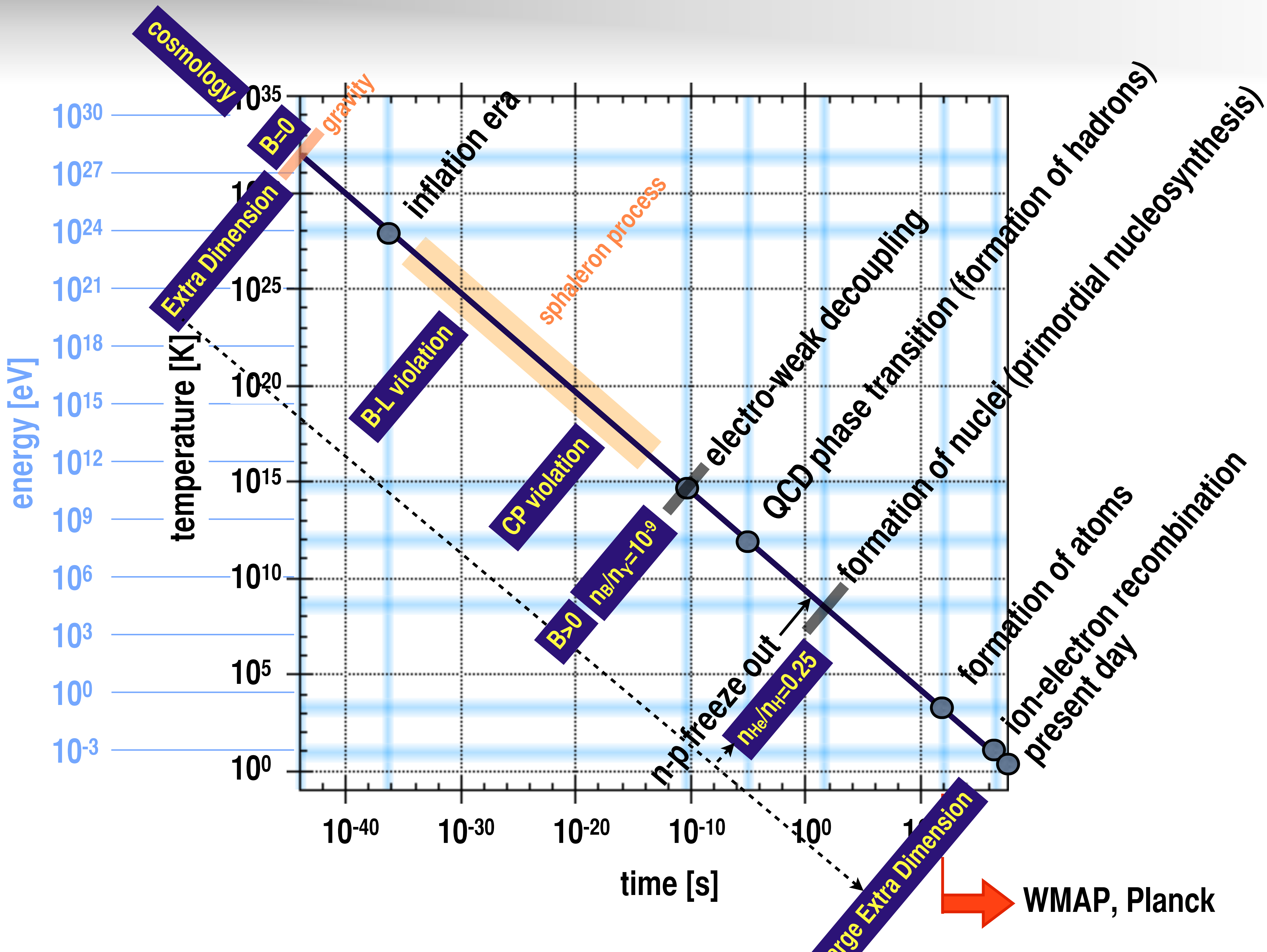
Discrete Symmetry Tests in Neutron-induced Compound States

@ Krakow, Poland
2017/06/10

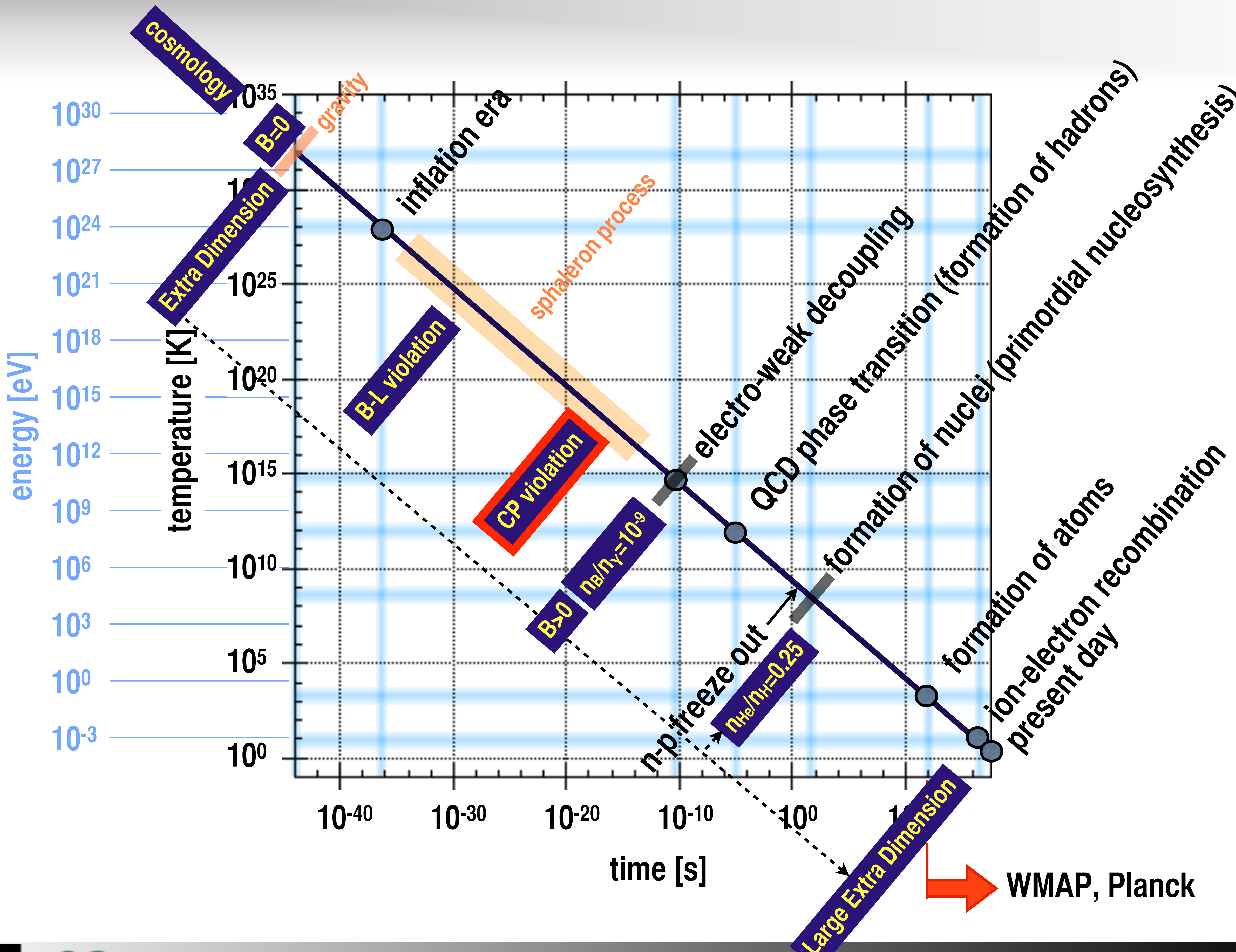
H.M.Shimizu
Department for Physics, Nagoya University
hirohiko.shimizu@nagoya-u.jp

on behalf of NOPTREX Collaboration

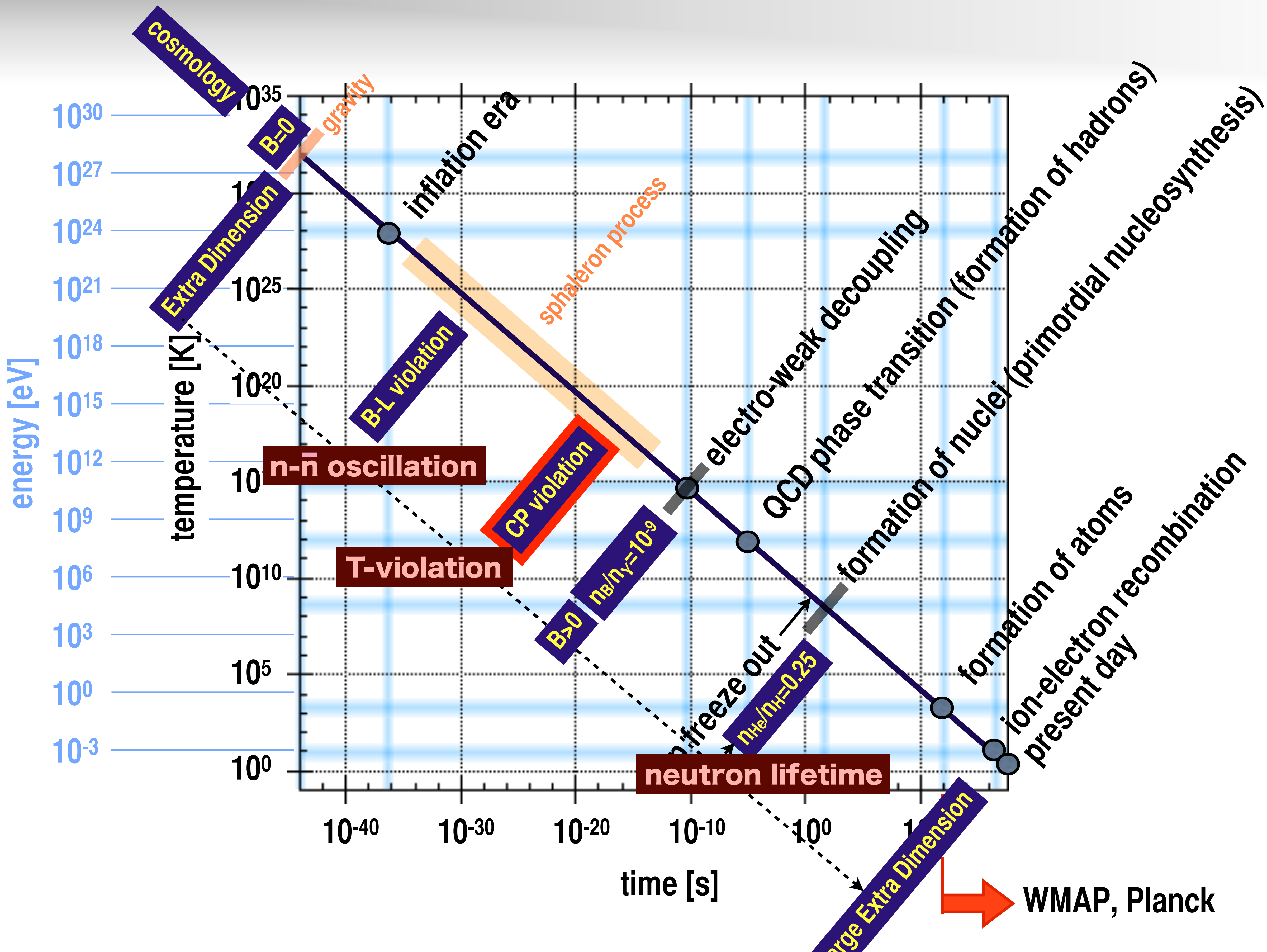
(Neutron OPtics for Time Reversal EXperiment)



cosmology
gravity
B=0
Extra Dimension
inflation era
sphaleron process
B-L violation
CP violation
electro-weak decoupling
QCD phase transition (formation of hadrons)
formation of nuclei (primordial nucleosynthesis)
n_B/n_γ~10^{-9}
B>0
n-p freeze out
n_{He}/n_H=0.25
formation of atoms
ion-electron recombination
present day
Large Extra Dimension
WMAP, Planck
energy [eV]
temperature [K]
time [s]

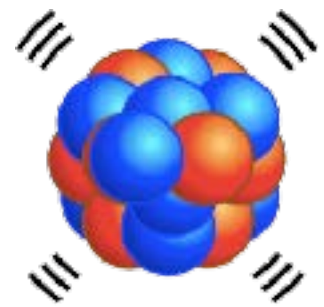


cosmology
gravity
B=0
Extra Dimension
inflation era
sphaleron process
B-L violation
CP violation
n_B/n_γ~10^{-9}
B>0
electro-weak decoupling
QCD phase transition (formation of hadrons)
formation of nuclei (primordial nucleosynthesis)
n-p freeze out
n_{He}/n_H=0.25
formation of atoms
ion-electron recombination
present day
Large Extra Dimension
WMAP, Planck
energy [eV]
10^{30}
10^{27}
10^{24}
10^{21}
10^{18}
10^{15}
10^{12}
10^{9}
10^{6}
10^{3}
10^{0}
10^{-3}
temperature [K]
10^{35}
10^{25}
10^{20}
10^{15}
10^{10}
10^{5}
10^{0}
time [s]
10^{-40}
10^{-30}
10^{-20}
10^{-10}
10^{0}

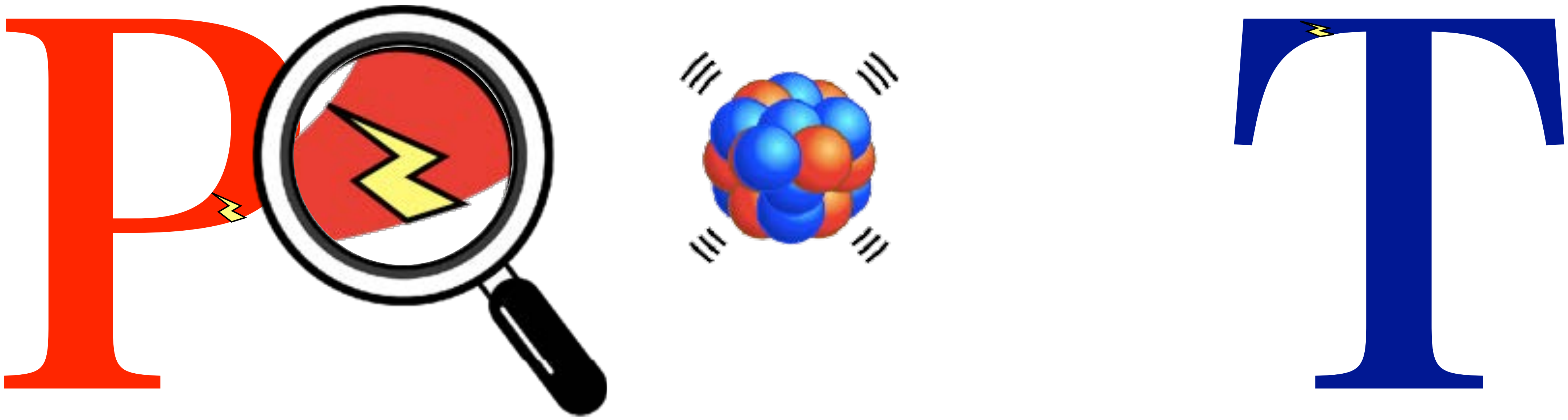

cosmology
gravity
B=0
inflation era
Extra Dimension
sphaleron process
electro-weak decoupling
QCD phase transition (formation of hadrons)
formation of nuclei (primordial nucleosynthesis)
B-L violation
n-n̄ oscillation
CP violation
T-violation
n_B/n_γ~10^{-9}
B>0
n freeze out
n_{He}/n_H=0.25
neutron lifetime
formation of atoms
ion-electron recombination
present day
Large Extra Dimension
WMAP, Planck
energy [eV]
temperature [K]
time [s]

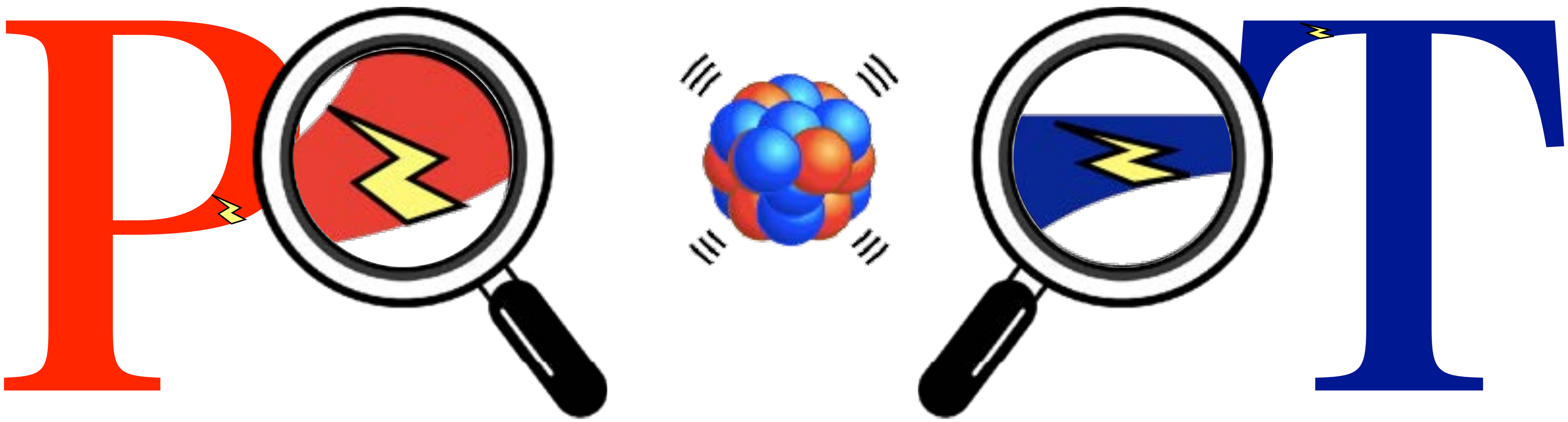
P

P




P


P
T


P
T

Discrete Symmetries in Quantum Field Theory

Charge conjugation

Parity (spatial inversion)

