Experimental Opportunity at J-PARC

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RIKEN Y.Yamagata

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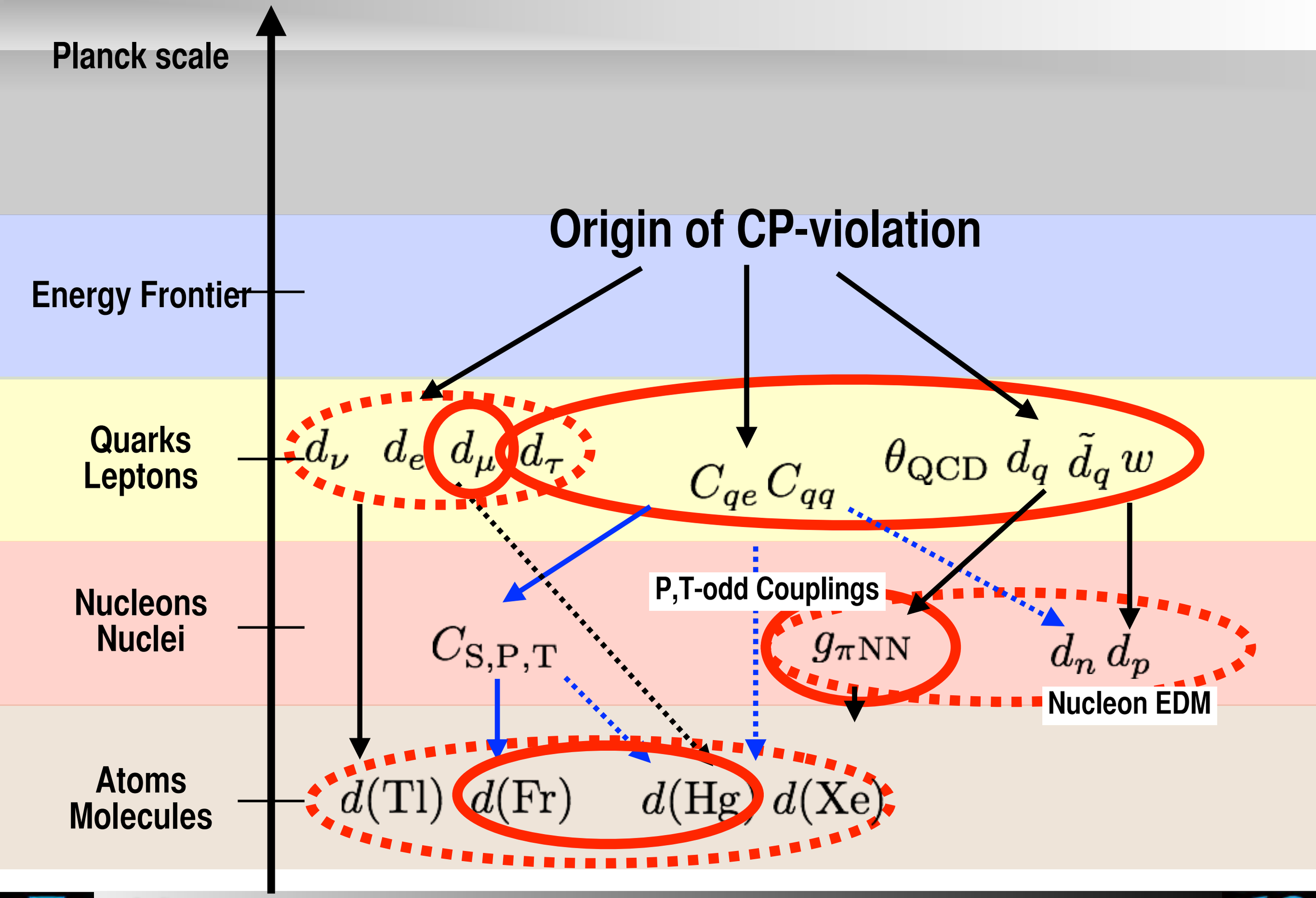
Univ. British Columbia

Y.Yamagata

Tokyo Institute of Technology

K.Asahi

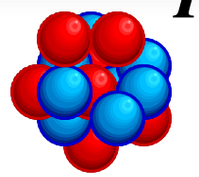
Indiana Univ. W.M.Snow


Planck scale
Origin of CP-violation
Energy Frontier
Quarks
Leptons
d_ν d_e d_μ d_τ
$C_{qe}\, C_{qq}$
$\theta_{\rm QCD}$ d_q $\tilde{d}_q$ w
Nucleons
Nuclei
P,T-odd Couplings
$C_{\rm S,P,T}$
$g_{\pi \rm NN}$
d_n d_p
Nucleon EDM
Atoms
Molecules
$d(\rm Tl)$ $d(\rm Fr)$ $d(\rm Hg)$ $d(\rm Xe)$

Enhanced Sensitivity to P-violation in Nuclear Process

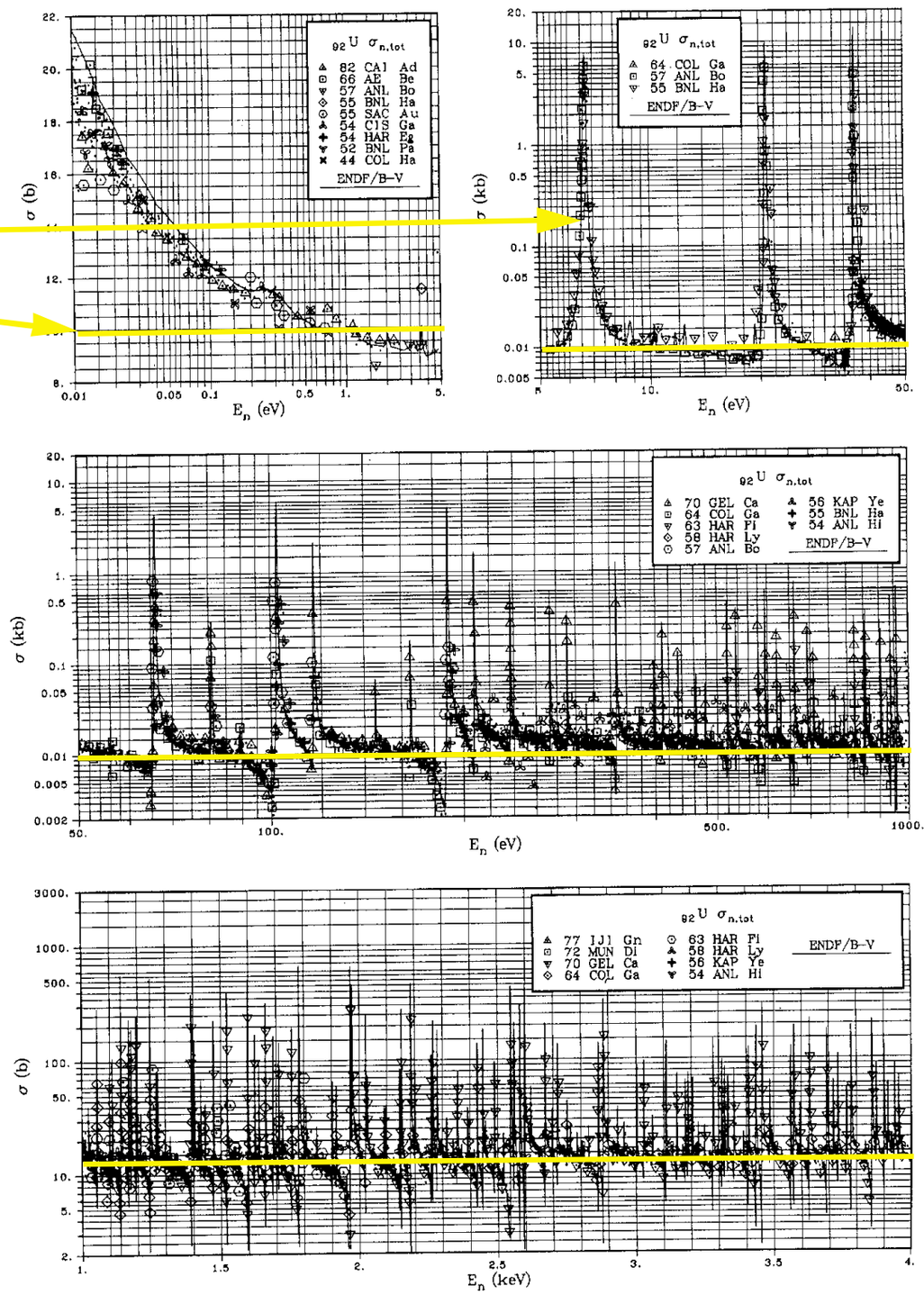
eV neutron capture

$s = 1/2$ $\xrightarrow{l = 0, 1, (2, \ldots)}$ I



$\sigma_{n,tot}$ U

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



Potential Scattering

Compound Resonance

$$\vec{J} = \vec{I} + \vec{j} \qquad \vec{j} = \vec{l} + \vec{s}$$

- $\vec{J}$: spin of the resonance
- $\vec{I}$: target spin
- $\vec{j}$: neutron total angular momentum

$l = 0$

s-wave resonance

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

$l = 1$

p-wave resonance

$j = 1/2$ or $3/2$

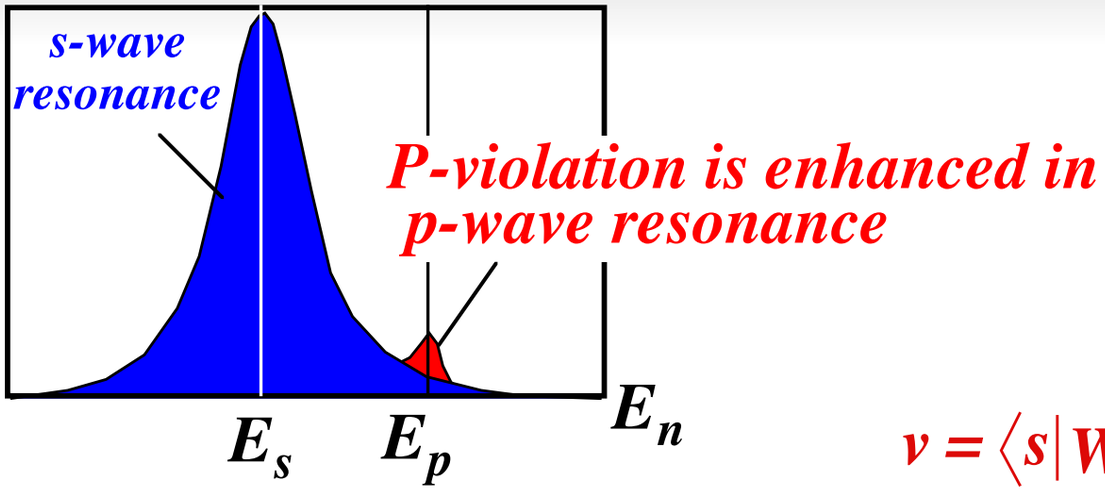
s — $I = 0$ → $J = 1/2$

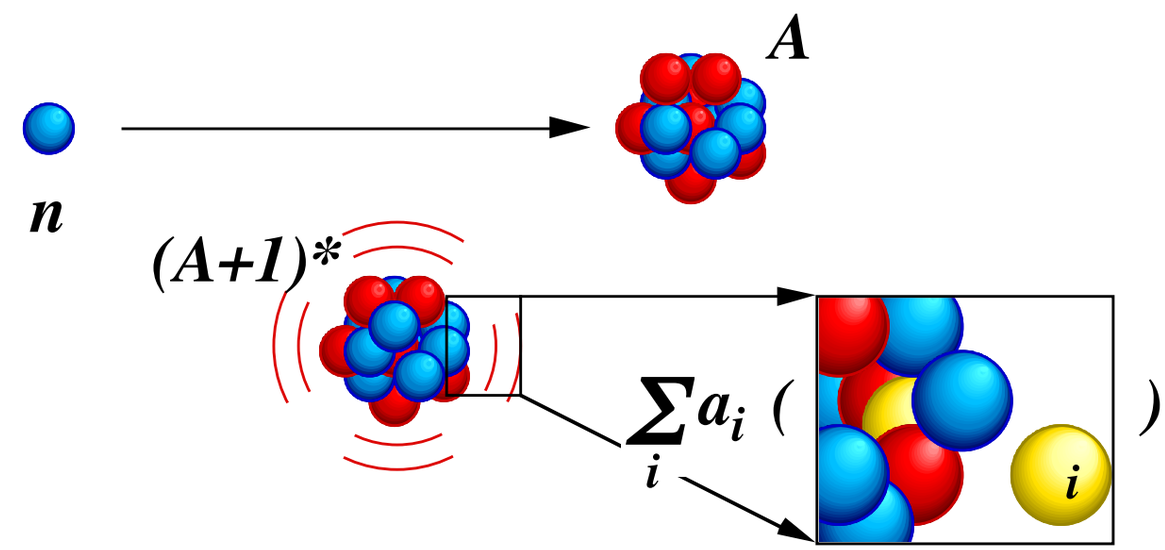
interference (common J)

$p_{1/2}$ — $J = 1/2$

$p_{3/2}$ — $J = 3/2$

Enhancement of P-violation in a Compound State





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

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

interference between neighboring s- and p-wave resonances

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

10 eV

PV in NN interaction

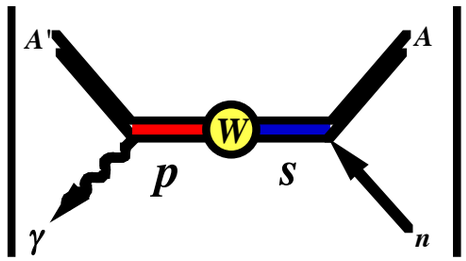
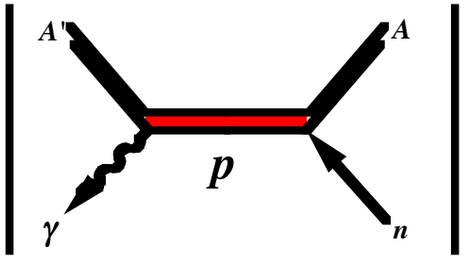
$$\frac{\langle s|W|p\rangle}{E_p - E_s} \sim \frac{\langle W\rangle}{\Delta E}\sqrt{N}$$

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

Parity Mixing (Entrance Channel)

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

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

$$2\,\frac{\left|\begin{array}{c}\text{  }\end{array}\right|}{\left|\begin{array}{c}\text{  }\end{array}\right|} \sim 2\,\frac{\left|\sqrt{\Gamma_p^{\gamma}}\,\dfrac{1}{E_n - E_p + i\dfrac{\Gamma_p}{2}}\,W\,\dfrac{1}{E_n - E_s + i\dfrac{\Gamma_s}{2}}\sqrt{\Gamma_s^{n}}\right|}{\left|\sqrt{\Gamma_p^{\gamma}}\,\dfrac{1}{E_n - E_p + i\dfrac{\Gamma_p}{2}}\sqrt{\Gamma_p^{n}}\right|} \sim \frac{2W}{\left|E_n - E_s + i\dfrac{\Gamma_s}{2}\right|}\sqrt{\frac{\Gamma_s^{n}}{\Gamma_p^{n}}}$$

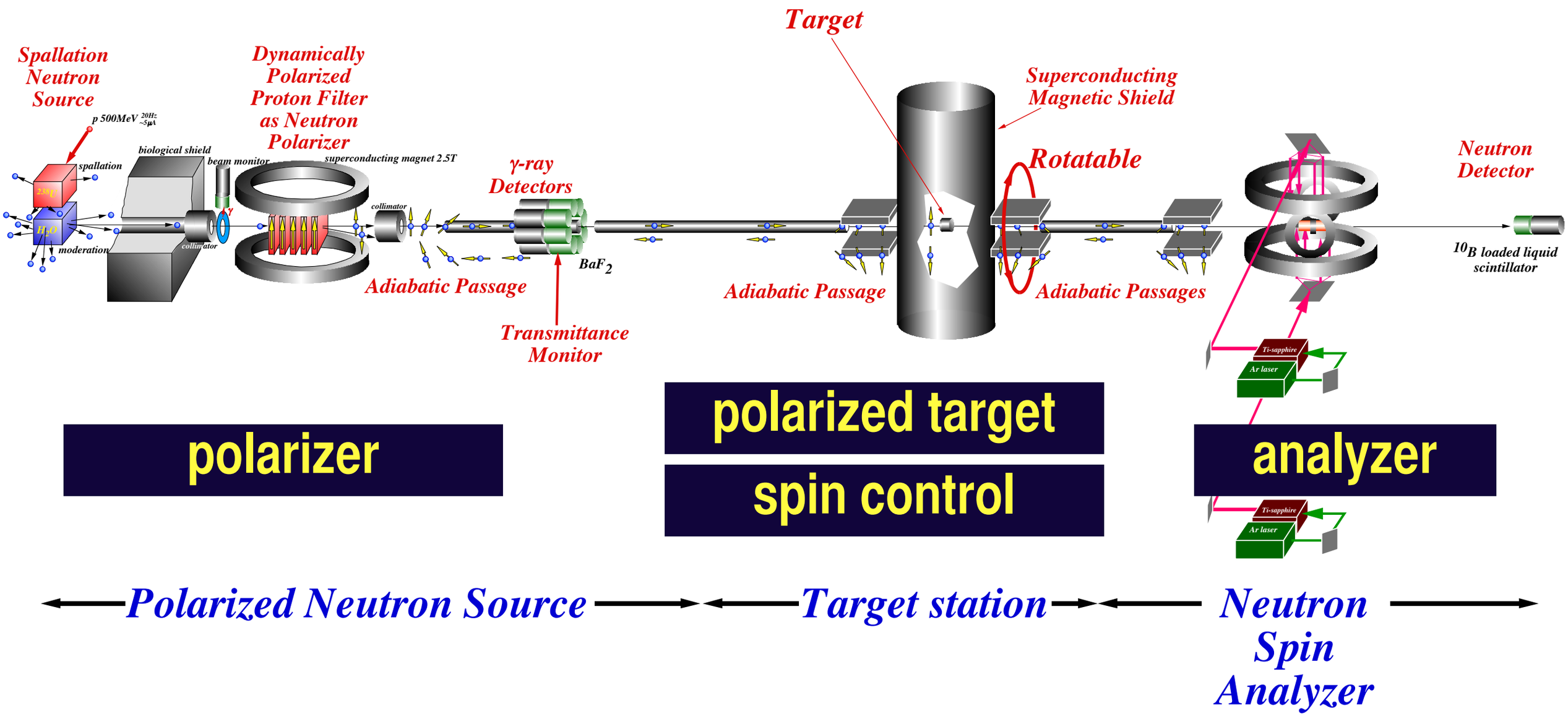
$$\xrightarrow[E_n = E_p]{} \frac{2W}{|E_p - E_s|}\sqrt{\frac{\Gamma_s^{n}}{\Gamma_p^{n}}}$$

