Symmetry Tests with Slow Neutrons

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Symmetry Tests with Slow Neutrons

spallation neutron sources

Spallation Neutron Source of Oak Ridge National Laboratory

Spallation Neutron Source of J-PARC

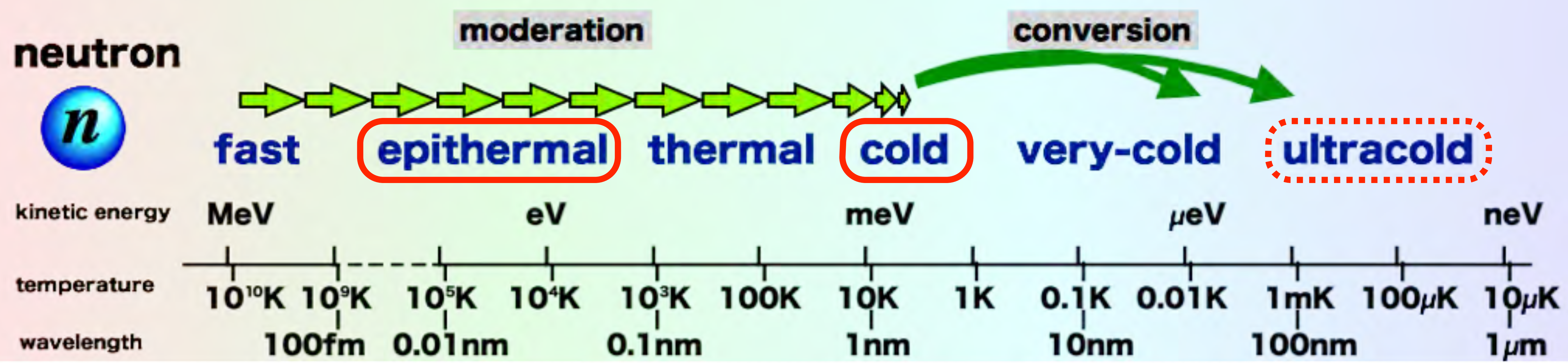
SINQ and Ultracold Neutron Source of Paul Scherrer Institute

Ultracold Neutron Source at TRIUMF

European Spallation Source at Lund

T-violation $\xleftrightarrow{\text{CPT theorem}}$ CP-violation

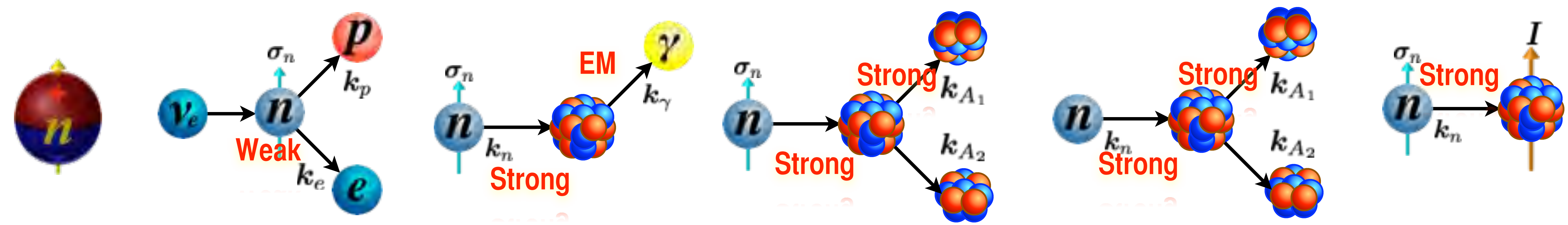
Symmetry Tests with Slow Neutrons



$$T : e^{i\boldsymbol{k}\cdot\boldsymbol{r}-\omega t}\chi \rightarrow e^{-i\boldsymbol{k}\cdot\boldsymbol{r}+\omega t}\chi^T$$

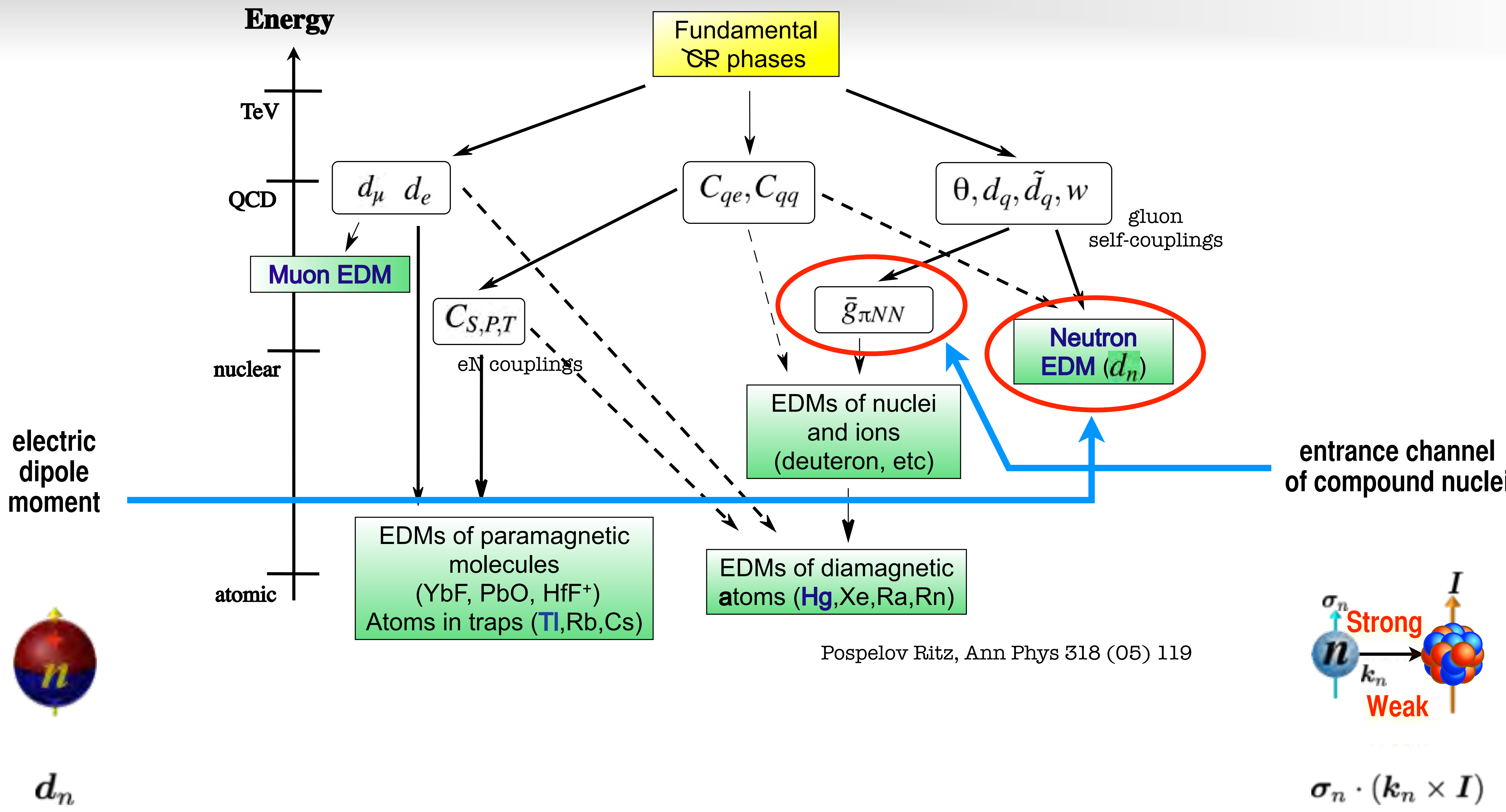
T-violation $\overset{\times}{\longleftarrow}$ / $\longrightarrow$ **T-odd observables changing sign under T**

electric dipole moment	D-coefficient in neutron β-decay	γ-ray angular distribution	ternary fission	ternary fission	entrance channel of compound nuclei



$\boldsymbol{d}_n$	$\boldsymbol{\sigma}_n\cdot(\boldsymbol{k}_p\times\boldsymbol{k}_e)$	$\boldsymbol{\sigma}_n\cdot(\boldsymbol{k}_n\times\boldsymbol{k}_\gamma)$	$\boldsymbol{\sigma}_n\cdot(\boldsymbol{k}_{A_1}\times\boldsymbol{k}_{A_2})$	$\boldsymbol{k}_n\cdot(\boldsymbol{k}_{A_1}\times\boldsymbol{k}_{A_2})$	$\boldsymbol{\sigma}_n\cdot(\boldsymbol{k}_n\times\boldsymbol{I})$

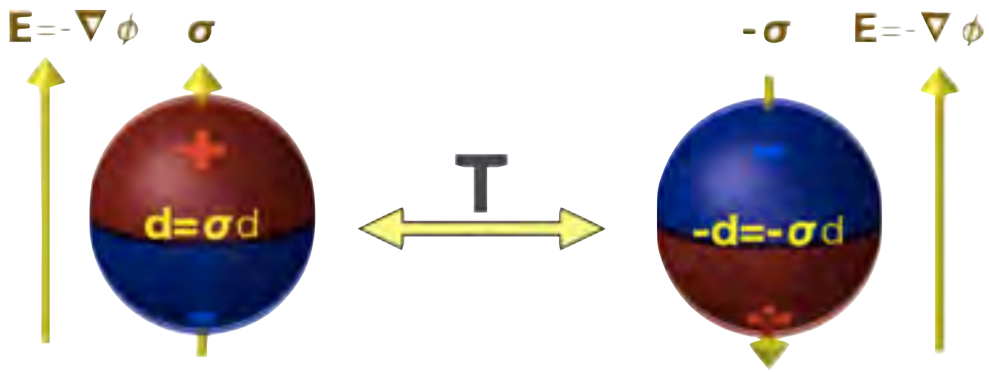
final state interaction (T-odd T-symmetric)