Time reversal

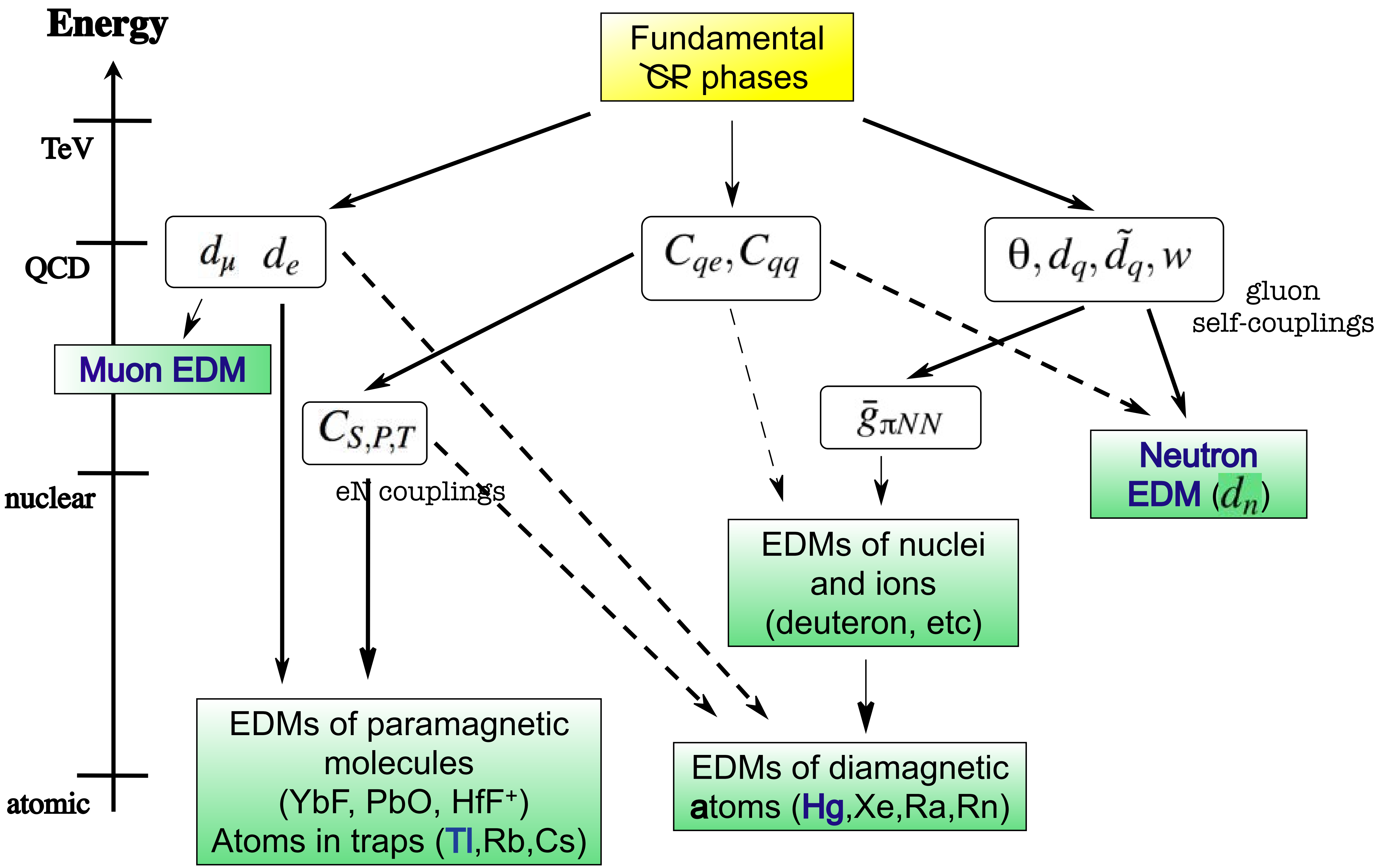
$$CPT = 1$$

$$CP \neq 1 \quad \longleftrightarrow \quad T \neq 1$$

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

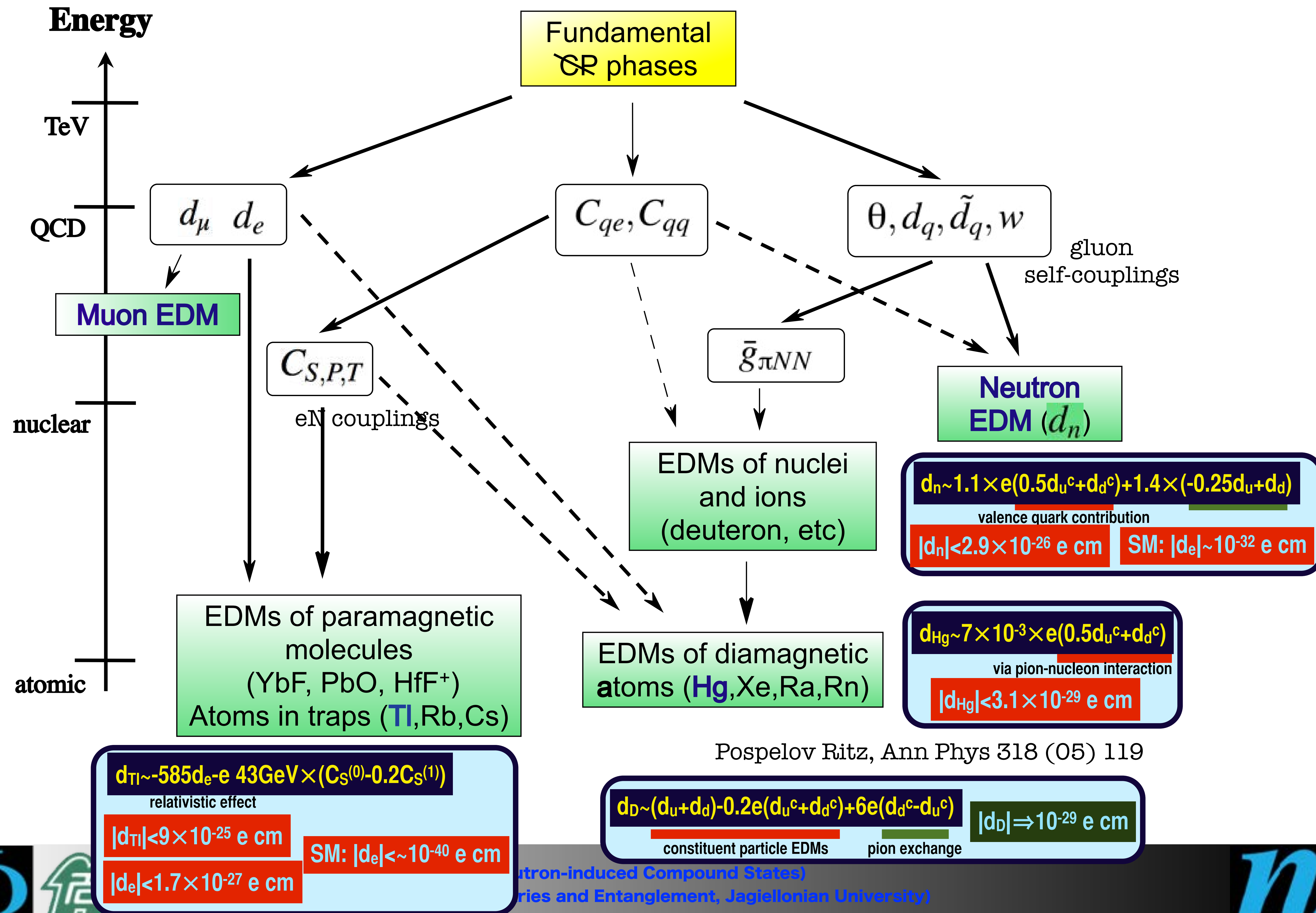
New physics related to additional CP-phase is strongly desired.

CP-violation in Low Energy Phenomena

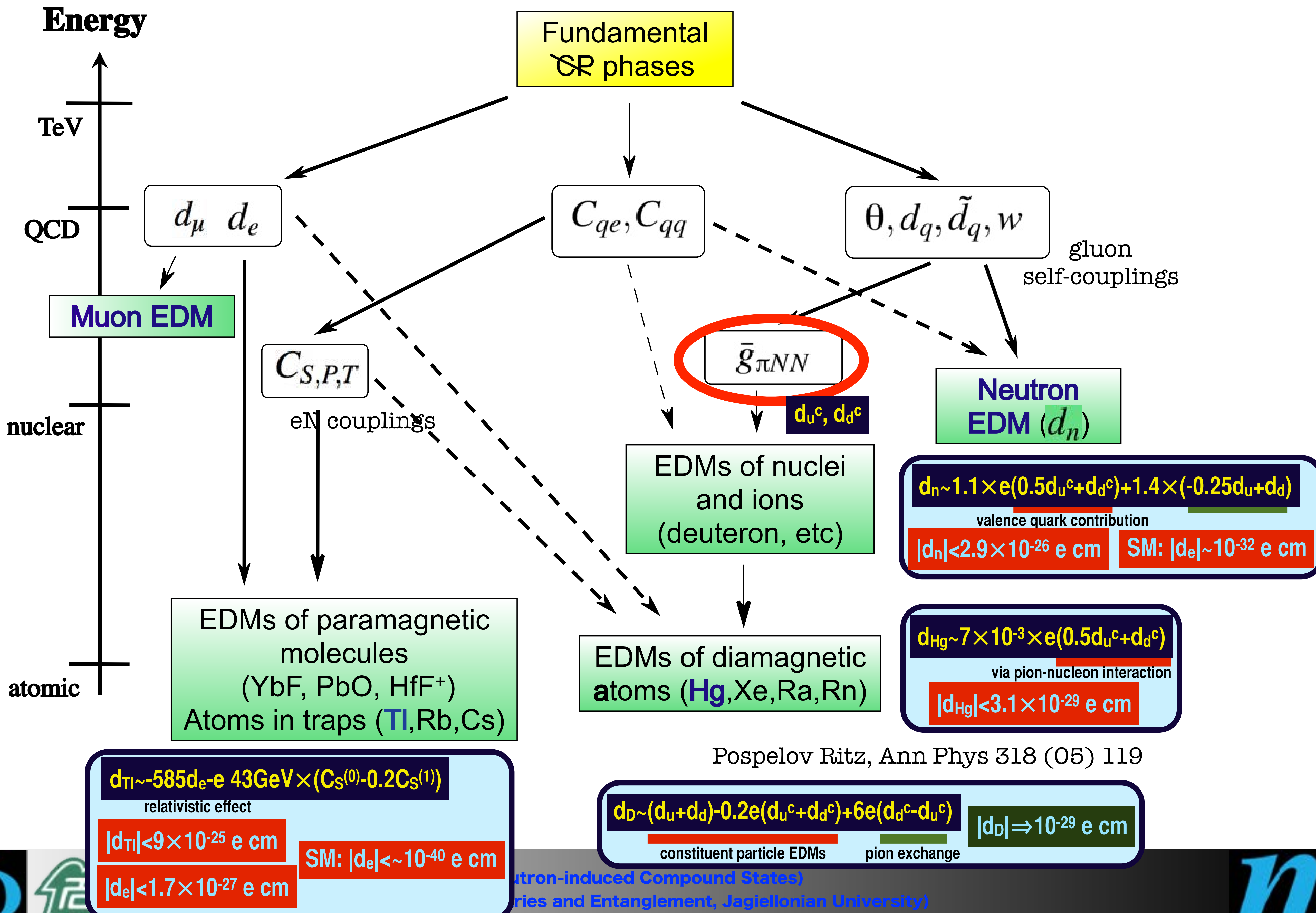


Pospelov Ritz, Ann Phys 318 (05) 119

CP-violation in Low Energy Phenomena

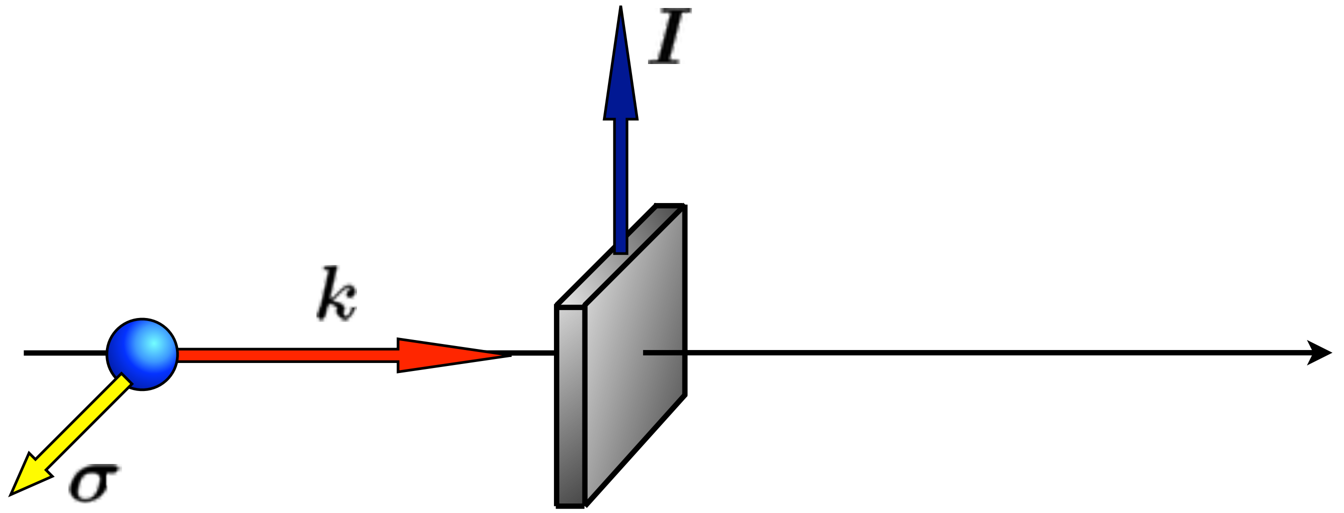


CP-violation in Low Energy Phenomena



T-violation in Neutron Optics

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



polarized neutron polarized target

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

Spin Independent
P-even T-even

Spin Dependent
P-even T-even

P-violation
P-odd T-even

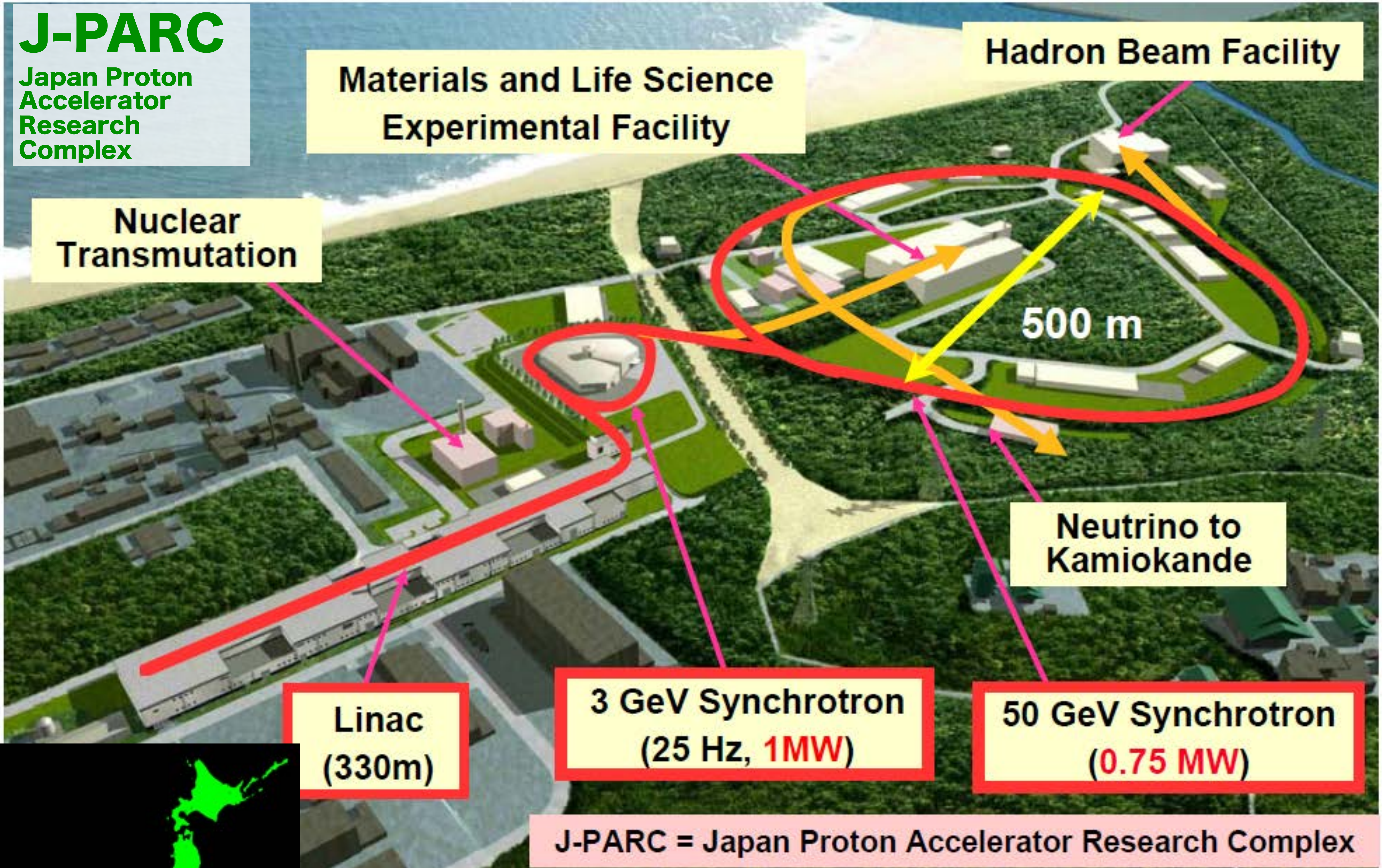
T-violation
P-odd T-odd

final-state-interaction free

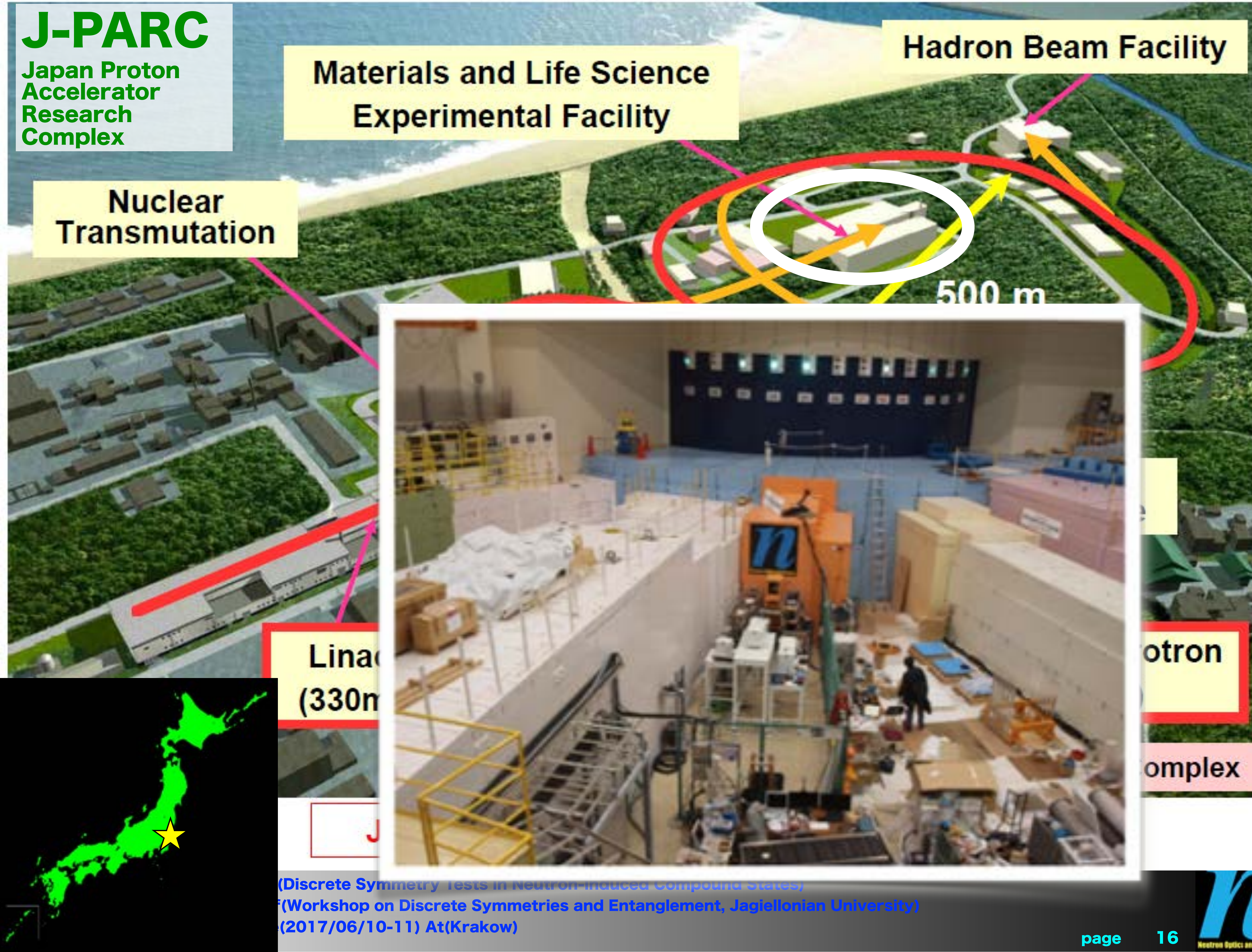
enhanced sensitivity to T-violation in compound states

toward new physics beyond the standard model via CP-violation

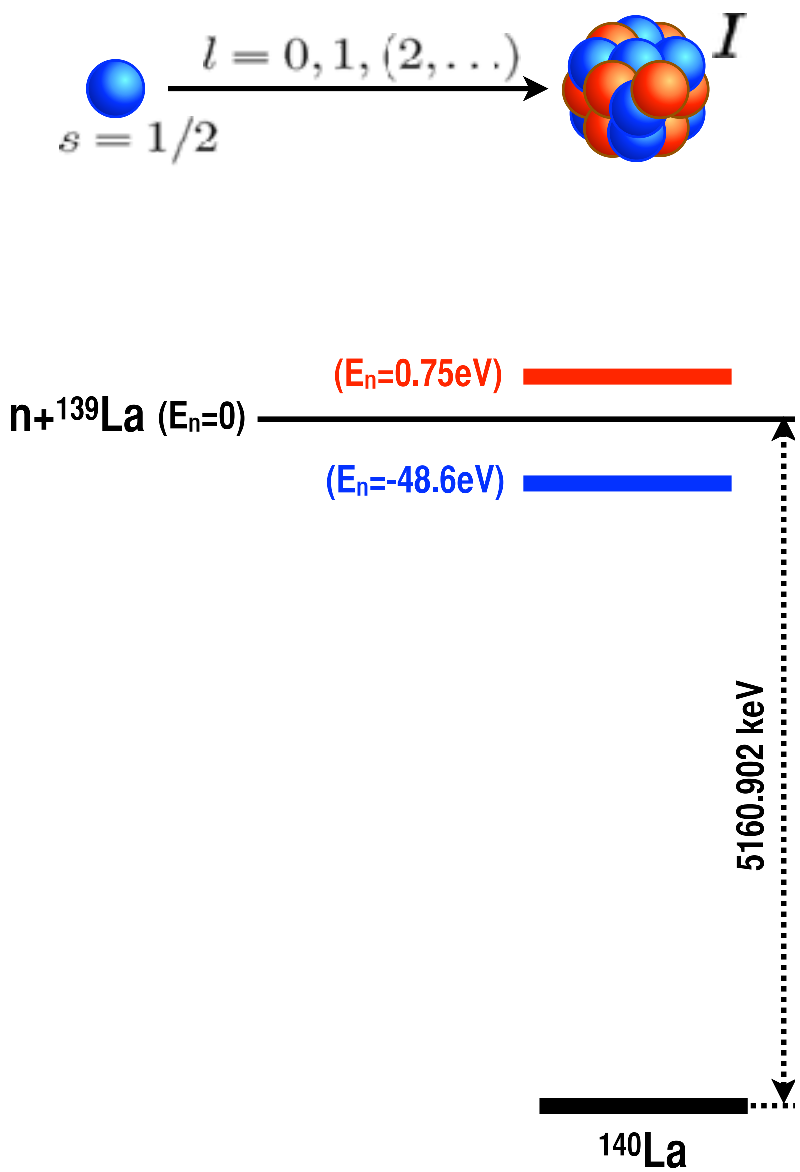
enabled by short-pulse spallation neutron sources

