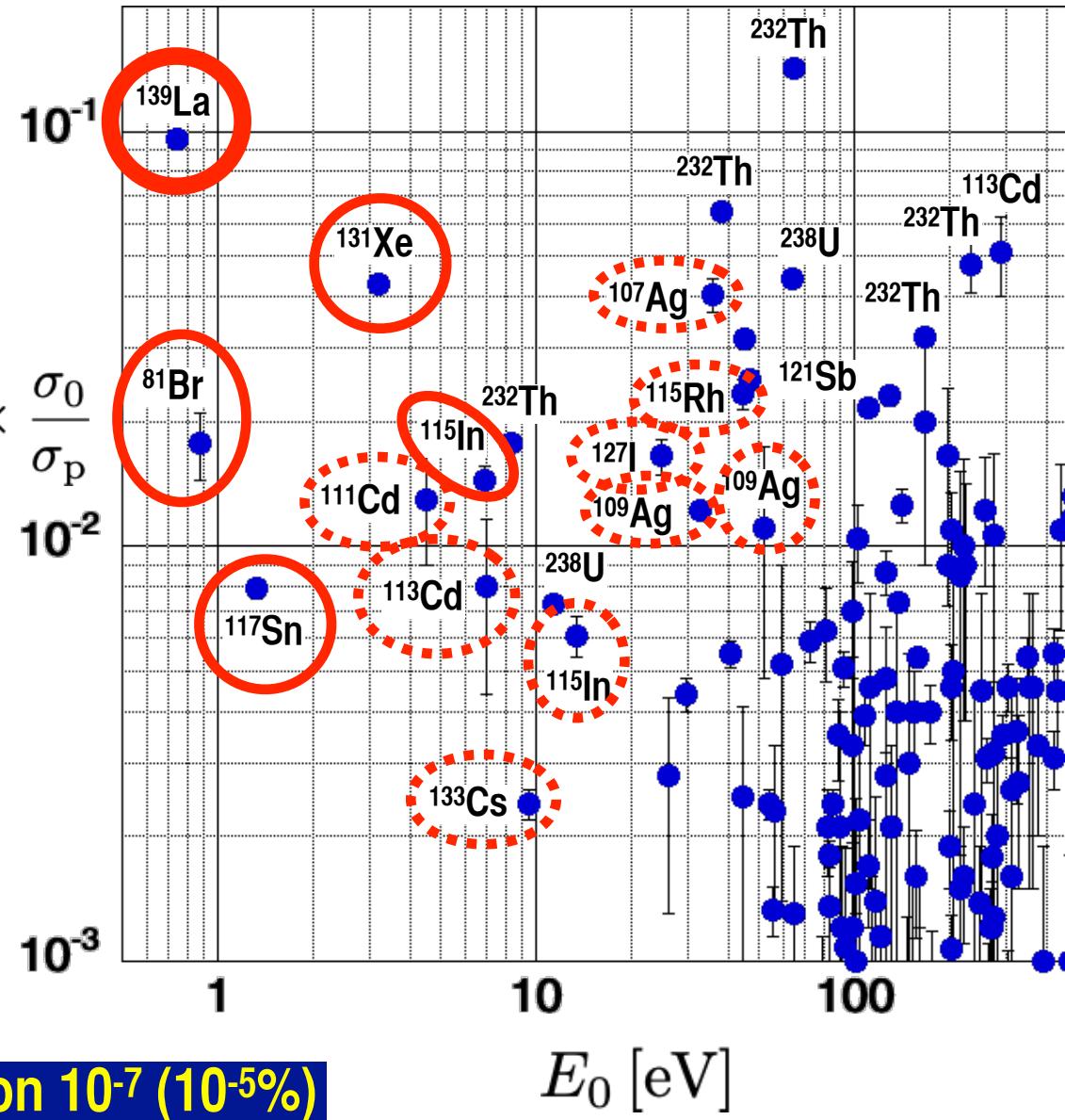


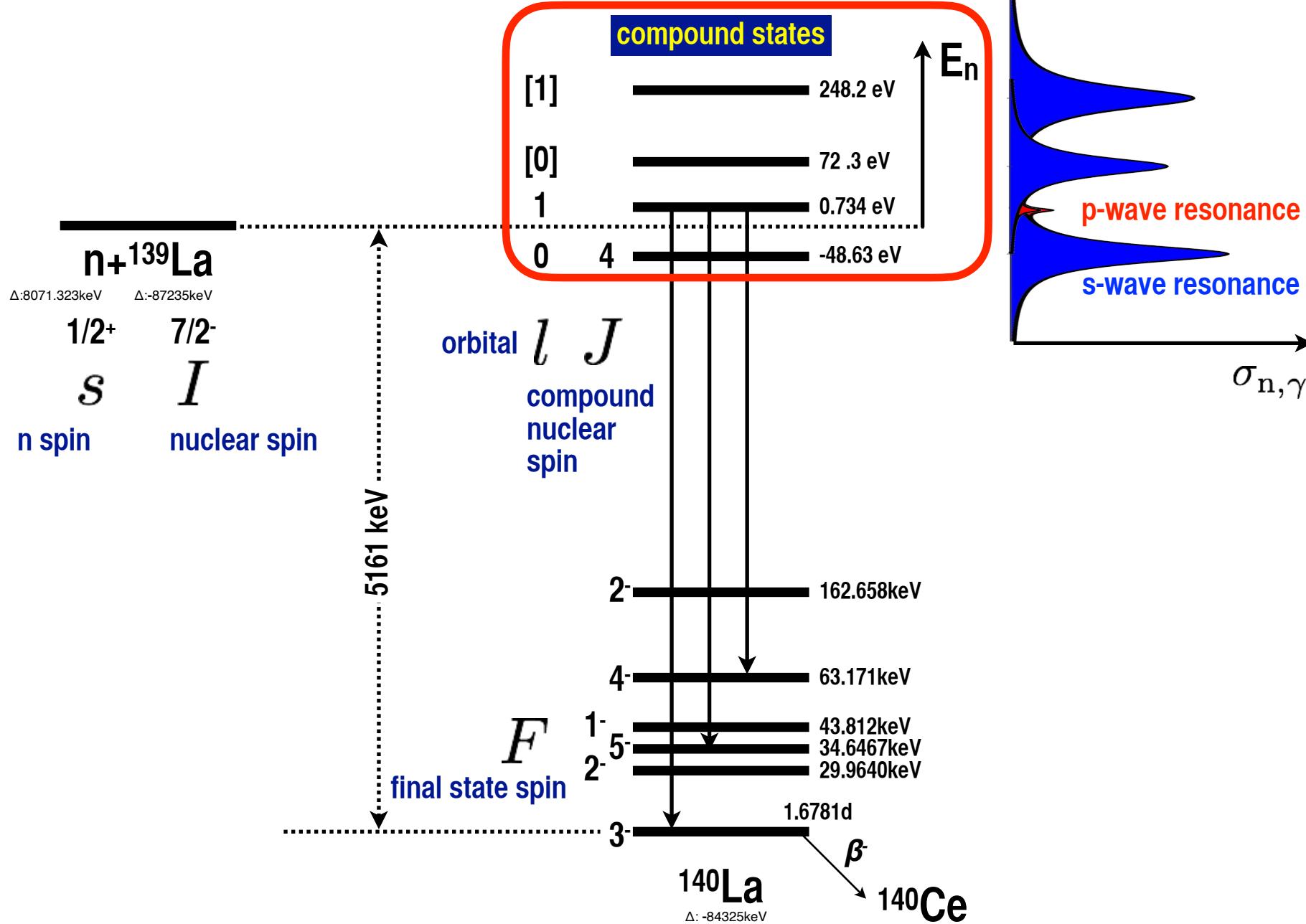
Enhancement of P-violation in Compound Resonances

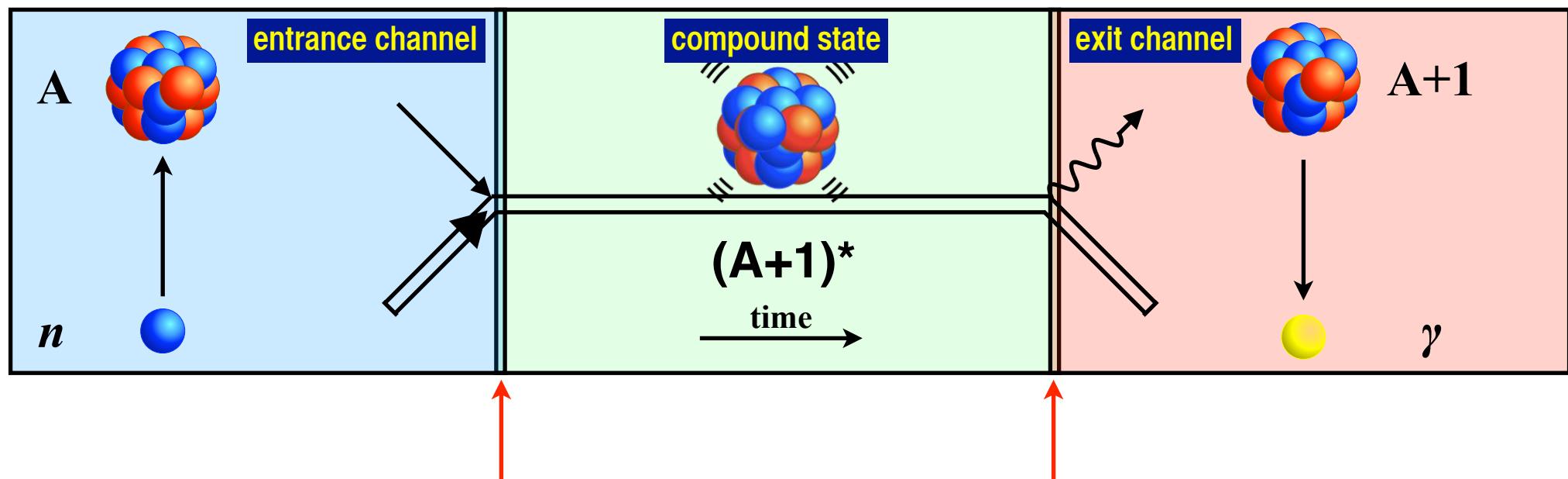
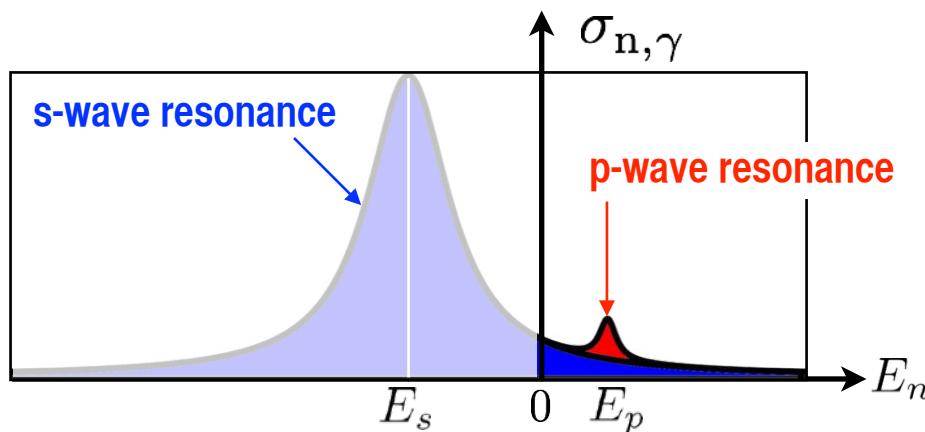
Mitchell, Phys. Rep. 354 (2001) 157
Shimizu, Nucl. Phys. A552 (1993) 293

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

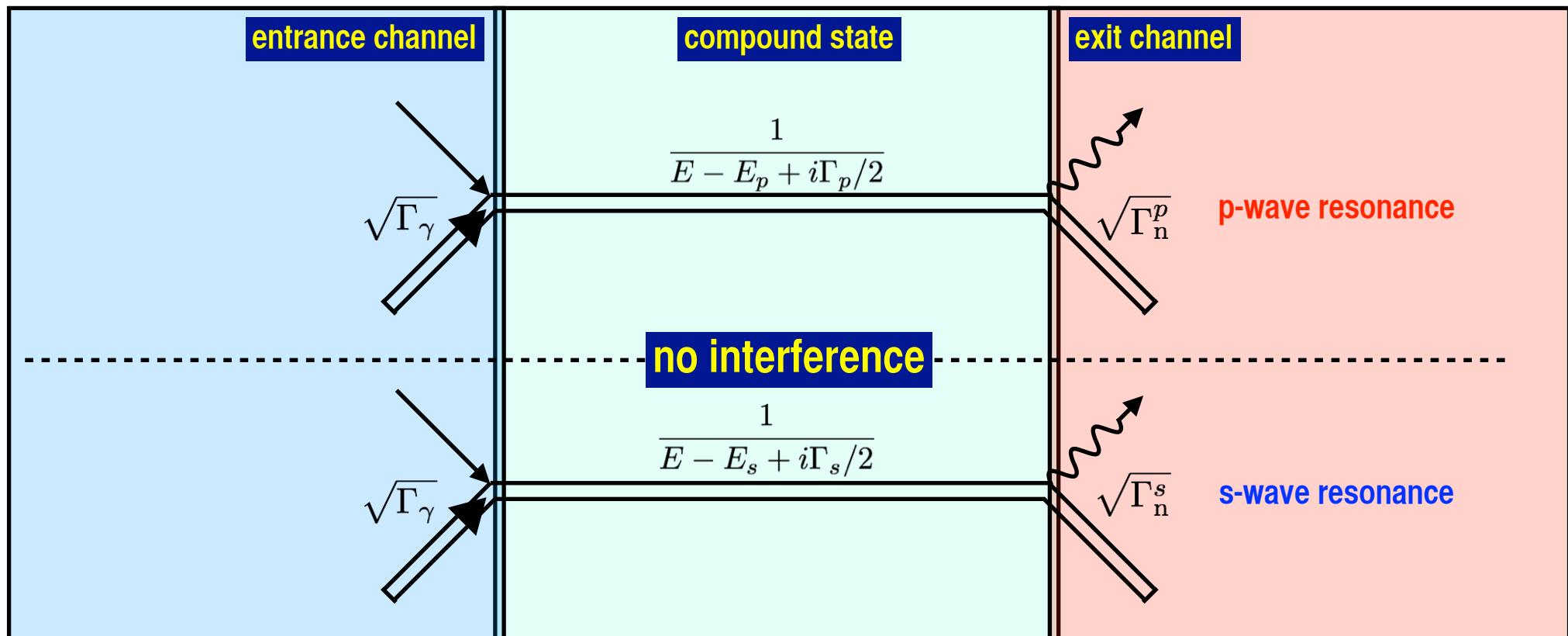
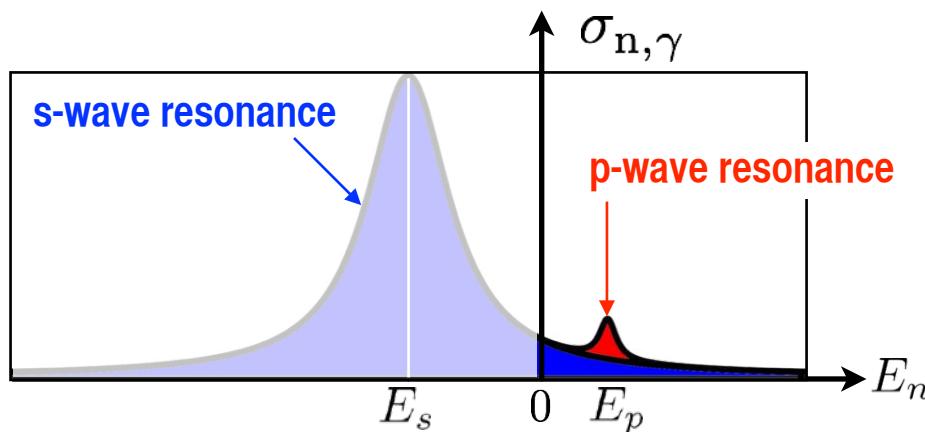
10⁻⁷ for NN

