Angular Correlations of Capture Gamma-rays from p-wave Resonances for the Study of the Boundary Condition at the Entrance Channel

— Enhanced Discrete Symmetry Breaking in Compound Nuclear States —

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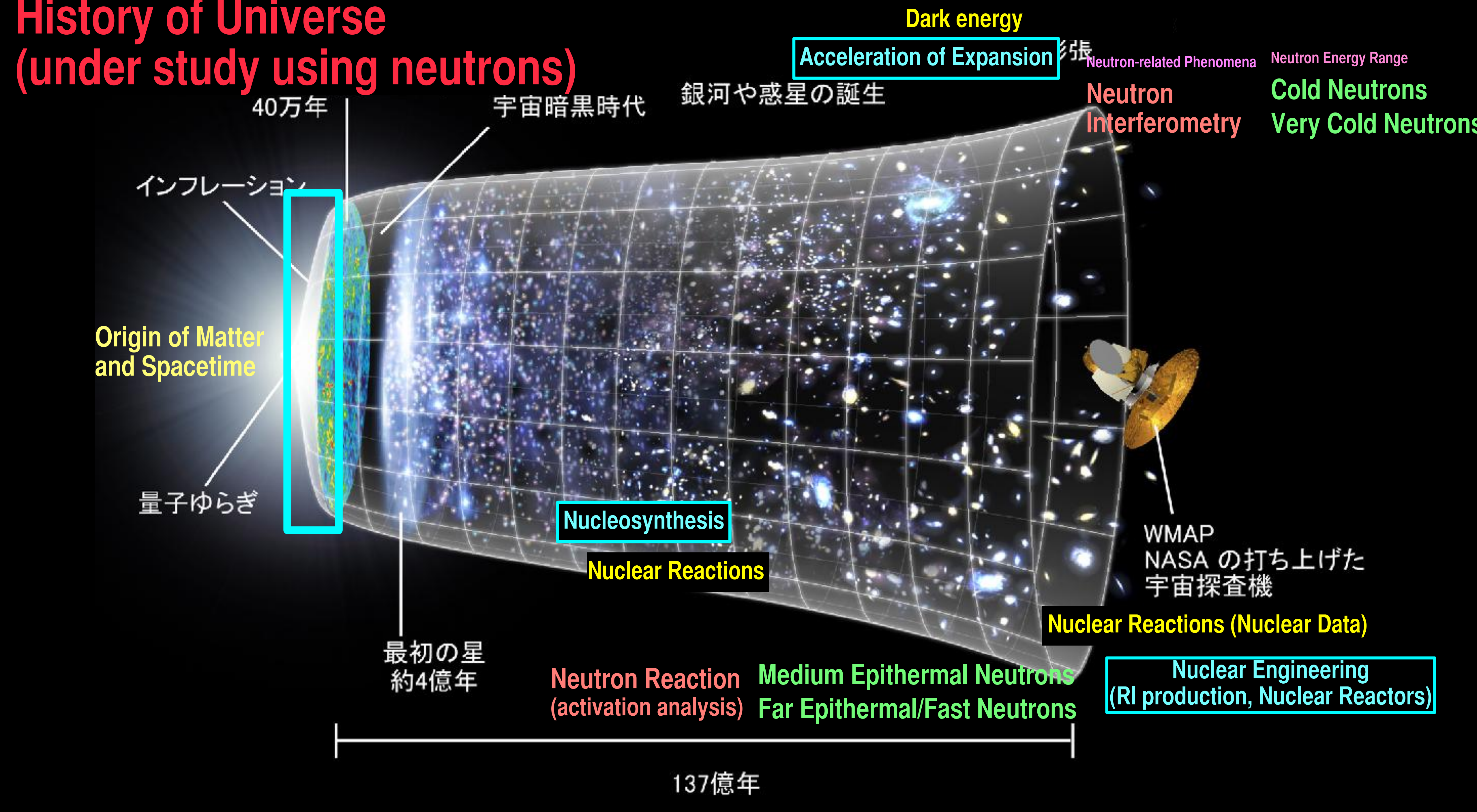
Extremely large breaking of the symmetry under the spatial inversion (P-violation) is observed in p-wave resonances of medium heavy nuclei. The enhanced P-violating effect is understood as the result of the combination of the interference between neutron scattering amplitudes of P-unfavored neighboring resonances, which is referred to the kinematical enhancement, and the variance of the P-violating nuclear interaction in compound nuclear states, which is referred as the dynamical enhancement. The kinematical enhancement has been studied by determination of partial neutron widths of p-wave amplitudes in energy-dependent angular correlations of individual gamma-ray transitions emitted in the relaxation process of compound nuclear states using pulsed neutron beam at the ANNRI beamline of the J-PARC spallation neutron source. In this paper, we overview the experimental results and discuss their consistency with theoretical models and possible extension to their application to search for the breaking of the time reversal invariance in nuclear interaction with the possible sensitivity to new physics beyond the standard model of elementary particles.

History of Universe
(under study using neutrons)



History of Universe

Origin of Matter and Spacetime

Neutron Energy Range	Neutron-related Phenomena
Ultracold	Neutron Electric Dipole Moment
Near-Epithermal	T-violation
Ultracold	Neutron-AntiNeutron Oscillation
Neutrino	Neutrino Physics
	Double Beta-decay
	Neutrino Oscillation
Cold	Neutron Interferometry
	Neutron Scatteirng
Very Cold	Neutron Diffraction
	(Neutron Gravitational Wave Antenna)
Cold/Very Cold	Interferometry
Medium Epithermal	
Far Epithermal/Fast	Nuclear Reaction

Symmetry

CP/T symmetry

Conservation Laws

Baryon Number

Lepton Number

Gravity→Spacetime

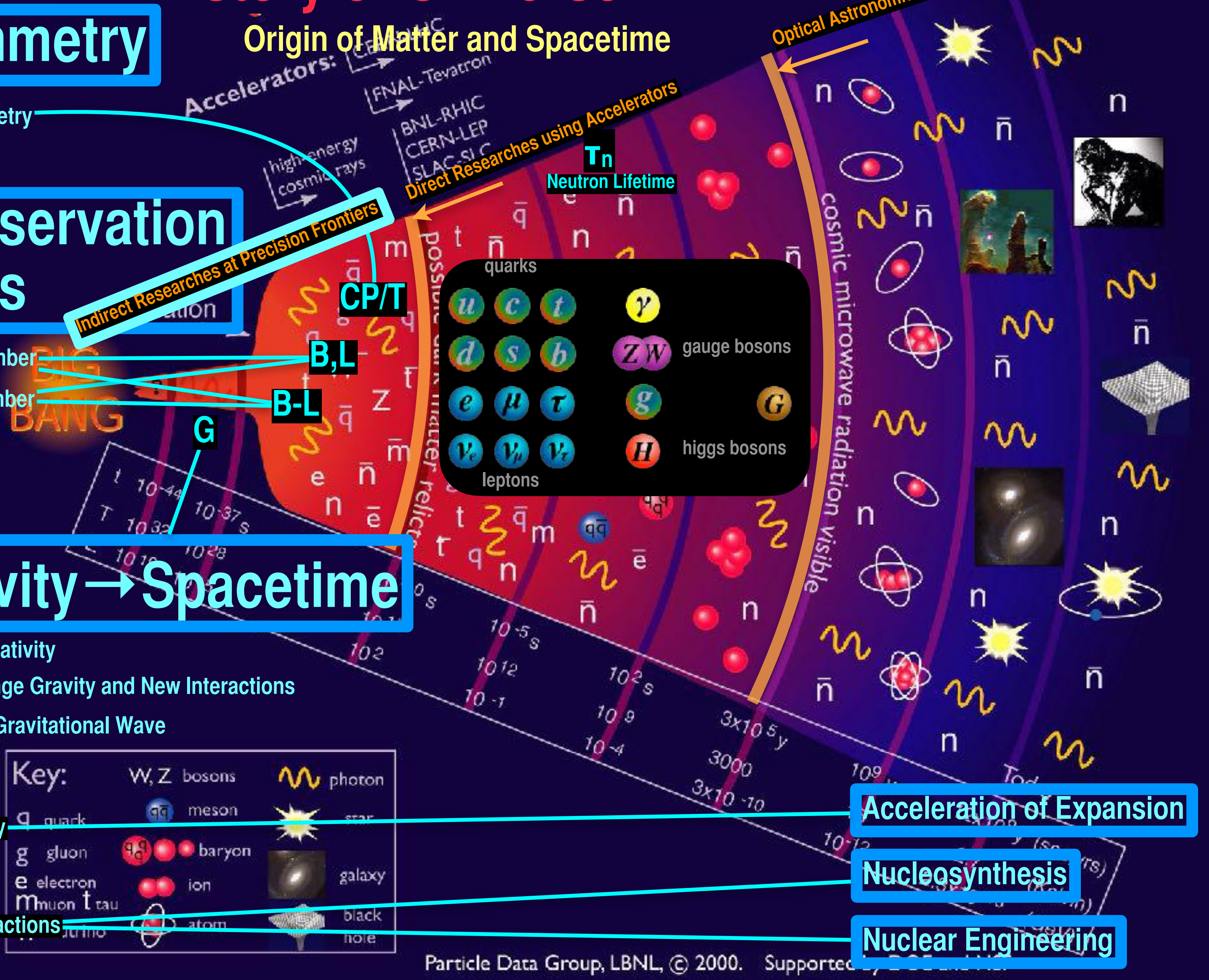
General Relativity

Medium-range Gravity and New Interactions

Primordial Gravitational Wave

Dark Energy

Nuclear Reactions



Acceleration of Expansion

Nucleosynthesis

Nuclear Engineering

Fundamental Discrete Symmetries

			standard model of elementary particles: ST strong interaction	WK weak interaction
P	spatial inversion, parity reversal	$\boldsymbol{r} \to -\boldsymbol{r}$	even	odd
T	time reversal	$t \to -t$	even	even odd

▲
CPT-theorem
▼

CP

C charge conjugation $q \to -q$

Fundamental Discrete Symmetries

			standard model of elementary particles		new physics
			ST strong interaction	**WK** weak interaction	beyond the standard model of elementary particles
P	spatial inversion parity reversal	$\boldsymbol{r} \rightarrow -\boldsymbol{r}$	even	odd	
T	time reversal	$t \rightarrow -t$	even odd	even odd	odd

▲
CPT-theorem
▼

CP   **C** charge conjugation $q \rightarrow -q$

NOPTREX

Neutron Optical Parity and Time Reversal EXperiment

— Enhanced Discrete Symmetry Breaking in Compound Nuclear States —

Experimental Fact

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

↓

(n,γ) spin-angular correlation terms

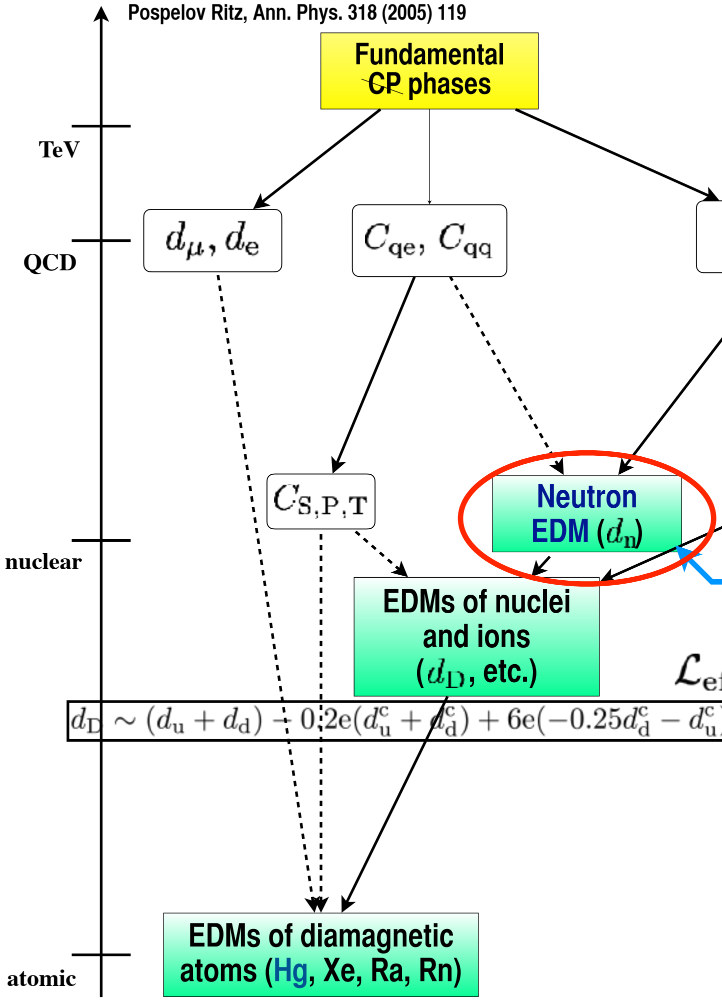
↓

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

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

New Type of New Physics Search

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



$$d_D \sim (d_u + d_d) + 0.2e(d_u^c + d_d^c) + 6e(-0.25 d_d^c - d_u^c)$$

$$d_{Tl} \sim -585 d_e - e\,43\text{GeV} \times (C_S^{(0)} - 0.2 C_S^{(1)})$$

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

NOPTREX

$$\frac{W_T}{W} = 5.3 \times 10^4 \, |\theta_{QCD}|$$

$$\frac{W_T}{W} \sim |-1.0(\bar{d}_u + \bar{d}_d + 24(\bar{d}_u - \bar{d}_d| \times 10^{20}\ \text{cm}^{-1}$$

J.de Vries, PRC92(2015)045201
V.V.Flambaum, PRC104(2022)015501

d_n

neutron EDM

$$d_n \sim 1.1e(0.5 d_u^c + d_d^c) + 1.4 \times (-0.25 d_u + d_d)$$

M.Pospelov, PLB530(2002)123

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

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

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

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

NOPTREX

Neutron Optical Parity and Time Reversal EXperiment

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Ashikaga Univ.	D.Takahashi
Japan Women's Univ.	R.Ishiguro
Univ. British Columbia	T.Momose
Kyungpook Univ.	G.N.Kim, S.W.Lee, H.J.Kim
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Eastern Kentucky Univ.	J.Fry
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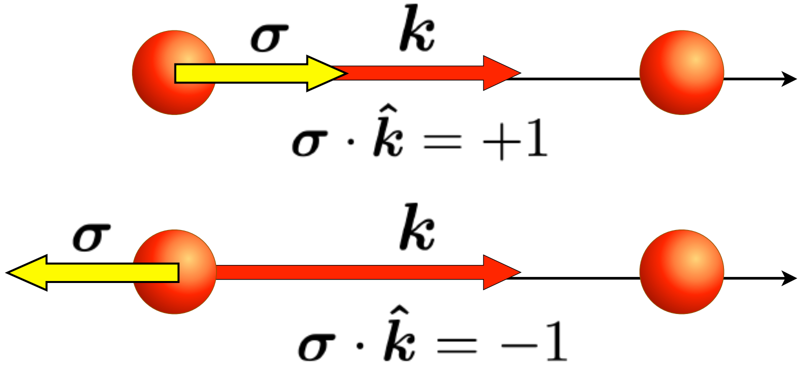
PSI	P.Hautle
NIST	C.C.Haddock
Ohio Univ.	P.King
Juelich	E.Babcock
Nottingham	M.Barlow
Depauw	A.Komives

Parity Violation in Compound States

P-violation in Nuclear Interaction

	ST	WK
	strong interaction	weak interaction
P: $\boldsymbol{\sigma} \to \boldsymbol{\sigma}$ $\quad \boldsymbol{k} \to -\boldsymbol{k}$ $\boldsymbol{\sigma} \cdot \boldsymbol{k} \to -\boldsymbol{\sigma} \cdot \boldsymbol{k}$	even	odd

nucleon-nucleon cross section $\quad \sigma = \sigma_0 + \Delta\sigma(\boldsymbol{\sigma} \cdot \hat{\boldsymbol{k}})$