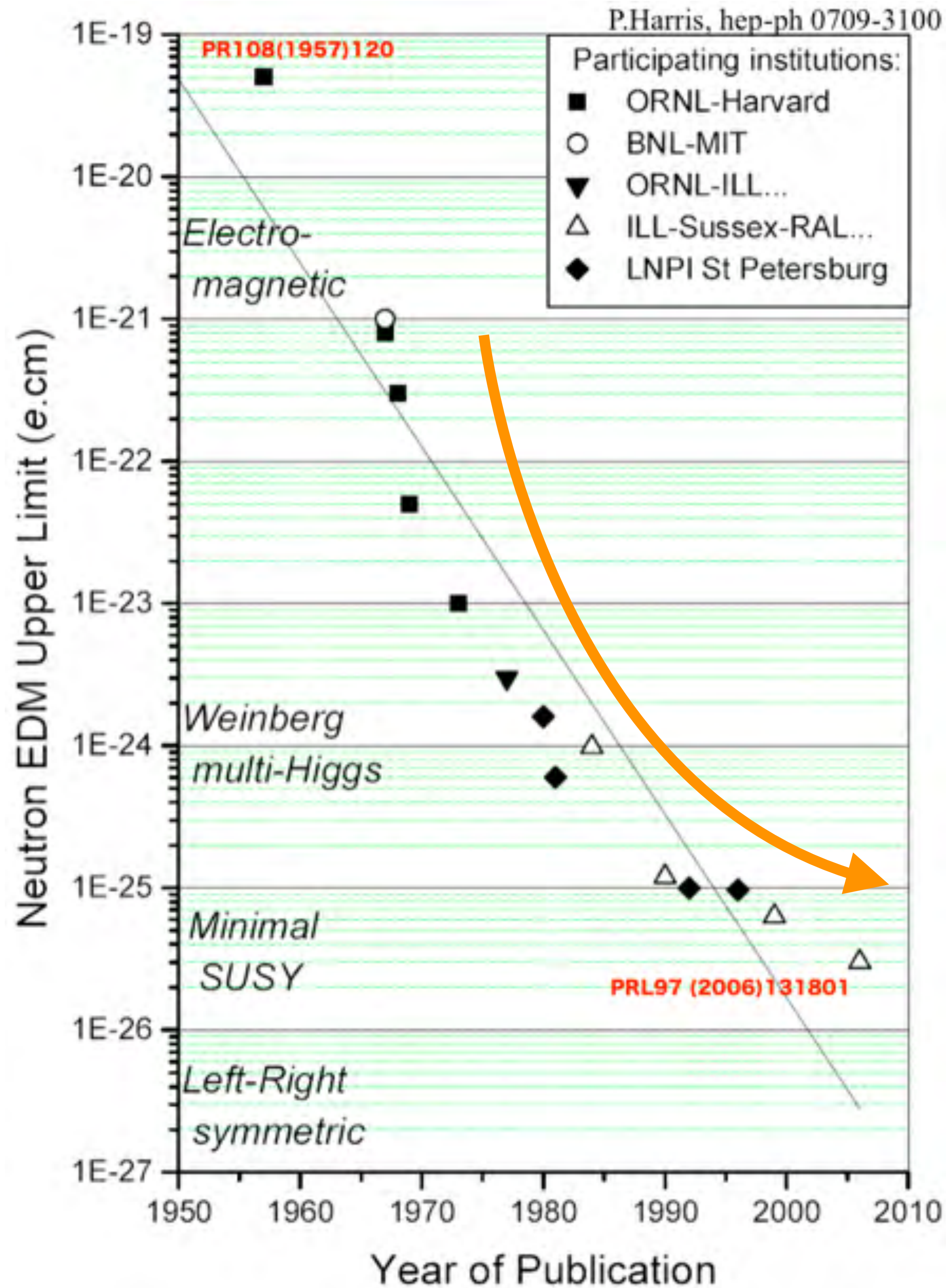

Energy
TeV
QCD
nuclear
atomic
Fundamental
CP phases
$d_\mu \quad d_e$
C_{qe}, C_{qq}
$\theta, d_q, \tilde{d}_q, w$
gluon
self-couplings
Muon EDM
$C_{S,P,T}$
eN couplings
$\bar{g}_{\pi NN}$
Neutron
EDM (d_n)
EDMs of nuclei
and ions
(deuteron, etc)
electric
dipole
moment
entrance channel
of compound nuclei
EDMs of paramagnetic
molecules
(YbF, PbO, HfF+)
Atoms in traps (Tl,Rb,Cs)
EDMs of diamagnetic
atoms (Hg,Xe,Ra,Rn)
Pospelov Ritz, Ann Phys 318 (05) 119
n
d_n
σ_n
I
Strong
Weak
k_n
$\sigma_n \cdot (k_n \times I)$

Electric Dipole Moment

$$d_n$$

Neutron Electric Dipole Moment





Neutron Electric Dipole Moment

$d_n = (0.2 \pm 1.5_{\rm stat} \pm 0.7_{\rm syst}) \times 10^{-26}\,[\rm e\,cm]$ $|d_n| < 2.9 \times 10^{-26}\,[\rm e\,cm]\,(90\%\rm C.L.)$

C.A.Baker et al., Phys. Rev. Lett. 97 (2006) 131801

PSI, TRIUMF, SNS → 10^{-27} -10^{-28} e cm
Proton, Deuteron Electric Dipole Moment → 10^{-30} e cm

Atomic Electric Dipole Moment

$d_{^{199}\rm Hg} = -(1.06 \pm 0.49_{\rm stat} \pm 0.40_{\rm syst}) \times 10^{-28}\,[\rm e\,cm]$

M.V.Romalis et al., Phys. Rev. Lett. 86 (2001) 2505

$d_{^{199}\rm Hg} = (0.49 \pm 1.29_{\rm stat} \pm 0.76_{\rm syst}) \times 10^{-29}\,[\rm e\,cm]$ $|d_{^{199}\rm Hg}| < 3.1 \times 10^{-29}\,[\rm e\,cm]\,(95\%\rm C.L.)$

W.C.Griffith et al., Phys. Rev. Lett. 102 (2009) 101601 $|d_n| < 5.8 \times 10^{-26}\,[\rm e\,cm]$

Molecular Electric Dipole Moment

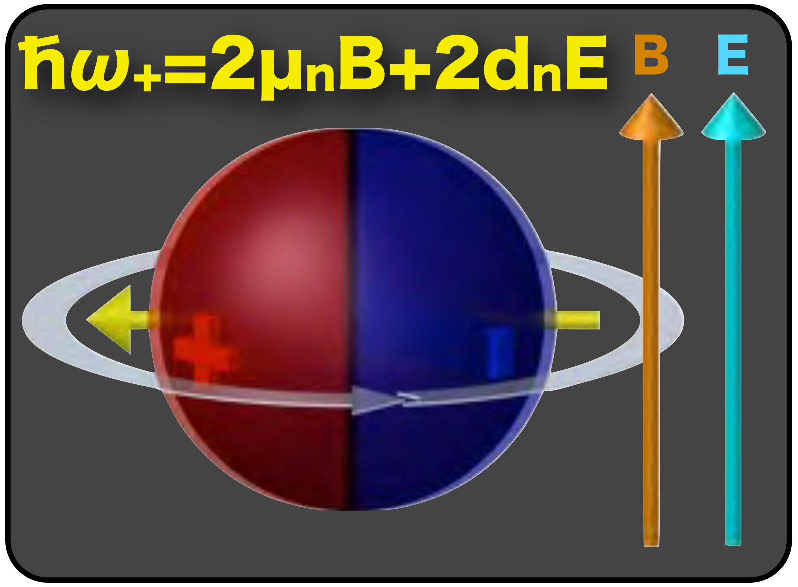
$d_e = (-2.1 \pm 3.7_{\rm stat} \pm 2.5_{\rm syst}) \times 10^{-29}\,[\rm e\,cm]$ $|d_e| < 8.7 \times 10^{-29}\,[\rm e\,cm]\,(90\%\rm C.L.)$

J.Baron et al., Science 343 (2013) 269

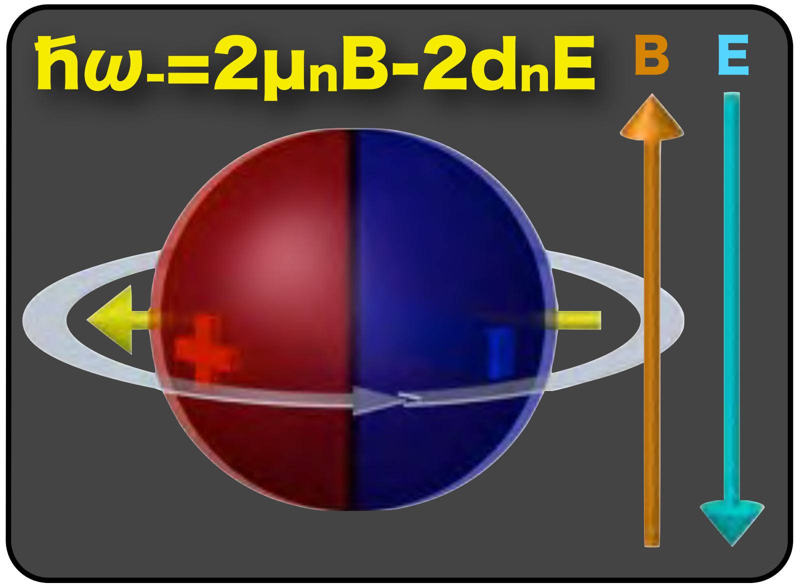
Measurement of Neutron Electric Dipole Moment

search for the phase change when the electric field is reversed

$$\hbar\omega_+ = 2d_nE + 2\mu_nB$$



$$\hbar\omega_- = 2d_nE - 2\mu_nB$$



$$\Delta\phi = \int(\omega_+ - \omega_-)\mathrm{d}t = \frac{2d_nET}{\hbar}$$

$$\Delta d_n = \frac{\hbar/2}{ET\sqrt{N}}$$

long precession time

Confined Ultracold Neutron

$E = 10^4$ V/cm, T=100s

$$ET \sim 10^6\,[\mathrm{s\,V/cm}]$$

strong electric field

Cold Neutron Diffraction by Single Crystal

$E = 10^9$ V/cm, T=1ms

resolved systematics

Guided Cold Neutron

$E = 10^5$ V/cm, T=0.1s

long precession time

Confined Ultracold Neutron

$E=10^4$ V/cm, T=100s

strong electric field

Cold Neutron Diffraction by Single Crystal

E=10

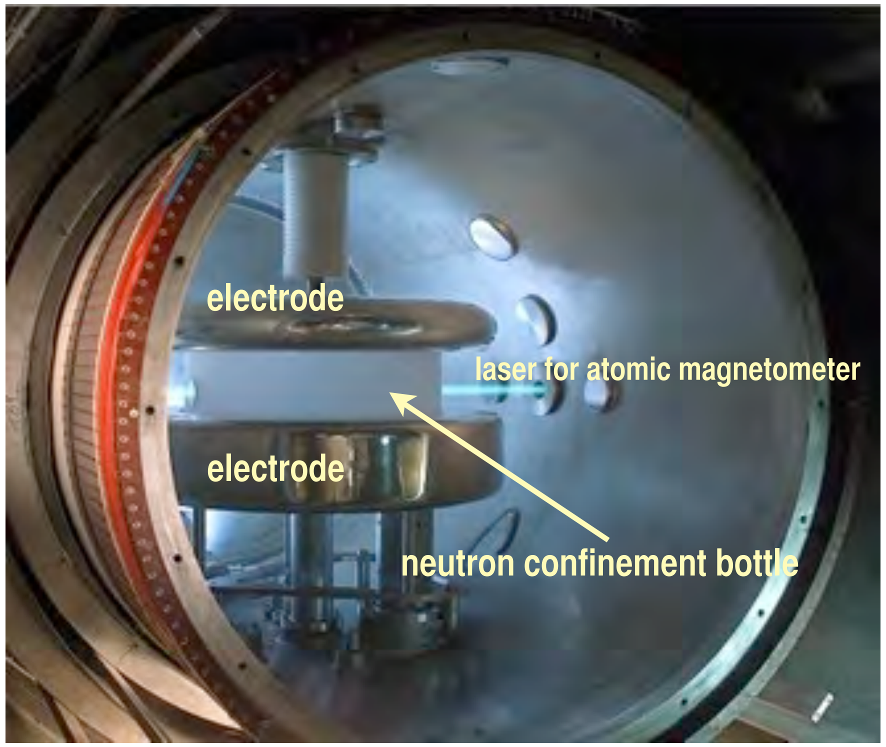
resolved systematics

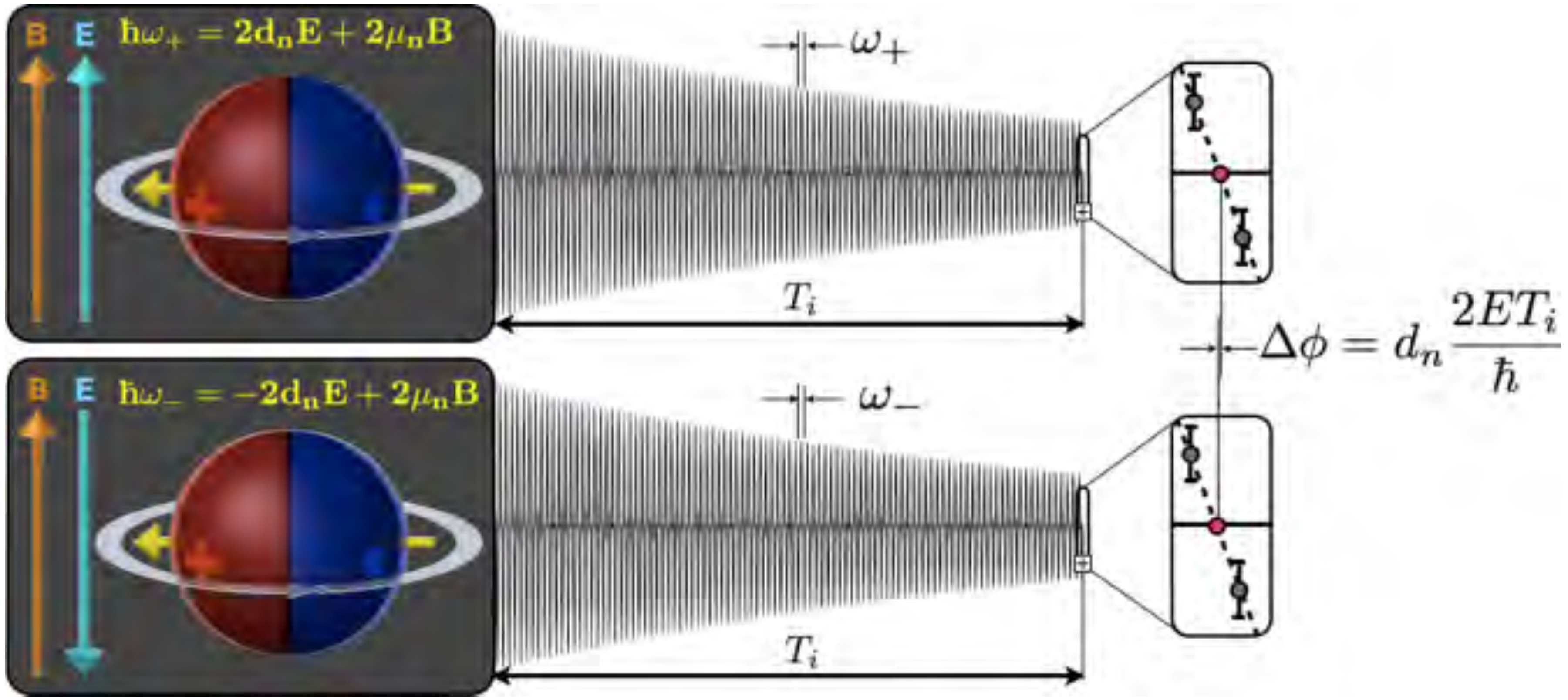
Guided Cold Neutron

E=10

Measurement of Neutron Electric Dipole Moment

Confined Ultracold Neutron Spin Precession Frequency





$$\frac{\omega_\pm}{2\pi} = \boxed{30[\mathrm{Hz}]\frac{B}{1\,[\mu\mathrm{T}]}} \pm \boxed{5\times10^{-8}[\mathrm{Hz}]\frac{d_n}{10^{-26}\,[\mathrm{e}\cdot\mathrm{cm}]}\frac{E}{10\,[\mathrm{kV/cm}]}}$$

