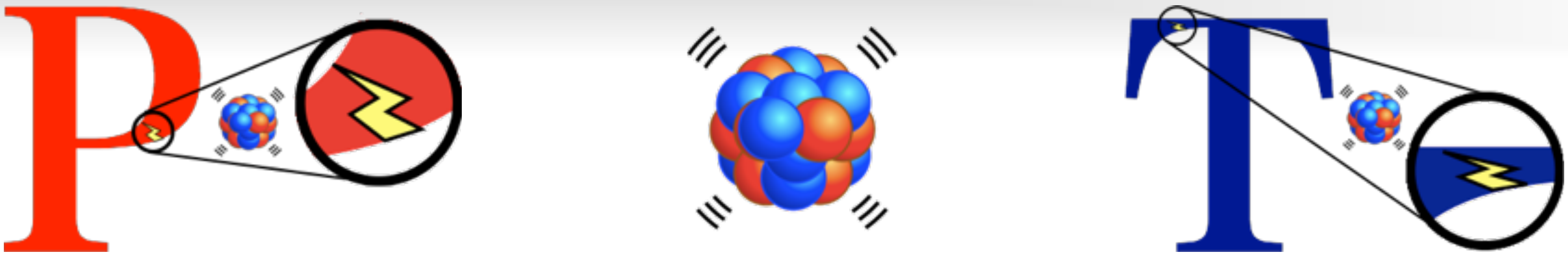

Discrete Symmetry Tests in Neutron-induced Compound States

@ Adelaide, Australia
2016/09/16

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and W.M.Snow, V.V.Gudkov
on behalf of NOPTREX Collaboration

Discrete Symmetries in Quantum Field Theory

Charge conjugation

Parity (spatial inversion)

Time reversal

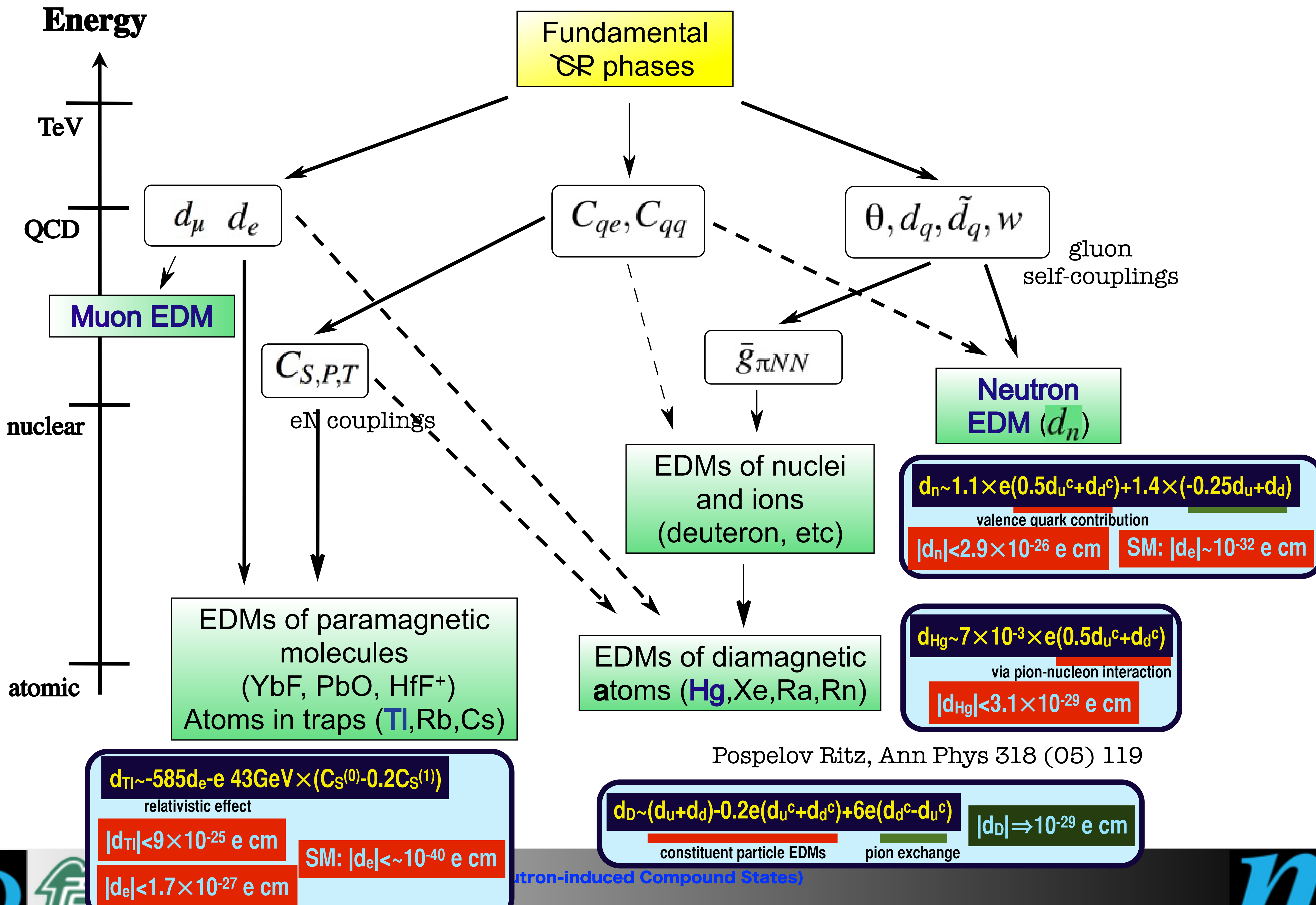
$$CPT = 1$$

$$CP \neq 1 \qquad T \neq 1$$

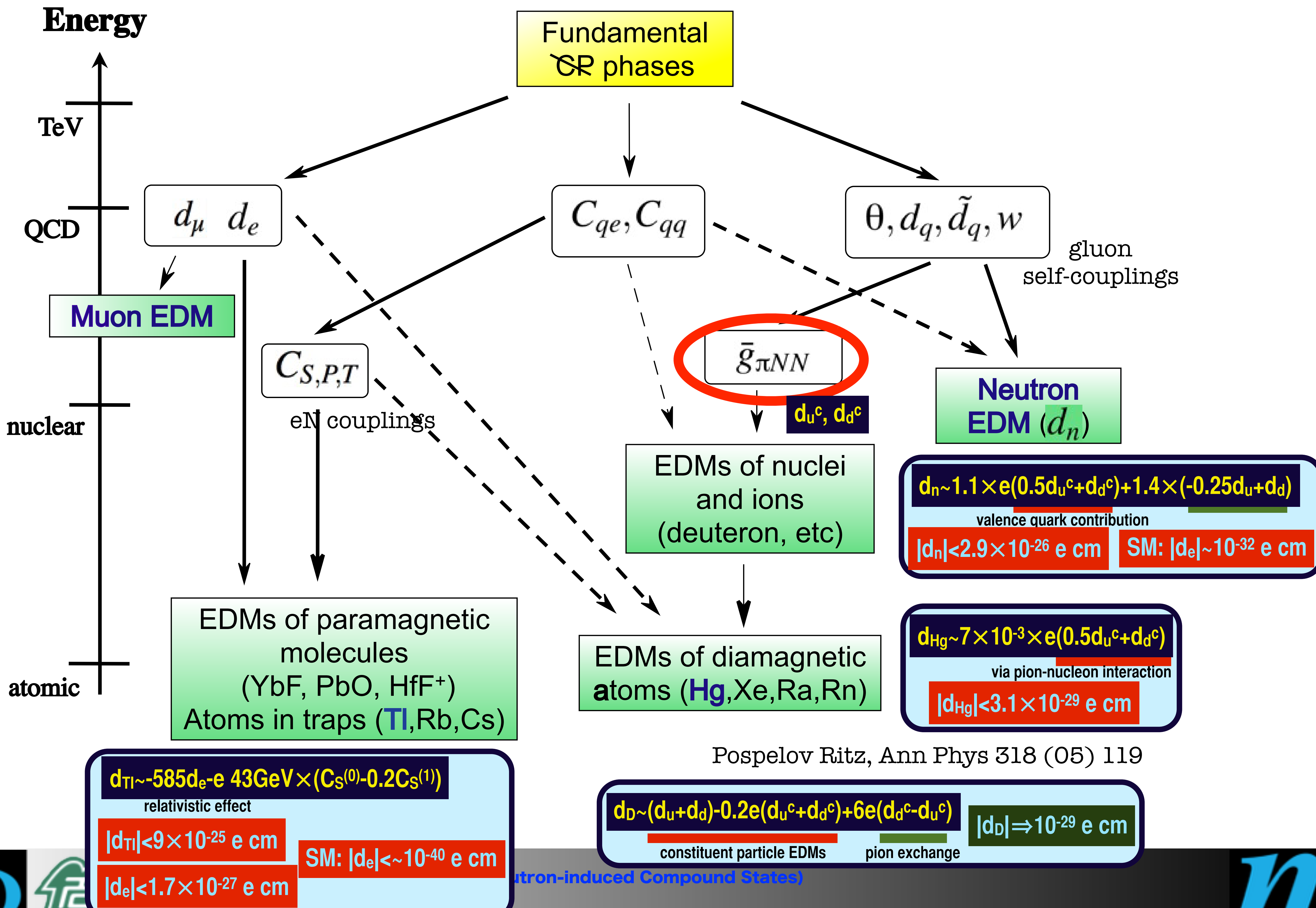
CP-phase in CKM-matrix is not sufficient to explain the baryon asymmetry

New physics related to additional CP-phase is strongly desired.

CP-violation in Low Energy Phenomena

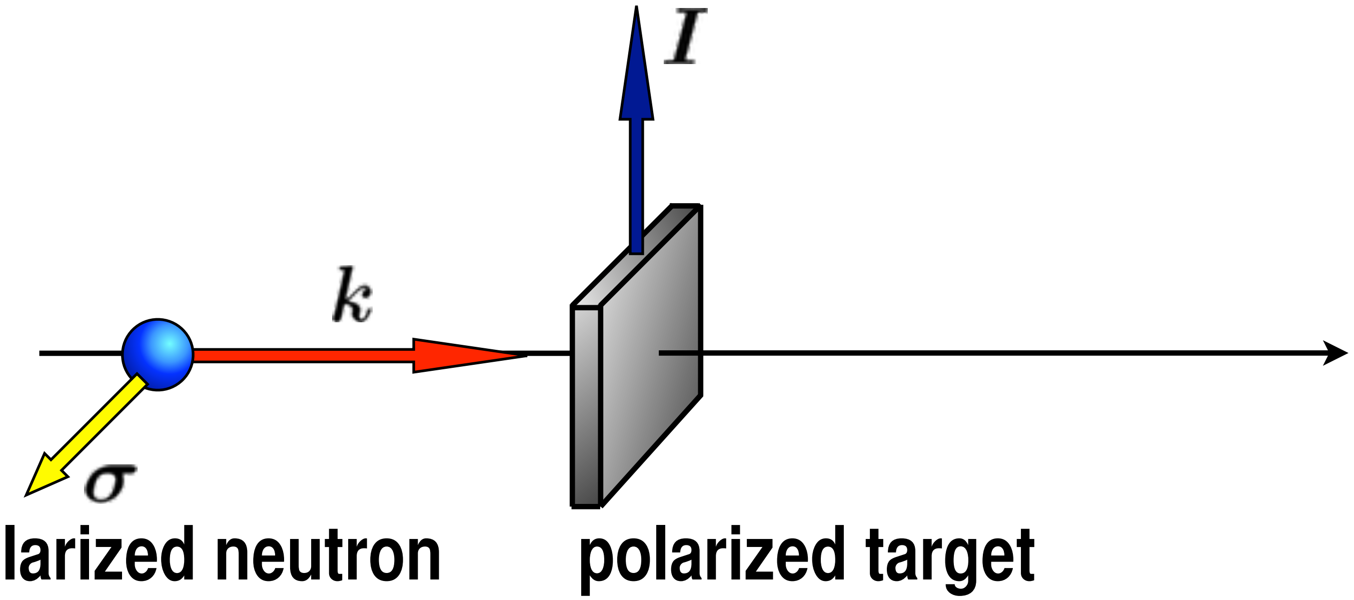


CP-violation in Low Energy Phenomena



T-violation in Neutron Optics

KEK-2015S12 “Applications of Pulsed Polarized Epithermal Neutrons”



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

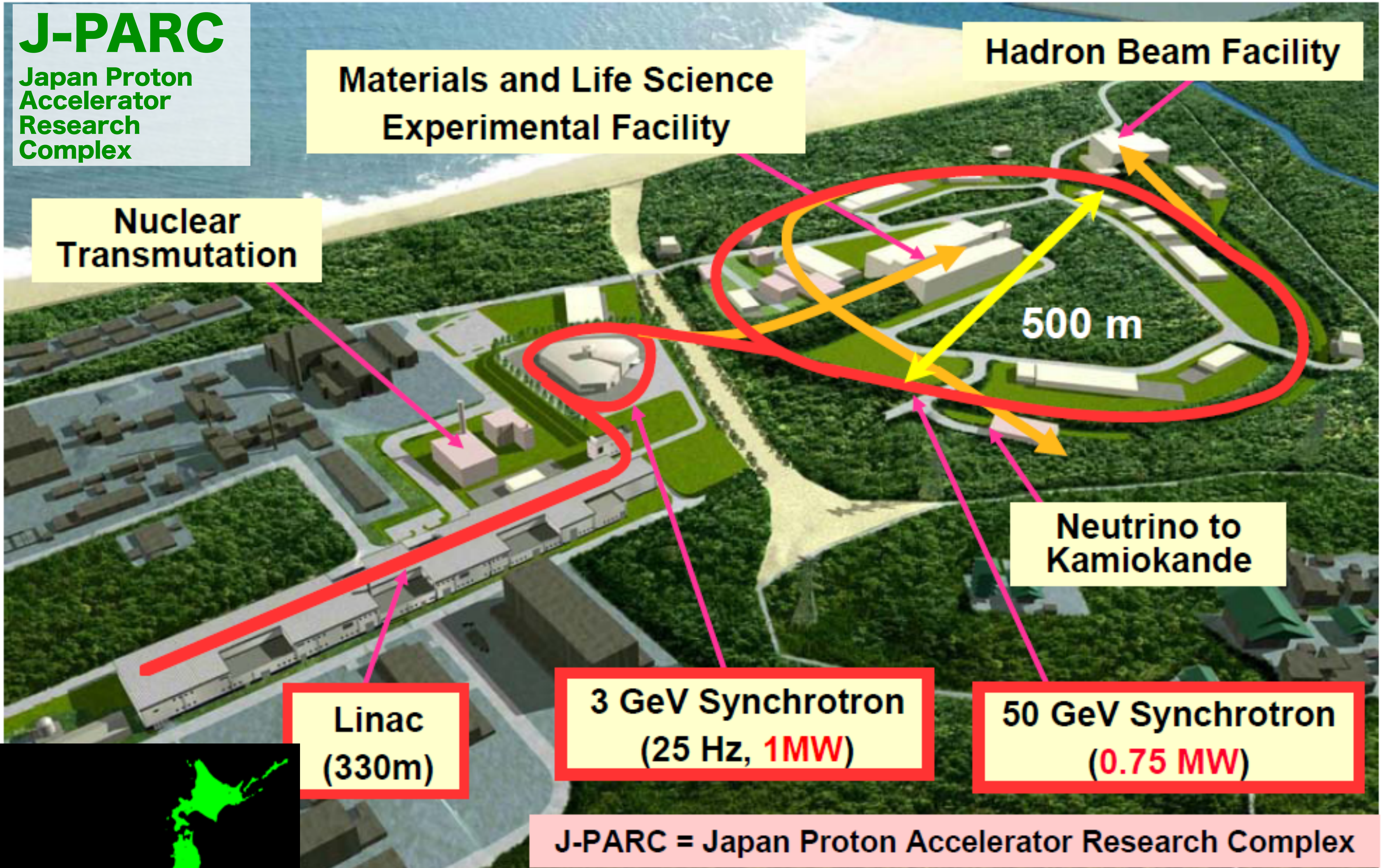
- A': Spin Independent, P-even T-even
- B': Spin Dependent, P-even T-even
- C': P-violation, P-odd T-even
- D': T-violation, P-odd T-odd

