NOPTREX

Neutron Optical Parity and Time Reversal EXperiment

Hirohiko SHIMIZU
(NOPTREX Collaboration)

Department of Physics, Nagoya University
hirohiko.shimizu@nagoya-u.jp

Experimental Fact

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

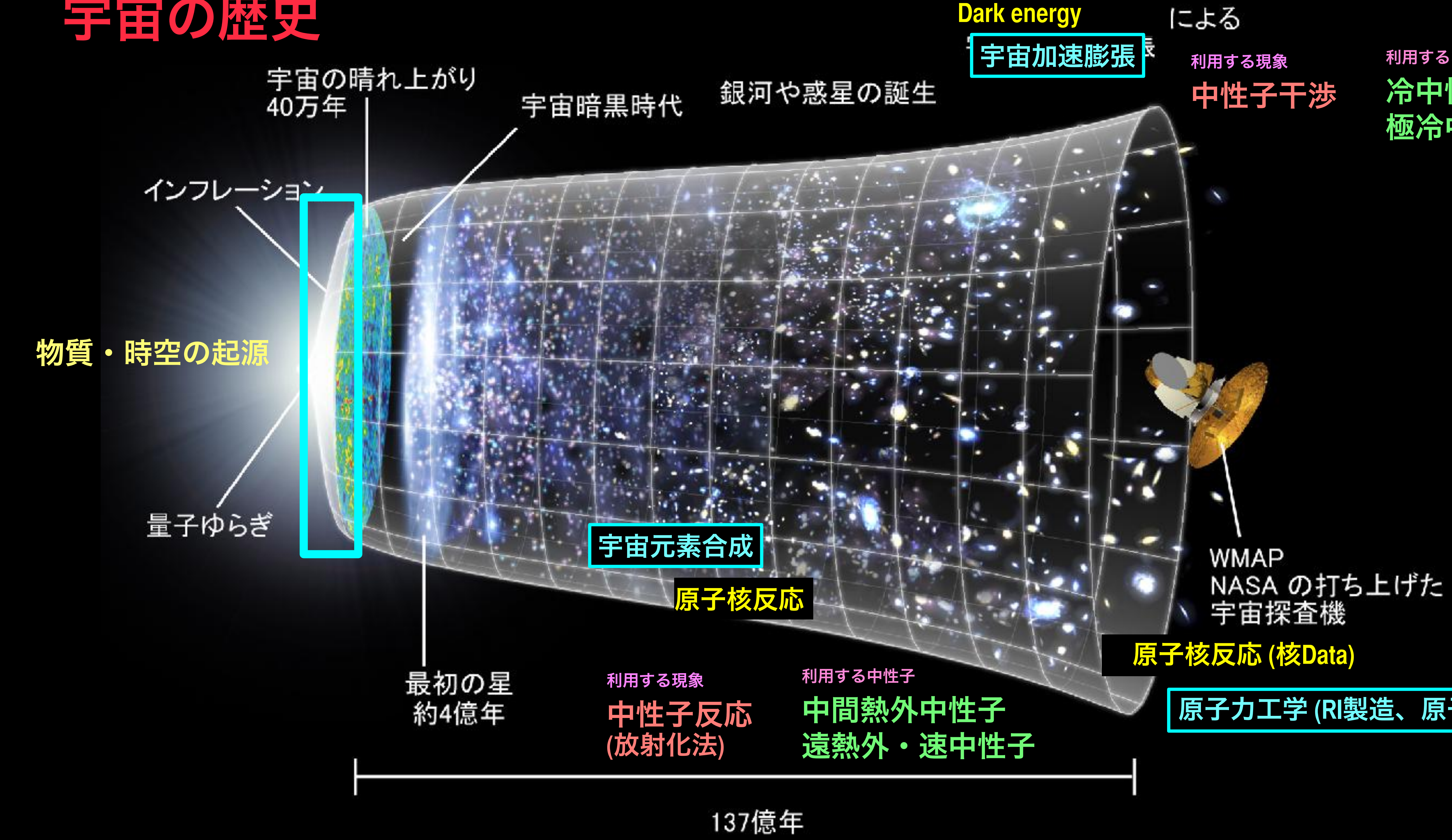
↓

Applicability of the Enhancement Mechanism to T-violation <-> CP-violation

to deliver new physics searches in T-violation, complementary to EDM searches

(mostly in P-odd T-odd interactions)

宇宙の歴史



物質・時空の起源

Dark energy

宇宙加速膨張

利用する現象

中性子干渉

利用する中性子

冷中性子
極冷中性子

宇宙元素合成

原子核反応

原子核反応 (核Data)

原子力工学 (RI製造、原子炉)

利用する現象

中性子反応
(放射化法)

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中間熱外中性子
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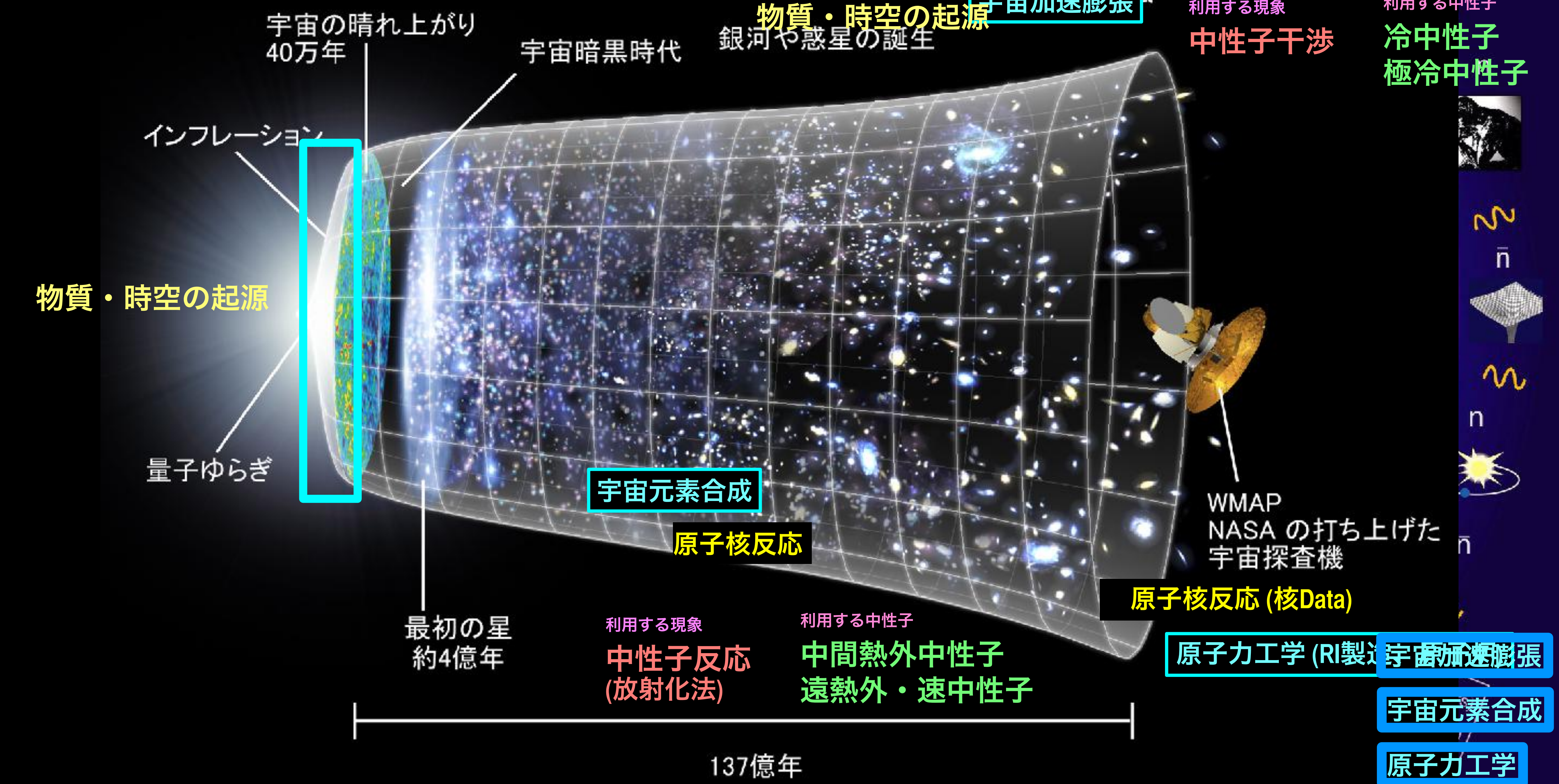

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原子力工学

利用する中性子	利用する現象
超冷中性子	中性子電気双極子能率
近熱外中性子	時間反転対称性
超冷中性子	中性子反中性子振動
Neutrino	Neutrino物理 二重veta崩壊 Neutrino振動
冷中性子	中性子干渉 中性子散乱
極冷中性子	中性子回折 (中性子重力波アンテナ)

宇宙の歴史

物質・時空の起源

Particle Data Group, LBNL, © 2000. Supported by DOE and N

対称性

CP対称性 時間反転対称性

保存則

Baryon数保存

Lepton数保存

重力→時空

一般相対論

近距離重力 (未知相互作用)

始原重力波

精密実験による間接探索

加速器直接探索

光学的天体観測

中性子寿命

τ_n

CP/T

B,L

B-L

G

宇宙加速膨張

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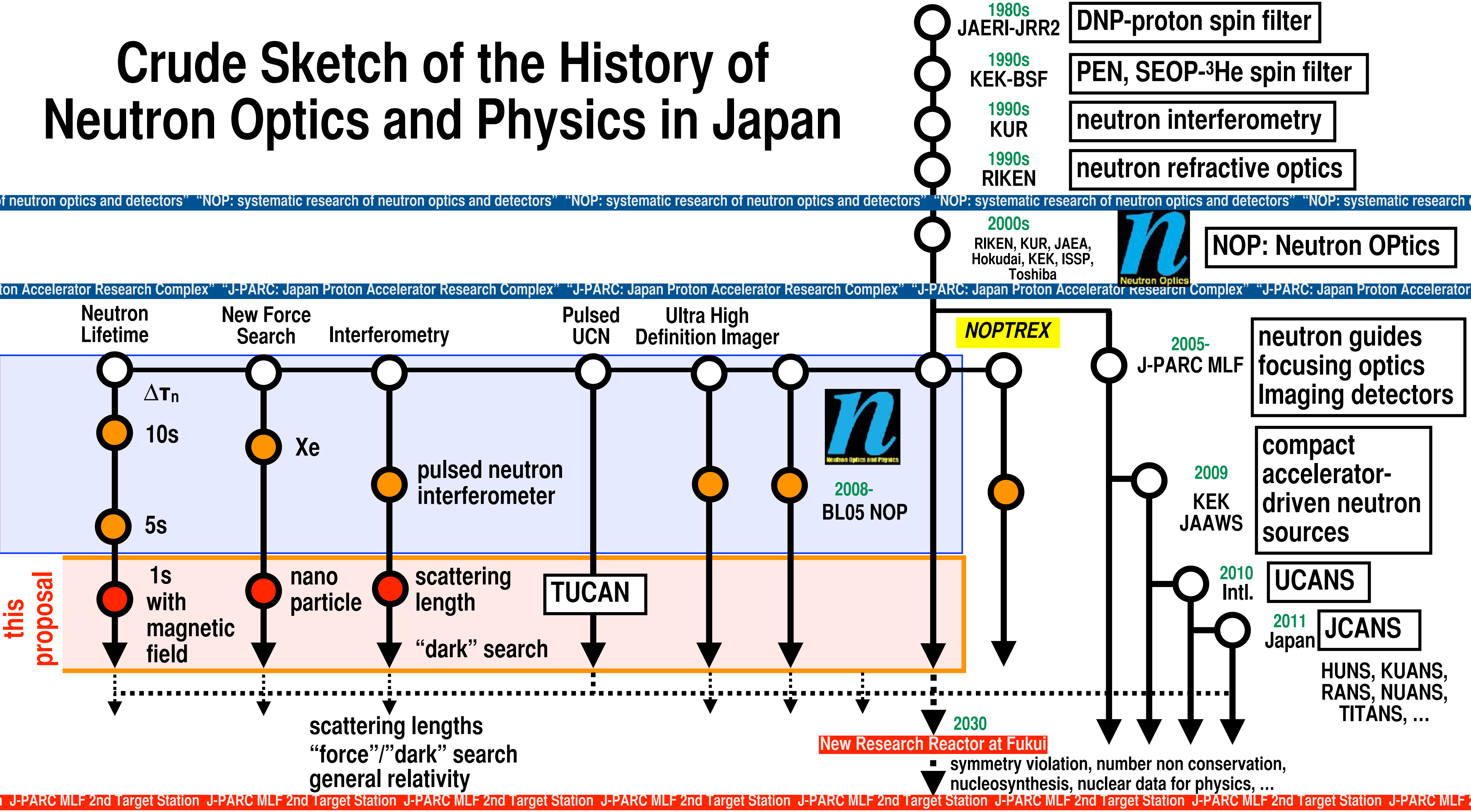
宇宙加速膨張

宇宙元素合成

原子力工学

Crude Sketch of the History of Neutron Optics and Physics in Japan



1980s JAERI-JRR2 — DNP-proton spin filter

1990s KEK-BSF — PEN, SEOP-^{3}He spin filter

1990s KUR — neutron interferometry

1990s RIKEN — neutron refractive optics

"NOP: systematic research of neutron optics and detectors"

2000s RIKEN, KUR, JAEA, Hokudai, KEK, ISSP, Toshiba — NOP: Neutron OPtics

"J-PARC: Japan Proton Accelerator Research Complex"

Neutron Lifetime — $\Delta\tau_n$ — 10s — 5s — 1s with magnetic field

New Force Search — Xe — nano particle

Interferometry — pulsed neutron interferometer — scattering length — "dark" search

Pulsed UCN — TUCAN

Ultra High Definition Imager

2008- BL05 NOP

NOPTREX

2005- J-PARC MLF — neutron guides focusing optics Imaging detectors

2009 KEK JAAWS — compact accelerator-driven neutron sources

2010 Intl. — UCANS

2011 Japan — JCANS

HUNS, KUANS, RANS, NUANS, TITANS, ...

this proposal

scattering lengths
"force"/"dark" search
general relativity

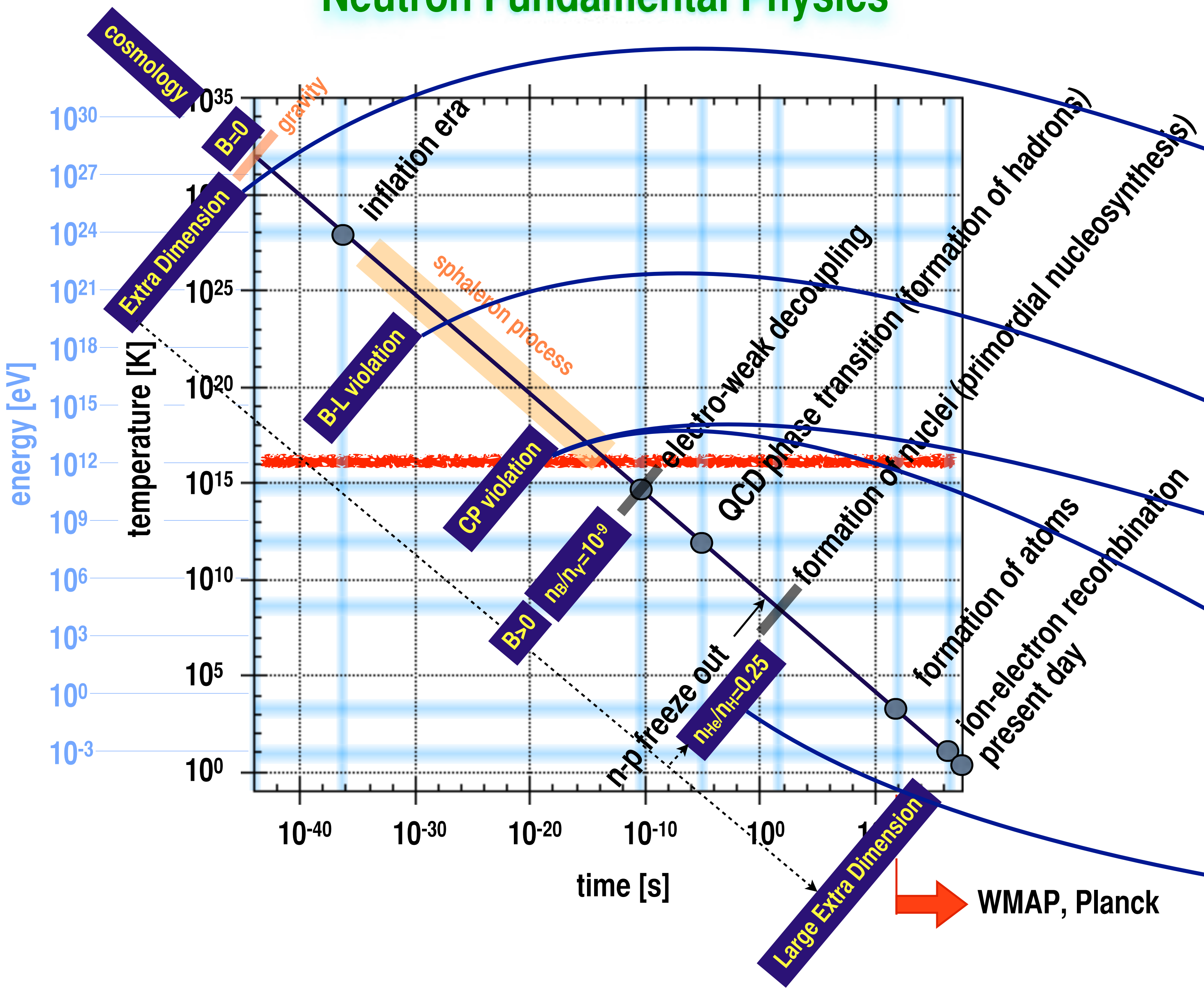
2030 New Research Reactor at Fukui

symmetry violation, number non conservation, nucleosynthesis, nuclear data for physics, ...