Dynamic Enhancement $10^2 \sim 10^3$

Structural Enhancement

Kinematical Enhancement $\sim 10^3$

Experimental Appratus



Principle used in this estimation

Gudkov, Phys. Rep. 212 (1992) 77

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

T-violation

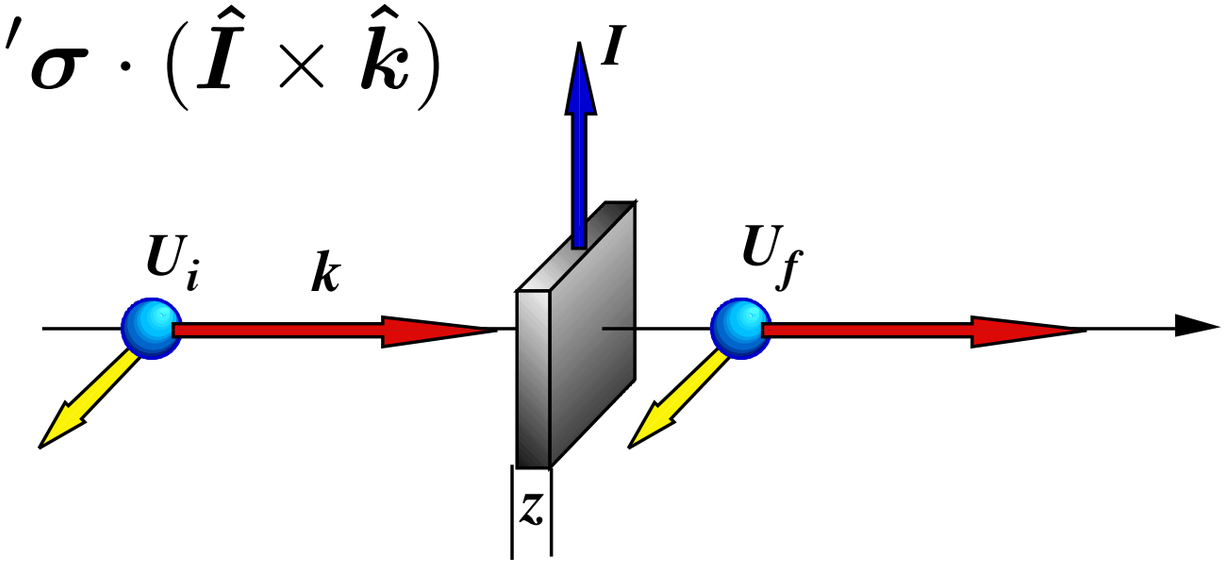
g_{CP}/g_P

P-violation

present d_n upper limit corresponds to 10^{-3}

T-violation in Neutron Optics

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



$$U_f = \delta U_i$$

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

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

$$A = e^{iZA'}\cos b$$

$$B = ie^{iZA'}\frac{\sin b}{b} ZB'$$

$$C = ie^{iZA'}\frac{\sin b}{b} ZC'$$

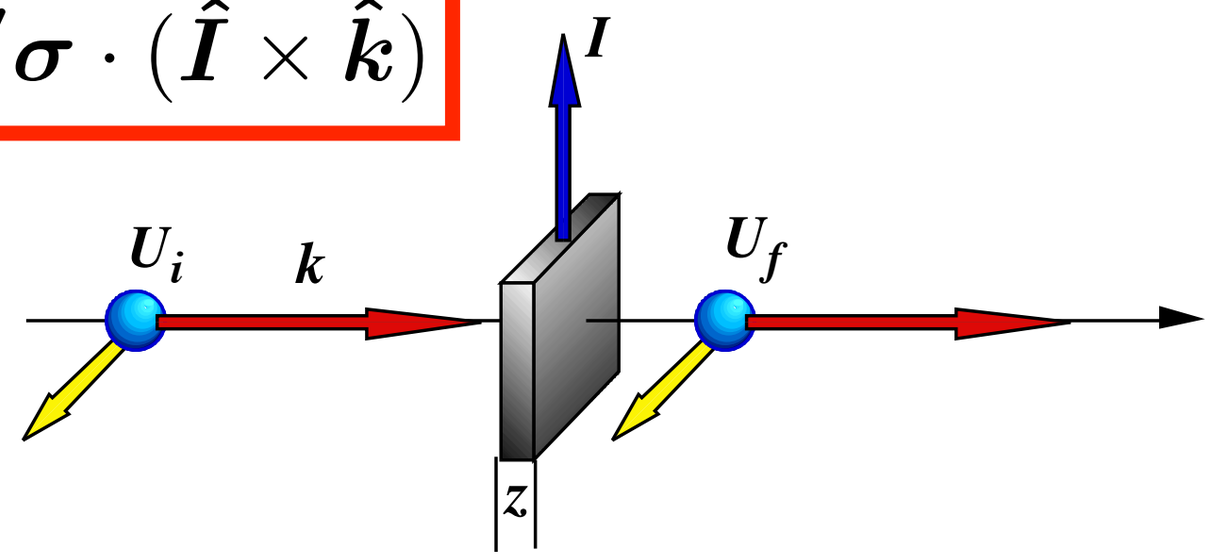
$$D = ie^{iZA'}\frac{\sin b}{b} ZD'$$

$$Z = \frac{2\pi\rho}{k} z$$

$$b = Z(B'^2 + C'^2 + D'^2)^{1/2}$$

T-violation in Neutron Optics

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



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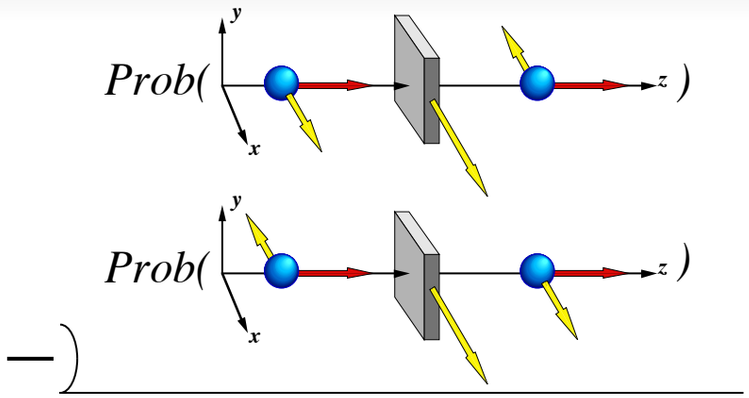
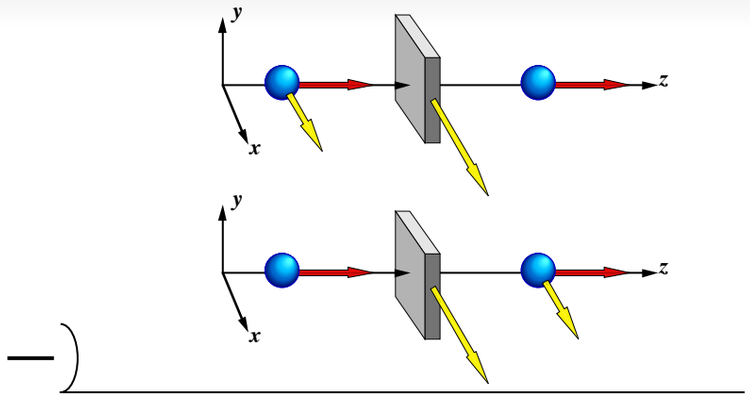
$$b = Z(B'^2 + C'^2 + D'^2)^{1/2}$$

Polarization Transfer

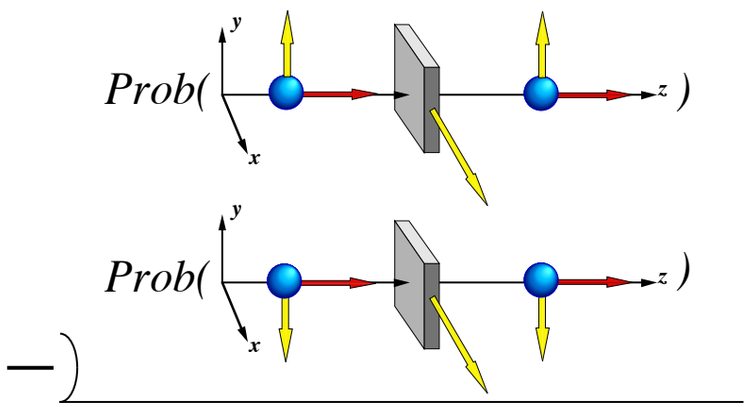
A(Analyzing Power) & P(Polarization)



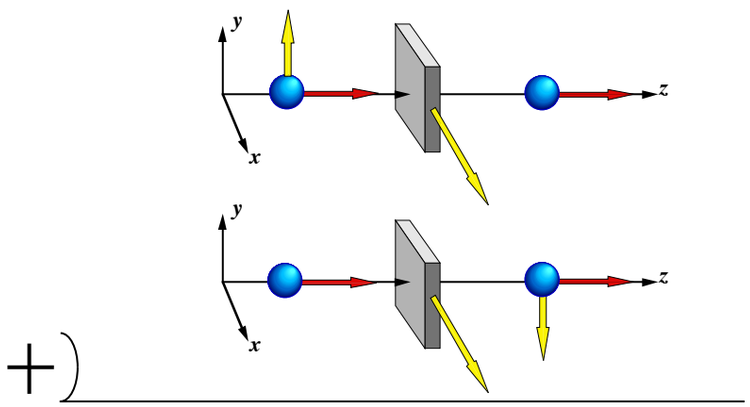
4 Im C*D



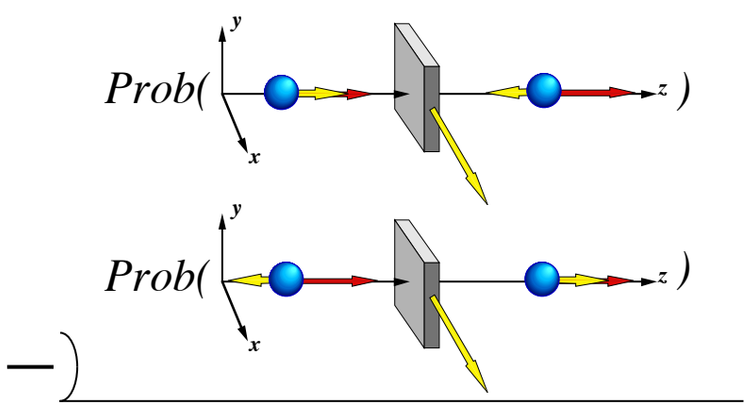
– 8 Im C*D



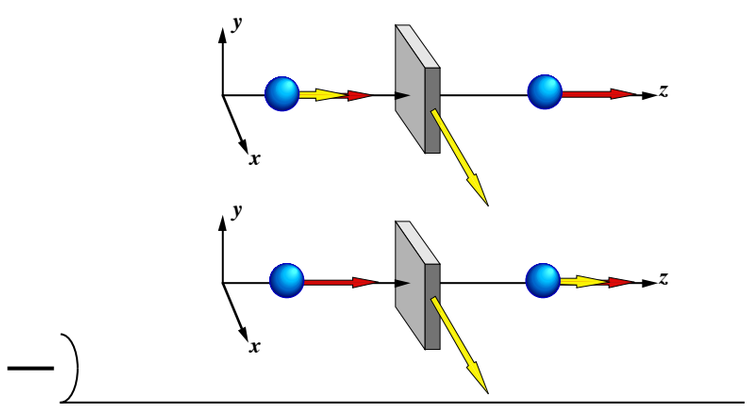
4 Im A*D



8 Re A*D



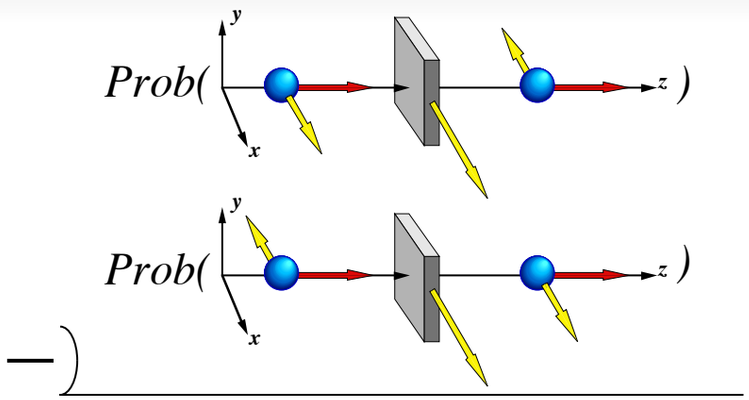
4 Im B*D



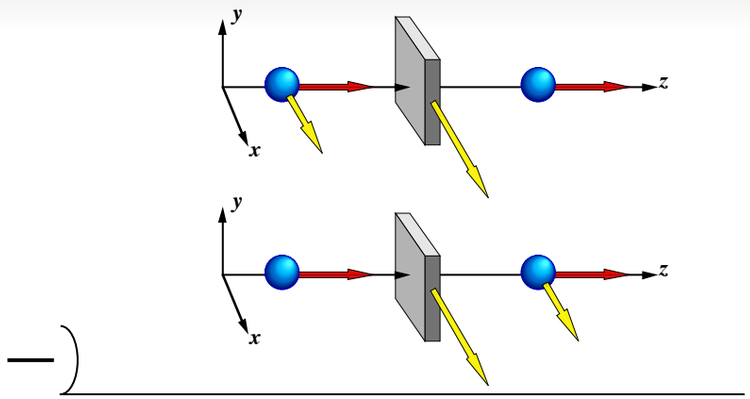
8 Im B*D

Polarization Transfer

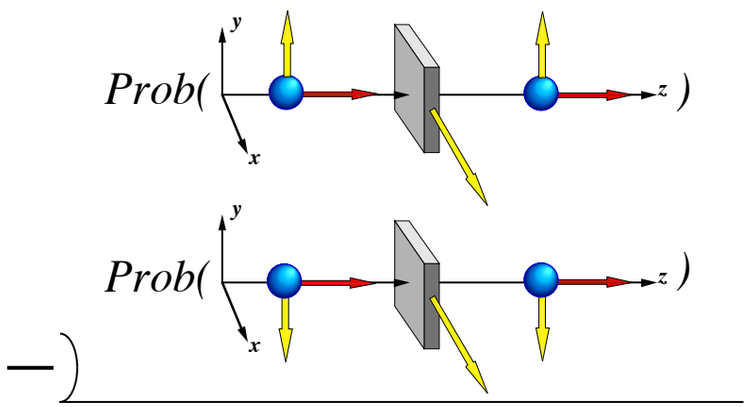
A(Analyzing Power) & P(Polarization)



4 Im C*D



− 8 Im C*D



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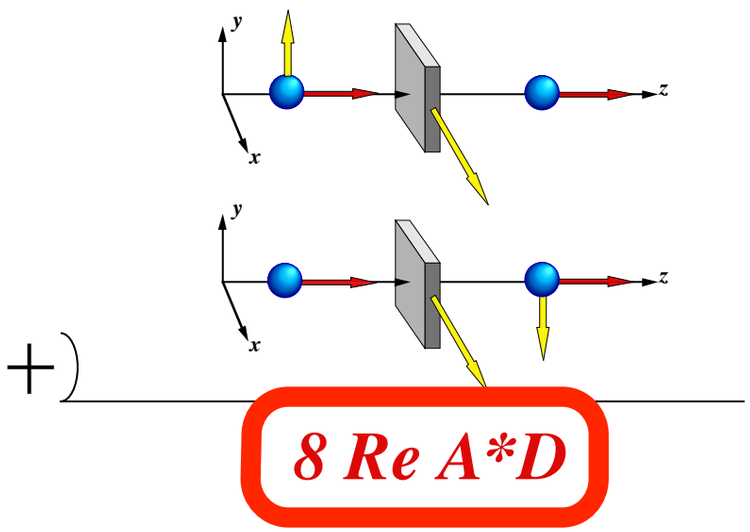
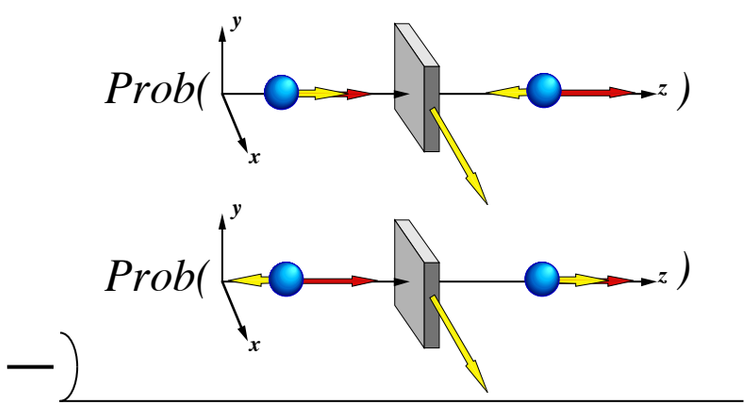
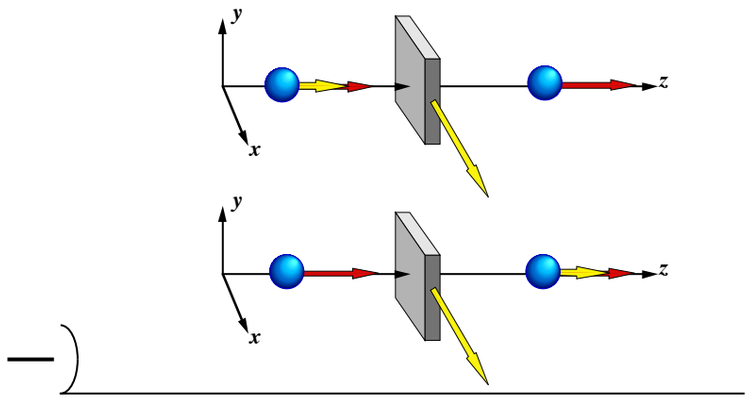