final-state-interaction free

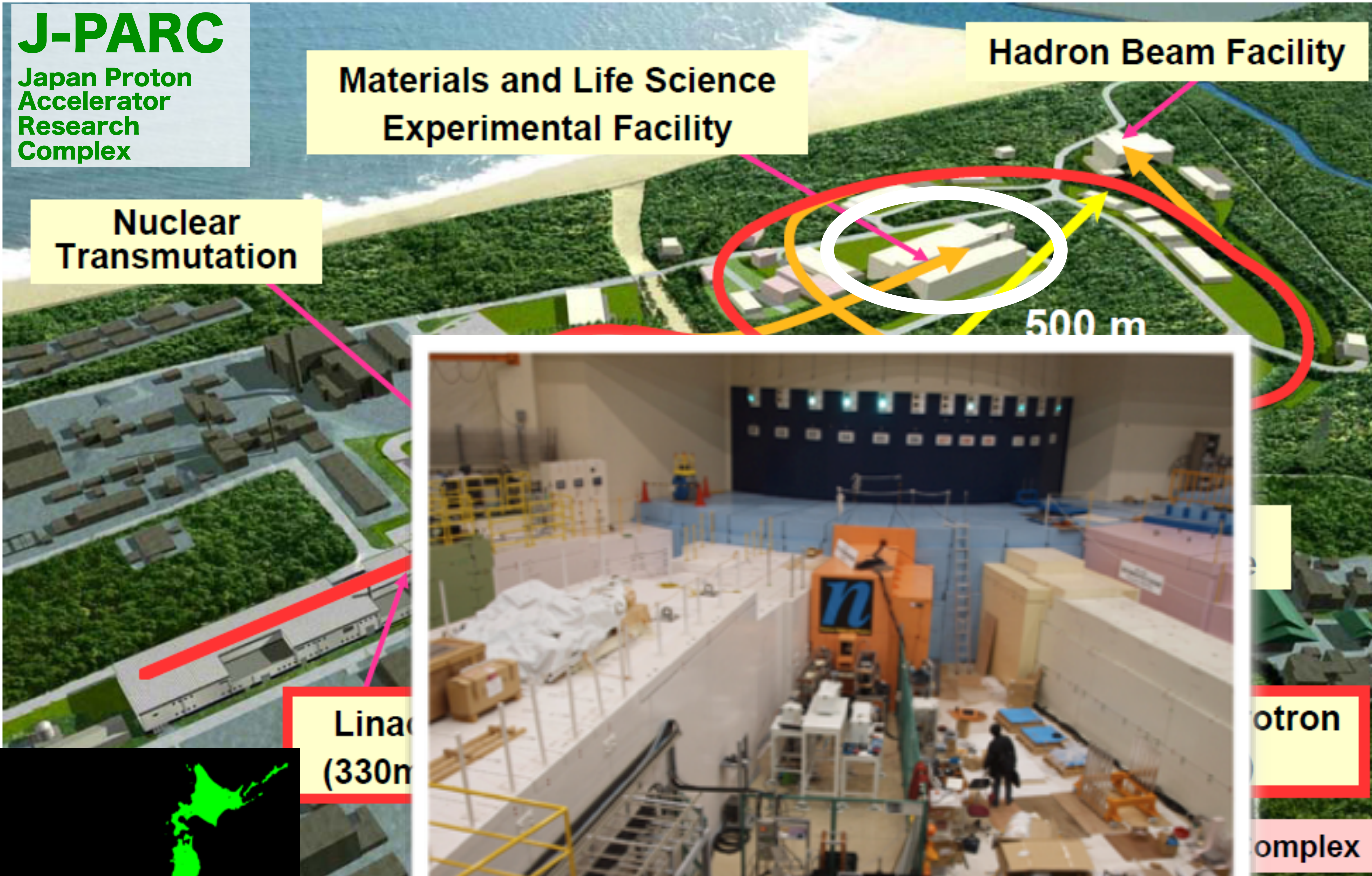
enhanced sensitivity to T-violation in compound states

toward new physics beyond the standard model via CP-violation

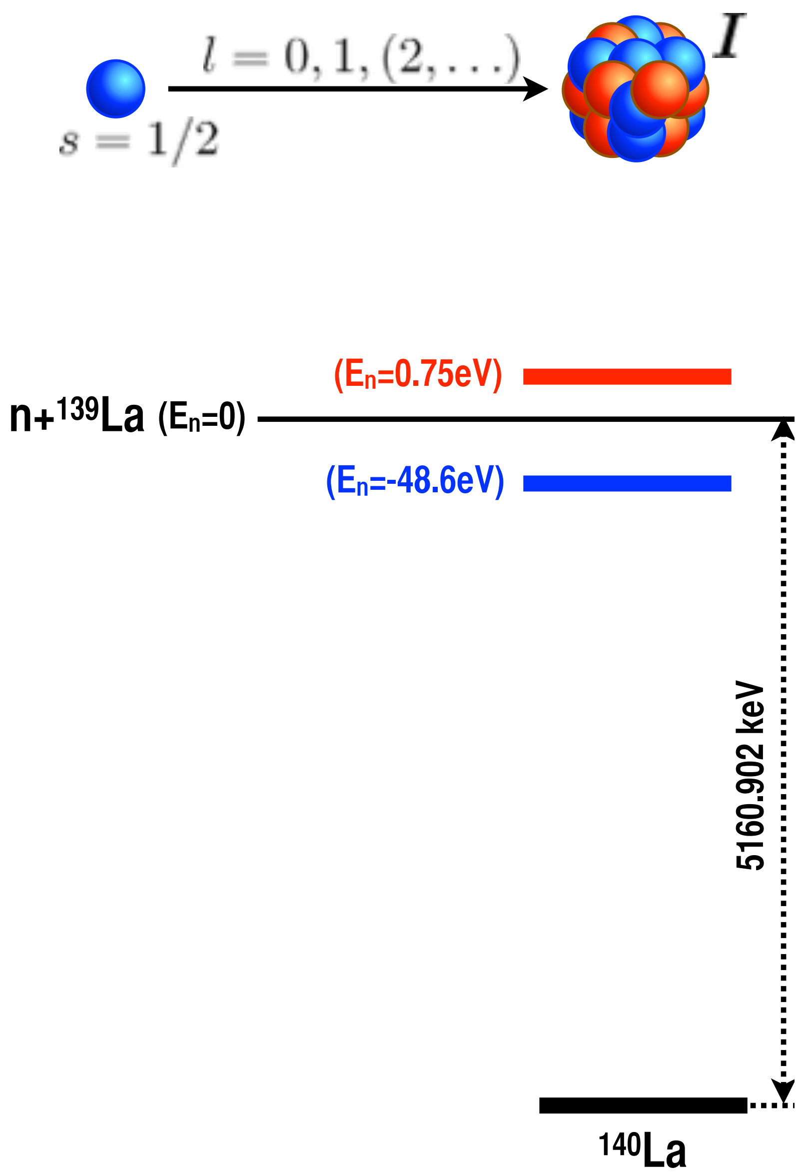
enabled by short-pulse spallation neutron sources

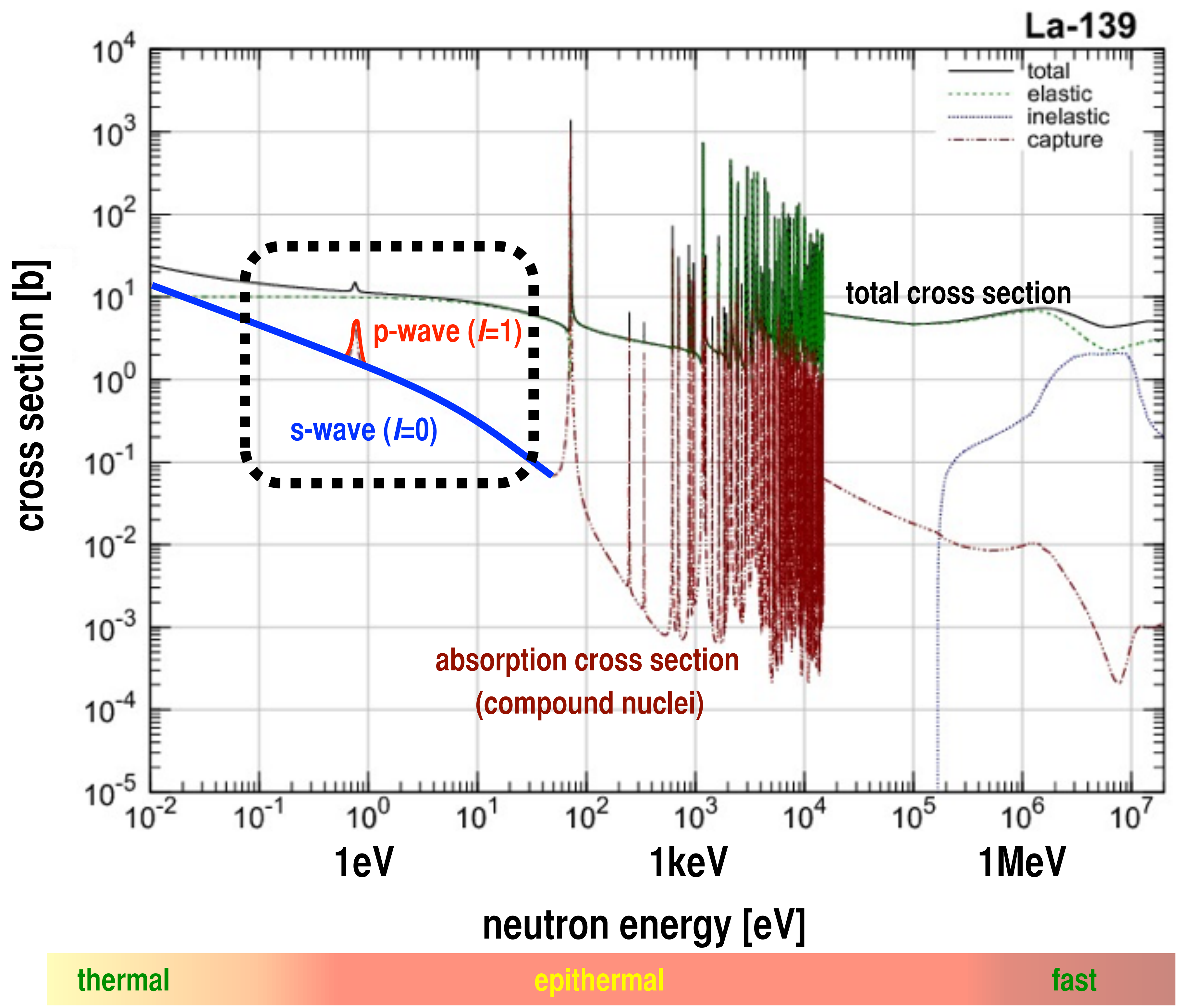


Joint Project between KEK and JAEA


J-PARC
Japan Proton Accelerator Research Complex
Materials and Life Science Experimental Facility
Hadron Beam Facility
Nuclear Transmutation
500 m

Compound States





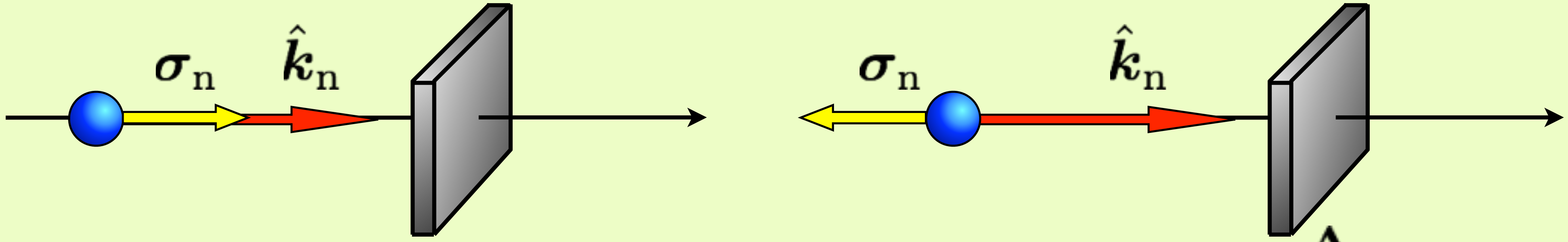
Projectile-Helicity Dependent Asymmetry (A_L)

P (spatial inversion)

	$\boldsymbol{\sigma}_\mathrm{n}$	$\hat{\boldsymbol{k}}_\mathrm{n}$	$\boldsymbol{\sigma}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\mathrm{n}$
P	$\updownarrow$	$\updownarrow$	$\updownarrow$ **P-odd**
	$\boldsymbol{\sigma}_\mathrm{n}$	$-\hat{\boldsymbol{k}}_\mathrm{n}$	$-\boldsymbol{\sigma}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\mathrm{n}$

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

P-violation ($\Delta\sigma$)



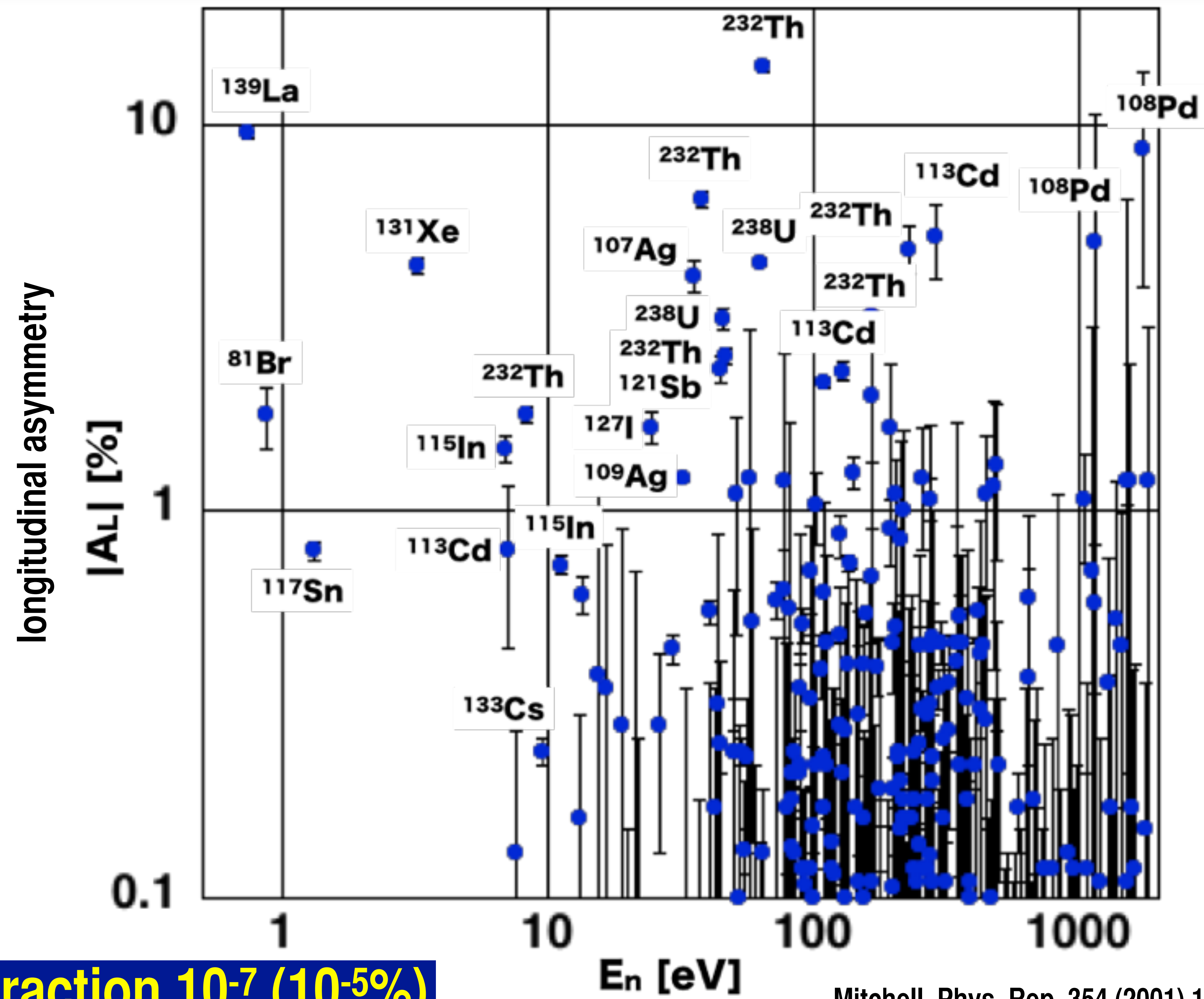
$$\sigma_+ = \sigma_0 + \Delta\sigma \qquad \sigma_- = \sigma_0 - \Delta\sigma$$

$$A_\mathrm{L} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}\left(=\frac{\Delta\sigma}{\sigma_0}\right)$$