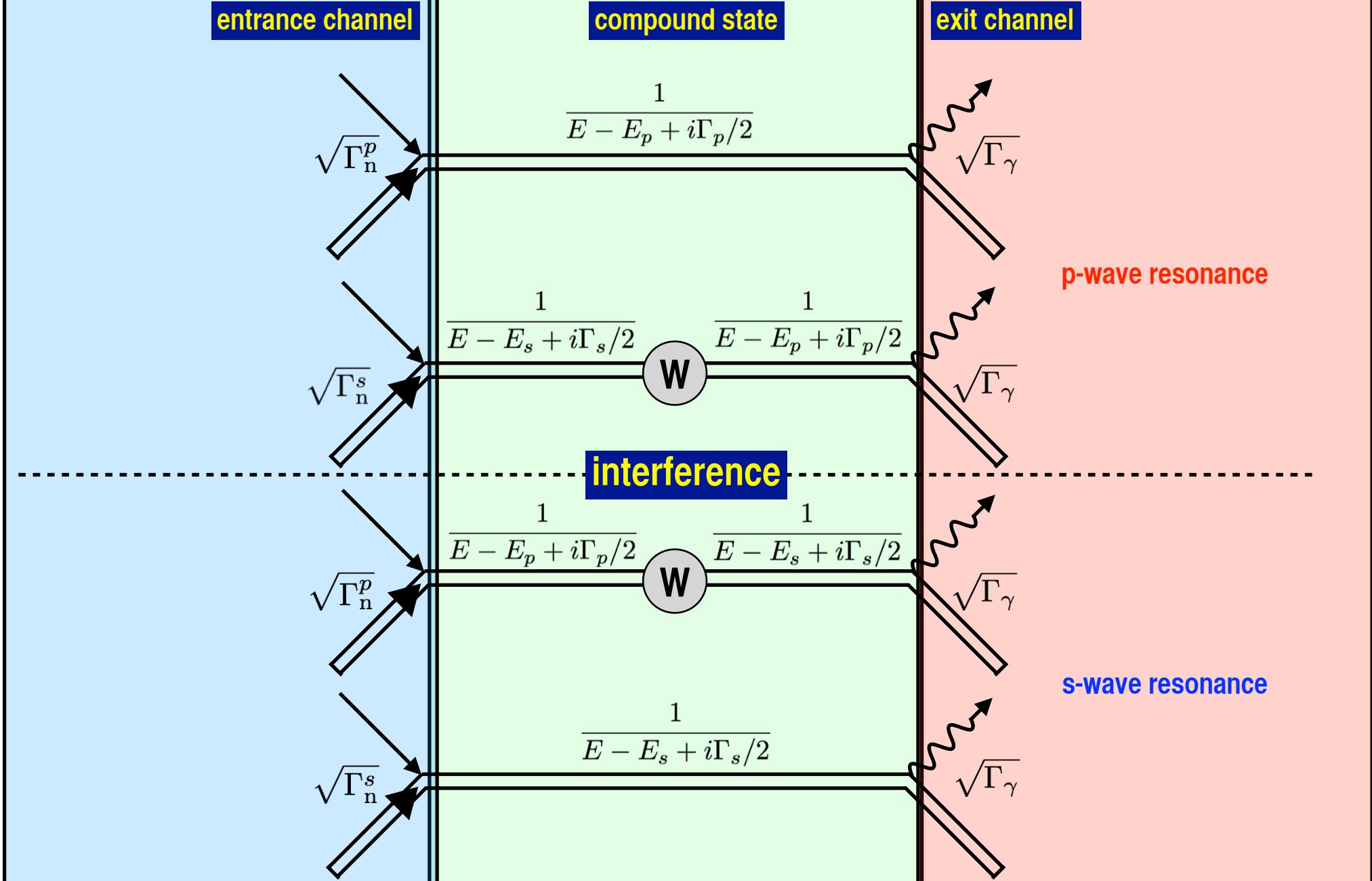






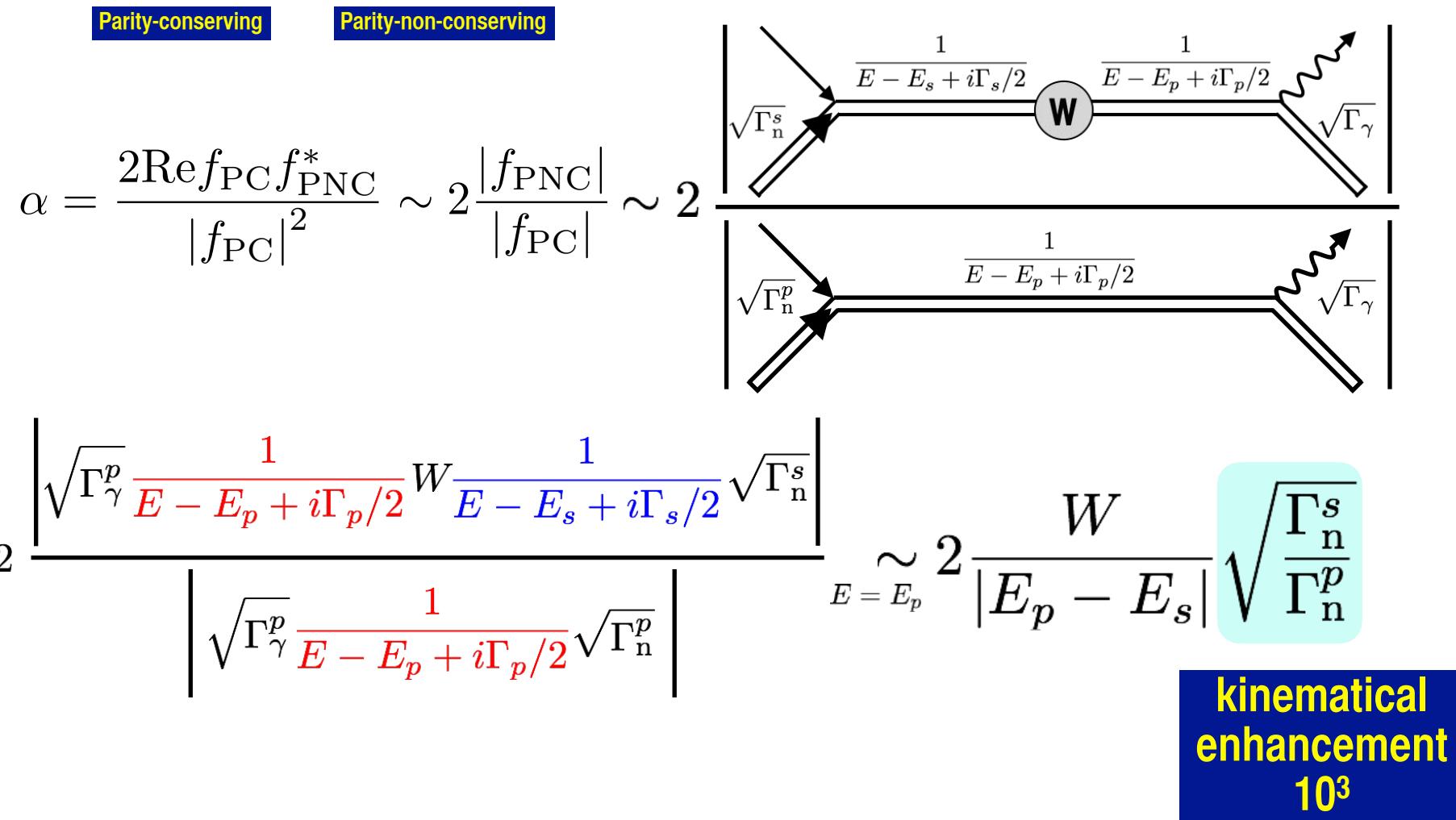
$$\sqrt{\Gamma_n} \frac{1}{E - E_0 + i\Gamma/2} \sqrt{\Gamma_\gamma}$$





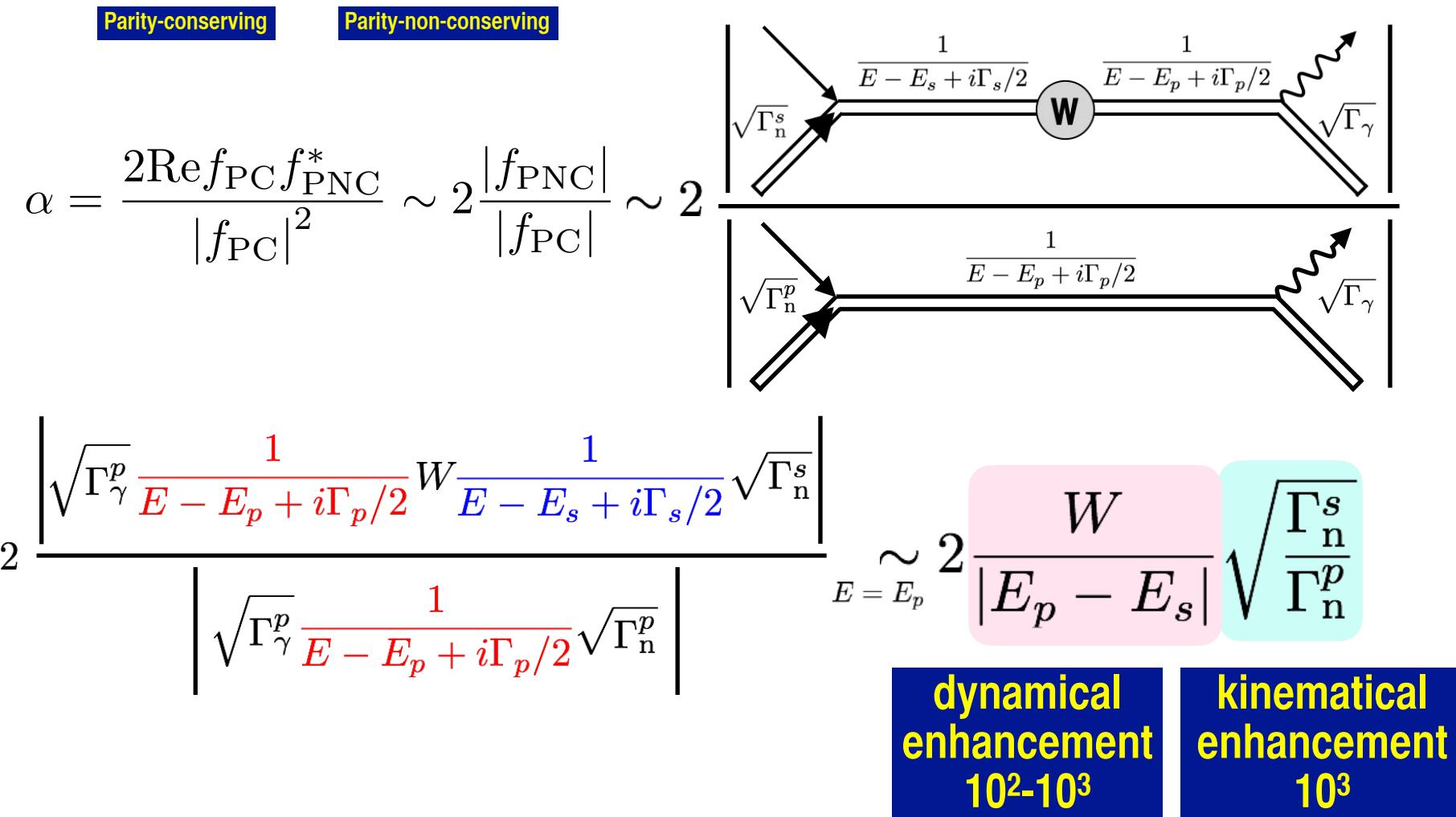
Enhancement of P-violation

$$|f|^2 = |f_{\text{PC}} + f_{\text{PNC}}|^2 = |f_{\text{PC}}|^2 + 2\text{Re}f_{\text{PC}}f_{\text{PNC}}^* + |f_{\text{PNC}}|^2$$