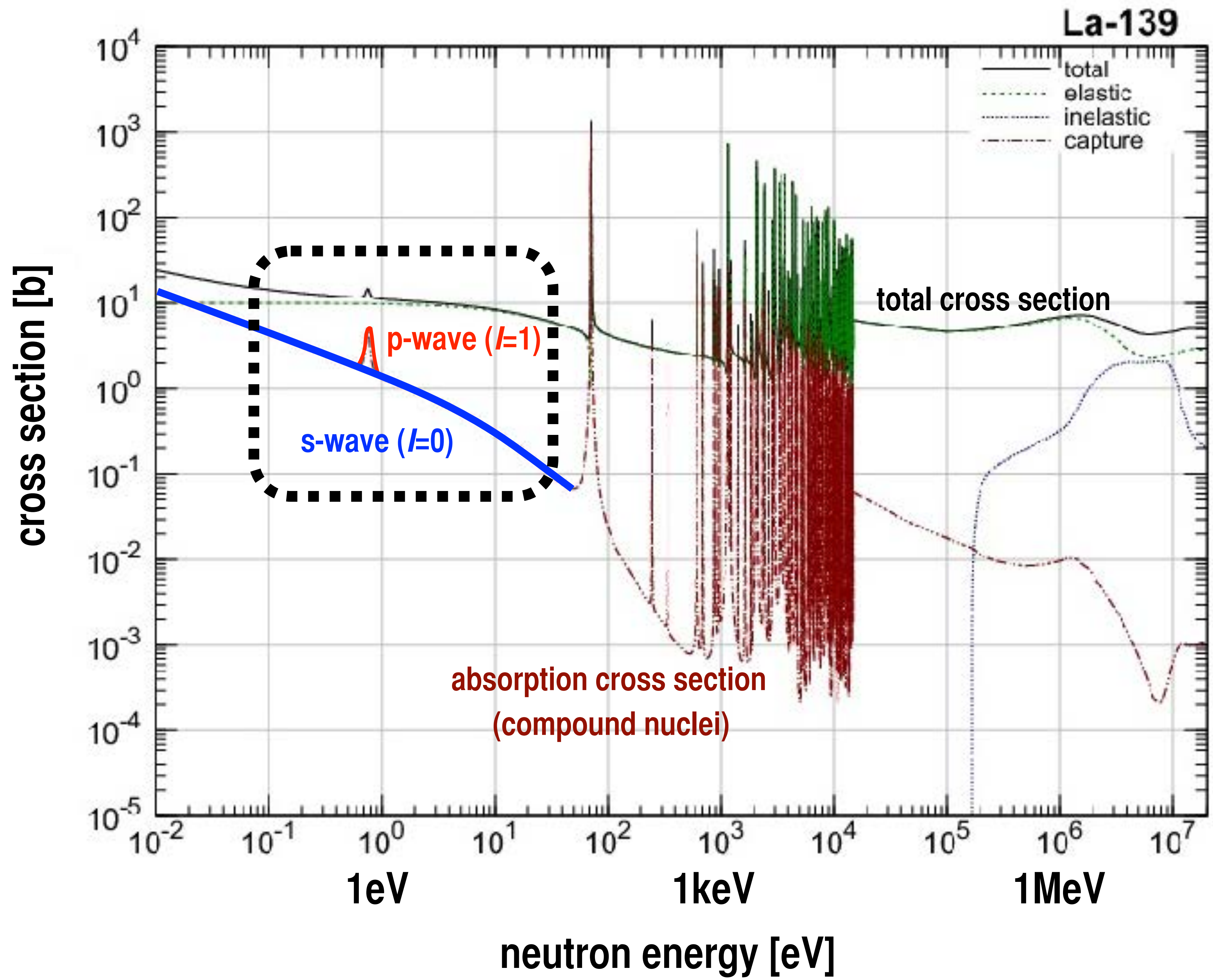


Joint Project between KEK and JAEA


J-PARC
Japan Proton Accelerator Research Complex
Materials and Life Science Experimental Facility
Hadron Beam Facility
Nuclear Transmutation
500 m
Linac
(330m
otron
omplex

Compound States





thermal epithermal fast

Projectile-Helicity Dependent Asymmetry (A_L)

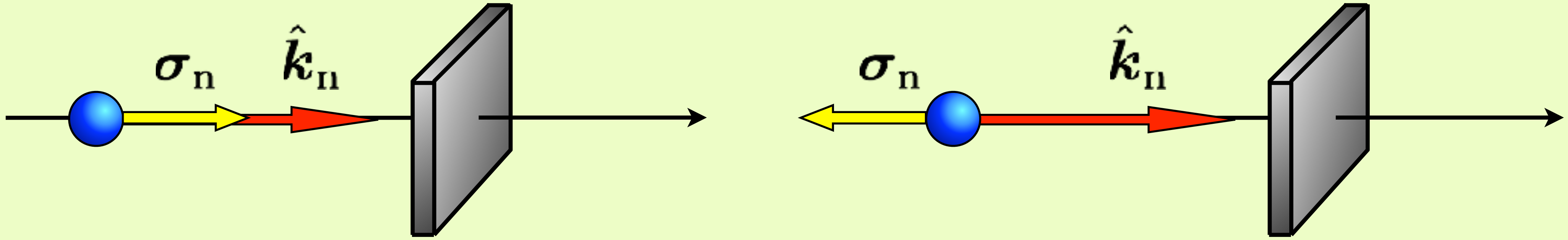
P (spatial inversion)

	$\boldsymbol{\sigma}_n$	$\hat{\boldsymbol{k}}_n$	$\boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{k}}_n$
P ↕	$\boldsymbol{\sigma}_n$	$-\hat{\boldsymbol{k}}_n$	$-\boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{k}}_n$

P-odd

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

P-violation



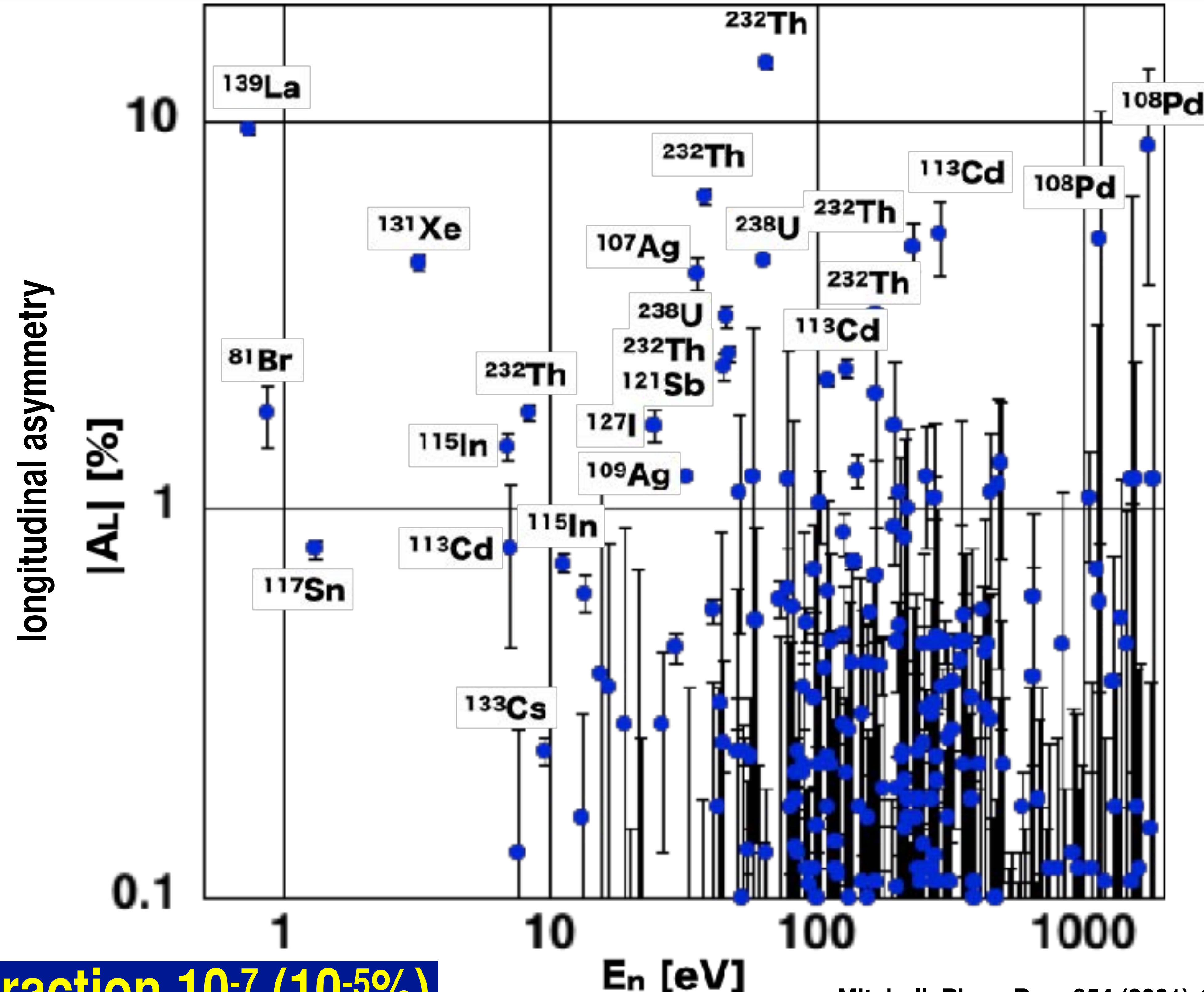
$$\sigma_+ = \sigma_0 + \Delta\sigma \qquad \sigma_- = \sigma_0 - \Delta\sigma$$

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

Longitudinal Asymmetry

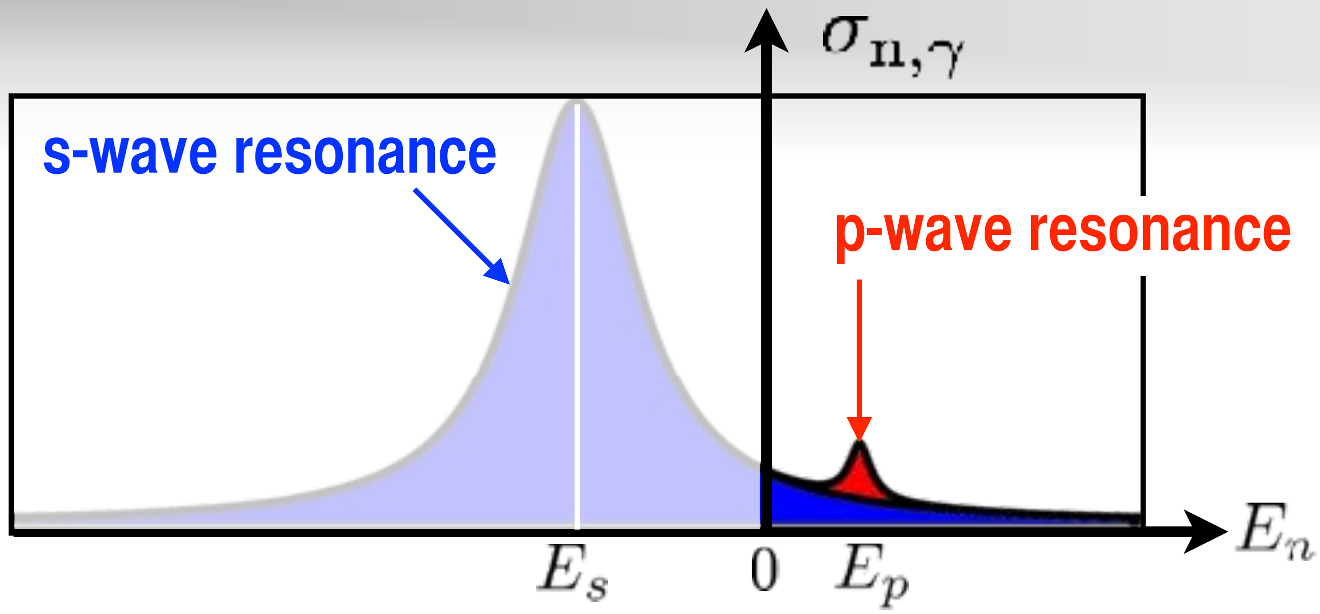
NN-interaction 10^{-7} (10^{-5}%)

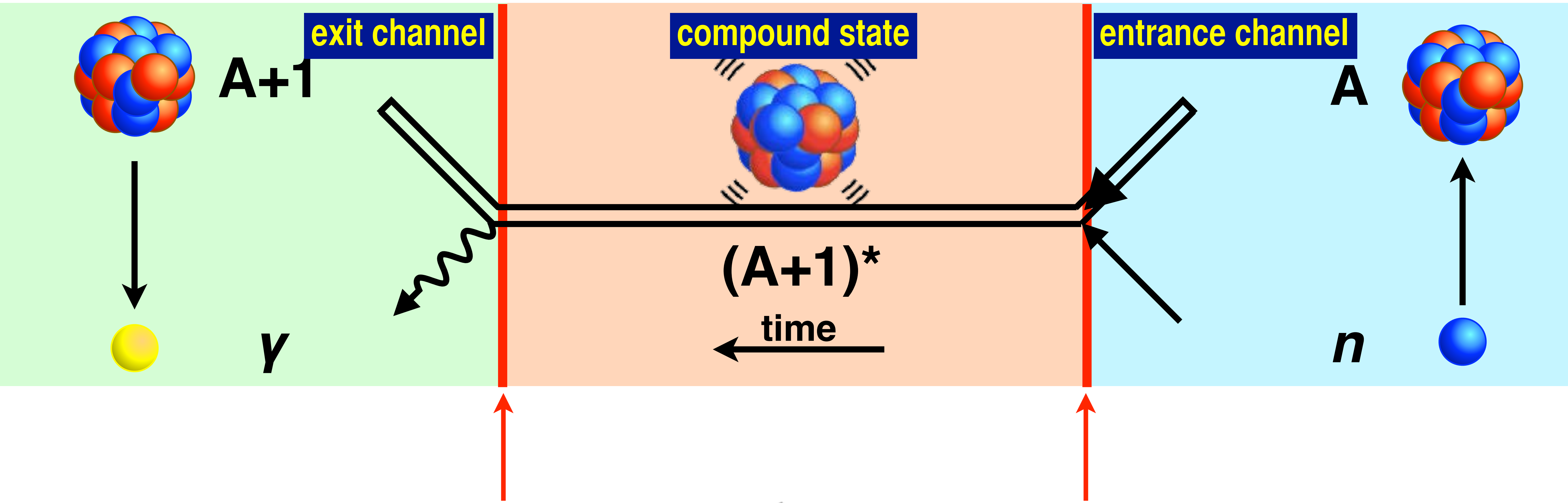
Enhanced P-violation in Compound States



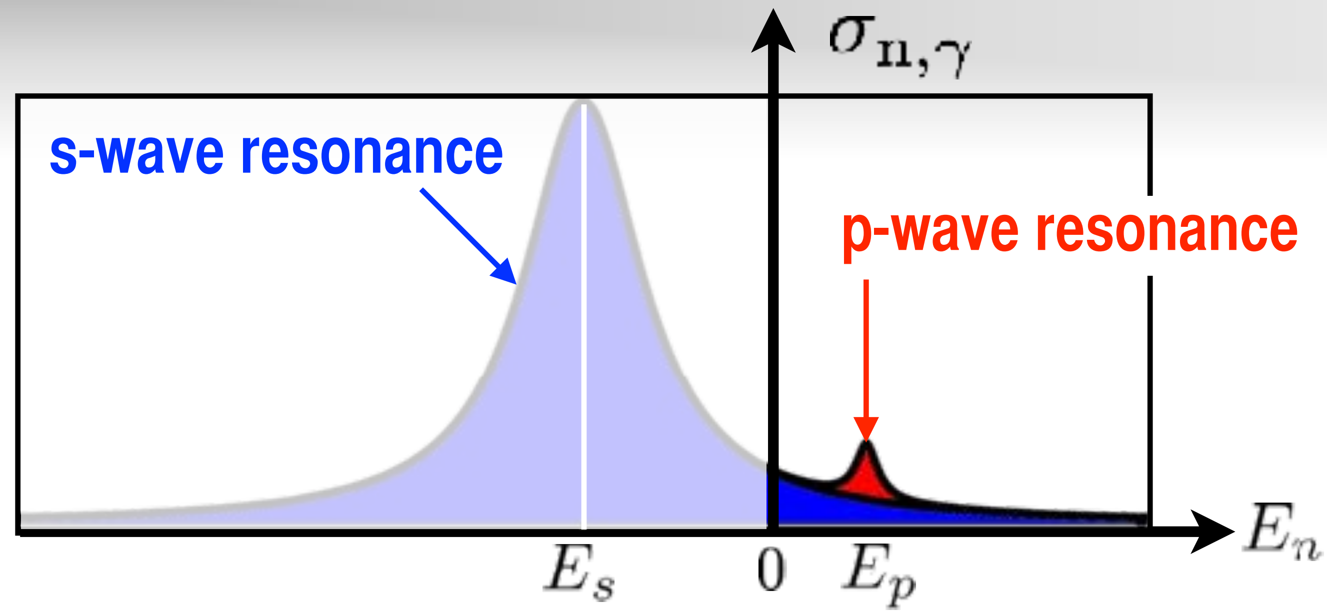
NN-interaction 10^{-7} (10^{-5}%)