magnetic field **1μT**

electric field **1fT equiv.**

Measurement of Neutron Electric Dipole Moment

Confined Ultracold Neutron Spin Precession Frequency

$$\frac{\omega_\pm}{2\pi} = \boxed{30[\mathrm{Hz}]\frac{B}{1\,[\mu\mathrm{T}]}} \pm \boxed{5\times 10^{-8}[\mathrm{Hz}]\frac{d_n}{10^{-26}\,[\mathrm{e}\cdot\mathrm{cm}]}\frac{E}{10\,[\mathrm{kV/cm}]}}$$

magnetic field **1μT** electric field **1fT equiv.**

precision control of magnetic field

density of confined neutrons

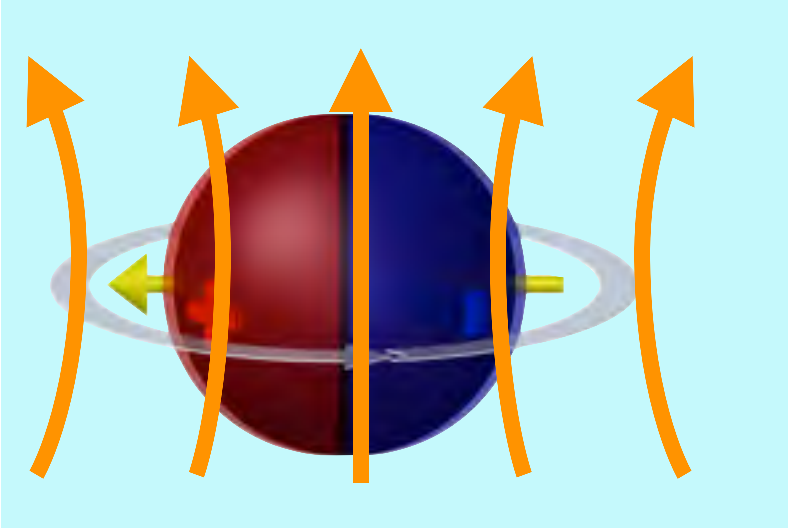
- **superthermal production of ultracold neutron**
- **transport optics with minimum density decrease**

control of the motion of confined neutrons

- **optical properties of neutron reflectors**

accuracy of the magnetic field measurement

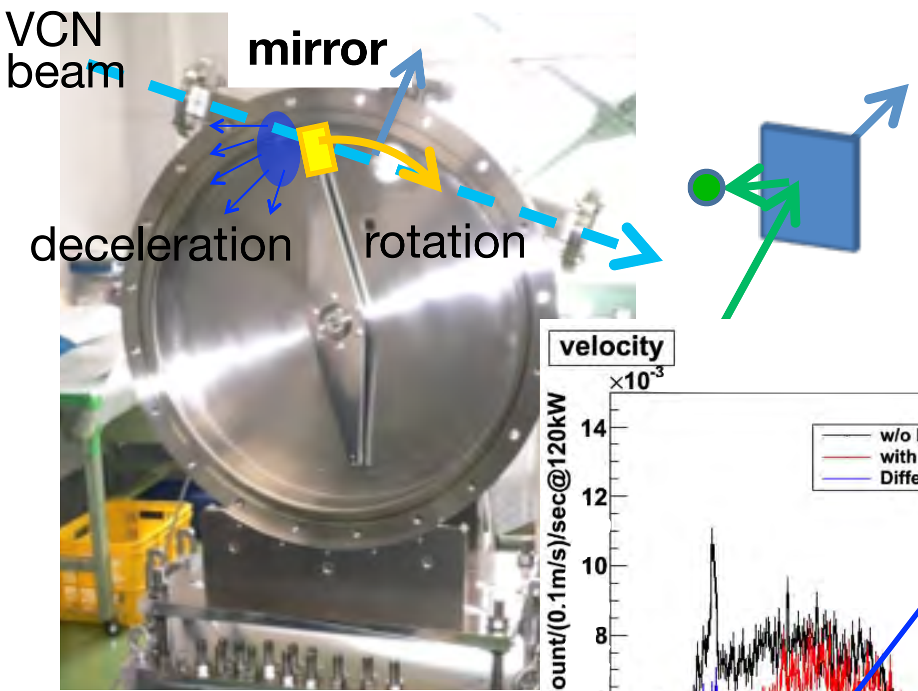
- **atomic magnetometry**

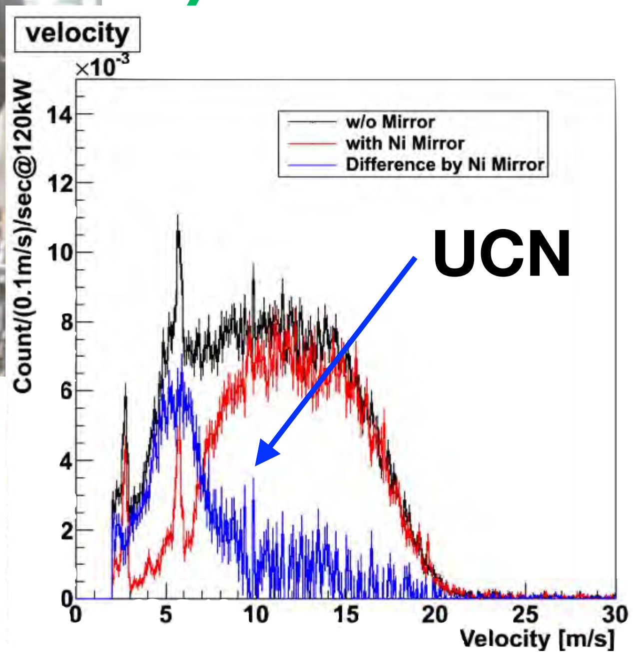


R & D for next generation neutron EDM

Doppler Shifter

pulsed UCN generator

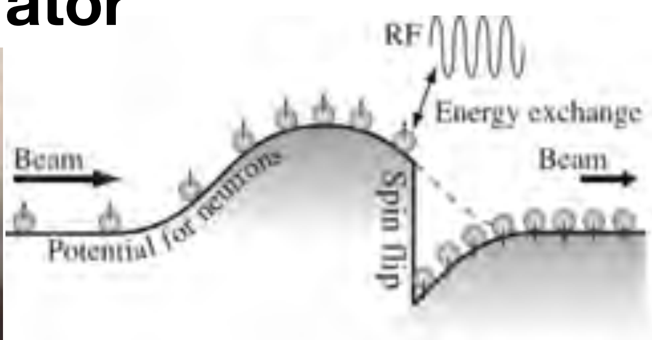


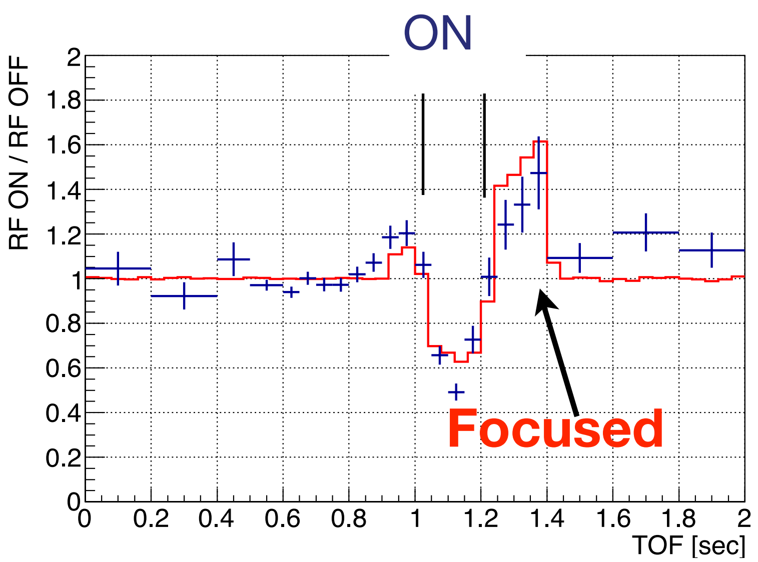


high Qc mirror for direct reflection m=10, R=0.4

UCN Rebuncher

neutron accelerator





Arimoto, et. al., PRA86, 023843(2013)

DLC mirror

high reflectivity, smooth, free-surface

UCN simulation

estimate systematics with high precision

long precession time

Confined Ultracold Neutron

E=10

strong electric field

Cold Neutron Diffraction by Single Crystal

$E=10^9$ V/cm, T=1ms

resolved systematics

Guided Cold Neutron

E=10

Measurement of Neutron Electric Dipole Moment

Cold Neutron Diffraction in Single Crystal

$$f(\boldsymbol{q}) = \underbrace{f_0}_{a} + \underbrace{f_{\mathrm{Schw}}(\boldsymbol{q})}_{i\frac{2e\mu_n}{\hbar c}(Z-F(q))\frac{\boldsymbol{\sigma}\cdot(\boldsymbol{k}\times\boldsymbol{q})}{q^2}} + \underbrace{f_{\mathrm{EDM}}(\boldsymbol{q})}_{i\frac{2med_n}{\hbar^2}(Z-F(q))\frac{\boldsymbol{\sigma}\cdot\boldsymbol{q}}{q}}$$

$$F(\boldsymbol{q}) = \int \rho(\boldsymbol{q}) e^{i\boldsymbol{q}\cdot\boldsymbol{r}} \mathrm{d}\boldsymbol{r}$$ atomic form factor