Longitudinal Asymmetry

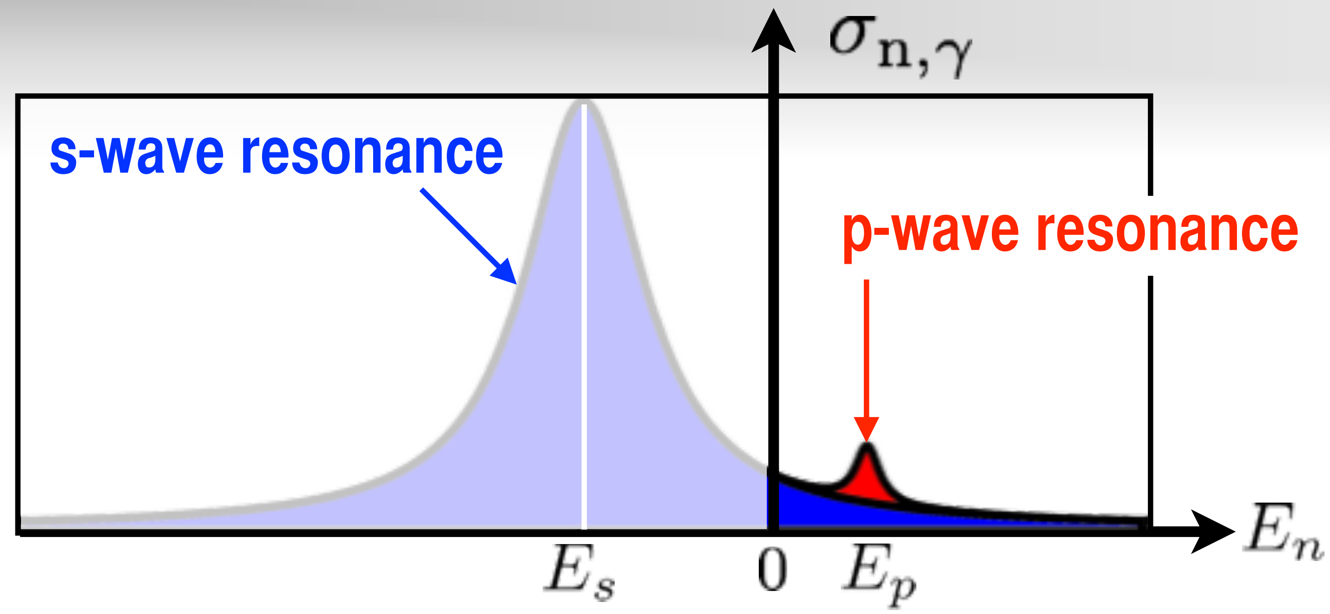
NN-interaction 10^{-7} (10^{-5}%)

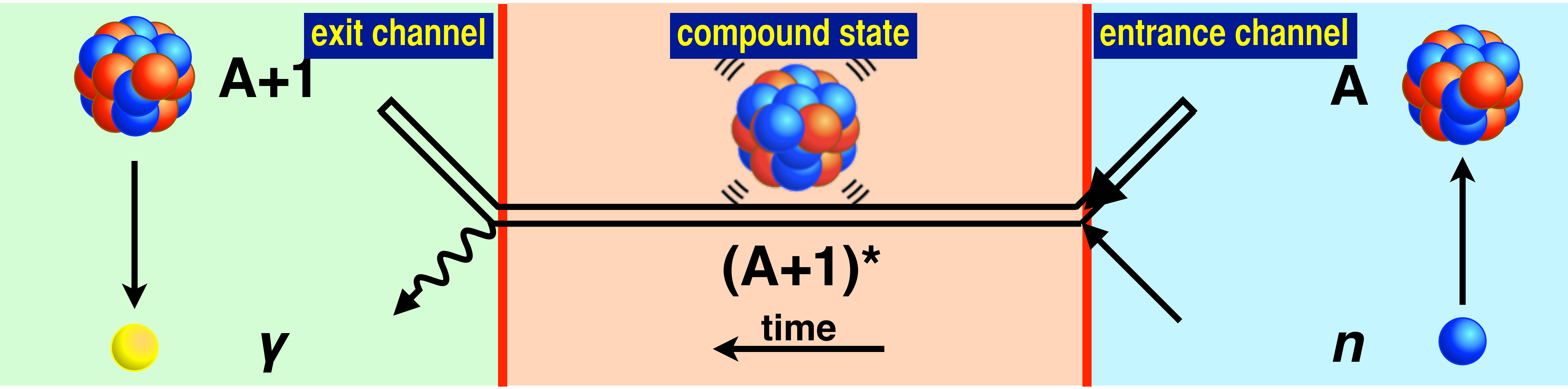
Enhanced P-violation in Compound States



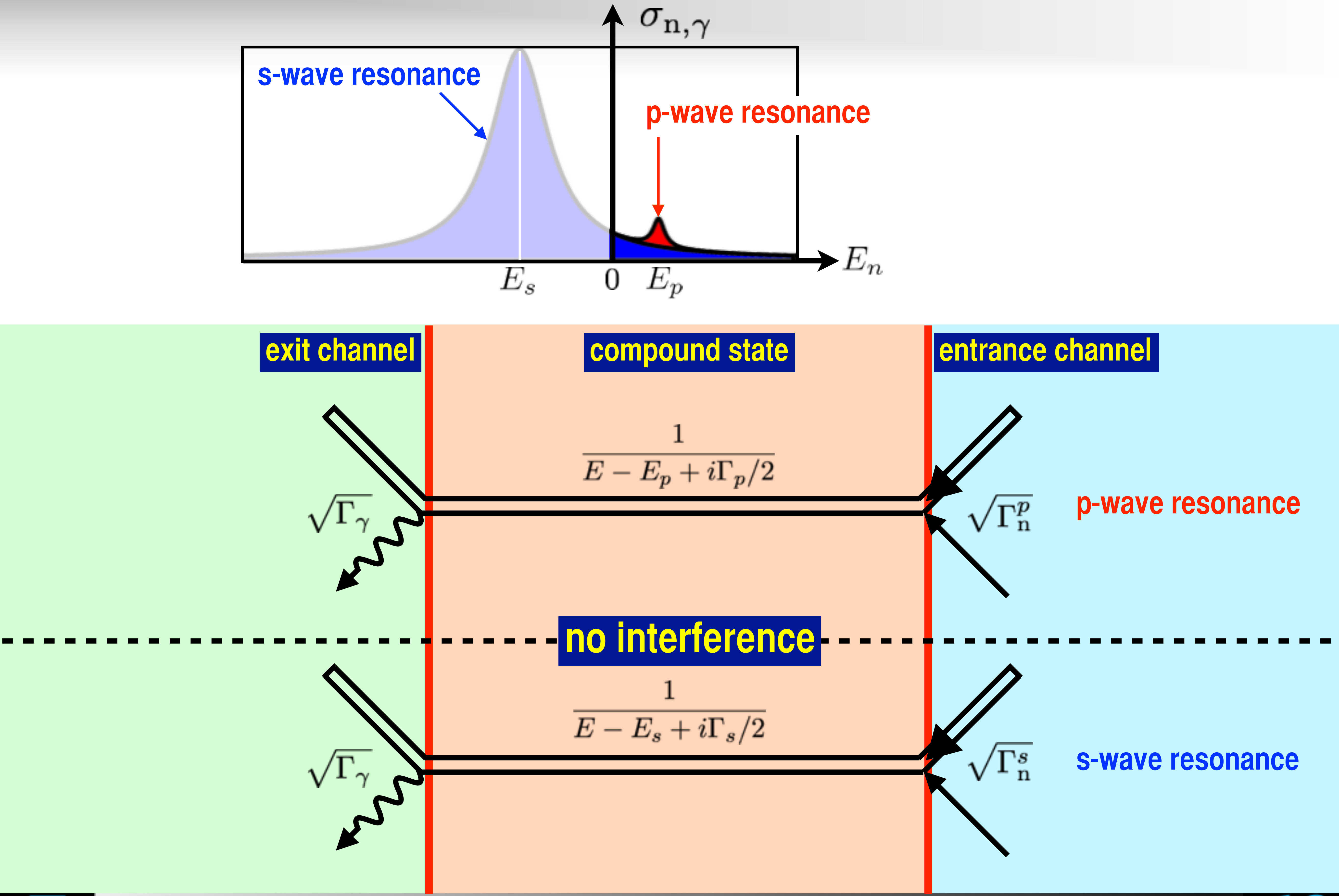
NN-interaction 10^{-7} (10^{-5}%)

Mitchell, Phys. Rep. 354 (2001) 157

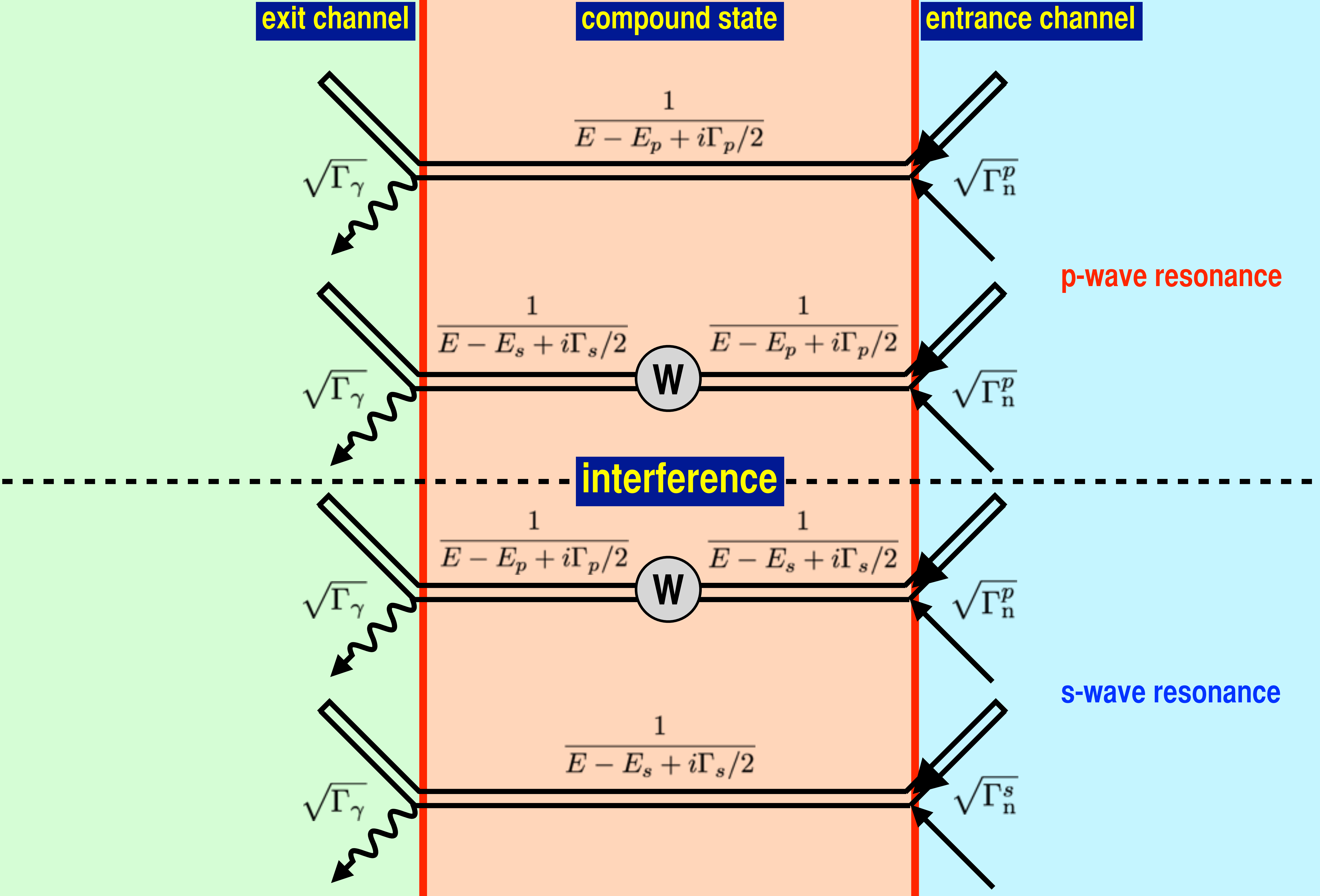




$$\sqrt{\Gamma_\gamma}\,\frac{1}{E - E_0 + i\Gamma/2}\,\sqrt{\Gamma_n}$$



$\sigma_{n,\gamma}$
s-wave resonance
p-wave resonance
E_n
E_s
0
E_p
exit channel
compound state
entrance channel
$\frac{1}{E - E_p + i\Gamma_p/2}$
$\sqrt{\Gamma_\gamma}$
$\sqrt{\Gamma_n^p}$
p-wave resonance
no interference
$\frac{1}{E - E_s + i\Gamma_s/2}$
$\sqrt{\Gamma_\gamma}$
$\sqrt{\Gamma_n^s}$
s-wave resonance

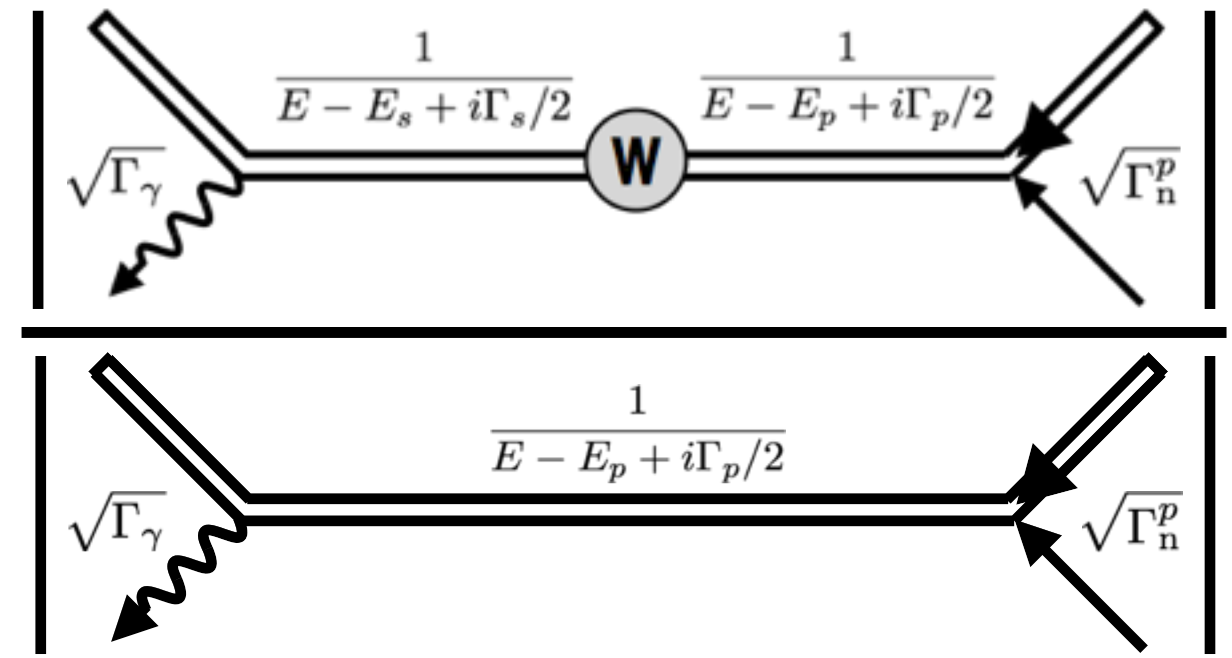

exit channel
compound state
entrance channel
$\frac{1}{E-E_p+i\Gamma_p/2}$
$\sqrt{\Gamma_\gamma}$
$\sqrt{\Gamma_n^p}$
p-wave resonance
$\frac{1}{E-E_s+i\Gamma_s/2}$
W
$\frac{1}{E-E_p+i\Gamma_p/2}$
$\sqrt{\Gamma_\gamma}$
$\sqrt{\Gamma_n^p}$
interference
$\frac{1}{E-E_p+i\Gamma_p/2}$
W
$\frac{1}{E-E_s+i\Gamma_s/2}$
$\sqrt{\Gamma_\gamma}$
$\sqrt{\Gamma_n^p}$
s-wave resonance
$\frac{1}{E-E_s+i\Gamma_s/2}$
$\sqrt{\Gamma_\gamma}$
$\sqrt{\Gamma_n^s}$