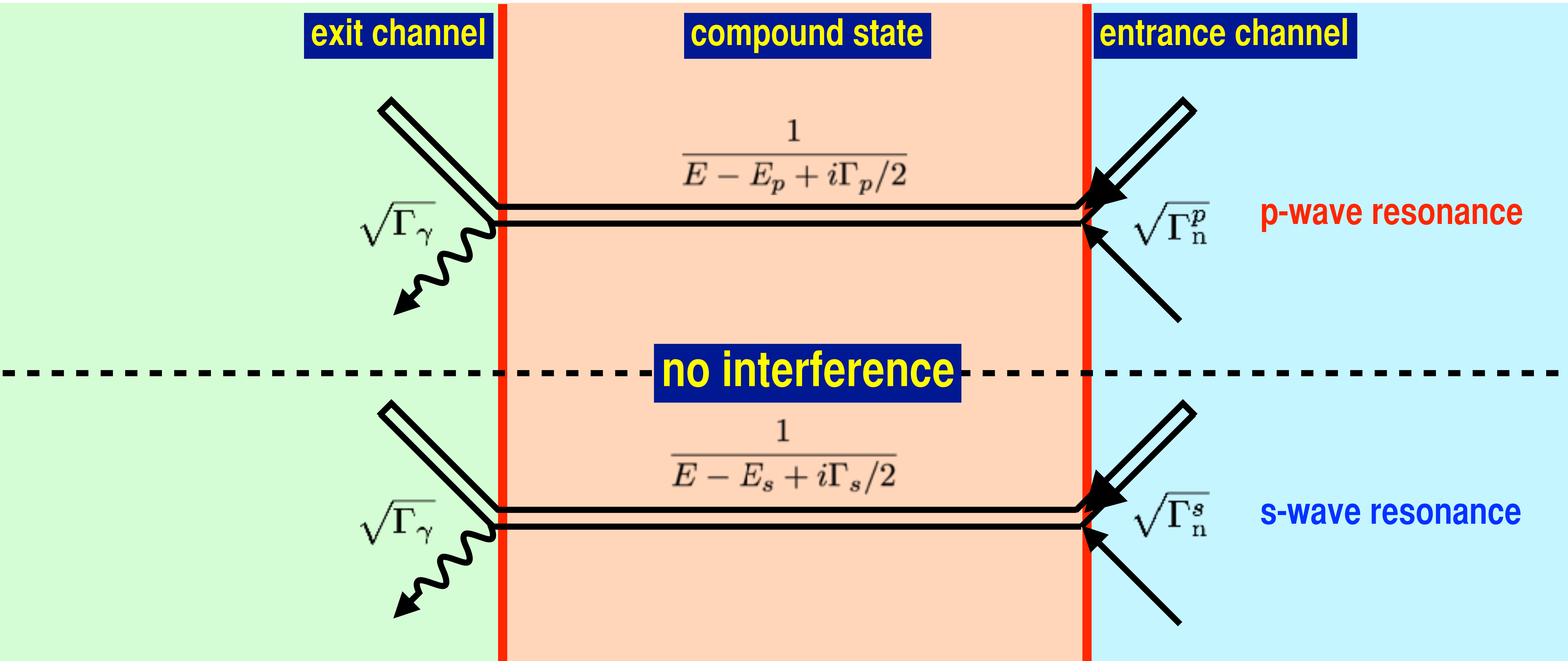
Mitchell, Phys. Rep. 354 (2001) 157

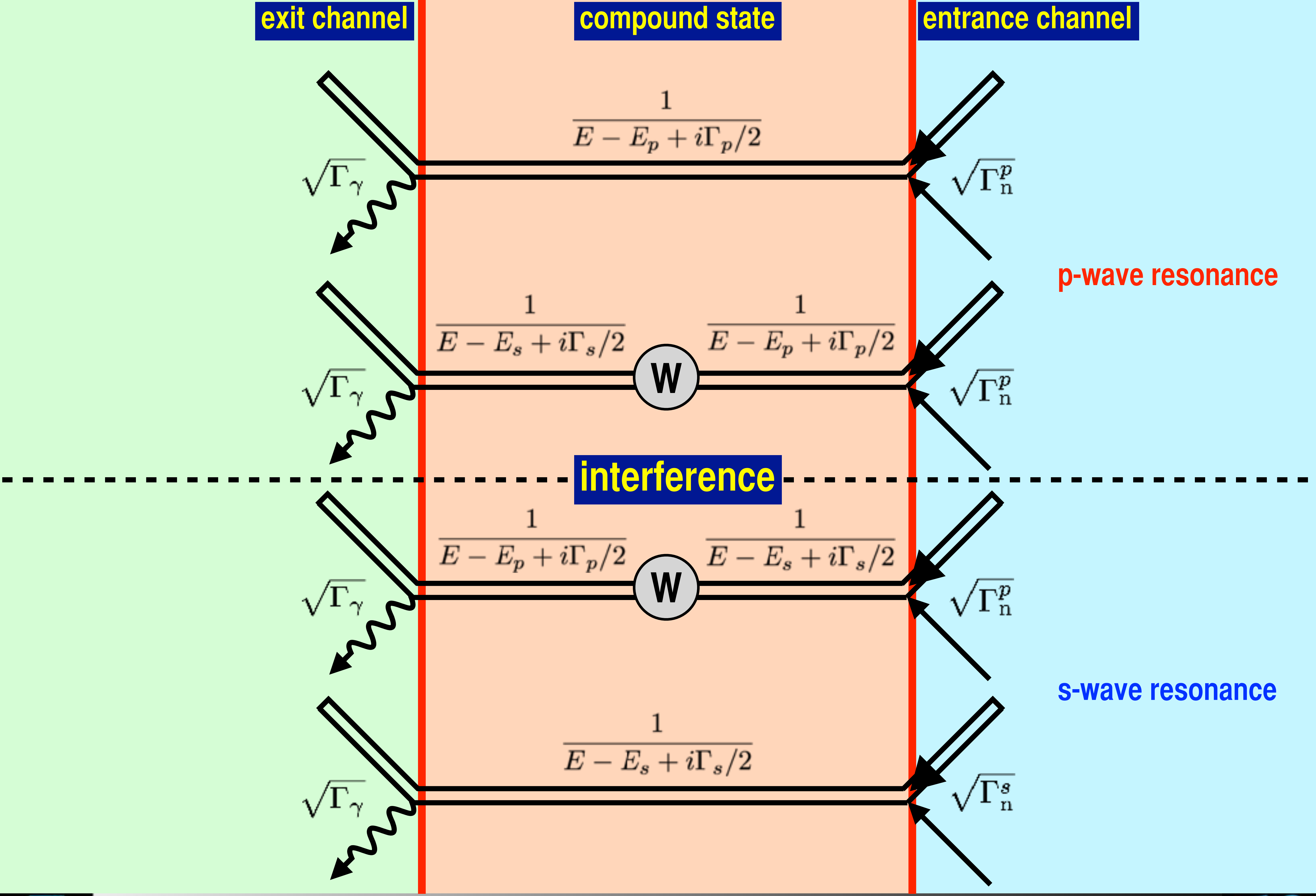




$$\sqrt{\Gamma_\gamma}\frac{1}{E-E_0+i\Gamma/2}\sqrt{\Gamma_n}$$


$\sigma_{n,\gamma}$
s-wave resonance
p-wave resonance
E_s
0
E_p
E_n


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

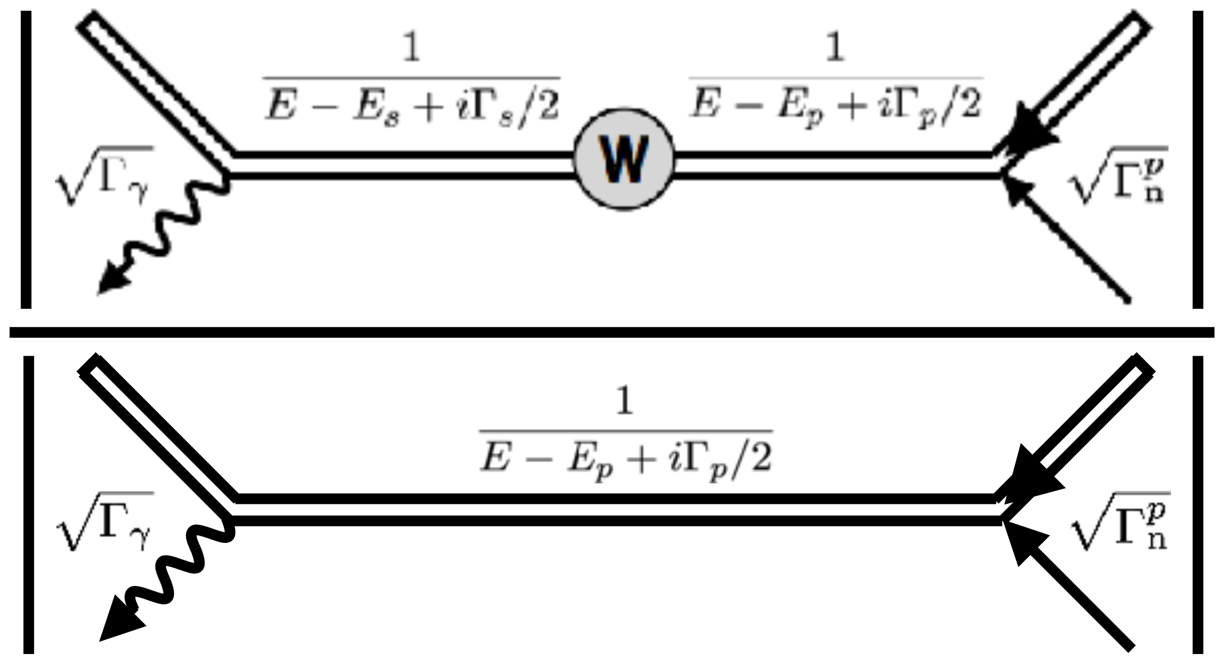

exit channel
compound state
entrance channel
$\frac{1}{E - E_p + i\Gamma_p/2}$
$\sqrt{\Gamma_\gamma}$
$\sqrt{\Gamma_n^p}$
p-wave resonance
$\frac{1}{E - E_s + i\Gamma_s/2}$
W
$\frac{1}{E - E_p + i\Gamma_p/2}$
$\sqrt{\Gamma_\gamma}$
$\sqrt{\Gamma_n^p}$
interference
$\frac{1}{E - E_p + i\Gamma_p/2}$
W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

Enhancement of P-violation

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

Parity-conserving   Parity-non-conserving

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



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

kinematical enhancement 10^3

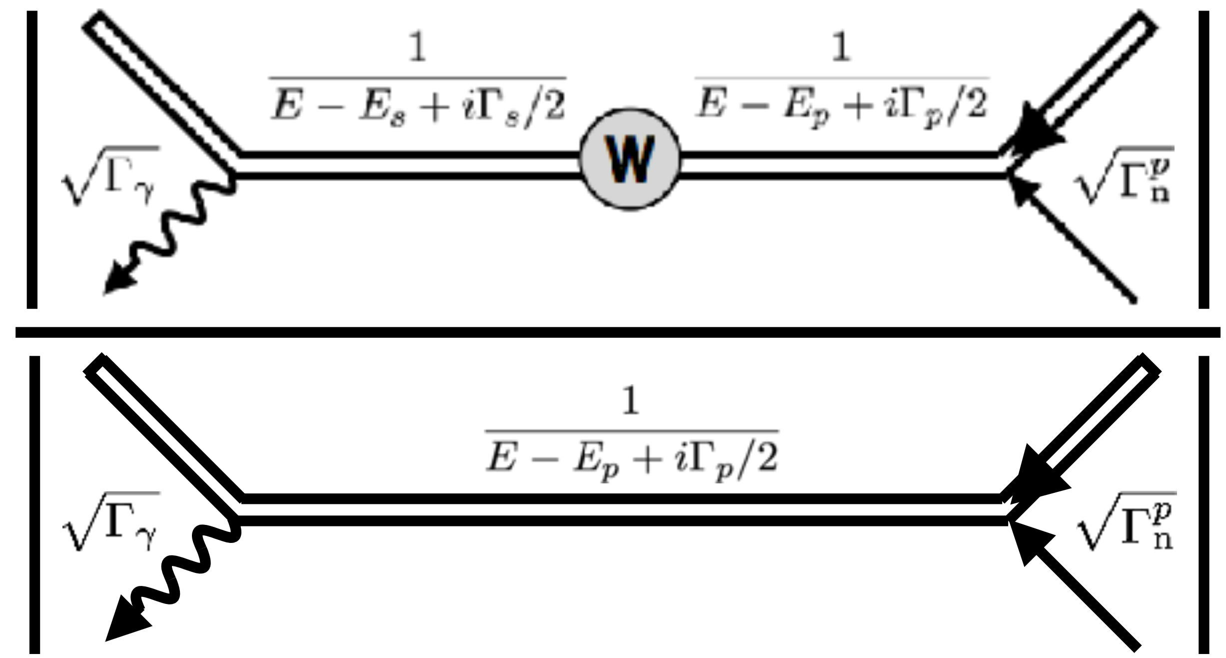
Enhancement of P-violation

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

Parity-conserving

Parity-non-conserving

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

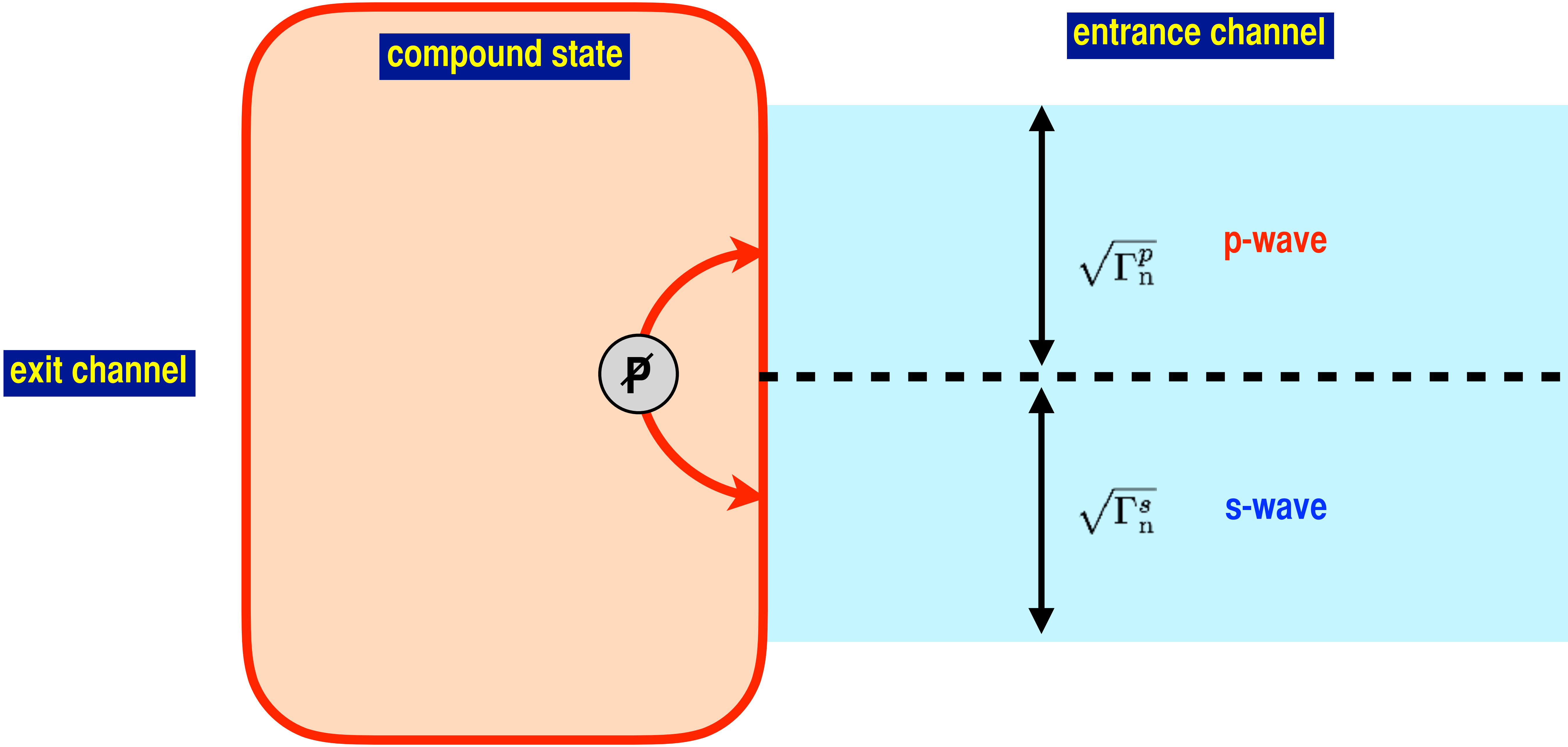


$$= 2\frac{\left|\sqrt{\Gamma^p_\gamma}\frac{1}{E - E_p + i\Gamma_p/2} W \frac{1}{E - E_s + i\Gamma_s/2}\sqrt{\Gamma^s_{\mathrm{n}}}\right|}{\left|\sqrt{\Gamma^p_\gamma}\frac{1}{E - E_p + i\Gamma_p/2}\sqrt{\Gamma^p_{\mathrm{n}}}\right|} \underset{E = E_p}{\sim} 2\frac{W}{|E_p - E_s|}\sqrt{\frac{\Gamma^s_{\mathrm{n}}}{\Gamma^p_{\mathrm{n}}}}$$