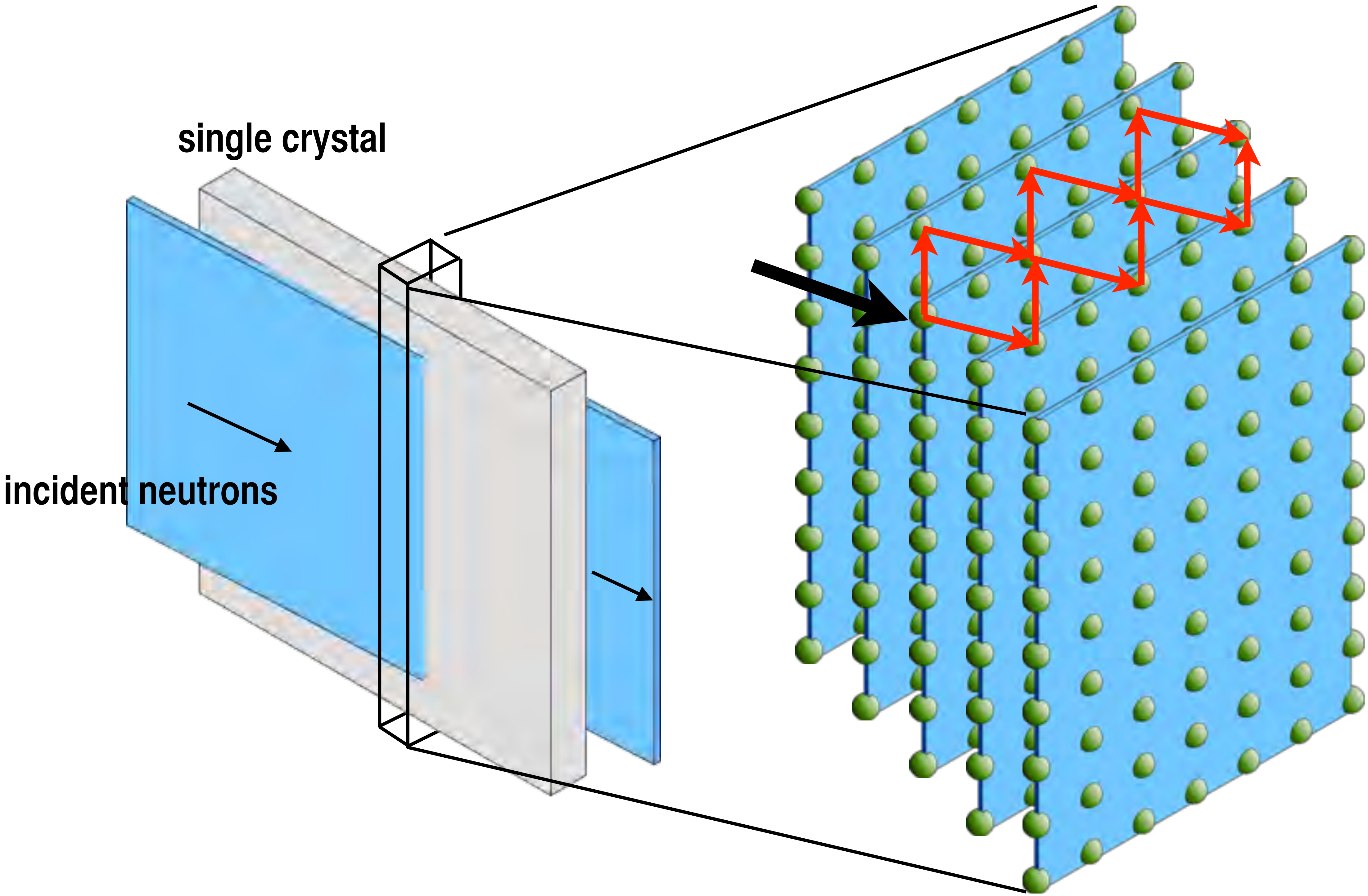
α-quartz (SiO_2)

$$d_n = (2.5 \pm 6.5_{\mathrm{stat}} \pm 5.5_{\mathrm{syst}}) \times 10^{-24}\ [\mathrm{e\,cm}]$$

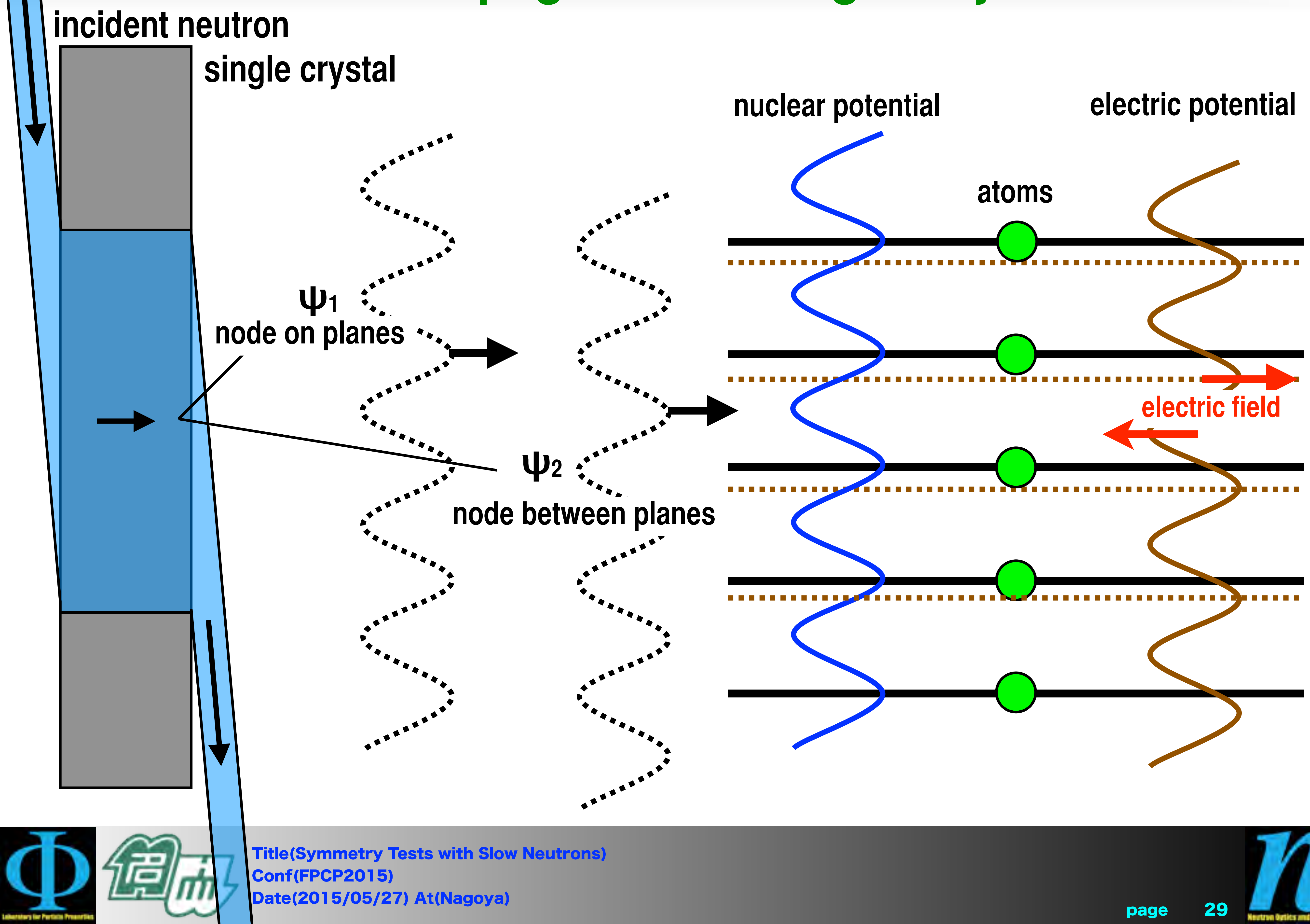
V.V.Fedorov et al., Phys. Lett. B694 (2010) 22

→ 10^{-26} e cm / 100 days

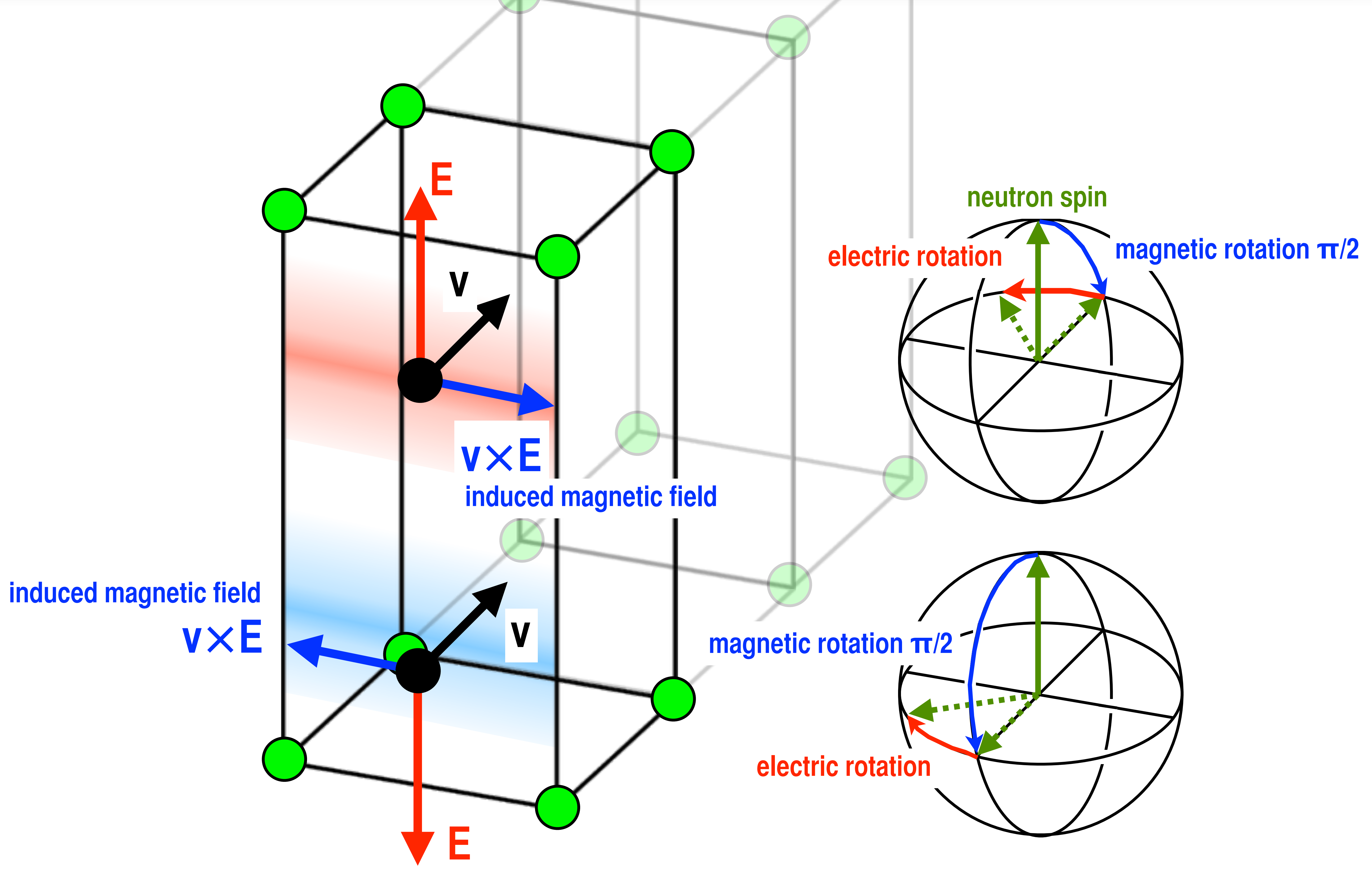
Neutron-wave Propagation in Single Crystal