Enhancement of P-violation

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

Parity-conserving Parity-non-conserving

$$\alpha = \frac{2\mathrm{Re} f_{\mathrm{PC}} f^*_{\mathrm{PNC}}}{|f_{\mathrm{PC}}|^2} \sim 2\frac{|f_{\mathrm{PNC}}|}{|f_{\mathrm{PC}}|} \sim 2$$



$$= 2\frac{\left|\sqrt{\Gamma^p_\gamma}\frac{1}{E - E_p + i\Gamma_p/2} W \frac{1}{E - E_s + i\Gamma_s/2}\sqrt{\Gamma^s_n}\right|}{\left|\sqrt{\Gamma^p_\gamma}\frac{1}{E - E_p + i\Gamma_p/2}\sqrt{\Gamma^p_n}\right|} \underset{E=E_p}{\sim} 2\frac{W}{|E_p - E_s|}\sqrt{\frac{\Gamma^s_n}{\Gamma^p_n}}$$

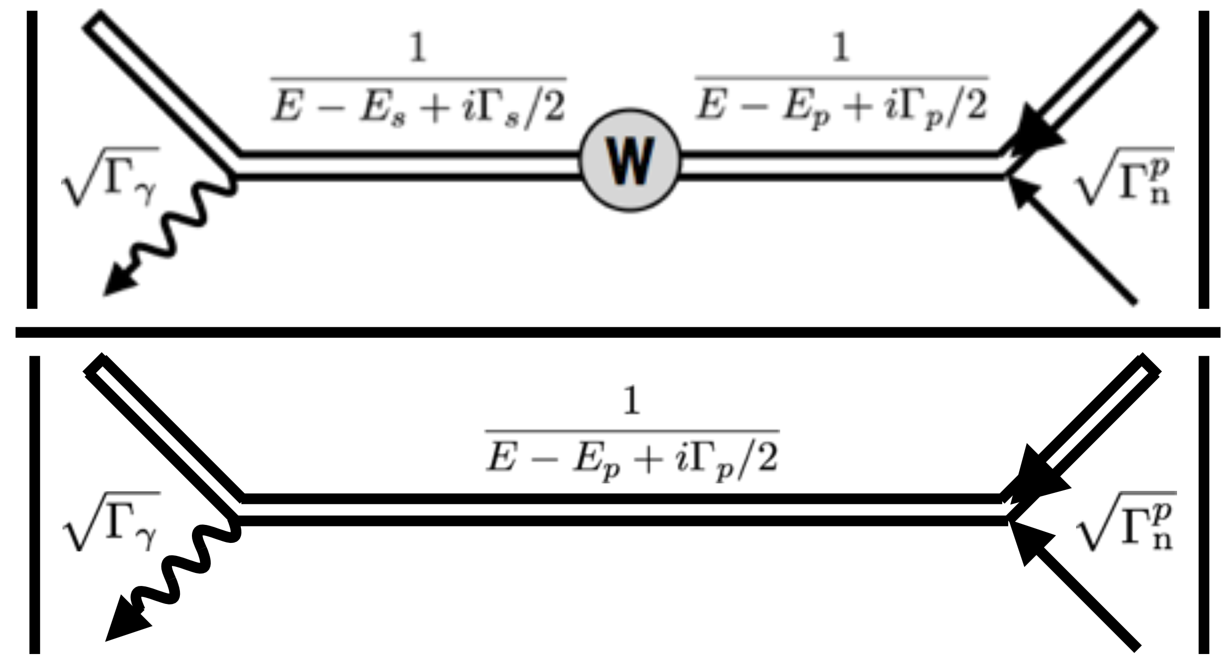
kinematical enhancement 10^3

Enhancement of P-violation

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

Parity-conserving   Parity-non-conserving

$$\alpha = \frac{2\mathrm{Re} f_{\mathrm{PC}} f^*_{\mathrm{PNC}}}{|f_{\mathrm{PC}}|^2} \sim 2\frac{|f_{\mathrm{PNC}}|}{|f_{\mathrm{PC}}|} \sim 2$$

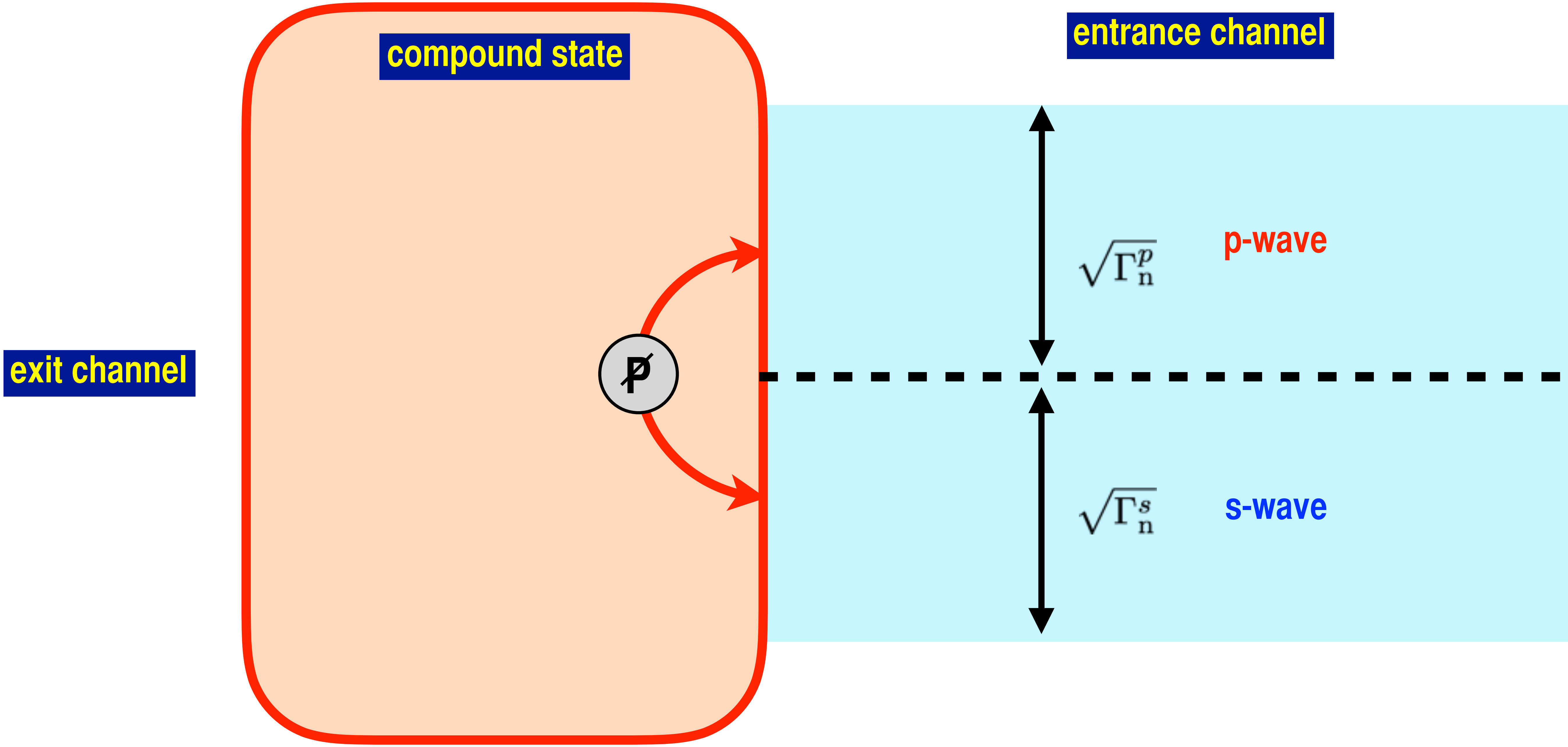


$$= 2\frac{\left|\sqrt{\Gamma^p_\gamma}\frac{1}{E - E_p + i\Gamma_p/2} W \frac{1}{E - E_s + i\Gamma_s/2}\sqrt{\Gamma^s_{\mathrm{n}}}\right|}{\left|\sqrt{\Gamma^p_\gamma}\frac{1}{E - E_p + i\Gamma_p/2}\sqrt{\Gamma^p_{\mathrm{n}}}\right|} \underset{E=E_p}{\sim} 2\frac{W}{|E_p - E_s|}\sqrt{\frac{\Gamma^s_{\mathrm{n}}}{\Gamma^p_{\mathrm{n}}}}$$

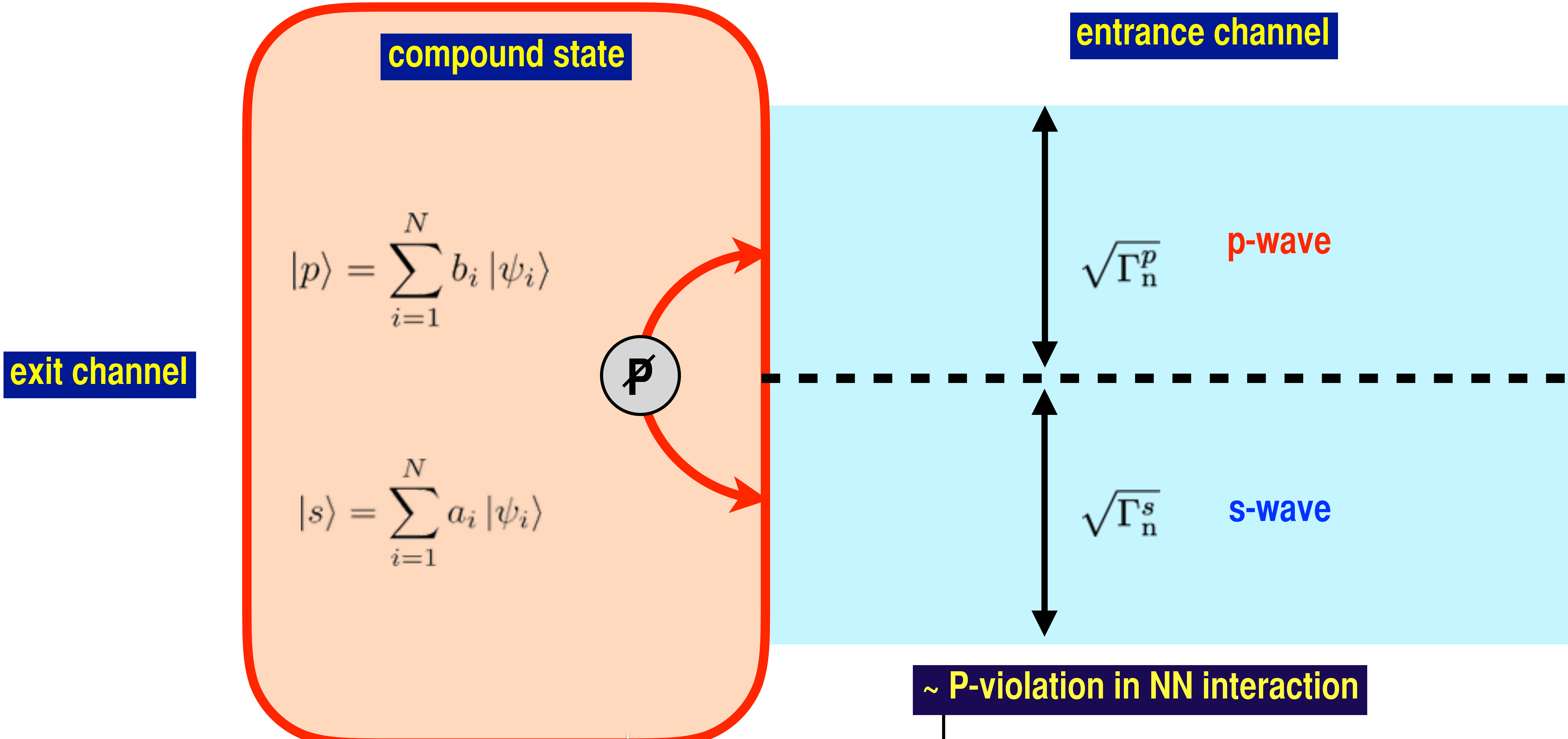
dynamical enhancement 10^2-10^3

kinematical enhancement 10^3

Dynamical Enhancement



Dynamical Enhancement



~ P-violation in NN interaction

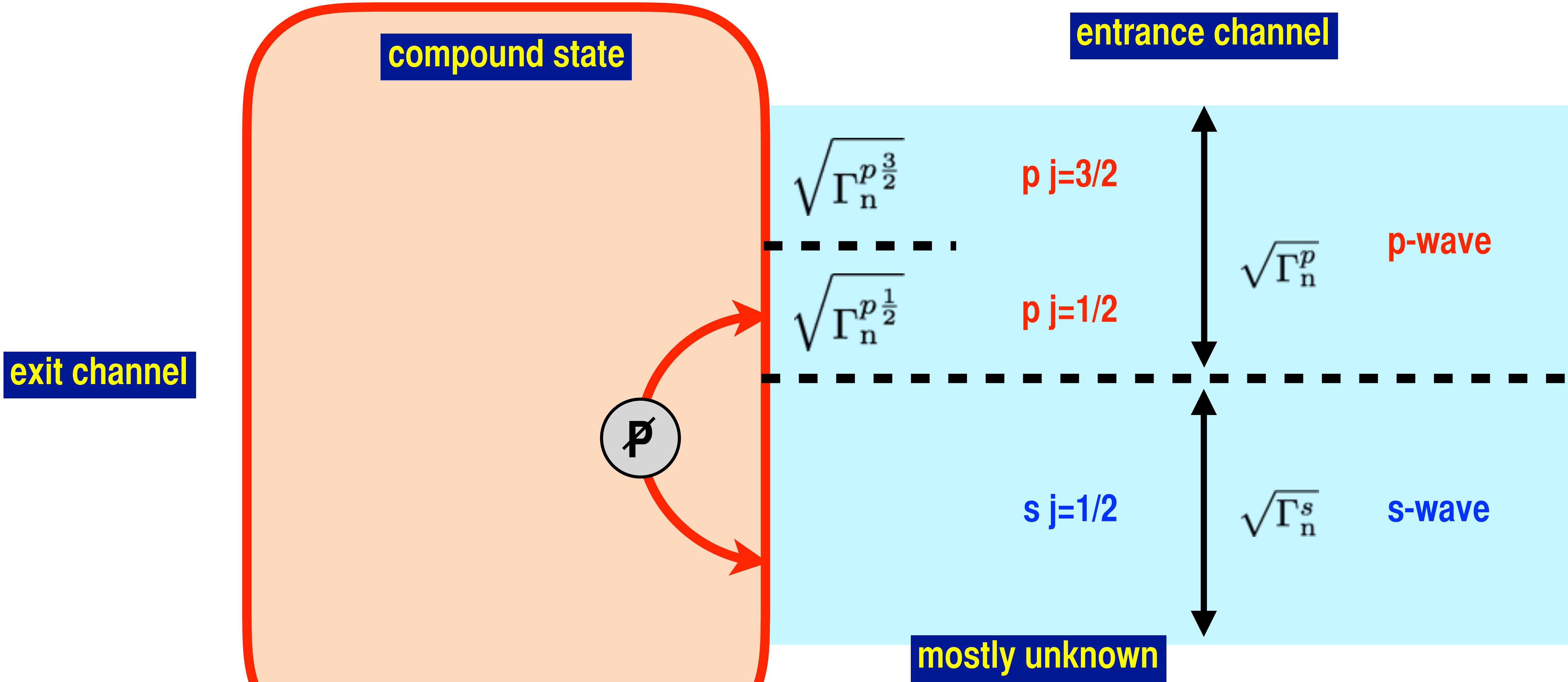
$$\langle s|W|p\rangle = \sum_{i,j}^{N} a_i^* b_j \langle \psi_i|W|\psi_j\rangle \sim \frac{1}{\sqrt{N}}\frac{1}{\sqrt{N}}\langle W\rangle\sqrt{N}$$