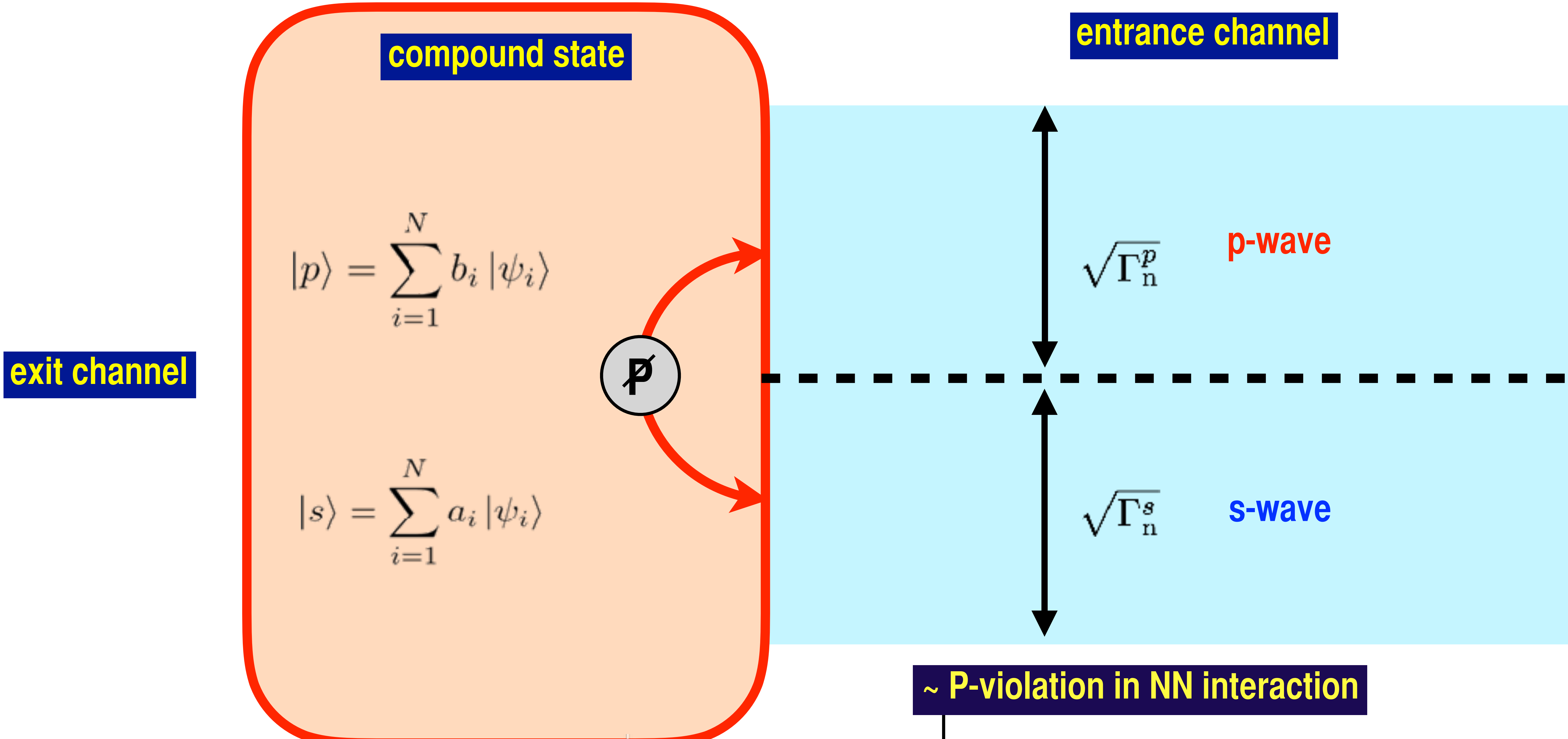
dynamical enhancement 10^2-10^3

kinematical enhancement 10^3

Dynamical Enhancement



Dynamical Enhancement



~ P-violation in NN interaction

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

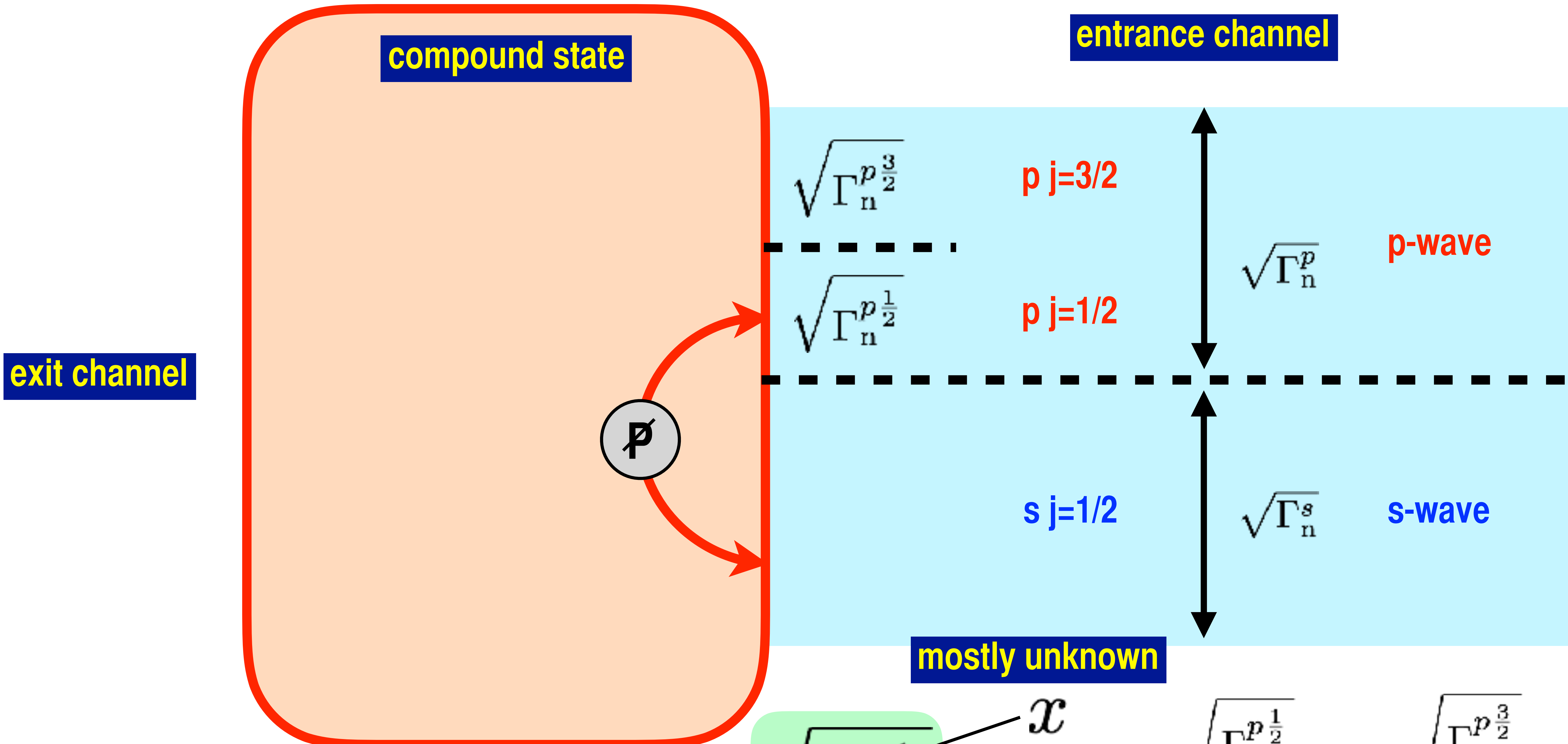
randomness of expansion coefficients

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

ΔE: 10^6 eV

D: 10 eV

Universality Check



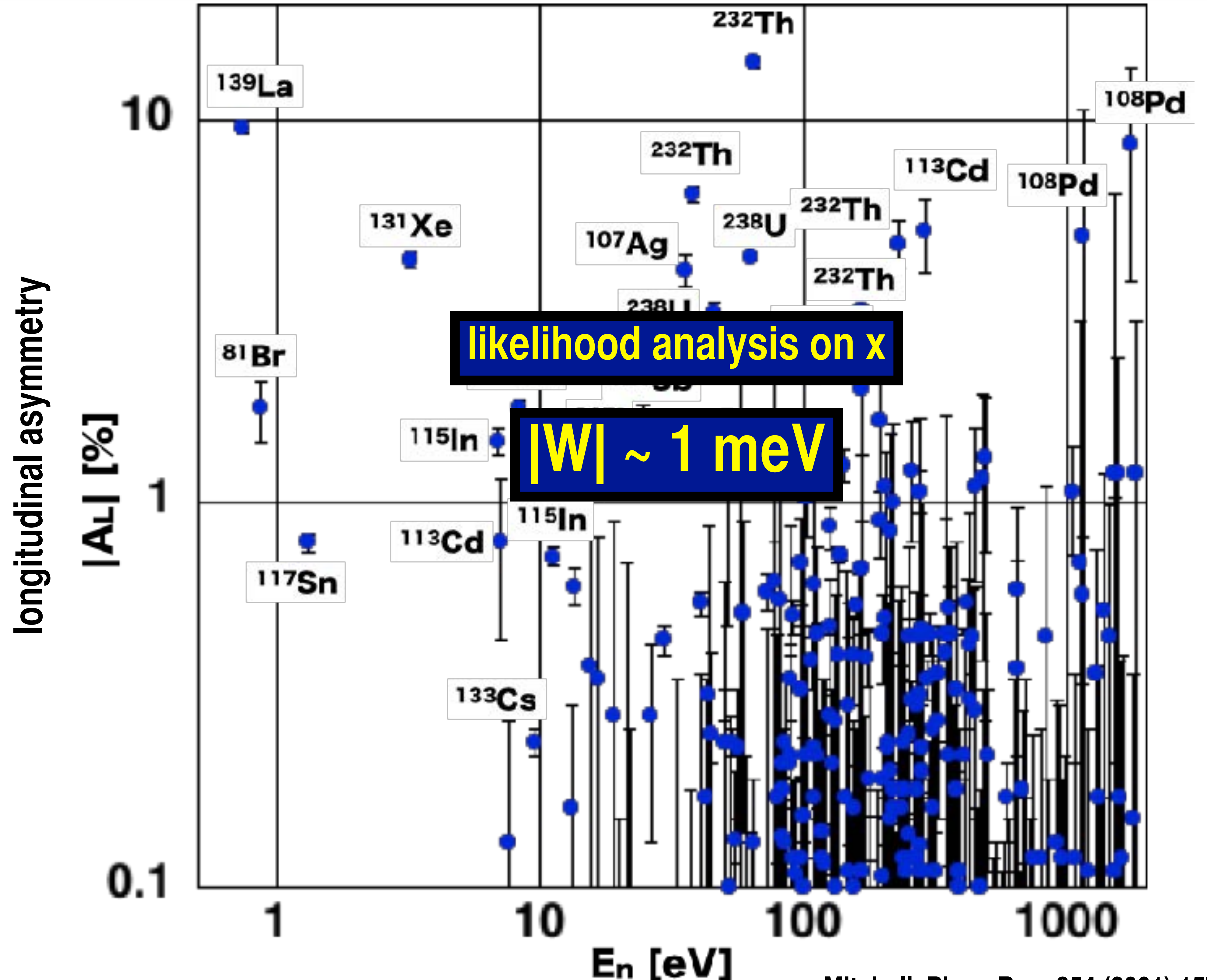
$$A_L = -\frac{2W}{E_p - E_s}\sqrt{\frac{\Gamma_n^s}{\Gamma_n^p}}\sqrt{\frac{\Gamma_n^{p\frac{1}{2}}}{\Gamma_n^p}}$$

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

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

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

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 $\boldsymbol{j}$ 　 $\boldsymbol{S}$ channel spin

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

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

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

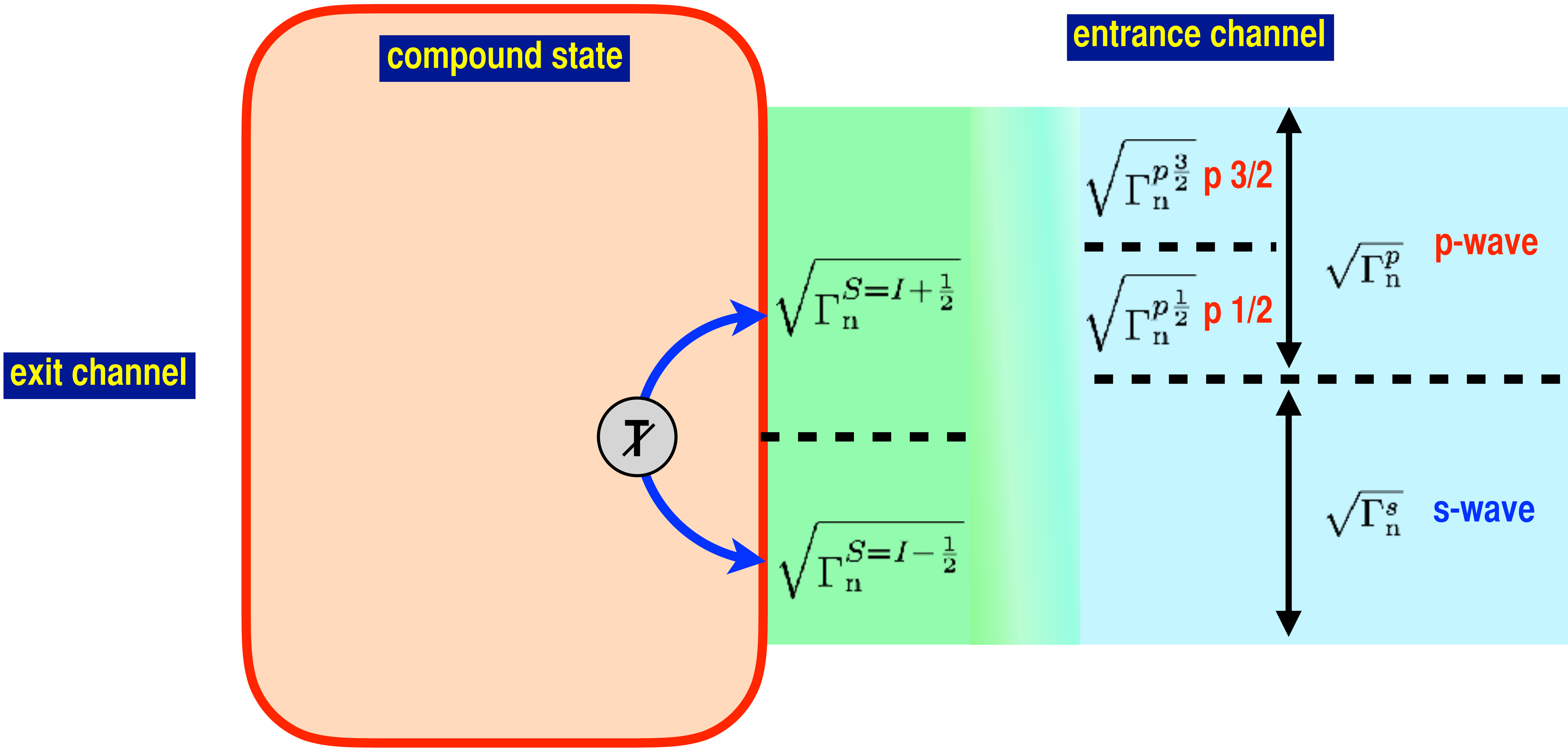
$$z_j = \left\{ \begin{array}{ll} x & (j=1/2) \\ y & (j=3/2) \end{array} \right. , \quad \tilde{z}_S = \left\{ \begin{array}{ll} x_S & (S=I-1/2) \\ y_S & (S=I+1/2) \end{array} \right. \quad \tilde{z}_S = \sum_j (-1)^{l+I+j+S} \sqrt{(2j+1)(2S+1)} \left\{ \begin{array}{ccc} l & s & j \\ I & J & S \end{array}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

s-p interference ⇔ channel-spin interference

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

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

T-odd ➡ Channel-spin Interference

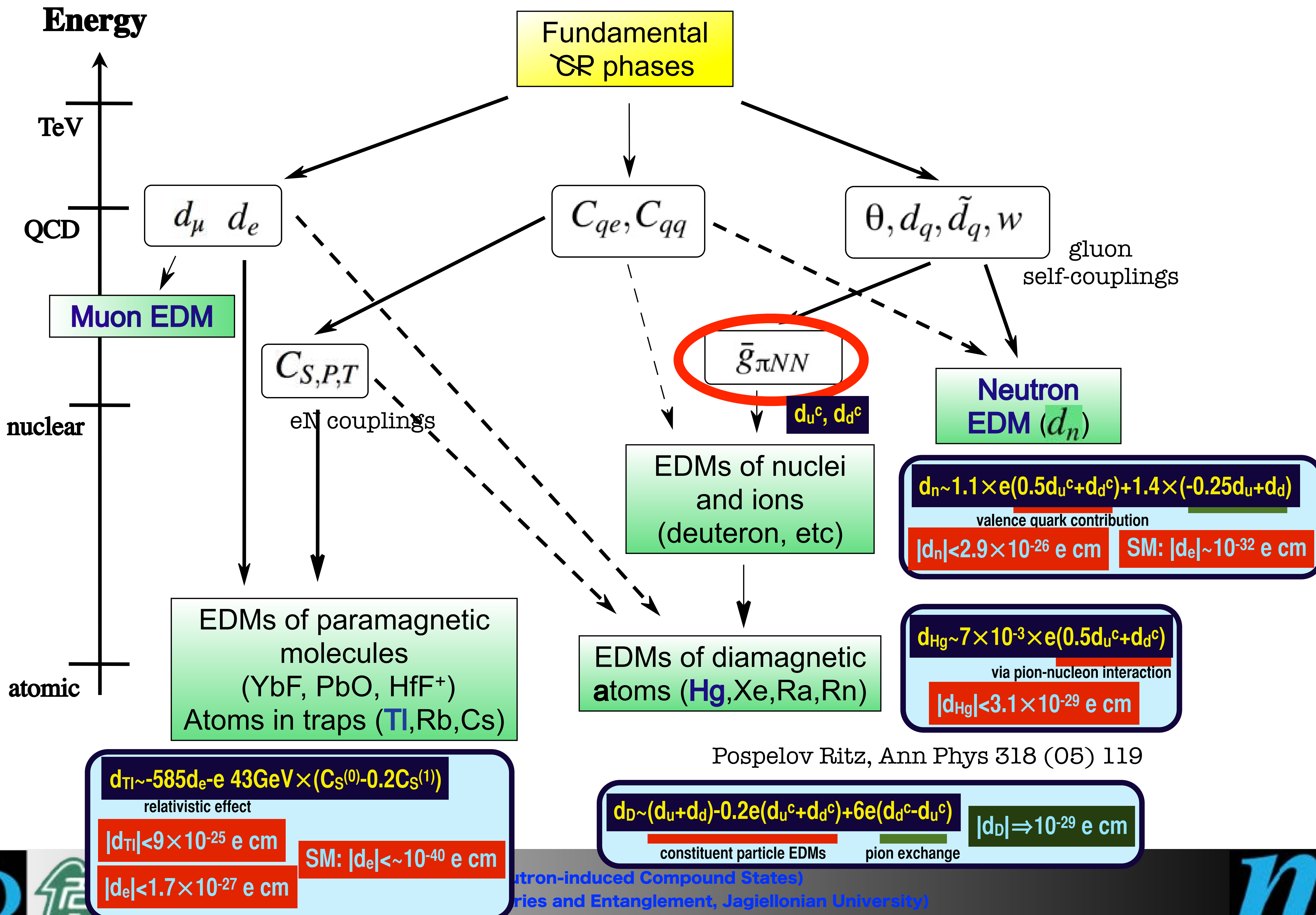


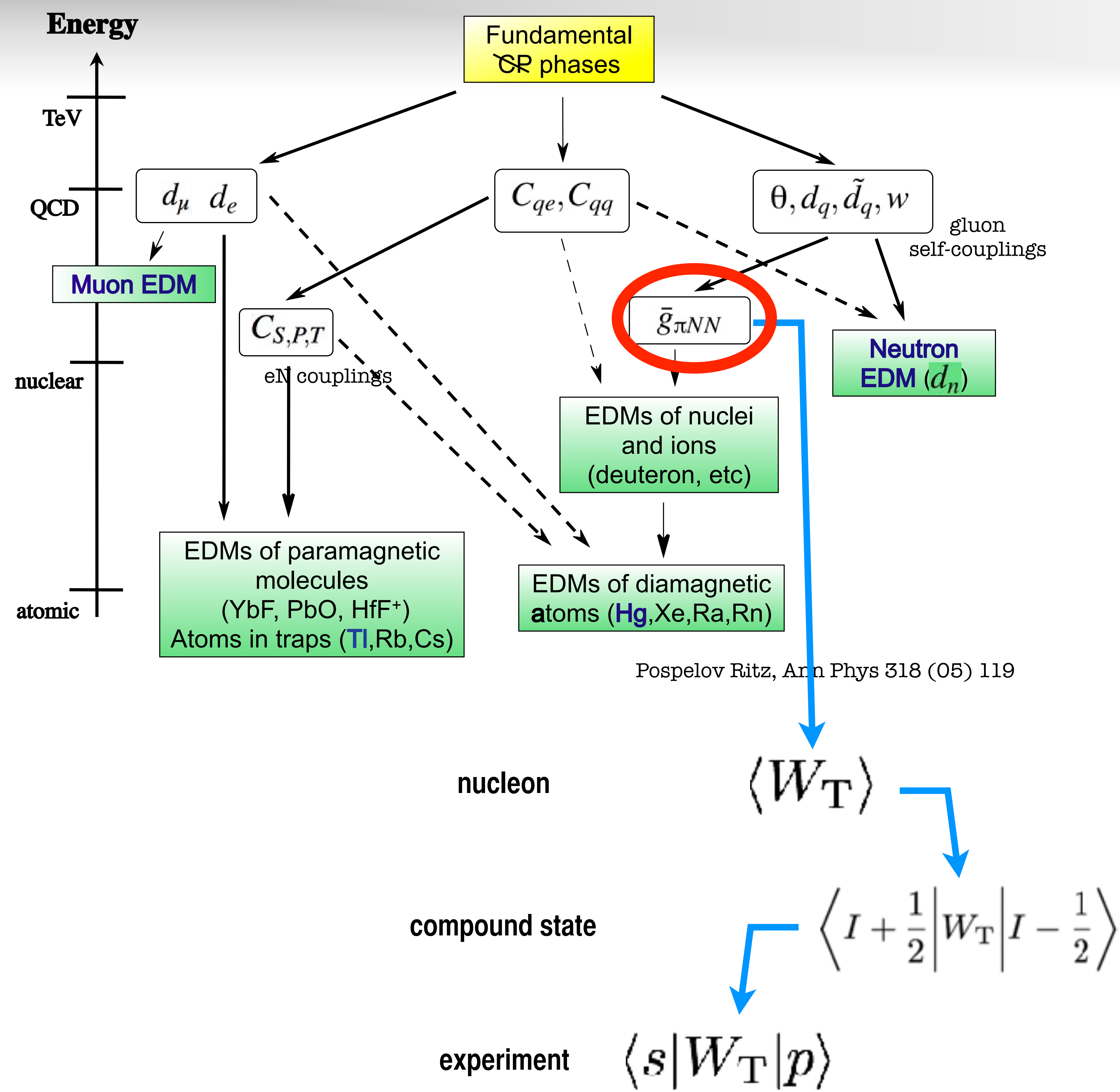
P-violation enhancement～10^6

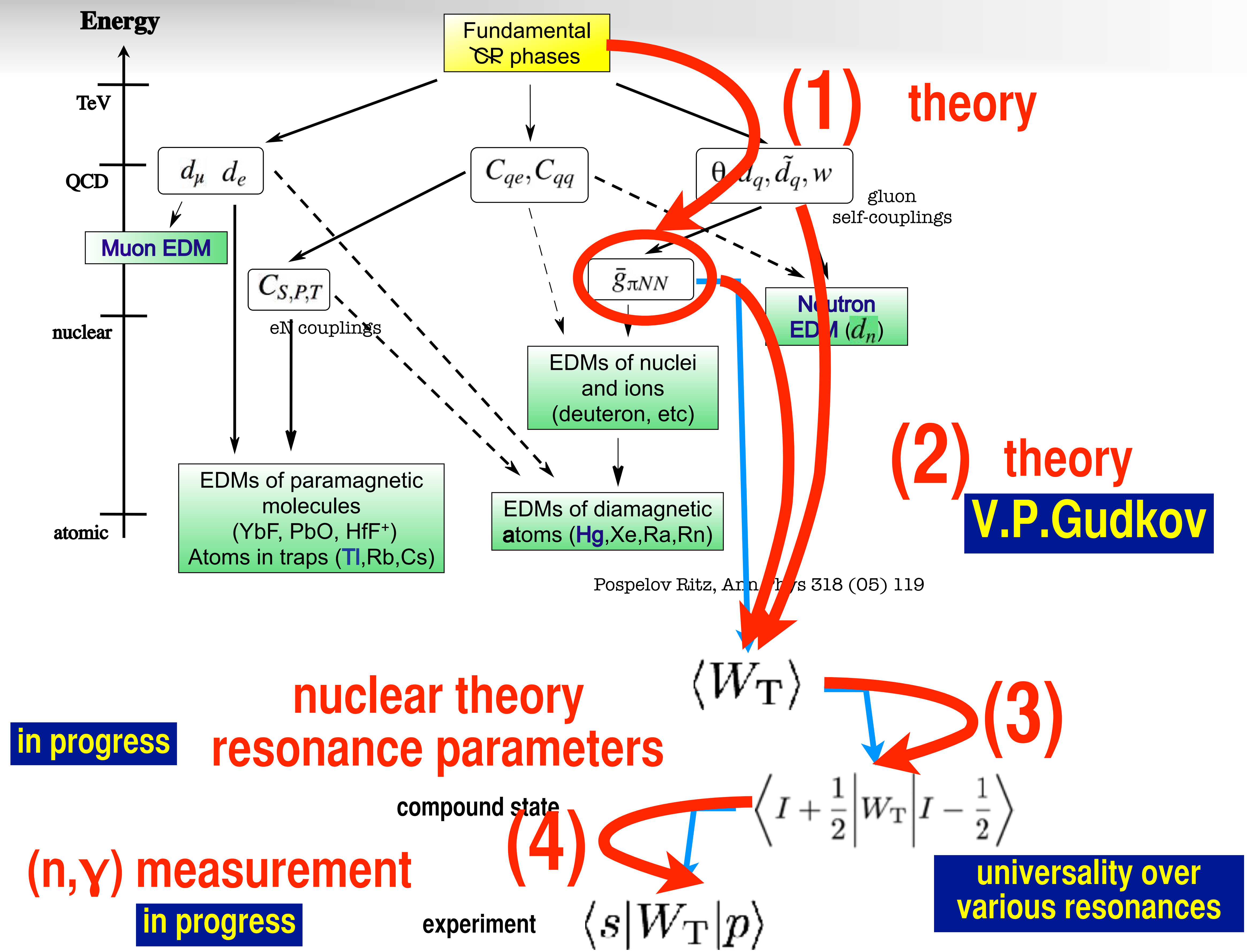
P-violation enhancement～10^6

T-violation enhancement～?