8 Re A*D

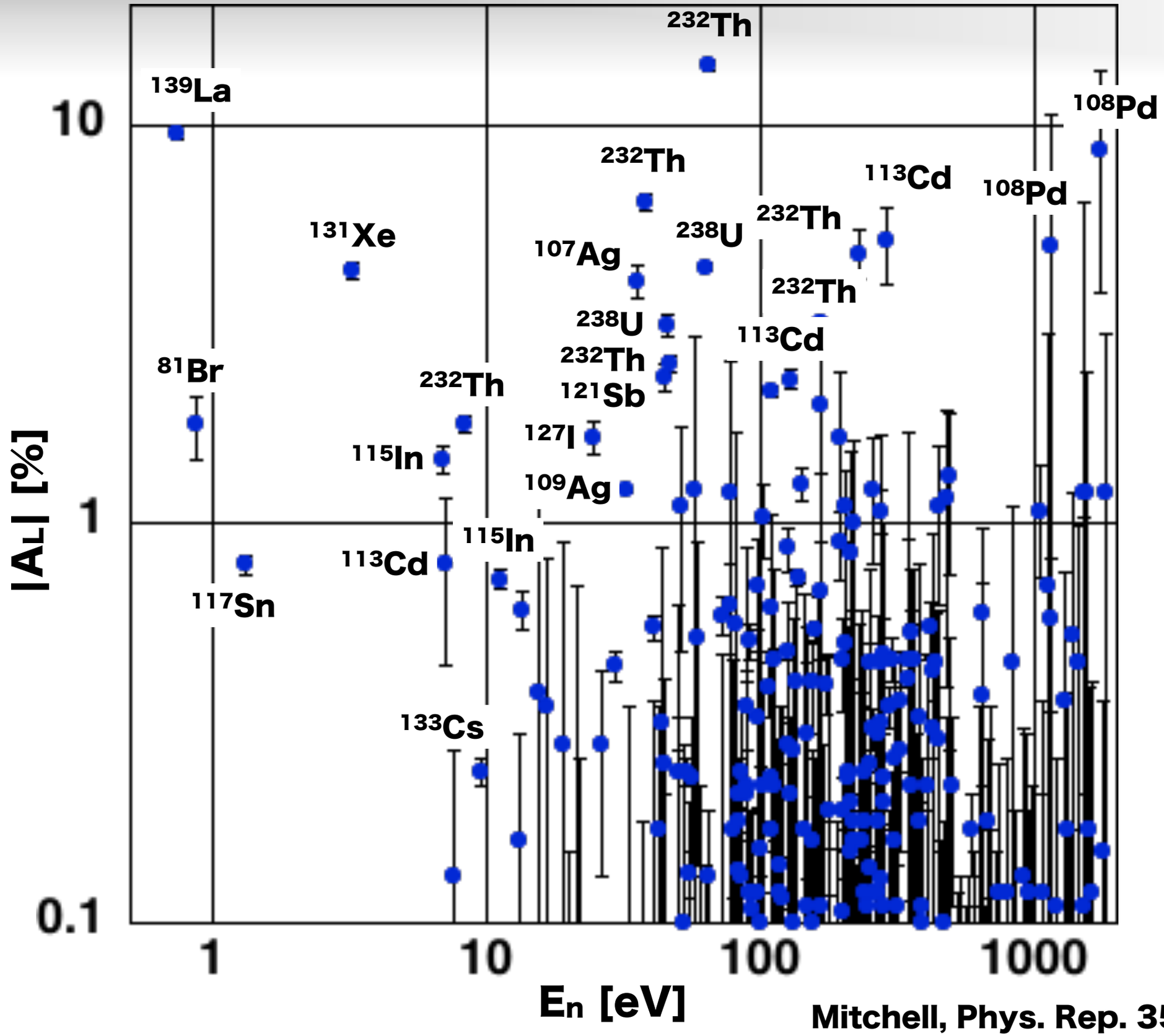


4 Im B*D

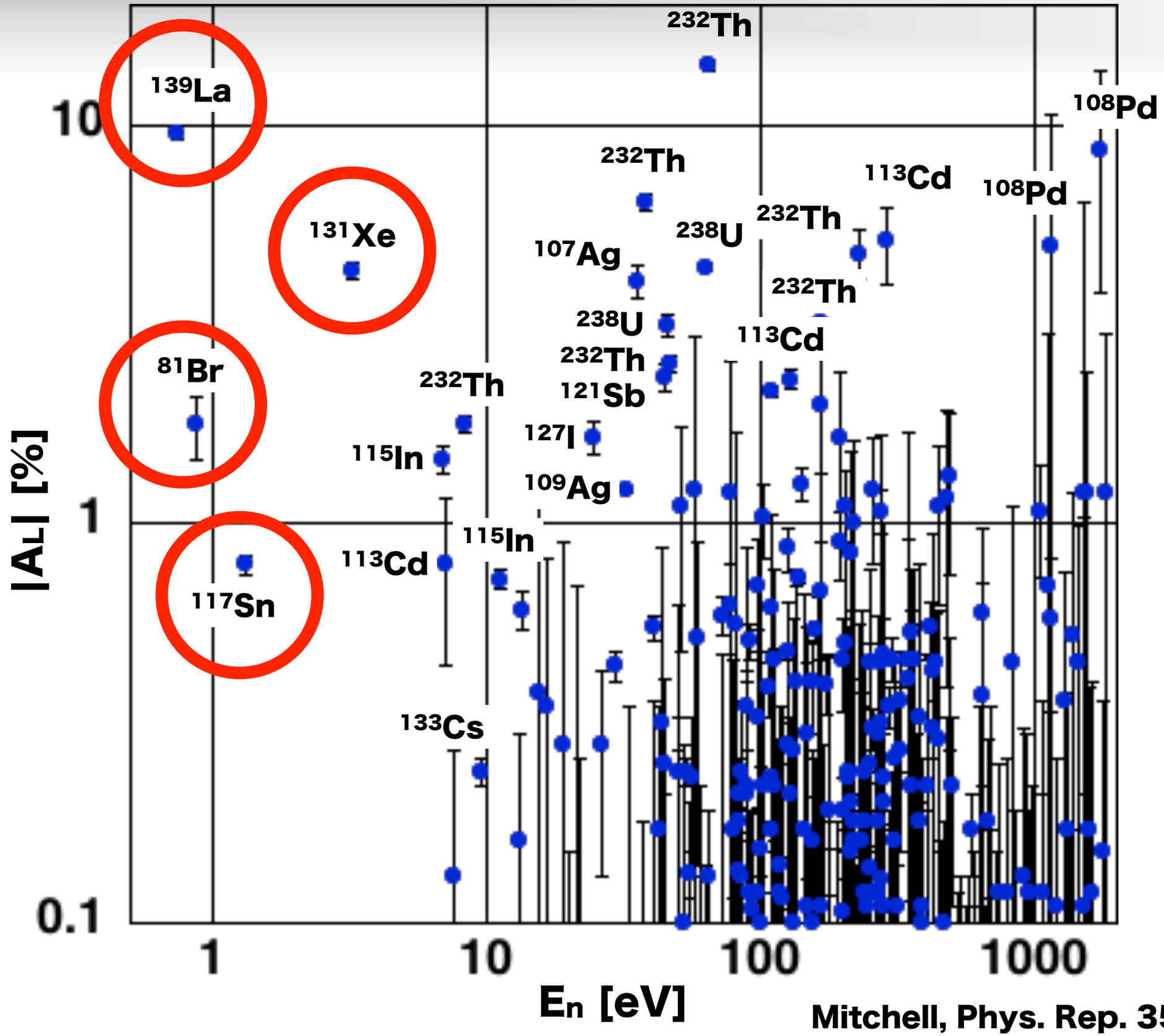


8 Im B*D

Choice of Target Nucleus



Mitchell, Phys. Rep. 354 (2001) 157

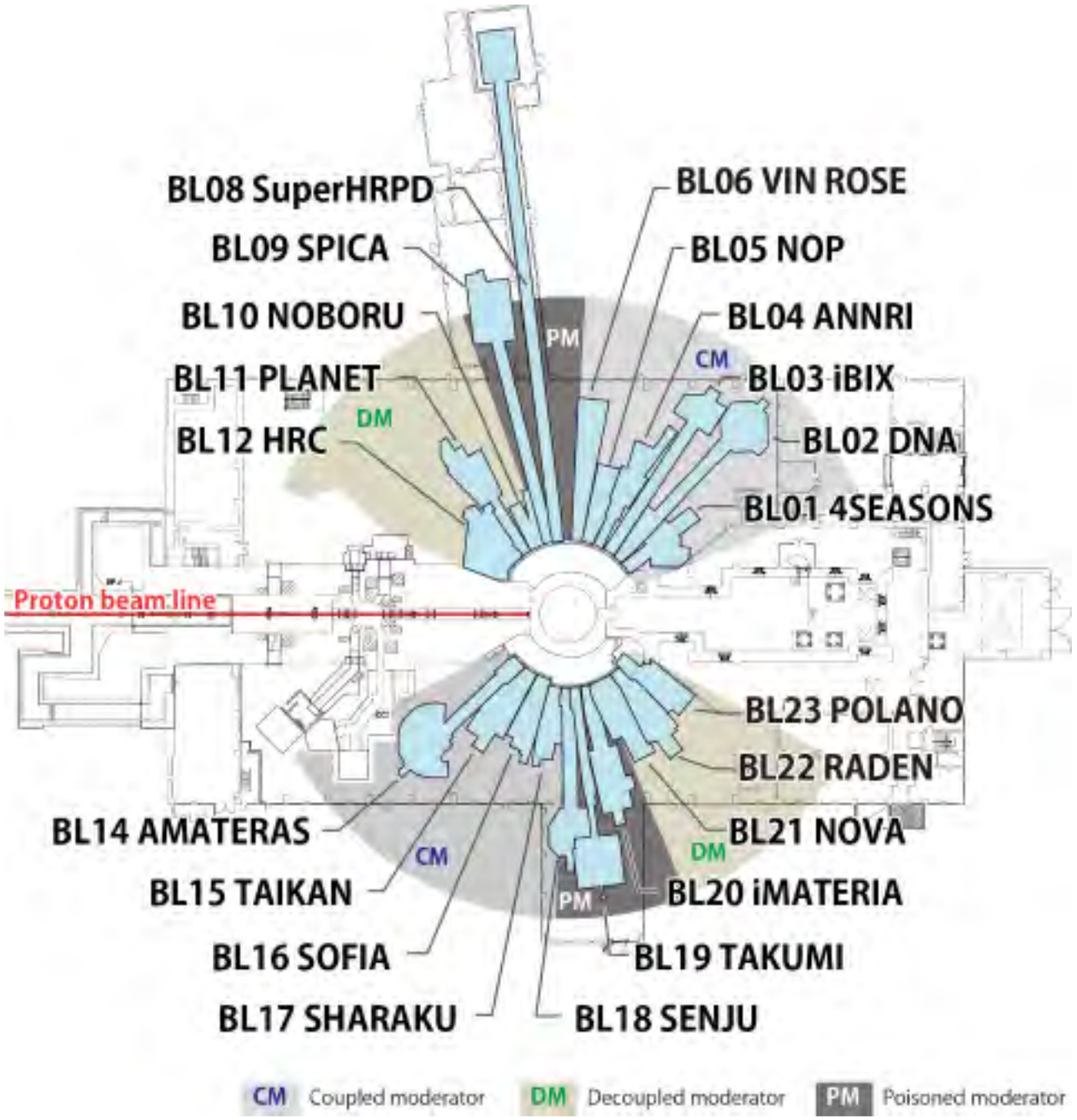


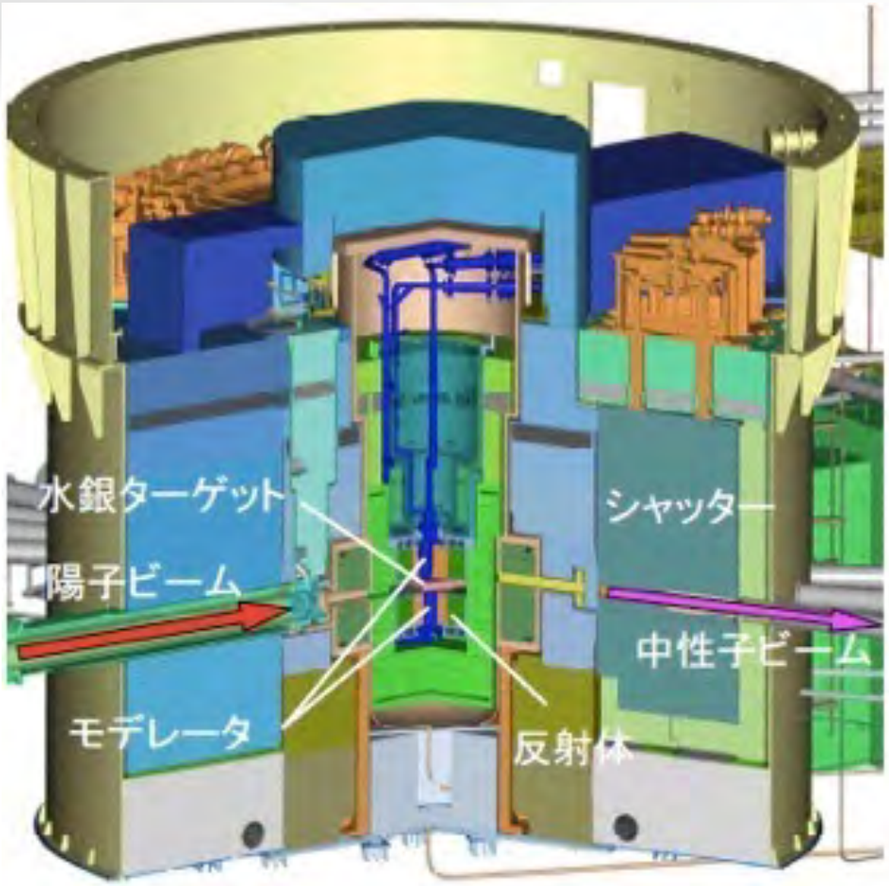
Mitchell, Phys. Rep. 354 (2001) 157

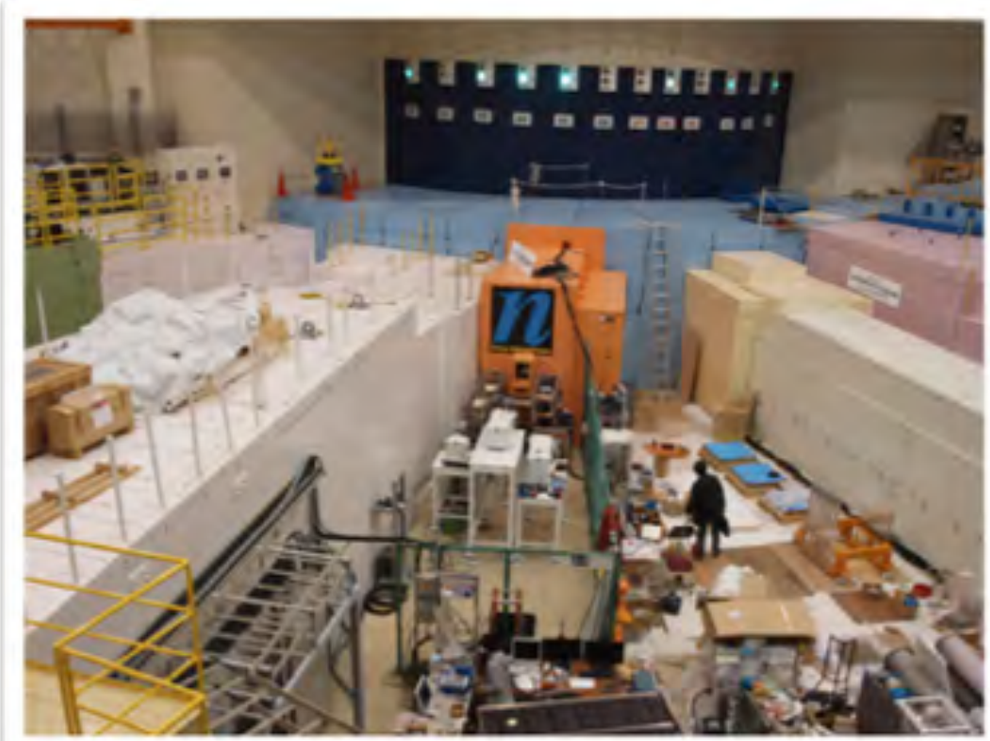
	^{139}La	^{81}Br	^{117}Sn	^{131}Xe
$\Delta\sigma_P$	◎	○	◎	◎
E_p [eV]		epithermal ~eV		