J-PARC MLF 2nd Target Station

Introduction of Neutron Fundamental Physics in Japan

Neutron Fundamental Physics



searches for new physics beyond the standard model

new-force search

(α, λ)

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

neutron scattering
neutron interferometry
Pendellosung interference
GRANIT

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

Dark Matter, Dark Energy

spontaneous transition from neutron to antineutron

$\tau_{n\bar{n}}$

neutron antineutron oscillation

breaking of time reversal invariance

d_n

neutron EDM
TUCAN

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

epithermal neutron optics
NOPTREX

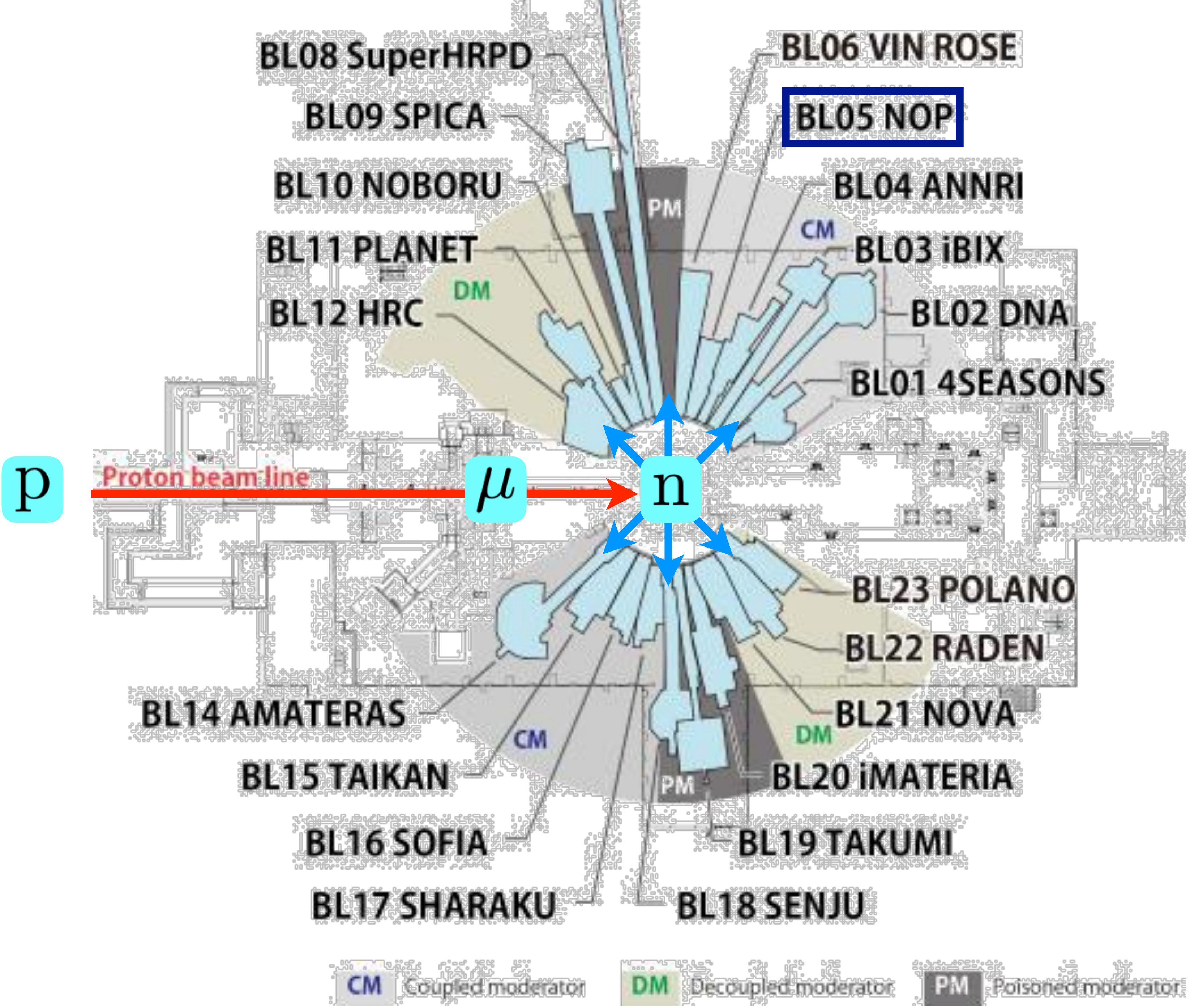
neutron β-decay

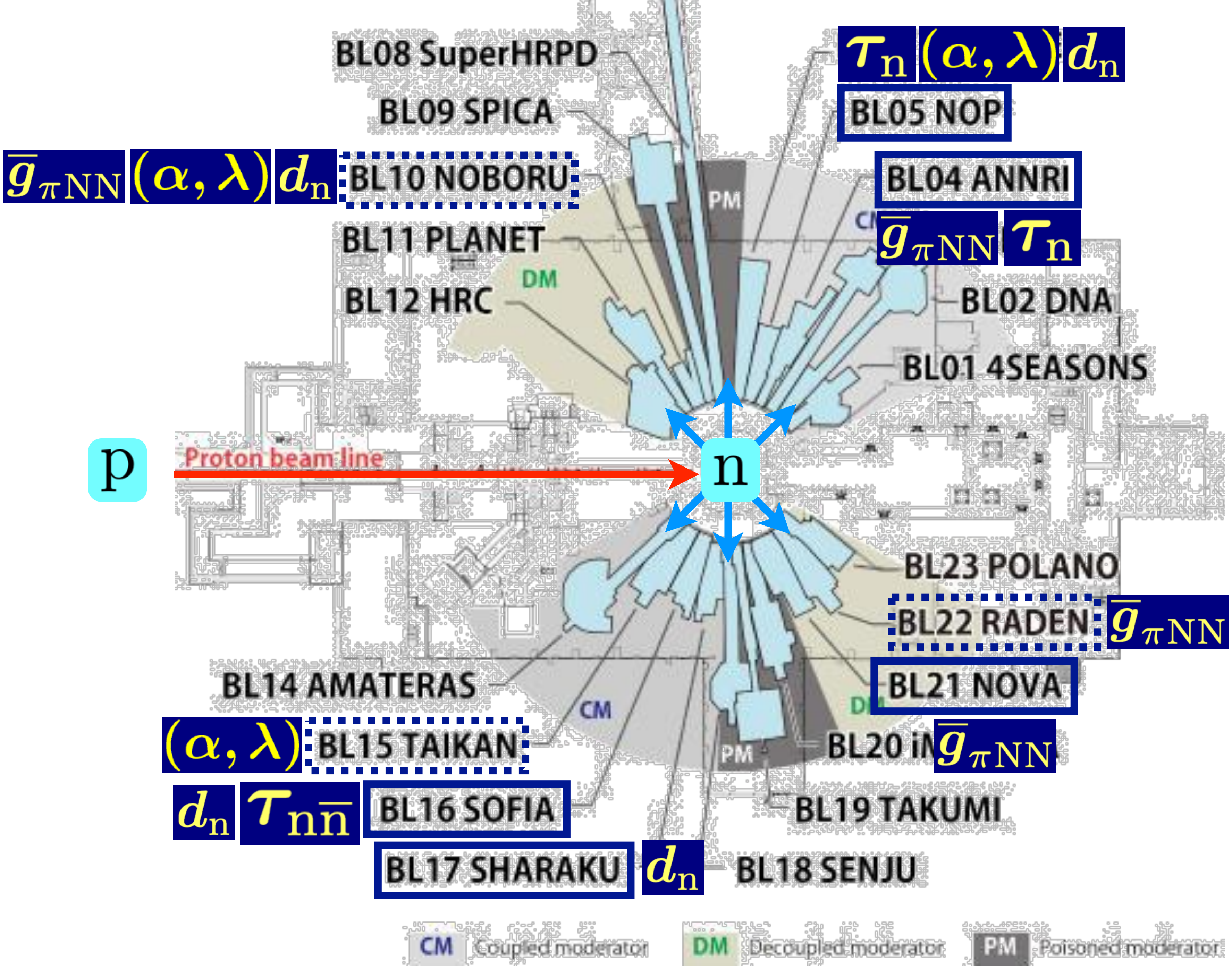
τ_n

neutron lifetime

J-PARC

Japan Proton Accelerator Research Complex


BL08 SuperHRPD
BL09 SPICA
BL10 NOBORU
BL11 PLANET
BL12 HRC
BL06 VIN ROSE
BL05 NOP
BL04 ANNRI
BL03 iBIX
BL02 DNA
BL01 4SEASONS
PM
CM
DM
p
Proton beam line
μ
n
BL23 POLANO
BL22 RADEN
BL21 NOVA
BL20 iMATERIA
BL19 TAKUMI
BL18 SENJU
BL14 AMATERAS
BL15 TAIKAN
BL16 SOFIA
BL17 SHARAKU
CM
DM
PM
CM Coupled moderator
DM Decoupled moderator
PM Poisoned moderator


BL08 SuperHRPD
BL09 SPICA
$\bar{g}_{\pi \mathrm{NN}}$ (α, λ) d_{n} BL10 NOBORU
BL11 PLANET
BL12 HRC
DM
PM
τ_{n} (α, λ) d_{n}
BL05 NOP
BL04 ANNRI
$\bar{g}_{\pi \mathrm{NN}}$ τ_{n}
BL02 DNA
BL01 4SEASONS
p
Proton beam line
n
BL23 POLANO
BL22 RADEN $\bar{g}_{\pi \mathrm{NN}}$
BL21 NOVA
DM
BL20 iM $\bar{g}_{\pi \mathrm{NN}}$
BL19 TAKUMI
BL18 SENJU
BL14 AMATERAS
CM
(α, λ) BL15 TAIKAN
d_{n} $\tau_{\mathrm{n\bar{n}}}$ BL16 SOFIA
PM
BL17 SHARAKU d_{n}
CM Coupled moderator
DM Decoupled moderator
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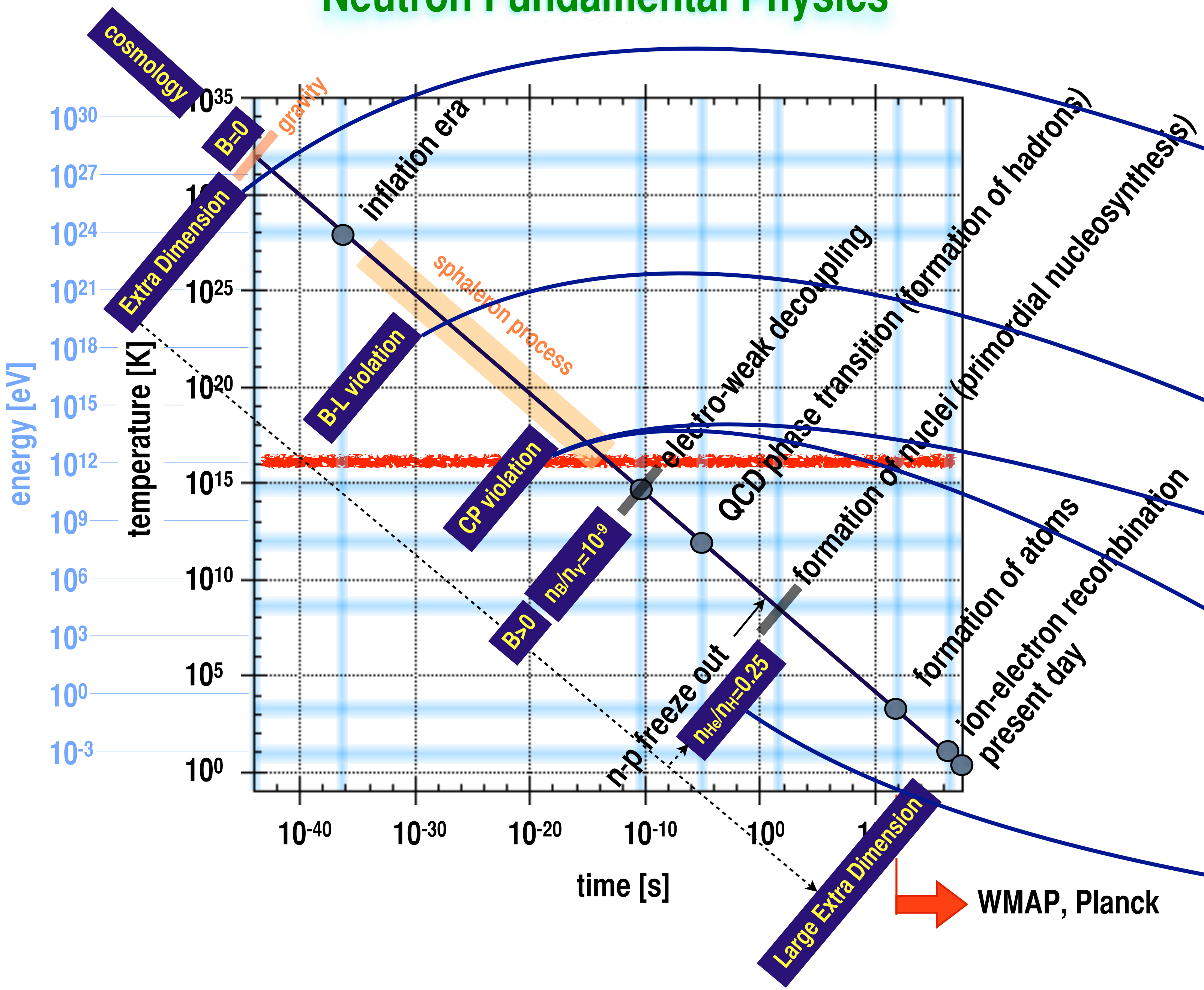
Neutron Fundamental Physics

searches for new physics beyond the standard model



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d_n

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

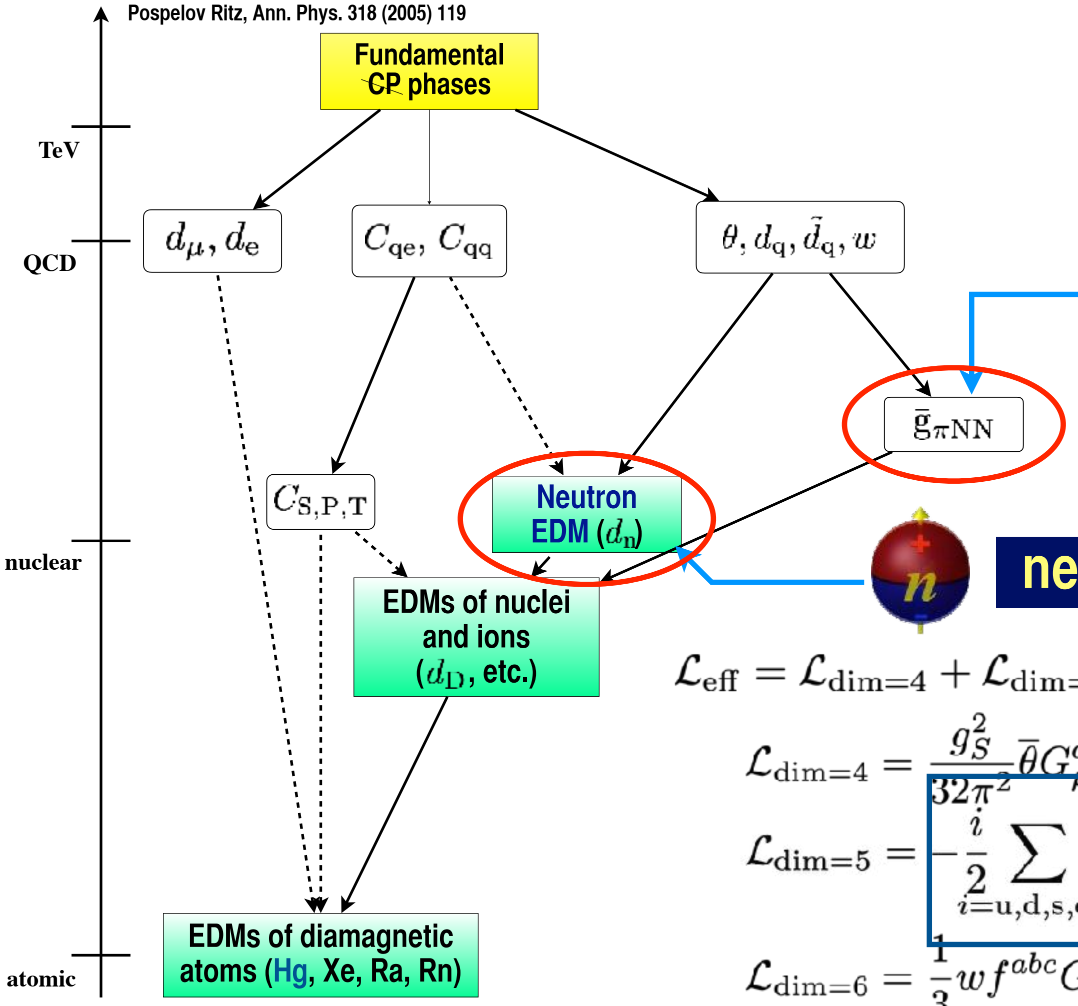
epithermal neutron optics
NOPTREX

neutron β-decay

τ_n

neutron lifetime

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



$\bar g_{\pi\mathrm{NN}}$

NOPTREX

d_n

neutron EDM

M.Pospelov, PLB530(2002)123

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm dim=4} + \mathcal{L}_{\rm dim=5} + \mathcal{L}_{\rm dim=6}$$

$$\mathcal{L}_{\rm dim=4} = \frac{g_S^2}{32\pi^2}\bar\theta G^a_{\mu\nu}\tilde G^{\mu\nu,a}$$

$$\mathcal{L}_{\rm dim=5} = \boxed{-\frac{i}{2}\sum_{i={\rm u,d,s,e},\mu} d_i\bar\psi_i(F\sigma)\gamma_5\psi_i - \boxed{\frac{i}{2}\sum_{i={\rm u,d,s}} \tilde d_i\bar\psi_i g_s(G\sigma)\gamma_5\psi_i}}$$

$$\mathcal{L}_{\rm dim=6} = \frac{1}{3}wf^{abc}G^a_{\mu\nu}\tilde G^{\nu\beta,b}G^{\mu,c}_{\beta} + \sum_{i,j} C_{ij}(\bar\psi_i\psi_i)(\bar\psi_j i\gamma_5\psi_j) + \cdots$$