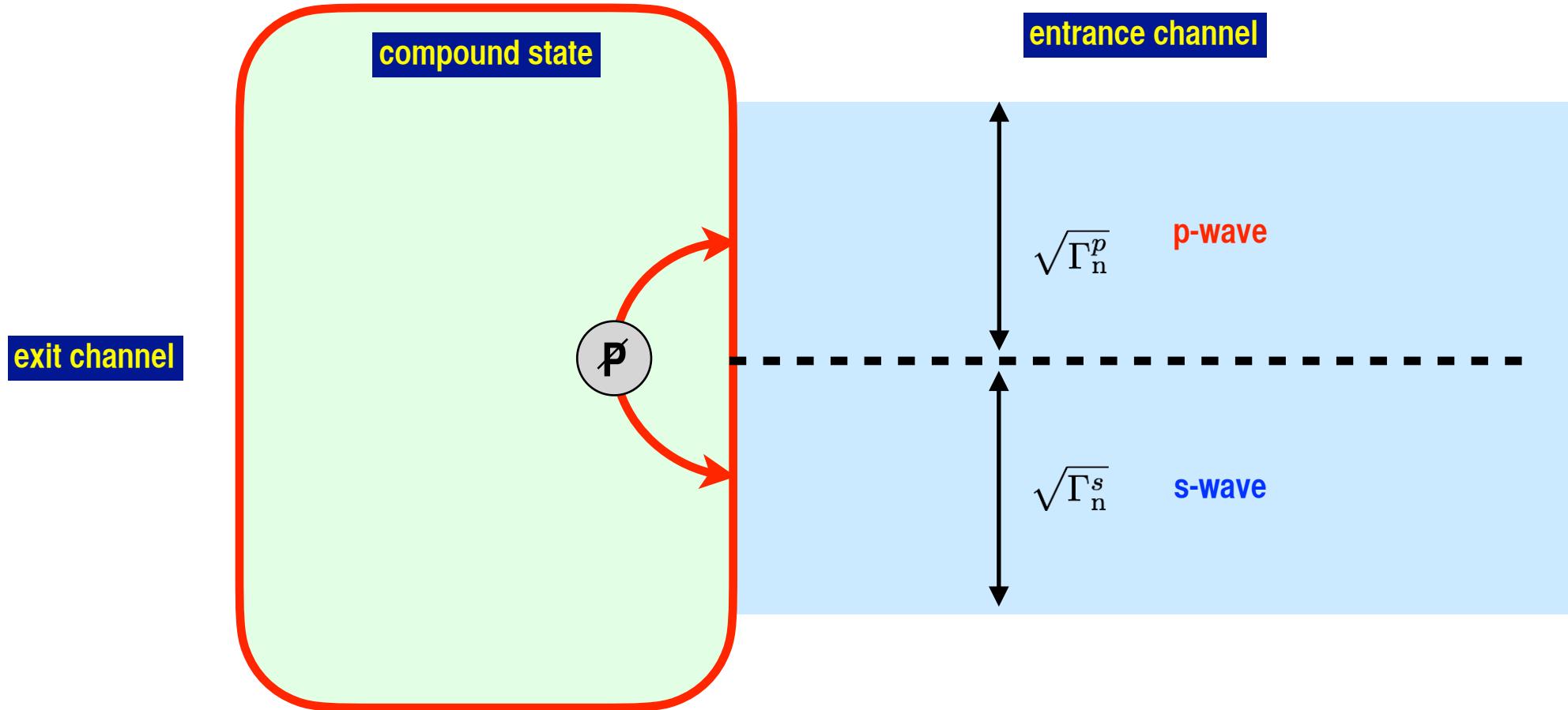


Enhancement of P-violation

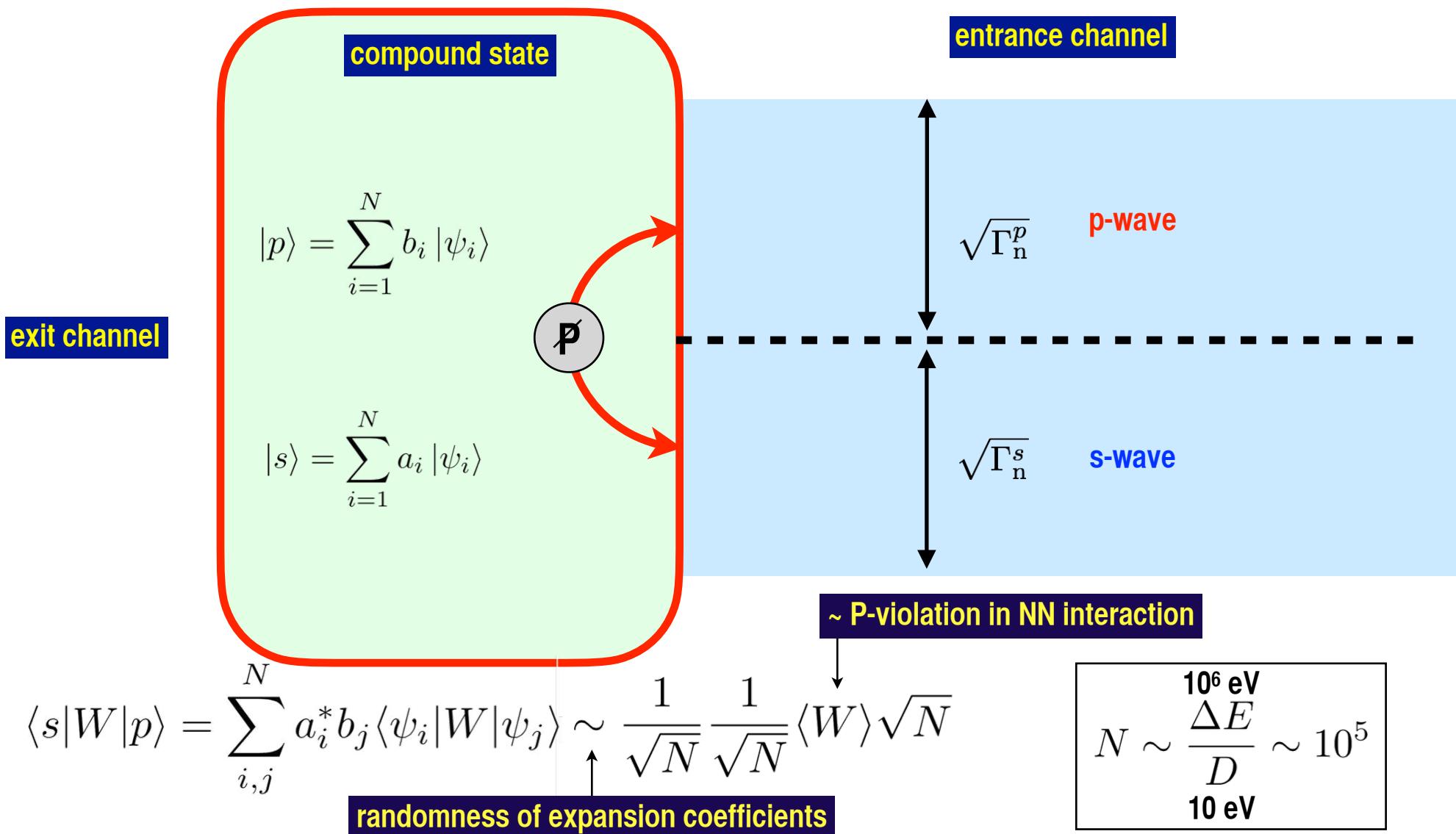
$$|f|^2 = |f_{\text{PC}} + f_{\text{PNC}}|^2 = |f_{\text{PC}}|^2 + 2\text{Re}f_{\text{PC}}f_{\text{PNC}}^* + |f_{\text{PNC}}|^2$$



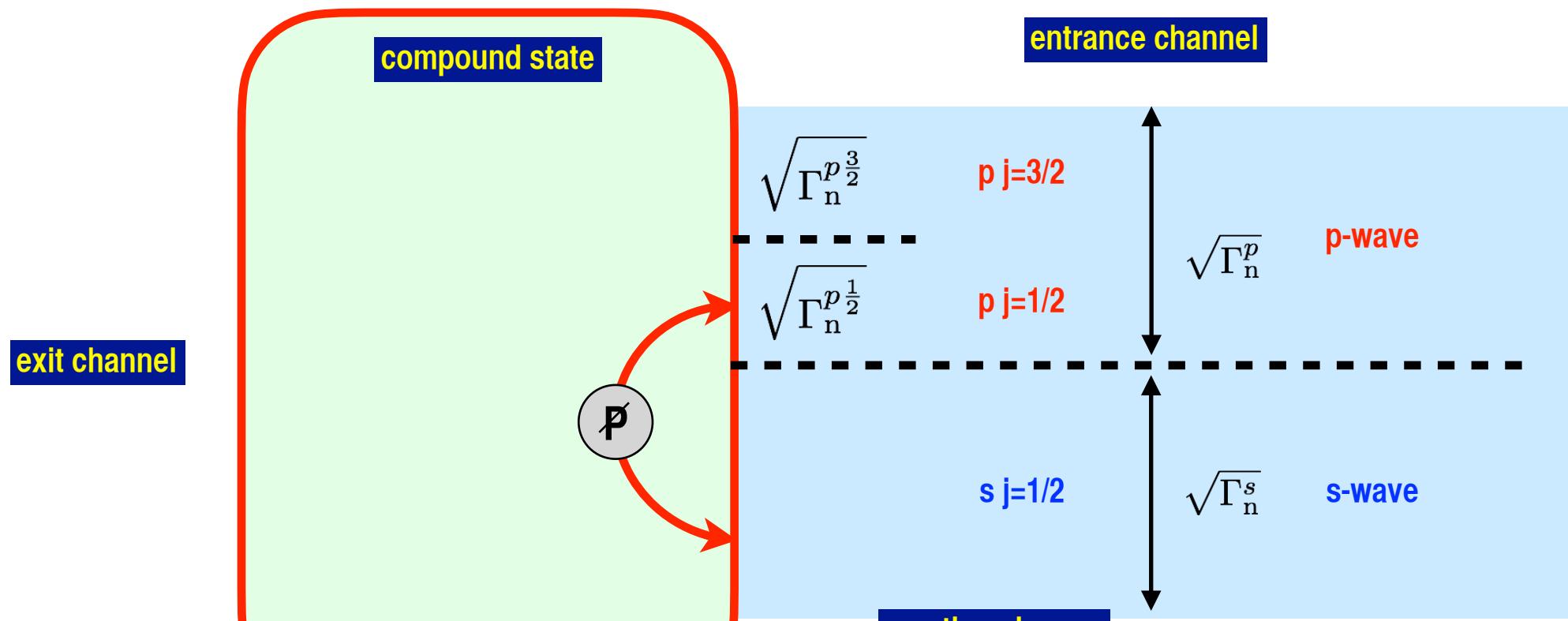
Dynamical Enhancement



Dynamical Enhancement



Detailed Study of Entrance Channel Boundary



$$A_L = -\frac{2W}{E_p - E_s} \sqrt{\frac{\Gamma_n^s}{\Gamma_n^p}} \sqrt{\frac{\Gamma_n^{p \frac{1}{2}}}{\Gamma_n^p}} \sqrt{\frac{\Gamma_n^{p \frac{3}{2}}}{\Gamma_n^p}}$$

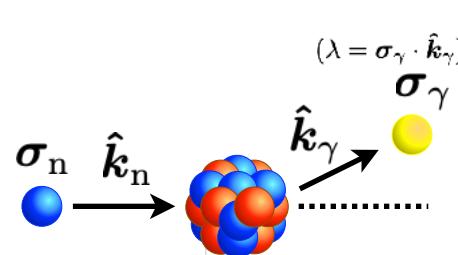
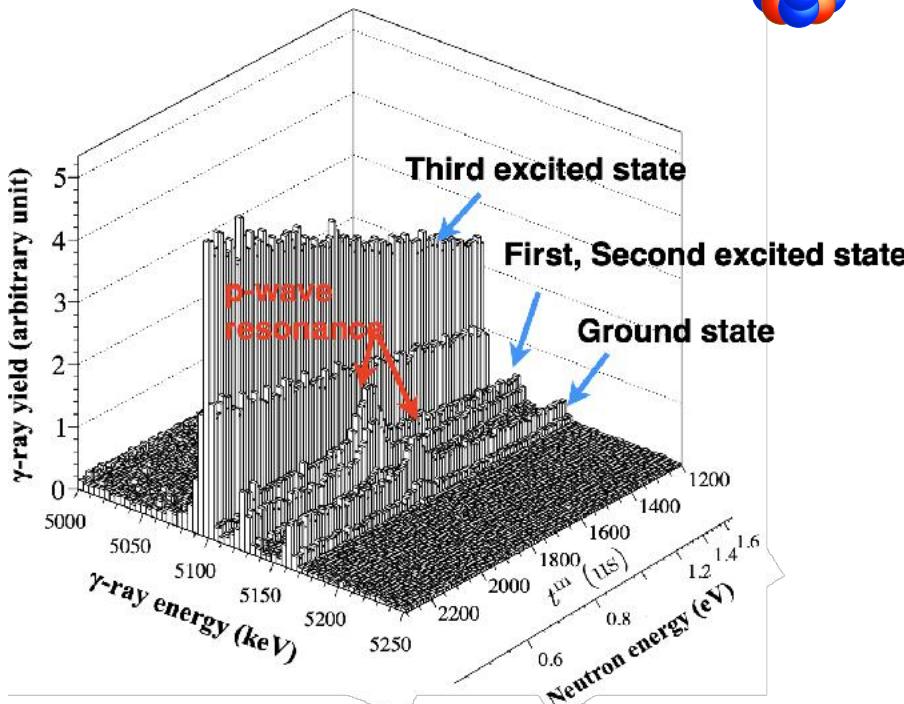
$$\begin{aligned}x &= \sqrt{\frac{\Gamma_n^{p \frac{1}{2}}}{\Gamma_n^p}} & y &= \sqrt{\frac{\Gamma_n^{p \frac{3}{2}}}{\Gamma_n^p}} \\x^2 + y^2 &= 1 \\x &= \cos \phi & y &= \sin \phi\end{aligned}$$