Polarized Epithermal Neutron Beam

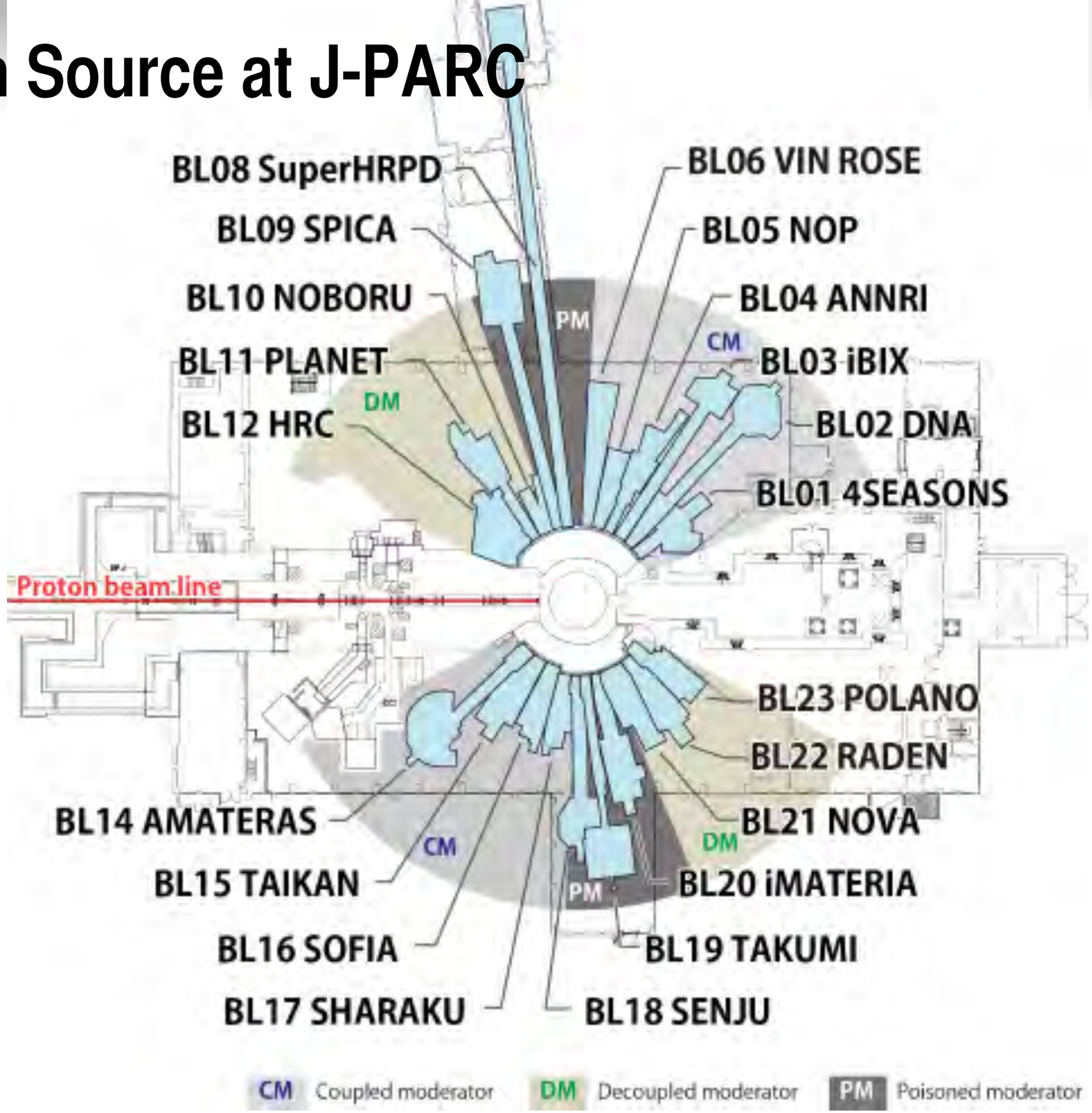
Spallation Source at J-PARC

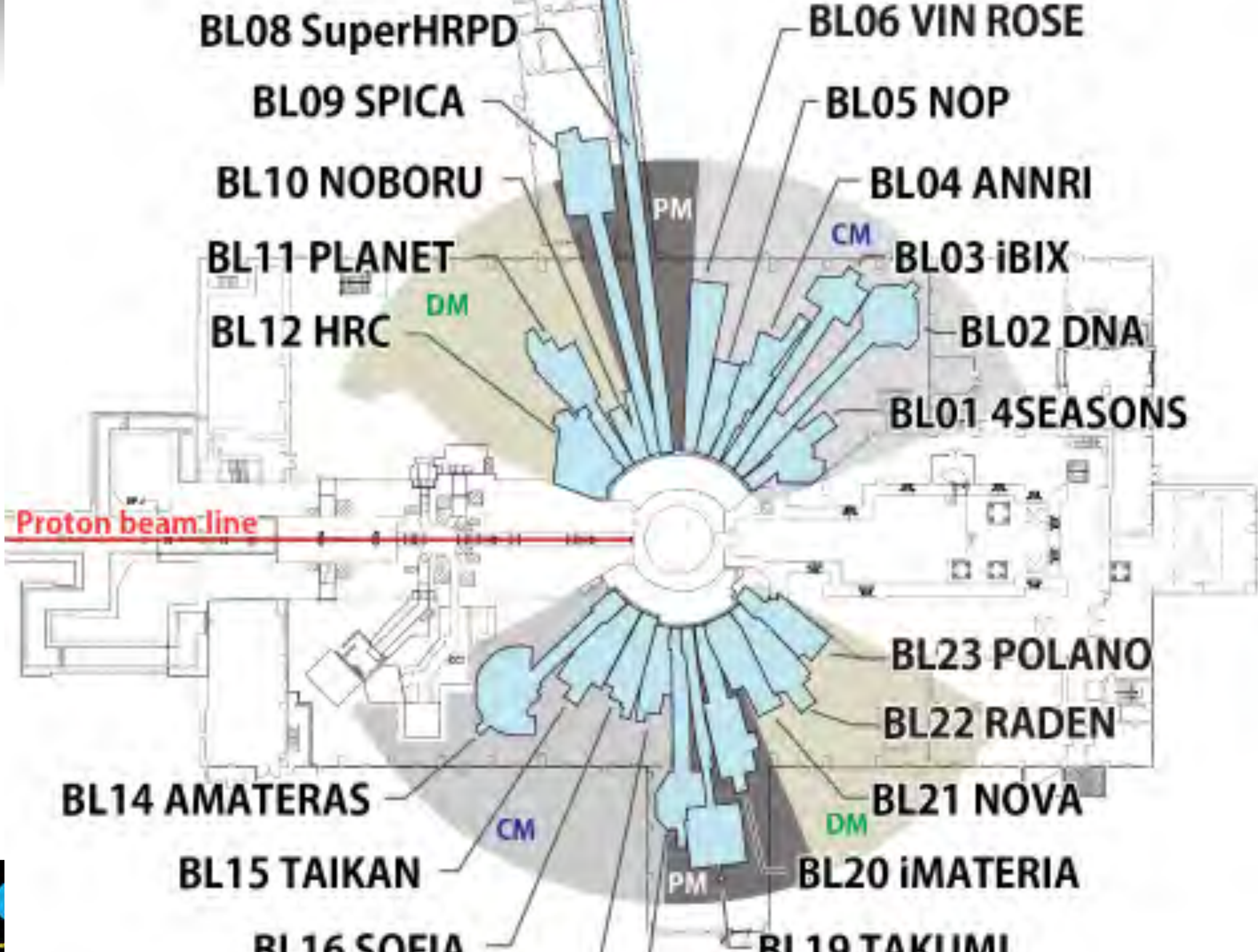


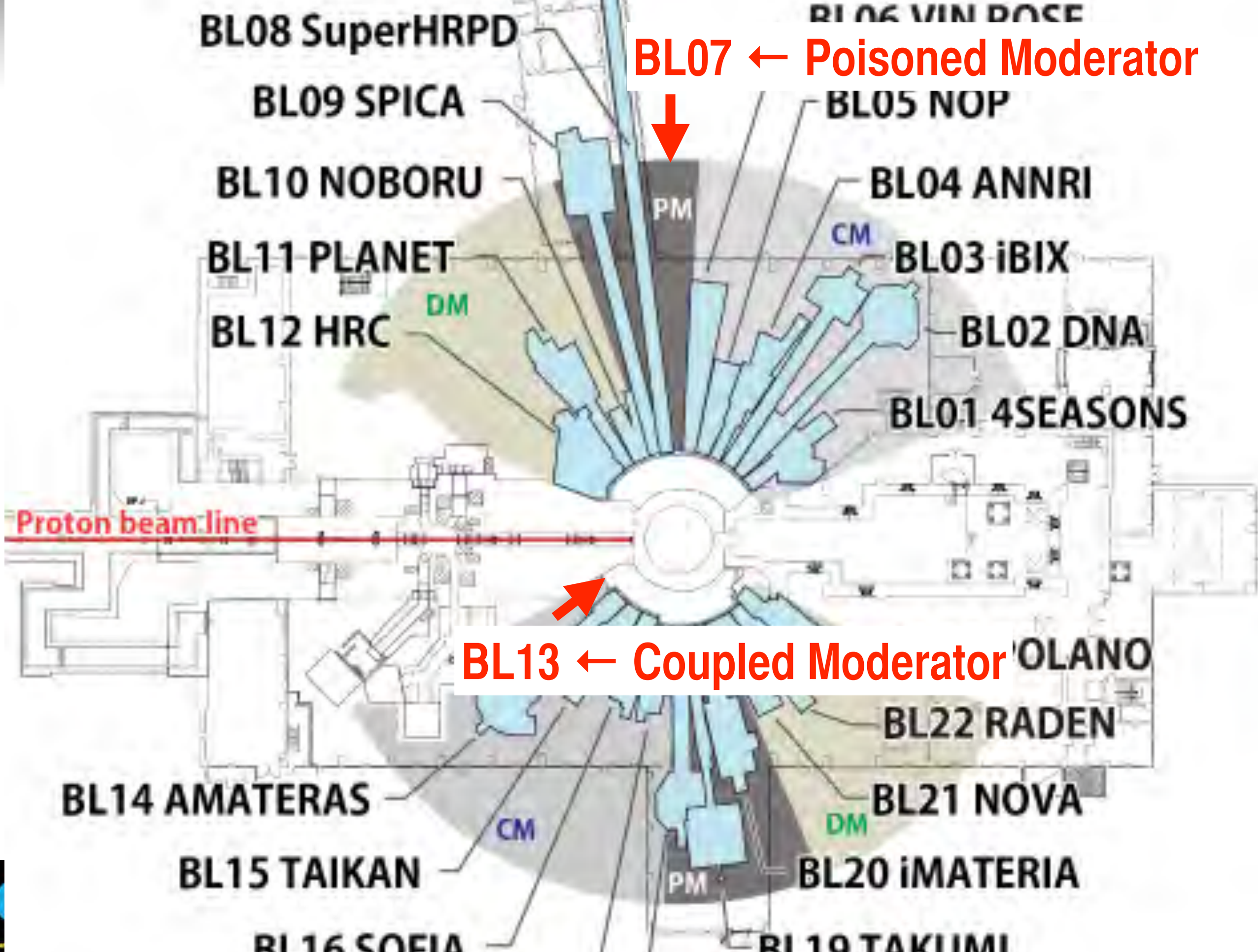




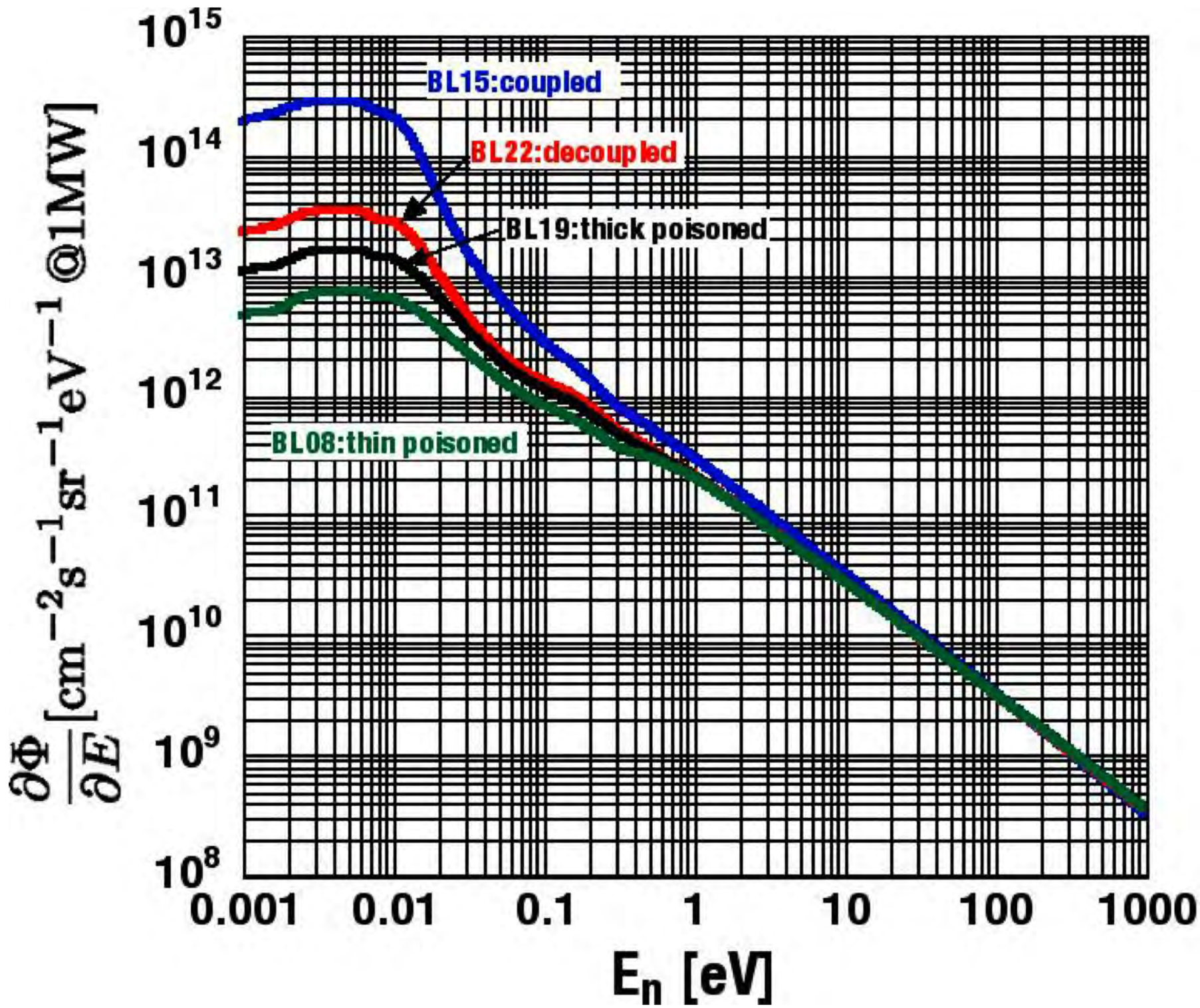
Spallation Source at J-PARC



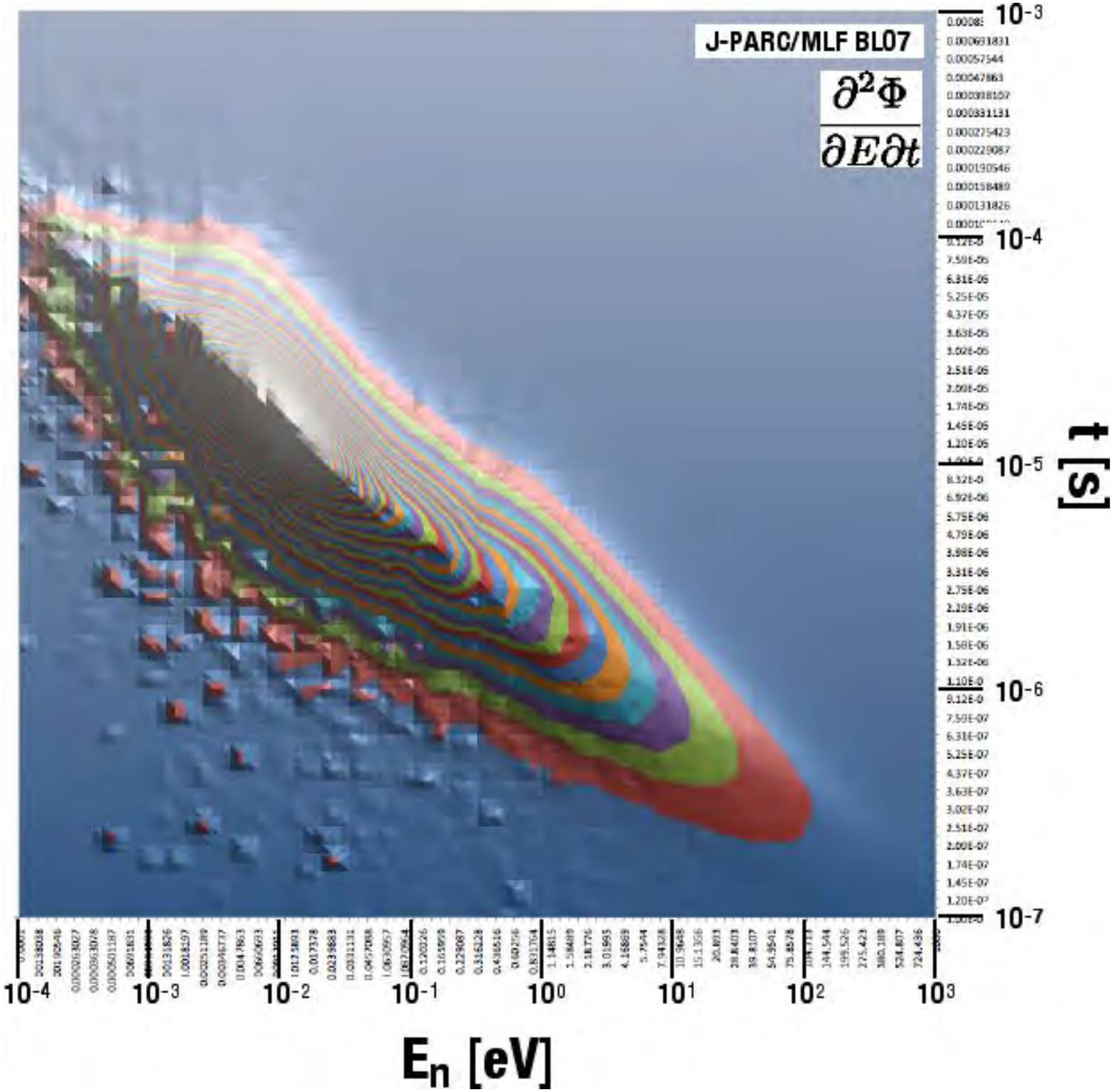

BL08 SuperHRPD
BL09 SPICA
BL10 NOBORU
BL11 PLANET
BL12 HRC
BL06 VIN ROSE
BL05 NOP
BL04 ANNRI
BL03 iBIX
BL02 DNA
BL01 4SEASONS
PM
CM
DM
Proton beam line
BL23 POLANO
BL22 RADEN
BL21 NOVA
BL20 iMATERIA
BL19 TAKUMI
BL14 AMATERAS
BL15 TAIKAN
BL16 SOFIA
CM
DM
PM


BL08 SuperHRPD
BL09 SPICA
BL10 NOBORU
BL11 PLANET
BL12 HRC
DM
PM
BL07 ← Poisoned Moderator
BL05 NOP
BL04 ANNRI
CM
BL03 iBIX
BL02 DNA
BL01 4SEASONS
Proton beam line
BL13 ← Coupled Moderator
BL22 RADEN
BL14 AMATERAS
CM
BL21 NOVA
DM
BL15 TAIKAN
PM
BL20 iMATERIA
BL16 SOFIA
BL19 TAKUMI