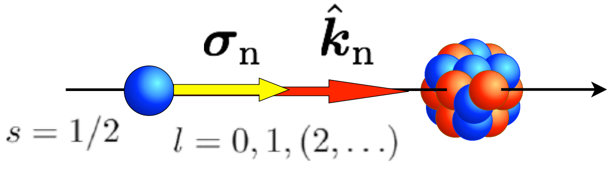


$$\sigma_0 + \Delta\sigma$$

$$\sigma_0 - \Delta\sigma$$

$$\frac{\Delta\sigma}{\sigma_0} \sim 10^{-7}$$

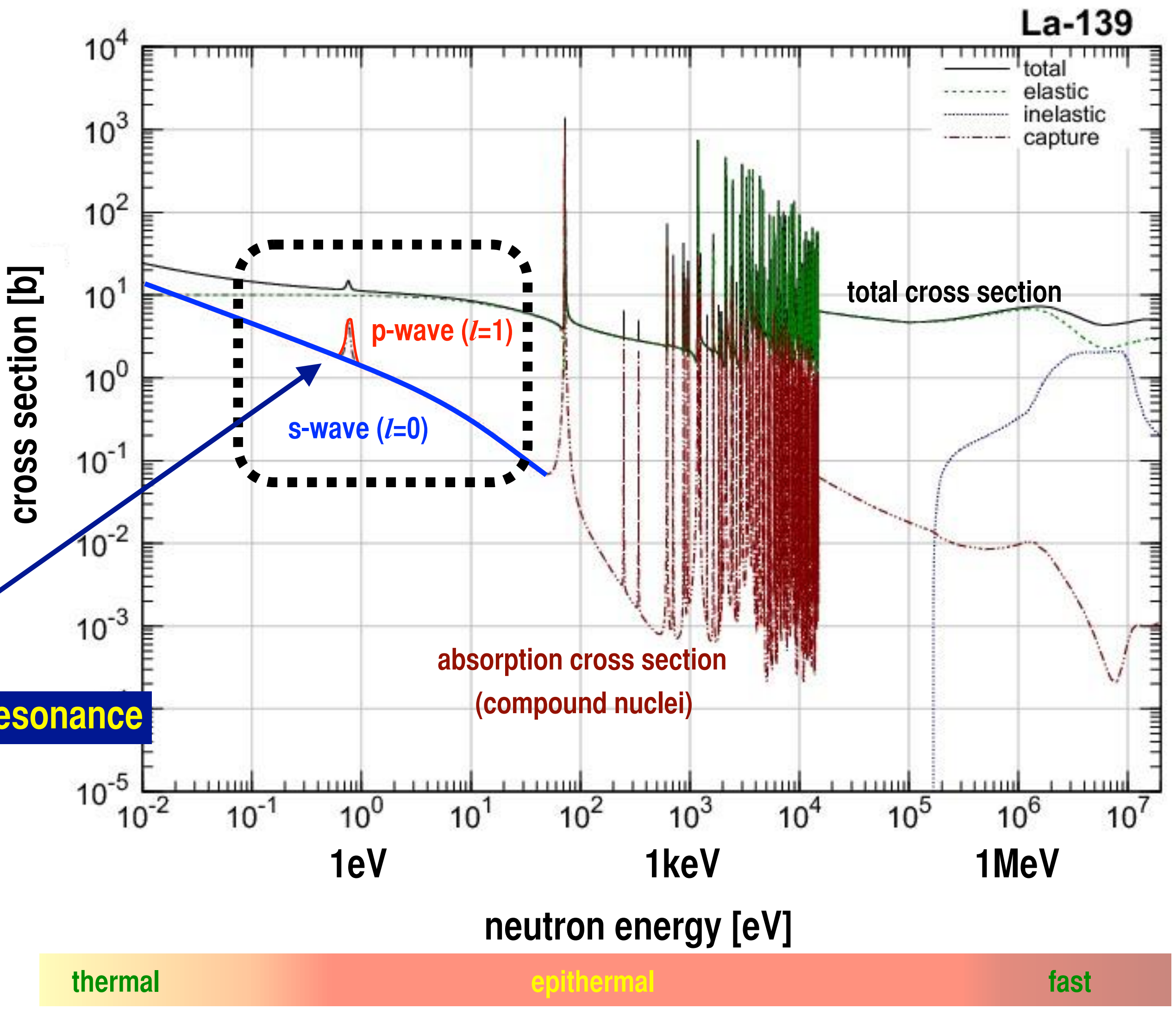
P-violation in Compound State



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

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

P-violation reaches 10^{-1} in this p-wave resonance

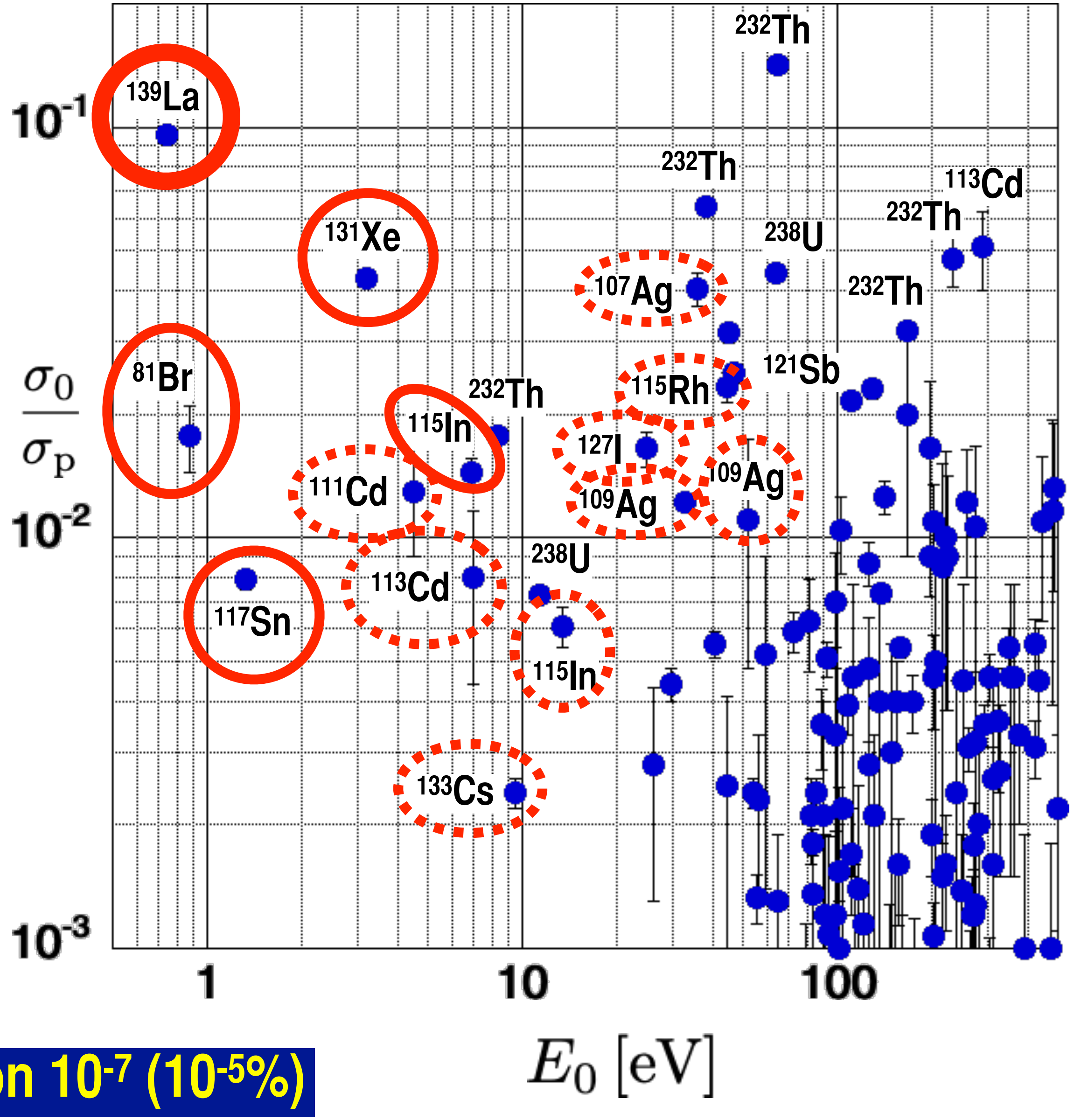


Enhancement of P-violation in Compound States

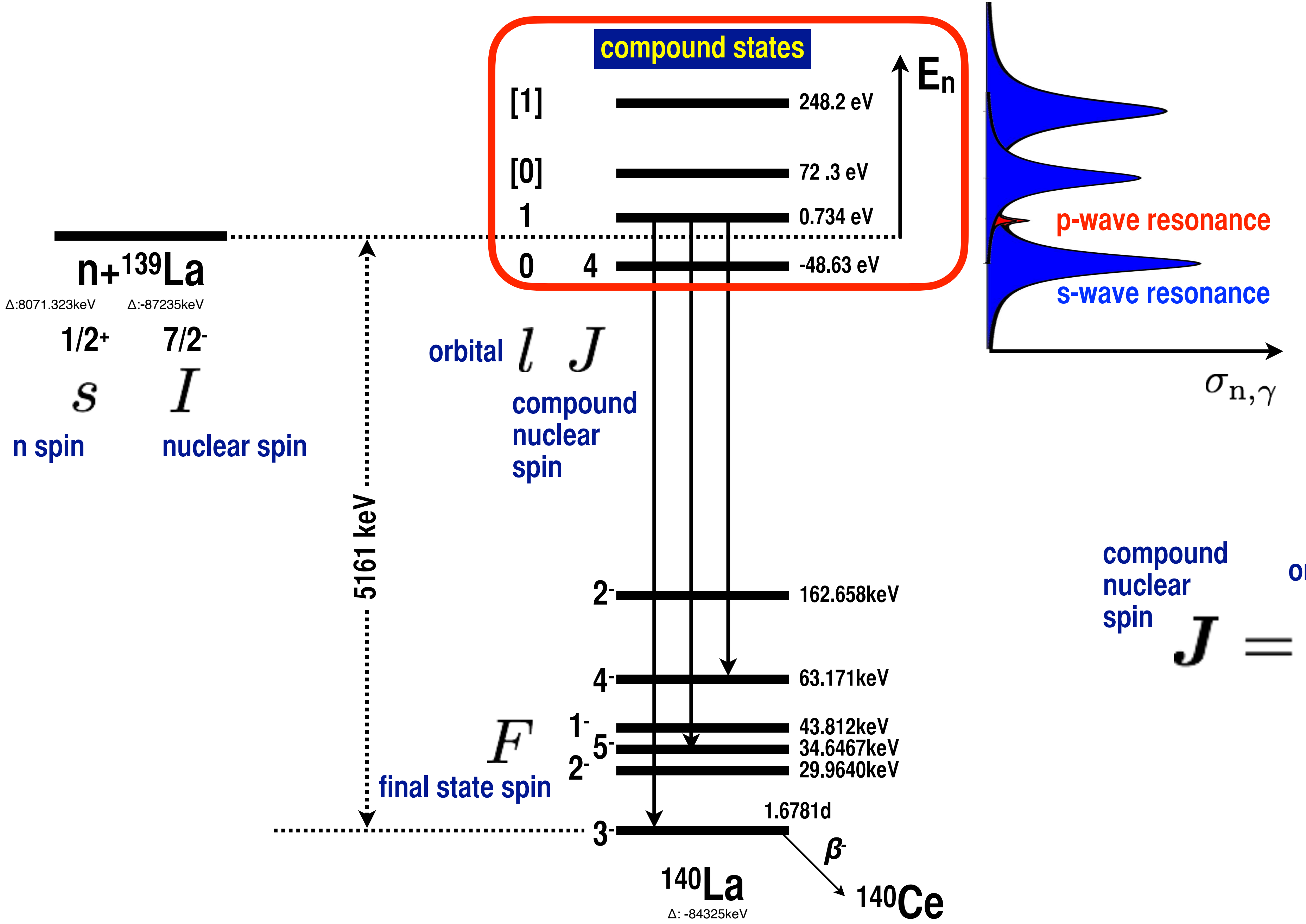
Mitchell, Phys. Rep. 354 (2001) 157
Shimizu, Nucl. Phys. A552 (1993) 293

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

10^{-7} for NN



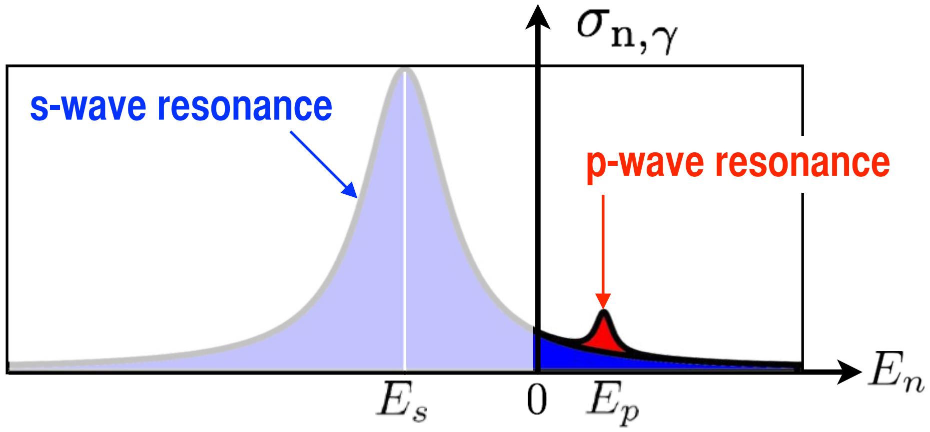
NN-interaction 10^{-7} (10^{-5}%)