NOPTREX

Neutron Optical Parity and Time Reversal EXperiment

1. Optical Test	final-state interaction free
2. Enhancement	dynamical and kinematical enhancement
3. New Type of New Physics Search	chromo-EDM

Sketch of NOPTREX Steps

neutron polarizer

Step 1: find P-violation

γ-detector
or polarized target

Step 2: determine ϕ and W
in (n,γ), spin-spin correlation

neutron polarizer/analyzer
and polarized target

Step 3: measure D’ (T-odd)

Sketch of NOPTREX Steps

neutron polarizer

Step 1: find P-violation

$$\boxed{W}$$

$$\boxed{\cos\phi} = \sqrt{\frac{\Gamma^{\mathrm{n}}_{\mathrm{p}\frac{1}{2}}}{\Gamma^{\mathrm{n}}_{\mathrm{p}}}}$$

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

$$\boxed{A_{\mathrm{L}}} = -2\frac{\boxed{W}}{E_{\mathrm{p}} - E_{\mathrm{s}}}\sqrt{\frac{\Gamma^{\mathrm{n}}_{\mathrm{s}}}{\Gamma^{\mathrm{n}}_{\mathrm{p}}}}\boxed{\cos\phi}$$

γ-detector or polarized target

Step 2: determine ϕ and W in (n,γ), spin-spin correlation

$$\boxed{a_1} = 2(-1)^{J_{\mathrm{s}}+J_{\mathrm{p}}+\frac{1}{2}+I+F}\sqrt{(2J_{\mathrm{s}}+1)(2J_{\mathrm{p}}+1)}$$
$$\times\begin{Bmatrix} 1 & 1 & 1 \\ F & J_{\mathrm{s}} & J_{\mathrm{p}} \end{Bmatrix}\left(\begin{Bmatrix} 1 & \frac{1}{2} & \frac{1}{2} \\ I & J_{\mathrm{p}} & J_{\mathrm{s}} \end{Bmatrix}\boxed{\cos\phi} - \sqrt{2}\begin{Bmatrix} 1 & \frac{1}{2} & \frac{3}{2} \\ I & J_{\mathrm{p}} & J_{\mathrm{s}} \end{Bmatrix}\boxed{\sin\phi}\right)$$
$$\times\frac{\sqrt{\mathrm{g}_{\mathrm{s}}\mathrm{g}_{\mathrm{p}}\Gamma^{\mathrm{n}}_{\mathrm{s}}(\Gamma^{\gamma}_{\mathrm{s}})_F\Gamma^{\mathrm{n}}_{\mathrm{p}}(\Gamma^{\gamma}_{\mathrm{p}})_F}}{4k^2}\frac{(E-E_{\mathrm{s}})(E-E_{\mathrm{p}})+\frac{\Gamma_{\mathrm{s}}\Gamma_{\mathrm{p}}}{4}}{\left((E-E_{\mathrm{s}})^2+\frac{\Gamma^2_{\mathrm{s}}}{4}\right)\left((E-E_{\mathrm{p}})^2+\frac{\Gamma^2_{\mathrm{p}}}{4}\right)}$$

$$\boxed{C'}$$

neutron polarizer/analyzer and polarized target

Step 3: measure D' (T-odd)

$$\frac{\boxed{D'}}{\boxed{C'}} = \boxed{\kappa(J)}\frac{\boxed{W_{\mathrm{T}}}}{\boxed{W}}$$

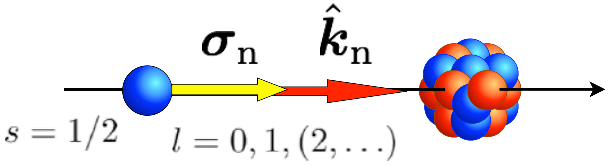
T-violating matrix element

Reliable values of potential parameters, spin assignment, resonance parameters, are the basis of NOPTREX.

P-violation in Compound State

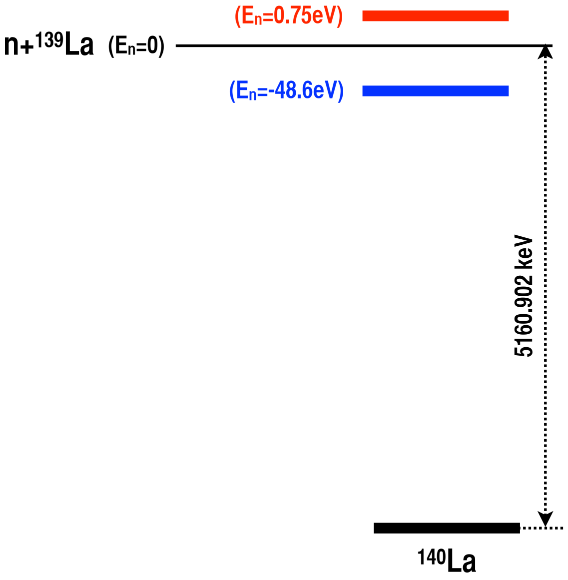
P-violation

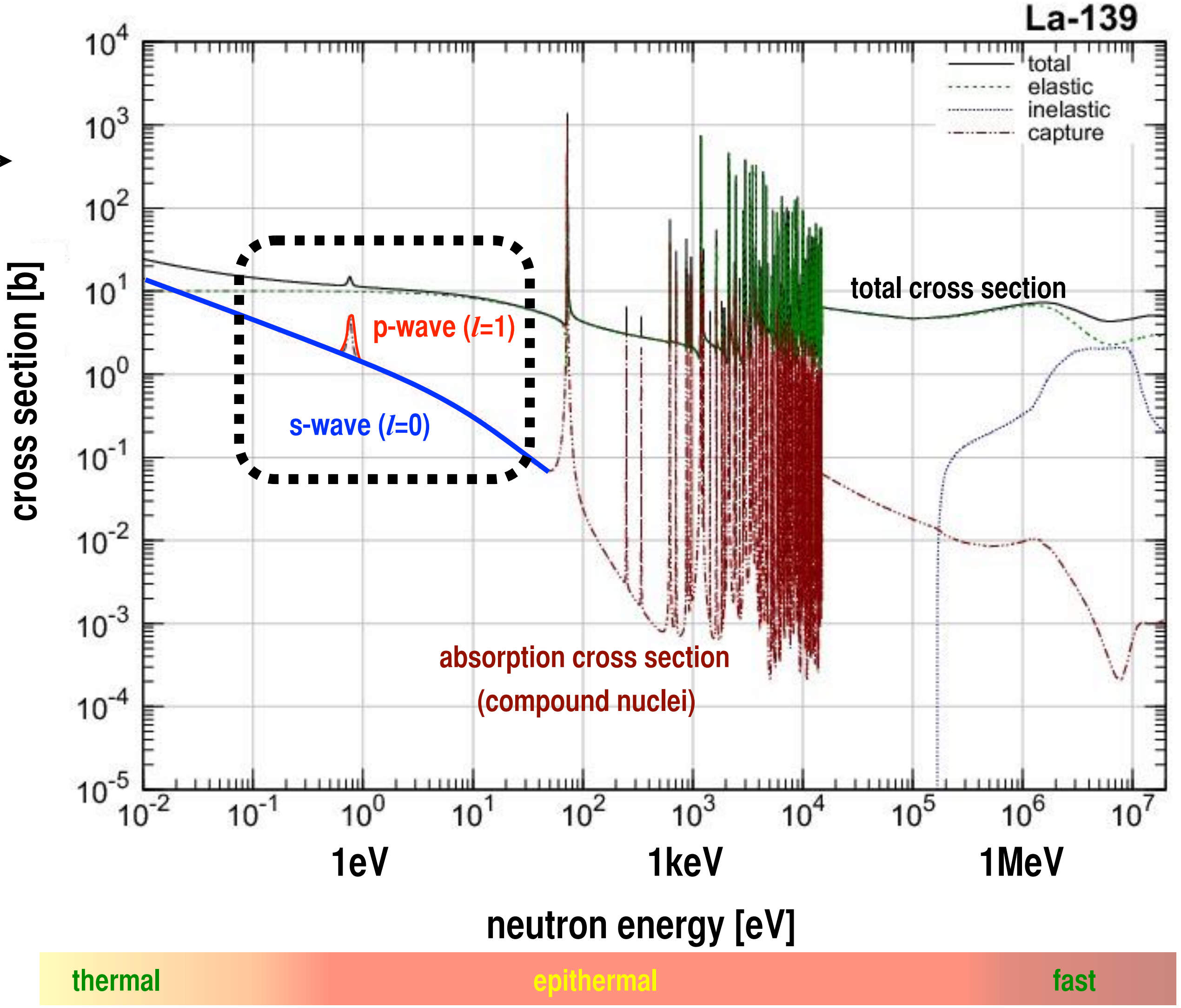
$$\sigma = \sigma_0 + \boxed{\Delta\sigma}(\boldsymbol{\sigma}_{\rm n} \cdot \hat{\boldsymbol{k}}_{\rm n})$$



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

10^{-7} for NN



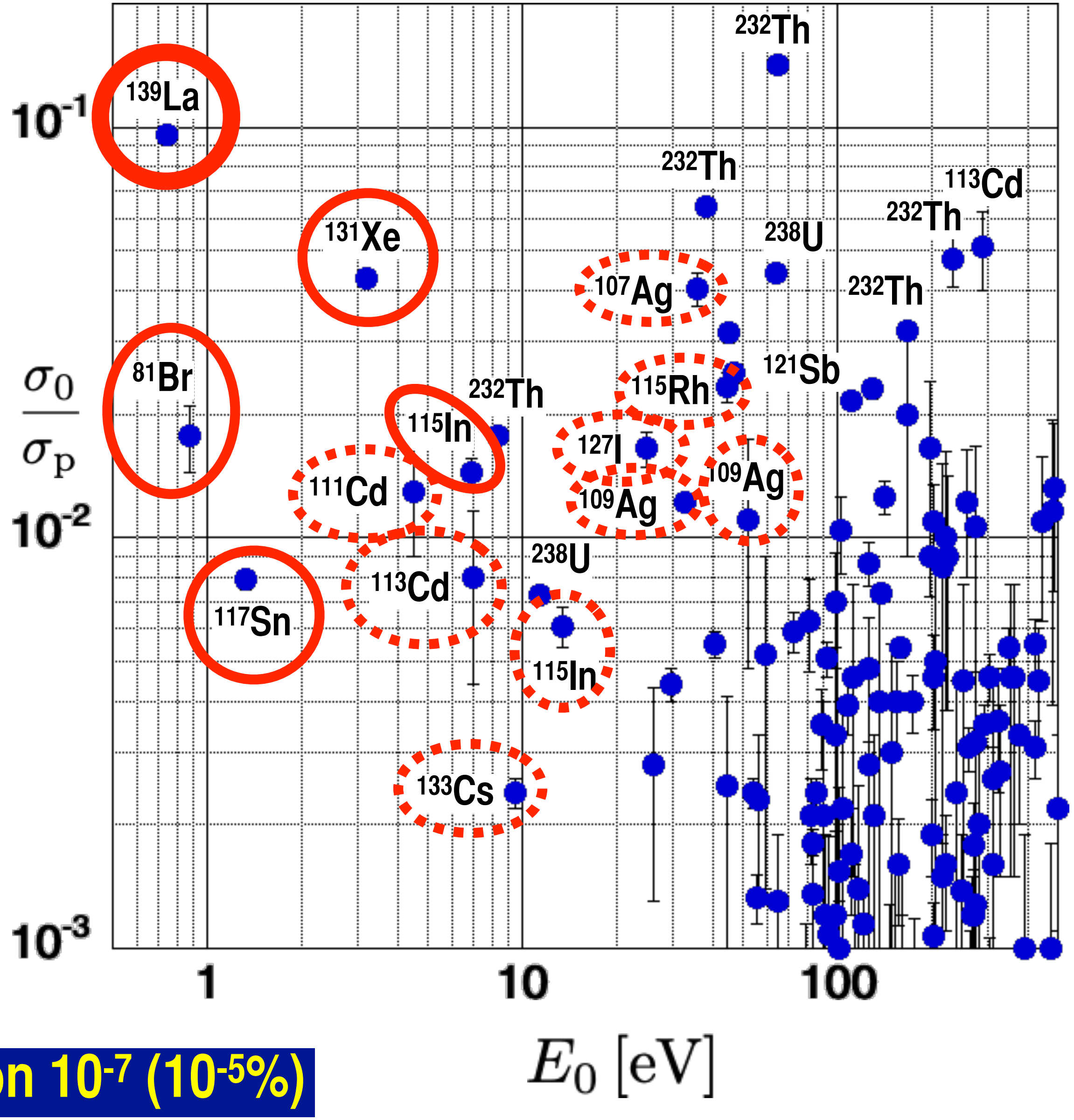


Enhancement of P-violation in Compound Resonances

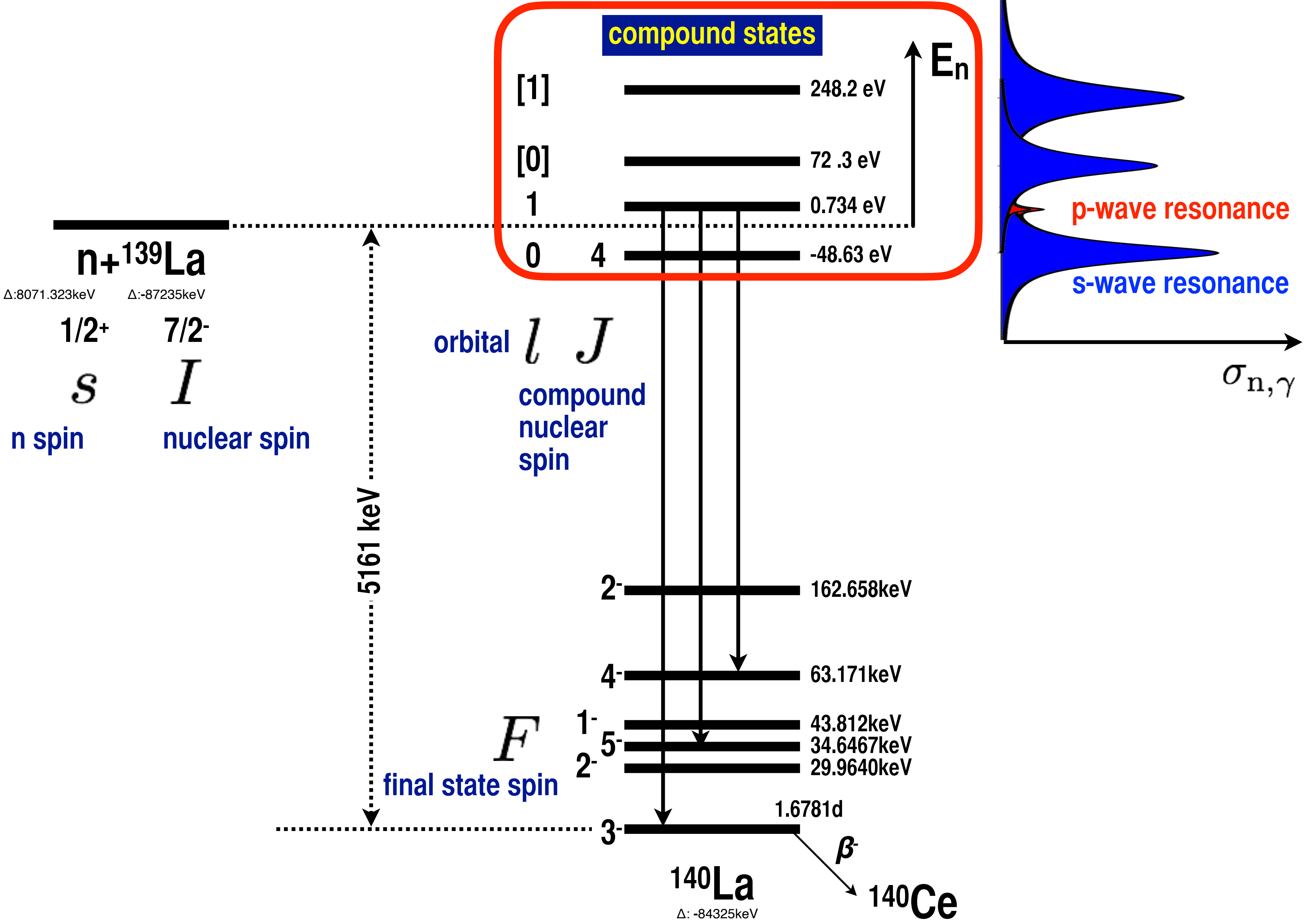
Mitchell, Phys. Rep. 354 (2001) 157
Shimizu, Nucl. Phys. A552 (1993) 293