Neutron-wave Propagation in Single Crystal



Neutron Spin Rotation in Single Crystal



by V.V.Fedorov

Properties of some noncentrosymmetric crystals suitable for EDM search

Crystal	Symmetry Group	hkl	d,(Å)	E_g, 10^9 V/cm	τ_a, ms	$E_g \tau_a$, kV s/cm
α-quartz (SiO_2)	32(D^6_3)	111	2.24	**0.23**	**1.0**	**230**
		110	2.46	**0.20**		**220**
$Bi_{12}GeO_{20}$	I23	433	1.74	0.52	0.9	468
		312	2.71	0.24		216
$PbTiO_3$	4mm	$41\bar{1}$	0.92	**1.78**	0.03	53
		002	2.08	**1.42**		43
BeO	6mm	011	2.06	0.54	**7.0**	**3700**
		201	1.13	0.65		**4500**
$Bi_4Si_3O_{12}$	-43m	242	2.10	0.46	**2.0**	**920**
		132	2.75	0.32		**640**

our choice

Measurement of Neutron Electric Dipole Moment

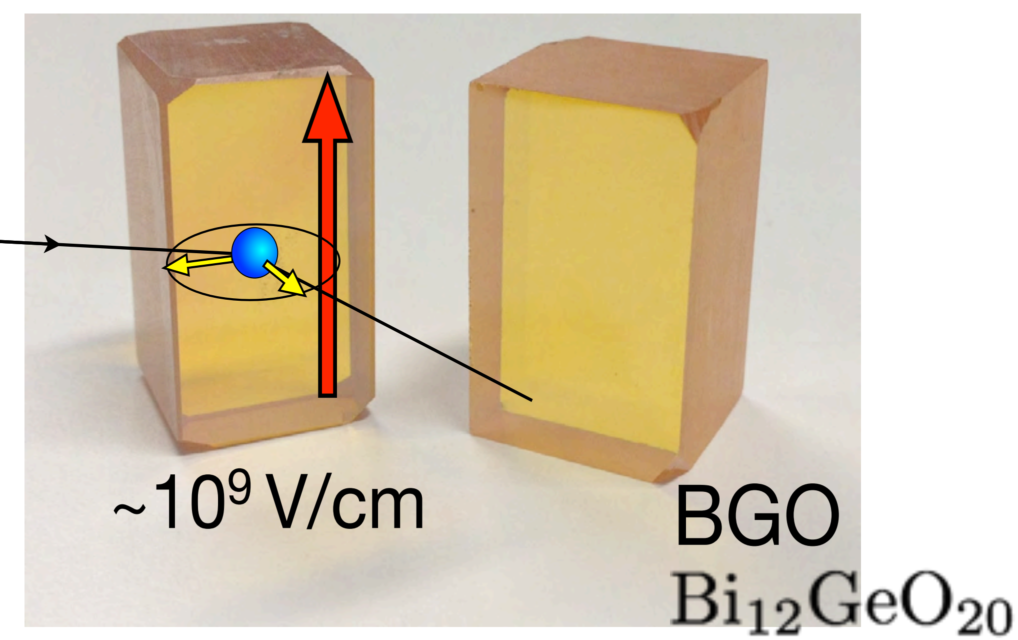
Cold Neutron Diffraction in Single Crystal

$$f(\boldsymbol{q}) = \underbrace{f_0}_{a} + \underbrace{f_{\mathrm{Schw}}(\boldsymbol{q})}_{i\frac{2e\mu_n}{\hbar c}(Z-F(q))\frac{\boldsymbol{\sigma}\cdot(\boldsymbol{k}\times\boldsymbol{q})}{q^2}} + \underbrace{f_{\mathrm{EDM}}(\boldsymbol{q})}_{i\frac{2med_n}{\hbar^2}(Z-F(q))\frac{\boldsymbol{\sigma}\cdot\boldsymbol{q}}{q}}$$

$$F(\boldsymbol{q}) = \int \rho(\boldsymbol{q})e^{i\boldsymbol{q}\cdot\boldsymbol{r}}\mathrm{d}\boldsymbol{r}$$ atomic form factor

completeness of crystal
is under study

by S.Itoh, M.Kitaguchi, …



long precession time

Confined Ultracold Neutron

E=10

strong electric field

Cold Neutron Diffraction by Single Crystal

E=10

resolved systematics

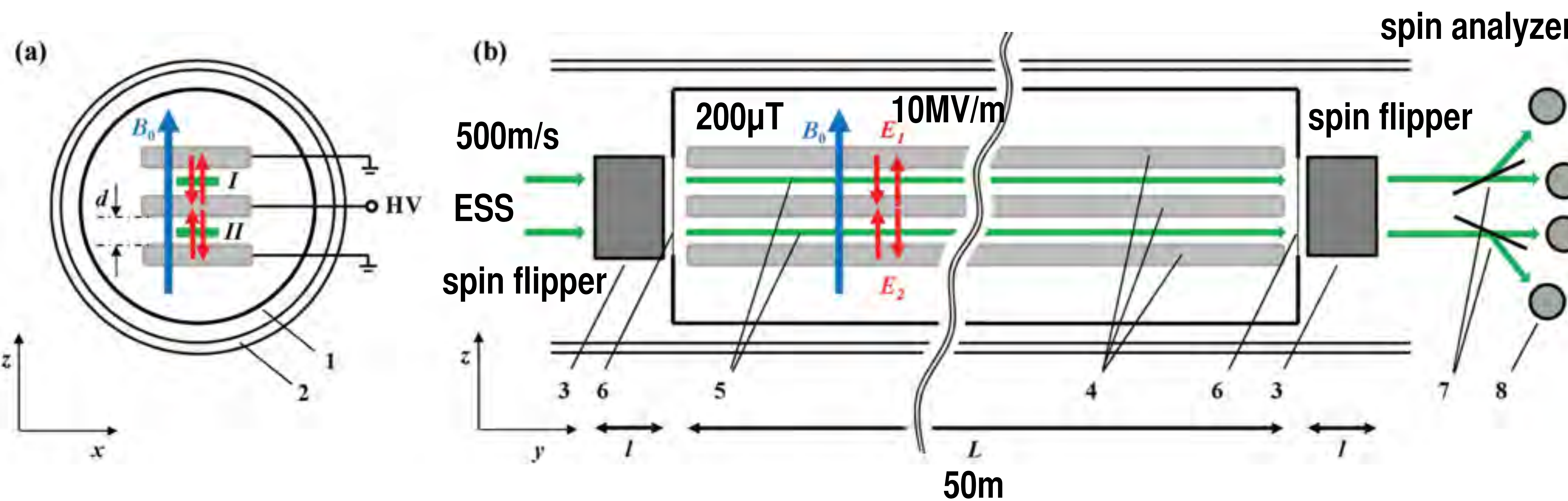
Guided Cold Neutron

$E=10^5$ V/cm, T=0.1s

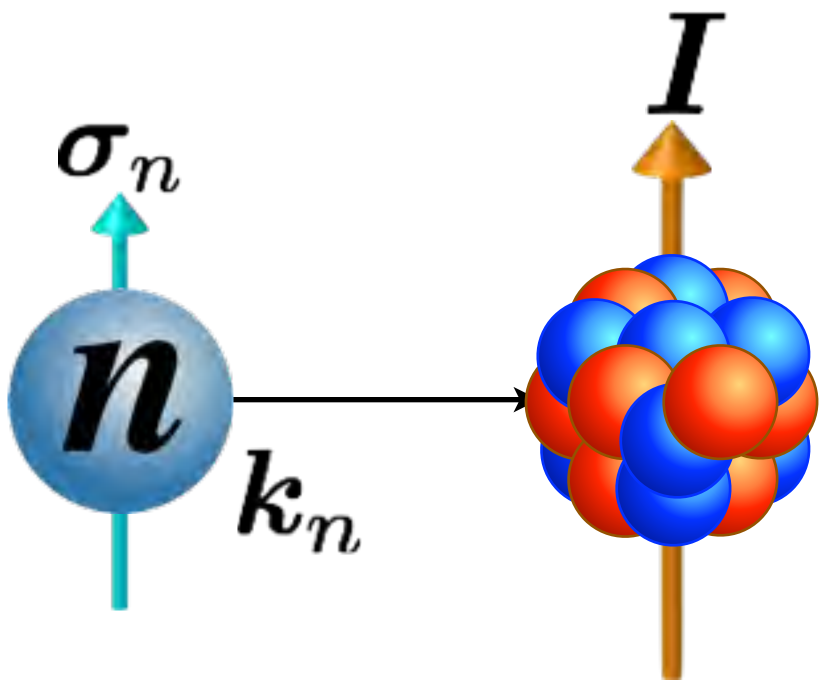
In-flight Measurement of Neutron Electric Dipole Moment

F.Piegsa, Phys. Rev. C 88 (2013) 045502

$|d_n| \sim 5\text{x}10^{-28}$ e cm / 100 days



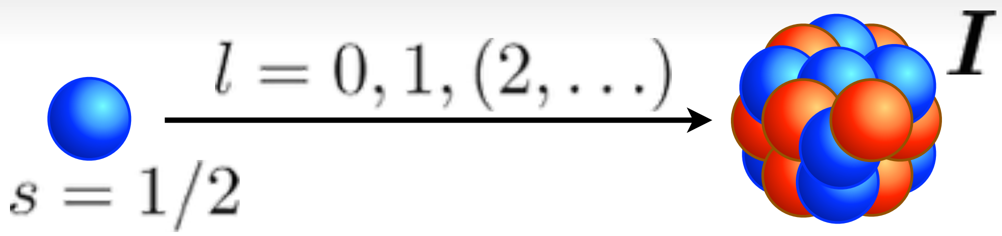
Entrance Channel of Compound Nuclei



$$\boldsymbol{\sigma}_n \cdot (\boldsymbol{k}_n \times \boldsymbol{I})$$

Enhanced Sensitivity to P-violation in Compound Resonance

eV neutron capture



potential scattering

compound resonance

$$J = I + j \qquad j = l + s$$

- J: resonance spin
- I: target spin
- j: neutron total angular momentum

$l = 0$ s-wave resonance s

$1/kR \sim 10^{-3}$

$l = 1$ p-wave resonance

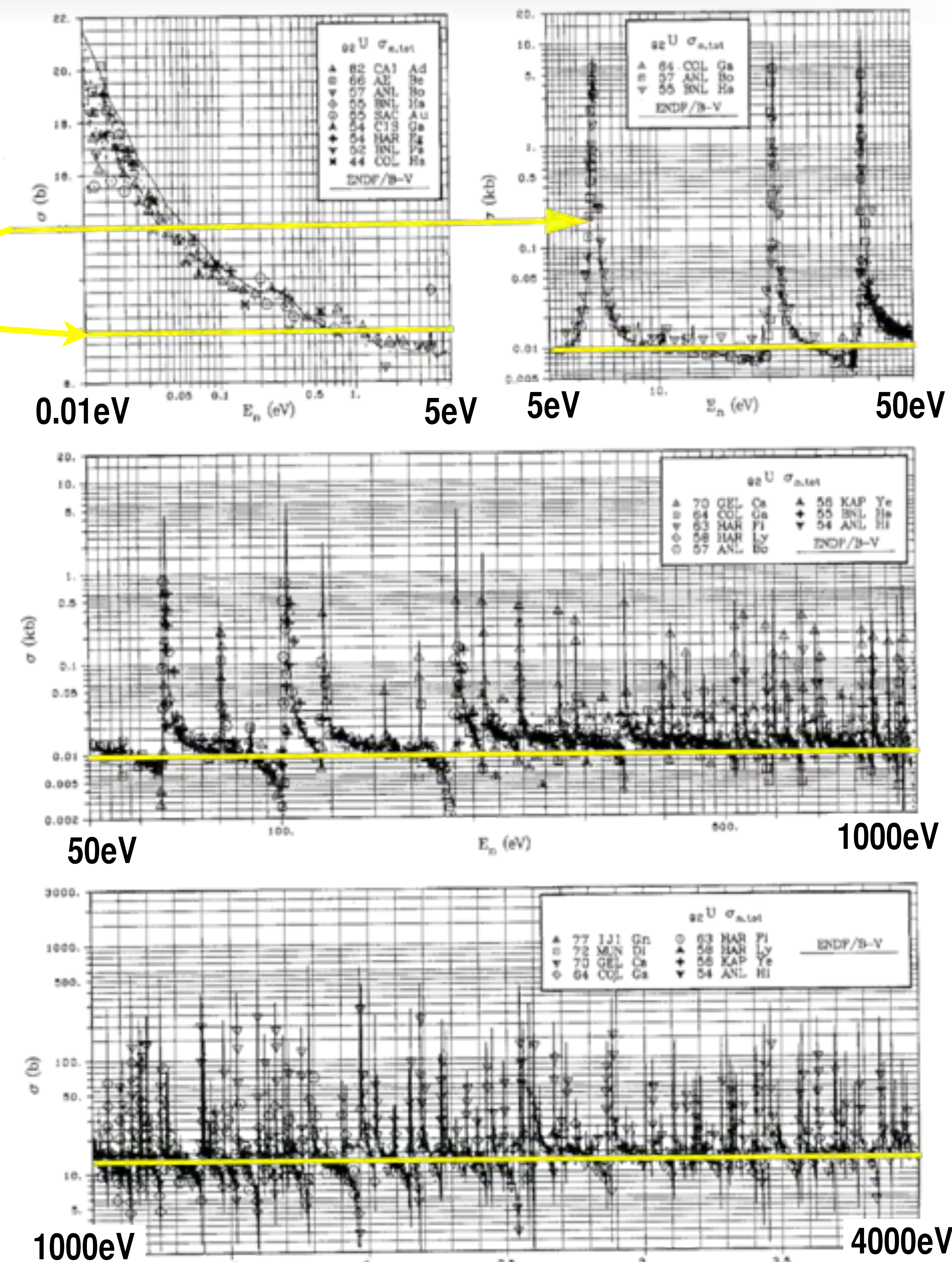
$j = 1/2 \quad p_{1/2}$

$j = 3/2 \quad p_{3/2}$

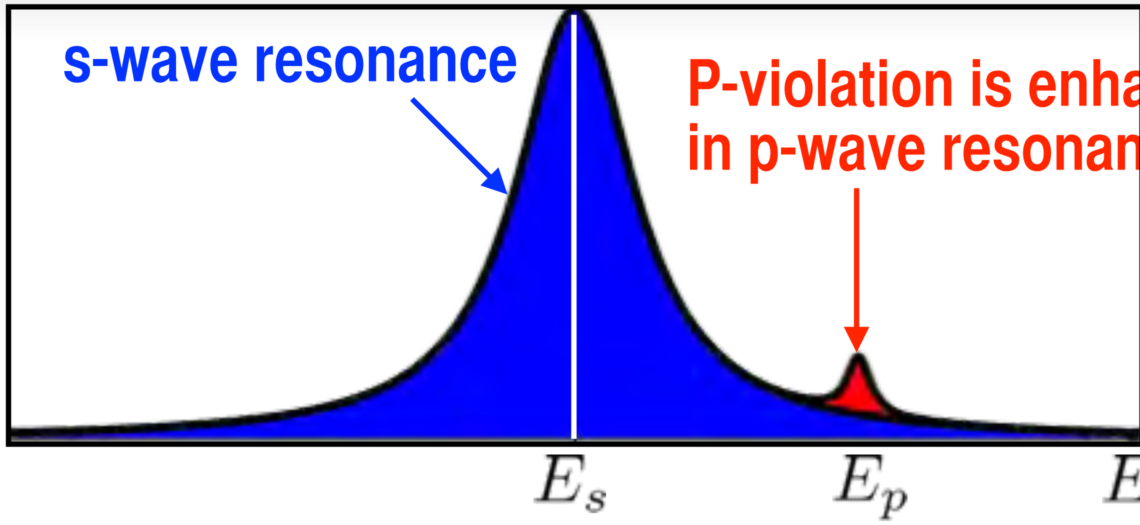
interference
(common J and j)