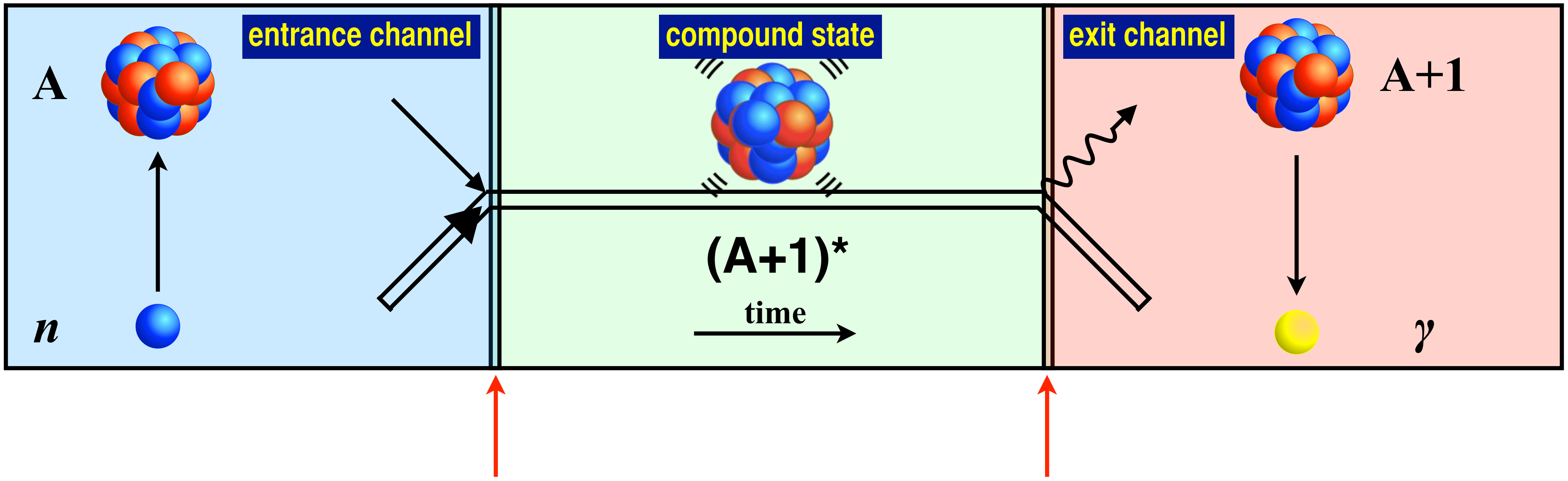


compound nuclear spin | orbital | n spin | target spin

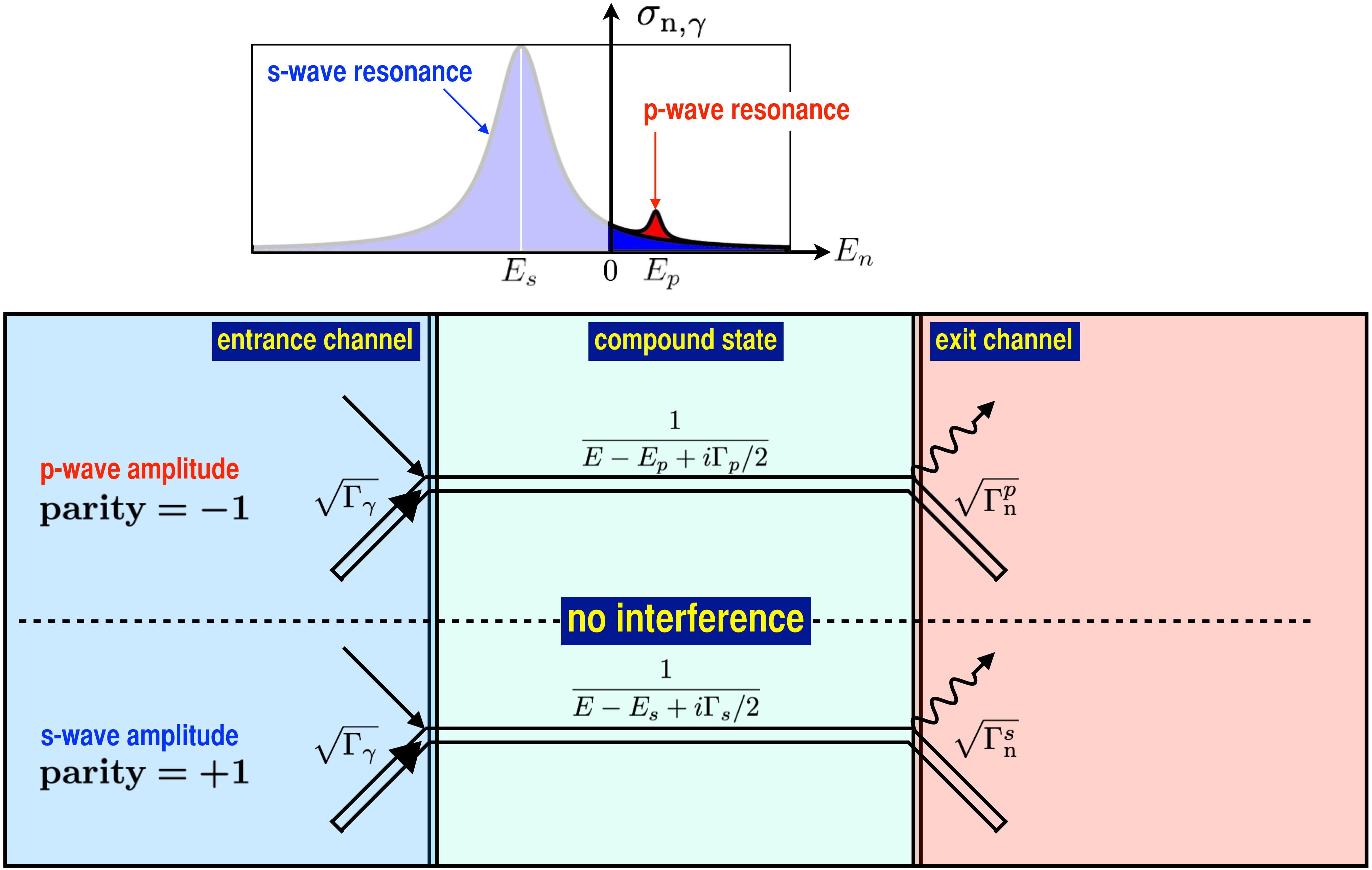
$$J = \underbrace{l + s}_{j} + I$$

j n total spin

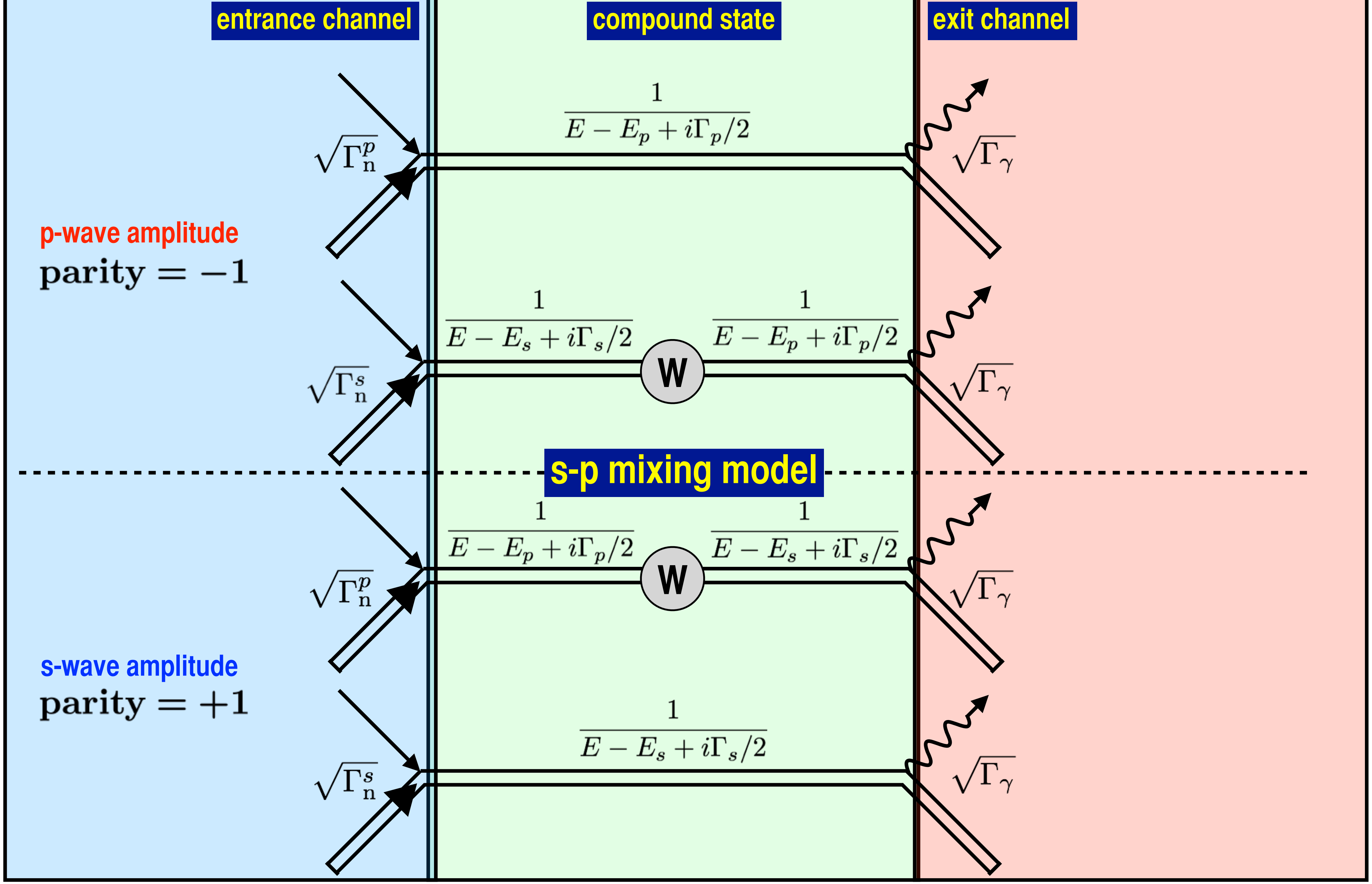




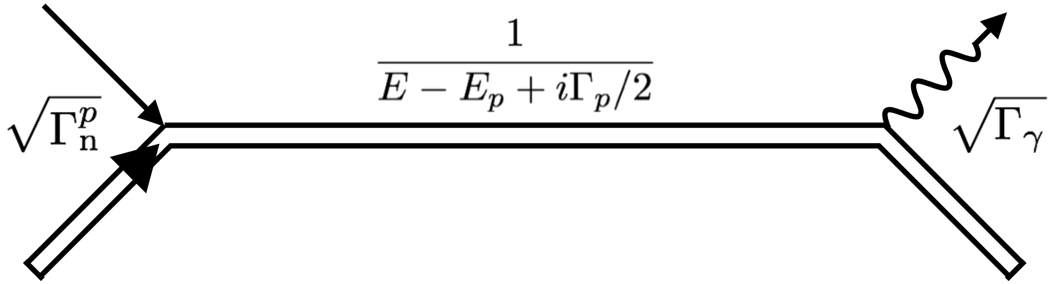
$$\sqrt{\Gamma_{\mathrm{n}}}\frac{1}{E - E_0 + i\Gamma/2}\sqrt{\Gamma_\gamma}$$



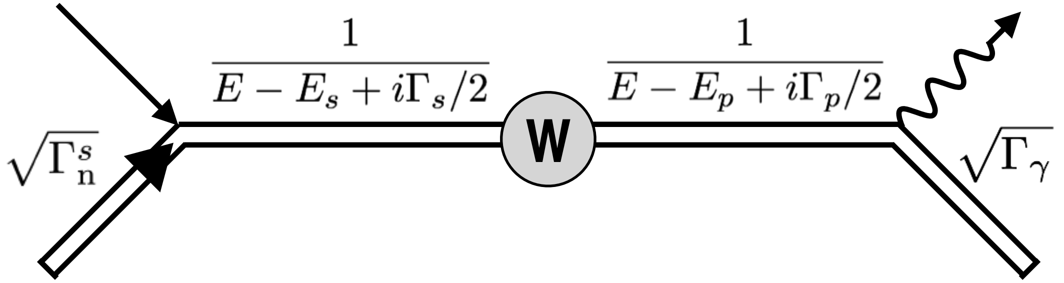
$\sigma_{\mathrm{n},\gamma}$
s-wave resonance
p-wave resonance
E_s
0
E_p
E_n
entrance channel
compound state
exit channel
p-wave amplitude
$\text{parity} = -1$
$\sqrt{\Gamma_\gamma}$
$\frac{1}{E - E_p + i\Gamma_p/2}$
$\sqrt{\Gamma_{\mathrm{n}}^{p}}$
no interference
s-wave amplitude
$\text{parity} = +1$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


entrance channel
compound state
exit channel
p-wave amplitude
$\mathrm{parity} = -1$
$\sqrt{\Gamma_n^p}$
$\frac{1}{E - E_p + i\Gamma_p/2}$
$\sqrt{\Gamma_\gamma}$
$\sqrt{\Gamma_n^s}$
$\frac{1}{E - E_s + i\Gamma_s/2}$
W
$\frac{1}{E - E_p + i\Gamma_p/2}$
$\sqrt{\Gamma_\gamma}$
s-p mixing model
$\sqrt{\Gamma_n^p}$
$\frac{1}{E - E_p + i\Gamma_p/2}$
W
$\frac{1}{E - E_s + i\Gamma_s/2}$
$\sqrt{\Gamma_\gamma}$
s-wave amplitude
$\mathrm{parity} = +1$
$\sqrt{\Gamma_n^s}$
$\frac{1}{E - E_s + i\Gamma_s/2}$
$\sqrt{\Gamma_\gamma}$

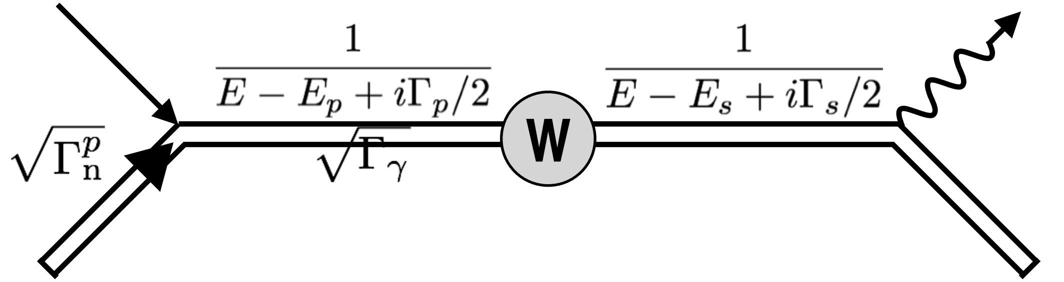
$$V_1 = \sqrt{\Gamma^{\mathrm{n}}_{\mathrm{s}}}\frac{1}{E - E_{\mathrm{s}} + i\Gamma_{\mathrm{s}}/2}\sqrt{\Gamma^{\gamma}_{\mathrm{s}}}$$



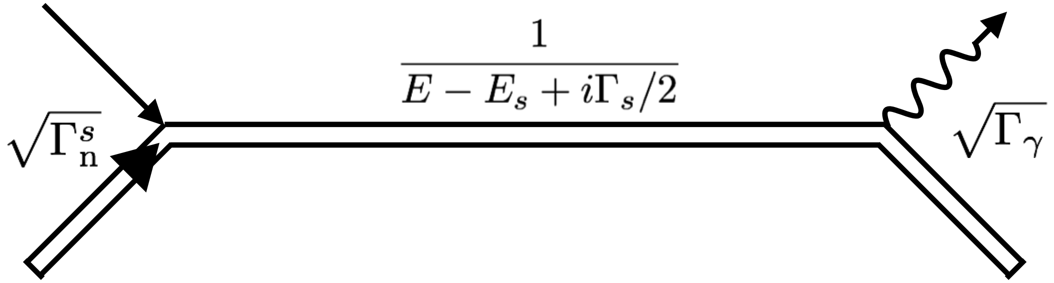
$$V_3 = \sqrt{\Gamma^{\mathrm{n}}_{\mathrm{s}}}\frac{1}{E - E_{\mathrm{s}} + i\Gamma_{\mathrm{s}}/2}W\frac{1}{E - E_{\mathrm{p}} + i\Gamma_{\mathrm{p}}/2}\sqrt{\Gamma^{\gamma}_{\mathrm{p}}}$$



$$V_4 = \sqrt{\Gamma^{\mathrm{n}}_{\mathrm{p}\frac{1}{2}}}\frac{1}{E - E_{\mathrm{p}} + i\Gamma_{\mathrm{p}}/2}W\frac{1}{E - E_{\mathrm{s}} + i\Gamma_{\mathrm{s}}/2}\sqrt{\Gamma^{\gamma}_{\mathrm{s}}}$$



$$V_2 = \sqrt{\Gamma^{\mathrm{n}}_{\mathrm{p}}}\frac{1}{E - E_{\mathrm{p}} + i\Gamma_{\mathrm{p}}/2}\sqrt{\Gamma^{\gamma}_{\mathrm{p}}}$$



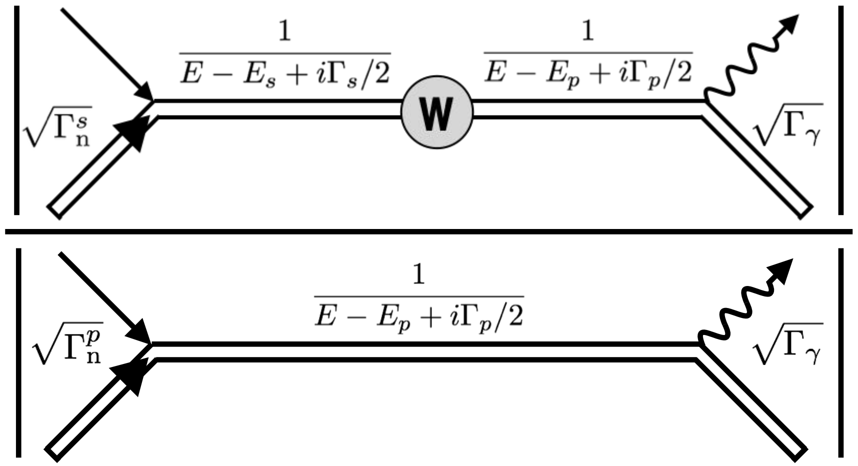
Crude Estimation of P-violation Enhancement