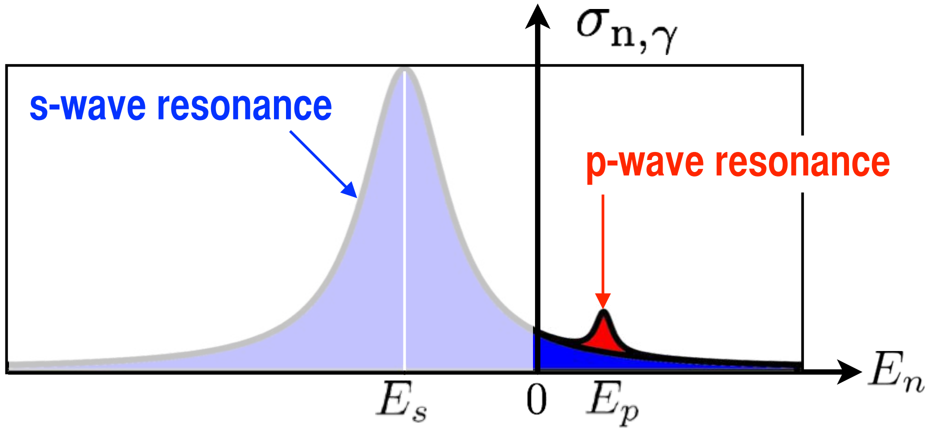
$$A_L = \frac{\Delta\sigma}{\sigma_0} \times \frac{\sigma_0}{\sigma_p}$$

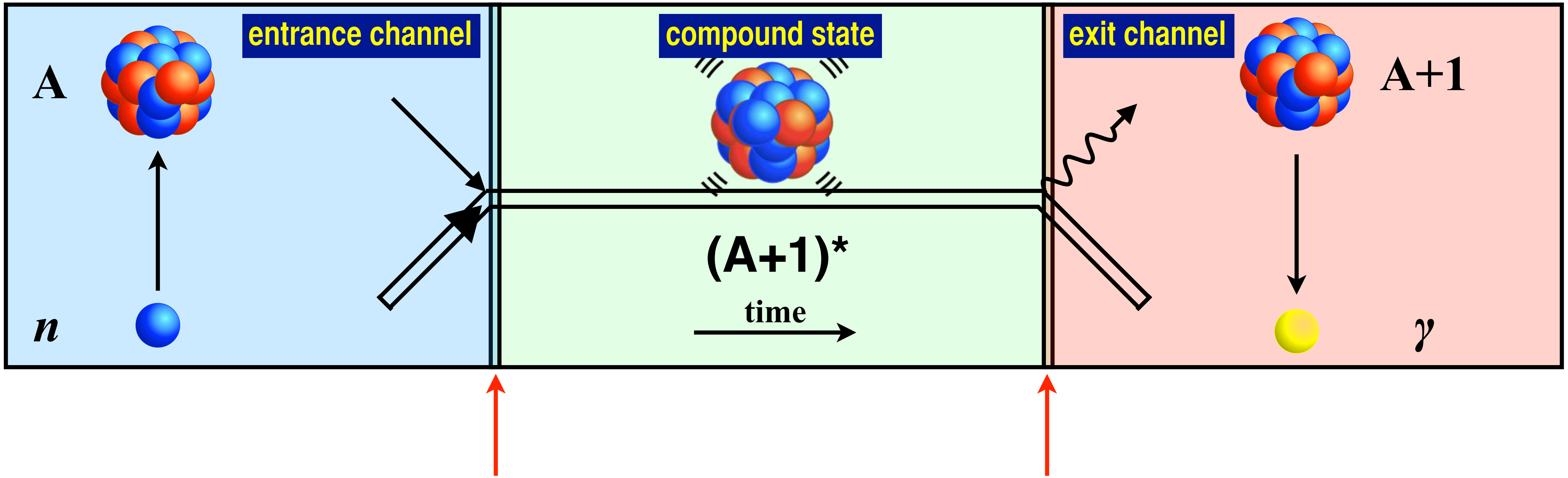
10^{-7} for NN



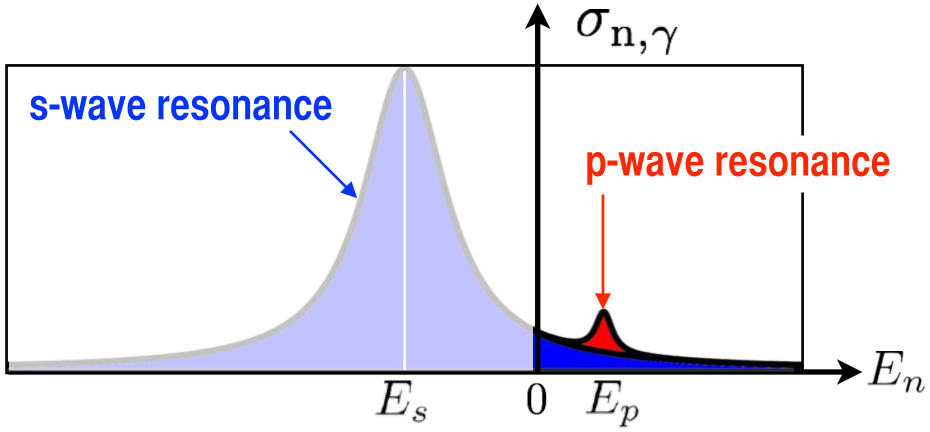
NN-interaction 10^{-7} (10^{-5}%)

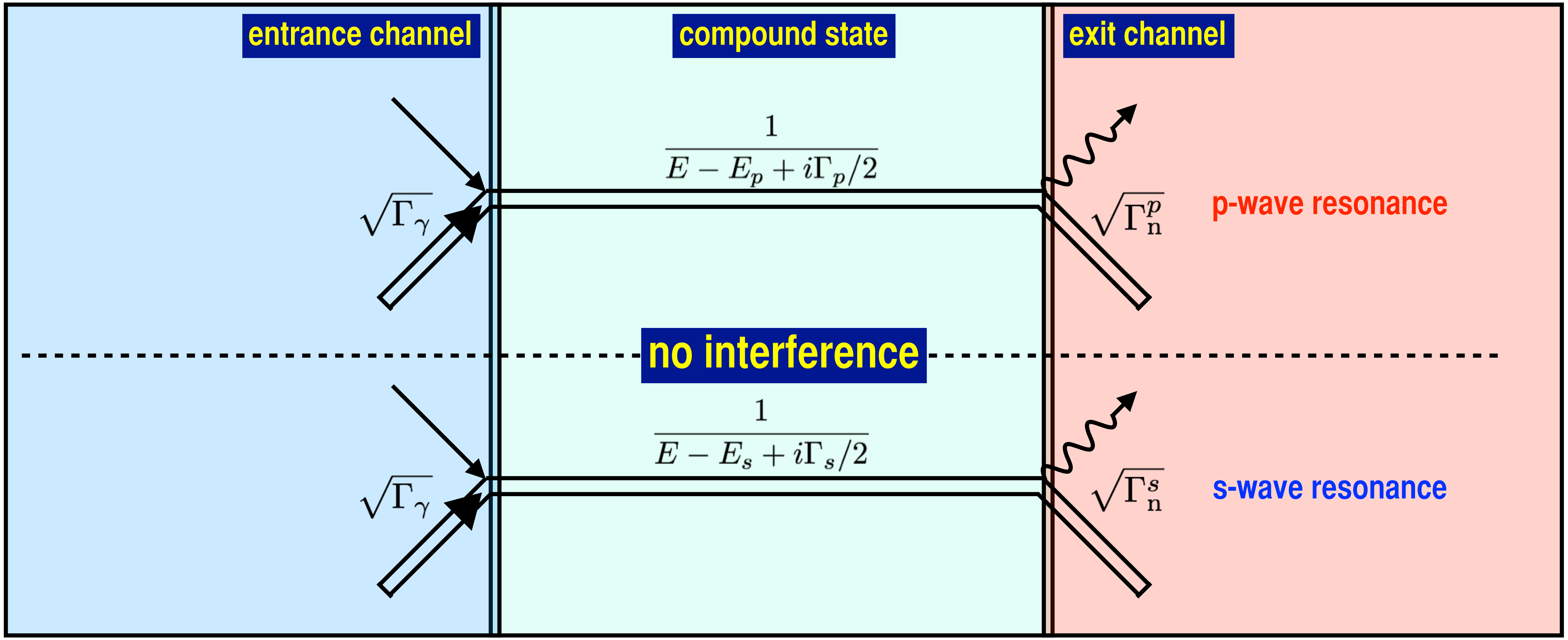

compound states
[1]
248.2 eV
[0]
72 .3 eV
1
0.734 eV
0
4
-48.63 eV
E_n
p-wave resonance
s-wave resonance
$\sigma_{n,\gamma}$
$n+^{139}La$
Δ:8071.323keV
Δ:-87235keV
$1/2^+$
$7/2^-$
s
I
n spin
nuclear spin
5161 keV
orbital l J
compound nuclear spin
2^-
162.658keV
4^-
63.171keV
F
1^-
43.812keV
5^-
34.6467keV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





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





entrance channel

compound state

exit channel

$$\frac{1}{E - E_p + i\Gamma_p/2}$$

$\sqrt{\Gamma_\gamma}$

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

p-wave resonance

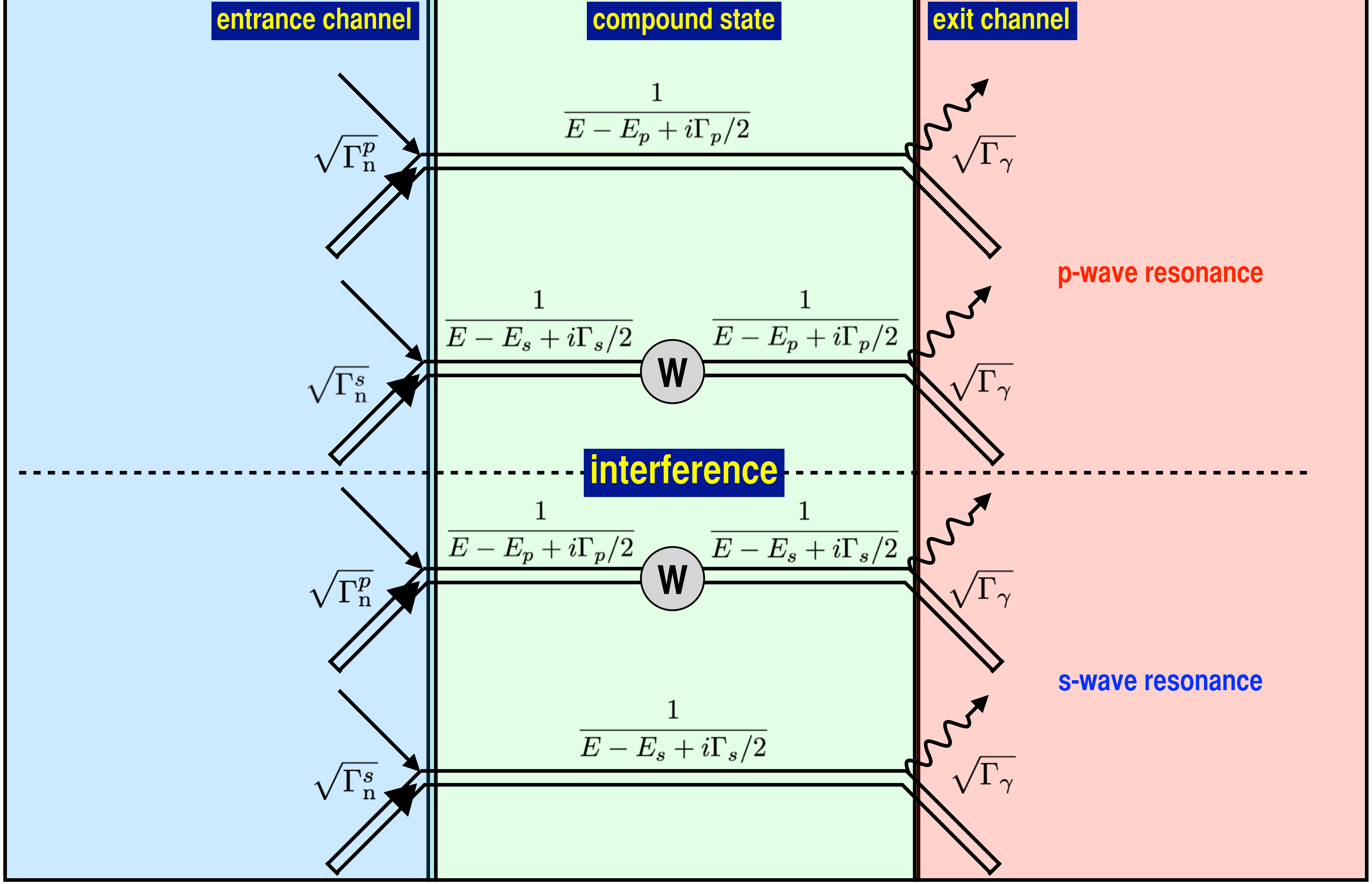
no interference

$$\frac{1}{E - E_s + i\Gamma_s/2}$$

$\sqrt{\Gamma_\gamma}$

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

s-wave resonance



entrance channel

compound state

exit channel

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

$\dfrac{1}{E - E_p + i\Gamma_p/2}$

$\sqrt{\Gamma_\gamma}$

p-wave resonance

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

$\dfrac{1}{E - E_s + i\Gamma_s/2}$ W $\dfrac{1}{E - E_p + i\Gamma_p/2}$

$\sqrt{\Gamma_\gamma}$

interference

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

$\dfrac{1}{E - E_p + i\Gamma_p/2}$ W $\dfrac{1}{E - E_s + i\Gamma_s/2}$

$\sqrt{\Gamma_\gamma}$

s-wave resonance

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

$\dfrac{1}{E - E_s + i\Gamma_s/2}$

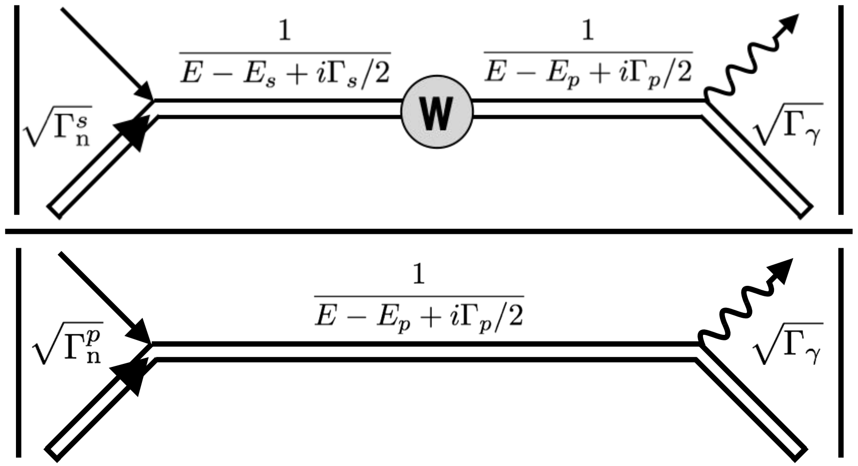
$\sqrt{\Gamma_\gamma}$

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**

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



$$= 2\frac{\left|\sqrt{\Gamma_\gamma^p}\frac{1}{E-E_p+i\Gamma_p/2}W\frac{1}{E-E_s+i\Gamma_s/2}\sqrt{\Gamma_n^s}\right|}{\left|\sqrt{\Gamma_\gamma^p}\frac{1}{E-E_p+i\Gamma_p/2}\sqrt{\Gamma_n^p}\right|} \underset{E=E_p}{\sim} 2\frac{W}{|E_p-E_s|}\sqrt{\frac{\Gamma_n^s}{\Gamma_n^p}}$$