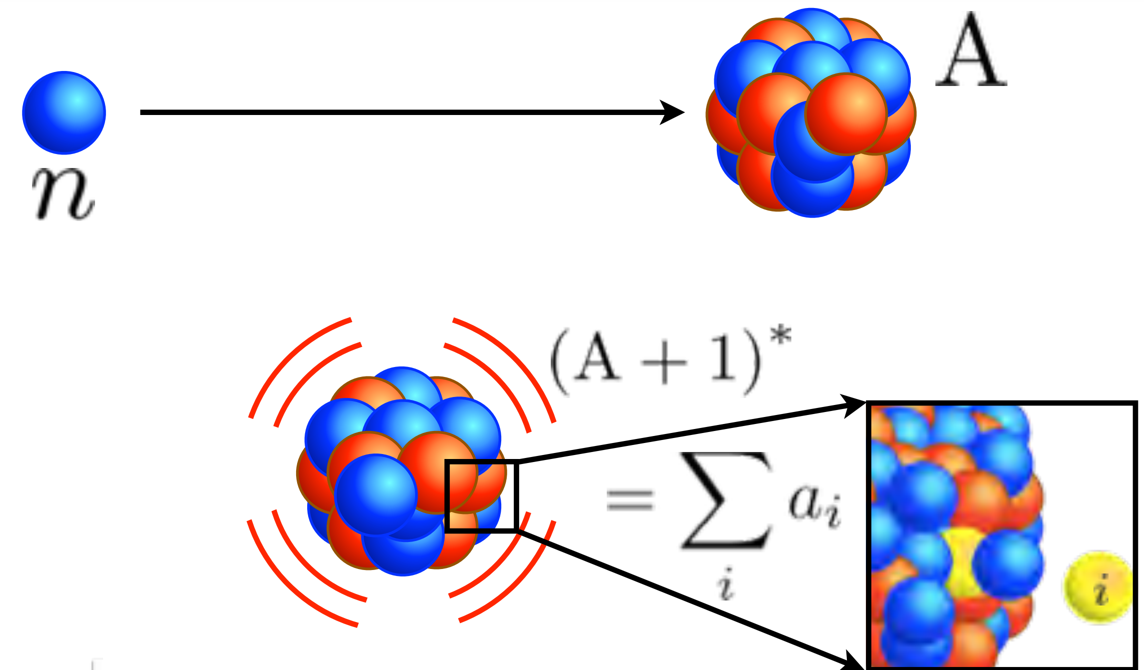
$\sigma_{n,tot}$ U

V.McLane et al. Neutron Cross Sections vol.2



P-violation in Compound Nuclei induced by Neutrons





$$v = \langle s|W|p\rangle$$

$$\Delta\sigma_{\mathrm{P}} = \frac{4\pi}{k^2}\mathrm{Im}\,\frac{(\Gamma_s^n)^{1/2}\, v\, (\Gamma_p^n)^{1/2}}{(E - E_s - i\Gamma_s/2)(E - E_p + i\Gamma_p/2)}$$

enhancement via the interference between neighboring s- and p-wave

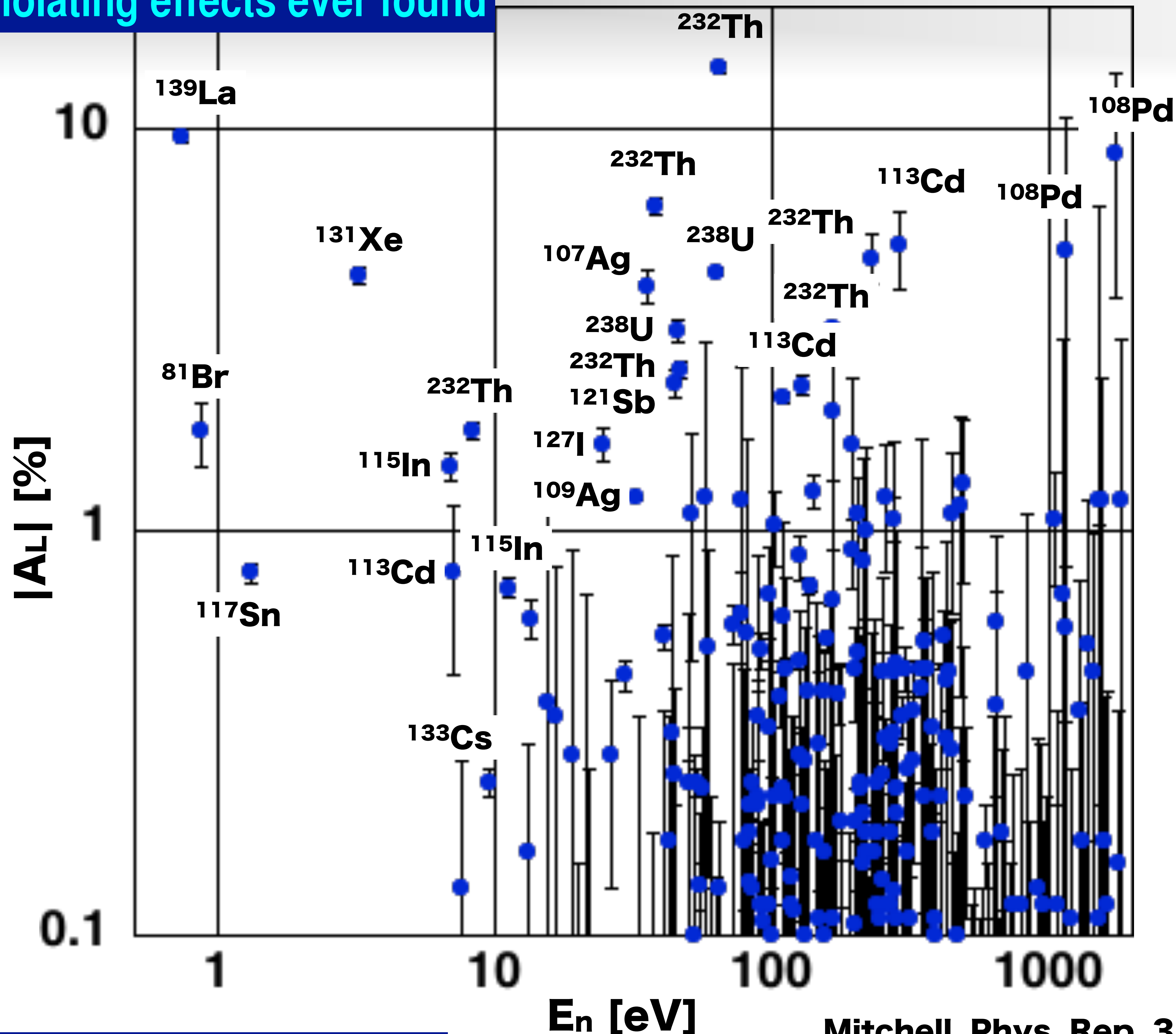
P-violation in NN interaction

10 eV

$$\frac{\langle s|W|p\rangle}{E_p - E_s} \sim \frac{\langle W\rangle}{\Delta E}\sqrt{N}$$

10^{-7} 10^{2}-10^{3}

Large P-violating effects ever found



Mitchell, Phys. Rep. 354 (2001) 157

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

The interference between s-wave and p-wave causes the interference between partial waves with different channel spin.

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

$$P : |lsI\rangle \to (-1)^l |lsI\rangle$$

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

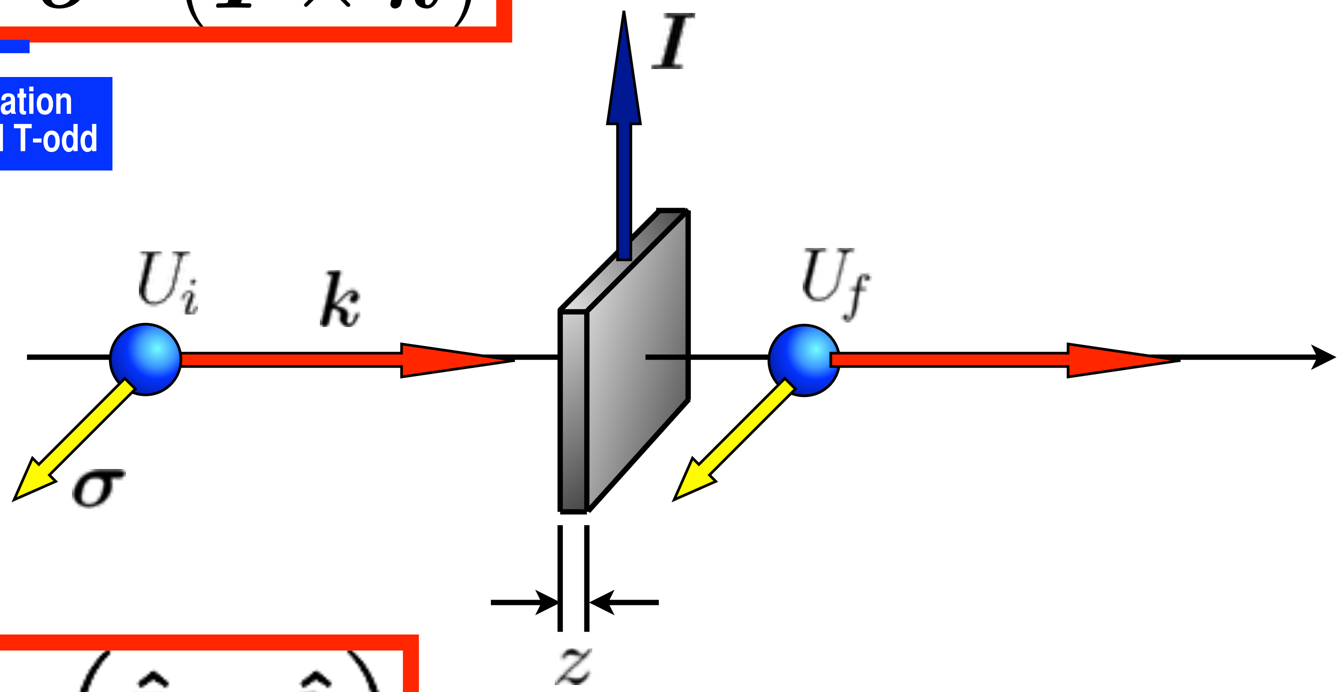
$$\begin{aligned}|((Is)S,l)J\rangle &= \sum_j \langle (I,(sl)j)J|((Is)S,l)J\rangle \, |(I,(sl)j)J\rangle \\ &= \sum_j (-1)^{l+s+I+J}\sqrt{(2j+1)(2S+1)} \left\{ \begin{array}{ccc} I & s & l \\ J & S & j \end{array} \right\} |(I,(sl)j)J\rangle\end{aligned}$$