ϕ : mixing angle of $p_{1/2}$ and $p_{3/2}$

Detailed Study of Entrance Channel Boundary

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

determination of Φ



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

neutron-energy-dependent γ -ray angular distribution

γ -ray transverse asymmetry

γ -ray circular polarization and longitudinal polarization

γ -ray asymmetry relative to neutron polarization

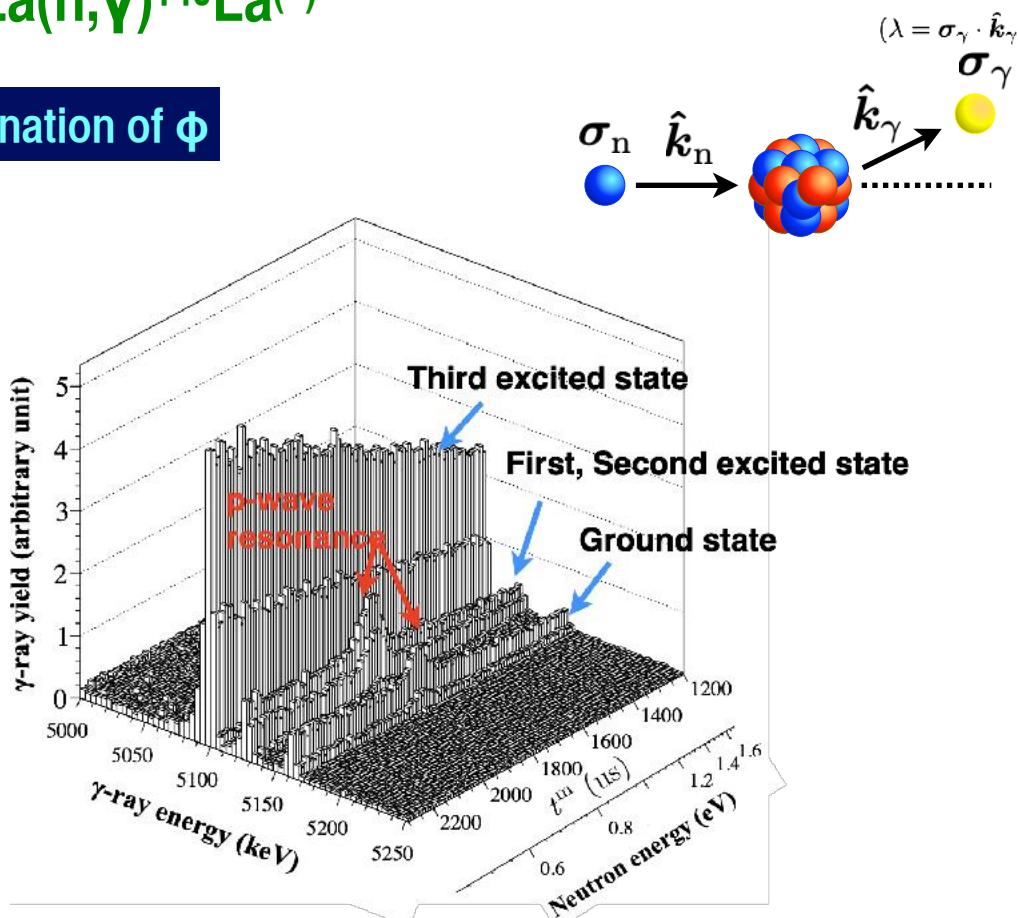
longitudinal asymmetry

γ -ray circular polarization

Detailed Study of Entrance Channel Boundary

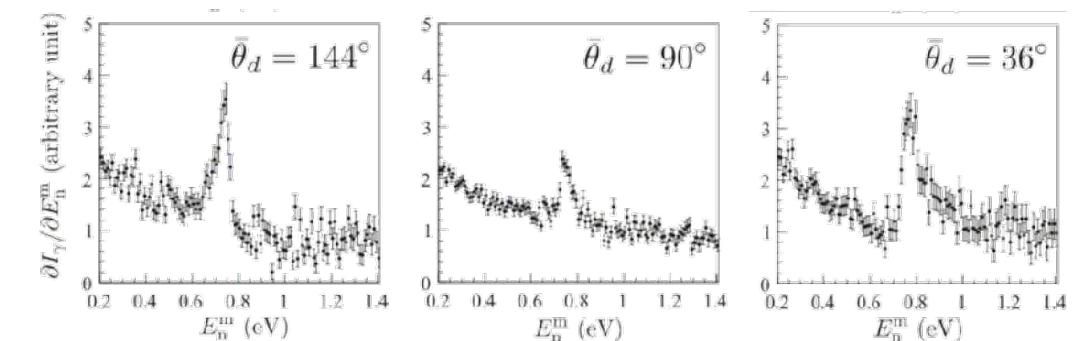
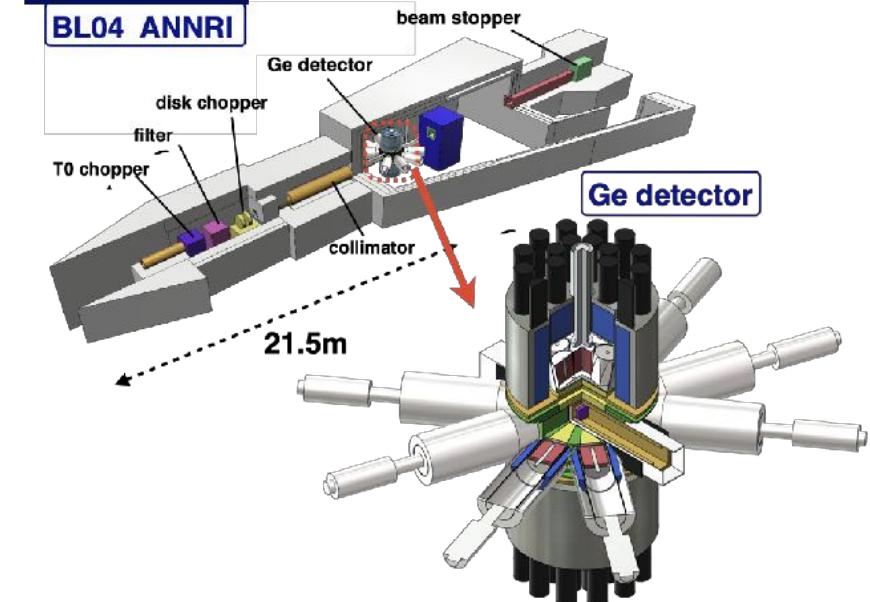
in $^{139}\text{La}(n,\gamma)^{140}\text{La}^{\ast}$

determination of ϕ



J-PARC MLF

BL04 ANNRI



$$\phi = (99.2^{+6.3})^\circ, (161.9^{+5.3})^\circ$$

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

T.Yamamoto et al., Phys. Rev. C101 (2020) 062624
T.O кудайра et al., Phys. Rev. C104 (2021) 014601

Detailed Study of Entrance Channel Boundary

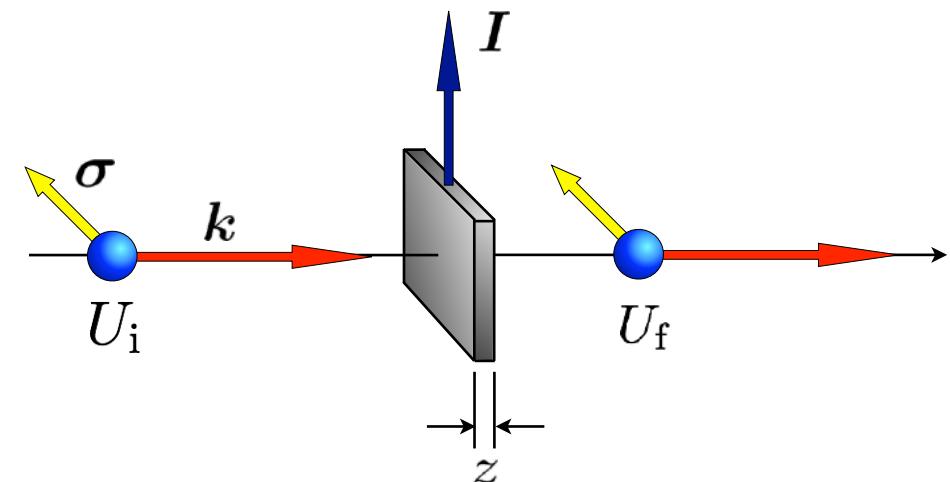
in $\vec{n} + {}^{139}\text{La}$

redundant information in pseudomagnetism

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

pseudomagnetism

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



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

$$\langle S'_K l_K | R^{J_K} | S_K l_K \rangle = i \frac{\sqrt{\Gamma_{l_K}^n(S'_K)} \sqrt{\Gamma_{l_K}^n(S_K)}}{E - E_K + i\Gamma_K/2} e^{i(\delta_{l_K}(S'_K) + \delta_{l_K}(S_K))} - 2ie^{i\delta_{l_K}(S_K S'_K)} \sin \delta_{l_K}(S_K S'_K)$$

compound resonance

potential scattering

$$\omega_P^s = \frac{4\pi N\hbar}{M_n} \frac{I}{(2I+1)} \left(a_+ - a_- - \sum_{K, l_K=0} \frac{\Gamma_K^n}{2k} \frac{(E - E_K)}{(E - E_K)^2 + (\Gamma_K/2)^2} \beta_K \right) \quad \beta_K = \begin{cases} 1 & (J_K = I + \frac{1}{2}) \\ -1 & (J_K = I - \frac{1}{2}) \end{cases}$$

T.Okudaira et al., Phys. Rev. C104 (2021) 014601

compound nuclear spin orbital n spin nuclear spin

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

$\boxed{\mathbf{j}}$ $\boxed{\mathbf{S}}$

n entrance spin channel spin

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

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

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

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

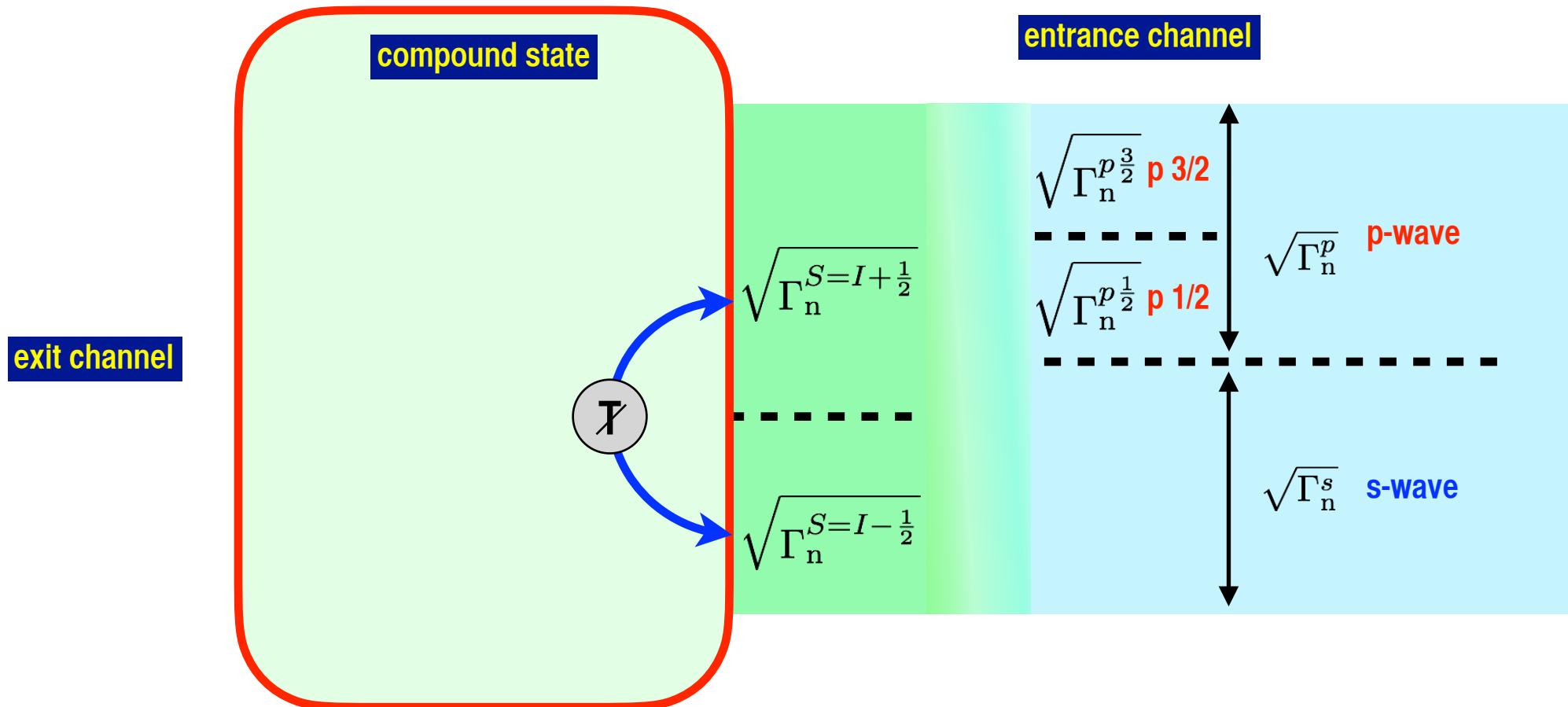
s-p interference \Leftrightarrow channel-spin interference