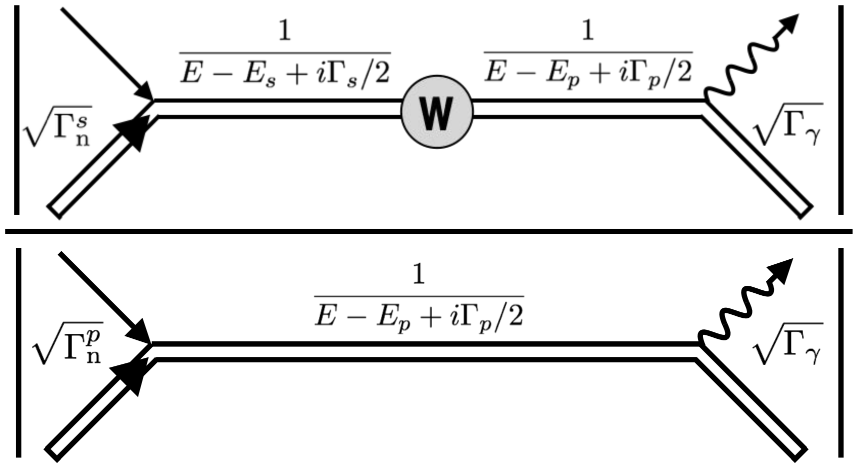
kinematical enhancement 10^3

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**

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

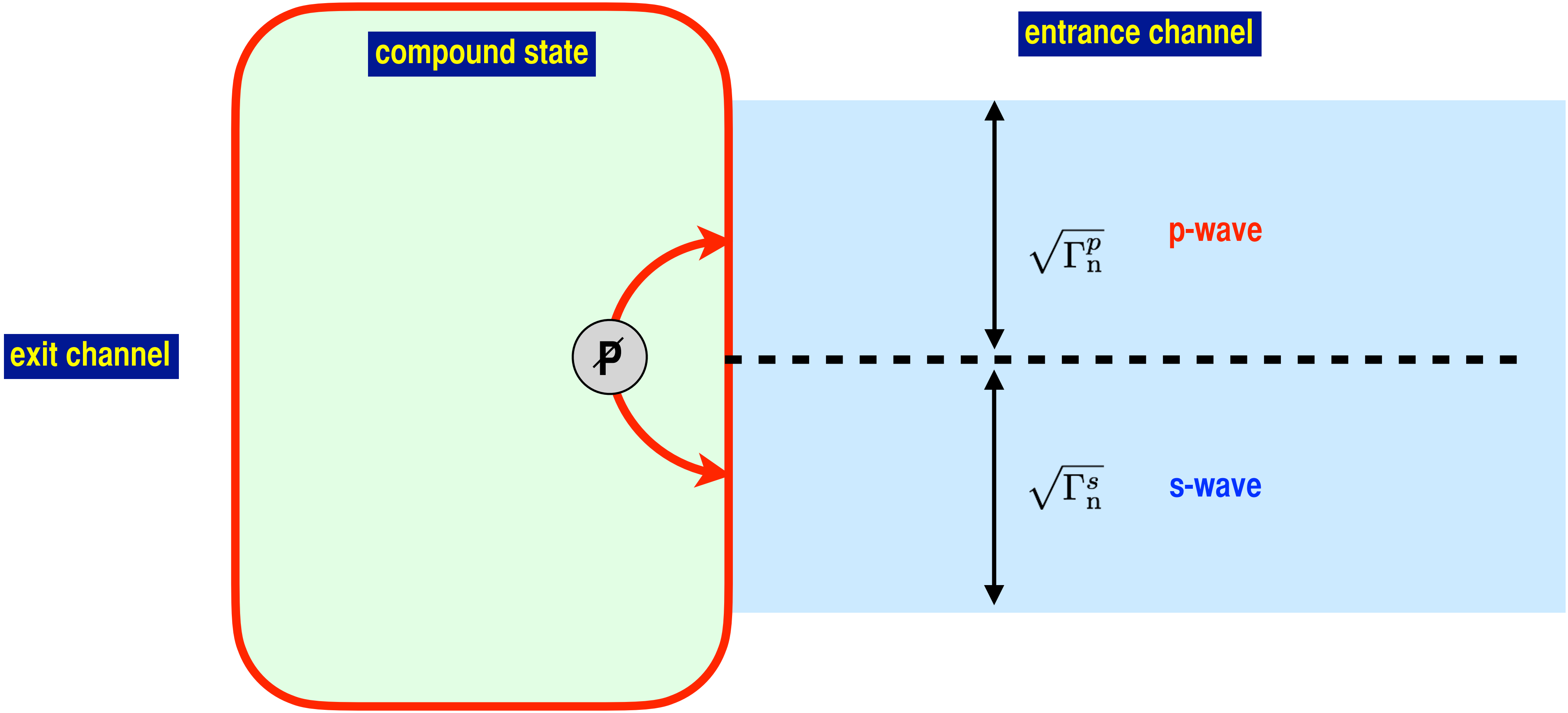


$$= 2\frac{\left|\sqrt{\Gamma^p_\gamma}\frac{1}{E-E_p+i\Gamma_p/2}W\frac{1}{E-E_s+i\Gamma_s/2}\sqrt{\Gamma^s_{\mathrm{n}}}\right|}{\left|\sqrt{\Gamma^p_\gamma}\frac{1}{E-E_p+i\Gamma_p/2}\sqrt{\Gamma^p_{\mathrm{n}}}\right|} \underset{E=E_p}{\sim} 2\frac{W}{|E_p-E_s|}\sqrt{\frac{\Gamma^s_{\mathrm{n}}}{\Gamma^p_{\mathrm{n}}}}$$

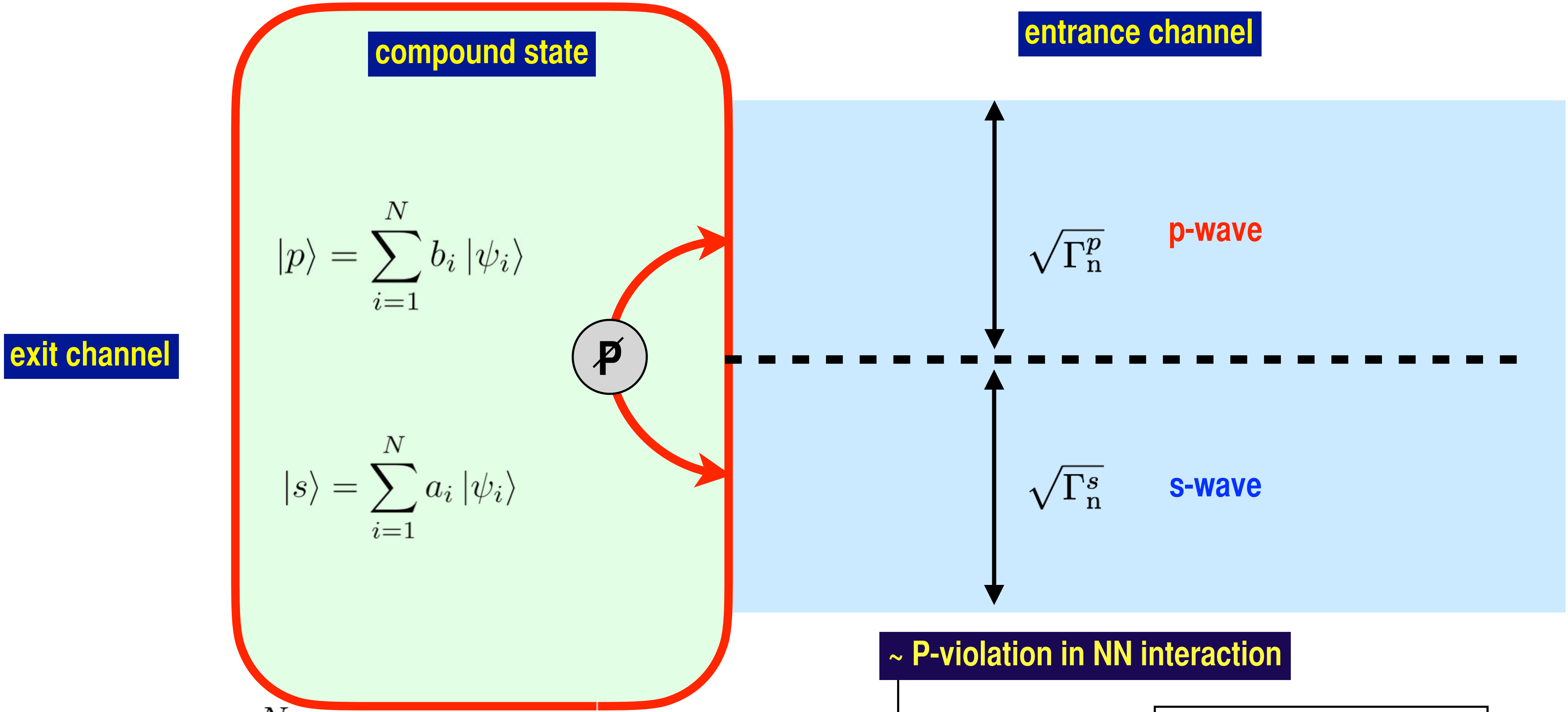
dynamical enhancement
10^2-10^3

kinematical enhancement
10^3

Dynamical Enhancement



Dynamical Enhancement



compound state

entrance channel

exit channel

$$|p\rangle = \sum_{i=1}^{N} b_i \, |\psi_i\rangle$$

$$|s\rangle = \sum_{i=1}^{N} a_i \, |\psi_i\rangle$$

$\not{P}$

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

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

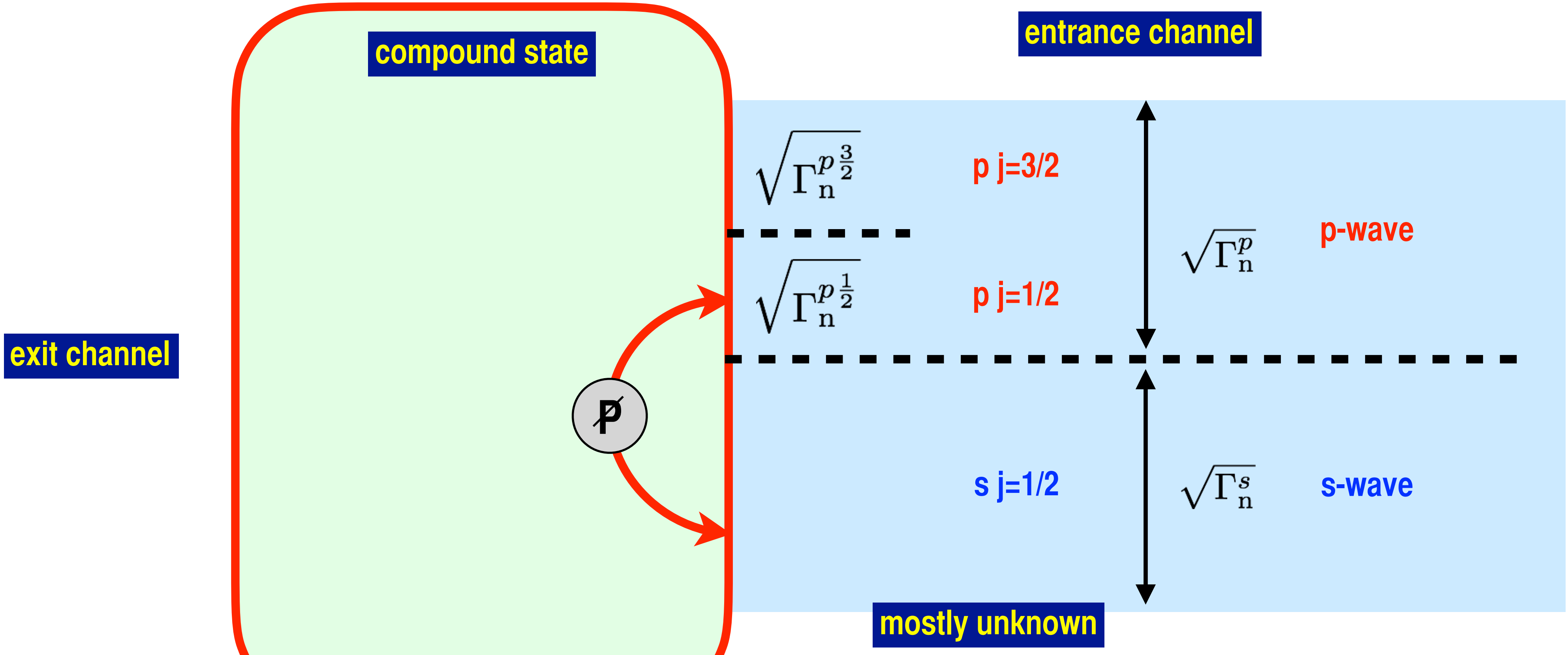
$$\langle s|W|p\rangle = \sum_{i,j}^{N} a_i^* b_j \langle\psi_i|W|\psi_j\rangle \sim \frac{1}{\sqrt{N}} \frac{1}{\sqrt{N}} \langle W \rangle \sqrt{N}$$

~ P-violation in NN interaction

randomness of expansion coefficients

$$\boxed{N \sim \frac{\overset{10^6\ \mathrm{eV}}{\Delta E}}{\underset{10\ \mathrm{eV}}{D}} \sim 10^5}$$

Detailed Study of Entrance Channel Boundary



mostly unknown

x

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

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

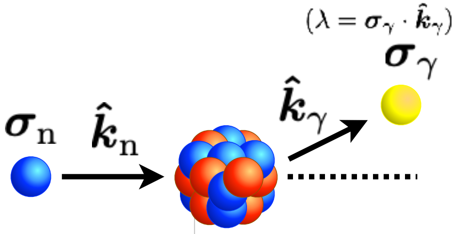
$$x^2 + y^2 = 1$$

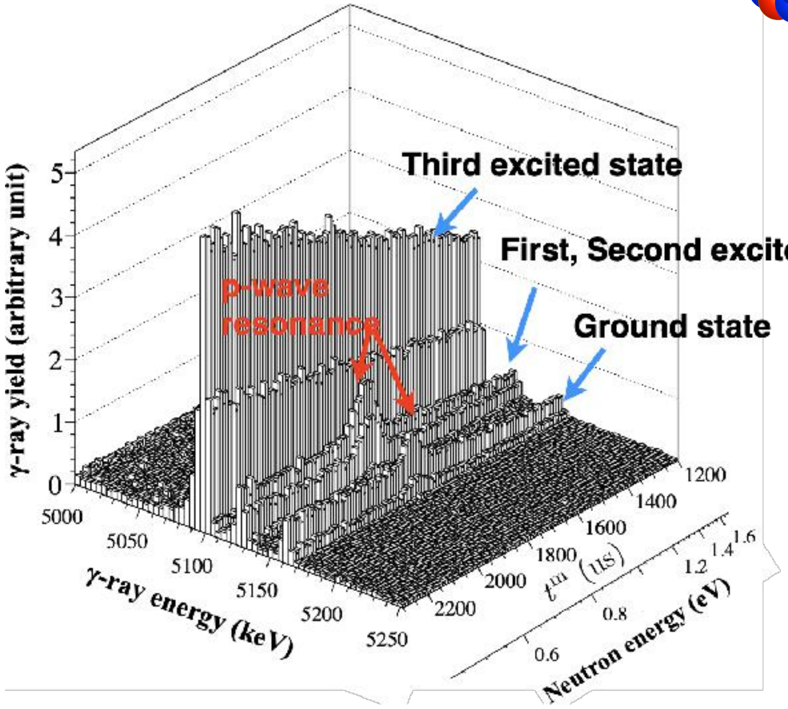
$$x = \cos\phi \quad y = \sin\phi$$

ϕ : mixing angle of $\mathrm{p}_{1/2}$ and $\mathrm{p}_{3/2}$

Detailed Study of Entrance Channel Boundary in ^{139}La(n,γ)^{140}La$^{(*)}$

determination of ϕ





$$2\frac{d\sigma}{d\Omega} = \boxed{a_0}$$

$$\boxed{+a_1\left[\hat{\boldsymbol{k}}_n\cdot\hat{\boldsymbol{k}}_\gamma\right]}$$

neutron-energy-dependent γ-ray angular distribution

$$\boxed{+a_2\left[\boldsymbol{\sigma}_n\cdot(\hat{\boldsymbol{k}}_n\times\hat{\boldsymbol{k}}_\gamma)\right]}$$

γ-ray transverse asymmetry

$$\boxed{+a_3\left[(\hat{\boldsymbol{k}}_n\cdot\hat{\boldsymbol{k}}_\gamma)^2-\frac{1}{3}\right]}$$

$$+a_4\left[(\hat{\boldsymbol{k}}_n\cdot\hat{\boldsymbol{k}}_\gamma)(\boldsymbol{\sigma}_n\cdot(\hat{\boldsymbol{k}}_n\times\hat{\boldsymbol{k}}_\gamma))\right]$$

$$+a_5\left[(\boldsymbol{\sigma}_\gamma\cdot\hat{\boldsymbol{k}}_\gamma)(\boldsymbol{\sigma}_n\cdot\hat{\boldsymbol{k}}_\gamma)\right]$$

$$\boxed{+a_6\left[(\boldsymbol{\sigma}_\gamma\cdot\hat{\boldsymbol{k}}_\gamma)(\boldsymbol{\sigma}_n\cdot\hat{\boldsymbol{k}}_n)\right]}$$

γ-ray circular polarization and longitudinal polarization

$$+a_7\left[(\boldsymbol{\sigma}_\gamma\cdot\hat{\boldsymbol{k}}_\gamma)((\boldsymbol{\sigma}_n\cdot\hat{\boldsymbol{k}}_\gamma)(\hat{\boldsymbol{k}}_\gamma\cdot\hat{\boldsymbol{k}}_n)-\frac{1}{3}(\boldsymbol{\sigma}_n\cdot\hat{\boldsymbol{k}}_n))\right]$$

$$+a_8\left[(\boldsymbol{\sigma}_\gamma\cdot\hat{\boldsymbol{k}}_\gamma)((\boldsymbol{\sigma}_n\cdot\hat{\boldsymbol{k}}_n)(\hat{\boldsymbol{k}}_\gamma\cdot\hat{\boldsymbol{k}}_n)-\frac{1}{3}(\boldsymbol{\sigma}_n\cdot\hat{\boldsymbol{k}}_\gamma))\right]$$

$$\boxed{+a_9\left[\boldsymbol{\sigma}_n\cdot\hat{\boldsymbol{k}}_\gamma\right]}$$