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

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

T-violation in Neutron Optics

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



$$U_f = \delta U_i$$

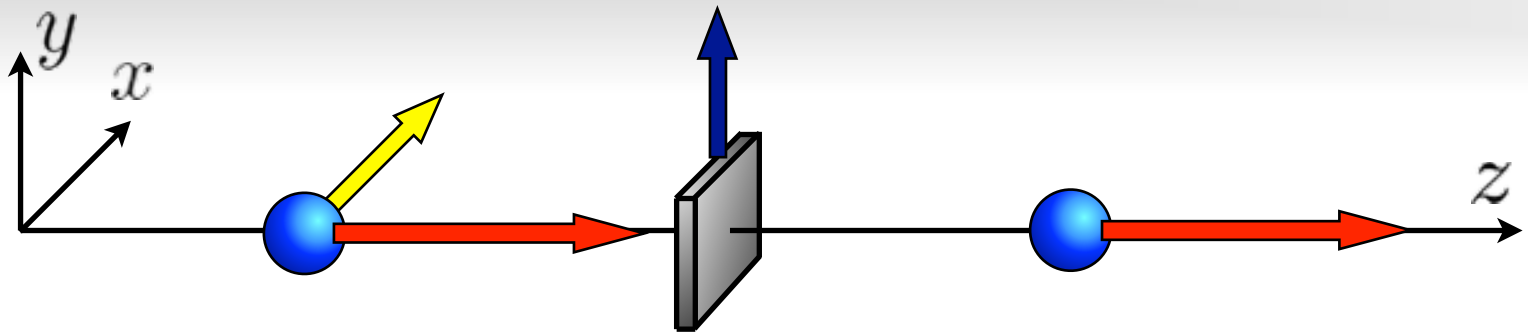
$$\delta = e^{i(n-1)kz} \qquad n = 1 + \frac{2\pi\rho}{k^2} f$$

$$\delta = \underbrace{A}_{\substack{\text{Spin Independent}\\ \text{P-even T-even}}} + \underbrace{B\boldsymbol{\sigma}\cdot\hat{\boldsymbol{I}}}_{\substack{\text{Spin Dependent}\\ \text{P-even T-even}}} + \underbrace{C\boldsymbol{\sigma}\cdot\hat{\boldsymbol{k}}}_{\substack{\text{P-violation}\\ \text{P-odd T-even}}} + \boxed{\underbrace{D\boldsymbol{\sigma}\cdot\left(\hat{\boldsymbol{I}}\times\hat{\boldsymbol{k}}\right)}_{\substack{\text{T-violation}\\ \text{P-odd T-odd}}}}$$

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

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

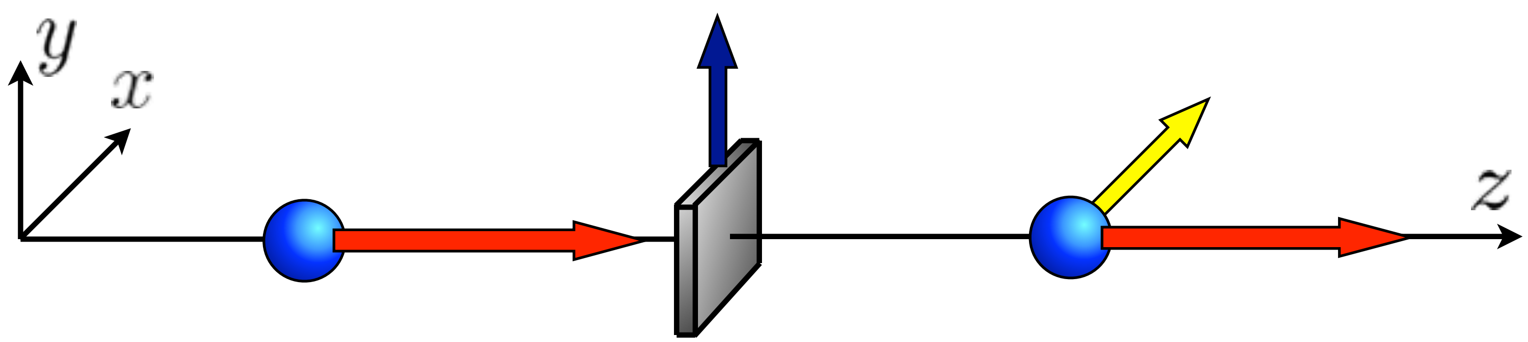
$$b = Z(B'^2 + C'^2 + D'^2)^{1/2} \qquad D = ie^{iZA'}\frac{\sin b}{b}ZD'$$



$$A_x \equiv \mathrm{Tr}\left[\delta^\dagger \sigma_x \delta\right] = 4\left(\mathrm{Re}\, A^* D + \mathrm{Im}\, B^* C\right)$$

Spin Independent P-even T-even | T-violation P-odd T-odd | Spin Dependent P-even T-even | P-violation P-odd T-even

解析能 (Analyzing Power)



$$P_x \equiv \mathrm{Tr}\left[\sigma_x \delta^\dagger \delta\right] = 4\left(\mathrm{Re}\, A^* D - \mathrm{Im}\, B^* C\right)$$

Spin Independent P-even T-even | T-violation P-odd T-odd | Spin Dependent P-even T-even | P-violation P-odd T-even

偏極 (Polarization)

+

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

Estimation of Sensitivity to T-violation

Gudkov, Phys. Rep. 212 (1992) 77

T-violating matrix element

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

$$D \text{ — } \Delta\sigma_{\mathrm{CP}} = \boxed{\kappa(J)}\,\boxed{\frac{w}{v}}\,\Delta\sigma_{\mathrm{P}}$$

T-violation

angular momentum factor

P-violation

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

(n,γ) measurement

P-violating matrix element

Gudkov, Phys. Rep. 212 (1992) 77

$$\Delta\sigma_{\mathrm{CP}} = \boxed{\kappa(J)}\frac{w}{v}\Delta\sigma_{\mathrm{P}}$$

T-violation **P-violation**

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

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

$$x^2 = \frac{\Gamma^n_{p,1/2}}{\Gamma^n_p} \qquad y^2 = \frac{\Gamma^n_{p,3/2}}{\Gamma^n_p}$$

single unknown parameter (ϕ)

$$x = \cos\boxed{\phi} \qquad y = \sin\boxed{\phi}$$

κ(J) as a function of ϕ

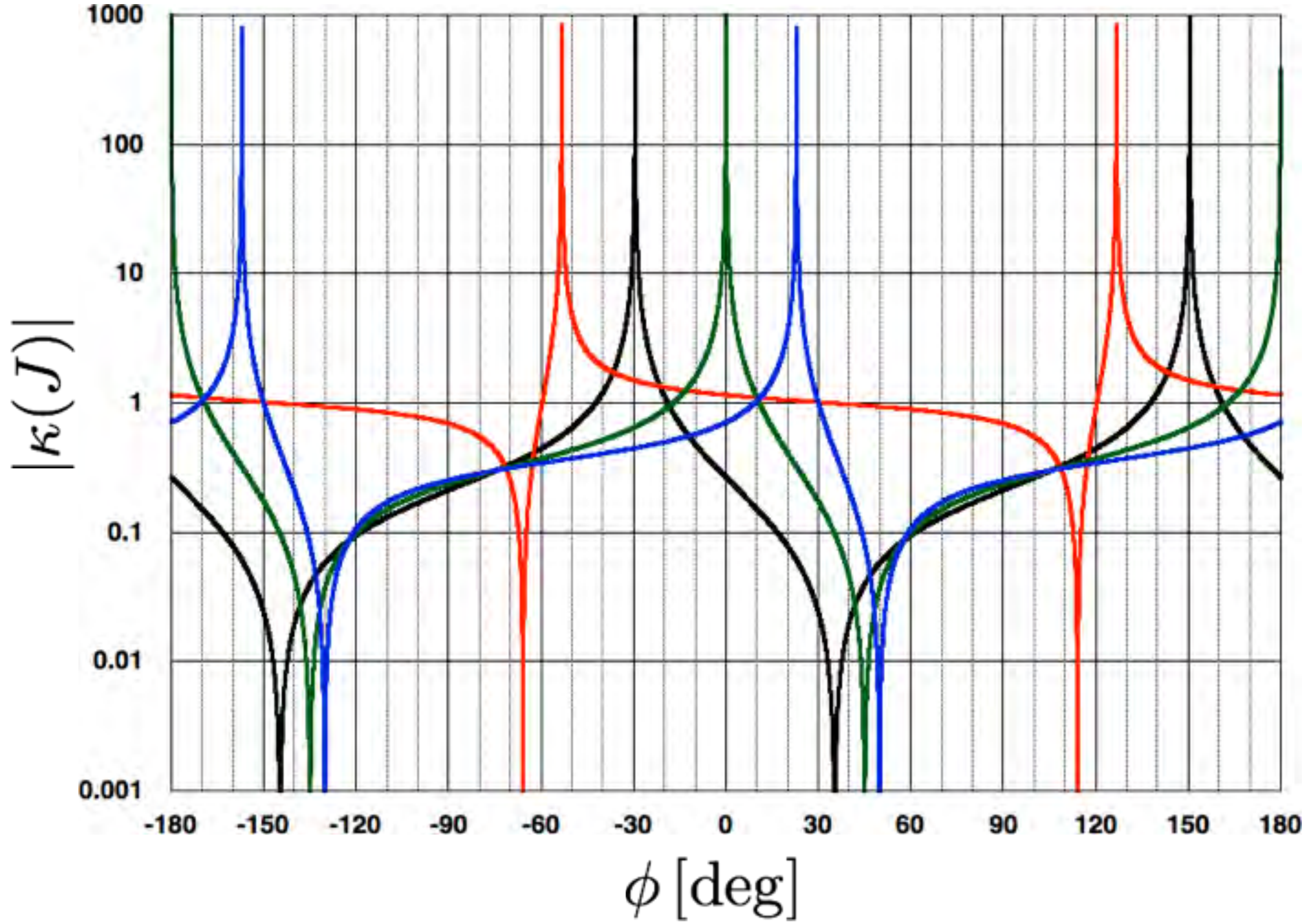
$$\overline{|\kappa|} \equiv \exp\left(\frac{1}{2\pi}\int_{-\pi}^{\pi} \log|\kappa|\,\mathrm{d}\phi\right)$$

I=3/2, J=1 (^{131}Xe)	1.01
I=1/2, J=1 (^{117}Sn)	0.23
I=3/2, J=2 (^{81}Br)	0.33
I=7/2, J=4 (^{139}La)	0.36

in average

$$J = I - \frac{1}{2}$$

is more suitable



determination of ϕ

Flambaum, Nucl. Phys. A435 (1985) 352

(n,γ) cross section (unpolarized case)

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

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

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

$$a_3 = \mathrm{Re} \sum_{J_\mathrm{s},j,J'_\mathrm{p},j'} V_2(J_\mathrm{p} j) V_2^*(J'_\mathrm{p} j') P(J_\mathrm{p} J'_\mathrm{p} j j' 2 I F) 3\sqrt{10} \left\{ \begin{array}{ccc} 2 & 1 & 1 \\ 0 & \frac{1}{2} & \frac{1}{2} \\ 2 & j & j' \end{array} \right\}$$

$$V_1 = \frac{1}{2k_s}\sqrt{\frac{E_s}{E}} \frac{\sqrt{g\Gamma_s^n \Gamma_\gamma}}{E - E_s + i\Gamma_s/2}$$