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

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

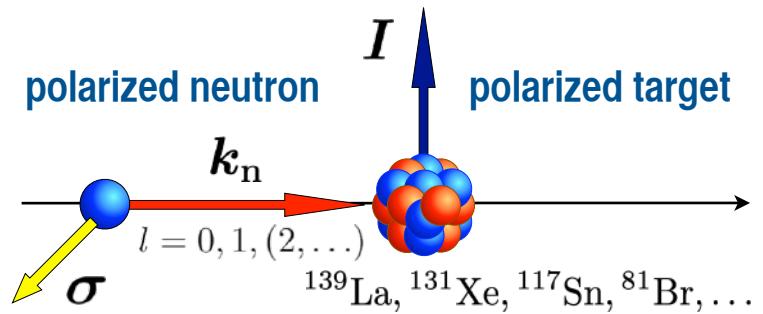
$S = I \pm 1/2$ **T-odd**

T-odd \rightarrow Channel-spin Interference



Forward Scattering Amplitude

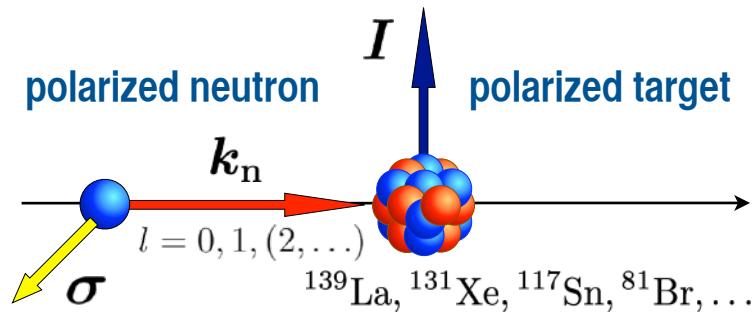
no fake T-violation



$$f(0) \rightarrow f = \underbrace{A'}_{\text{Spin Independent P-even T-even}} + \underbrace{B' \boldsymbol{\sigma} \cdot \hat{\mathbf{I}}}_{\text{Spin Dependent P-even T-even}} + \underbrace{C' \boldsymbol{\sigma} \cdot \hat{\mathbf{k}}}_{\text{P-violation P-odd T-even}} + \underbrace{D' \boldsymbol{\sigma} \cdot (\hat{\mathbf{I}} \times \hat{\mathbf{k}})}_{\text{T-violation P-odd T-odd}}$$

Forward Scattering Amplitude

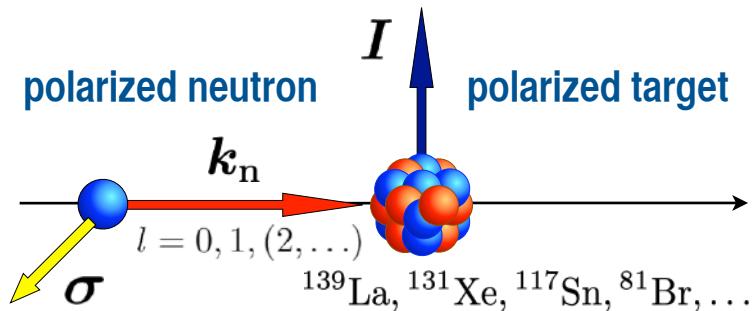
no fake T-violation



$$f(0) \rightarrow f = \underbrace{A'}_{\substack{\text{Spin Independent} \\ \text{P-even T-even}}} + \underbrace{B' \boldsymbol{\sigma} \cdot \hat{\mathbf{I}}}_{\substack{\text{Spin Dependent} \\ \text{P-even T-even}}} + \underbrace{C' \boldsymbol{\sigma} \cdot \hat{\mathbf{k}}}_{\substack{\text{P-violation} \\ \text{P-odd T-even}}} + \underbrace{D' \boldsymbol{\sigma} \cdot (\hat{\mathbf{I}} \times \hat{\mathbf{k}})}_{\substack{\text{T-violation} \\ \text{P-odd T-odd}}}$$

$$\begin{aligned} f = & \underbrace{A'}_{\substack{\text{P-even T-even}}} + P_1 \underbrace{H'(\hat{\mathbf{k}}_n \cdot \hat{\mathbf{I}})}_{\substack{\text{P-odd T-even}}} + P_2 \underbrace{E'}_{\substack{\text{P-even T-even}}} \left((\hat{\mathbf{k}}_n \cdot \hat{\mathbf{I}})^2 - \frac{1}{3} \right) \\ & + (\boldsymbol{\sigma} \cdot \hat{\mathbf{I}}) \left\{ P_1 \underbrace{B'}_{\substack{\text{P-even T-even}}} + P_2 \underbrace{F'(\hat{\mathbf{k}}_n \cdot \hat{\mathbf{I}})}_{\substack{\text{P-odd T-even}}} + P_3 \frac{B'_3}{3} \left((\hat{\mathbf{k}}_n \cdot \hat{\mathbf{I}})^2 - 1 \right) \right\} \\ & + (\boldsymbol{\sigma} \cdot \hat{\mathbf{k}}_n) \left\{ C' + P_1 \underbrace{K'(\hat{\mathbf{k}}_n \cdot \hat{\mathbf{I}})}_{\substack{\text{P-odd T-even}}} - P_2 \frac{F'}{3} + P_3 \frac{2B'_3}{3} (\hat{\mathbf{k}}_n \cdot \hat{\mathbf{I}}) \right\} \\ & + (\boldsymbol{\sigma} \cdot (\hat{\mathbf{k}}_n \times \hat{\mathbf{I}})) \left(P_1 \underbrace{D'}_{\substack{\text{P-odd T-odd}}} + P_2 \underbrace{G'(\hat{\mathbf{k}}_n \cdot \hat{\mathbf{I}})}_{\substack{\text{P-even T-odd}}} \right) \end{aligned}$$

P-even T-even



$$f(0) \rightarrow f = \underbrace{A'}_{\text{P-even T-even}} + \underbrace{B' \sigma \cdot \hat{I}}_{\text{Spin Independent P-odd T-even}} + \underbrace{C' \sigma \cdot \hat{k}}_{\text{Spin Dependent P-even T-even}} + \underbrace{D' \sigma \cdot (\hat{I} \times \hat{k})}_{\text{T-violation P-odd T-odd}}$$

Spin Independent
P-odd T-even

Spin Dependent
P-even T-even

P-violation
P-odd T-even

T-violation
P-odd T-odd

$$f = \underbrace{A'}_{\text{P-even T-even}} + P_1 \underbrace{H'(\hat{k}_n \cdot \hat{I})}_{\text{P-odd T-even}} + P_2 \underbrace{E' \left((\hat{k}_n \cdot \hat{I})^2 - \frac{1}{3} \right)}_{\text{P-even T-even}}$$

$$+ \underbrace{(\sigma \cdot \hat{I})}_{\text{P-even T-even}} \left\{ P_1 \underbrace{B'}_{\text{P-even T-even}} + P_2 \underbrace{F'(\hat{k}_n \cdot \hat{I})}_{\text{P-odd T-even}} + P_3 \frac{\underbrace{B'_3}_{3}}{3} \left((\hat{k}_n \cdot \hat{I})^2 - 1 \right) \right\}$$

$$+ \underbrace{(\sigma \cdot \hat{k}_n)}_{\text{P-odd T-odd}} \left\{ C' + P_1 \underbrace{K'(\hat{k}_n \cdot \hat{I})}_{\text{P-odd T-even}} - P_2 \frac{\underbrace{F'}_{3}}{3} + P_3 \frac{2\underbrace{B'_3}_{3}}{3} (\hat{k}_n \cdot \hat{I}) \right\}$$

$$+ \underbrace{(\sigma \cdot (\hat{k}_n \times \hat{I}))}_{\text{P-odd T-odd}} \left(P_1 \underbrace{D'}_{\text{P-even T-odd}} + P_2 \underbrace{G'(\hat{k}_n \cdot \hat{I})}_{\text{P-even T-odd}} \right)$$

T-violation in Compound Nuclear States

A'
P-even T-even

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

C'
P-odd T-even

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

10⁶ enhancement
in compound nuclear state

B'
P-even T-even

D'
P-odd T-odd

10⁶ enhancement
in compound nuclear state

T-violation in Compound Nuclear States

$$\frac{A'}{\text{P-even T-even}}$$

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

polarized neutron

$$\frac{C'}{\text{P-odd T-even}} \quad (\sigma_n \cdot \hat{k}_n)$$

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

10⁶ enhancement
in compound nuclear state

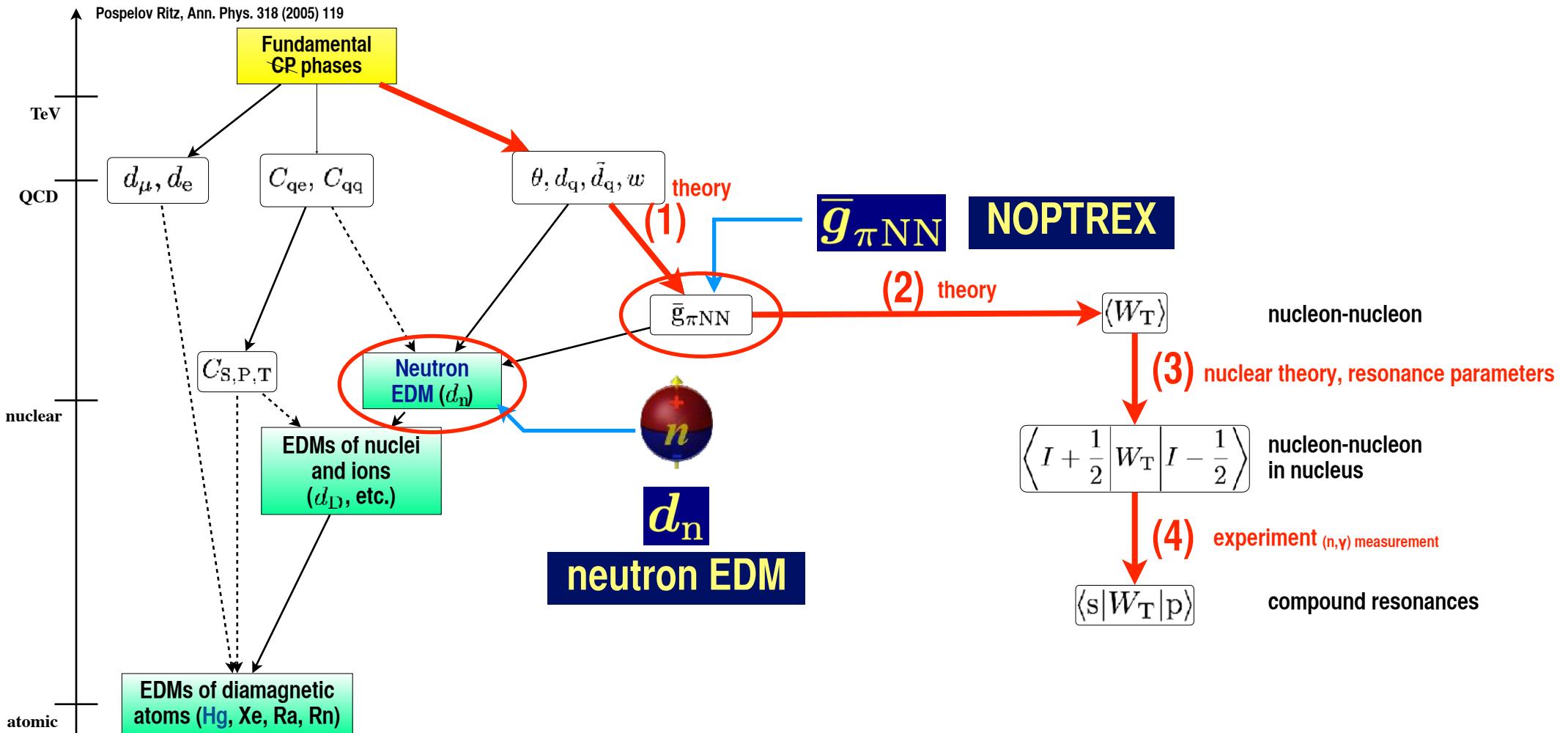
polarized target

$$\frac{B'}{\text{P-even T-even}} \quad (\sigma_n \cdot \hat{I})$$

$$\frac{D'}{\text{P-odd T-odd}} \quad \sigma_n \cdot (\hat{k}_n \times \hat{I})$$

10⁶ enhancement
in compound nuclear state

Propagation of CP-violation beyond the Standard Model into Low Energy Observables