γ-ray asymmetry relative to neutron polarization

$$\boxed{+a_{10}\left[\boldsymbol{\sigma}_n\cdot\hat{\boldsymbol{k}}_n\right]}$$

longitudinal asymmetry

$$+a_{11}\left[(\boldsymbol{\sigma}_n\cdot\hat{\boldsymbol{k}}_\gamma)(\hat{\boldsymbol{k}}_n\cdot\hat{\boldsymbol{k}}_\gamma)-\frac{1}{3}(\boldsymbol{\sigma}_n\cdot\hat{\boldsymbol{k}}_n)\right]$$

$$+a_{12}\left[(\boldsymbol{\sigma}_n\cdot\hat{\boldsymbol{k}}_n)(\hat{\boldsymbol{k}}_n\cdot\hat{\boldsymbol{k}}_\gamma)-\frac{1}{3}(\boldsymbol{\sigma}_n\cdot\hat{\boldsymbol{k}}_\gamma)\right]$$

$$\boxed{+a_{13}\left[(\boldsymbol{\sigma}_\gamma\cdot\hat{\boldsymbol{k}}_\gamma)\right]}$$

γ-ray circular polarization

$$+a_{14}\left[(\boldsymbol{\sigma}_\gamma\cdot\hat{\boldsymbol{k}}_\gamma)(\hat{\boldsymbol{k}}_n\cdot\hat{\boldsymbol{k}}_\gamma)\right]$$

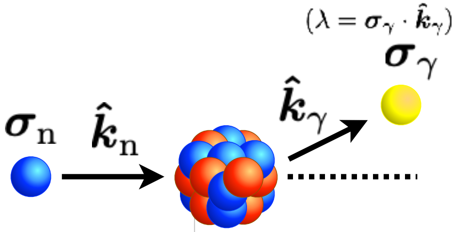
$$+a_{15}\left[(\boldsymbol{\sigma}_\gamma\cdot\hat{\boldsymbol{k}}_\gamma)(\boldsymbol{\sigma}_n\cdot(\hat{\boldsymbol{k}}_n\times\hat{\boldsymbol{k}}_\gamma))\right]$$

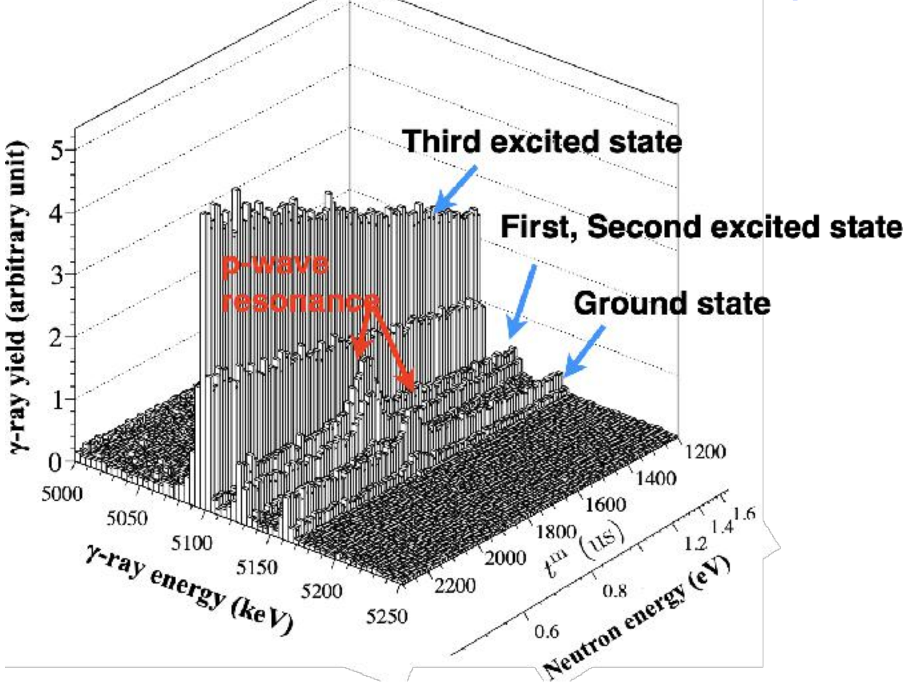
$$+a_{16}\left[(\boldsymbol{\sigma}_\gamma\cdot\hat{\boldsymbol{k}}_\gamma)((\hat{\boldsymbol{k}}_n\cdot\hat{\boldsymbol{k}}_\gamma)^2-\frac{1}{3})\right]$$

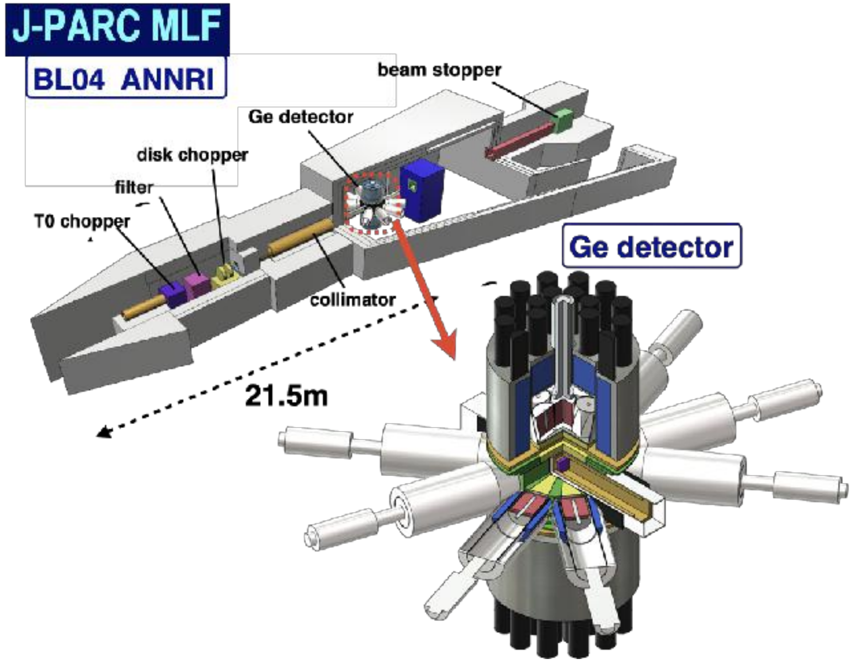
$$+a_{17}\left[(\boldsymbol{\sigma}_\gamma\cdot\hat{\boldsymbol{k}}_\gamma)(\hat{\boldsymbol{k}}_n\cdot\hat{\boldsymbol{k}}_\gamma)(\boldsymbol{\sigma}_n\cdot(\hat{\boldsymbol{k}}_n\times\hat{\boldsymbol{k}}_\gamma))\right]$$

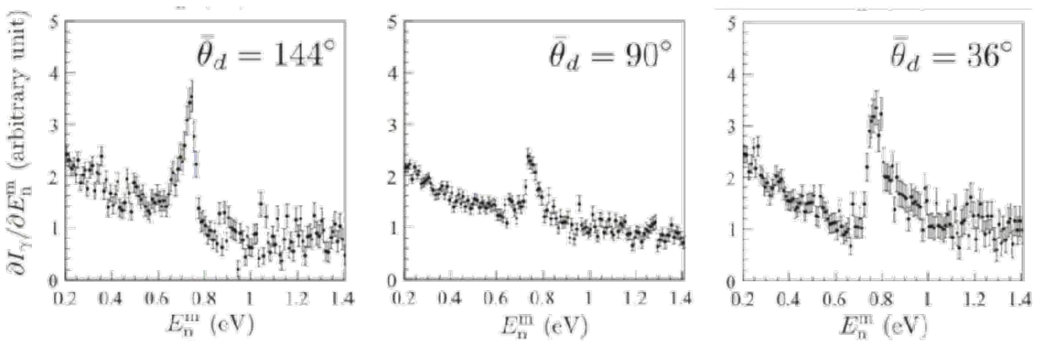
Detailed Study of Entrance Channel Boundary in $^{139}La(n,\gamma)^{140}La^{(*)}$

determination of φ









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

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

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

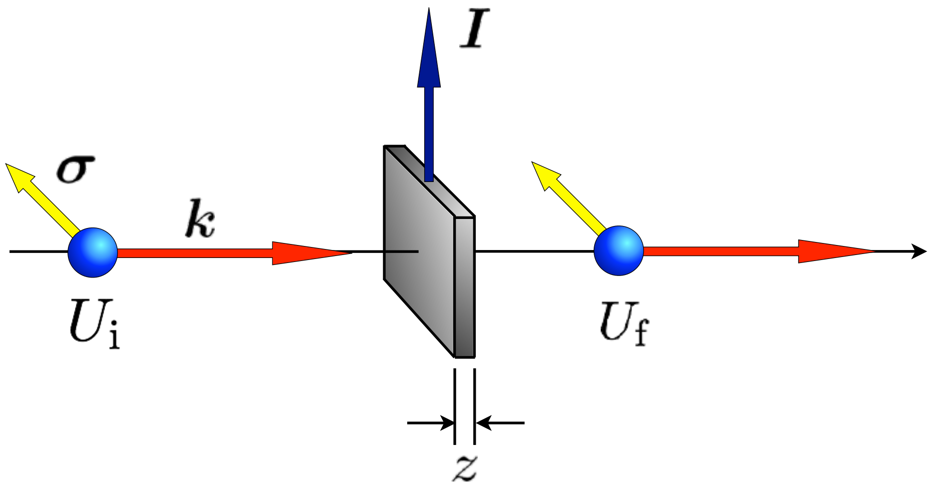
Detailed Study of Entrance Channel Boundary in $\vec{n}+{}^{139}$La

redundant information in pseudomagnetism

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

pseudomagnetism

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

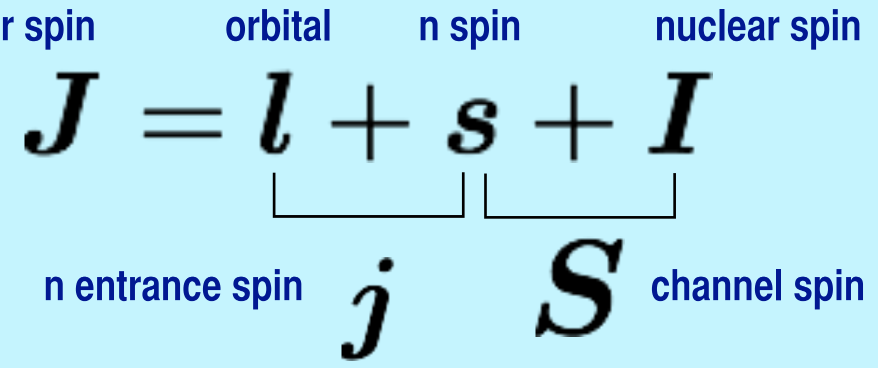


$$f_\mu = \frac{i}{2k}\sum_{JlSS'M_I}(2l+1)\langle s\mu IM_I|S'm'_s\rangle\langle S'm'_sl0|JM\rangle\underline{\langle S'l|R^J|Sl\rangle}\langle JM|Sm_sl0\rangle\langle Sm_s|s\mu IM_I\rangle\,.$$

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

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

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



compound nuclear spin　orbital　n spin　nuclear spin

$$J = l + s + I$$

n entrance spin j　S channel spin

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

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

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

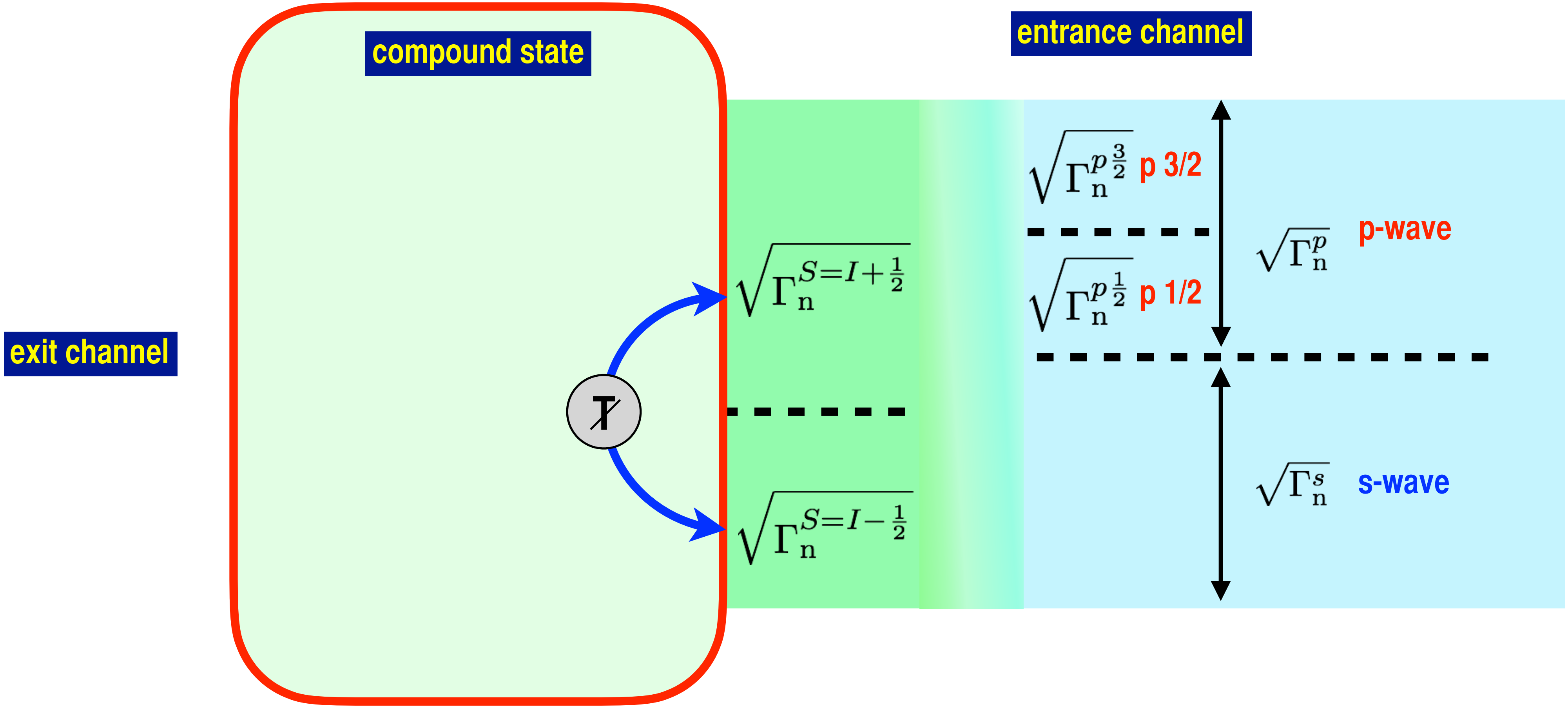
$$z_j = \begin{cases} x & (j=1/2) \\ y & (j=3/2) \end{cases}, \quad \tilde{z}_S = \begin{cases} x_S & (S=I-1/2) \\ y_S & (S=I+1/2) \end{cases} \qquad \tilde{z}_S = \sum_j (-1)^{l+I+j+S}\sqrt{(2j+1)(2S+1)} \begin{Bmatrix} l & s & j \\ I & J & S \end{Bmatrix} z_j$$

s-p interference ⇔ channel-spin interference

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

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

T-odd ➡ Channel-spin Interference



compound state

entrance channel

exit channel

$\not{T}$

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

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

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

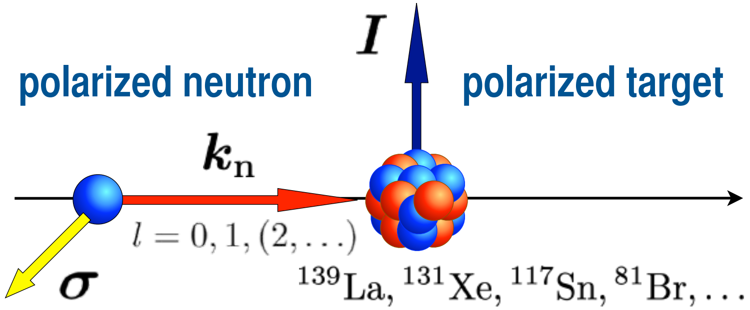
$\sqrt{\Gamma_{\mathrm{n}}^{p\frac{1}{2}}}$ p 1/2