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

$V_2(j=1/2) = xV_2 = V_2 \cos\phi$

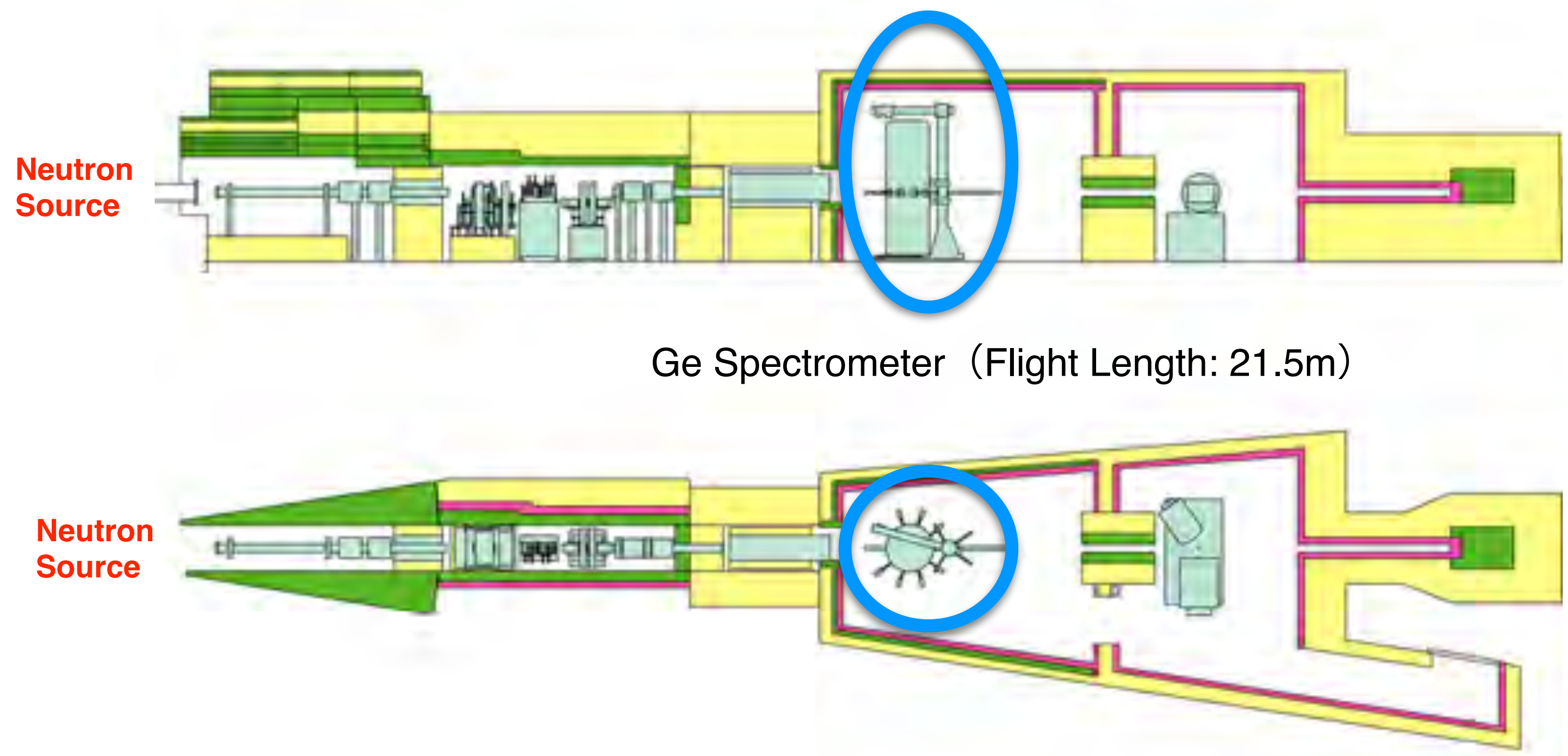
$V_2(j=3/2) = yV_2 = V_2 \sin\phi$

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

J-PARC MLF BL04 ANNRI

14 Ge（+BGO）Detectors

θ＝70,90,110 deg.



Ge Spectrometer（Flight Length: 21.5m）

Sample Materials：^{nat}La, $La^{nat}Br_3$, ^{nat}Xe

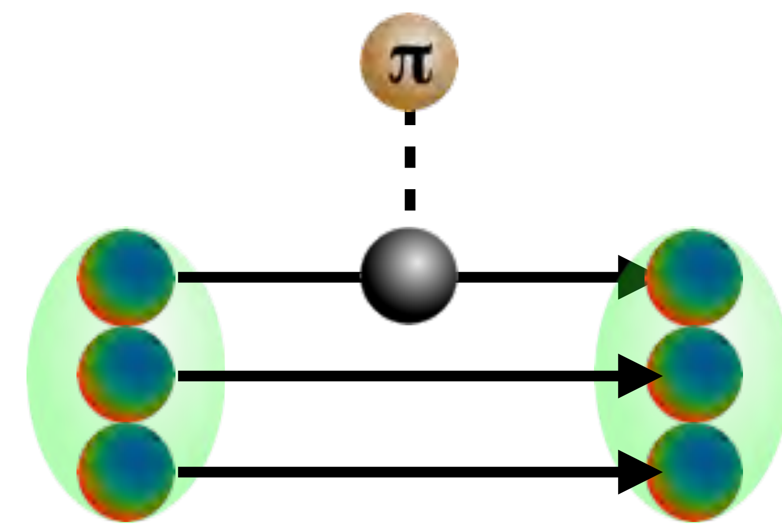
Intensity :　～3 x 10^5 n/cm^2/s　:　0.9 eV < En < 1.1eV @300kW

$\sigma(E_\gamma, E_n,, \theta)$ of (n,γ) reaction.

Estimation in Effective Field Theory

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

T-odd P-odd meson couplings



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

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

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

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

Estimation in Effective Field Theory

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

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

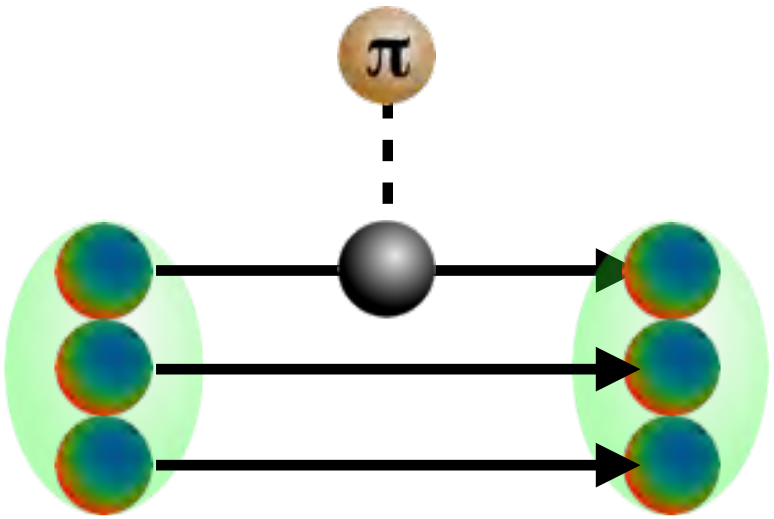
$$\tilde{d}_d \simeq 0.22\bar{g}_\pi^{(1)}$$

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

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

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

T-odd P-odd meson couplings



Estimation of Sensitivity to T-violation

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

and neglecting isovector and isotensor

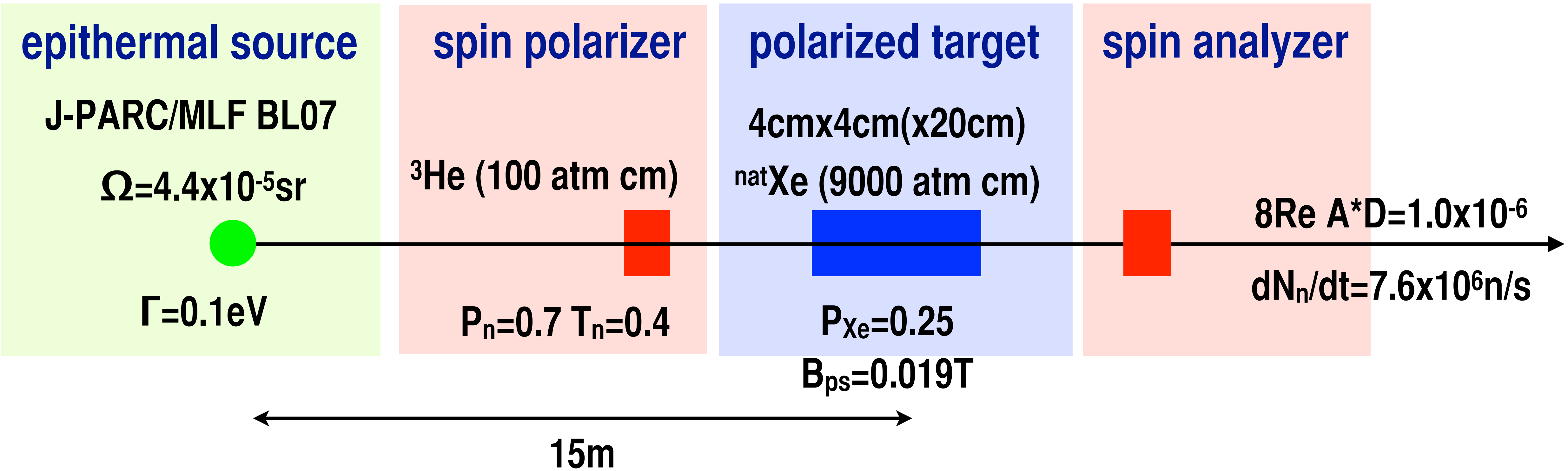
then a discovery potential is at the level of

$$\left|\Delta\sigma_{\mathrm{T}}^{nA}\right| < \underbrace{2.5 \times 10^{-4}[\mathrm{b}]}_{\text{present upper limit}} \times \underbrace{\kappa(J)}_{\sim 1}$$

T-odd term to be measured

NOP-T (Neutron Optics for T-violation)

assembling promising technologies



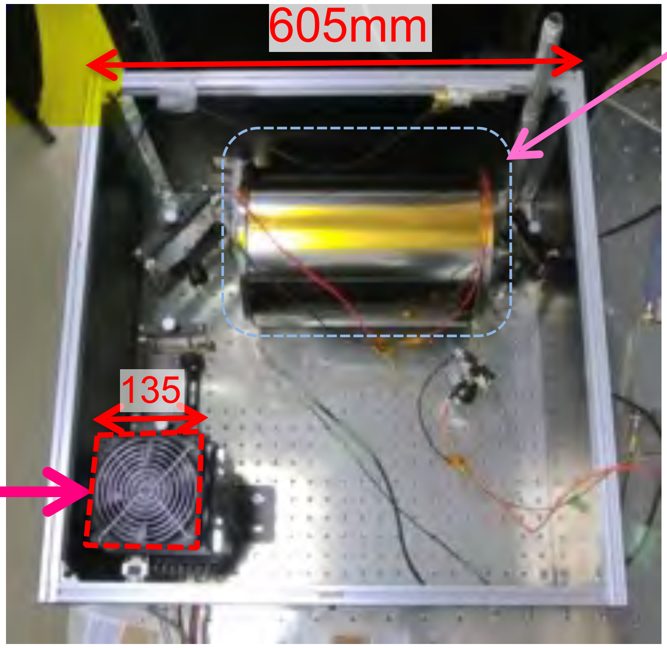
discovery potential → $T \simeq 4 \times 10^5\ [\mathrm{s}] = 4.5\ [\mathrm{days}]$

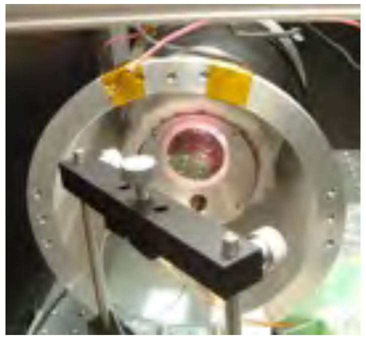
NOP-T (Neutron Optics for T-violation)

Polarized Neutrons

SEOP ^{3}He spin filter is available

7 atm cm → 100 atm cm





Polarized Target

Solid Polarized Xe with laser

Epithermal neutron Detector

^{10}B doped liquid scintillator

Epithermal neutron Optics

epithermal neutron transport optics,spin control, . . .

NOP-T (Neutron Optics for T-violation)

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S.Awano, F.Goto, K.Nagamoto, M.Yokohashi, N.Oi, A.Okada

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RIKEN Y.Yamagata

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Tokyo Institute of Technology K.Asahi

Indiana Univ. W.M.Snow

Summary

CP-Symmetry Tests using Slow Neutrons

Neutron Electric Dipole Moment

Confined Ultracold Neutron aiming $|d_n| \sim 10^{-27}$-10^{-28} e cm

Cold Neutron Diffraction in Single Crystal

$|d_n| < 10^{-26}$ e cm

Entrance Channel of Compound Nuclei

Epithermal Neutron Optics $|d_n| < 10^{-26}$ e cm

aiming $|d_n| < 10^{-27}$ e cm or less

Various approaches with different systematics are important.