Present Sensitivity Estimation in Effective Field Theory

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

T-odd P-odd meson couplings

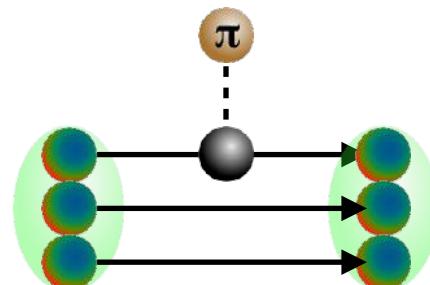
$$V_{\text{CP}} = \left[-\frac{\bar{g}_\eta^{(0)} g_\eta}{2m_N} \frac{m_\eta^2}{4\pi} Y_1(x_\eta) + \frac{\bar{g}_\omega^{(0)} g_\omega}{2m_N} \frac{m_\omega^2}{4\pi} Y_1(x_\omega) \right] \boldsymbol{\sigma}_- \cdot \hat{\mathbf{r}}$$

$$+ \left[-\frac{\bar{g}_\pi^{(0)} g_\pi}{2m_N} \frac{m_\pi^2}{4\pi} Y_1(x_\pi) + \frac{\bar{g}_\rho^{(0)} g_\rho}{2m_N} \frac{m_\rho^2}{4\pi} Y_1(x_\rho) \right] \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 \boldsymbol{\sigma}_- \cdot \hat{\mathbf{r}}$$

$$+ \left[-\frac{\bar{g}_\pi^{(2)} g_\pi}{2m_N} \frac{m_\pi^2}{4\pi} Y_1(x_\pi) + \frac{\bar{g}_\rho^{(2)} g_\rho}{2m_N} \frac{m_\rho^2}{4\pi} Y_1(x_\rho) \right] T_{12}^z \boldsymbol{\sigma}_- \cdot \hat{\mathbf{r}}$$

$$+ \left[-\frac{\bar{g}_\pi^{(1)} g_\pi}{2m_N} \frac{m_\pi^2}{4\pi} Y_1(x_\pi) + \frac{\bar{g}_\eta^{(1)} g_\eta}{2m_N} \frac{m_\eta^2}{4\pi} Y_1(x_\eta) + \frac{\bar{g}_\rho^{(1)} g_\rho}{2m_N} \frac{m_\rho^2}{4\pi} Y_1(x_\rho) + \frac{\bar{g}_\omega^{(1)} g_\omega}{2m_N} \frac{m_\omega^2}{4\pi} Y_1(x_\omega) \right] \boldsymbol{\tau}_+ \boldsymbol{\sigma}_- \cdot \hat{\mathbf{r}}$$

$$+ \left[-\frac{\bar{g}_\pi^{(1)} g_\pi}{2m_N} \frac{m_\pi^2}{4\pi} Y_1(x_\pi) - \frac{\bar{g}_\eta^{(1)} g_\eta}{2m_N} \frac{m_\eta^2}{4\pi} Y_1(x_\eta) - \frac{\bar{g}_\rho^{(1)} g_\rho}{2m_N} \frac{m_\rho^2}{4\pi} Y_1(x_\rho) + \frac{\bar{g}_\omega^{(1)} g_\omega}{2m_N} \frac{m_\omega^2}{4\pi} Y_1(x_\omega) \right] \boldsymbol{\tau}_+ \boldsymbol{\sigma}_+ \cdot \hat{\mathbf{r}}$$



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

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

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

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

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

$$d_{^3\text{He}} \sim (-0.0542d_p + 0.868d_n) + 0.0$$

$$d_d \sim 0.19\bar{g}_\pi^{(1)} + 0.0035\bar{g}_\eta^{(1)} + 0.0017\bar{g}_\rho^{(1)}$$

$$d_{^3\text{H}} \sim (0.868d_p - 0.0552d_n) - 0.072 \left[\bar{g}_\pi^{(0)} \right]$$

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

$$\frac{1}{N} \frac{d\phi_{\text{CP}}}{dz} = (-65 \text{rad} \cdot \text{fm}^2) \left[\bar{g}_\pi^{(0)} + 0.26\bar{g}_\pi^{(1)} \right]$$

Present Sensitivity Estimation in Effective Field Theory

$$\frac{\langle s|W_T|p\rangle}{\langle s|W|p\rangle} = Q \frac{\langle W_T \rangle}{\langle W \rangle}$$

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

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

$Q \simeq 1 - 0.2$
Fadeev, Phys. Rev. C 100(2019) 015504

$$\bar{g}_\pi^{(1)} < 0.5 \times 10^{-11} \quad \leftarrow \text{atomic EDM}$$

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

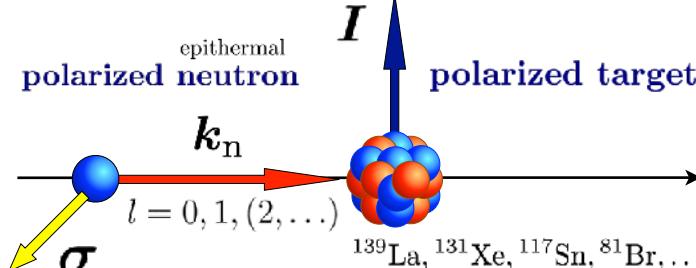
$$\downarrow$$

$$\bar{g}_\pi^{(0)} < 2.5 \times 10^{-10} \quad \leftarrow \text{neutron EDM}$$

$$\uparrow$$

$$\left| \frac{\langle W_T \rangle}{\langle W \rangle} \right| < 3.9 \times 10^{-4} \quad \leftarrow \text{estimated discovery potential}$$

T-violation in Epithermal Neutron Optics



$$f = A' + \underbrace{B' \sigma_n \cdot \hat{I}}_{\text{Spin independent P-even T-even}} + \underbrace{C' \sigma_n \cdot \hat{k}_n}_{\text{Spin dependent P-even T-even}} + \underbrace{D' \sigma_n \cdot (\hat{k}_n \times \hat{I})}_{\text{P-violation P-odd T-even}} + \underbrace{\hat{k}_n \cdot \hat{I}}_{\text{T-violation P-odd T-odd}}$$

T-violating matrix element
 $\frac{D'}{C'}$ being measured
 measured $\frac{W_T}{W}$
 spin factor $\kappa(J)$ measured
 P-violating matrix element

$$\frac{W_T}{W} = Q \frac{g_{PT}}{g_P}$$

T-violating nucleon coupling constant

P-violating nucleon coupling constant

$$\frac{\langle s | W_T | p \rangle}{\langle s | W | p \rangle} = Q \frac{\langle W_T \rangle}{\langle W \rangle}$$

Gudkov, Phys. Rep. 212 (1992) 77
 (Koonin, Phys. Rev. Lett. 69 (1992) 1163)
 $Q \simeq 1 - 0.2$
 Fadeev, Phys. Rev. C 100(2019)015504

$$\frac{\langle W_T \rangle}{\langle W \rangle} \simeq -0.47 \left(\frac{g_\pi^{(0)}}{h_\pi^1} + 0.26 \frac{g_\pi^{(1)}}{h_\pi^1} \right)$$

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

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

← atomic EDM

$$h_\pi^1 \sim 3 \times 10^{-7}$$

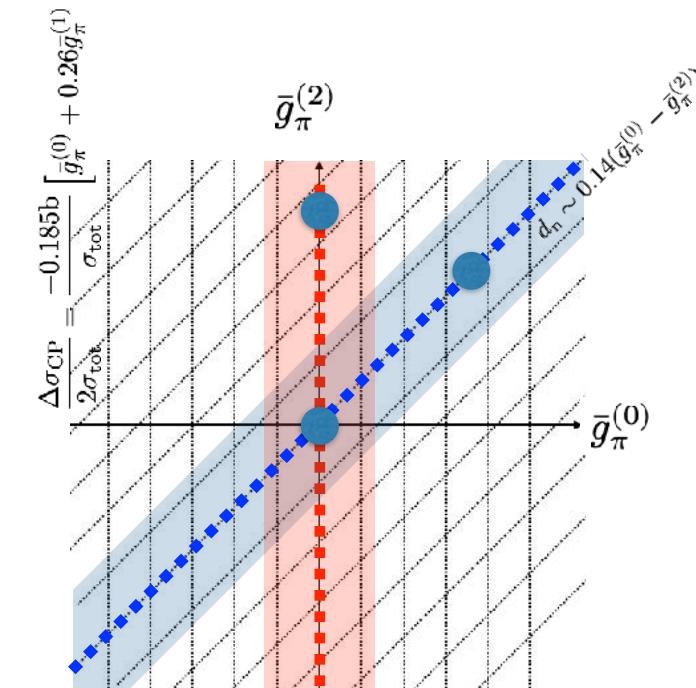
$n + p \rightarrow d + \gamma$

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

← neutron EDM

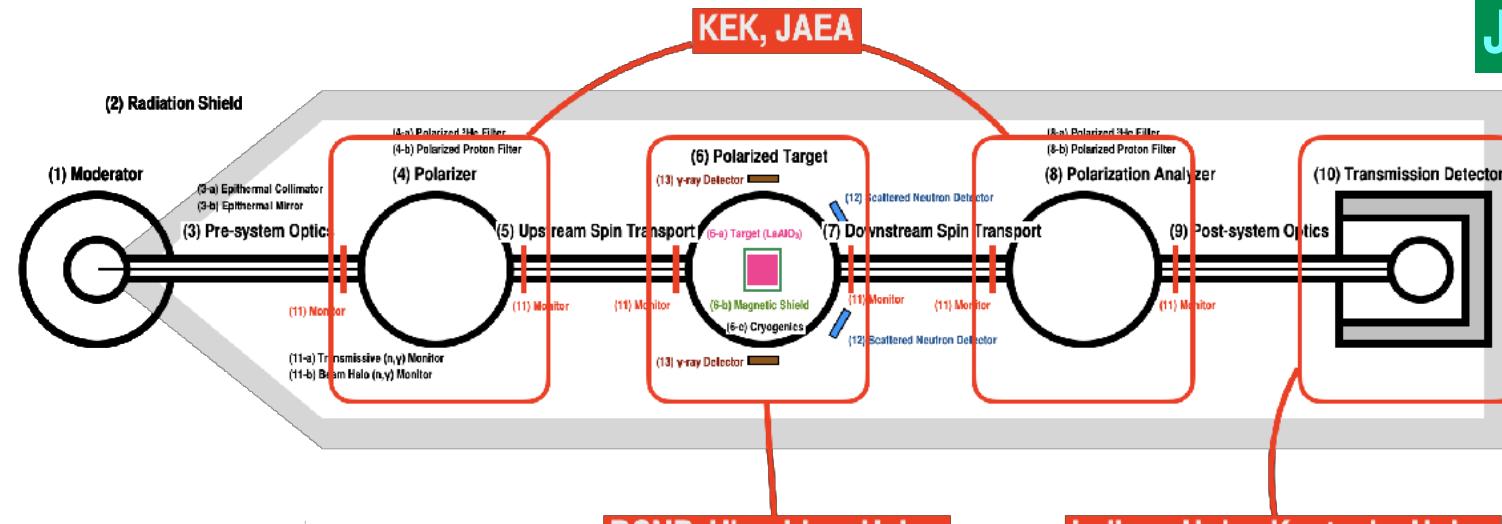
$$\left| \frac{\langle W_T \rangle}{\langle W \rangle} \right| < 3.9 \times 10^{-4}$$

← estimated discovery potential



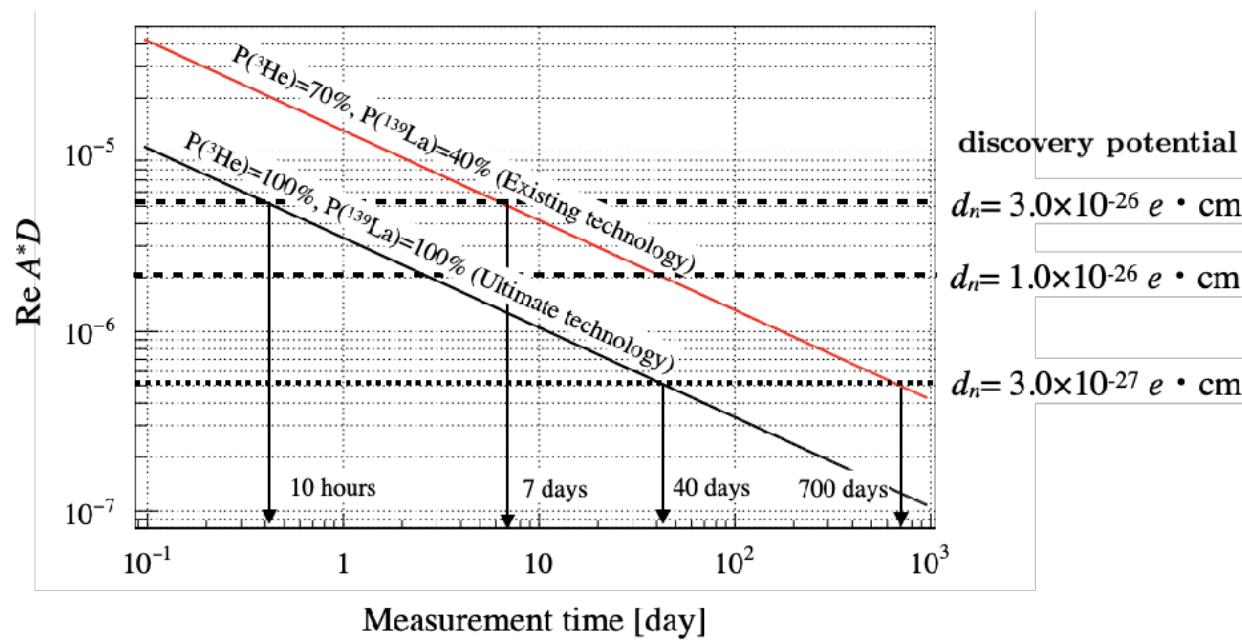
NOPTREX

Neutron Optical Parity and Time Reversal EXperiment

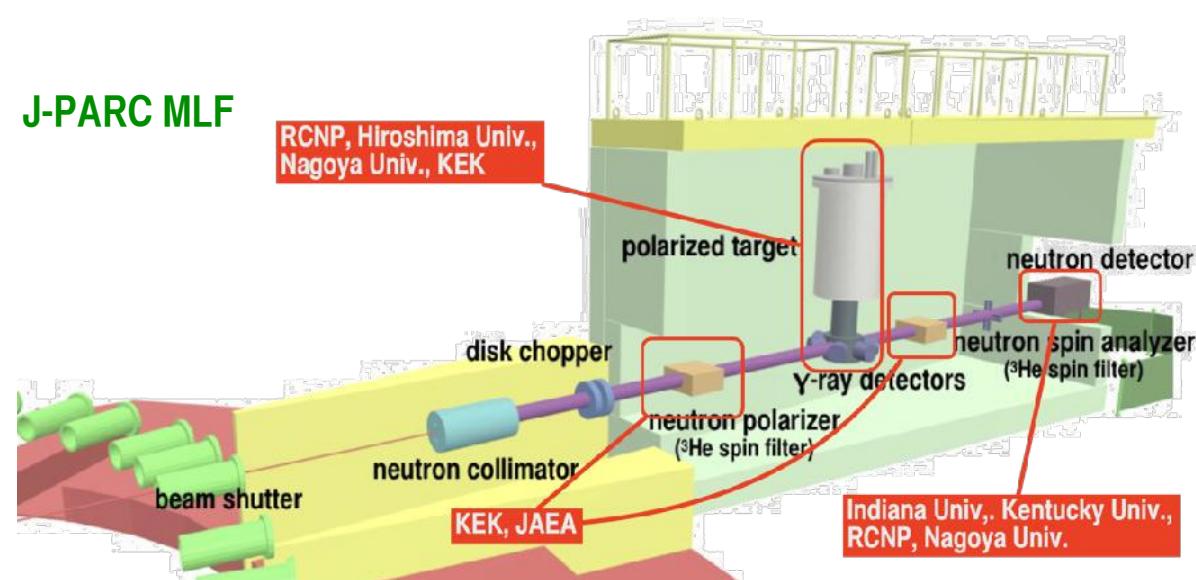


RCNP, Hiroshima Univ., Nagoya Univ., KEK

Indiana Univ., Kentucky Univ., RCNP, Nagoya Univ.