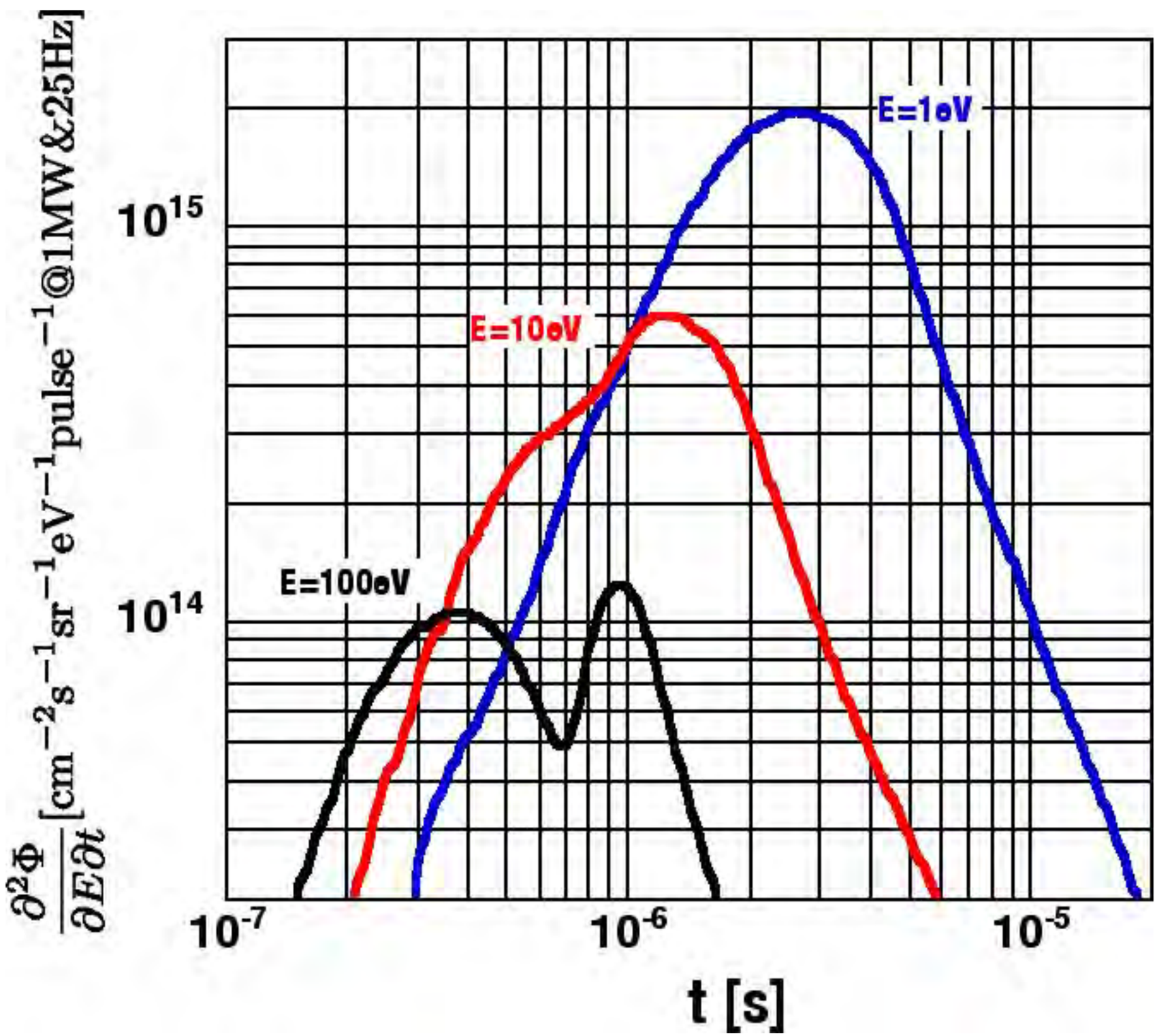
BL07 Beam Intensity



Pulse Shape


J-PARC/MLF BL07
$\frac{\partial^2 \Phi}{\partial E \partial t}$
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
t [s]
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
E_n [eV]

Pulse Shape


E=1eV
E=10eV
E=100eV
10^{15}
10^{14}
10^{-7}
10^{-6}
10^{-5}
t [s]
$\frac{\partial^2\Phi}{\partial E\partial t}$ [cm^{-2}s^{-1}sr^{-1}eV^{-1}pulse^{-1}@1MW&25Hz]

	^{139}La	^{81}Br	^{117}Sn	^{131}Xe
$\Delta\sigma_P$	◎	○	◎	◎
E_p [eV]	◎	◎	○	○

	^{139}La	^{81}Br	^{117}Sn	^{131}Xe
$\Delta\sigma_P$	◎	○	◎	◎
E_p [eV]	◎	◎	○	○
I	7/2 △	3/2 ○	1/2 ◎	3/2 ○
isotopic abn	◎	○	×	△

	^{139}La	^{81}Br	^{117}Sn	^{131}Xe
$\Delta\sigma_P$	◎	○	◎	◎
E_p [eV]	◎	◎	○	○
I	7/2 △	3/2 ○	1/2 ◎	3/2 ○
isotopic abn	◎	○	×	△
κ(J)				

	^{139}La	^{81}Br	^{117}Sn	^{131}Xe
$\Delta\sigma_P$	◎	○	◎	◎
E_p [eV]	◎	◎	○	○
I	7/2 △	3/2 ○	1/2 ◎	3/2 ○
isotopic abn	◎	○	×	△
κ(J)				

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

T-violation g_{CP}/g_P P-violation

Gudkov, Phys. Rep. 212 (1992) 77

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

T-violation g_{CP}/g_P P-violation

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

$$\boldsymbol{j} = \boldsymbol{l} + \boldsymbol{s}$$

$$\boldsymbol{S} = \boldsymbol{s} + \boldsymbol{I}$$

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

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

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

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

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

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

Gudkov, Phys. Rep. 212 (1992) 77

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

T-violation **g_{CP}/g_P** **P-violation**

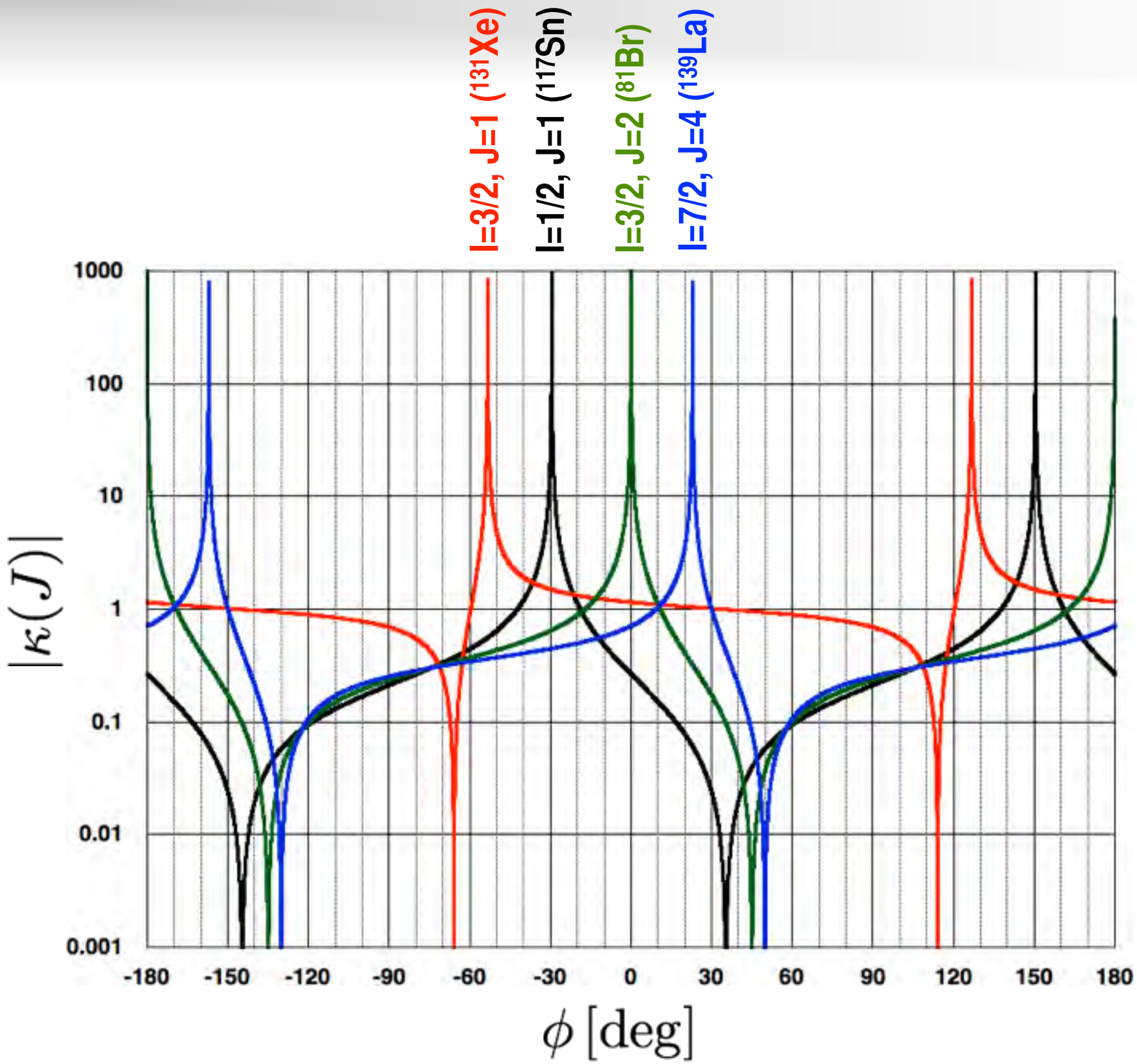
$$\kappa(J = I + \frac{1}{2}) = \frac{3}{2\sqrt{2}}\left(\frac{2I+1}{2I+3}\right)\frac{\sqrt{2I+1}(2\sqrt{I}x - \sqrt{2I+3}y)}{(2I-3)\sqrt{2I+3}x - (2I+9)\sqrt{I}y}$$

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

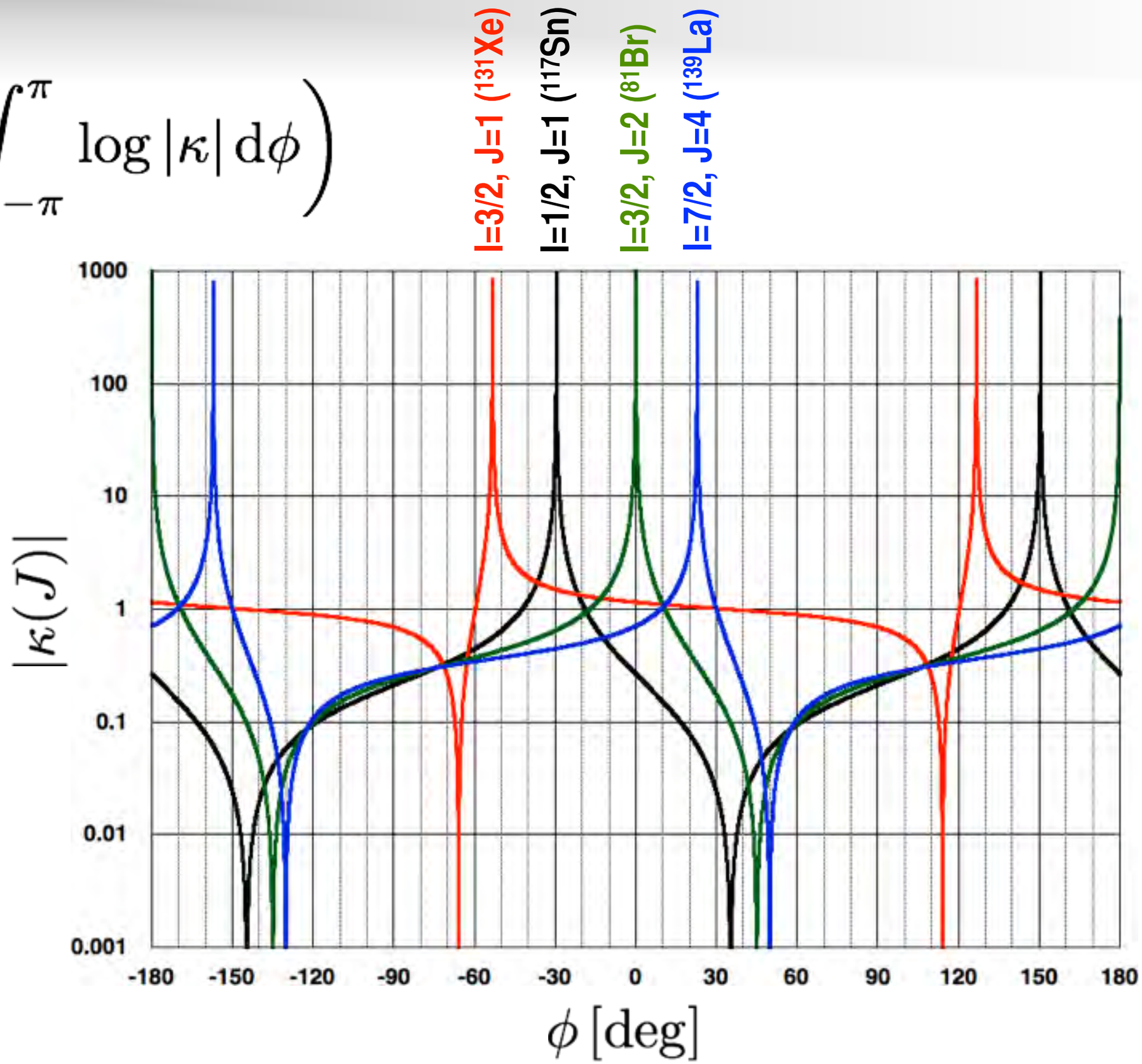
$$x^2 = \frac{\Gamma^n_{p,1/2}}{\Gamma^n_p} \qquad y^2 = \frac{\Gamma^n_{p,3/2}}{\Gamma^n_p}$$

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

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


I=3/2, J=1 (131Xe)
I=1/2, J=1 (117Sn)
I=3/2, J=2 (81Br)
I=7/2, J=4 (139La)
1000
100
10
1
0.1
0.01
0.001
|κ(J)|
-180
-150
-120
-90
-60
-30
0
30
60
90
120
150
180
φ [deg]

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



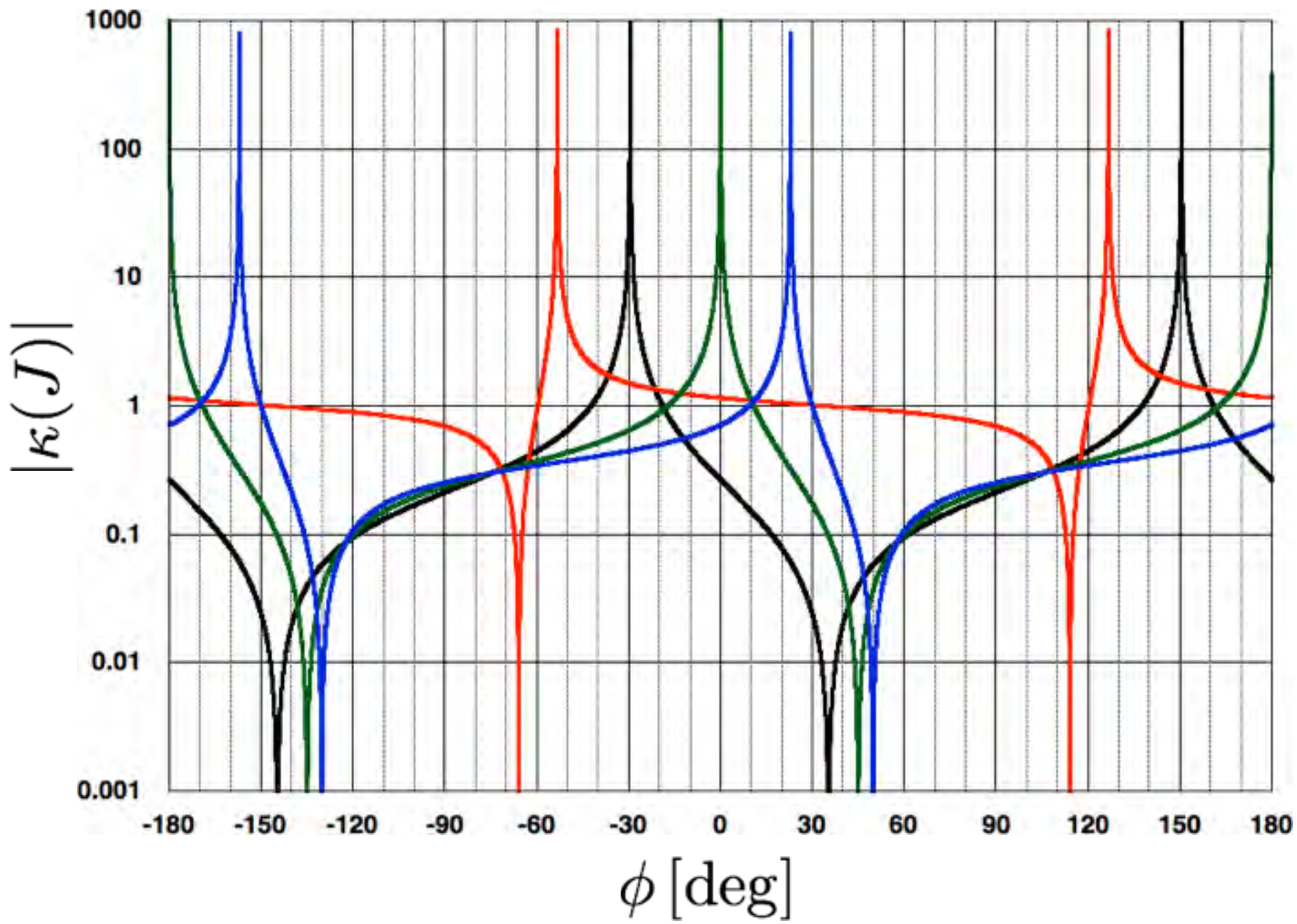
$$\overline{|\kappa|} \equiv \exp\left(\frac{1}{2\pi}\int_{-\pi}^{\pi} \log|\kappa|\,\mathrm{d}\phi\right)$$

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

The case of

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

is generally advantageous.