randomness of expansion coefficients

$$N \sim \frac{\Delta E}{D} \sim 10^5$$

ΔE: 10^6 eV; D: 10 eV

Universality Check



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

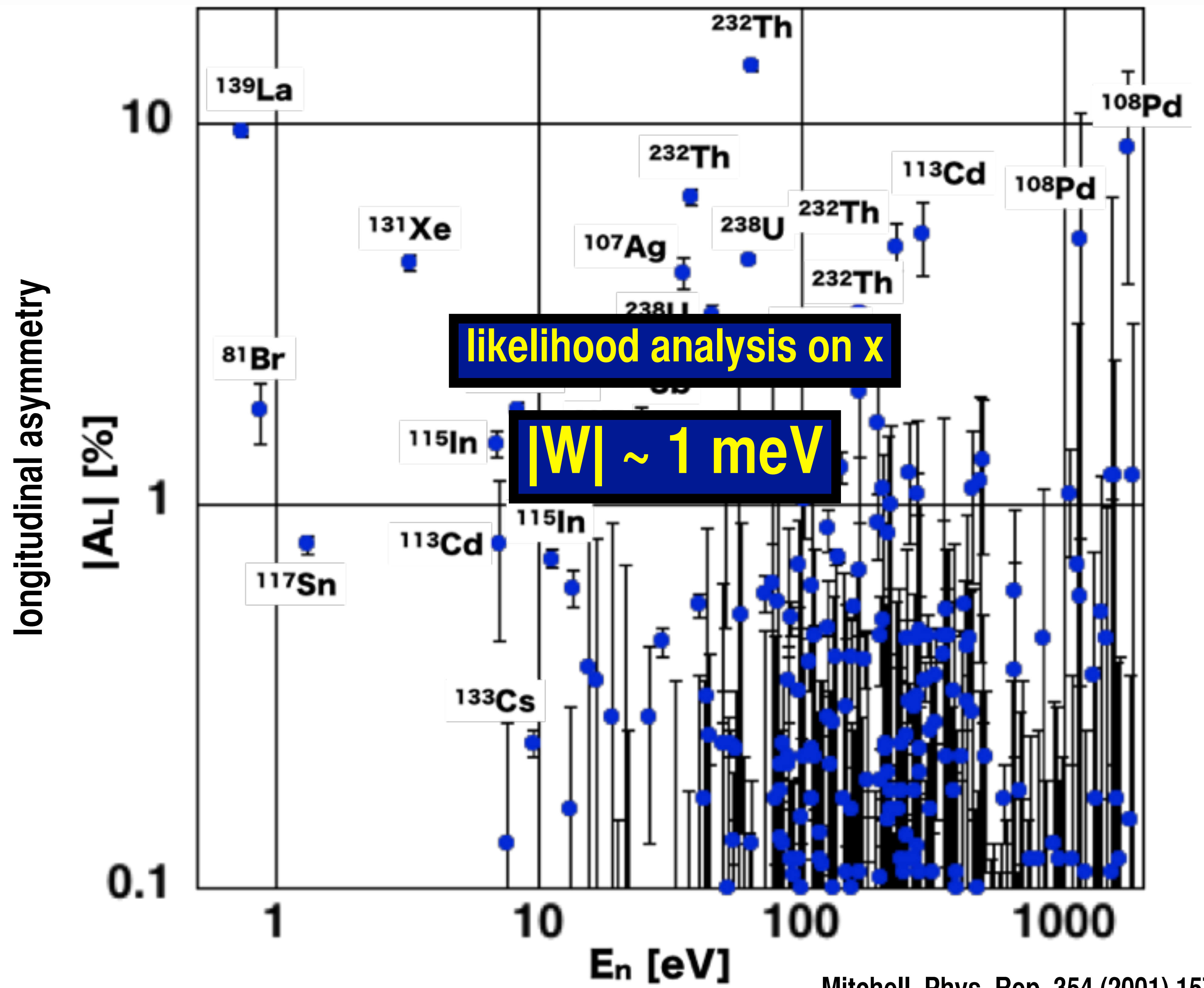
x

$$x = \sqrt{\frac{\Gamma_n^{p\frac{1}{2}}}{\Gamma_n^p}} \quad y = \sqrt{\frac{\Gamma_n^{p\frac{3}{2}}}{\Gamma_n^p}}$$

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

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

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

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

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

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

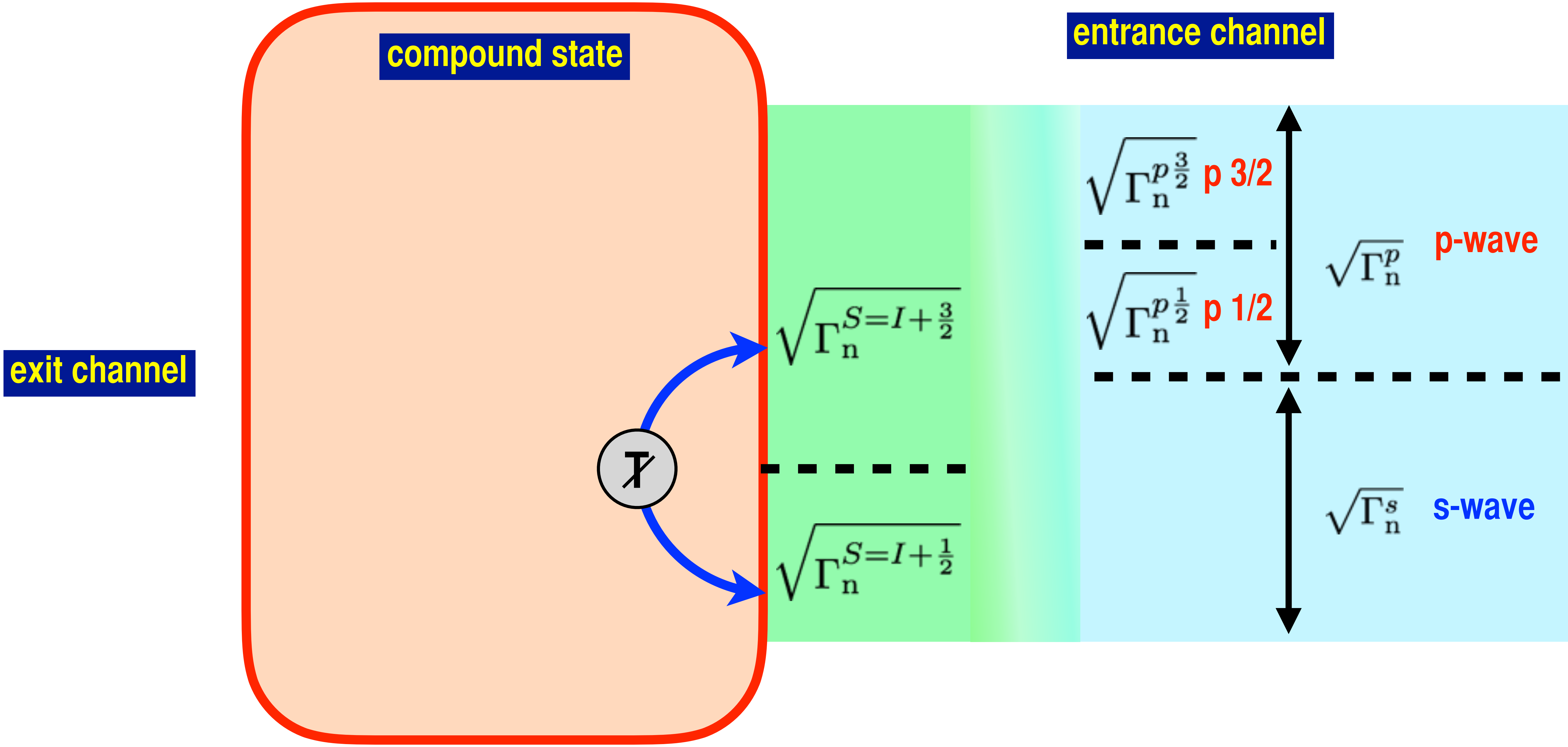
$$z_j = \begin{cases} x & (j=1/2) \\ y & (j=3/2) \end{cases}, \quad \tilde{z}_S = \begin{cases} x_S & (S=I-1/2) \\ y_S & (S=I+1/2) \end{cases} \quad \tilde{z}_S = \sum_j (-1)^{l+I+j+S}\sqrt{(2j+1)(2S+1)} \begin{Bmatrix} l & s & j \\ I & J & S \end{Bmatrix} z_j$$