J-PARC MLF



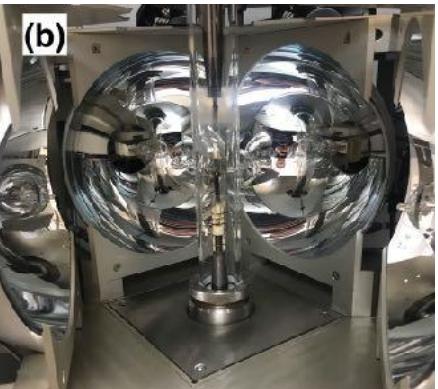
Development of Polarized Target

Study of Dynamic Nuclear Polarization
Study of Crystal Growth

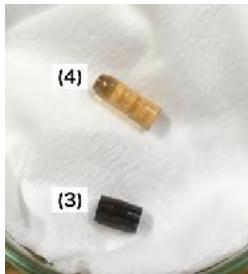
in progress under the support of

RCNP Project, Osaka University
Institute of Material Research, Tohoku University

Crystal Growth



IMR, Tohoku Univ.



IMR, Tohoku Univ.
Hiroshima Univ.
Nagoya Univ.

Dynamic Nuclear Polarization



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

RCNP, Osaka Univ.



Cryogenics



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

Development of
Refrigeration with Large
Cooling Power at Very Low
Temperature

Polarized Lanthanum Target



LaAlO_3
Nd-doped crystal
pure crystal

Active Control of Spin-lattice Relaxation Time

NSCBRD, Hiroshima Univ.
Hiroshima Univ.
Nagoya Univ.



Control of Spin-lattice Relaxation
Time via Optically-induced Triplet
Paramagnetism of Aromatic
Molecules

Development of Polarized Target

$\text{La}(\text{Nd}^{3+})\text{AlO}_3$ P.Hautle and M.Iinuma, Nucl. Instrum. Methods A440 (2000) 638

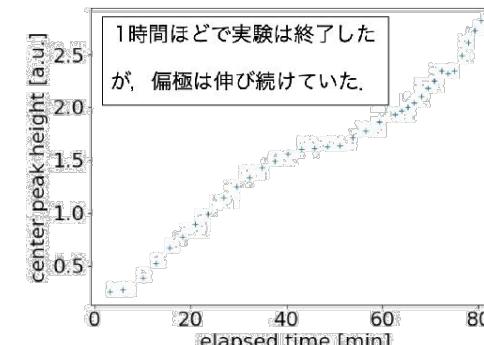
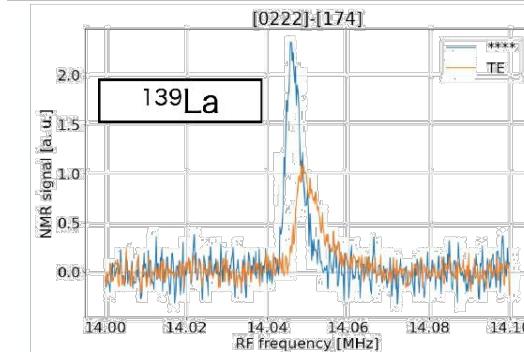
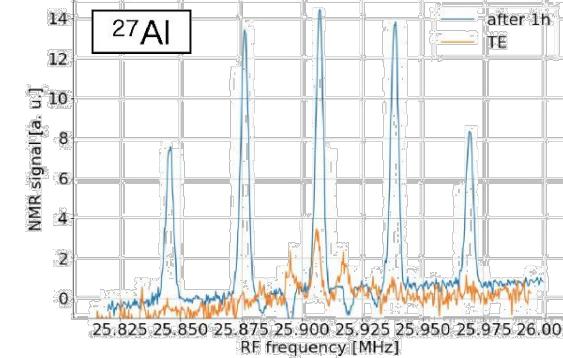
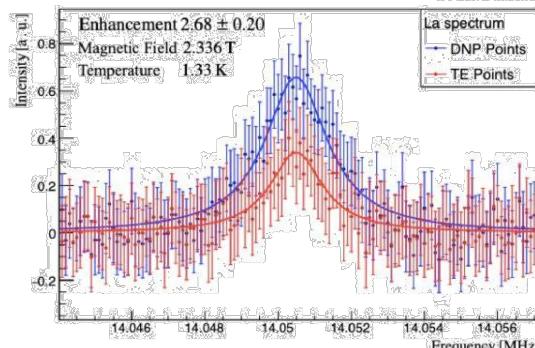
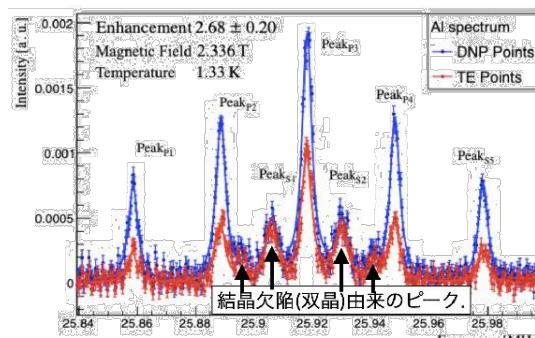
(Nd : 0.03mol%)

(Nd : 0.01mol%)



measurement of spin relaxation time

K.Ishizaki et al., arXiv:2105.06299
(accepted NIMA)





Neutron Optical Parity and Time Reversal EXperiment

^{139}La ^{117}Sn ^{131}Xe ^{115}In ^{81}Br ^{133}Cs ...

10^6 Enhancement of P-violation in Compound Nuclear States

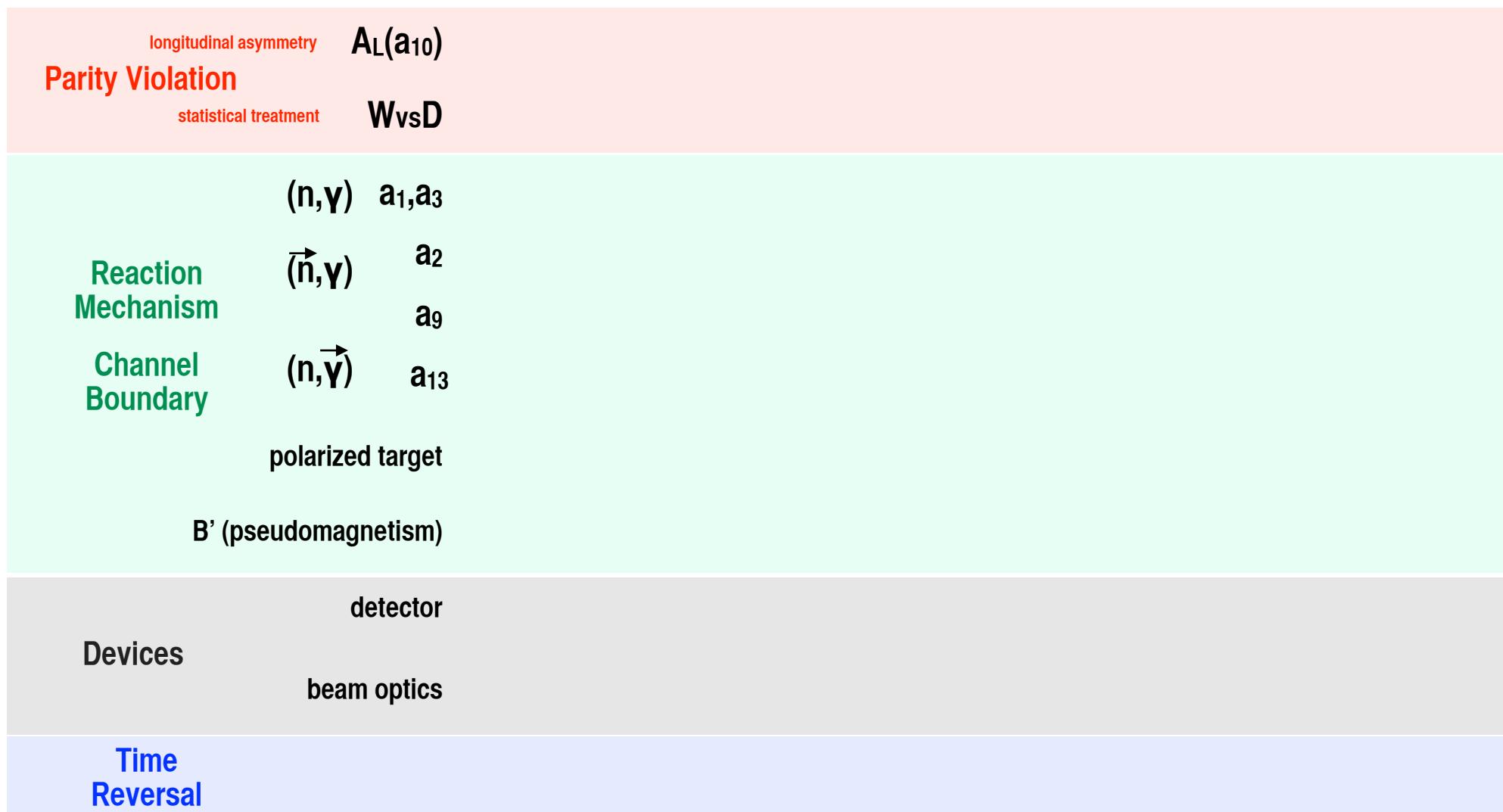
Interference between s- and p-waves in the entrance channel

Statistical nature of compound nuclear states

Reaction mechanism
direct process and compound process
(kinetic freedom dissipation → quantum decoherence?)

Polarized target and neutron spin control

↓
New physics search with enhanced sensitivity to T-violation



FY2020

		139La	131Xe	117Sn	Pd	81Br	111,113Cd	115In
Parity Violation	longitudinal asymmetry	A _L (a ₁₀) (a1)	studied before us	studied before us	studied before us		studied before us	studied before us
	statistical treatment	WvsD (a2)	studied before us	studied before us	studied before us	✓ in progress	studied before us	studied before us
Reaction Mechanism	(n,γ) a _{1,a₃} (β1)	DONE		✓ in progress	DONE			
	(n,γ) a ₂ (β2)	DONE						
	a ₉ (β3)		✓ in progress					
	(n,γ) a ₁₃ (β4)		✓ being prepared					
	polarized target (γ1)		✓ in progress	✓ in progress				
Channel Boundary	B' (pseudomagnetism) (γ2)		✓ under discussion	✓ in progress				
	detector (δ1)	✓ in progress	✓ in progress	✓ in progress	✓ in progress			
	beam optics (δ2)	✓ in progress	✓ in progress	✓ in progress	✓ in progress			
Time Reversal	(ε)	★	★					

		^{139}La	^{131}Xe	^{117}Sn	Pd	^{81}Br	$^{111,113}\text{Cd}$	^{115}In
Parity Violation	longitudinal asymmetry	$A_L(a_{10})$	(a1)	studied before us				
	statistical treatment	WvsD	(a2)	studied before us	studied before us	studied before us	in progress	studied before us
Reaction Mechanism	(n,γ)	a_1, a_3	($\beta 1$)	DONE	 in progress	DONE	DONE	DONE
	(\bar{n},γ)	a_2	($\beta 2$)	DONE		DONE	DONE	DONE
		a_9	($\beta 3$)	 in progress	 in progress	 in progress	 in progress	 in progress
	$(n,\vec{\gamma})$	a_{13}	($\beta 4$)					
	polarized target		($\gamma 1$)	 in progress	 in progress	 in progress	 in progress	 in progress
Channel Boundary	B' (pseudomagnetism)		($\gamma 2$)					
	detector		($\delta 1$)	 in progress	 in progress	 in progress	 in progress	 in progress
	beam optics		($\delta 2$)					
Time Reversal			(ϵ)					

		^{139}La	^{131}Xe	^{117}Sn	Pd	^{81}Br	$^{111,113}\text{Cd}$	^{115}In
Parity Violation	longitudinal asymmetry	$A_L(a_{10})$	(a1)	studied before us	studied before us	studied before us	studied before us	studied before us
	statistical treatment	WvsD	(a2)	studied before us	studied before us	studied before us	in progress	studied before us
Reaction Mechanism	(n,γ)	a_1, a_3	($\beta 1$)	DONE	✓ in progress	DONE		
	(\bar{n},γ)	a_2	($\beta 2$)	DONE		DONE		
Channel Boundary		a_9	($\beta 3$)	✓ in progress				
	$(n,\vec{\gamma})$	a_{13}	($\beta 4$)	✓ in progress				
Devices	polarized target		($\gamma 1$)	✓ in progress	✓ in progress			
	B' (pseudomagnetism)		($\gamma 2$)	✓ in progress	✓ in progress			
Time Reversal	detector		($\delta 1$)	✓ in progress	✓ in progress	✓ in progress		
	beam optics		($\delta 2$)	✓ in progress	✓ in progress	✓ in progress		

Summary

Some p-wave compound resonances enhance parity-violating effects.

due to dense quantum-mechanical freedom
in closely-located parity-unfavored states

Enhancement of time-reversal-breaking effects is expected.