(n,γ) Cross Section (un-polarized case)

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

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

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

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

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

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

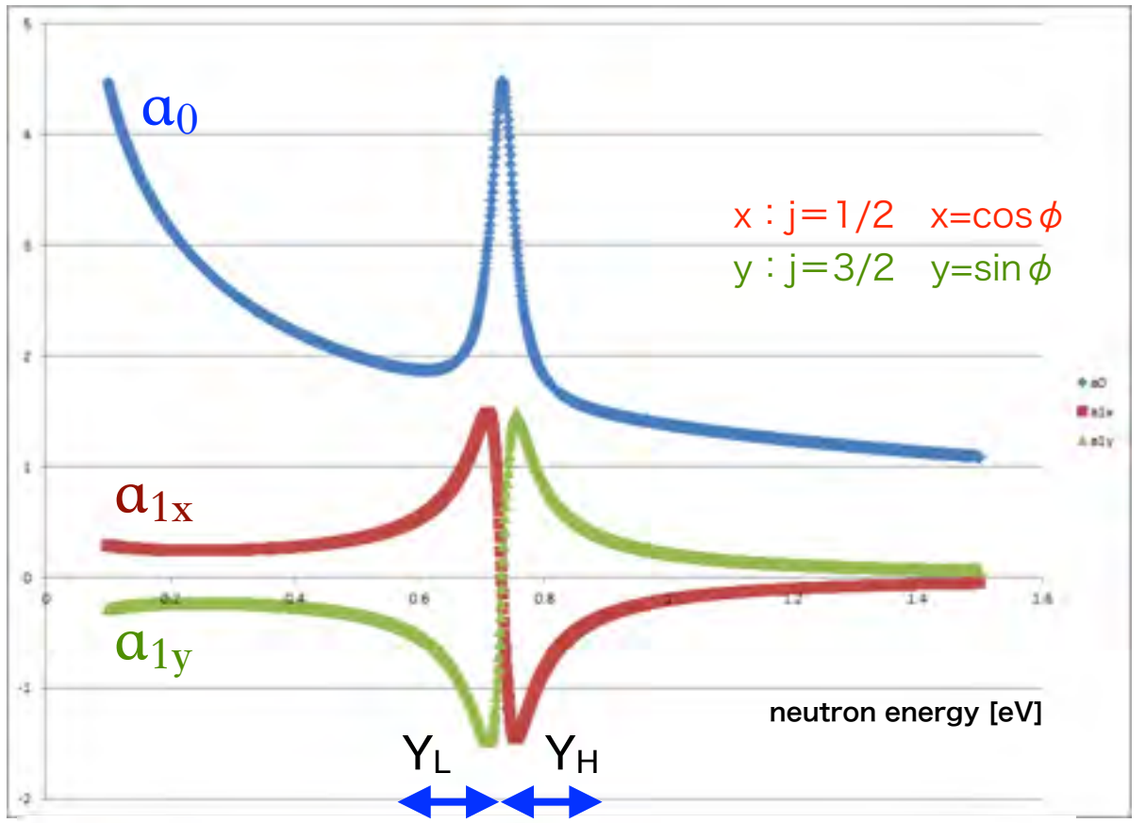
$V_2(j=1/2)=xV_2 = V_2\cos\varphi$

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

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

a_0, a_1 and a_3 Calcuration

^{139}La(n,γ) P-wave resonance 0.73 eV

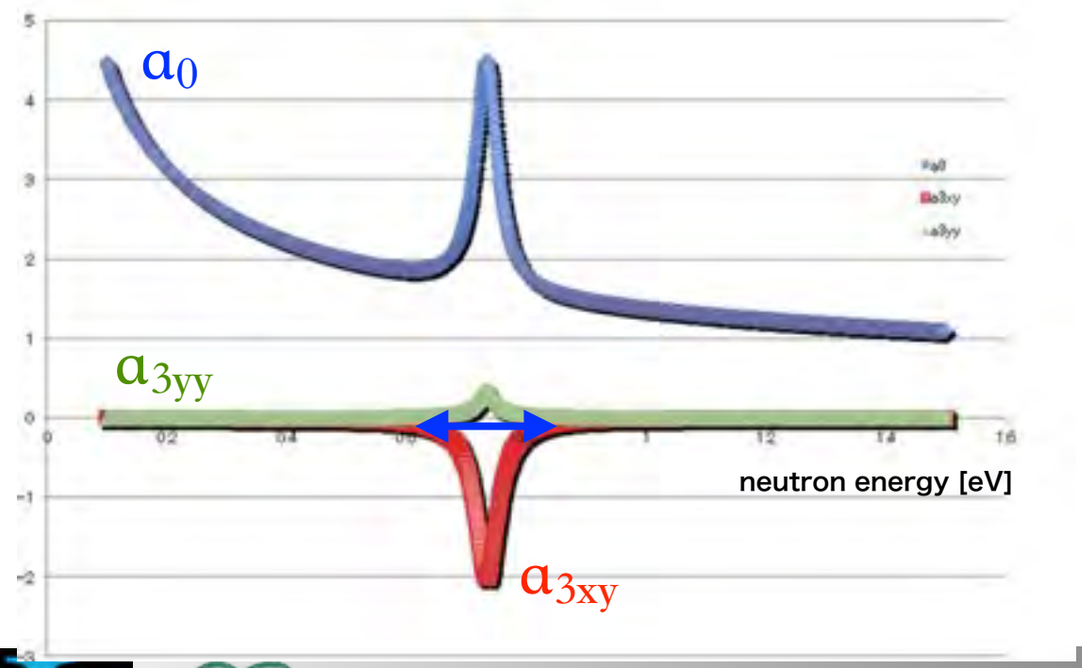


$$\frac{d\sigma}{d\Omega} = \frac{1}{2}(a_0 + a_1 \mathbf{k}_n \cdot \mathbf{k}_\gamma + a_3((\mathbf{k}_n \cdot \mathbf{k}_\gamma)^2 - \frac{1}{3}))$$

$$a_1 = a_{1x} cos\phi + a_{1y} sin\phi$$

$$a_3 = a_{3xy} cos\phi sin\phi + a_{3yy} sin^2\phi$$

The Coefficients a_{1x} and a_{1y} change their sign at resonance energy.



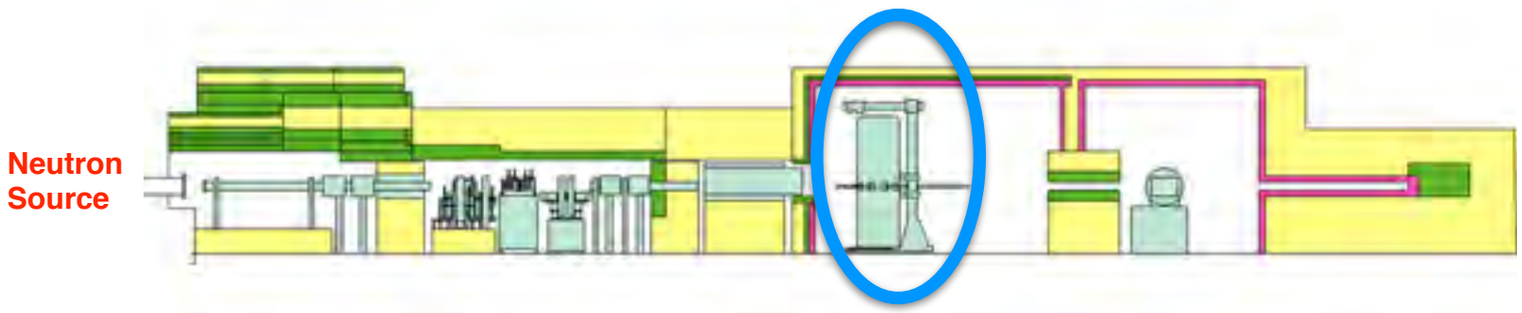
We determine the ϕ by comparing the experimental and theoretical values of

$$\frac{Y_L - Y_H}{Y_L + Y_H}.$$

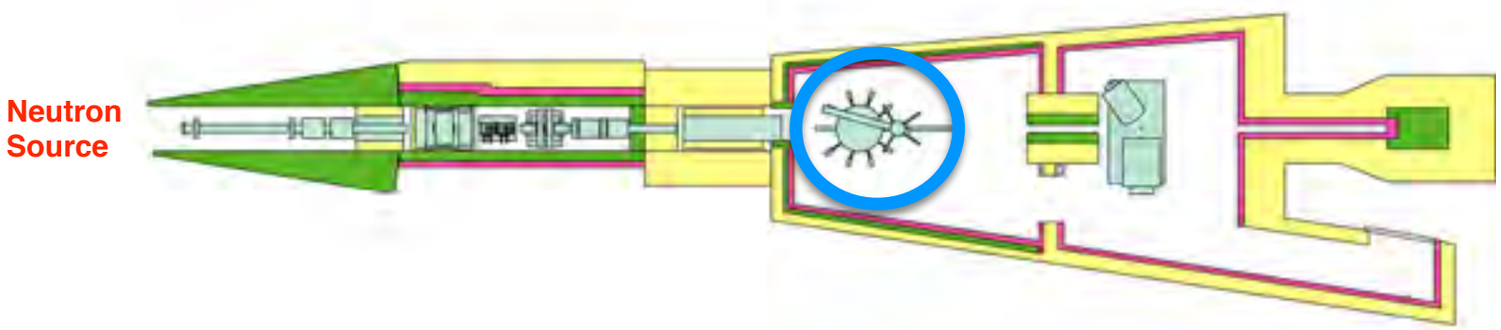
J-PARC MLF BL04 ANNRI

14 Ge（+BGO）Detectors

θ＝70,90,110 deg.



Ge Spectrometer（Flight Length: 21.5m）

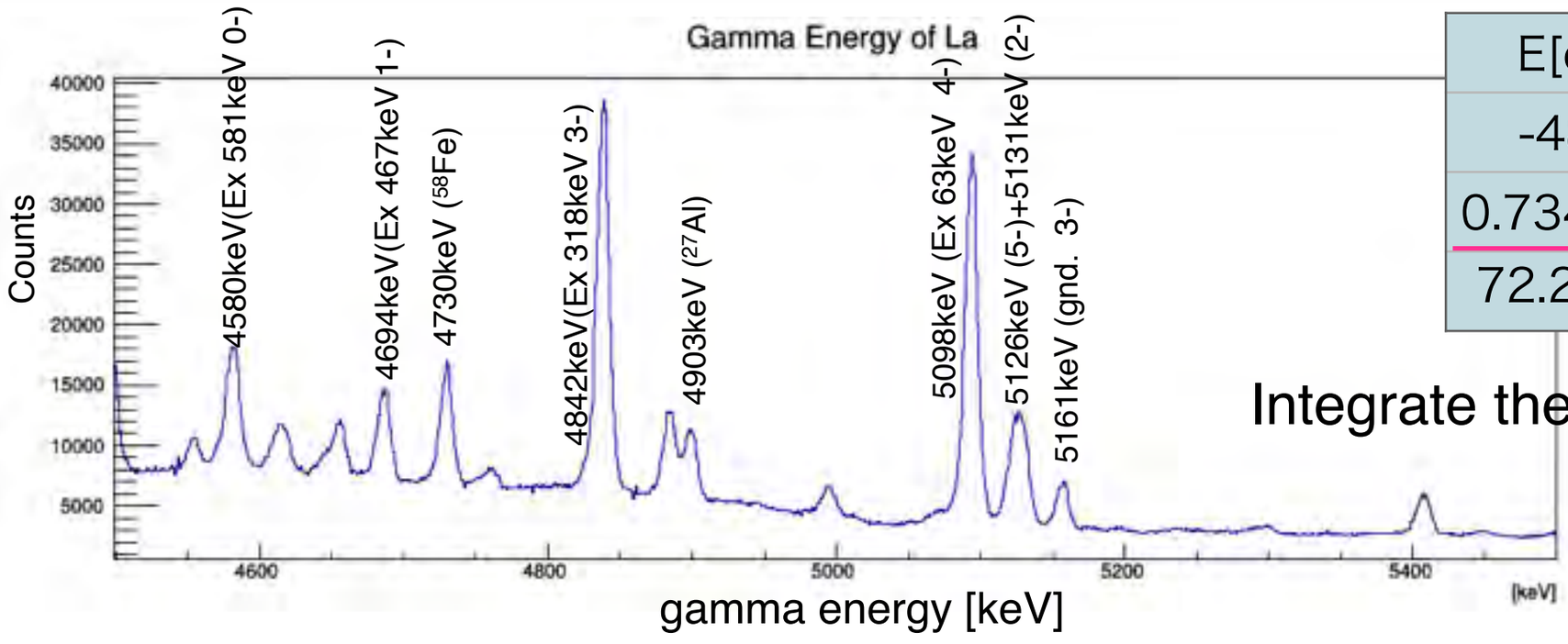


Sample Materials：^{nat}La, $La^{nat}Br_3$, ^{nat}In

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

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

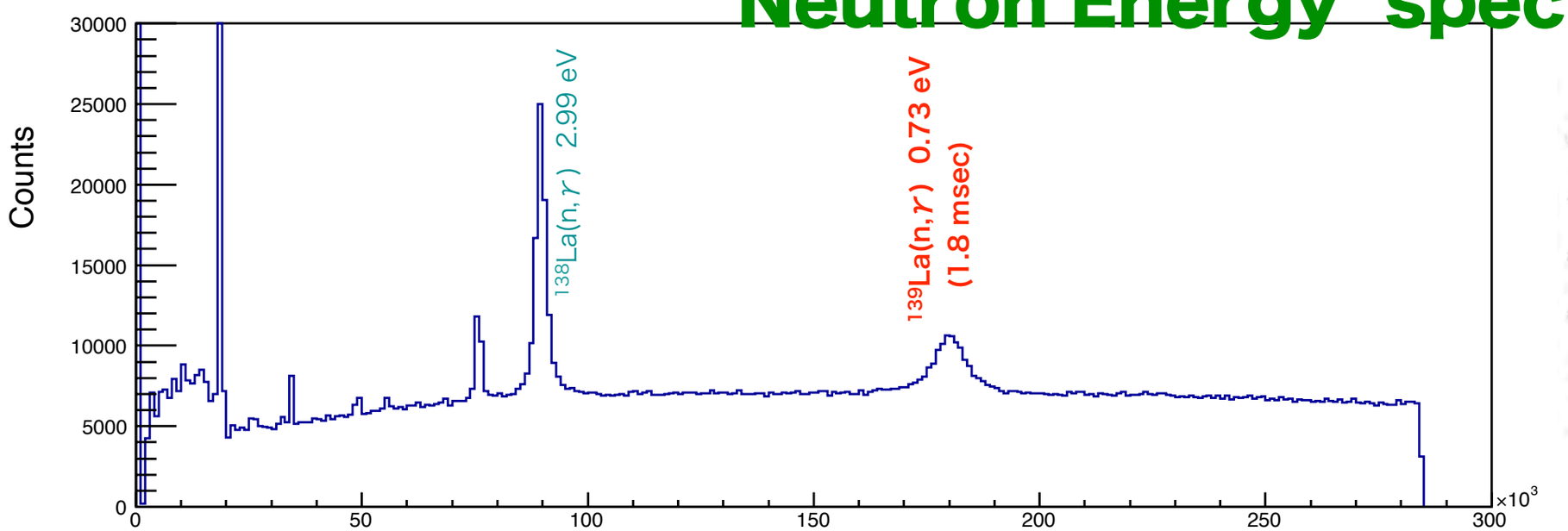
^{139}La(n,γ)

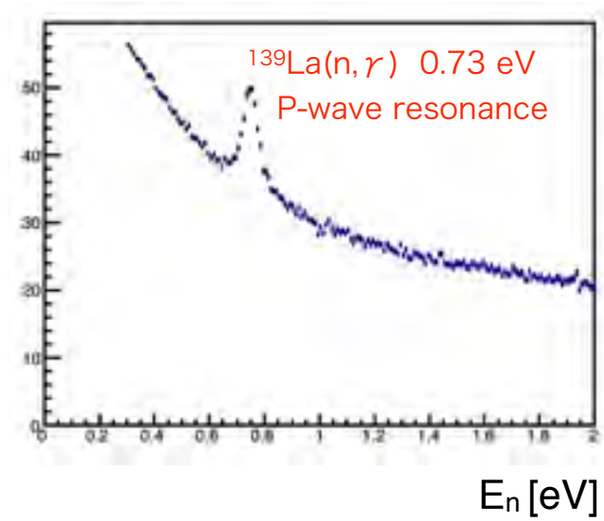


E[eV]	ℓ	gΓn [meV]
-48.6	0	80 $\sqrt{E}$
0.734±0.1	1	(3.75±0.18)x10^{-5}
72.2±0.1	0	16.6±0.5

Integrate the neutron energy

Neutron Energy spectrum σ(En)