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

Parity-conserving

Parity-non-conserving

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

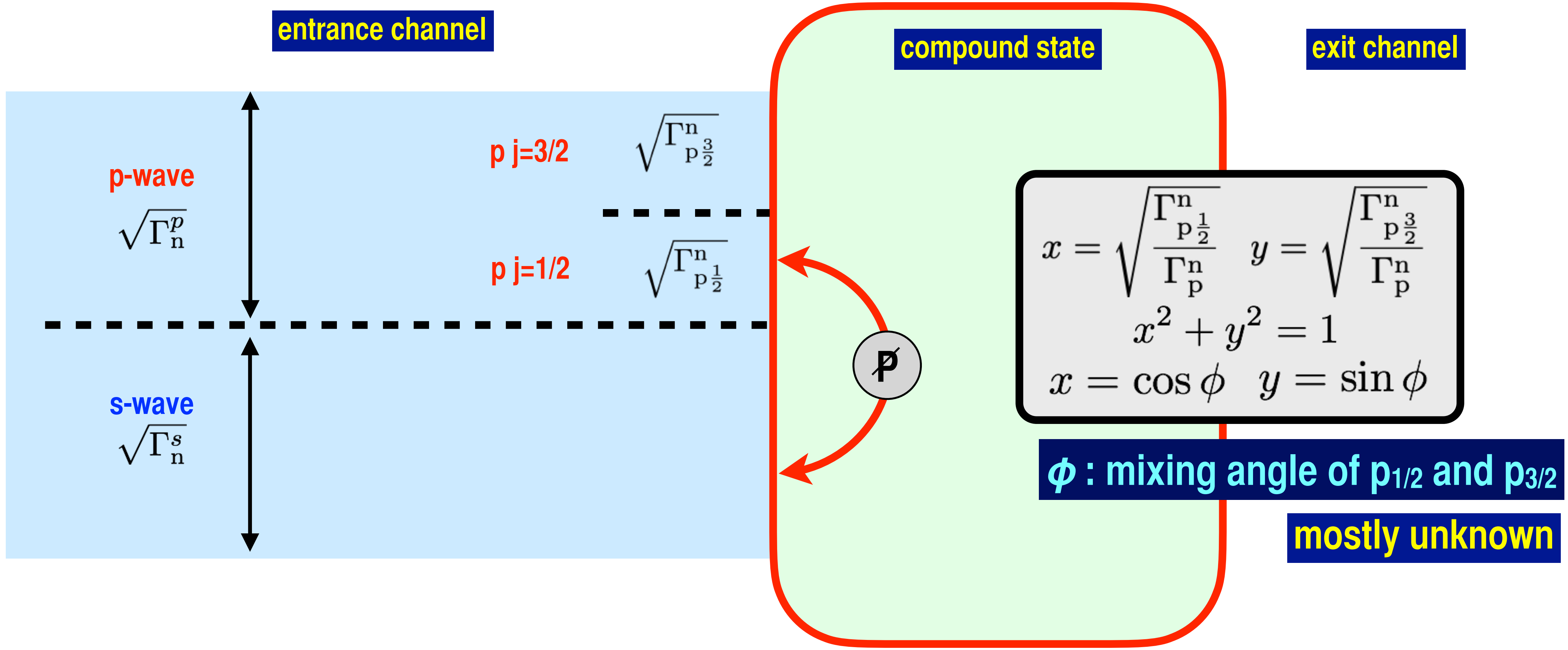


$$= 2\frac{\left|\sqrt{\Gamma_\gamma^p}\frac{1}{E - E_p + i\Gamma_p/2} W \frac{1}{E - E_s + i\Gamma_s/2}\sqrt{\Gamma_{\mathrm{n}}^s}\right|}{\left|\sqrt{\Gamma_\gamma^p}\frac{1}{E - E_p + i\Gamma_p/2}\sqrt{\Gamma_{\mathrm{n}}^p}\right|} \underset{E=E_p}{\sim} 2\frac{W}{|E_p - E_s|}\sqrt{\frac{\Gamma_{\mathrm{n}}^s}{\Gamma_{\mathrm{n}}^p}}$$

dynamical enhancement 10^2-10^3

kinematical enhancement 10^3

Details of Kinematical Enhancement and Entrance Channel Boundary



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

Neutron-total-spin representation and Channel-spin representation

compound nuclear spin　orbital　n spin　nuclear spin

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

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

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

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

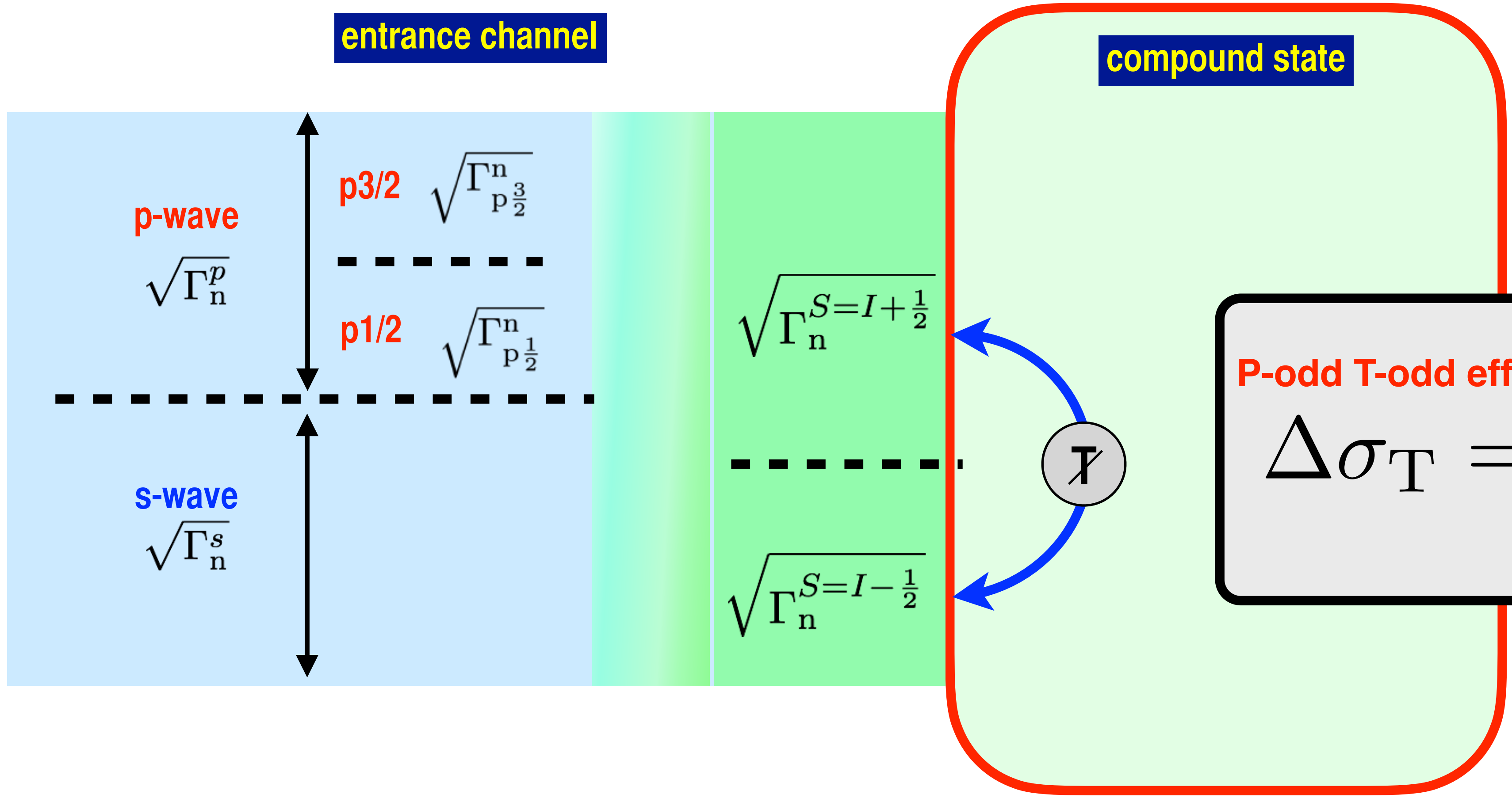
$$z_j = \begin{cases} x & (j=1/2) \\ y & (j=3/2) \end{cases}, \quad \tilde{z}_S = \begin{cases} x_S & (S=I-1/2) \\ y_S & (S=I+1/2) \end{cases} \quad \tilde{z}_S = \sum_j (-1)^{l+I+j+S}\sqrt{(2j+1)(2S+1)} \begin{Bmatrix} l & s & j \\ I & J & S \end{Bmatrix} z_j$$

s-p mixing ⇔ channel-spin mixing

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

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

Channel-spin mixing ➡ Kinematical Enhancement of T-violation



V. P. Gudkov. *Phys. Rep.*, 212:77, 1992.

P-odd T-odd effect

T-violating matrix element

P-odd effect

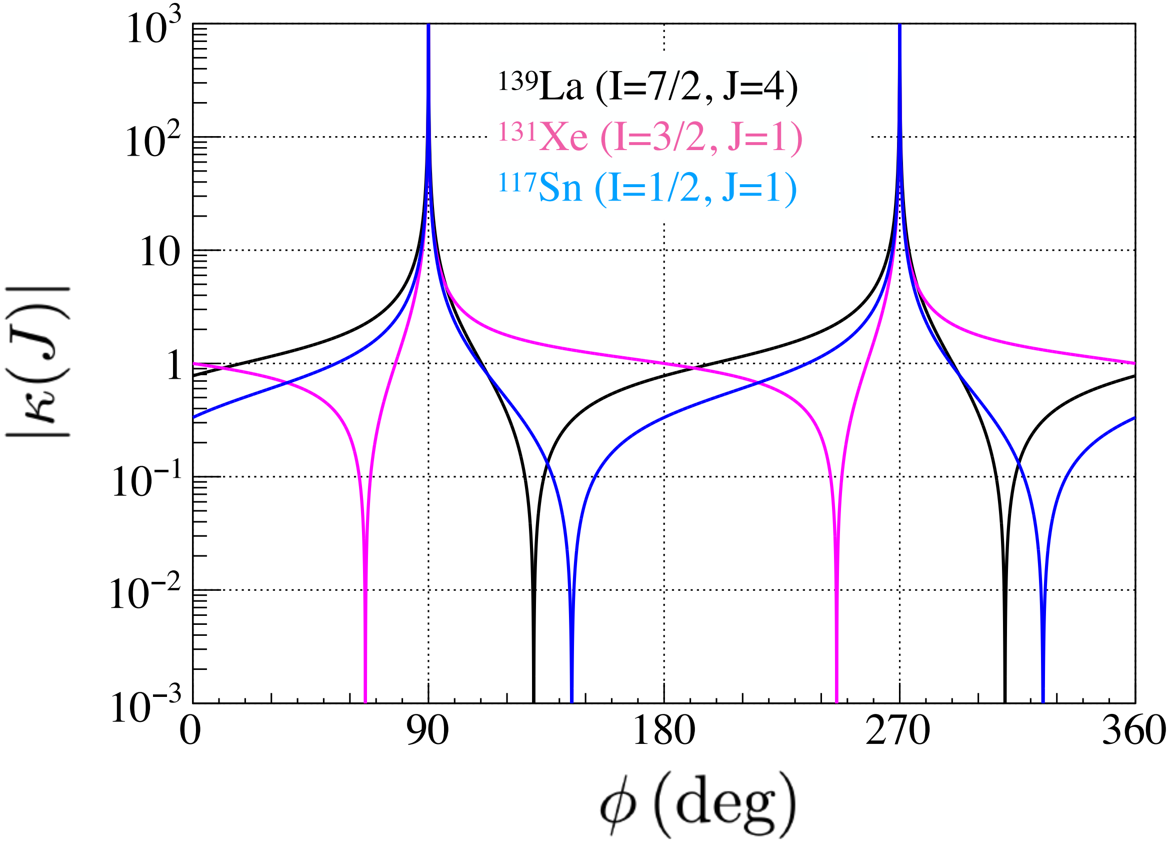
$$\Delta\sigma_{\mathrm{T}} = \boxed{\kappa(J)}\,\frac{W_{\mathrm{T}}}{W}\,\Delta\sigma_{\mathrm{P}}$$

P-violating matrix element

spin factor

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

Conversion factor of P-violation Enhancement and T-violation Enhancement



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

Measurement of (n,γ) Correlation Terms

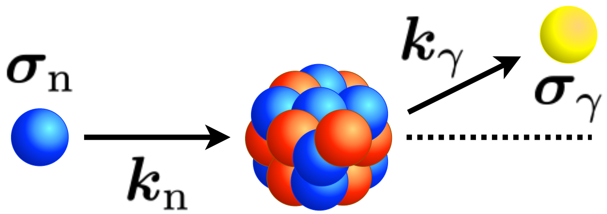
for the determination of ϕ mixing angle of $p_{1/2}$ and $p_{3/2}$ partial amplitudes which leads to the estimation of T-violation enhancement

for the refinement of resonance parameters including negative resonances

for the suggestion of J compound nuclear spin

(n,γ) spin-angular correlation terms with s- and p-waves

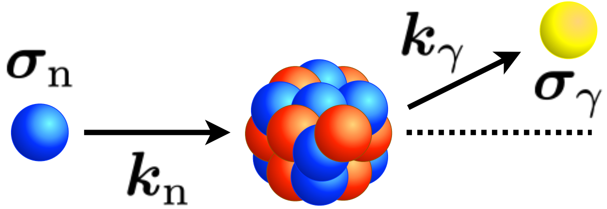
Flambaum, Nucl. Phys. A435 (1985) 352



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

Flambaum, Nucl. Phys. A435 (1985) 352

(n,γ) spin-angular correlation terms with s- and p-waves



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

$$\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}$$

(n,γ) spin-angular correlation terms with s- and p-waves

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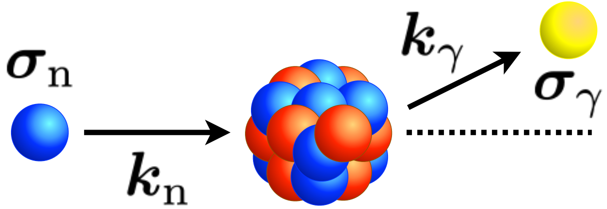


$$
\begin{aligned}
\frac{\mathrm{d}\sigma_{\mathrm{n}\gamma_f}}{\mathrm{d}\Omega_\gamma} &= \frac{1}{2}\Bigg(a_0 + a_1\hat{\boldsymbol{k}}_{\rm n}\cdot\hat{\boldsymbol{k}}_\gamma + a_2\boldsymbol{\sigma}_{\rm n}\cdot(\hat{\boldsymbol{k}}_{\rm n}\times\hat{\boldsymbol{k}}_\gamma) + a_3\left((\hat{\boldsymbol{k}}_{\rm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