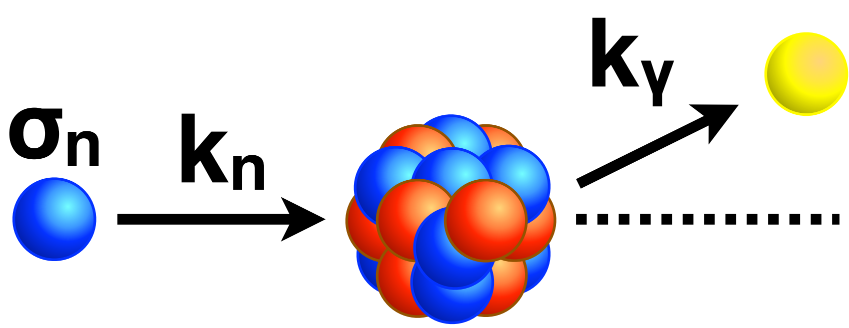
CP-violation in Low Energy Phenomena




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

(4) Details of Entrance Channel



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

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

ϕ

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

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

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

coeff.	$\boldsymbol{\sigma}_n$-dep.	$\boldsymbol{\sigma}_\gamma$-dep.	P	T	correlation
a_0	no	no	P-even	T-even	1
a_1	no	no	P-even	T-even	$\boldsymbol{k}_n \cdot \boldsymbol{k}_\gamma$
a_2	yes	no	P-even	T-odd	$\boldsymbol{\sigma}_n \cdot (\boldsymbol{k}_n \times \boldsymbol{k}_\gamma)$
a_3	no	no	P-even	T-even	$(\boldsymbol{k}_n \cdot \boldsymbol{k}_\gamma)^2 - \frac{1}{3}$
a_4	yes	no	P-even	T-odd	$(\boldsymbol{k}_n \cdot \boldsymbol{k}_\gamma)\, \boldsymbol{\sigma}_n \cdot (\boldsymbol{k}_n \times \boldsymbol{k}_\gamma)$
a_5	yes	yes	P-even	T-even	$(\boldsymbol{\sigma}_\gamma \cdot \boldsymbol{k}_\gamma)\,(\boldsymbol{\sigma}_n \cdot \boldsymbol{k}_\gamma)$
a_6	yes	yes	P-even	T-even	$(\boldsymbol{\sigma}_\gamma \cdot \boldsymbol{k}_\gamma)\,(\boldsymbol{\sigma}_n \cdot \boldsymbol{k}_\gamma)$
a_7	yes	yes	P-even	T-even	$(\boldsymbol{\sigma}_\gamma \cdot \boldsymbol{k}_\gamma)\,[(\boldsymbol{\sigma}_n \cdot \boldsymbol{k}_\gamma)\,(\boldsymbol{k}_\gamma \cdot \boldsymbol{k}_n) - \frac{1}{3}(\boldsymbol{\sigma}_n \cdot \boldsymbol{k}_n)]$
a_8	yes	yes	P-even	T-even	$(\boldsymbol{\sigma}_\gamma \cdot \boldsymbol{k}_\gamma)\,[(\boldsymbol{\sigma}_n \cdot \boldsymbol{k}_n)\,(\boldsymbol{k}_n \cdot \boldsymbol{k}_\gamma) - \frac{1}{3}(\boldsymbol{\sigma}_n \cdot \boldsymbol{k}_\gamma)]$
a_9	yes	no	P-odd	T-even	$(\boldsymbol{\sigma}_n \cdot \boldsymbol{k}_\gamma)$
a_{10}	yes	no	P-odd	T-even	$(\boldsymbol{\sigma}_n \cdot \boldsymbol{k}_n)$
a_{11}	yes	no	P-odd	T-even	$(\boldsymbol{\sigma}_n \cdot \boldsymbol{k}_\gamma)\,(\boldsymbol{k}_\gamma \cdot \boldsymbol{k}_n) - \frac{1}{3}(\boldsymbol{\sigma}_n \cdot \boldsymbol{k}_n)$
a_{12}	yes	no	P-odd	T-even	$(\boldsymbol{\sigma}_n \cdot \boldsymbol{k}_n)\,(\boldsymbol{k}_n \cdot \boldsymbol{k}_\gamma) - \frac{1}{3}(\boldsymbol{\sigma}_n \cdot \boldsymbol{k}_\gamma)$
a_{13}	no	yes	P-odd	T-even	$(\boldsymbol{\sigma}_\gamma \cdot \boldsymbol{k}_\gamma)$
a_{14}	no	yes	P-odd	T-even	$(\boldsymbol{\sigma}_\gamma \cdot \boldsymbol{k}_\gamma)\,(\boldsymbol{k}_n \cdot \boldsymbol{k}_\gamma)$
a_{15}	yes	yes	P-odd	T-odd	$(\boldsymbol{\sigma}_\gamma \cdot \boldsymbol{k}_\gamma)\, \boldsymbol{\sigma}_n \cdot (\boldsymbol{k}_n \times \boldsymbol{k}_\gamma)$
a_{16}	no	yes	P-odd	T-even	$(\boldsymbol{\sigma}_\gamma \cdot \boldsymbol{k}_\gamma)\,[(\boldsymbol{k}_n \cdot \boldsymbol{k}_\gamma)^2 - \frac{1}{3}]$
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_s} |V_1(J_s)|^2 + \sum_{J_s,j} |V_2(J_pj)|^2 \\
a_1 &= 2\mathrm{Re}\textstyle\sum_{J_s,J_p,j} V_1(J_s)V_2^*(J_pj)P(J_sJ_p\frac{1}{2}j1IF) \\
a_2 &= -2\mathrm{Im}\textstyle\sum_{J_s,J_p,j} V_1(J_s)V_2^*(J_pj)\beta_j P(J_sJ_p\frac{1}{2}j1IF) \\
a_3 &= \mathrm{Re}\textstyle\sum_{J_s,j,J_p',j'} V_2(J_pj)V_2^*(J_p'j')P(J_pJ_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_s,j,J_p',j'} V_2(J_pj)V_2^*(J_p'j')P(J_pJ_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_s,J_s'} V_1(J_sj)V_1^*(J_s'j')P(J_sJ_s'\frac{1}{2}\frac{1}{2}1IF) + \sum_{J_p,j,J_p',j'} V_2(J_pj)V_2^*(J_p'j')P(J_pJ_p'j. \right. \\
a_6 &= -2\mathrm{Re}\textstyle\sum_{J_s} V_1(J_sj)V_2^*(J_p = J_s, \frac{1}{2}) \\
a_7 &= \mathrm{Re}\textstyle\sum_{J_s,J_p} V_1(J_s)V_2^*(J_p\frac{3}{2})P(J_sJ_p\frac{1}{2}\frac{3}{2}2IF) \\
a_8 &= -\mathrm{Re}\textstyle\sum_{J_p,j,J_p',j'} V_2(J_pj)V_2^*(J_p'j')P(J_pJ_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_s,J_s'} V_1(J_sj)V_3^*(J_s'j')P(J_sJ_s'\frac{1}{2}\frac{1}{2}1IF) + \sum_{J_p,j,J_p',j'} V_2(J_pj)V_4^*(J_p'j')P(J_pJ_p'. \right. \\
a_{10} &= -2\mathrm{Re}\textstyle\sum_{J_s} \left[V_2(J_p = J_s, \frac{1}{2})V_3^*(J_s) + V_1(J_s)V_4^*(J_p = J_s, \frac{1}{2})\right] \\
a_{11} &= 2\mathrm{Re}\textstyle\sum_{J_s,J_p} \left[V_2(J_p\frac{3}{2})V_3^*(J_s) + V_1(J_s)V_4^*(J_p\frac{3}{2})\right]\sqrt{3}P(J_sJ_p\frac{1}{2}\frac{1}{3}2IF) \\
a_{12} &= -\mathrm{Re}\textstyle\sum_{J_s,j,J_p',j'} V_2(J_pj)V_4^*(J_p'j')P(J_pJ_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_s} V_1(J_s)V_3^*(J_s) + \sum_{J_pj} V_2(J_pj)V_4^*(J_pj)\right] \\
a_{14} &= 2\mathrm{Re}\textstyle\sum_{J_sJ_pj} \left[V_2(J_pj)V_3^*(J_s) + V_1(J_s)V_4^*(J_pj)\right]P(J_sJ_p\frac{1}{2}j1IF) \\
a_{15} &= 2\mathrm{Im}\textstyle\sum_{J_sJ_pj} \left[V_2(J_pj)V_3^*(J_s) - V_1(J_s)V_4^*(J_pj)\right]\beta_j P(J_sJ_p\frac{1}{2}j1IF) \\
a_{16} &= 2\mathrm{Re}\textstyle\sum_{J_p,j,J_p',j'} V_2(J_pj)V_4^*(J_p'j')P(J_pJ_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_p,j,J_p',j'} V_2(J_pj)V_4^*(J_p'j')P(J_pJ_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}
$$

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

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

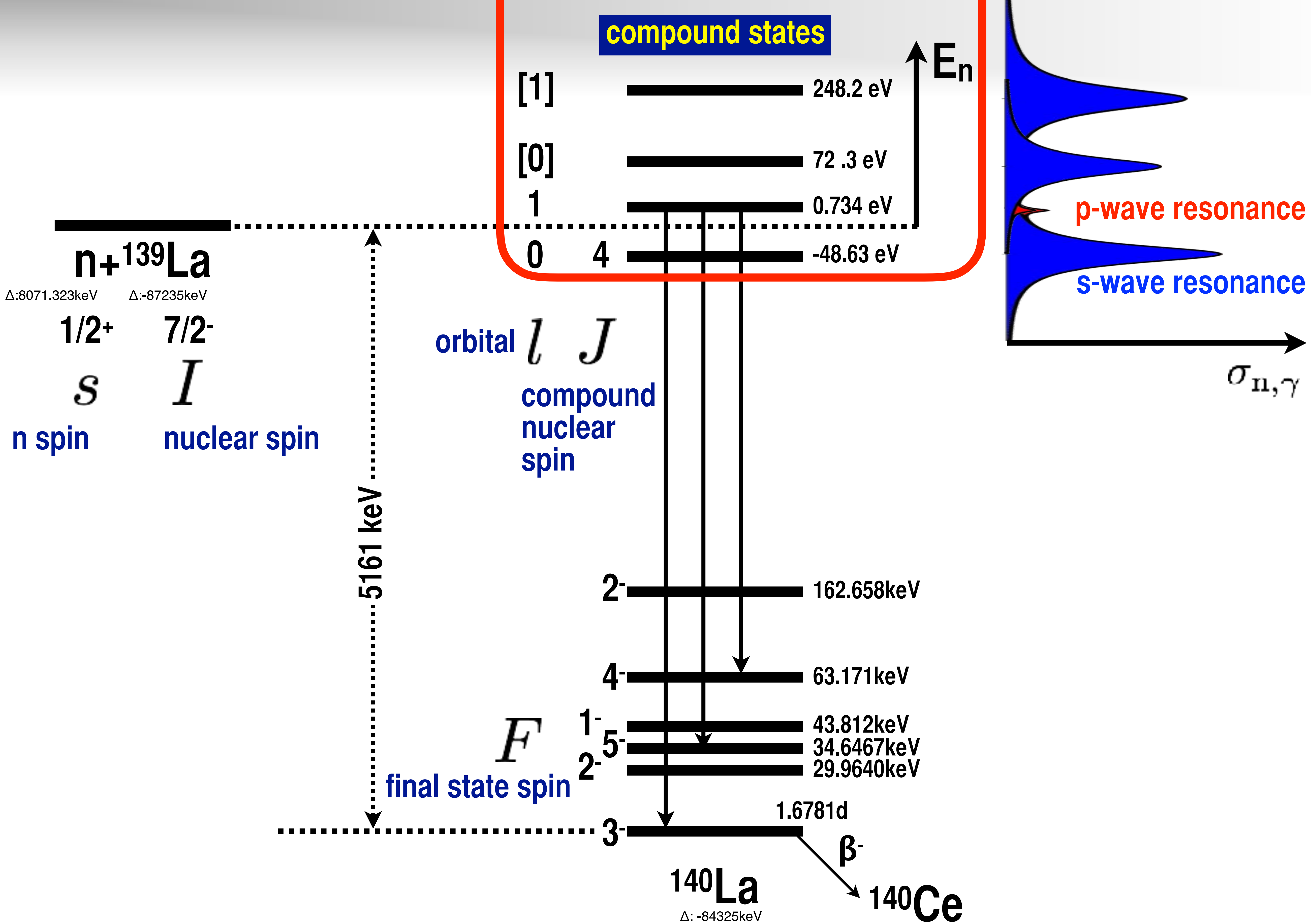
$$\phi$$

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

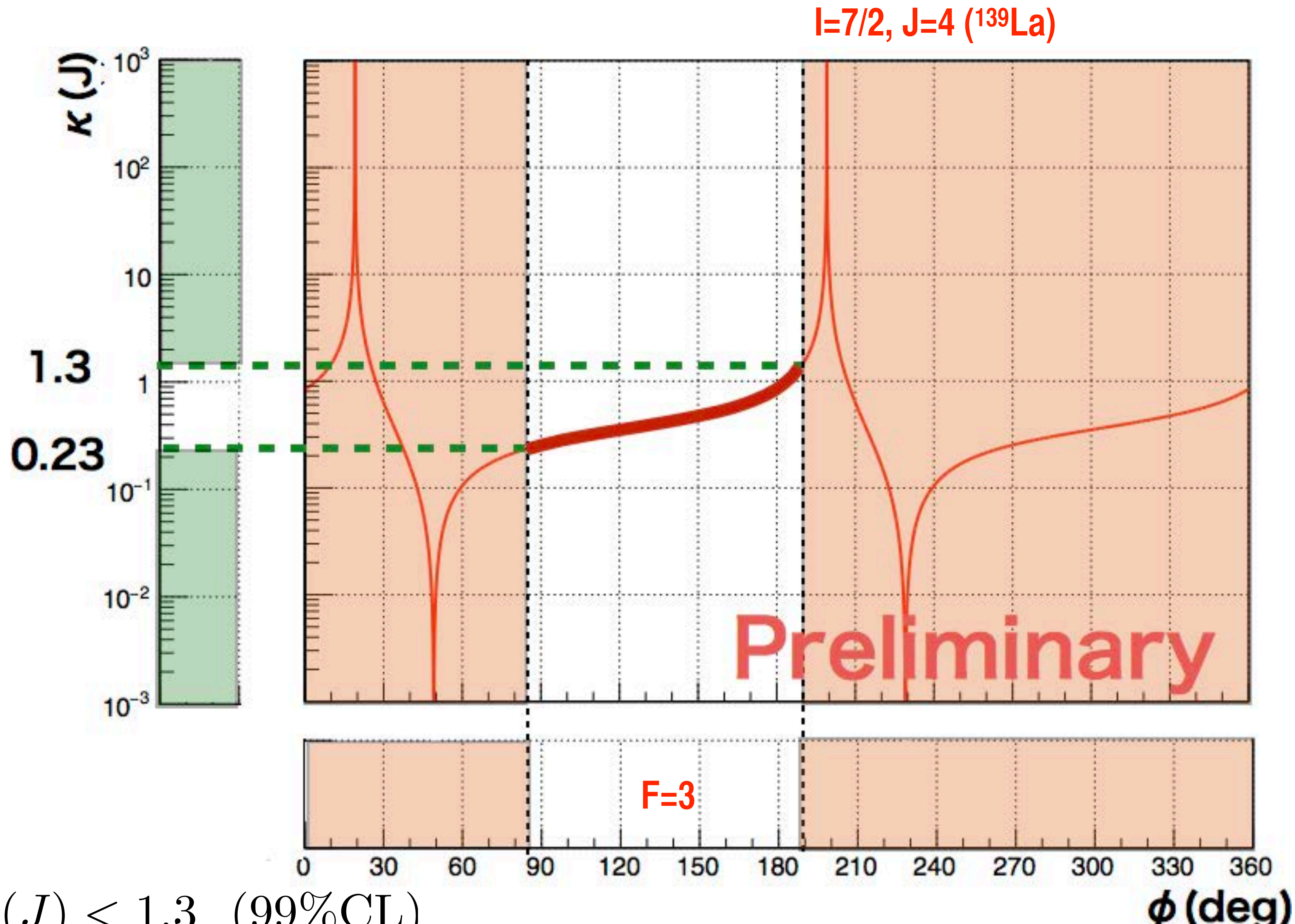
$$\Gamma^n_{p,1/2} \quad \Gamma^n_{p,3/2}$$

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

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


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

κ(J) for ^{139}La(n,γ)^{140}La(F=3)



$$0.23 < \kappa(J) < 1.3 \quad (99\%\mathrm{CL})$$

T-violation in Neutron Optics

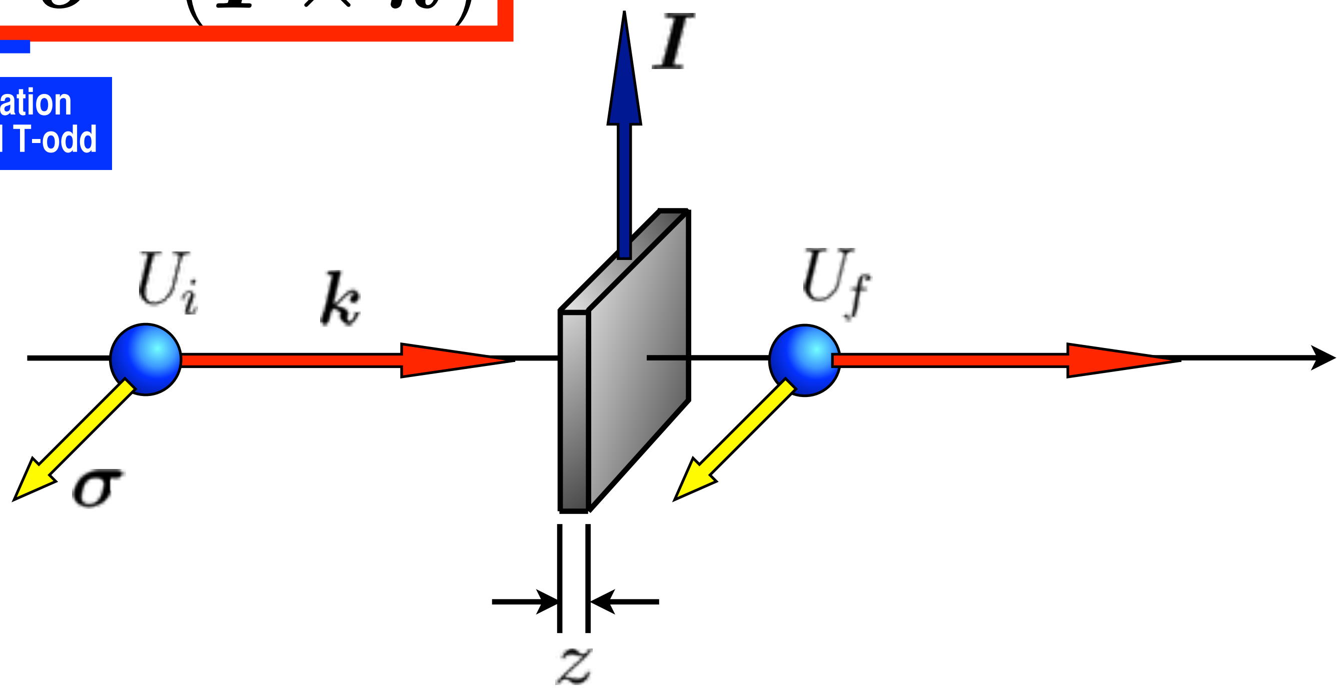
$$f = A' + B'\boldsymbol{\sigma}\cdot\hat{\boldsymbol{I}} + C'\boldsymbol{\sigma}\cdot\hat{\boldsymbol{k}} + D'\boldsymbol{\sigma}\cdot(\hat{\boldsymbol{I}}\times\hat{\boldsymbol{k}})$$

Spin Independent
P-even T-even

Spin Dependent
P-even T-even

P-violation
P-odd T-even

T-violation
P-odd T-odd



Order Estimation of T-violation Sensitivity

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

- 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

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

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

- 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

Gudkov, Phys. Rep. 212 (1992) 77

T-violating matrix element

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

$$\frac{W_{\mathrm{T}}}{W} \sim \frac{g_{\mathrm{CP}}}{g_{\mathrm{P}}}$$

- $\Delta\sigma_{\mathrm{CP}}$: T-violation
- $\kappa(J)$: angular momentum factor
- $\Delta\sigma_{\mathrm{P}}$: P-violation