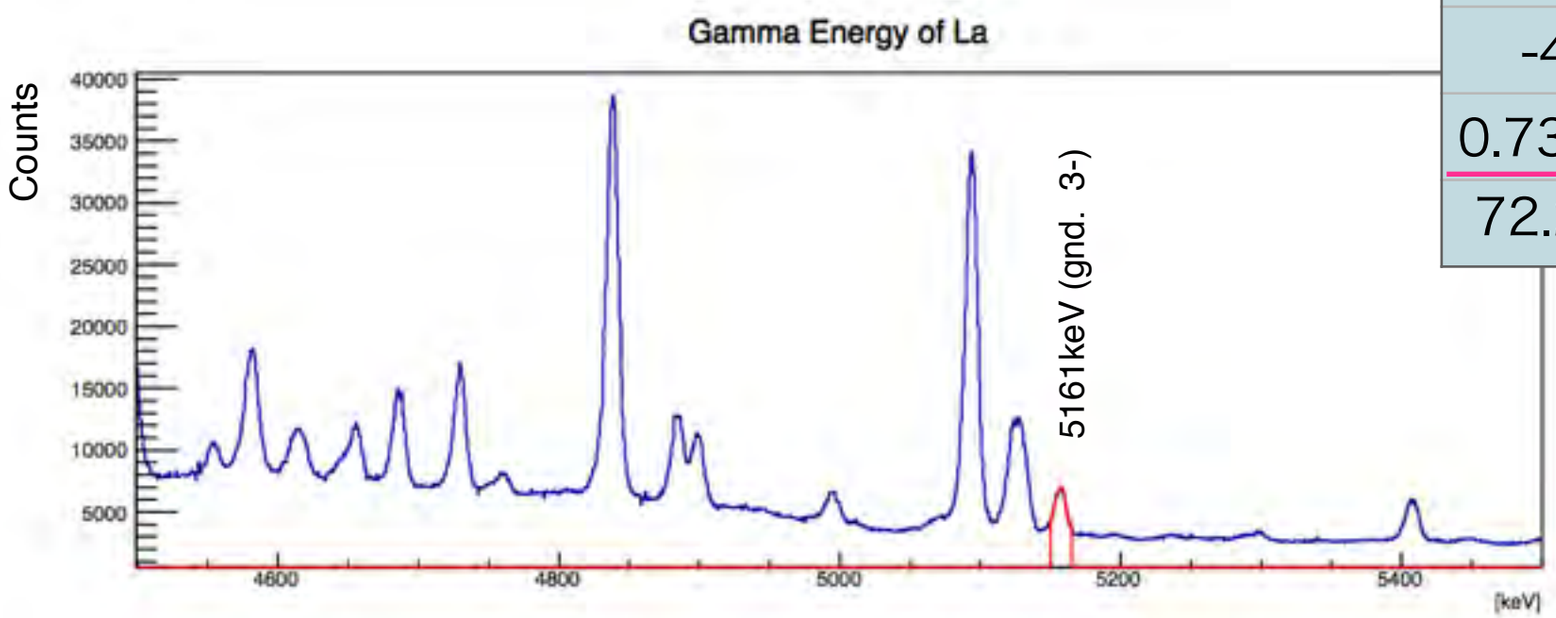


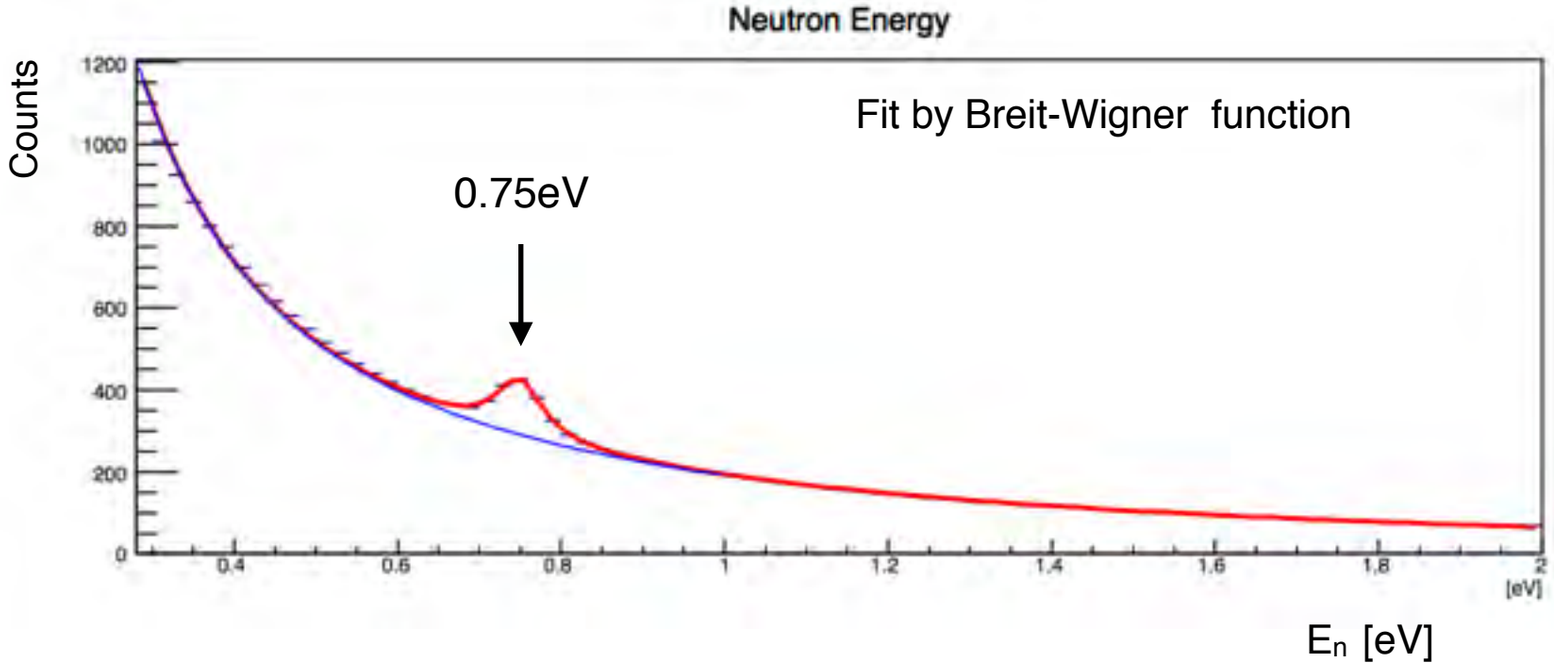
Integrate the gamma energy

neutron TOF ：10 nsec unit

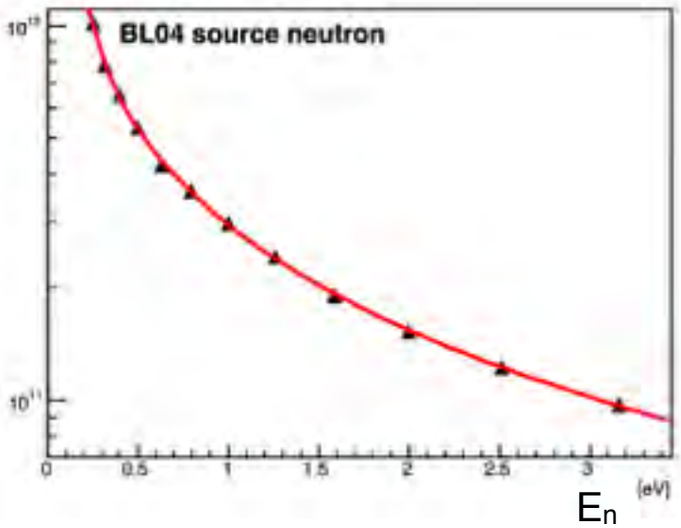
Check of the resonance energy

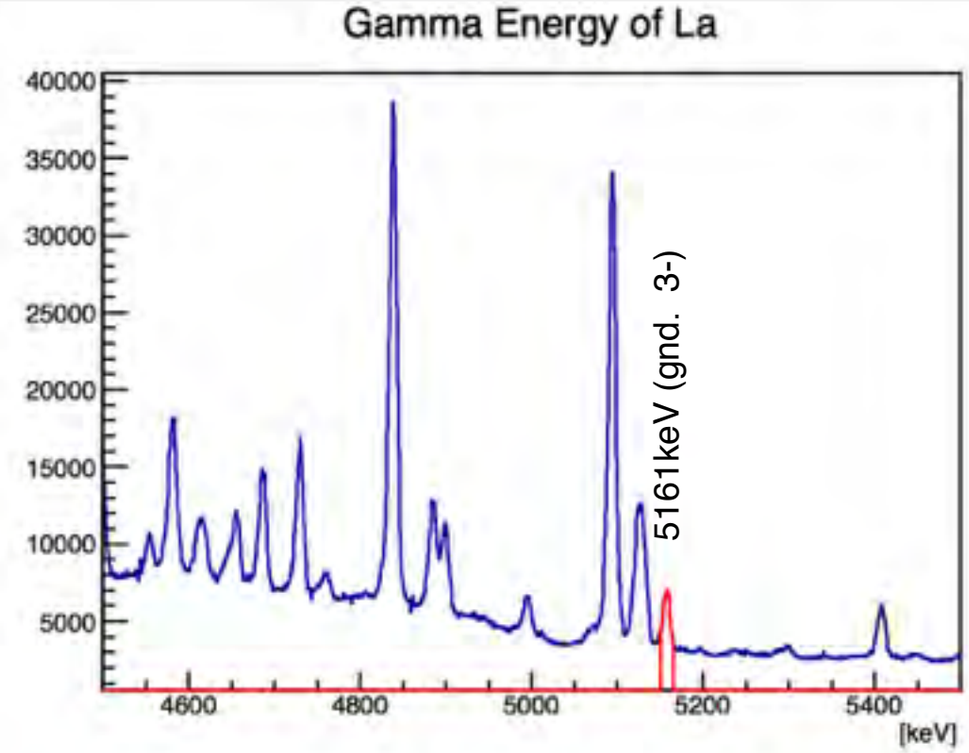
E[eV]	ℓ	g Γ n [meV]
-48.6	0	80 √ E
0.734±0.1	1	(3.75±0.18)x10^{-5}
72.2±0.1	0	16.6±0.5



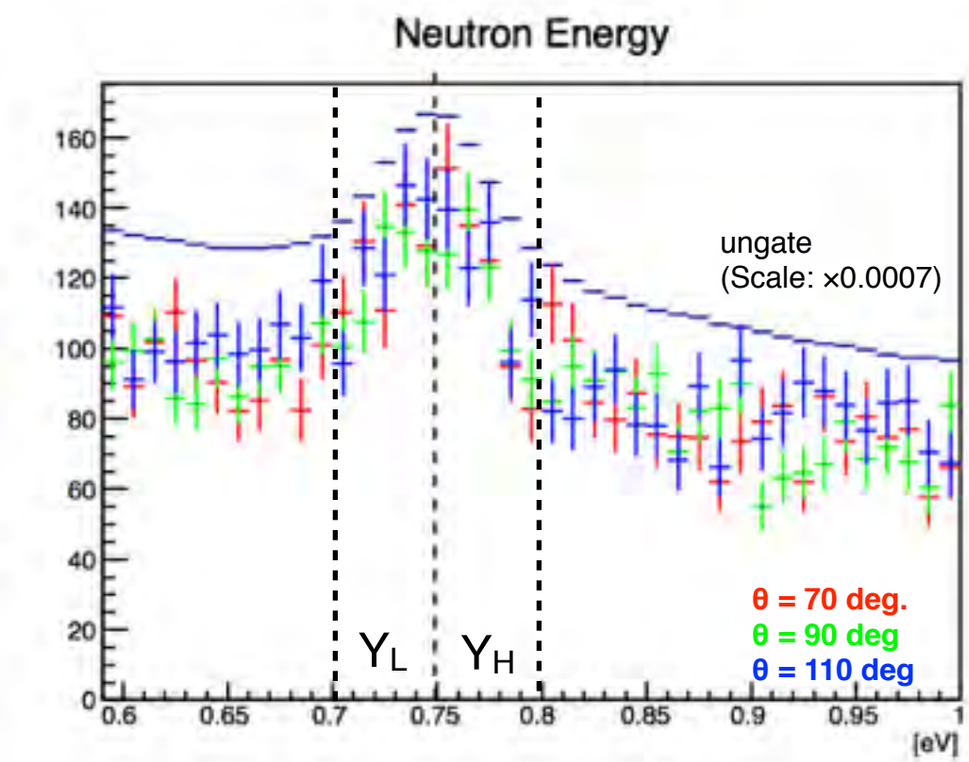


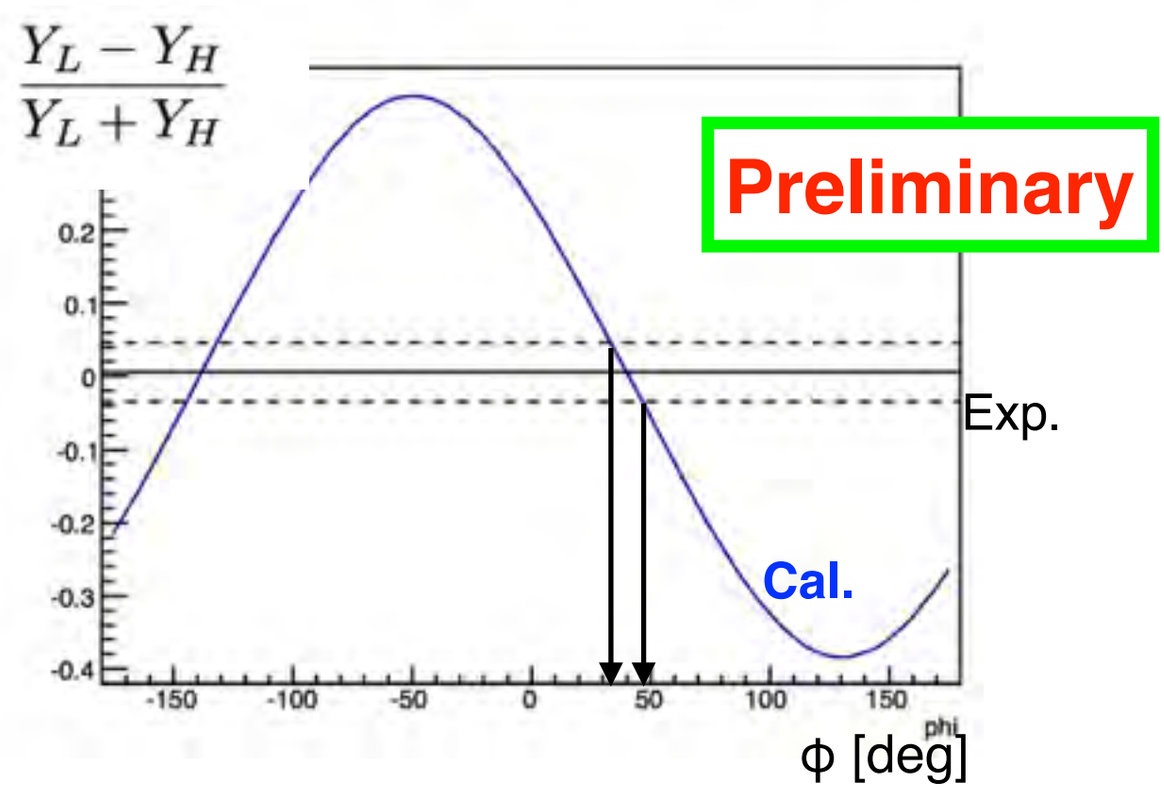
beam intensity correction



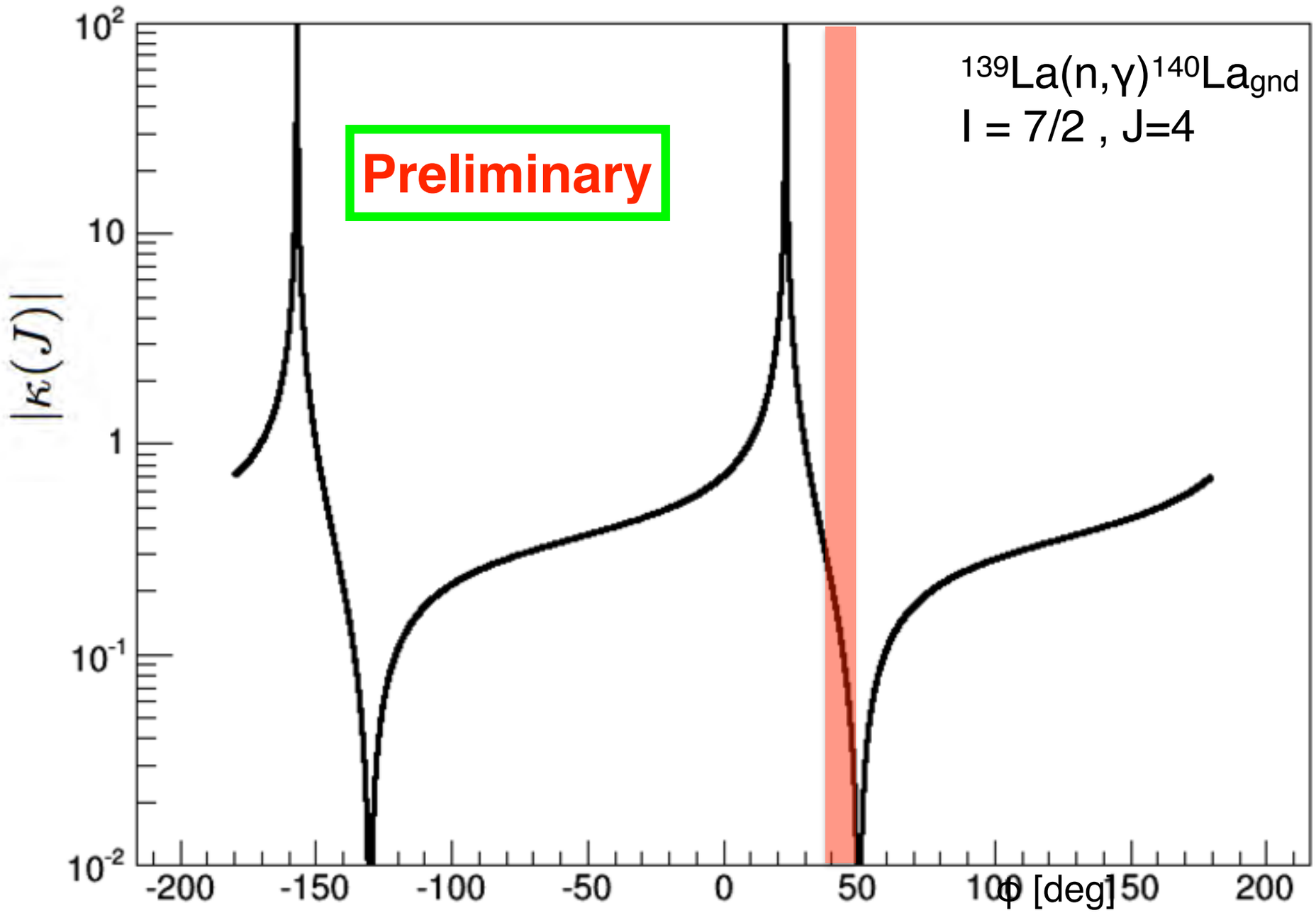


$$\frac{d\sigma}{d\Omega} = \frac{1}{2}(a_0 + a_1 \mathbf{k}_n \cdot \mathbf{k}_\gamma + a_3((\mathbf{k}_n \cdot \mathbf{k}_\gamma)^2 - \frac{1}{3}))$$





Only $^{139}La(n,\gamma)^{140}La_{gnd}$. Other transitions are being analyzed.



$$A_L = -\frac{2xW}{|E_p - E_s|}\sqrt{\frac{\Gamma_p^n}{\Gamma_s^n}}$$

$$= -\frac{2W}{|E_p - E_s|}\sqrt{\frac{\Gamma_p^n}{\Gamma_s^n}}\cos\phi$$

Very small cosϕ implies very large W value,,,

P-violating matrix element

	^{139}La	^{81}Br	^{117}Sn	^{131}Xe
$\Delta\sigma_P$	◎	○	◎	◎
E_p [eV]	◎	◎	○	○
I	7/2 △	3/2 ○	1/2 ◎	3/2 ○
isotopic abn	◎	○	×	△
κ(J)	△	△	△	○