$$
\begin{aligned}
a_0 &= \textstyle\sum_{J_{\rm s}} |V_1(J_{\rm s})|^2 + \sum_{J_{\rm s},j} |V_2(J_{\rm p}j)|^2\\
a_1 &= 2\mathrm{Re}\textstyle\sum_{J_{\rm s},J_{\rm p},j} V_1(J_{\rm s})V_2^*(J_{\rm p}j)P(J_{\rm s}J_{\rm p}\frac{1}{2}j1IF)\\
a_2 &= -2\mathrm{Im}\textstyle\sum_{J_{\rm s},J_{\rm p},j} V_1(J_{\rm s})V_2^*(J_{\rm p}j)\beta_j P(J_{\rm s}J_{\rm p}\frac{1}{2}j1IF)\\
a_3 &= \mathrm{Re}\textstyle\sum_{J_{\rm s},j,J'_{\rm p},j'} V_2(J_{\rm p}j)V_2^*(J'_{\rm p}j')P(J_{\rm p}J'_{\rm p}jj'2IF)\\
a_4 &= -\mathrm{Im}\textstyle\sum_{J_{\rm s},j,J'_{\rm p},j'} V_2(J_{\rm p}j)V_2^*(J'_{\rm p}j')P(J_{\rm p}J'_{\rm p}jj'2IF\\
a_5 &= -\mathrm{Re}\Big[\textstyle\sum_{J_{\rm s},J'_{\rm s}} V_1(J_{\rm s}j)V_1^*(J'_{\rm s}j')P(J_{\rm s}J'_{\rm s}\frac{1}{2}\frac{1}{2}1IF) +\\
a_6 &= -2\mathrm{Re}\textstyle\sum_{J_{\rm s}} V_1(J_{\rm s}j)V_2^*(J_{\rm p}=J_{\rm s},\frac{1}{2})\\
a_7 &= \mathrm{Re}\textstyle\sum_{J_{\rm s},J_{\rm p}} V_1(J_{\rm s})V_2^*(J_{\rm p}\frac{3}{2})P(J_{\rm s}J_{\rm p}\frac{1}{2}\frac{3}{2}2IF)\\
a_8 &= -\mathrm{Re}\textstyle\sum_{J_{\rm p},j,J'_{\rm p},j'} V_2(J_{\rm p}j)V_2^*(J'_{\rm p}j')P(J_{\rm p}J'_{\rm p}jj'1IF\\
a_9 &= -2\mathrm{Re}\Big[\textstyle\sum_{J_{\rm s},J'_{\rm s}} V_1(J_{\rm s}j)V_3^*(J'_{\rm s}j')P(J_{\rm s}J'_{\rm s}\frac{1}{2}\frac{1}{2}1IF)\\
a_{10} &= -2\mathrm{Re}\textstyle\sum_{J_{\rm s}} [V_2(J_{\rm p}=J_{\rm s},\frac{1}{2})V_3^*(J_{\rm s}) + V_1(J_{\rm s})V_4^*(\\
a_{11} &= 2\mathrm{Re}\textstyle\sum_{J_{\rm s},J_{\rm p}} [V_2(J_{\rm p}\frac{3}{2})V_3^*(J_{\rm s}) + V_1(J_{\rm s})V_4^*(J_{\rm p}\frac{3}{2})]\\
a_{12} &= -\mathrm{Re}\textstyle\sum_{J_{\rm s},j,J'_{\rm p},j'} V_2(J_{\rm p}j)V_4^*(J'_{\rm p}j')P(J_{\rm p}J'_{\rm p}jj'1IF\\
a_{13} &= 2\mathrm{Re}\Big[\textstyle\sum_{J_{\rm s}} V_1(J_{\rm s})V_3^*(J_{\rm s}) + \sum_{J_{\rm p}j} V_2(J_{\rm p}j)V_4^*(J_{\rm p}\\
a_{14} &= 2\mathrm{Re}\textstyle\sum_{J_{\rm s}J_{\rm p}j} [V_2(J_{\rm p}j)V_3^*(J_{\rm s}) + V_1(J_{\rm s})V_4^*(J_{\rm p}j)]\\
a_{15} &= 2\mathrm{Im}\textstyle\sum_{J_{\rm s}J_{\rm p}j} [V_2(J_{\rm p}j)V_3^*(J_{\rm s}) - V_1(J_{\rm s})V_4^*(J_{\rm p}j)]\\
a_{16} &= 2\mathrm{Re}\textstyle\sum_{J_{\rm p},j,J'_{\rm p},j'} V_2(J_{\rm p}j)V_4^*(J'_{\rm p}j')P(J_{\rm p}J'_{\rm p}jj'2IF\\
a_{17} &= -2\mathrm{Im}\textstyle\sum_{J_{\rm p},j,J'_{\rm p},j'} V_2(J_{\rm p}j)V_4^*(J'_{\rm p}j')P(J_{\rm p}J'_{\rm p}jj'2IF)6\sqrt{5}\begin{Bmatrix} 2 & 1 & 1\\ 1 & \frac{1}{2} & \frac{1}{2}\\ 2 & j & j' \end{Bmatrix}
\end{aligned}
$$

target spin | compound nuclear spin | resonance energy | resonance width | neutron width | gamma width | final state spin

$$
\begin{array}{lccccccc}
|s\rangle & & J_s & E_s & \Gamma_s & \Gamma_s^n & \Gamma_s^\gamma & \\
 & I & & & & & & F\\
|p\rangle & & J_p & E_p & \Gamma_p & \Gamma_p^n & \Gamma_p^\gamma &
\end{array}
$$

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

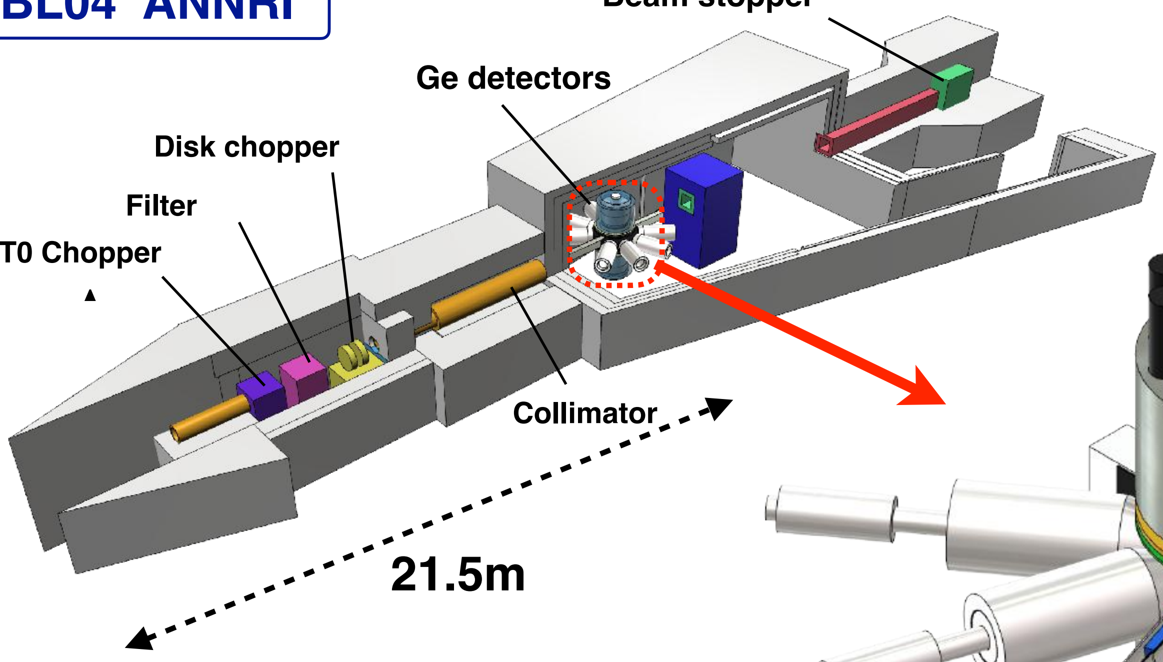
$|p_{1/2}\rangle$ $\Gamma^n_{p,1/2}$ $\quad x^2 = \dfrac{\Gamma^n_{p,1/2}}{\Gamma^n_p}$ $\quad x = \cos\phi$

$|p_{3/2}\rangle$ $\Gamma^n_{p,3/2}$ $\quad y^2 = \dfrac{\Gamma^n_{p,3/2}}{\Gamma^n_p}$ $\quad y = \sin\phi$

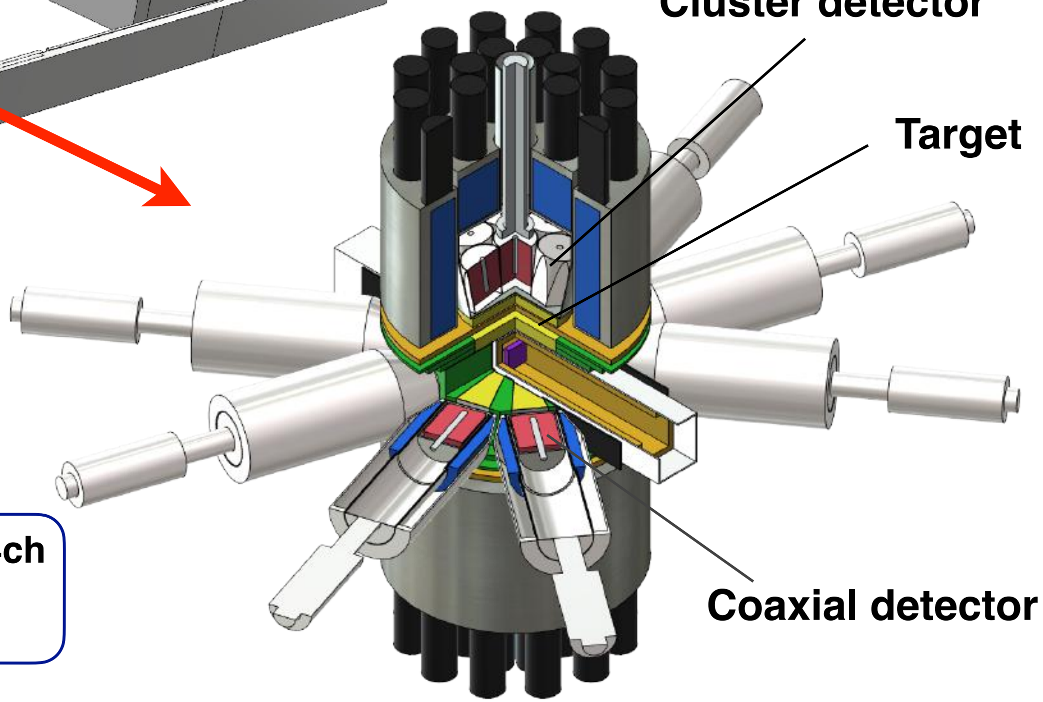
(n,γ) spin-angular correlation terms with s- and p-waves

The experiments to determine κ(J) is ongoing at ANNRI (Accurate Neutron-Nucleus Reaction measurement Instrument) beam line in J-PARC

BL04 ANNRI



Ge Detectors @ ANNRI



2 Cluster Detector (up·down) 7ch ×2 : 14ch
8 Coaxial Detector (side) 8ch
Total 22ch

a_1: angular distribution without polarization

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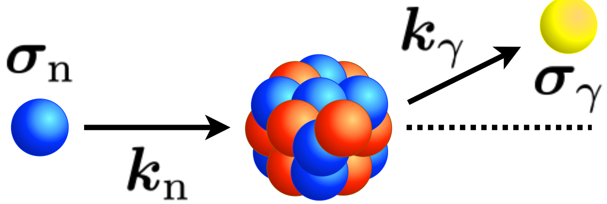
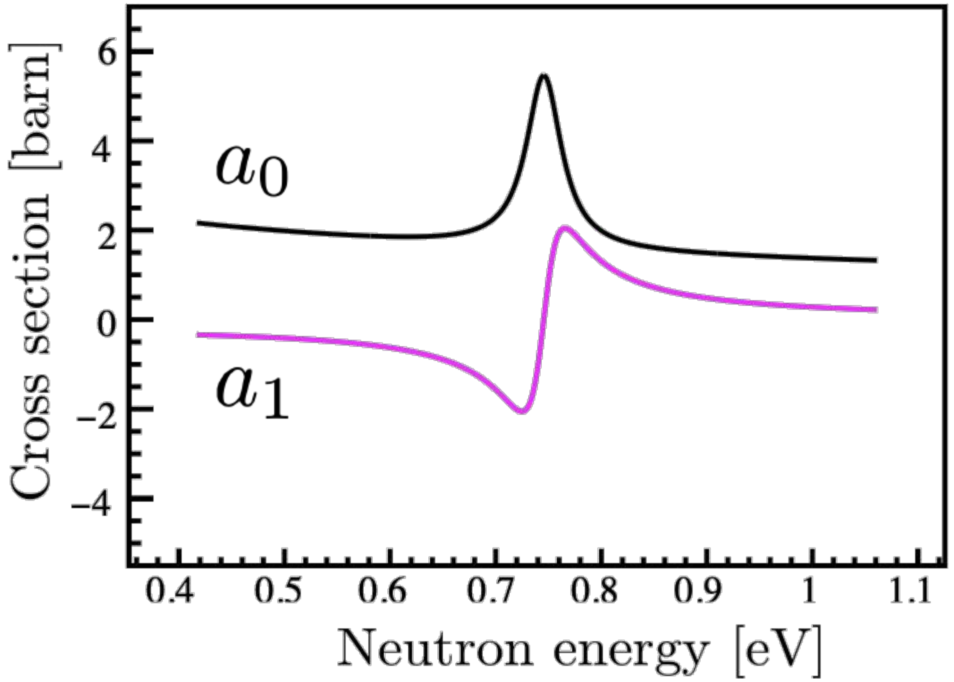


unpolarized case

$$\frac{d\sigma}{d\Omega} = \frac{1}{2}\left(a_0 + a_1 \boldsymbol{k}_n \cdot \boldsymbol{k}_\gamma + a_3\left((\boldsymbol{k}_n \cdot \boldsymbol{k}_r)^2 - \frac{1}{3}\right)\right)$$
$$= \frac{1}{2}\left(a_0 + a_1 \cos\theta_\gamma + a_3(\cos^2\theta_\gamma - \frac{1}{3})\right)$$

energy dependent angular distribution ⇔ angular-dependent distortion of resonance shape



$$a_0 = \sum_{J_\mathrm{s}} |V_1(J_\mathrm{s})|^2 + \sum_{J_\mathrm{s},j} |V_2(J_\mathrm{p}j)|^2$$

$$a_1 = 2\mathrm{Re}\sum_{J_\mathrm{s},J_\mathrm{p},j} V_1(J_\mathrm{s})V_2^*(J_\mathrm{p}j)P(J_\mathrm{s}J_\mathrm{p}\frac{1}{2}j1IF)$$

$$a_3 = \mathrm{Re}\sum_{J_\mathrm{s},j,J'_\mathrm{p},j'} V_2(J_\mathrm{p}j)V_2^*(J'_\mathrm{p}j')P(J_\mathrm{p}J'_\mathrm{p}jj'2IF)3\sqrt{10}\begin{Bmatrix} 2 & 1 & 1 \\ 0 & \frac{1}{2} & \frac{1}{2} \\ 2 & j & j' \end{Bmatrix}$$

$$V_1 = \frac{1}{2k_s}\sqrt{\frac{E_s}{E}}\frac{\sqrt{g\Gamma_s^n\Gamma_\gamma}}{E - E_s + i\Gamma_s/2} \qquad V_2(j{=}\frac{1}{2}) = V_2\cos\phi$$

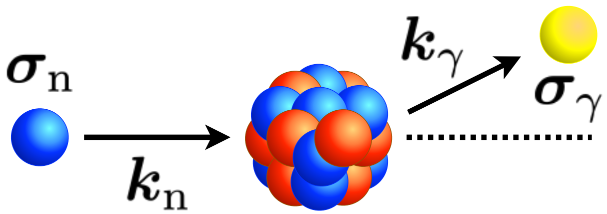
$$V_2(j) = \frac{1}{2k_p}\sqrt{\frac{E_p}{E}}\sqrt{\frac{\Gamma_{pj}^n}{\Gamma_p^n}}\frac{\sqrt{g\Gamma_p^n\Gamma_\gamma}}{E - E_p + i\Gamma_p/2} \qquad V_2(j{=}\frac{3}{2}) = V_2\sin\phi$$

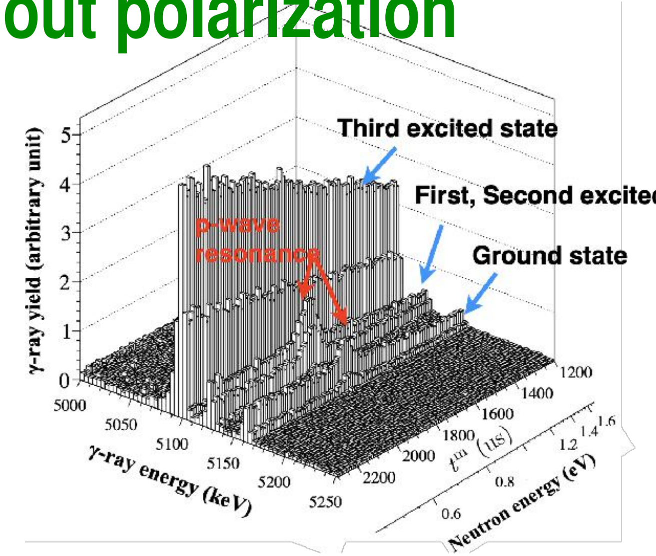
$$P(JJ'jj'kIF) = (-1)^{J+J'+j'+I+F}\frac{3}{2}\sqrt{(2J+1)(2J'+1)(2j+1)(2j'+1)}\begin{Bmatrix} j & j & j' \\ I & J' & J \end{Bmatrix}\begin{Bmatrix} k & 1 & 1 \\ F & J & J' \end{Bmatrix}$$