s-p interference ⇔ channel-spin interference

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

$l = 0, 1$ **P-odd** $\qquad S = I \pm 1/2$ **T-odd**

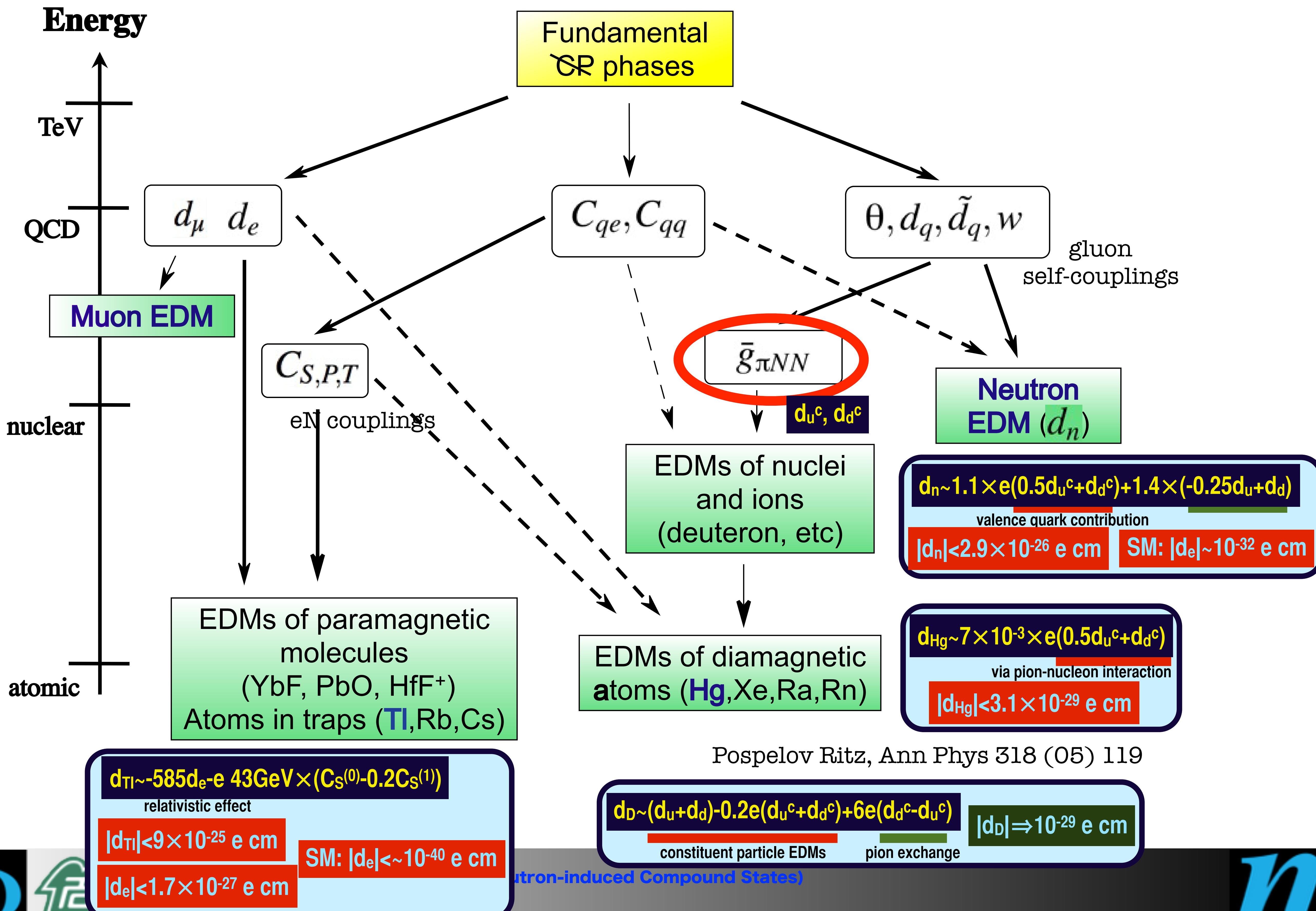
T-odd ➡ Channel-spin Interference

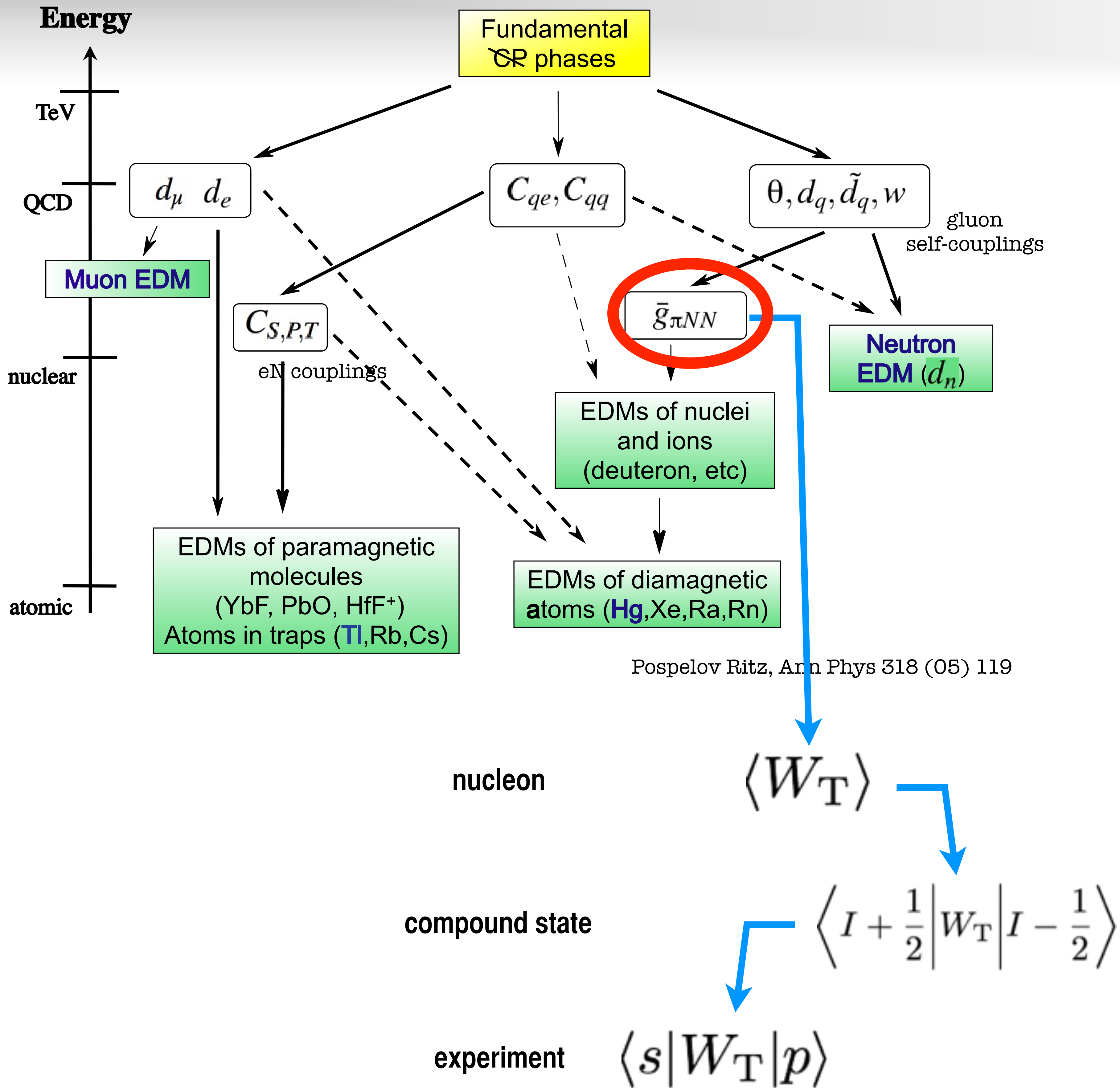


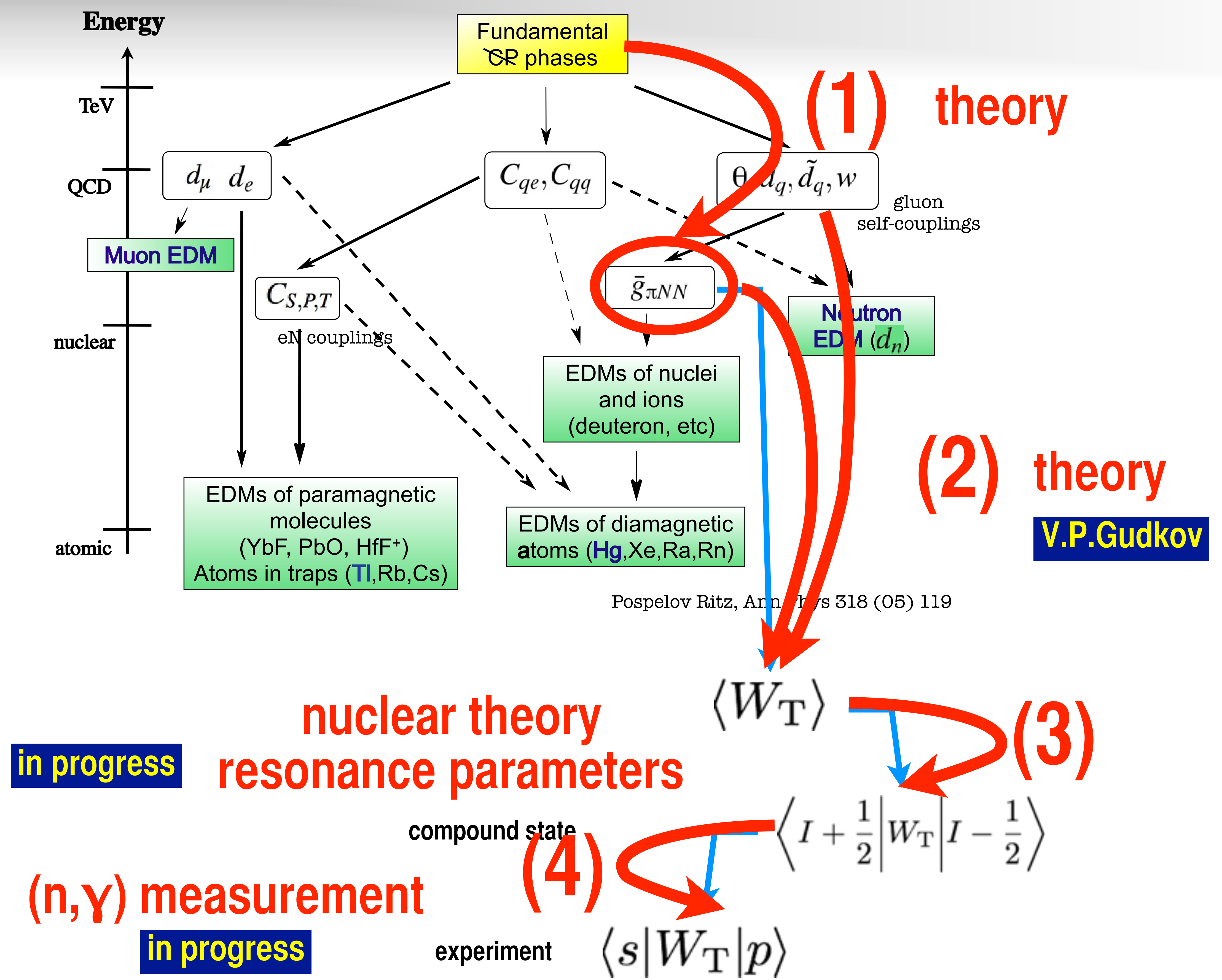
P-violation enhancement～10^6

T-violation enhancement～?

CP-violation in Low Energy Phenomena




Energy
TeV
QCD
nuclear
atomic
Fundamental CP phases
$d_\mu \quad d_e$
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)
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
nucleon
$\langle W_{\mathrm{T}} \rangle$
compound state
$\left\langle I+\frac{1}{2} \middle| W_{\mathrm{T}} \middle| I-\frac{1}{2} \right\rangle$
experiment
$\langle s | W_{\mathrm{T}} | p \rangle$

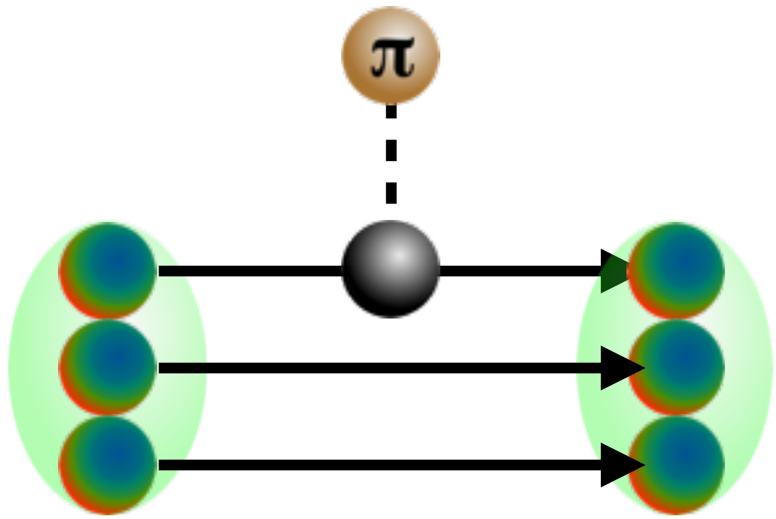


Energy
TeV
QCD
nuclear
atomic
Fundamental
CP phases
(1) theory
$d_\mu \; d_e$
C_{qe}, C_{qq}
$\theta, d_q, \tilde{d}_q, w$
gluon
self-couplings
Muon EDM
$C_{S,P,T}$
eN couplings
$\bar{g}_{\pi NN}$
Neutron
EDM (d_n)
EDMs of nuclei
and ions
(deuteron, etc)
(2) theory
V.P.Gudkov
EDMs of paramagnetic
molecules
(YbF, PbO, HfF⁺)
Atoms in traps (Tl,Rb,Cs)
EDMs of diamagnetic
atoms (Hg,Xe,Ra,Rn)
Pospelov Ritz, Ann Phys 318 (05) 119
$\langle W_T \rangle$
nuclear theory
resonance parameters
in progress
(3)
compound state
$\left\langle I+\frac{1}{2}\middle| W_T \middle| I-\frac{1}{2}\right\rangle$
(4)
(n,γ) measurement
in progress
experiment
$\langle s | W_T | p \rangle$

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

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

T-odd P-odd meson couplings



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

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

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

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

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

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

$$\tilde{d}_p \simeq 0.14\bar{g}_\pi^{(2)}$$

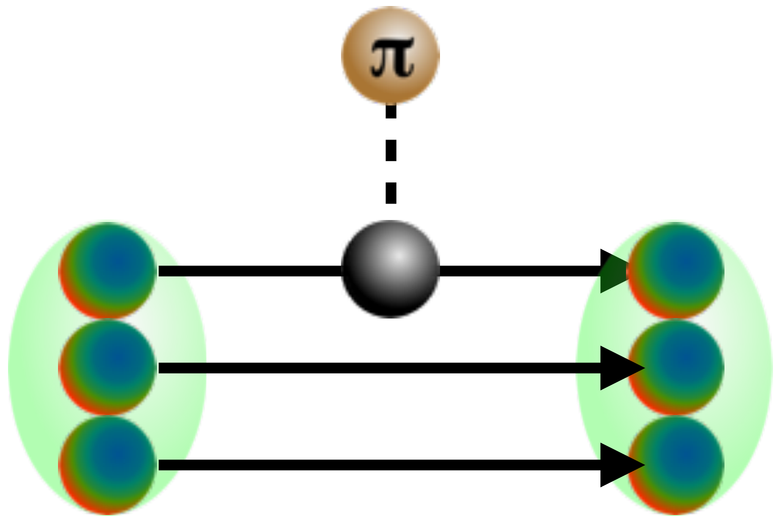
$$\tilde{d}_d \simeq 0.22\bar{g}_\pi^{(1)}$$

$$\tilde{d}_{^3\mathrm{He}} \simeq 0.2\bar{g}_\pi^{(0)} + 0.14\bar{g}_\pi^{(1)}$$

$$\tilde{d}_{^3\mathrm{H}} \simeq 0.22\bar{g}_\pi^{(0)} - 0.14\bar{g}_\pi^{(1)}$$

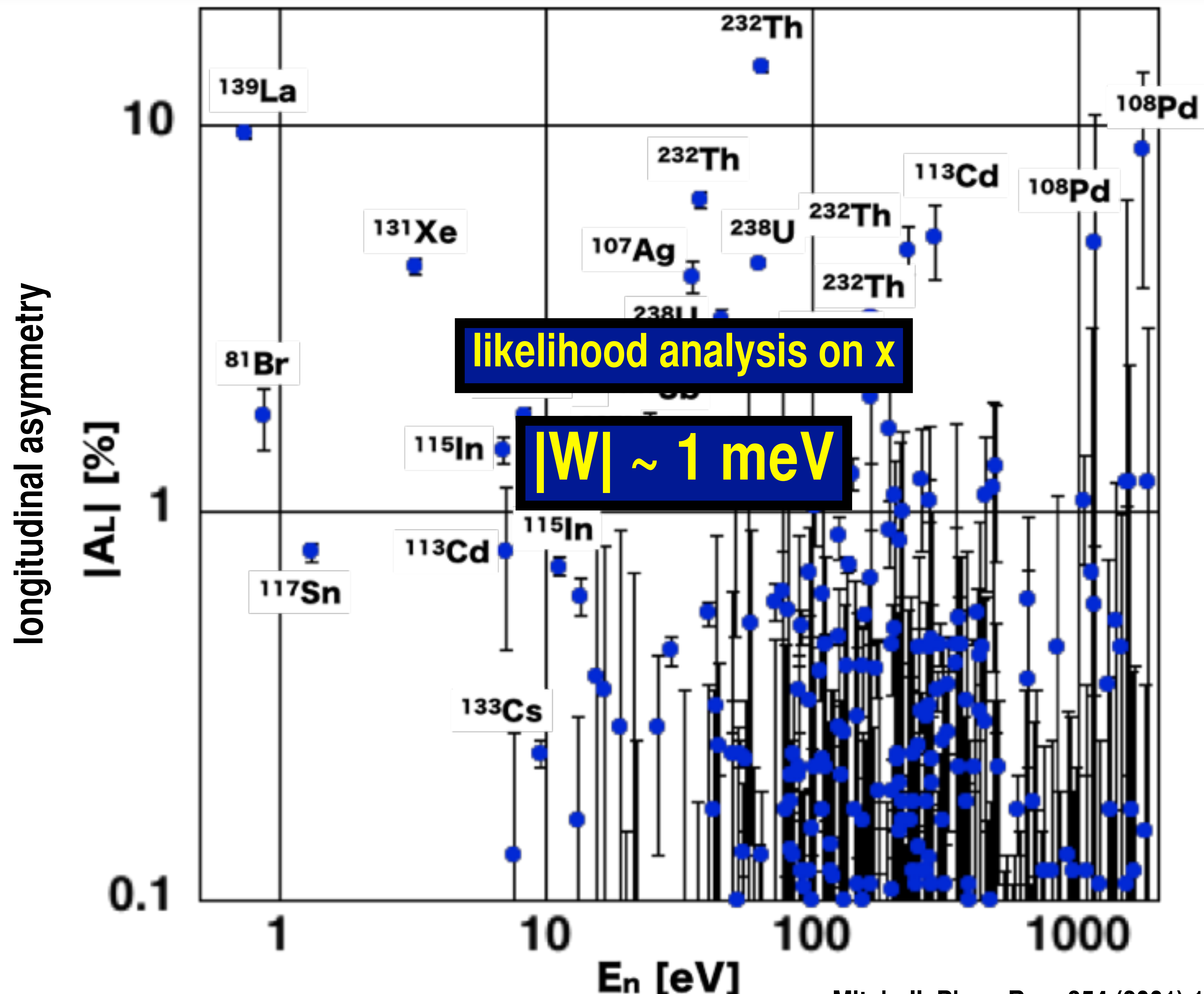
$$\frac{\Delta\sigma_{\mathrm{CP}}}{2\sigma_{\mathrm{tot}}} = \frac{-0.185[\mathrm{b}]}{2\sigma_{\mathrm{tot}}}\left(\bar{g}_\pi^{(0)} + 0.26\bar{g}_\pi^{(1)}\right)$$

T-odd P-odd meson couplings



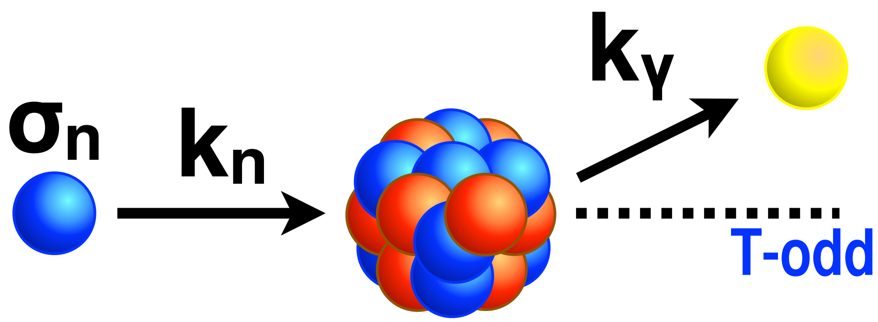
(3) Universality of P-violation

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



Mitchell, Phys. Rep. 354 (2001) 157

(4) Details of Entrance Channel



	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	$\boldsymbol{k}_n \cdot \boldsymbol{k}_\gamma$
T-odd	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	$(\boldsymbol{k}_n \cdot \boldsymbol{k}_\gamma)^2 - \frac{1}{3}$
T-odd	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	$(\boldsymbol{\sigma}_n \cdot \boldsymbol{k}_\gamma)$
P-violation	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	$(\boldsymbol{\sigma}_\gamma \cdot \boldsymbol{k}_\gamma)\,(\boldsymbol{k}_n \cdot \boldsymbol{k}_\gamma)$
T-odd	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	$(\boldsymbol{\sigma}_\gamma \cdot \boldsymbol{k}_\gamma)\left[(\boldsymbol{k}_n \cdot \boldsymbol{k}_\gamma)^2 - \frac{1}{3}\right]$
T-odd	a_{17}	yes	yes	P-odd	T-odd	$(\boldsymbol{\sigma}_\gamma \cdot \boldsymbol{k}_\gamma)\,(\boldsymbol{k}_n \cdot \boldsymbol{k}_\gamma)\, \boldsymbol{\sigma}_n \cdot (\boldsymbol{k}_n \times \boldsymbol{k}_\gamma)$