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

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

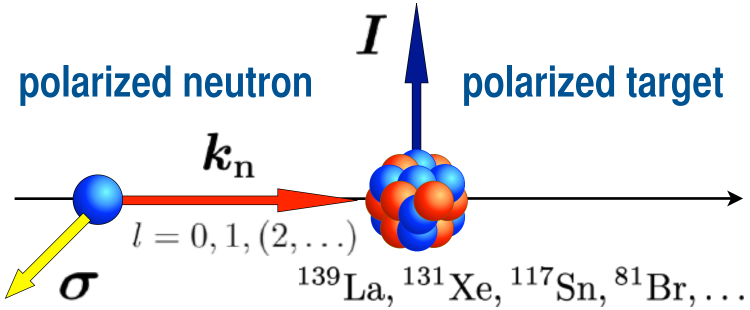
Forward Scattering Amplitude

no fake T-violation



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

Forward Scattering Amplitude



no fake T-violation

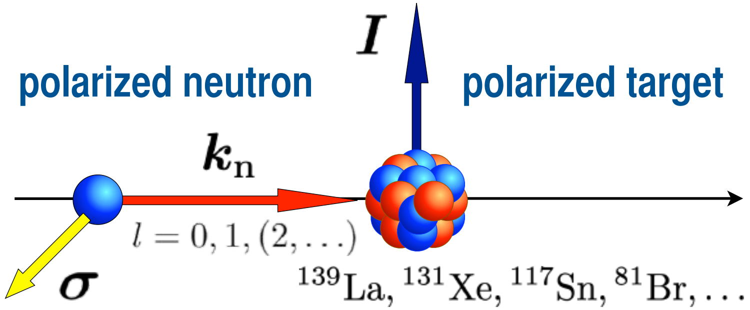
$$f(0) \rightarrow f = \underbrace{A'}_{\substack{\text{Spin Independent}\\ \text{P-even T-even}}} + \underbrace{B'}_{\substack{\text{Spin Dependent}\\ \text{P-even T-even}}} \boldsymbol{\sigma} \cdot \hat{\boldsymbol{I}} + \underbrace{C'}_{\substack{\text{P-violation}\\ \text{P-odd T-even}}} \boldsymbol{\sigma}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

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

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

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

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



P-even T-even

P-odd T-even

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

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

P-even T-even

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

P-odd T-odd

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

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

T-violation in Compound Nuclear States

A'

P-even T-even

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

C' $(\boldsymbol{\sigma}_{\mathrm{n}} \cdot \hat{\boldsymbol{k}}_{\mathrm{n}})$

P-odd T-even

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

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

10^6 enhancement
in compound nuclear state

B' $(\boldsymbol{\sigma}_{\mathrm{n}} \cdot \hat{\boldsymbol{I}})$

P-even T-even

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

P-odd T-odd

10^6 enhancement
in compound nuclear state

T-violation in Compound Nuclear States

A'

P-even T-even

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

polarized neutron

C' $(\boldsymbol{\sigma}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\mathrm{n})$

P-odd T-even

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

10^6 enhancement in compound nuclear state

polarized target

B' $(\boldsymbol{\sigma}_\mathrm{n}\cdot\hat{\boldsymbol{I}})$

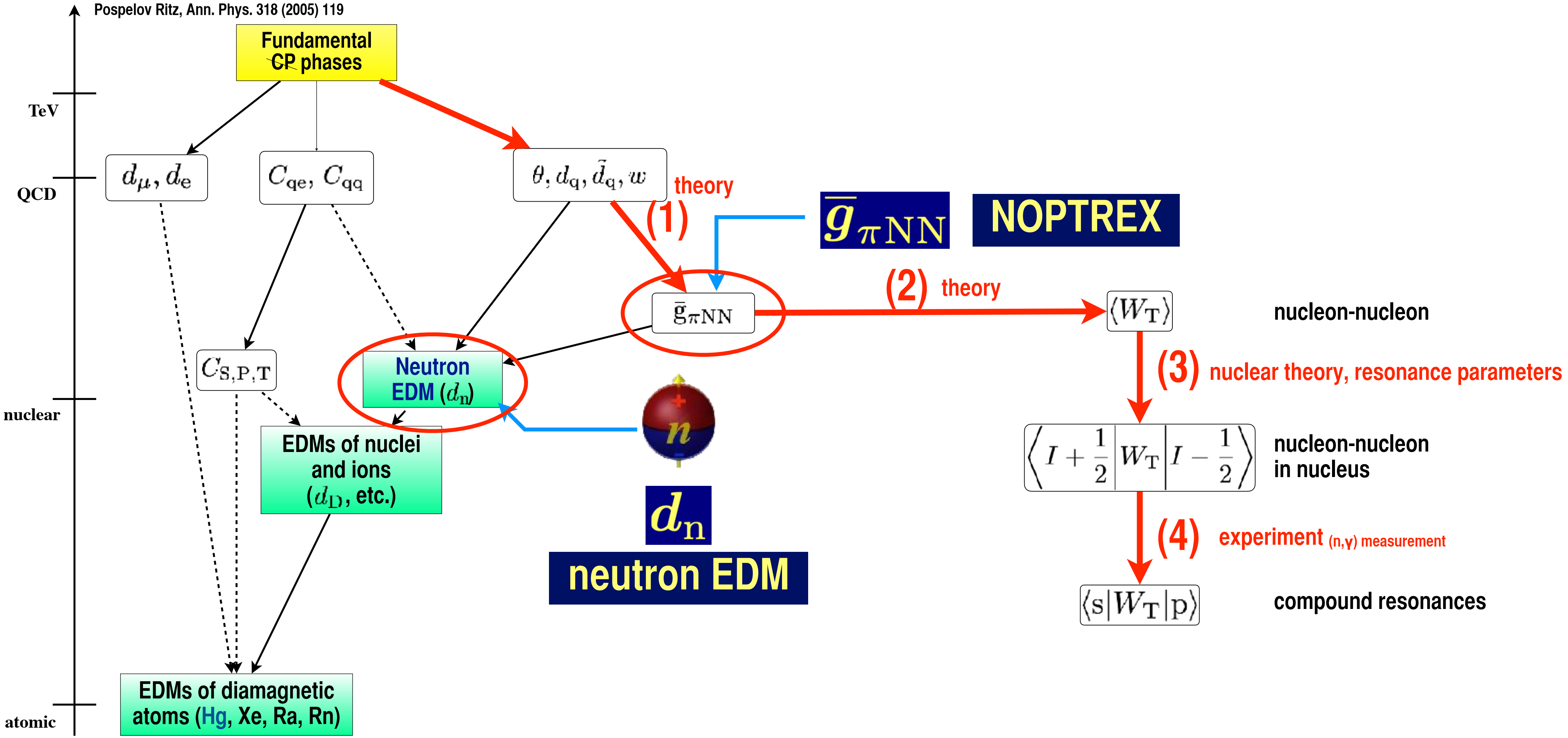
P-even T-even

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

P-odd T-odd

10^6 enhancement in compound nuclear state

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



Pospelov Ritz, Ann. Phys. 318 (2005) 119

TeV

QCD

nuclear

atomic

Fundamental ~~CP~~ phases

d_μ, d_e

C_{qe}, C_{qq}

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

theory

(1)

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

NOPTREX

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

(2) theory

$\langle W_T \rangle$ nucleon-nucleon

(3) nuclear theory, resonance parameters

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

(4) experiment (n,γ) measurement

$\langle s | W_T | p \rangle$ compound resonances

$C_{S,P,T}$

Neutron EDM (d_n)

EDMs of nuclei and ions (d_D, etc.)

d_n

neutron EDM

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

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

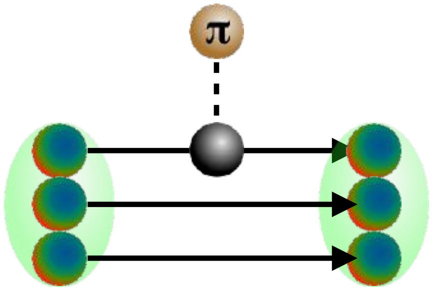
$$V_{\mathrm{CP}}=\left[-\frac{\bar{g}_\eta^{(0)}g_\eta}{2m_N}\frac{m_\eta^2}{4\pi}Y_1(x_\eta)+\frac{\bar{g}_\omega^{(0)}g_\omega}{2m_N}\frac{m_\omega^2}{4\pi}Y_1(x_\omega)\right]\boldsymbol{\sigma}_-\cdot\hat{\boldsymbol{r}}$$

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

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

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

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



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

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

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

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

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

$$d_{^3\mathrm{He}}\sim(-0.0542d_{\mathrm{p}}+0.868d_{\mathrm{n}})+0.0$$

$$d_{\mathrm{d}}\sim 0.19\bar{g}_\pi^{(1)}+0.0035\bar{g}_\eta^{(1)}+0.0017\bar{g}$$

$$d_{^3\mathrm{H}}\sim(0.868d_{\mathrm{p}}-0.0552d_{\mathrm{n}})-0.072\left[\bar{g}_\pi^{(0}\right.$$

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

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

Present Sensitivity Estimation in Effective Field Theory

nuclear

nuclear effect

nucleon

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

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

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

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

$$\overline{g}_{\pi}^{(1)} < 0.5 \times 10^{-11}$$ ←atomic EDM

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

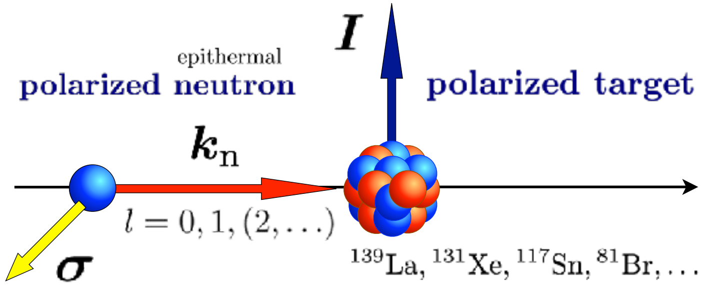
$$\downarrow$$

$$\overline{g}_{\pi}^{(0)} < 2.5 \times 10^{-10}$$ ←neutron EDM

$$\updownarrow$$

$$\left|\frac{\langle W_{\mathrm{T}}\rangle}{\langle W\rangle}\right| < 3.9 \times 10^{-4}$$ ←estimated discovery potential

T-violation in Epithermal Neutron Optics



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

T-violating matrix element

to be measured

measured

being measured

$$\frac{\boxed{D'}}{\boxed{C'}} = \boxed{\kappa(J)} \frac{\boxed{W_{\mathrm{T}}}}{\boxed{W}}$$

spin factor

measured

P-violating matrix element

$$\frac{W_{\mathrm{T}}}{W} = Q \frac{g_{\mathrm{PT}}}{g_{\mathrm{P}}}$$

T-violating nucleon coupling constant

P-violating nucleon coupling constant

nuclear

nuclear effect

nucleon

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

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

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

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

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

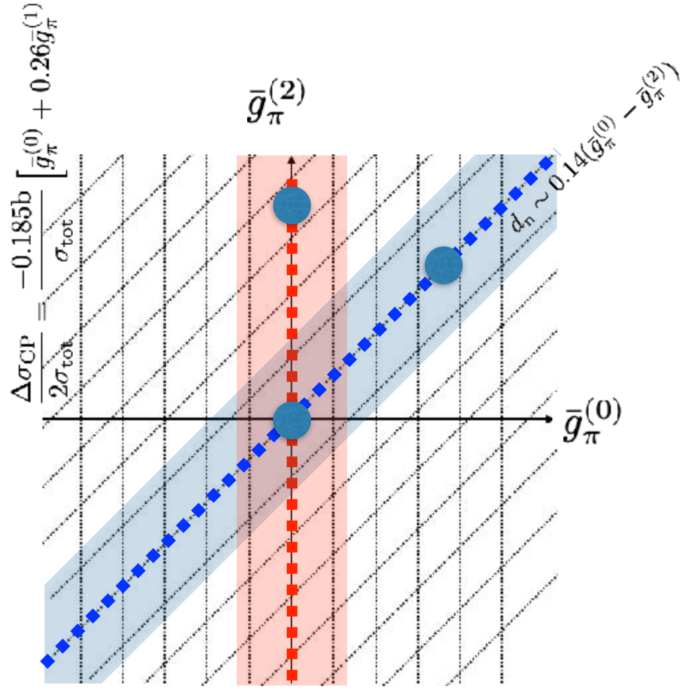
$h_{\pi}^{1} \sim 3 \times 10^{-7}$ $\mathrm{n} + \mathrm{p} \to \mathrm{d} + \gamma$

↓

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

↕

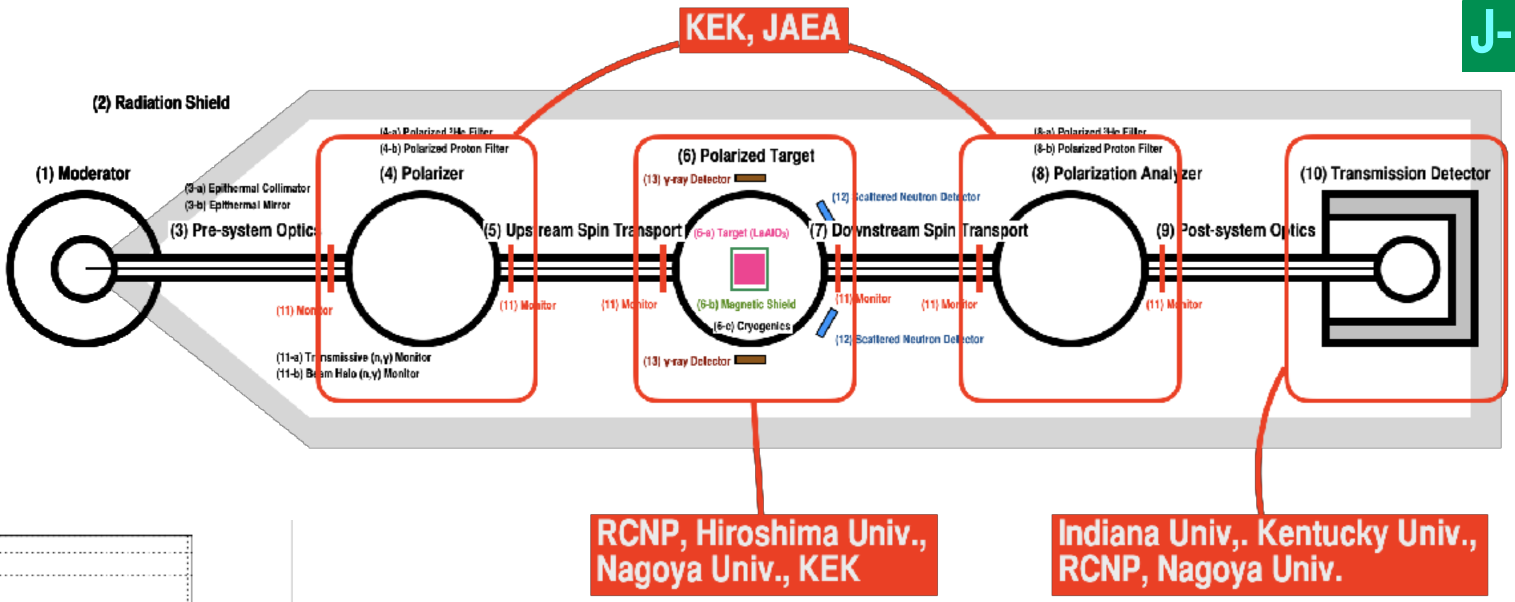
$\left| \frac{\langle W_{\mathrm{T}}\rangle}{\langle W\rangle} \right| < 3.9 \times 10^{-4}$ ←estimated discovery potential