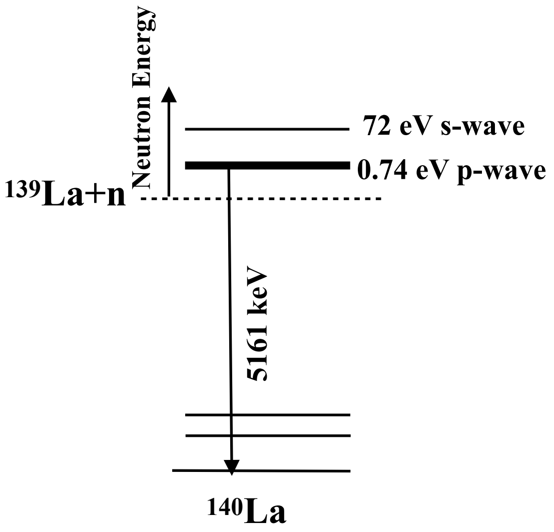
courtesy of T.Okudaira

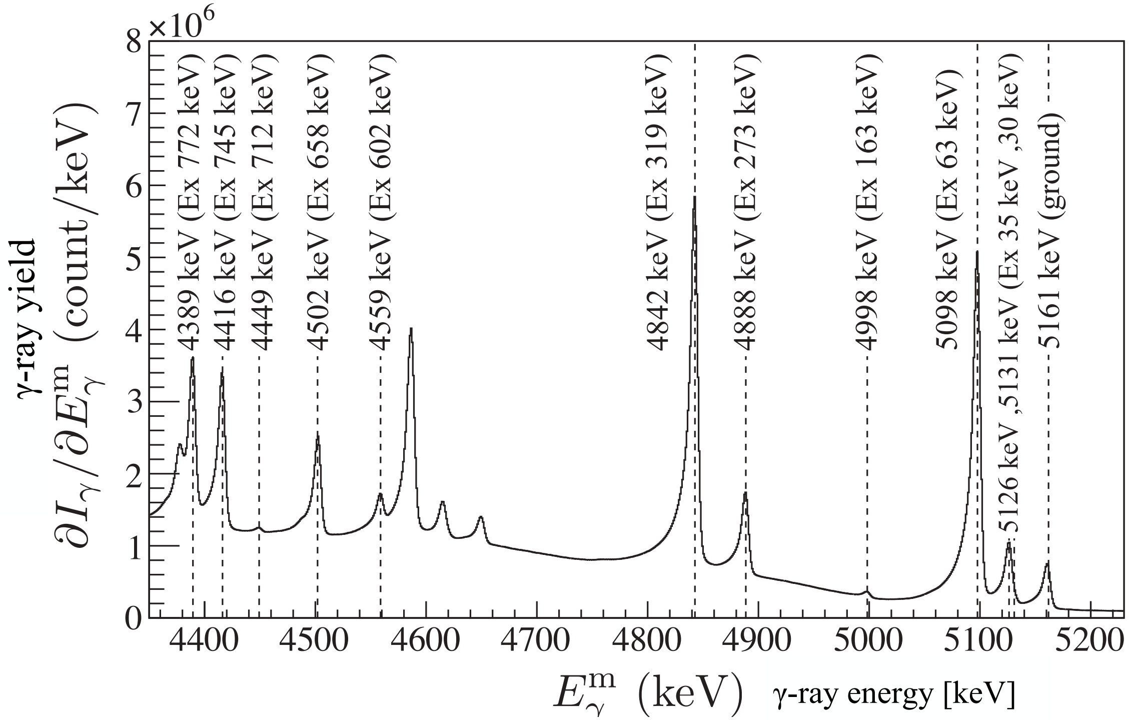
a1: angular distribution without polarization

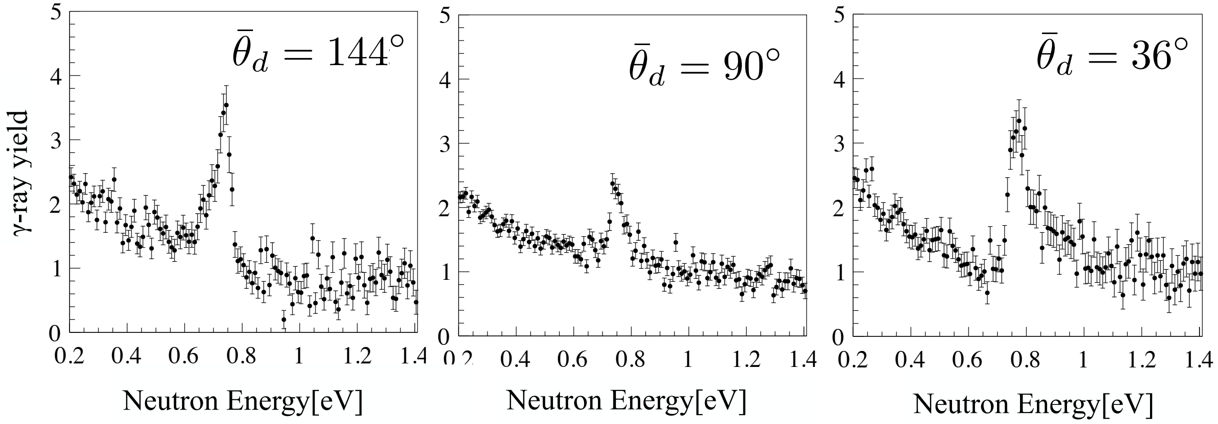
Okudaira, Phys. Rev. C93 (2018) 034622







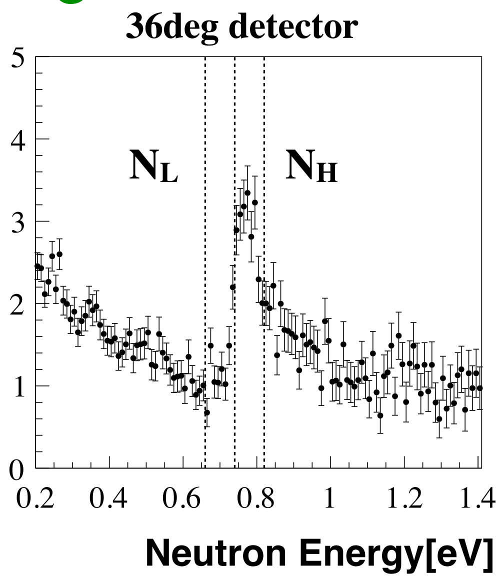




angular-dependent asymmetric resonance shape

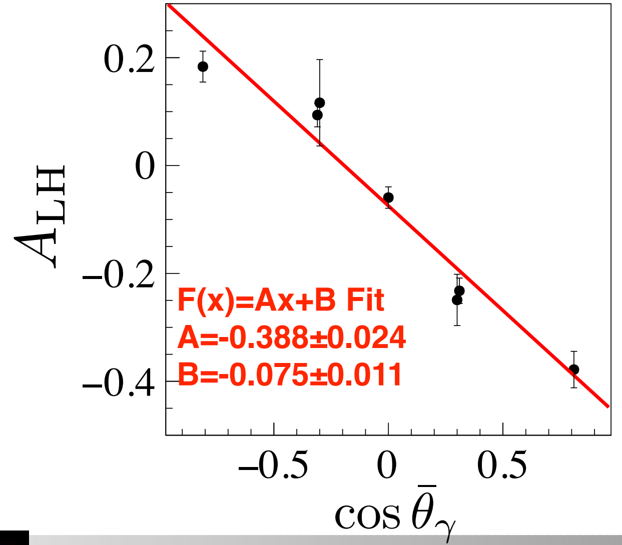
a_1: angular distribution without polarization

Okudaira, Phys. Rev. C93 (2018) 034622



$$A_{LH} = \frac{N_L - N_H}{N_L + N_H}.$$

angular-dependent asymmetric resonance shape
analyzed as
the angular distribution of low-high asymmetry



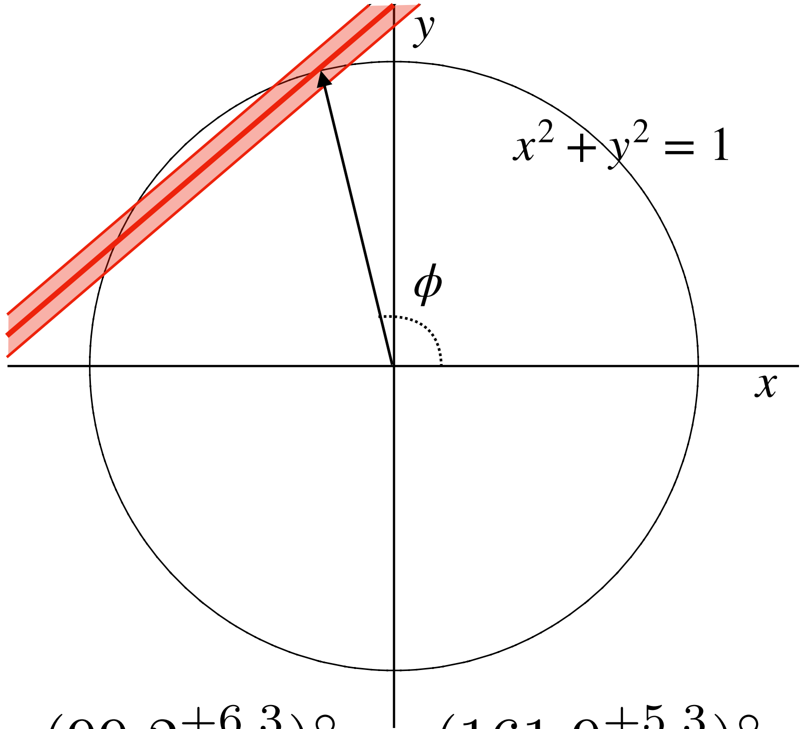
and compared with the s-p mixing model

$$\boxed{-0.388 \pm 0.024} = \boxed{0.295\cos\phi \quad - 0.345\sin\phi}$$

Experimental result

Theoretical calculation

to restrict the allowed region of the mixing angle



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

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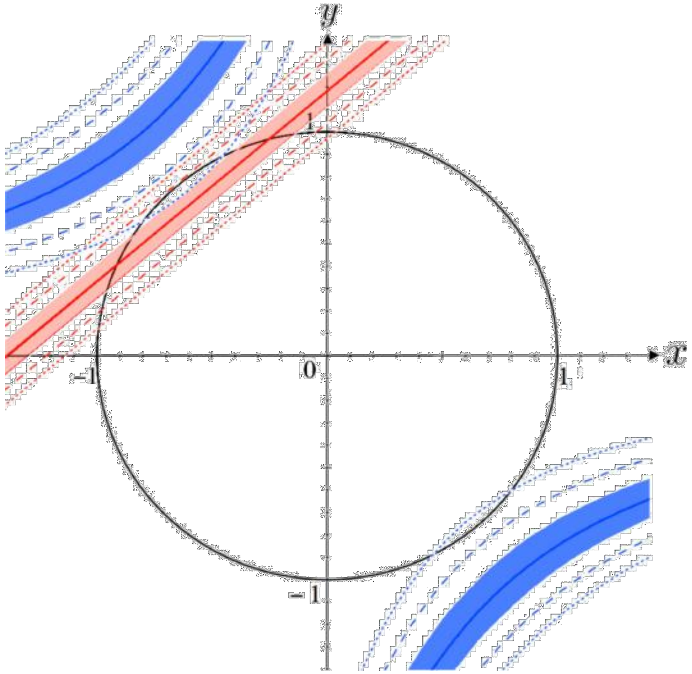
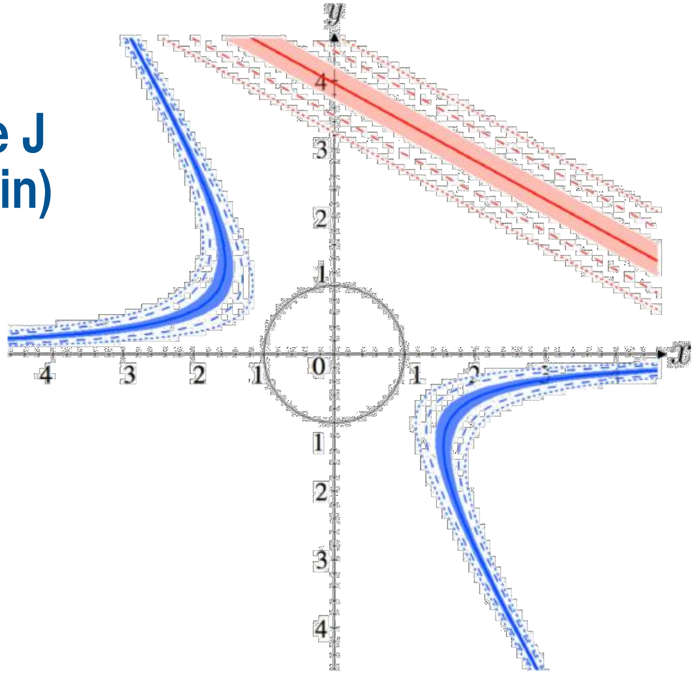
a_1: comparison of the cases for J=4 and J=3

$J_s = J_p = 4$



applicable to determine J
(compound nuclear spin)

$J_s = J_p = 3$

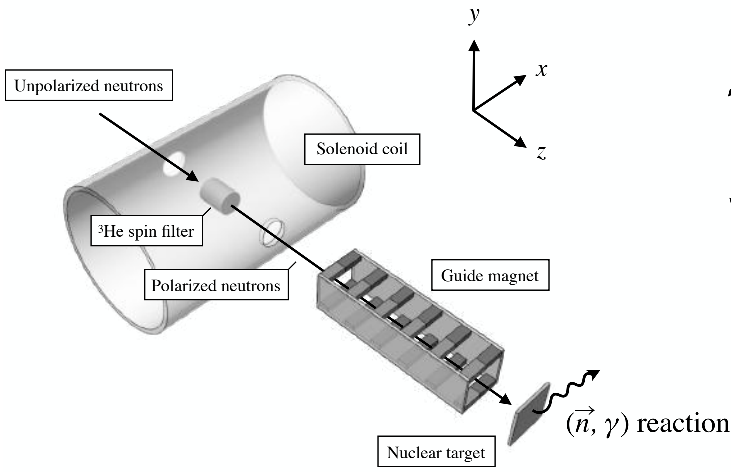


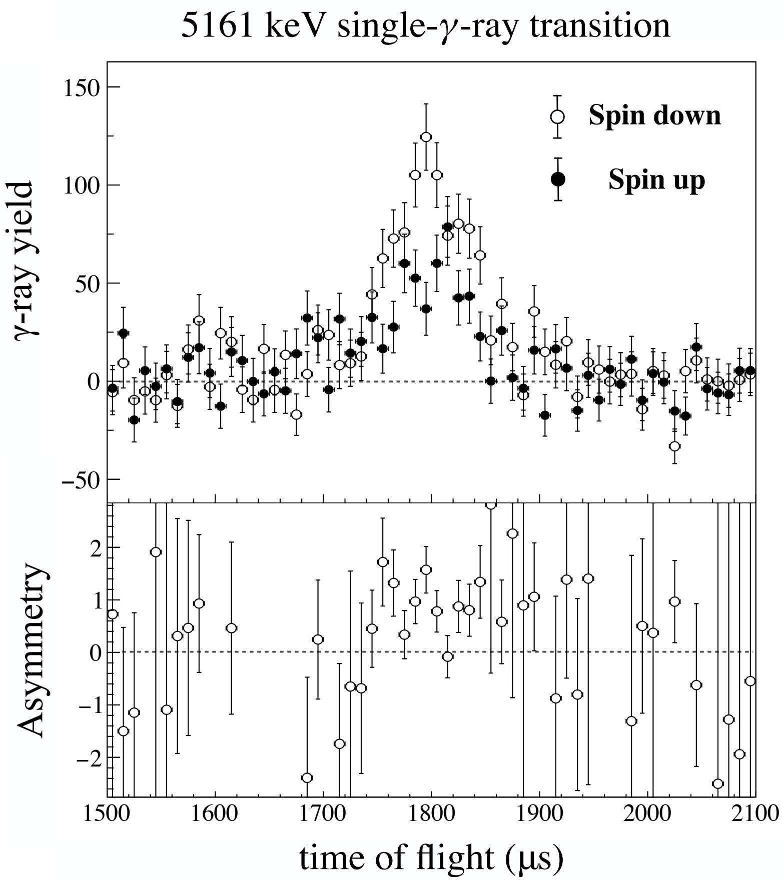
Another approach to detemrine compound nuclear spin