(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}\tfrac{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}\tfrac{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} \left[\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}\tfrac{1}{2}\tfrac{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}jj'1IF) 6 \begin{Bmatrix} 0 & 1 & 1 \\ 1 & \frac{1}{2} & \frac{1}{2} \\ 1 & j & j' \end{Bmatrix} \right] \\
a_6 &= -2\mathrm{Re} \textstyle\sum_{J_\mathrm{s}} V_1(J_\mathrm{s}j) V_2^*(J_\mathrm{p}=J_\mathrm{s},\tfrac{1}{2}) \\
a_7 &= \mathrm{Re} \textstyle\sum_{J_\mathrm{s},J_\mathrm{p}} V_1(J_\mathrm{s}) V_2^*(J_\mathrm{p}\tfrac{3}{2}) P(J_\mathrm{s}J_\mathrm{p}\tfrac{1}{2}\tfrac{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} \left[\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}\tfrac{1}{2}\tfrac{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}jj'1IF) 6 \begin{Bmatrix} 0 & 1 & 1 \\ 1 & \frac{1}{2} & \frac{1}{2} \\ 1 & j & j' \end{Bmatrix} \right] \\
a_{10} &= -2\mathrm{Re} \textstyle\sum_{J_\mathrm{s}} \left[V_2(J_\mathrm{p}=J_\mathrm{s},\tfrac{1}{2}) V_3^*(J_\mathrm{s}) + V_1(J_\mathrm{s}) V_4^*(J_\mathrm{p}=J_\mathrm{s},\tfrac{1}{2}) \right] \\
a_{11} &= 2\mathrm{Re} \textstyle\sum_{J_\mathrm{s},J_\mathrm{p}} \left[V_2(J_\mathrm{p}\tfrac{3}{2}) V_3^*(J_\mathrm{s}) + V_1(J_\mathrm{s}) V_4^*(J_\mathrm{p}\tfrac{3}{2}) \right] \sqrt{3} P(J_\mathrm{s}J_\mathrm{p}\tfrac{1}{2}\tfrac{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}\tfrac{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}\tfrac{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}
$$

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

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

ϕ

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

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

T-violation in Neutron Optics

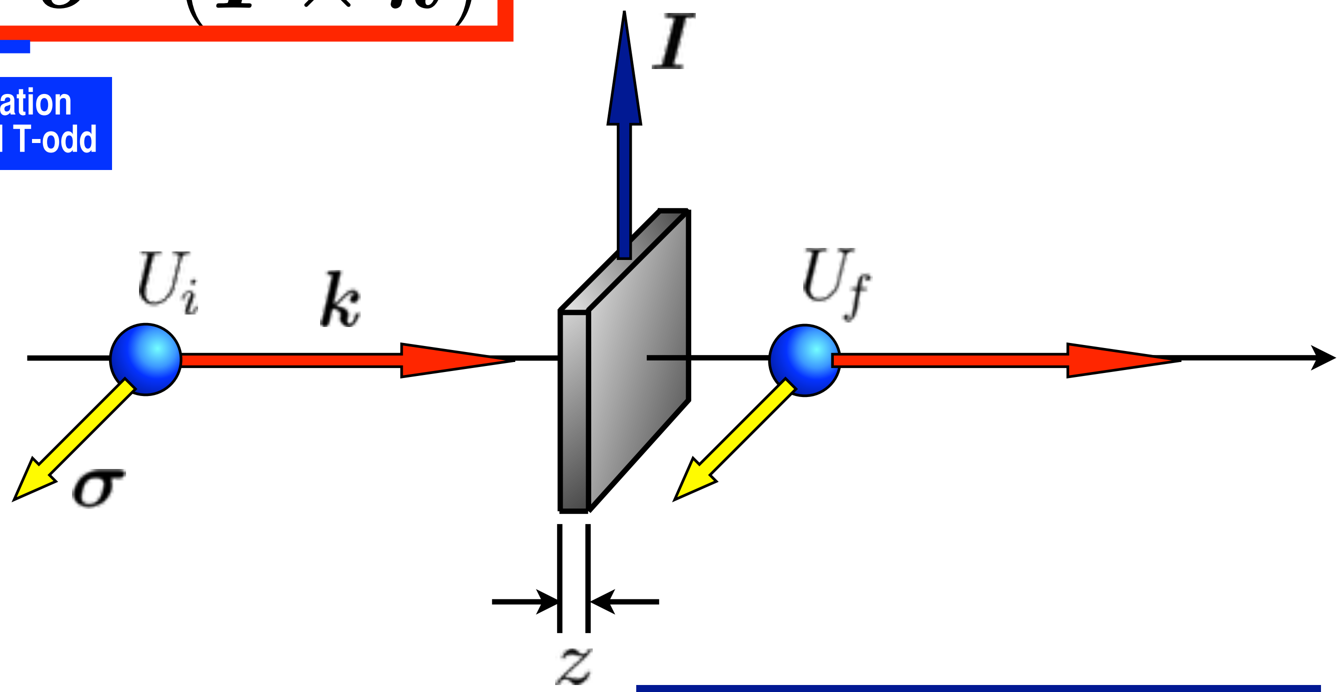
$$f = A' + B'\boldsymbol{\sigma}\cdot\hat{\boldsymbol{I}} + C'\boldsymbol{\sigma}\cdot\hat{\boldsymbol{k}} + D'\boldsymbol{\sigma}\cdot(\hat{\boldsymbol{I}}\times\hat{\boldsymbol{k}})$$

Spin Independent
P-even T-even

Spin Dependent
P-even T-even

P-violation
P-odd T-even

T-violation
P-odd T-odd

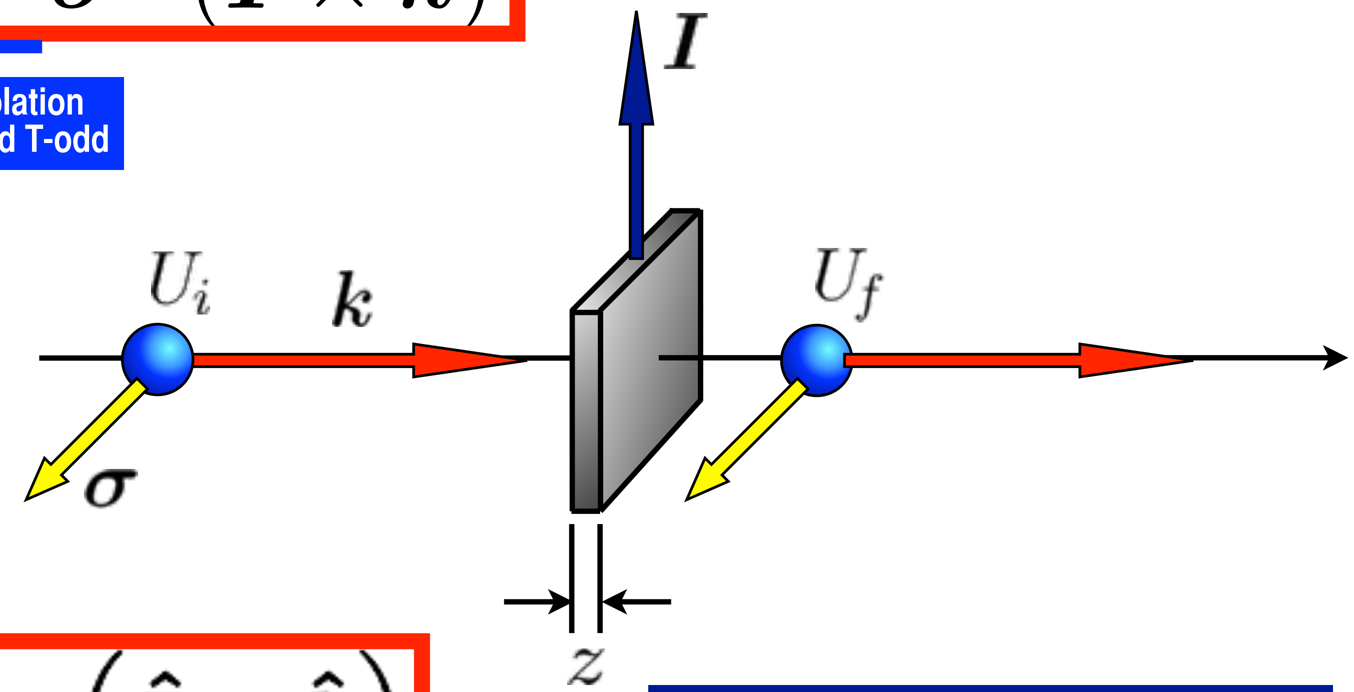


fake T-odd negligible

T-violation in Neutron Optics

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

- A': Spin Independent, P-even T-even
- $B'\boldsymbol{\sigma}\cdot\hat{\boldsymbol{I}}$: Spin Dependent, P-even T-even
- $C'\boldsymbol{\sigma}\cdot\hat{\boldsymbol{k}}$: P-violation, P-odd T-even
- $D'\boldsymbol{\sigma}\cdot(\hat{\boldsymbol{I}}\times\hat{\boldsymbol{k}})$: T-violation, P-odd T-odd



$$U_f = \delta U_i$$

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

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

- A: Spin Independent, P-even T-even
- $B\boldsymbol{\sigma}\cdot\hat{\boldsymbol{I}}$: Spin Dependent, P-even T-even
- $C\boldsymbol{\sigma}\cdot\hat{\boldsymbol{k}}$: P-violation, P-odd T-even
- $D\boldsymbol{\sigma}\cdot(\hat{\boldsymbol{I}}\times\hat{\boldsymbol{k}})$: T-violation, P-odd T-odd

fake T-odd negligible

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

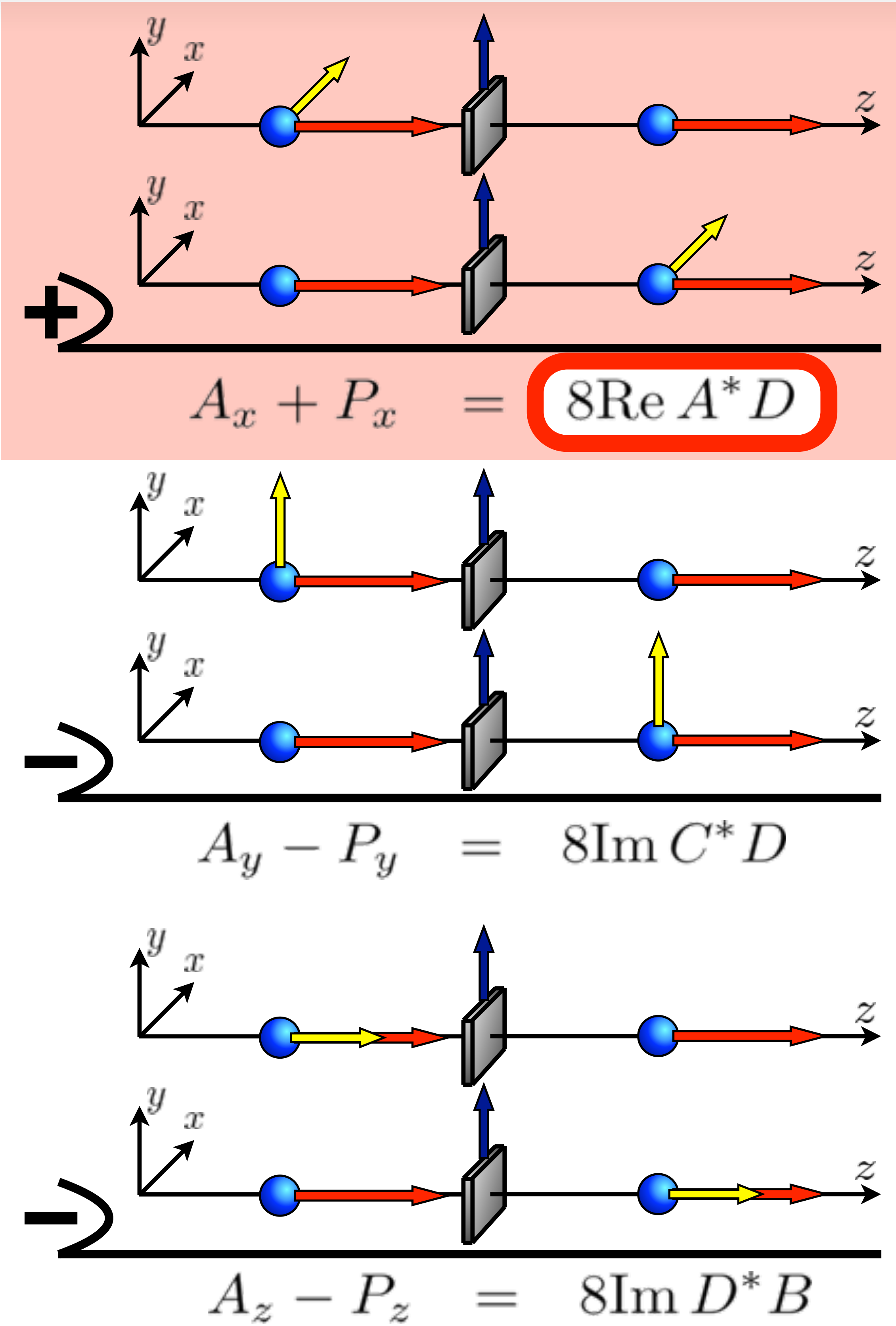
$$Z = \frac{2\pi\rho}{k}z \qquad C = ie^{iZA'}\frac{\sin b}{b}ZC'$$