(equivalent to CP-violating effects under the CPT-theorem)

Further study of P-enhancement mechanism and
device development for T-violation are in progress.



Neutron Optical Parity and Time Reversal EXperiment

NOPTREX

Neutron Optical Parity and Time Reversal EXperiment

Nagoya Univ.

H.M.Shimizu, M.Kitaguchi, T.Okudaira, K.Ishizaki, I.Ido,
H.Tada, H.Hotta, T.Hasegawa, Y.Ito, N.Wada,
T.Matsushita

Kyushu Univ.

T.Yoshioka, S.Takada, J.Koga

JAEA

S.Endo, A.Kimura, H.Harada, K.Sakai, T.Oku

Osaka Univ.

T.Shima, H.Yoshikawa, K.Ogata, H.Kohri, M.Yosoi

Tokyo Inst. Tech.

H.Fujioka, Y.Tani, K.Kameda

Hirosshima Univ.

M.Iinuma, M.Abe, S.Wada

Yamagata Univ.

T.Iwata, Y.Miyachi, D.Miura

Tohoku Univ.

M.Fujita, Y.Ikeda, T.Taniguchi

KEK

T.Ino, S.Ishimoto, K.Hirota, K.Taketani,
K.Mishima, G.Ichikawa

Kyoto Univ.

K.Hagino, Y.I.Takahashi, M.Hino

RIKEN

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Ashikaga Univ.

D.Takahashi

Japan Women's Univ.

R.Ishiguro

Univ. British Columbia

T.Momose

Kyungpook Univ.

G.N.Kim, S.W.Lee, H.J.Kim

CSNS, IHEP

J.Tang, X.Tong, J.Wei, G.Y.Luan

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W.M.Snow, C.Auton, J.Carini, J.Curole,
K.Dickerson, J.Doskow, H.Lu, G.Otero,
J.Vanderwerp, G.Visser

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V.Gudkov

Oak Ridge National Lab.

J.D.Bowman, S.Penttila, P.Jiang

Univ. Kentucky

C.Crawford, B.Plaster, H.Dhahri

Los Alamos National Lab.

D.Schaper

Southern Illinois Univ.

B.M.Goodson

Middle Tennessee State Univ.

R.Mahurin

Eastern Kentucky Univ.

J.Fry

Western Kentucky Univ.

I.Novikov

UNAM

L.Barron-Palos, A.Perez-Martin

Berea College

M.Veillette

PSI

P.Hautle

NIST

C.C.Haddock

Ohio Univ.

P.King

Juelich

E.Babcock

Nottingham

M.Barlow

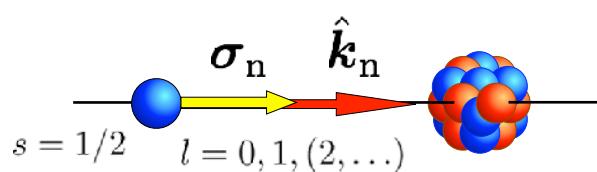
Depauw

A.Komives

BACKUP/APPENDIX

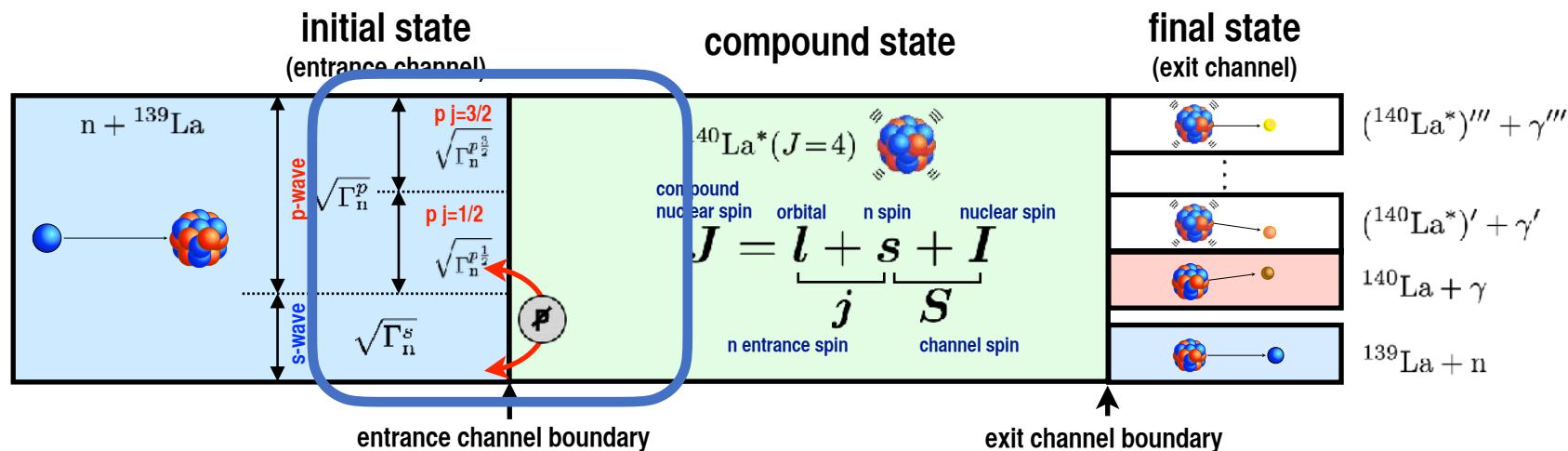
Enhancement Mechanism (questions from us)

Enhancement Mechanism

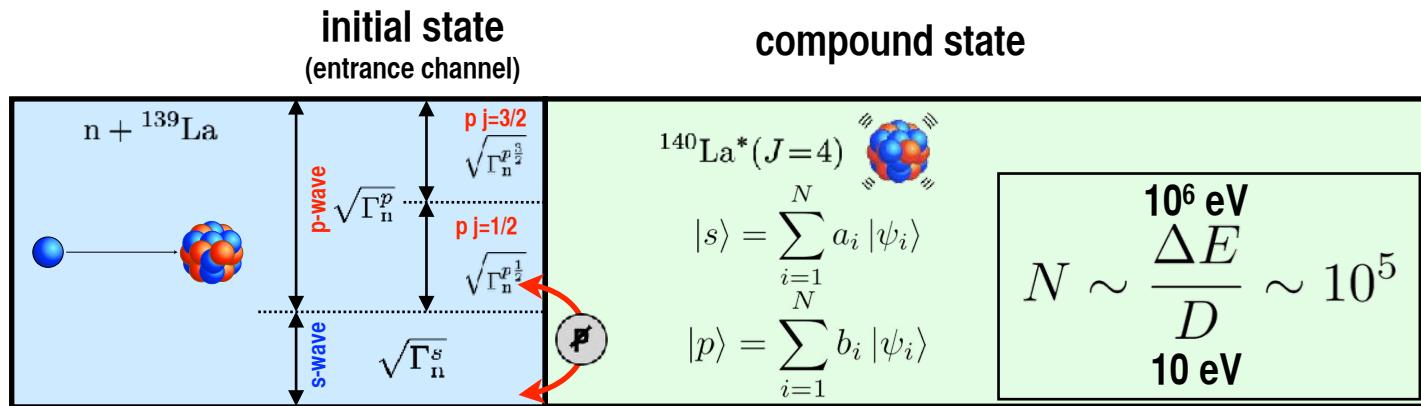


$$\sigma = \sigma_0 + \boxed{\Delta\sigma} (\boldsymbol{\sigma}_n \cdot \hat{\mathbf{k}}_n)$$

10⁻⁷ for NN



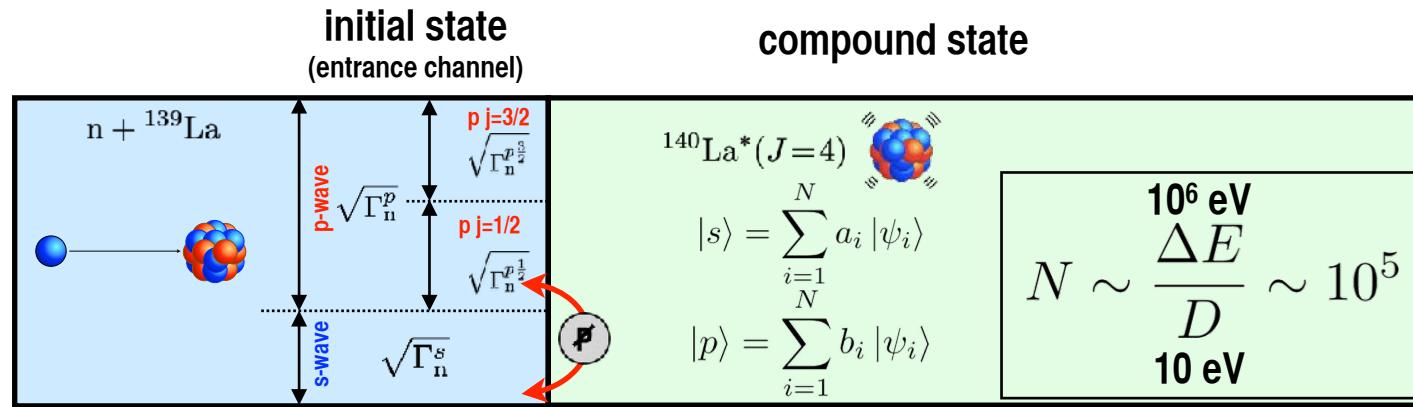
$$\langle s | W | p \rangle = \sum_{i,j}^N a_i^* b_j \langle \psi_i | W | \psi_j \rangle$$



$$\sim \frac{1}{\sqrt{N}} \frac{1}{\sqrt{N}} \langle W \rangle \sqrt{N}$$

randomness of expansion coefficients

Enhancement Mechanism



$$\langle s|W|p\rangle = \sum_{i,j}^N a_i^* b_j \langle \psi_i|W|\psi_j\rangle$$

$$\sim \frac{1}{\sqrt{N}} \frac{1}{\sqrt{N}} \langle W \rangle \sqrt{N}$$

randomness of expansion coefficients

compound state = strongly correlated (isolated) quantum system

enhancement = deviation of perturbative symmetry-breaking of randomly distributed contributions in the densely correlated quantum system with huge number of freedom

direct connection between the entrance channel to the compound state

We are going to apply this statistical nature to search for new physics.
How reliably can we expect the enhancement of T-violation?

How does the system evolve from the entrance channel to the compound state?

entrance channel : wave-like compound state : particle-like (looks quantum mechanically uncorrelated accumulation)

Friction? Where does it come from?

Intermediate channel(s) seems very thin (since the cross section and correlation terms are consistent with Breit-Wigner-type amplitudes).

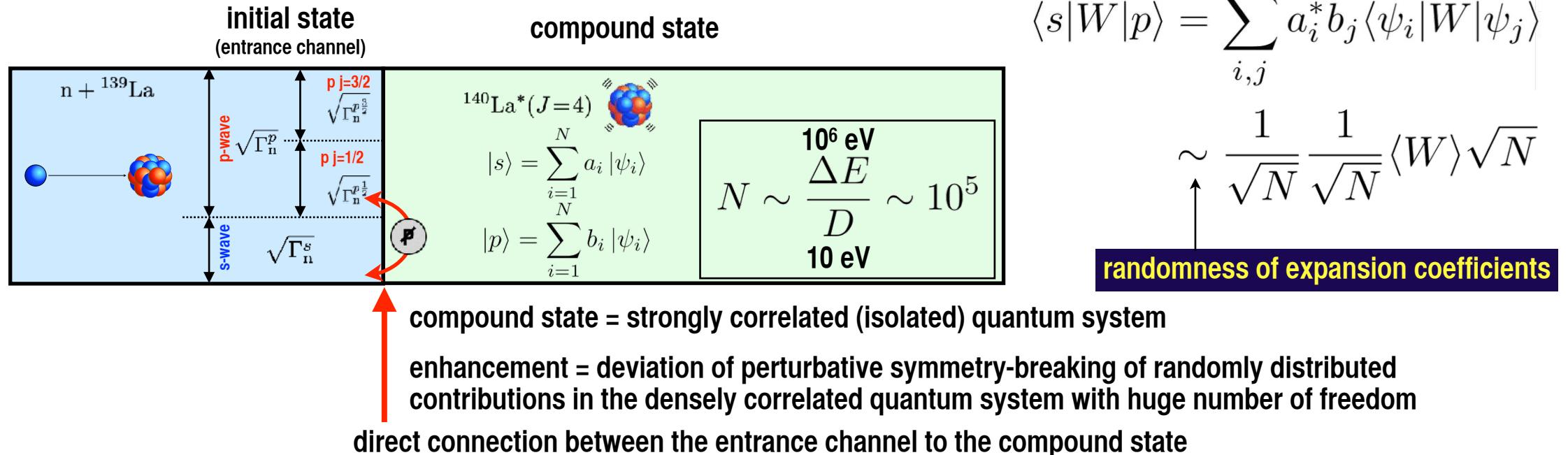
How precisely valid? <- The large enhancement may be built very quickly due to possible quantum mechanical random walk?

Microscopic assessment of the random matrix theory may be difficult.

Accumulation of experimental results, which deny hypothetical possibilities out of random matrix theory, may be the possible approach.

What kind of observables is appropriate to pick up deviations from the random matrix theory?

Enhancement Mechanism



We are going to apply this statistical nature to search for new physics.
How reliably can we expect the enhancement of T-violation?

What kind of observables is appropriate to pick up deviations from the random matrix theory?

deviation from the
Porter-Thomas distribution

“Anomalous Fluctuations of s-Wave Reduced Neutron Widths of $^{192,194}\text{Pt}$ Resonances”
P.E.Koehler et al., Phys. Rev. Lett. 105 (2010) 072502
“Neutron Resonance Widths and the Porter-Thomas Distribution”
A.Volya, H.A.Weidenmuller, V.Zelevinsky, Phys. Rev. Lett. 115 (2015) 052501

What is the possible effect(s) to the enhanced sensitivity to T-violation?
(under the constraint of the experimentally observed P-violation enhancement)