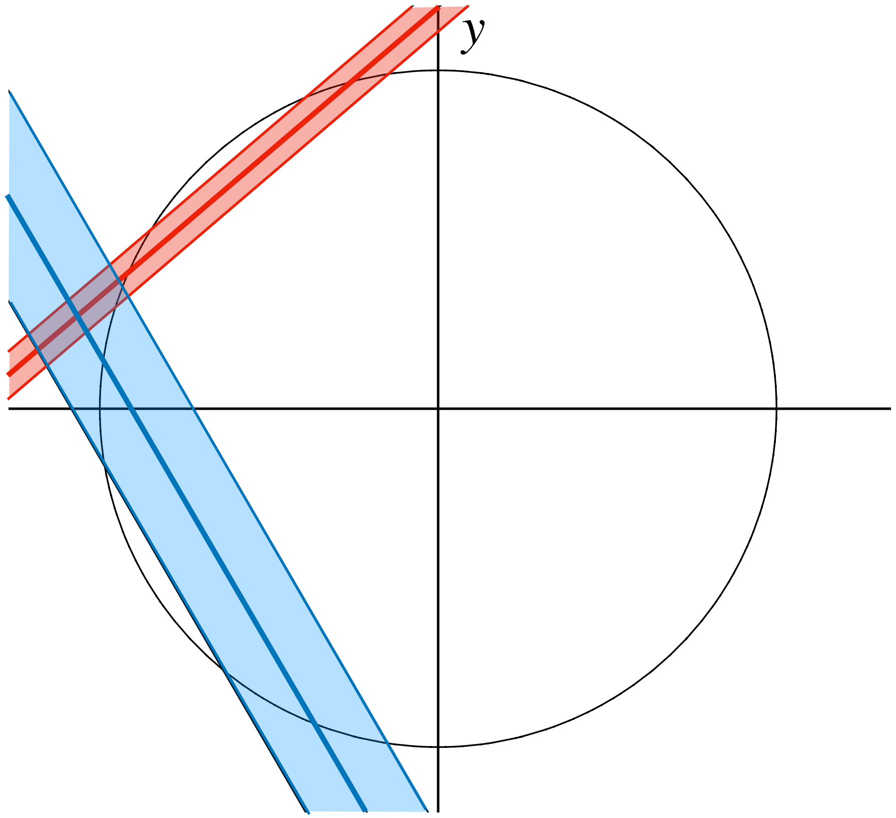
➡ **S.Kawamura's poster**
"Study of the Spin-Memory Effect with Low-energy Gamma-rays in ^{177}Hf(n,γ)^{178}Hf Reaction Measurement"

a_2: left-right asymmetry with transversely polarized neutron

Yamamoto, Phys. Rev. C97 (2020) 064624







$$\sigma_n \cdot (\hat{k}_n \times \hat{k}_\gamma)$$

γ

$$A_{\rm LR} = \frac{1}{P_n} \frac{N_{\rm up} - N_{\rm down}}{N_{\rm up} + N_{\rm down}}$$

$$-0.59 \pm 0.12 = 0.719 \cos\phi + 0.418 \sin\phi$$

Experimental result

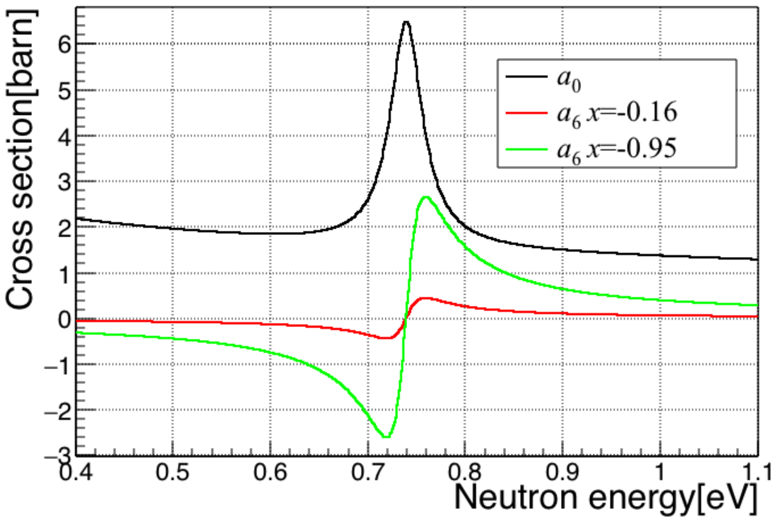
Theoretical calculation with s-p mixing

a_6,a_{13}: γ-ray polarization ($\lambda = \sigma_\gamma \cdot k_\gamma$)

Neutron energy dependent γ-ray polarization polarization

γ-ray polarization with polarized neutrons

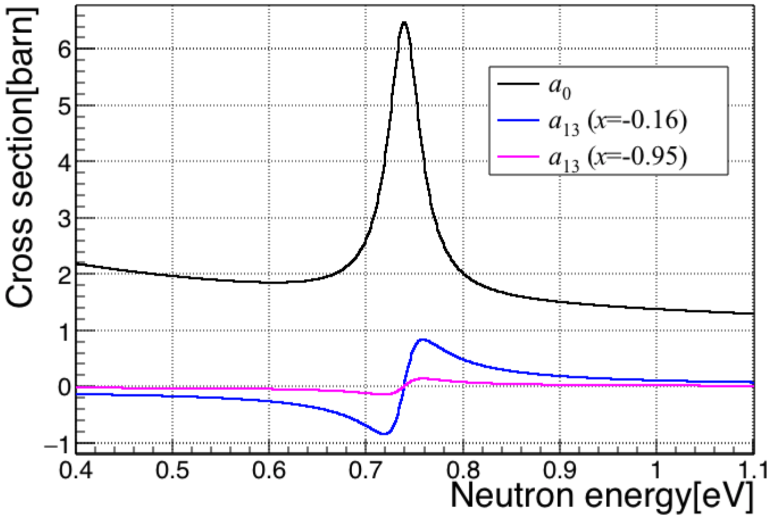
$$a_6 \lambda (\sigma_\mathrm{n} \cdot k_\mathrm{n})$$



P-even

γ-ray polarization with unpolarized neutrons

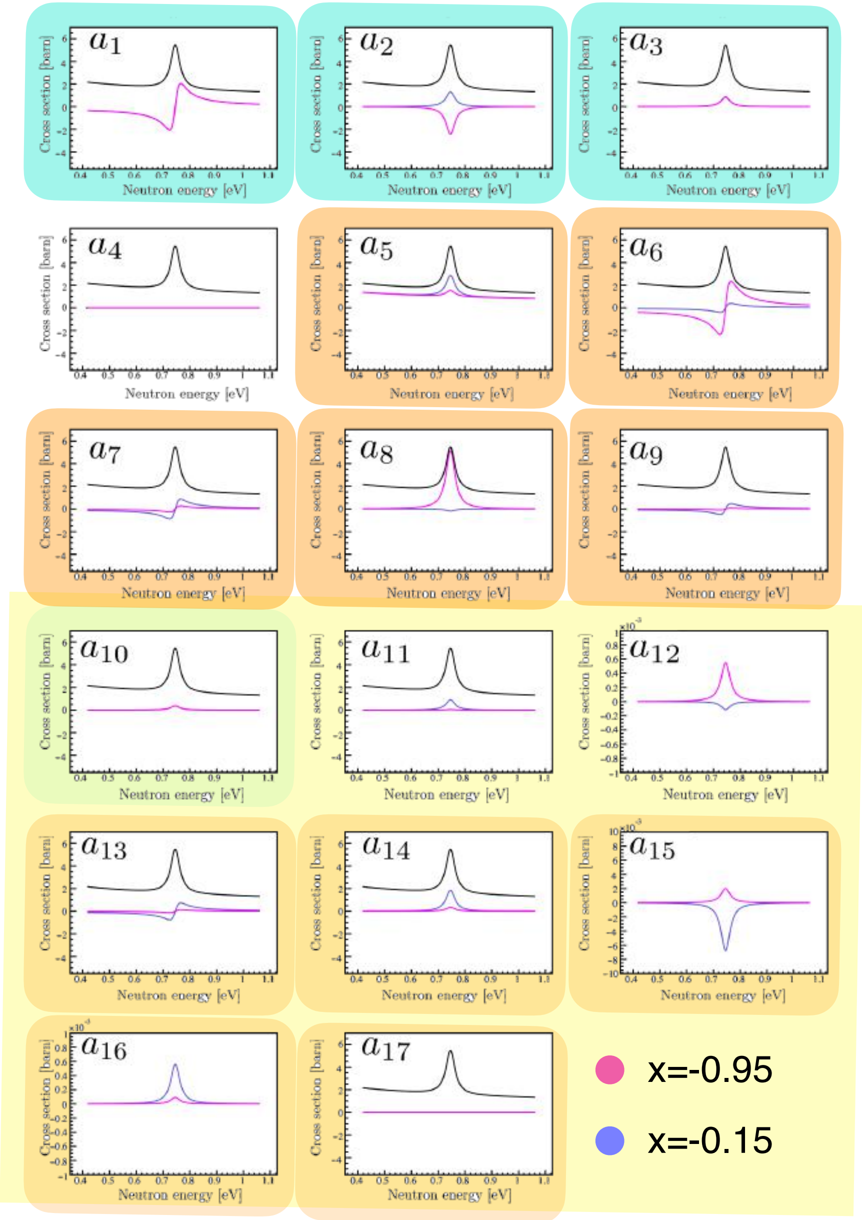
$$a_{13} \lambda$$



P-odd

➡ **S.Endo's poster**
"Circular polarization of γ-rays emitted from $^{32}S(n,\gamma)^{33}Sn$" reaction with polarized neutrons"

^{139}La+n spin-angular correlation terms for F=4



Measured

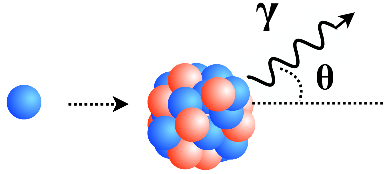
P-violating

γ-ray polarization

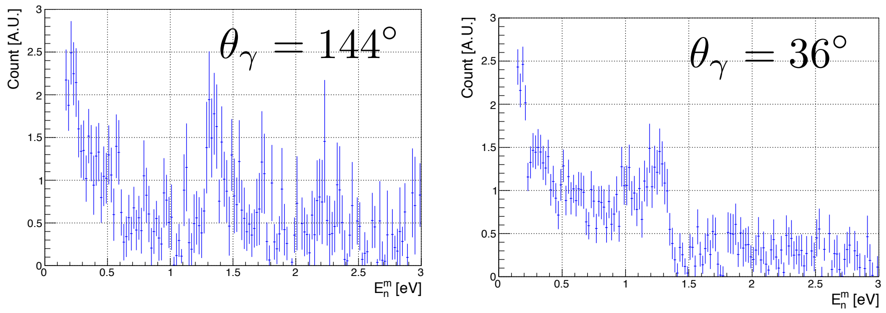
$$
\begin{aligned}
\frac{\mathrm{d}\sigma_{\mathrm{n}\gamma_f}}{\mathrm{d}\Omega_\gamma} = \; & \frac{1}{2}\Bigg(a_0 + a_1 \hat{\boldsymbol{k}}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\gamma + a_2 \boldsymbol{\sigma}_\mathrm{n}\cdot(\hat{\boldsymbol{k}}_\mathrm{n}\times\hat{\boldsymbol{k}}_\gamma) + a_3\left((\hat{\boldsymbol{k}}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_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