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

D≠0 ➡ D'≠0

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

Analyzing Power and Polarization

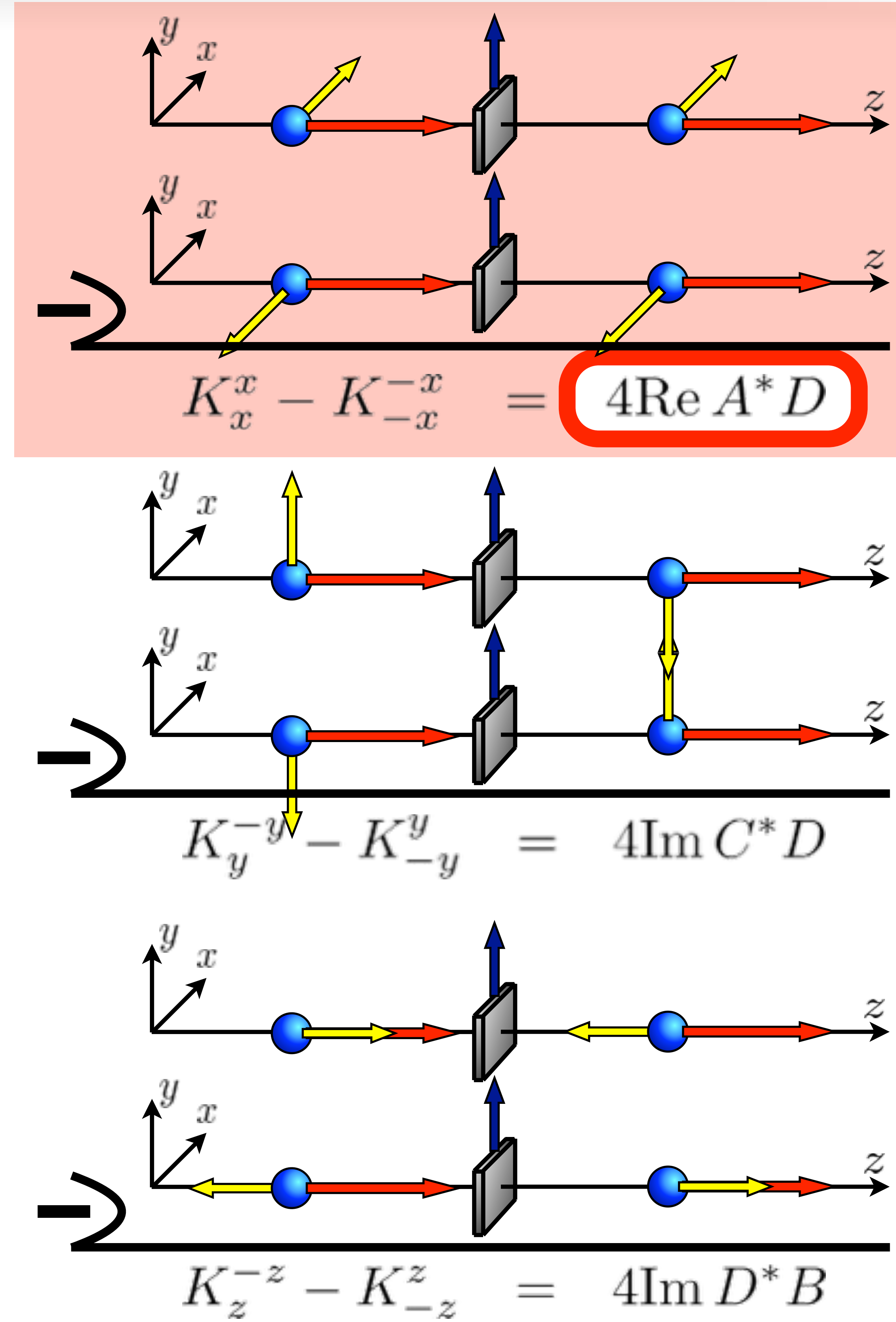


$$A_x + P_x = 8\mathrm{Re}\,A^*D$$

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

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

Polarization Transfer Coefficient



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

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

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

Order Estimation of T-violation Sensitivity

Gudkov, Phys. Rep. 212 (1992) 77

T-violating matrix element

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

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

P-violating matrix element

Order Estimation of T-violation Sensitivity

Gudkov, Phys. Rep. 212 (1992) 77

T-violating matrix element

$$\frac{g_{\mathrm{CP}}}{g_{\mathrm{P}}}$$

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

T-violation

angular momentum factor

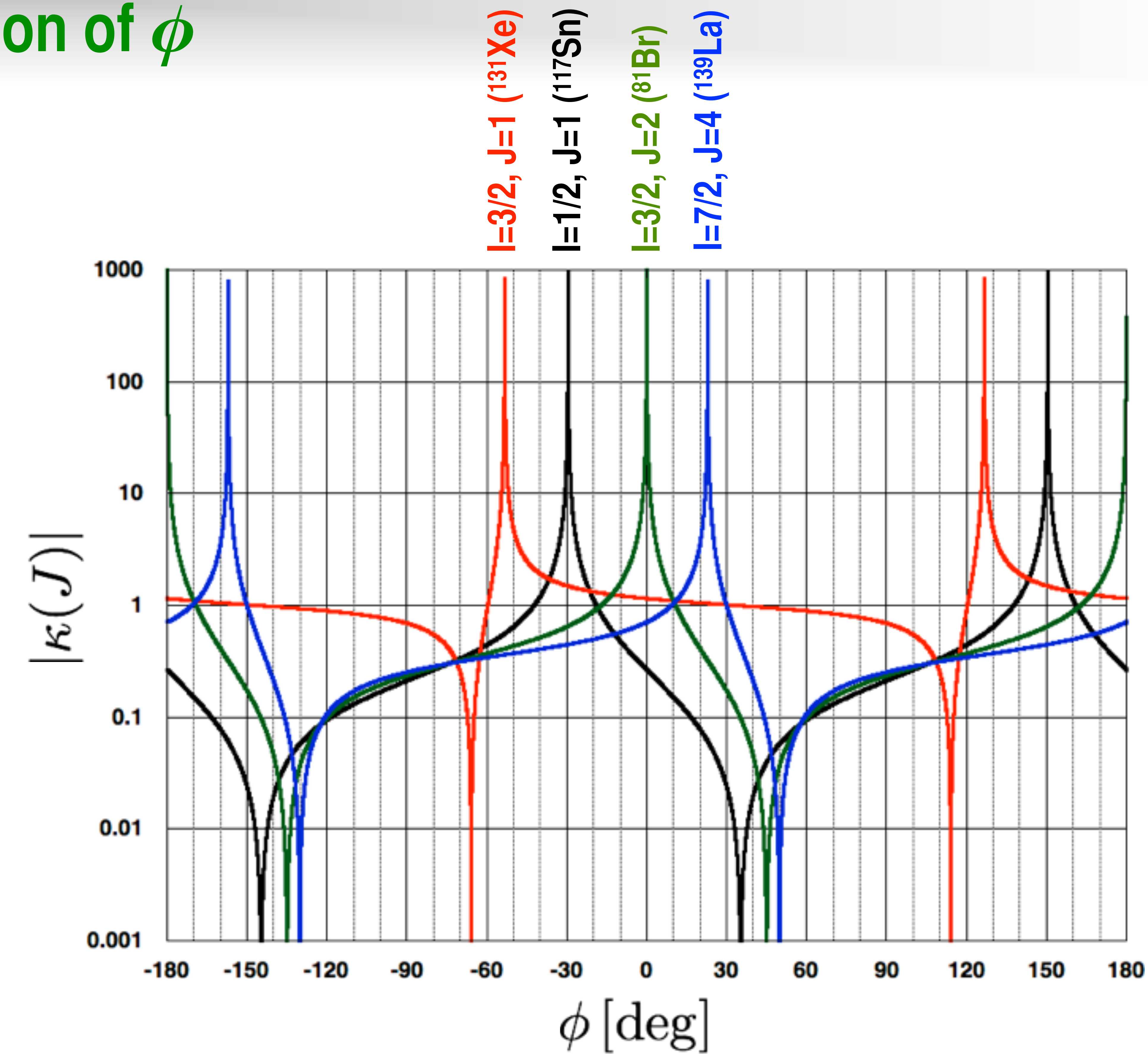
P-violation

we choose target nuclei with known $\Delta\sigma_{\mathrm{P}}$

(n,γ) measurement

P-violating matrix element

κ(J) as a function of ϕ



Estimation of Discovery Potential

If $\frac{w}{v} \sim \frac{g_{\mathrm{CP}}}{g_{\mathrm{P}}}$ i.e. $\left|\tilde{d}_n\right| \sim |d_n| < 2.9 \times 10^{-26}\,[\mathrm{e\,cm}]\ (90\%\mathrm{C.L.})$

and neglecting isovector and isotensor

then a discovery potential is at the level of

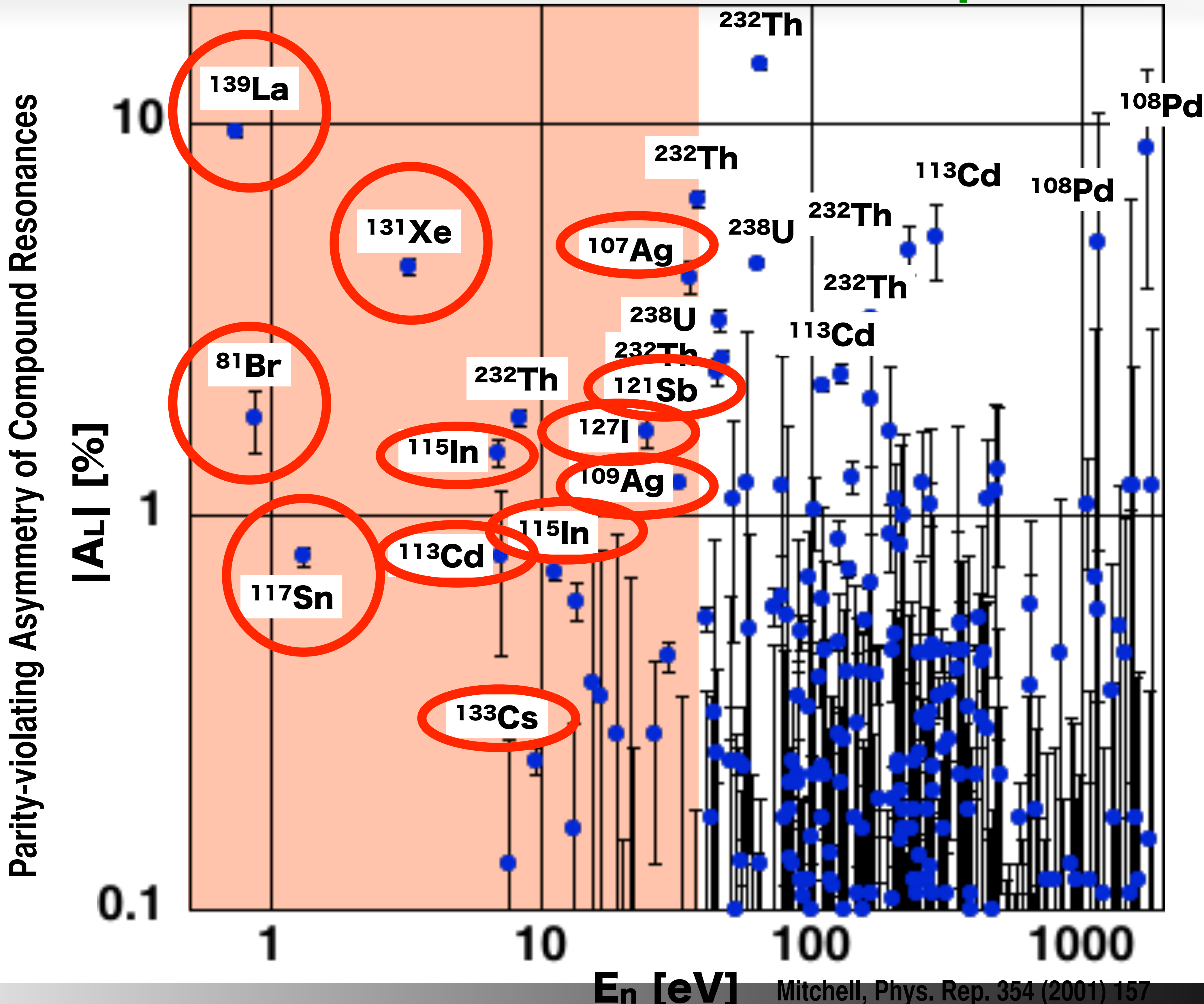
$$\left|\Delta\sigma_{\mathrm{T}}^{nA}\right| < \underline{2.5 \times 10^{-4}[\mathrm{b}]} \times \underline{\kappa(J)}$$

present upper limit

~ 1

T-odd term to be measured

Candidate Resonances for the T-violation Experiment



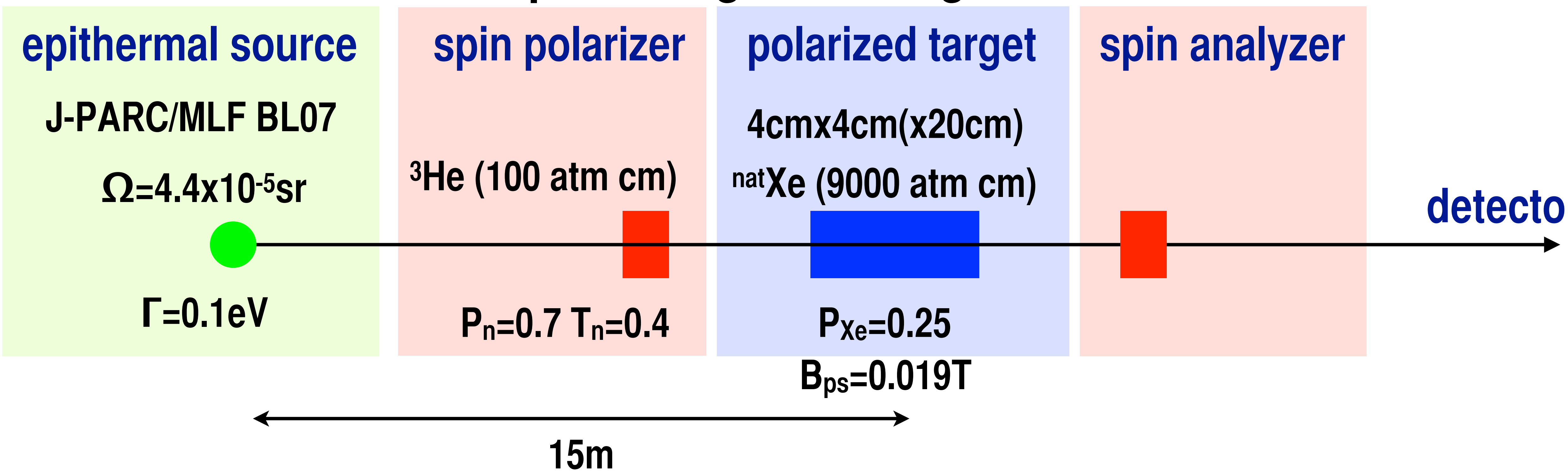
Mitchell, Phys. Rep. 354 (2001) 157

Choice of Target Nuclei

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

Experimental Possibility

A crude estimation with promising technologies …



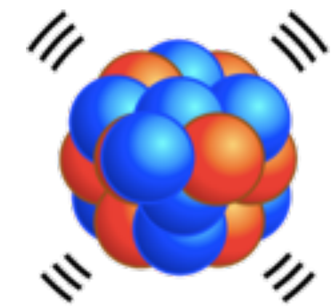
discovery potential ~ 5 day statistics (to be improved and refined)

Systematics can be examined in the observation of the spin behavior as a function of time-of-flight.

Summary

Short-pulse spallation neutron sources have become operational.

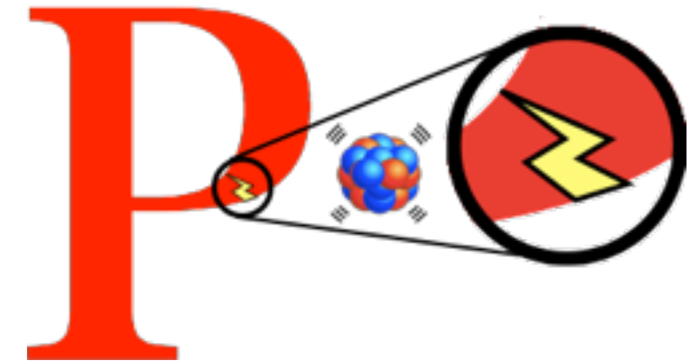
↓



Details of the entrance channel to neutron-induced compound states with large P-violation is in progress.

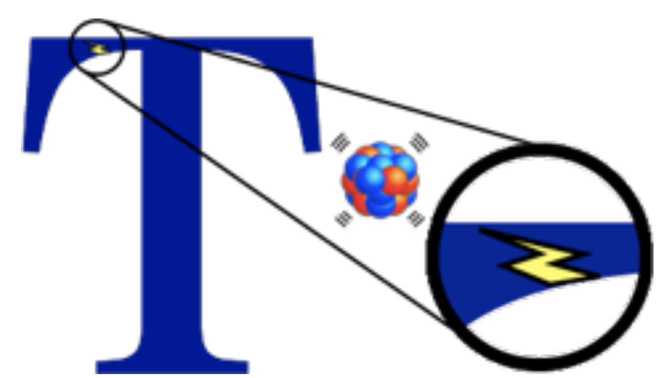
➡ next talk by Takuya OKUDAIRA

➡ poster by Shusuke TAKADA



New discovery potential of new physics beyond the standard model is introduced at the sensitivity level competitive with nEDM.

➡ R&D in progress: poster by Katsuya HIROTA



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