P-violating matrix element

Order Estimation of T-violation Sensitivity

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

- 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

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

P-violating matrix element

(n,γ) measurement

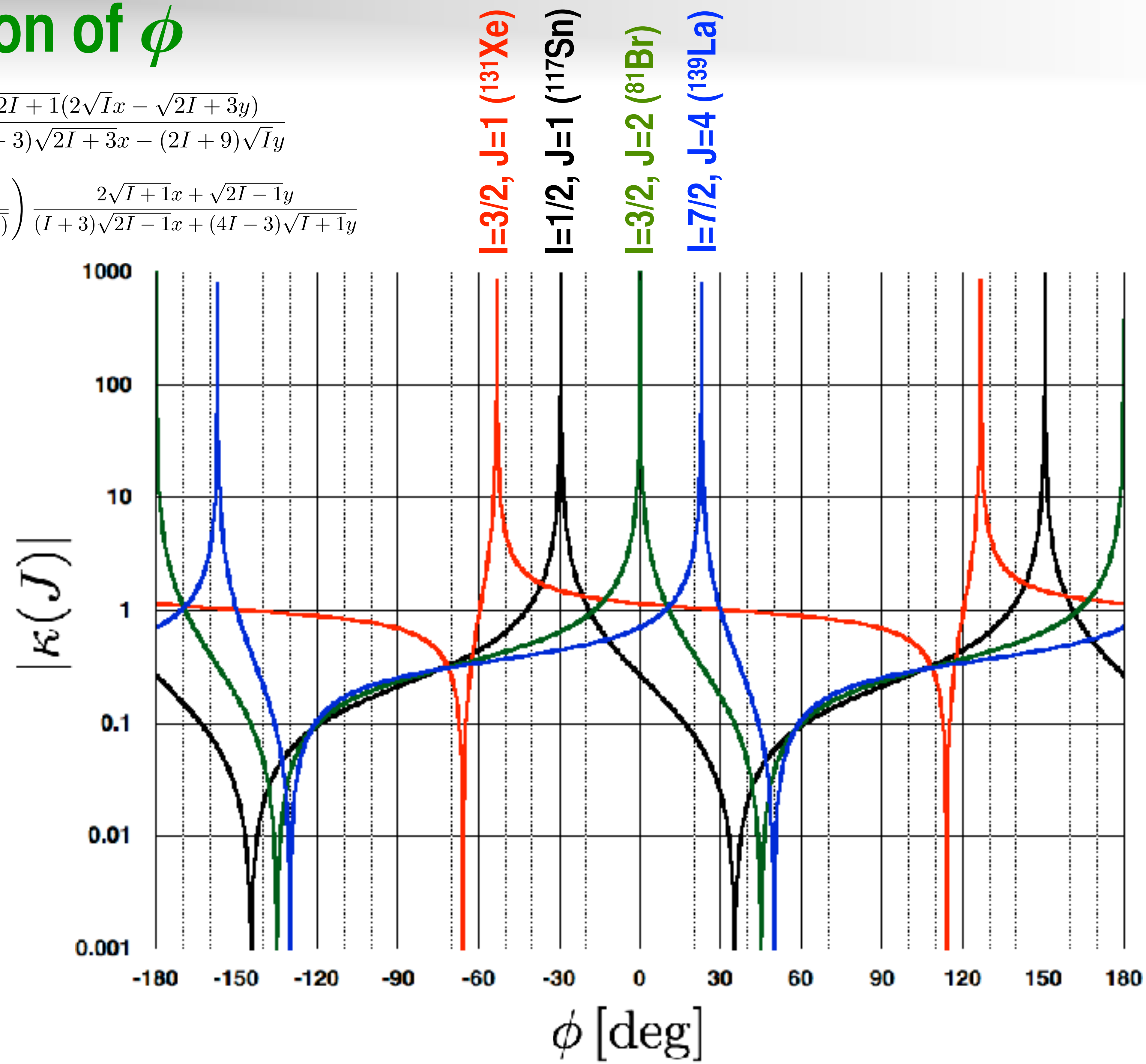
$$\kappa(J=I+\frac{1}{2}) = \frac{3}{2\sqrt{2}}\left(\frac{2I+1}{2I+3}\right)\frac{\sqrt{2I+1}(2\sqrt{I}x-\sqrt{2I+3}y)}{(2I-3)\sqrt{2I+3}x-(2I+9)\sqrt{I}y}$$

$$\kappa(J=I-\frac{1}{2}) = -\frac{3}{2\sqrt{2}}\left(\frac{(2I+1)\sqrt{I}}{\sqrt{(I+1)(2I-1)}}\right)\frac{2\sqrt{I+1}x+\sqrt{2I-1}y}{(I+3)\sqrt{2I-1}x+(4I-3)\sqrt{I+1}y}$$

κ(J) as a function of ϕ

$$\kappa(J=I+\frac{1}{2}) = \frac{3}{2\sqrt{2}}\left(\frac{2I+1}{2I+3}\right)\frac{\sqrt{2I+1}(2\sqrt{I}x-\sqrt{2I+3}y)}{(2I-3)\sqrt{2I+3}x-(2I+9)\sqrt{I}y}$$

$$\kappa(J=I-\frac{1}{2}) = -\frac{3}{2\sqrt{2}}\left(\frac{(2I+1)\sqrt{I}}{\sqrt{(I+1)(2I-1)}}\right)\frac{2\sqrt{I+1}x+\sqrt{2I-1}y}{(I+3)\sqrt{2I-1}x+(4I-3)\sqrt{I+1}y}$$



$$\sqrt{\frac{\Gamma_n^{p\frac{1}{2}}}{\Gamma_n}} = x = \cos\phi$$

$$\sqrt{\frac{\Gamma_n^{p\frac{3}{2}}}{\Gamma_n}} = y = \sin\phi$$

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

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

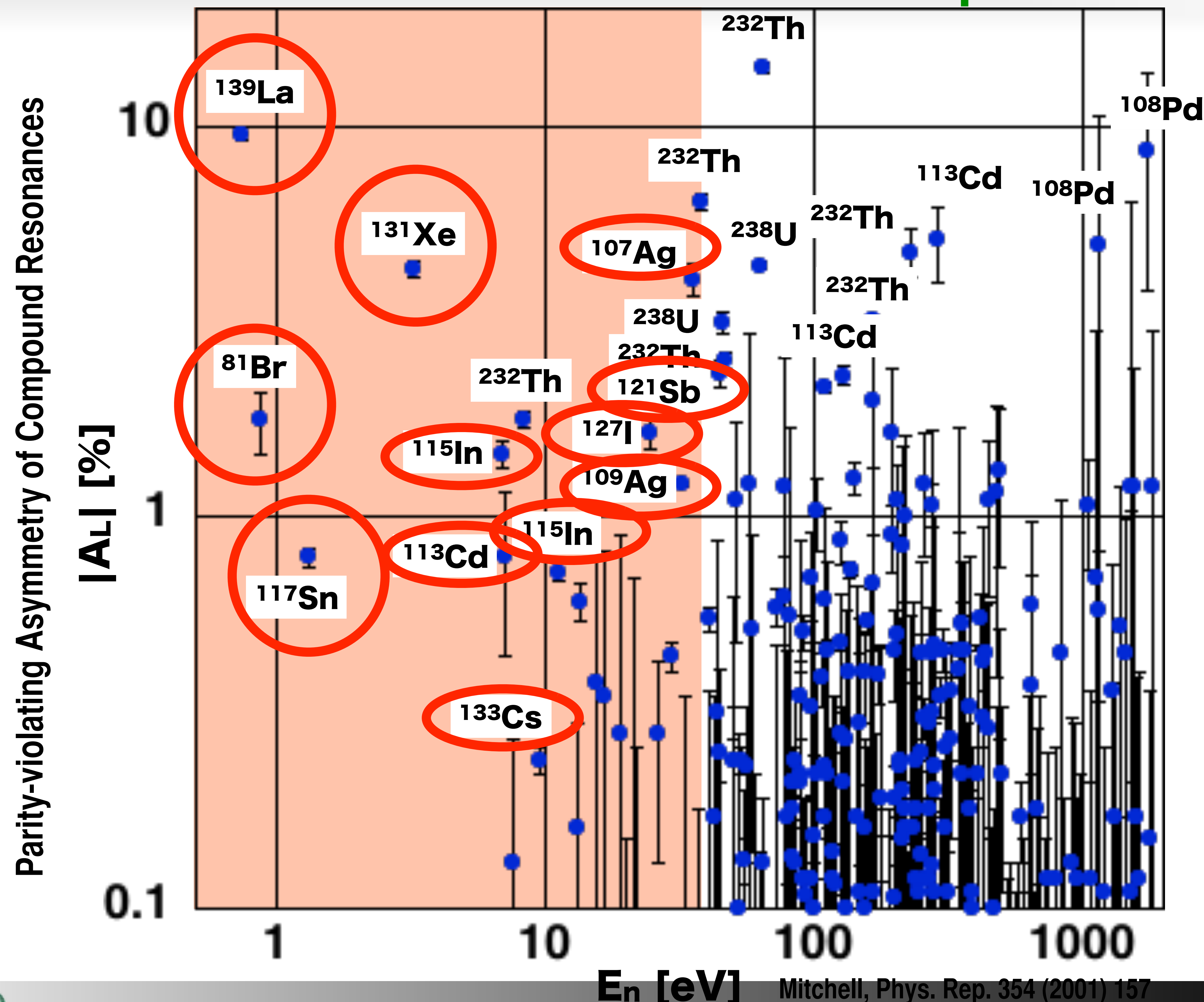
present upper limit

~ 1

↑

T-odd term to be measured

Candidate Resonances for the T-violation Experiment



Mitchell, Phys. Rep. 354 (2001) 157

Candidate 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 $\|\kappa(J)\|$	?	?	?	○?	?

Candidate 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 $\vert\kappa(J)\vert$	?	?	?	○?	?
method of pol.				OP	

Choice of Target Nuclei

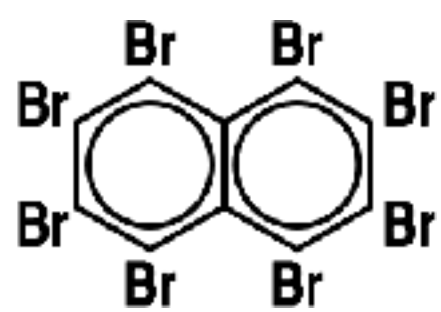
	^{139}La	^{81}Br	^{117}Sn	^{131}Xe	^{115}In
large $\Delta\sigma_P$	◎	○	◎	◎	◎
low E_p [eV]	◎	◎	○	○	△
small nonzero I	7/2 △	3/2 ○	1/2 ◎	3/2 ○	9/2 △
isotopic abn	◎	○	×	△	◎
large |κ(J)|	○?	?	?	○?	?
method of pol.	DNP	—	—	OP	—

$La(Nd)AlO_3$

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 $\lvert\kappa(J)\rvert$	○?	?	?	○?	?
method of pol.	DNP	Triplet -DNP?	—	OP	—

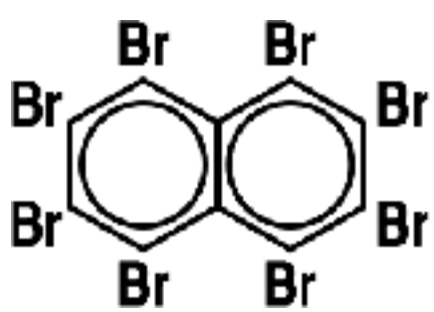
$La(Nd)AlO_3$



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 $\lvert\kappa(J)\rvert$	○?	?	○?	○?	?
method of pol.	DNP	Triplet -DNP?	—	OP	—

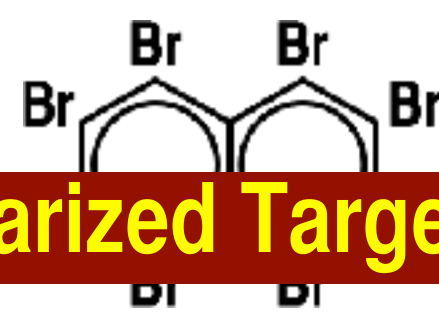
$La(Nd)AlO_3$



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	Triplet -DNP?	—	OP	—

La(Nd)AlO_3



Key-technique: Polarized Target

T-violation in Neutron Optics

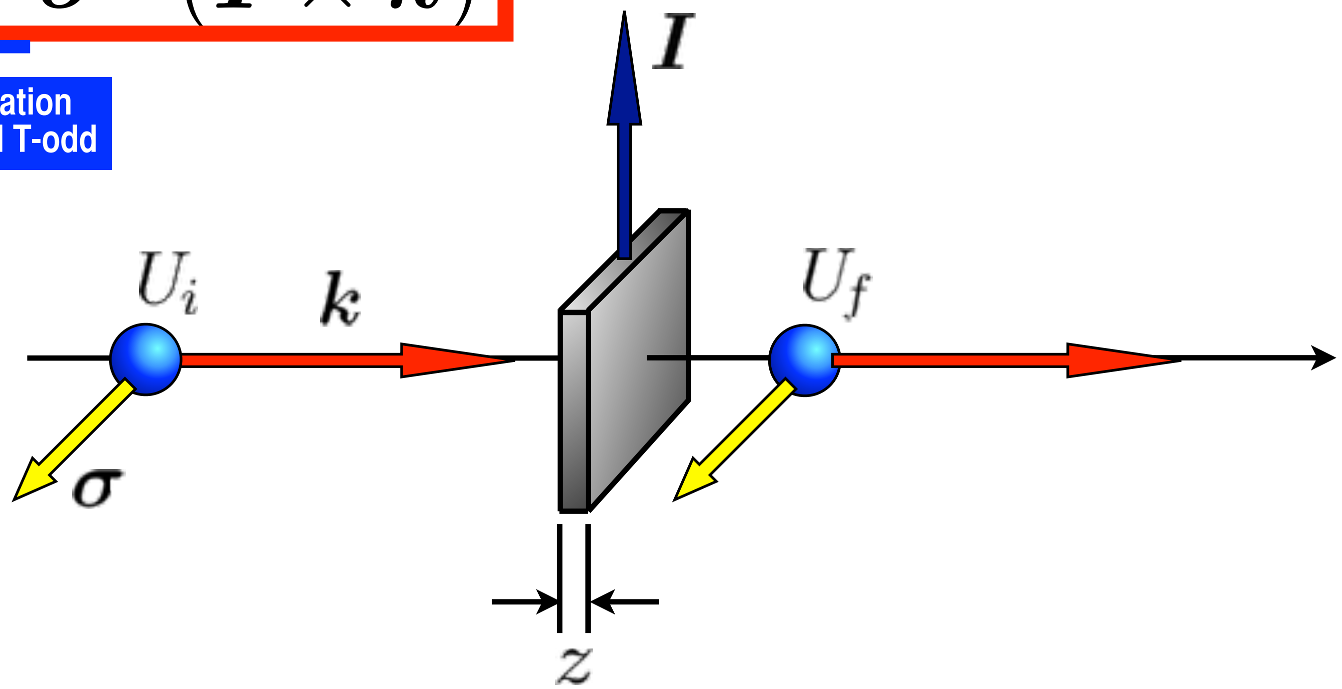
$$f = A' + B'\boldsymbol{\sigma}\cdot\hat{\boldsymbol{I}} + C'\boldsymbol{\sigma}\cdot\hat{\boldsymbol{k}} + D'\boldsymbol{\sigma}\cdot(\hat{\boldsymbol{I}}\times\hat{\boldsymbol{k}})$$

Spin Independent
P-even T-even

Spin Dependent
P-even T-even

P-violation
P-odd T-even

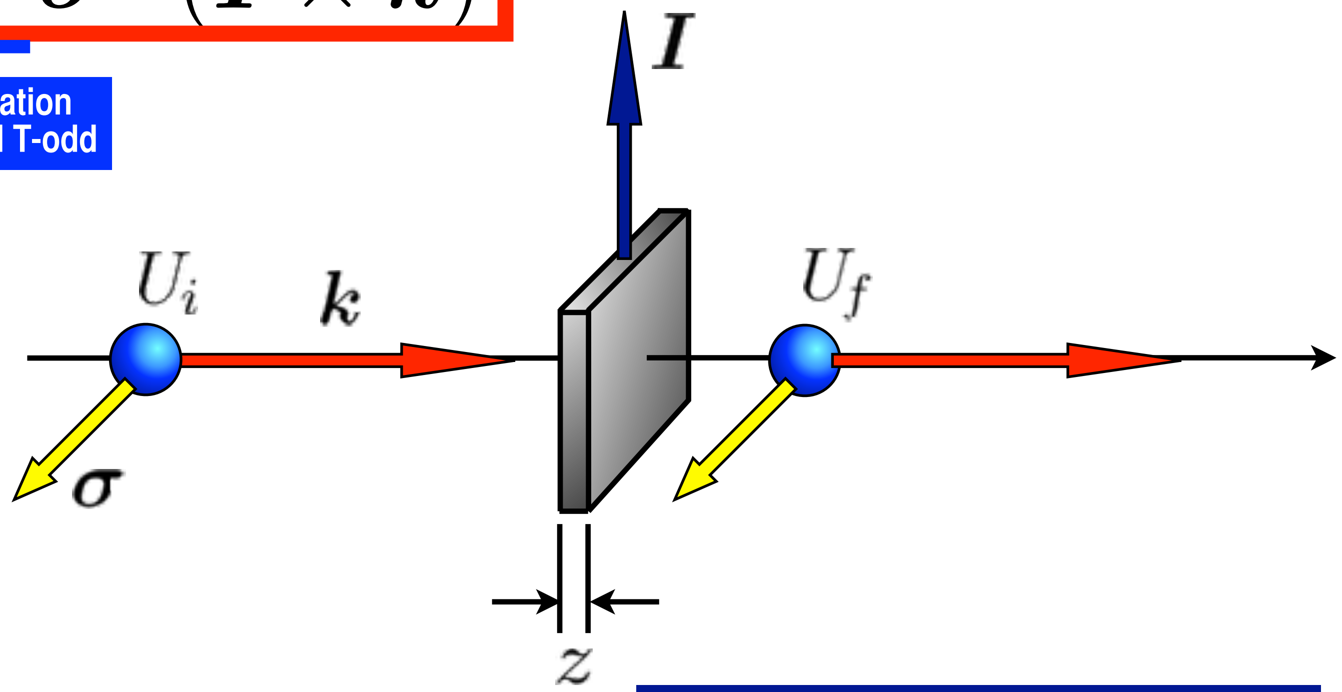
T-violation
P-odd T-odd



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

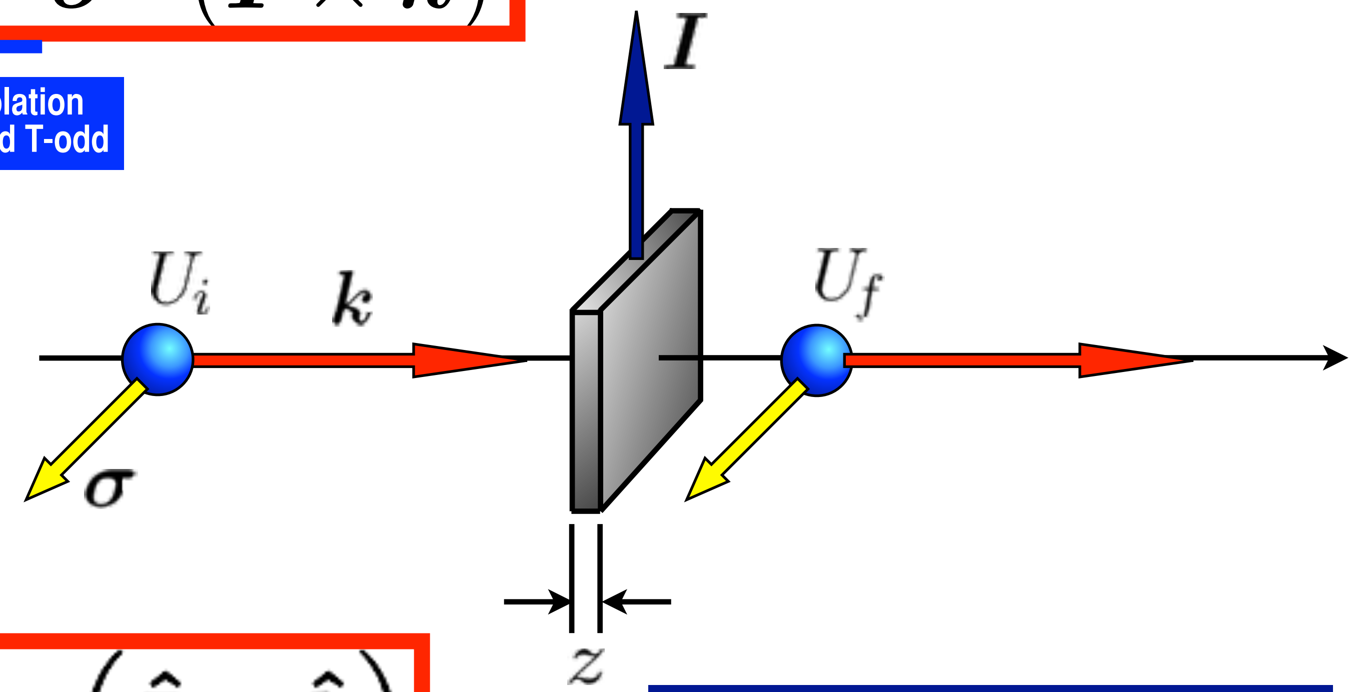


fake T-odd negligible

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

fake T-odd negligible

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

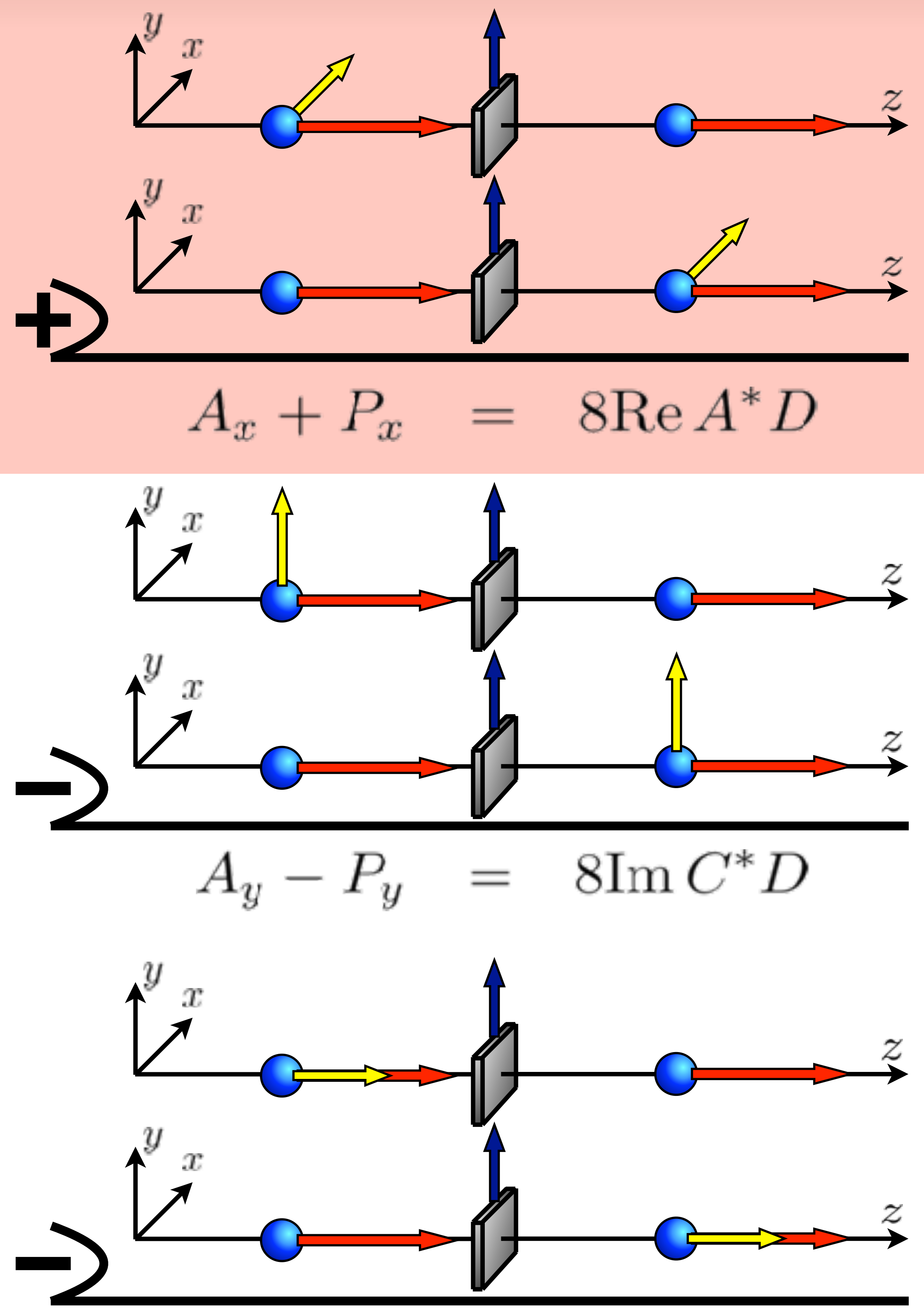
$$Z = \frac{2\pi\rho}{k}z \qquad C = ie^{iZA'}\frac{\sin b}{b}ZC'$$