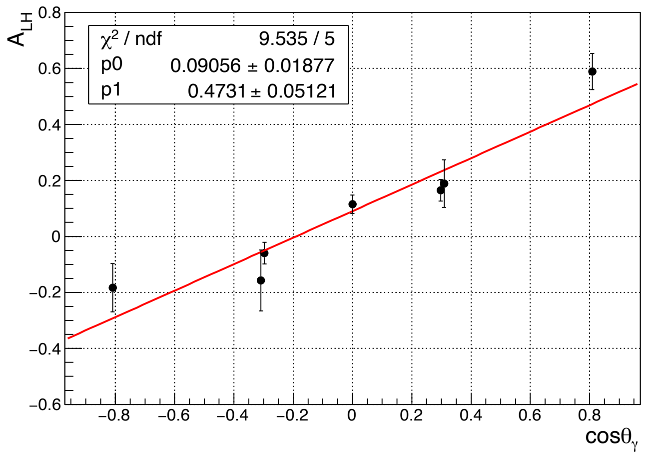
a_1: ^{117}Sn+n

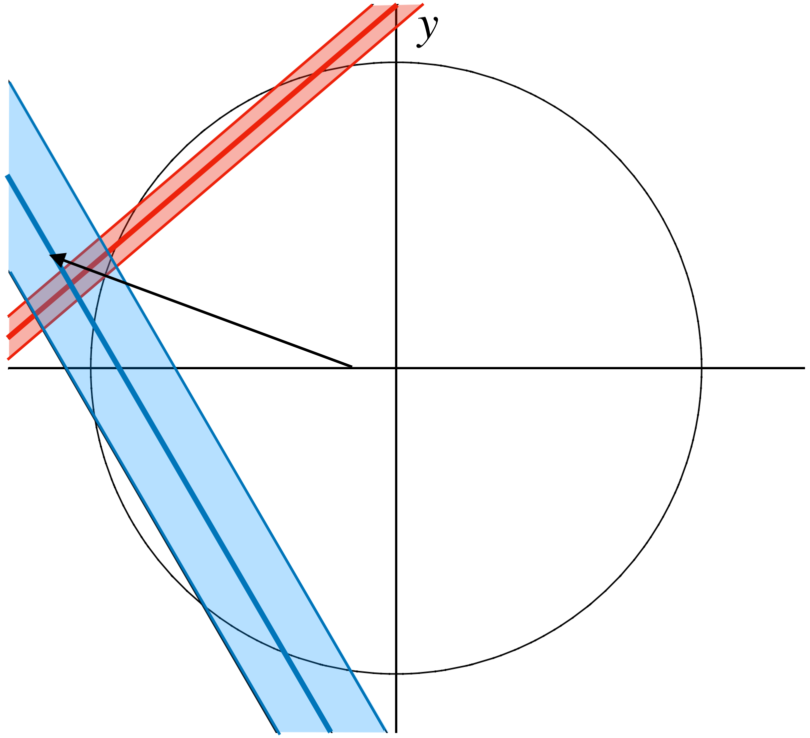
1.33eV p-wave



Koga, Phys. Rev. C105 (2021) 054615

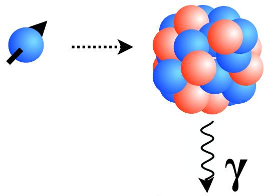




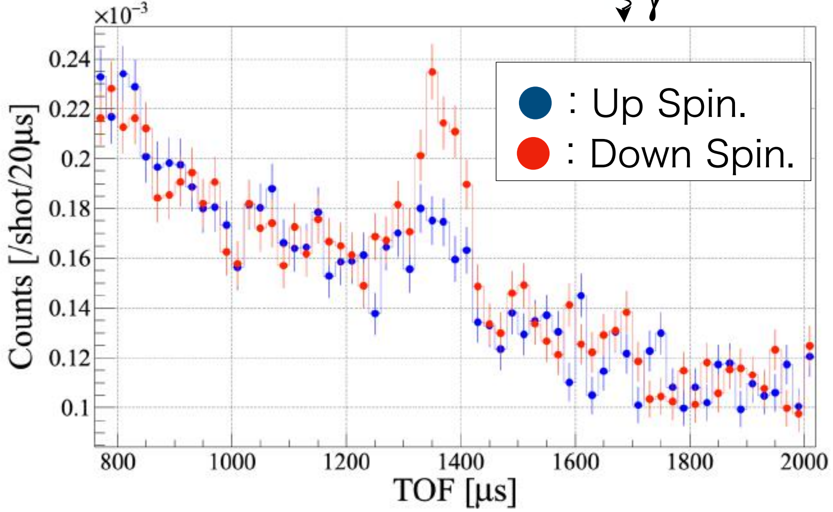


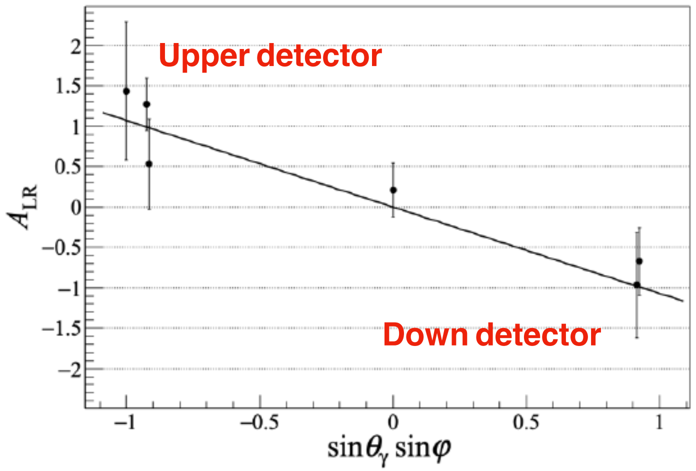
a_2: ^{117}Sn+n

1.33eV p-wave

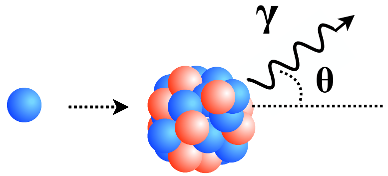


Endo, Phys. Rev. C106 (2022) 064601

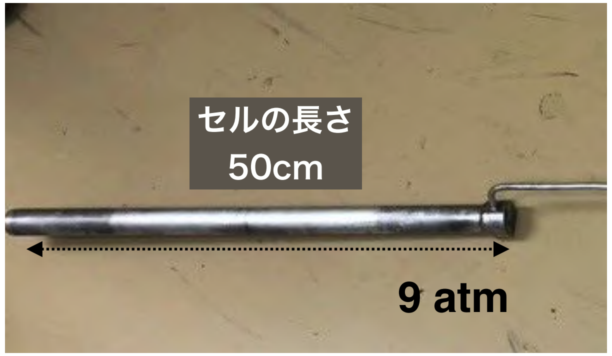




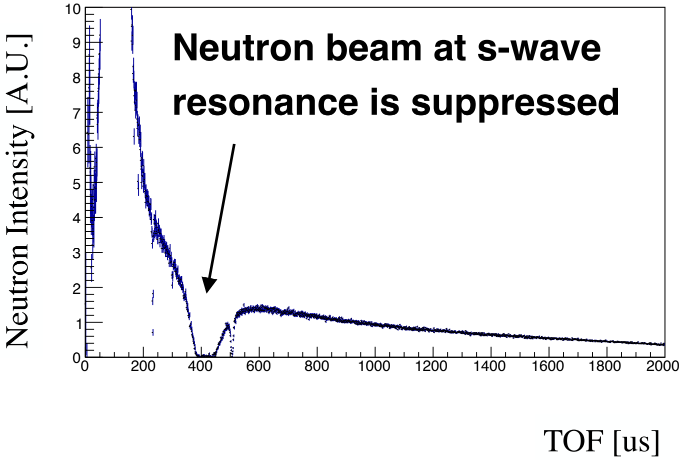
a_1: ^{131}Xe+n

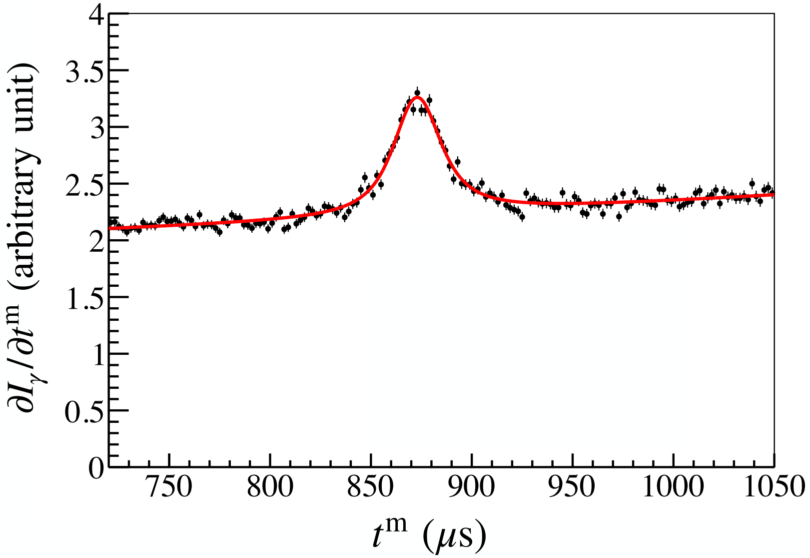


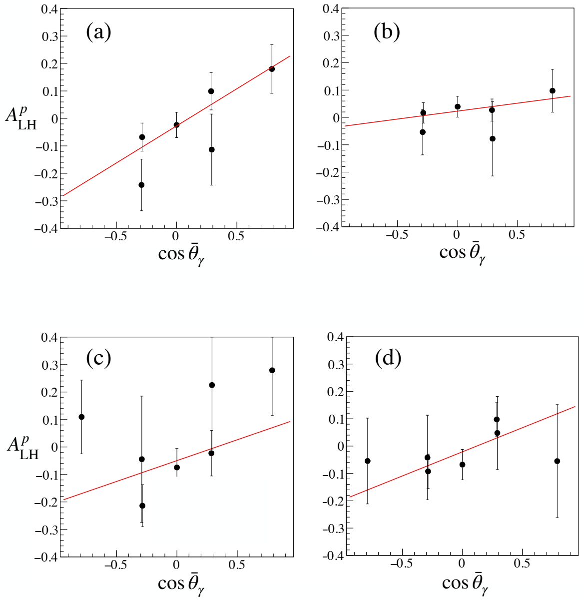
Self filter made by U.S. group



Neutron Beam spectrum at Xe target







NOPTREX

Neutron Optical Parity and Time Reversal EXperiment

Summary

^{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

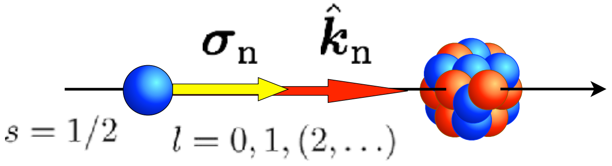
↓

New physics search with enhanced sensitivity to T-violation

APPENDIX

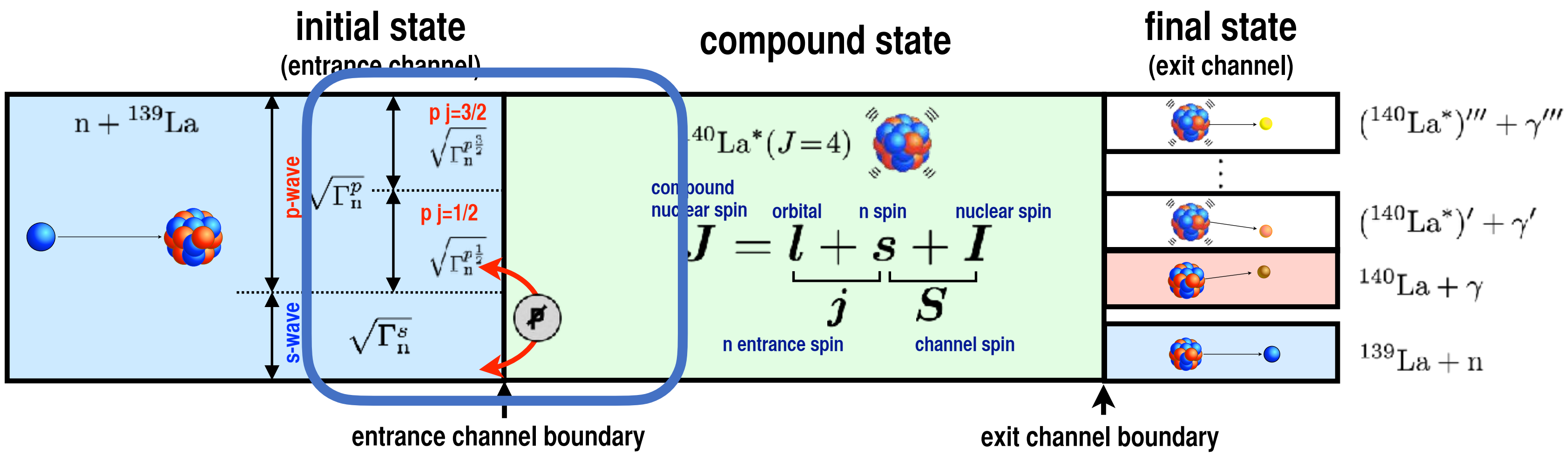
Enhancement Mechanism
(questions from us)

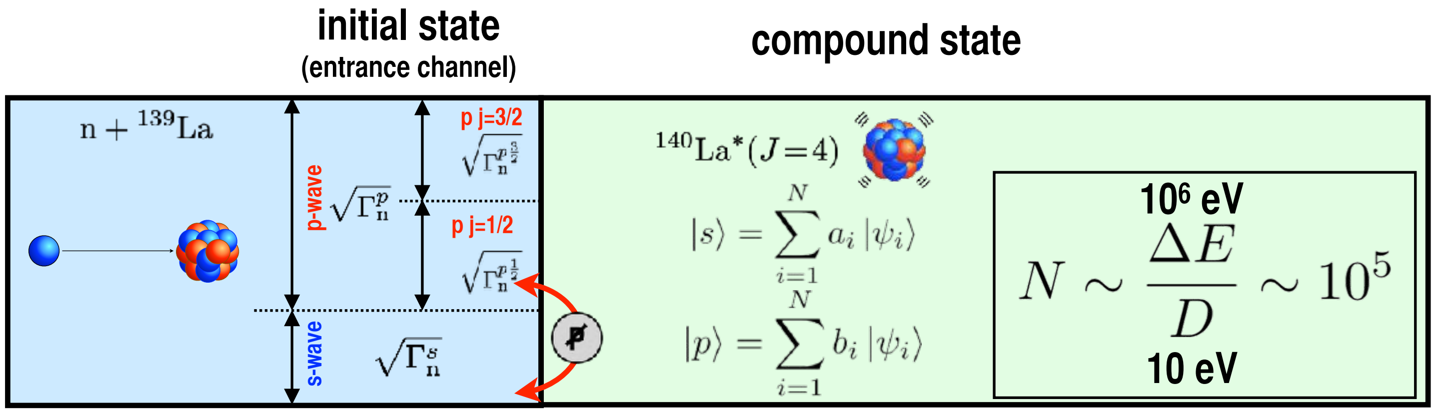
Enhancement Mechanism



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

10^{-7} for NN





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

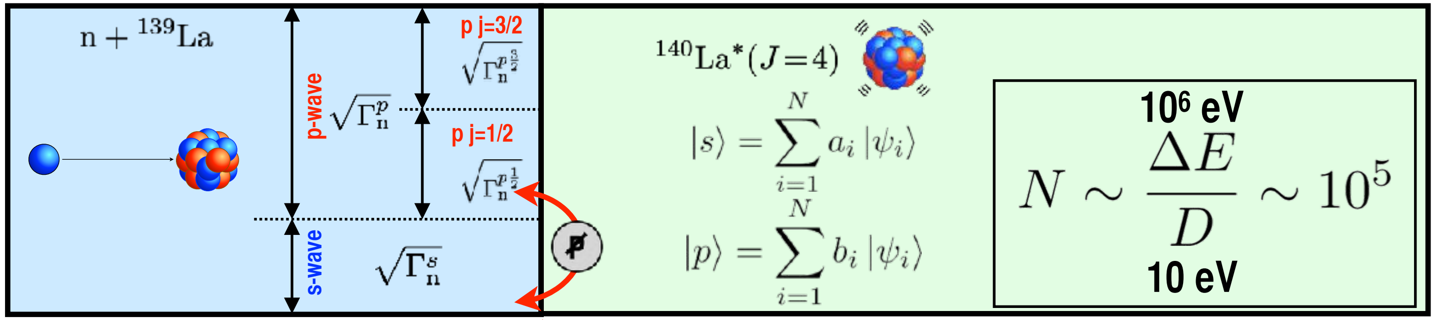
$$\sim \frac{1}{\sqrt{N}} \frac{1}{\sqrt{N}} \langle W \rangle \sqrt{N}$$

randomness of expansion coefficients

Enhancement Mechanism

initial state
(entrance channel)

compound state



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

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

randomness of expansion coefficients

compound state = strongly correlated (isolated) quantum system

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

direct connection between the entrance channel to the compound state

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

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

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

Friction? Where does it come from?

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

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

Microscopic assessment of the random matrix theory may be difficult.

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

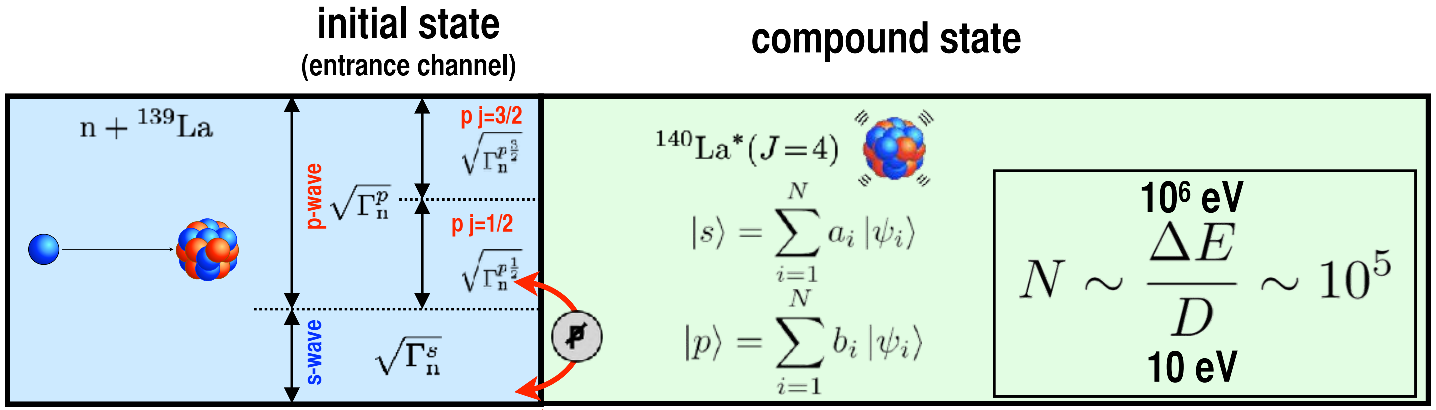
What kind of observables is appropriate to pick up deviations from the random matrix theory?

Enhancement Mechanism

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

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

randomness of expansion coefficients



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

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

deviation from the Porter-Thomas distribution

"Anomalous Fluctuations of s-Wave Reduced Neutron Widths of ^{192,194}Pt Resonances"
P.E.Koehler et al., Phys. Rev. Lett. 105 (2010) 072502

"Neutron Resonance Widths and the Porter-Thomas Distribution"
A.Volya, H.A.Weidenmuller, V.Zelevinsky, Phys. Rev. Lett. 115 (2015) 052501

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

Merci pour votre attention.