NOPTREX

Neutron Optical Parity and Time Reversal EXperiment

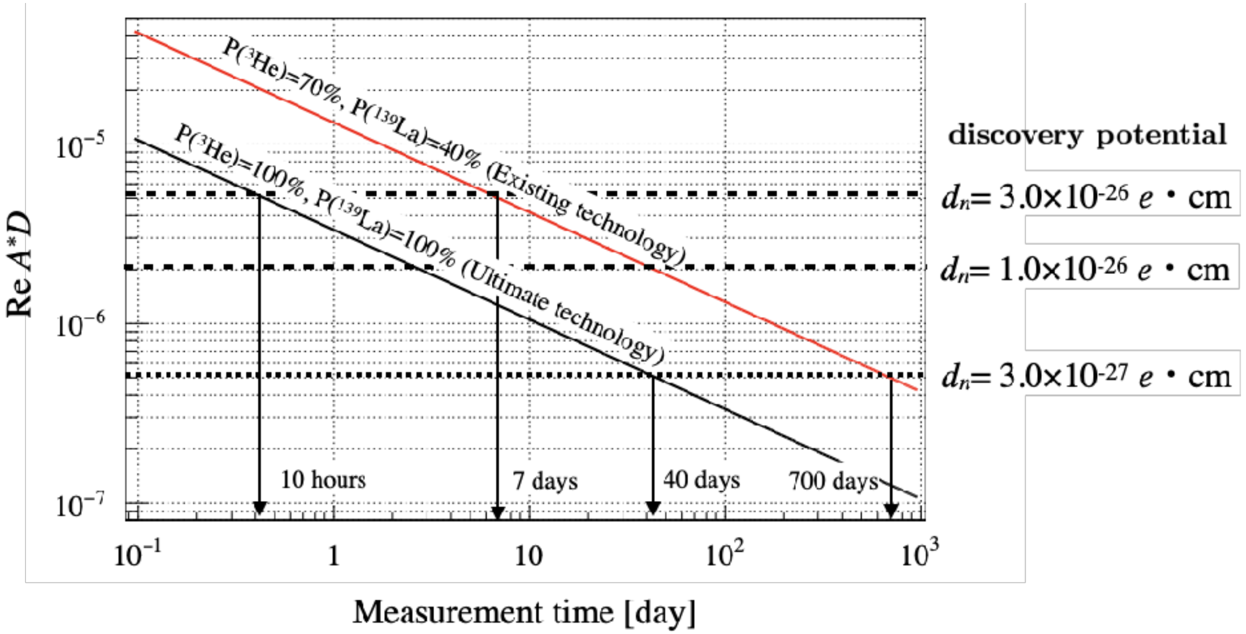
KEK 2018S12
J-PARC P76



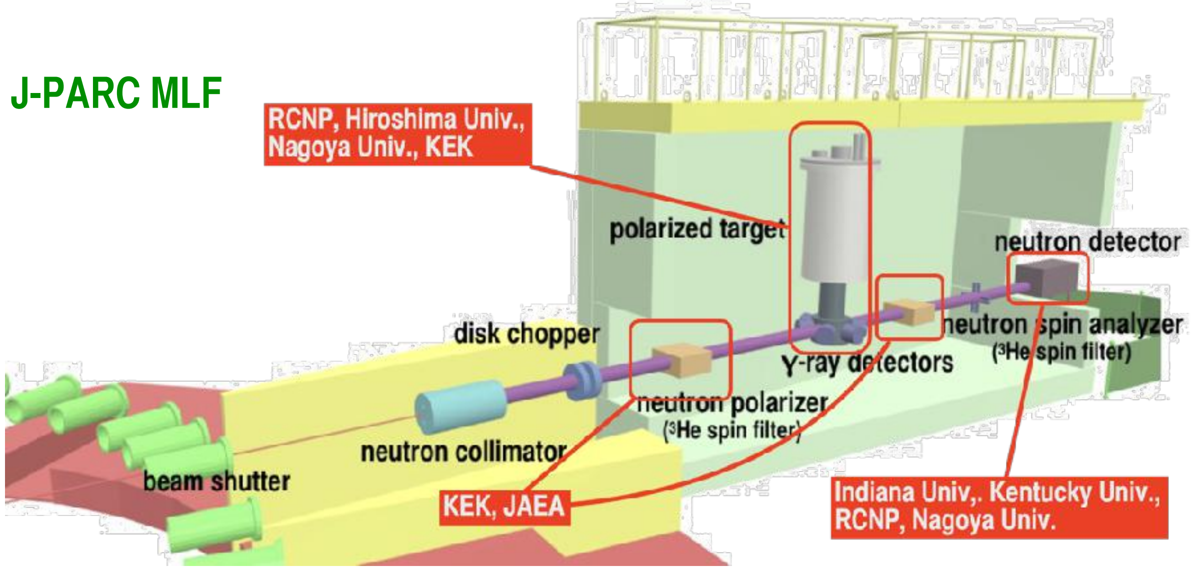
KEK, JAEA

RCNP, Hiroshima Univ., Nagoya Univ., KEK

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



J-PARC MLF



RCNP, Hiroshima Univ., Nagoya Univ., KEK

KEK, JAEA

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

Development of Polarized Target

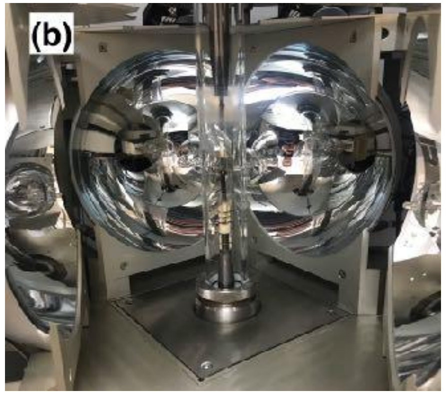
Study of Dynamic Nuclear Polarization
Study of Crystal Growth

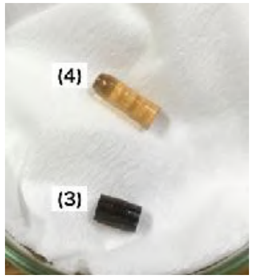
in progress under the support of

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

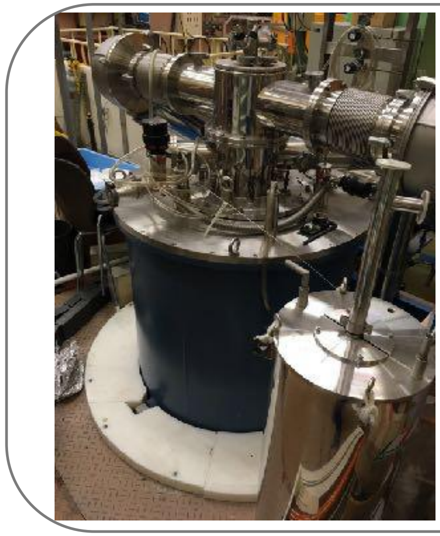
RCNP, Osaka Univ.

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

Polarized Lanthanum Target

$LaAlO_3$
Nd-doped crystal
pure crystal

Cryogenics



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

Development of Refrigeration with Large Cooling Power at Very Low Temperature

Active Control of Spin-lattice Relaxation Time

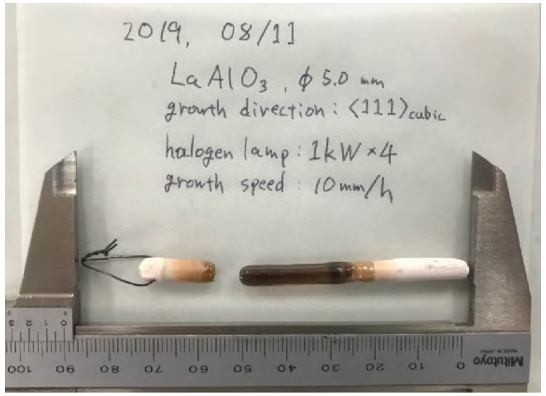
NSCBRD, Hiroshima Univ.

Hiroshima Univ.
Nagoya Univ.

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

Development of Polarized Target

crystal growth



2019, 08/11

LaAlO$_3$, ϕ 5.0 mm

growth direction : $\langle 111 \rangle_{cubic}$

halogen lamp : 1kW × 4

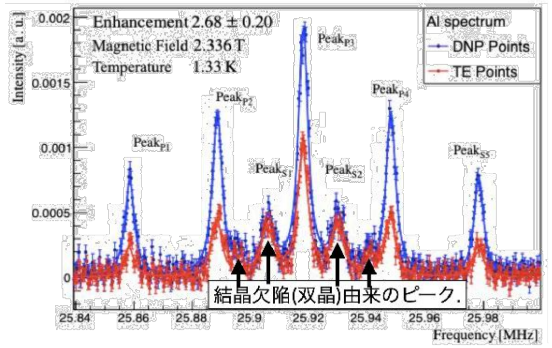
growth speed : 10 mm/h

measurement of spin relaxation time

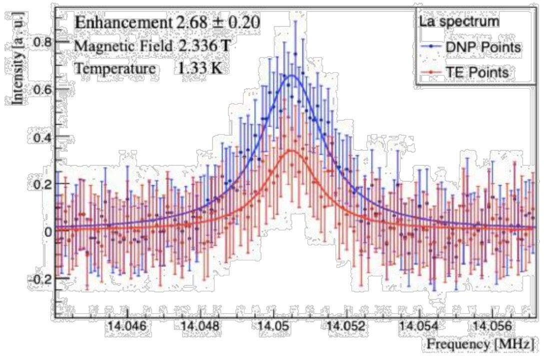
K.Ishizaki et al., arXiv:2105.06299 (accepted NIMA)

$\mathrm{La(Nd^{3+})AlO_3}$ P.Hautle and M.Iinuma, Nucl. Instrum. Methods A440 (2000) 638

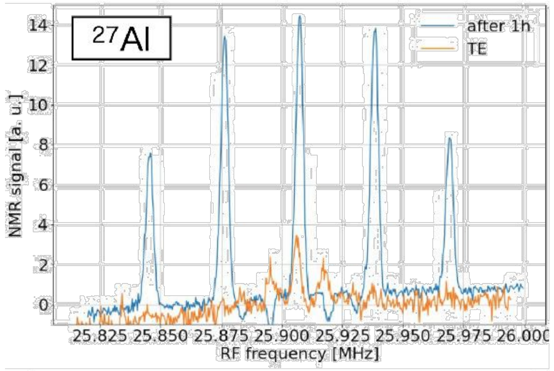
(Nd : 0.03mol%)

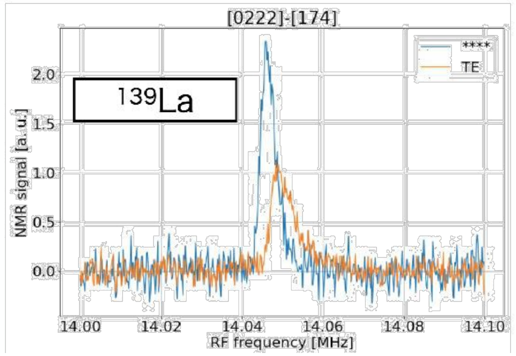


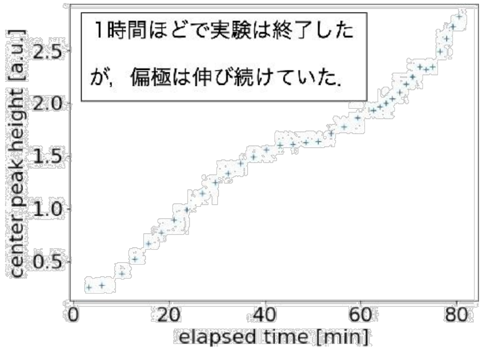
結晶欠陥(双晶)由来のピーク.



(Nd : 0.01mol%)







1時間ほどで実験は終了したが，偏極は伸び続けていた.

NOPTREX

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

Parity Violation	longitudinal asymmetry	$A_L(a_{10})$
	statistical treatment	$W_{\mathrm{vs}}D$
Reaction Mechanism **Channel Boundary**	(n,γ)	a_1,a_3
	$(\vec{n},\gamma)$	a_2 a_9
	$(n,\vec{\gamma})$	a_{13}
		polarized target
		B’ (pseudomagnetism)
Devices		detector
		beam optics
Time Reversal		

FY2020

NOPTREX

Neutron Optical Parity and Time-Reversal EXperiment

				^{139}La	^{131}Xe	^{117}Sn	Pd	^{81}Br	^{111,113}Cd	^{115}In
Parity Violation	longitudinal asymmetry	$A_L(a_{10})$	(α1)	studied before us	studied before us	studied before us			studied before us	
	statistical treatment	WvsD	(α2)	studied before us	studied before us	studied before us	✅ in progress		studied before us	
Reaction Mechanism Channel Boundary	(n,γ)	a_1,a_3	(β1)	DONE	✅ in progress	DONE				
	$(\vec{n},\gamma)$	a_2	(β2)	DONE						
		a_9	(β3)	✅ in progress						
	$(n,\vec{\gamma})$	a_{13}	(β4)	☑ being prepared						
	polarized target		(γ1)	✅ in progress	✅ in progress					
	B’ (pseudomagnetism)		(γ2)	☑ under discussion	✅ in progress					
Devices	detector		(δ1)	✅ in progress	✅ in progress	✅ in progress				
	beam optics		(δ2)	✅ in progress	✅ in progress	✅ in progress				
Time Reversal			(ε)	★	★					

FY2021

NOPTREX
Neutron Optical Parity and Time-Reversal EXperiment

				^{139}La	^{131}Xe	^{117}Sn	Pd	^{81}Br	^{111,113}Cd	^{115}In
Parity Violation	longitudinal asymmetry	$A_L(a_{10})$	(α1)	studied before us	studied before us	studied before us			studied before us	
	statistical treatment	WvsD	(α2)	studied before us	studied before us	studied before us	✓ in progress		studied before us	
Reaction Mechanism Channel Boundary	(n,γ)	a_1,a_3	(β1)	DONE	✓ in progress	DONE				
	$(\vec{n},\gamma)$	a_2	(β2)	DONE		DONE				
		a_9	(β3)	✓ in progress						
	$(n,\vec{\gamma})$	a_{13}	(β4)	✓ in progress						
	polarized target		(γ1)	✓ in progress	✓ in progress					
	B’ (pseudomagnetism)		(γ2)	✓ in progress	✓ in progress					
Devices	detector		(δ1)	✓ in progress	✓ in progress	✓ in progress				
	beam optics		(δ2)	✓ in progress	✓ in progress	✓ in progress				
Time Reversal			(ε)	★	★					

FY2022

Neutron Optical Parity and Time-Reversal EXperiment

				^{139}La	^{131}Xe	^{117}Sn	Pd	^{81}Br	^{111,113}Cd	^{115}In
Parity Violation	longitudinal asymmetry	$A_L(a_{10})$	(α1)	studied before us	studied before us	studied before us			studied before us	
	statistical treatment	WvsD	(α2)	studied before us	studied before us	studied before us	✓ in progress		studied before us	
Reaction Mechanism Channel Boundary	(n,γ)	a_1,a_3	(β1)	DONE	✓ in progress	DONE				
	$(\vec{n},\gamma)$	a_2	(β2)	DONE		DONE				
		a_9	(β3)	✓ in progress						
	$(n,\vec{\gamma})$	a_{13}	(β4)	✓ in progress						
	polarized target		(γ1)	✓ in progress	✓ in progress					
	B' (pseudomagnetism)		(γ2)	✓ in progress	✓ in progress					
Devices	detector		(δ1)	✓ in progress	✓ in progress	✓ in progress				
	beam optics		(δ2)	✓ in progress	✓ in progress	✓ in progress				
Time Reversal			(ε)	★	★					

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.

NOPTREX

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.Ide, 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
Hiroshima 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	Y.Yamagata, T.Uesaka, K.Tateishi, H.Ikegami
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
Indiana Univ.	W.M.Snow, C.Auton, J.Carini, J.Curole, K.Dickerson, J.Doskow, H.Lu, G.Otero, J.Vanderwerp, G.Visser
Univ. South Carolina	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

KEK-BSF PEN

Nuclear Physics A552 (1993) 293–305
North-Holland

3kW spallation source

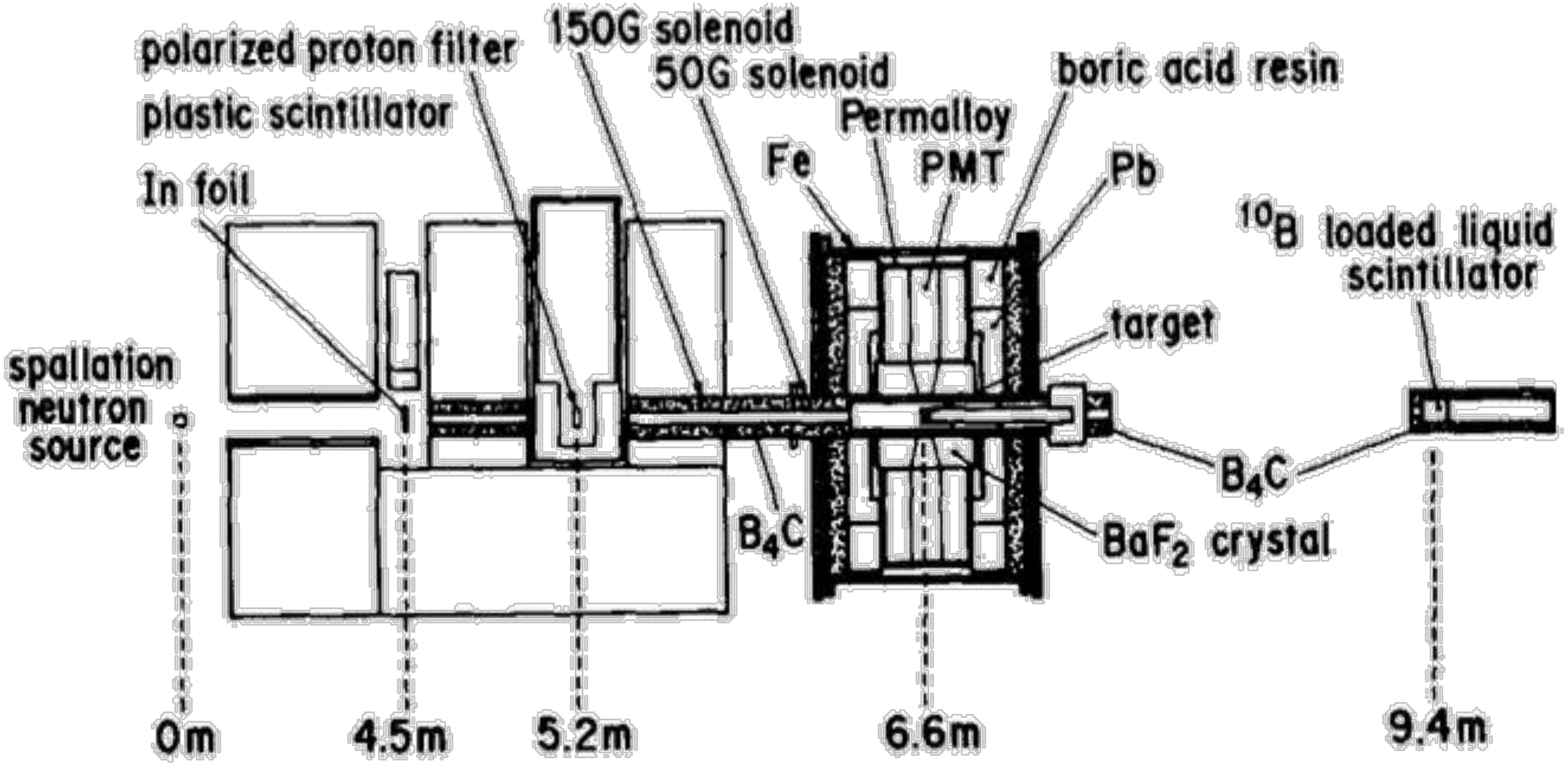


Fig. 1. Experimental arrangement of the beam line is schematically shown with the BaF_2 γ-ray counter used for the measurement of A_L in a large solid angle and $a_{L,\gamma}(\theta)$. The BaF_2 crystals are arranged to detect capture γ-rays at $\theta = 55°$, 90° and 125°. The crystals cover 85% of 4π steradians in total.