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

D≠0 ➡ D'≠0

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

Analyzing Power and Polarization

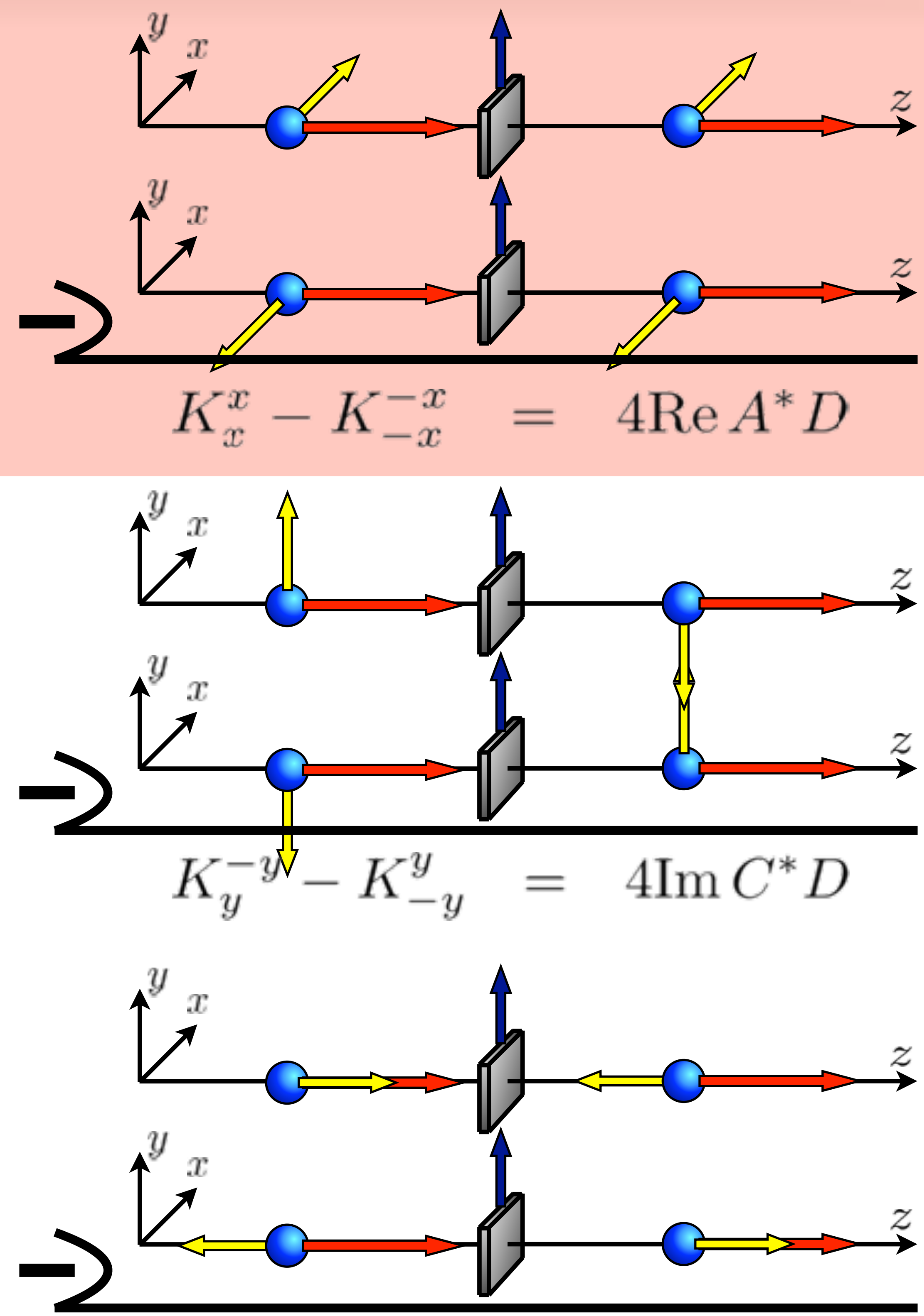


$$A_x + P_x = 8\mathrm{Re}\, A^* D$$

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

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

Polarization Transfer Coefficient

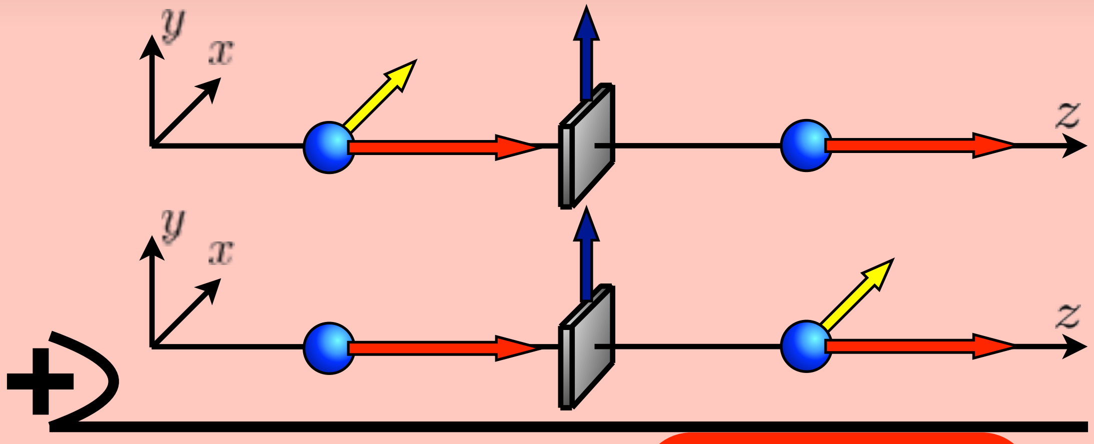


$$K_x^x - K_{-x}^{-x} = 4\mathrm{Re}\, A^* D$$

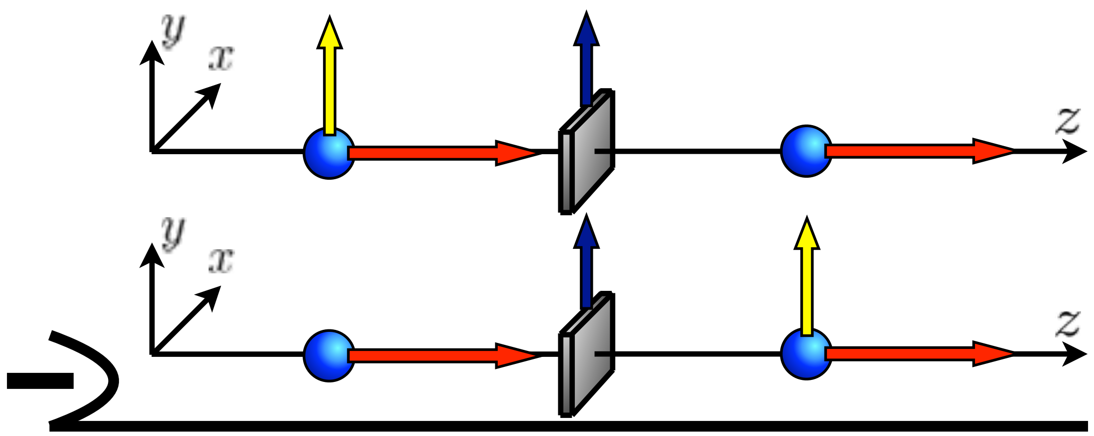
$$K_y^{-y} - K_{-y}^y = 4\mathrm{Im}\, C^* D$$

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

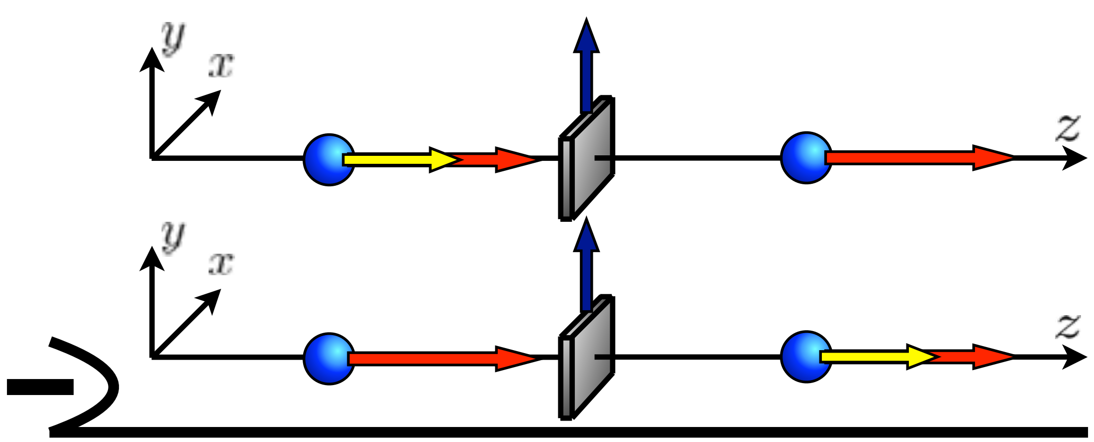
Analyzing Power and Polarization



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

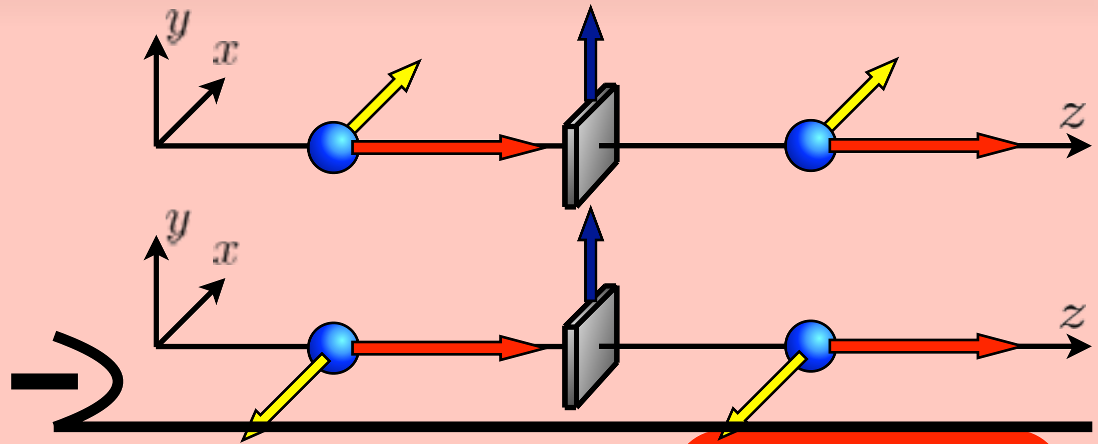


$$A_y - P_y = 8\mathrm{Im}\, C^* D$$

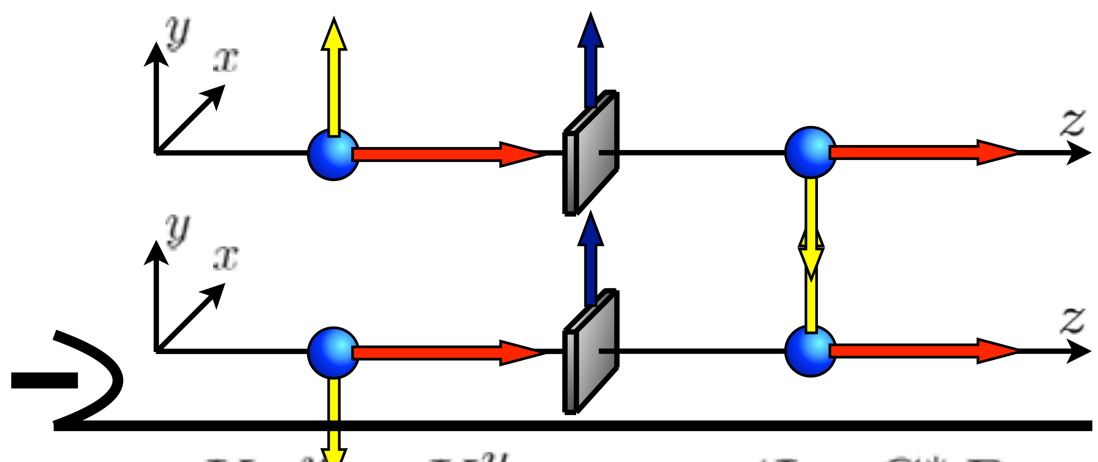


$$A_z - P_z = 8\mathrm{Im}\, D^* B$$

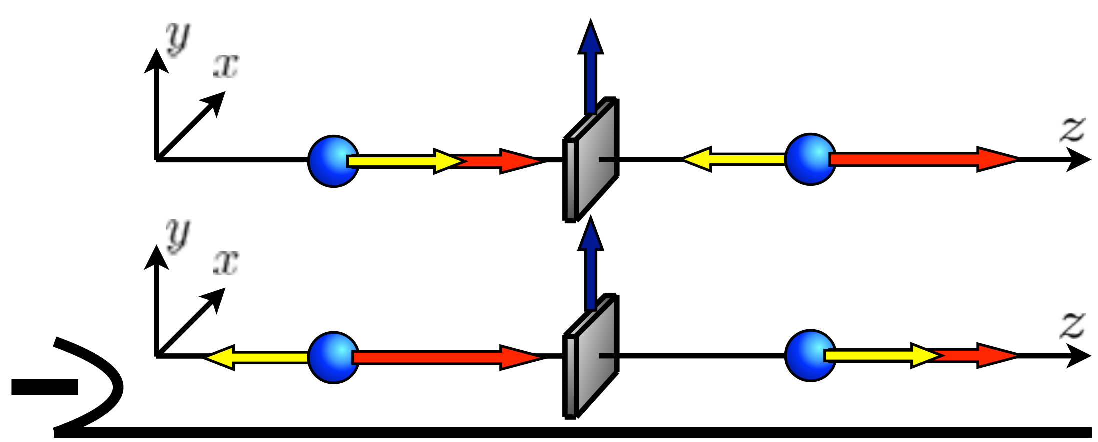
Polarization Transfer Coefficient



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



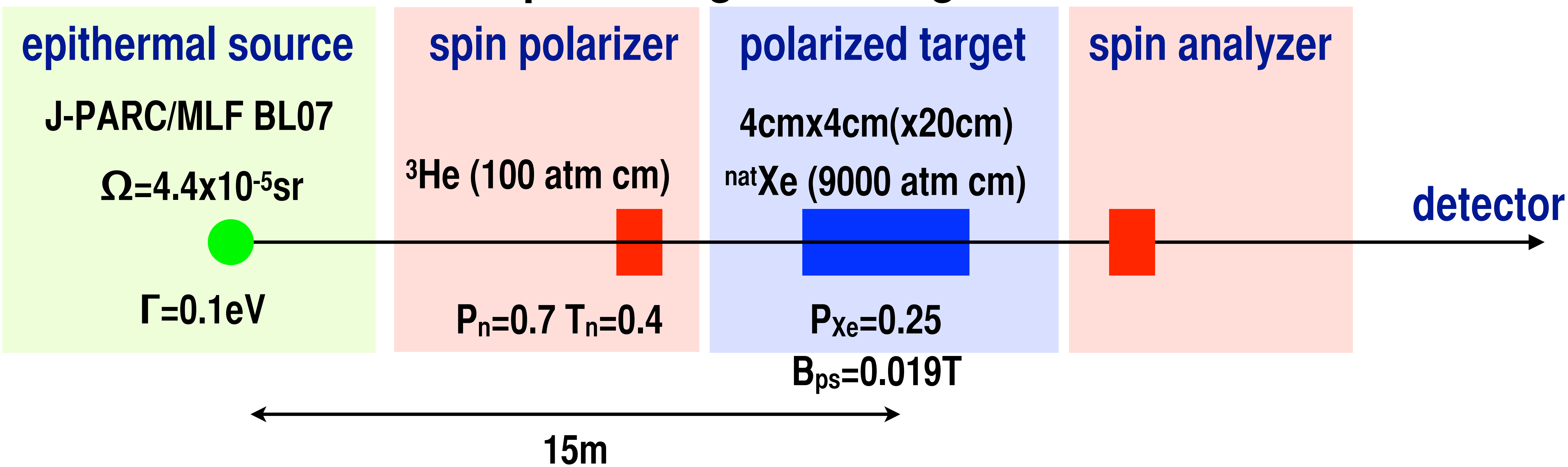
$$K_y^{-y} - K_{-y}^{y} = 4\mathrm{Im}\, C^* D$$



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

Experimental Possibility

A crude estimation with promising technologies …

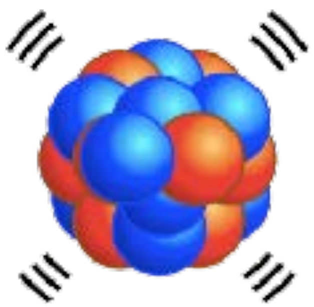


discovery potential ~ 5 day statistics (to be improved and refined)

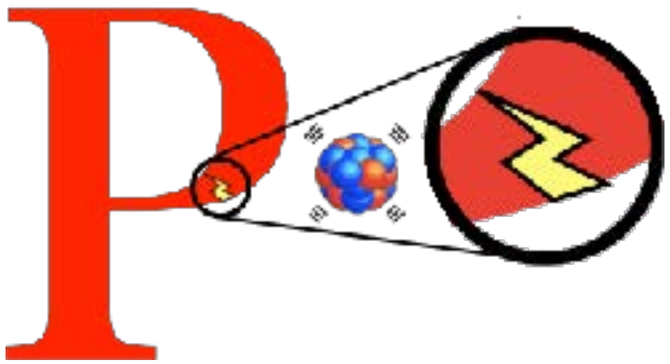
Systematics can be examined in the observation of the spin behavior as a function of time-of-flight.

Summary

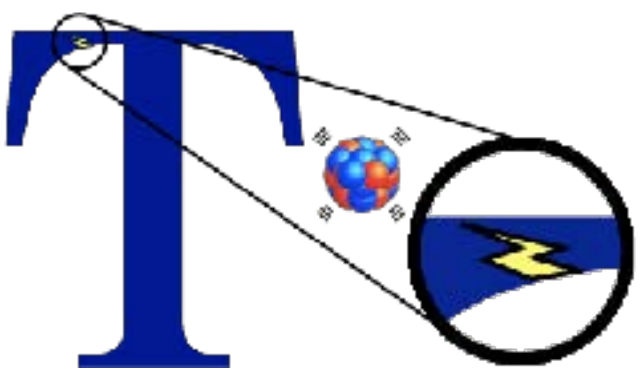
Short-pulse spallation neutron sources have become operational.



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



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



Key-technique: Polarized Target

NOPTREX Collaboration (Neutron OPtics for Time Reversal EXperiment)

Nagoya University
H.M.Shimizu, M.Kitaguchi, K.Hirota, T.Okudaira, N.Oi, C.C.Haddock, T.Yamamoto, T.Morishima, G.Ichikawa, Y.Kiyanagi

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

JAEA
K.Sakai, A.Kimura, H.Harada

Univ. British Columbia
T.Momose

Yamagata Univ.
T.Iwata, Y.Miyachi

Osaka University
H.Kohri

Hiroshima University
M.Iinuma

RIKEN
N.Yamanaka, Y.Yamagata

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

Kyoto Univ.
M.Hino

Indiana University
W.M.Snow, J.Curole

Univ. South Carolina
V.Gudkov

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

Kentucky Univ.
B.Plaster, D.Schaper

Paul Scherrer Institut
P.Hautle

Southern Illinois University
B.M.Goodson

Univ. California Berkeley
A.S.Tremsin