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

	^{139}La	81	117	^{131}Xe
$\Delta\sigma_P$	◎	○	◎	◎
E_p [eV]	◎	◎	○	○
I	7/2 △	3/2	1/2	3/2 ○
isotopic abn	◎	○	×	△
κ(J)	△	△	△	○
method of pol.	DNP	—	—	OP

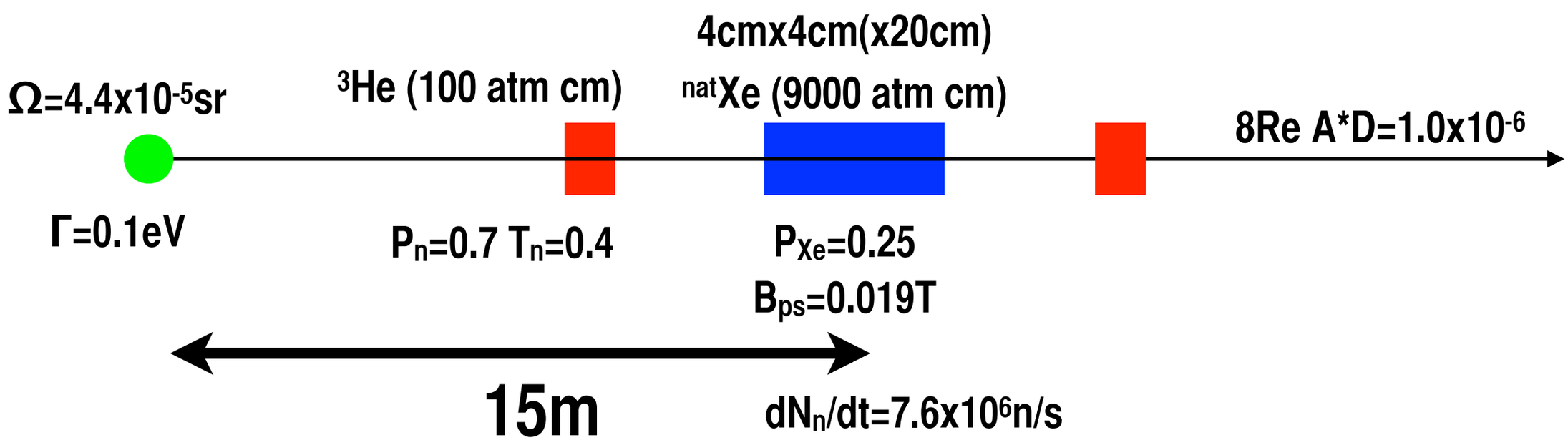
	^{139}La	81	117	^{131}Xe
$\Delta\sigma_P$	◎	○	◎	◎
E_p [eV]	◎	◎	○	○
I	7/2 △	3/2	1/2	3/2 ○
isotopic abn	◎	○	×	△
κ(J)	△	△	△	○
method of pol.	DNP	—	—	OP
practical abn	$LaAlO_3$			solid Xe
practical abn	○			○

	^{139}La	81	117	^{131}Xe
$\Delta\sigma_P$	◎	○	◎	◎
E_p [eV]	◎	◎	○	○
I	7/2 △	3/2	1/2	3/2 ○
isotopic abn	◎	○	×	△
κ(J)	△	△	△	○
method of pol.	DNP	—	—	OP
practical abn	$LaAlO_3$			solid Xe
practical abn	○			○

J-PARC/MLF – JSNS BL07

solid Xe with natural abundance as an example

$$\frac{\partial}{\partial z}(8\mathrm{Re}A^*D) = 0 \rightarrow (8\mathrm{Re}A^*D)|_{z=18000[\mathrm{atm\cdot cm}]} \sim 3.3\times 10^{-5}$$



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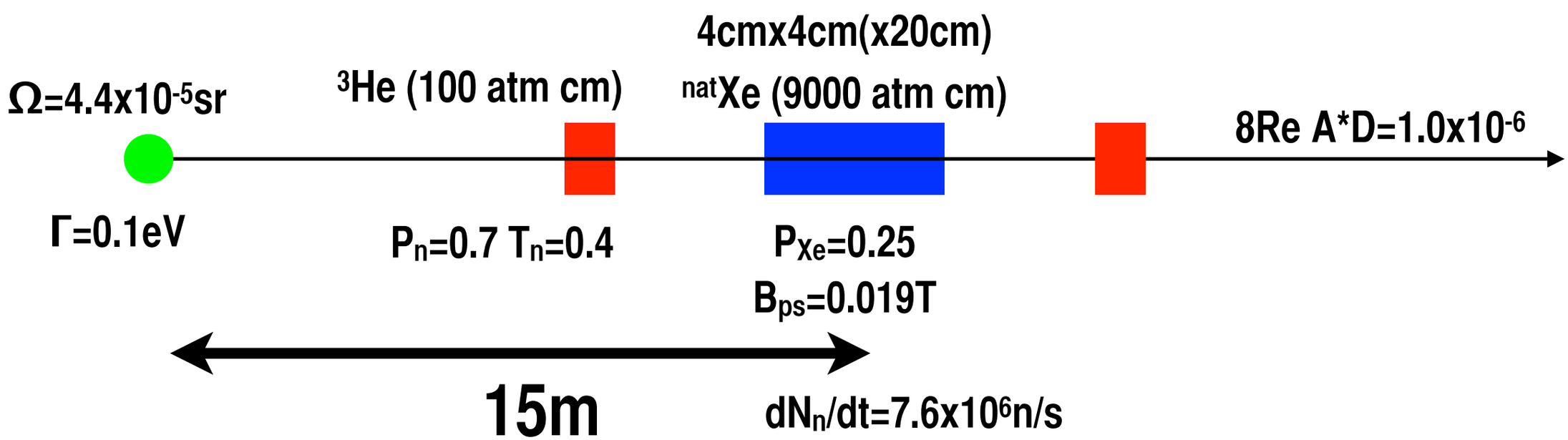

$$\kappa(J) = 1$$

$$\frac{w}{v} = \frac{g_{\mathrm{CP}}}{g_{\mathrm{P}}} = 10^{-3}$$

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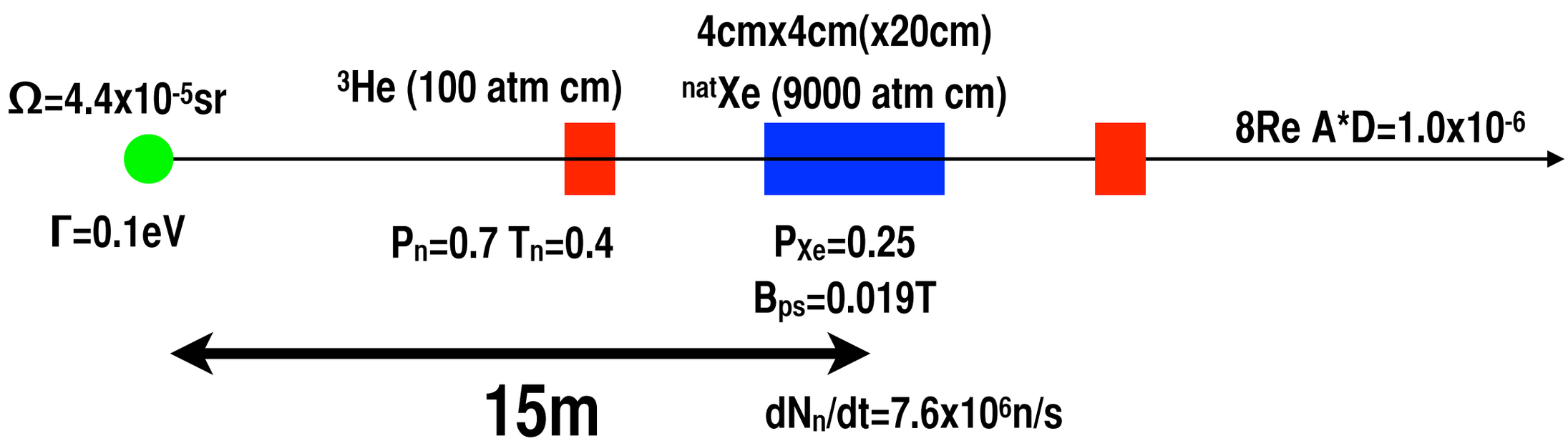


$$\kappa(J) = 1$$

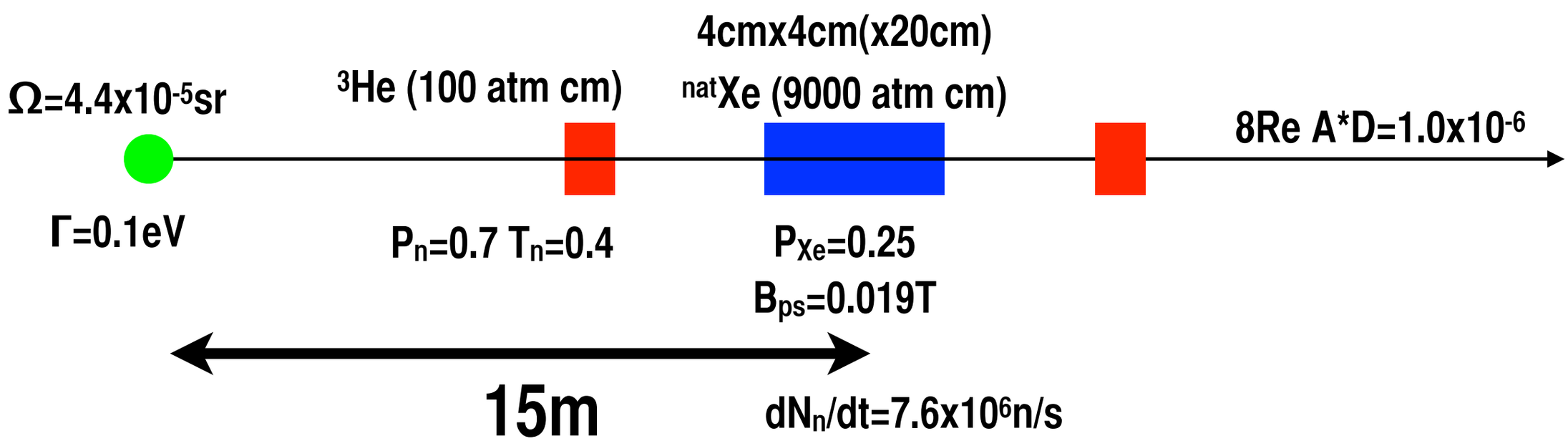
$$\frac{w}{v} = \frac{g_{\mathrm{CP}}}{g_{\mathrm{P}}} = 10^{-3}$$

$$\longrightarrow \quad T \simeq 4\times 10^5\,[\mathrm{s}] = 4.5\,[\mathrm{days}]$$

J-PARC/MLF – JSNS BL07

solid Xe with natural abundance as an example

$$\frac{\partial}{\partial z}(8\mathrm{Re}A^*D) = 0 \rightarrow (8\mathrm{Re}A^*D)|_{z=18000[\mathrm{atm\cdot cm}]} \sim 3.3\times 10^{-5}$$



$$\kappa(J) = 1$$

$$\frac{w}{v} = \frac{g_{\mathrm{CP}}}{g_{\mathrm{P}}} = 10^{-3}$$

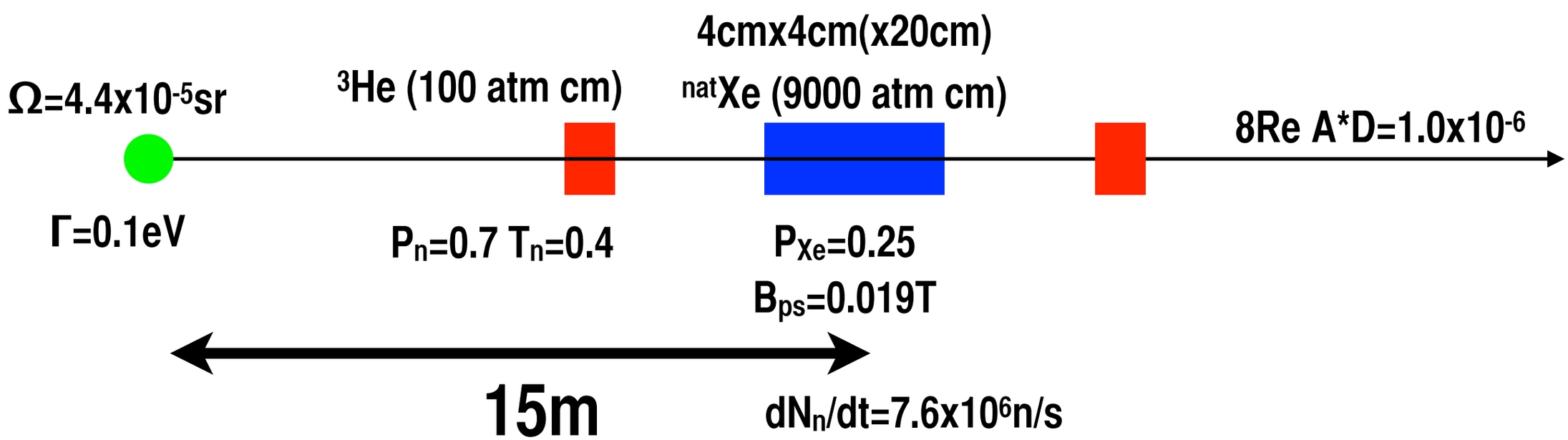
$$\longrightarrow \quad T \simeq 4\times 10^5\,[\mathrm{s}] = 4.5\,[\mathrm{days}]$$

feasible

J-PARC/MLF – JSNS BL07

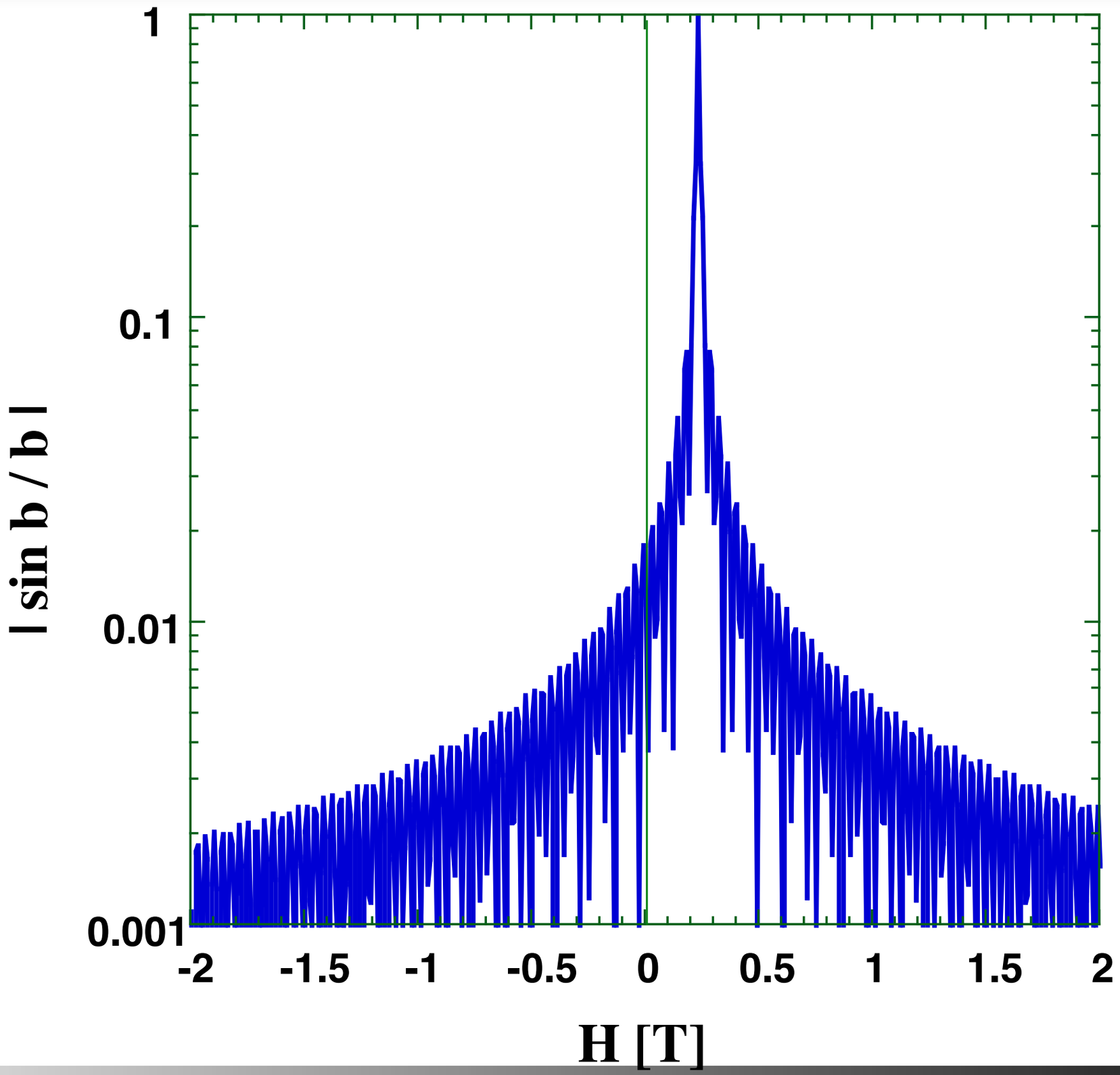
solid Xe with natural abundance as an example

$$\frac{\partial}{\partial z}(8\mathrm{Re}A^*D) = 0 \rightarrow (8\mathrm{Re}A^*D)|_{z=18000[\mathrm{atm\cdot cm}]} \sim 3.3 \times 10^{-5}$$



Alignment, inhomogeneous polarization distribution and field control can be simultaneously monitored observing the spin behavior as a function of time-of-flight.

|sinb/b| in 100% polarized $LaAlO_3$ as a function of external field H



Summary

If we have a sufficiently thick polarized solid Xe →

CP-violation can be studied in epithermal neutron optics with the sensitivity comparable with or better than the neutron EDM combining existing technologies at J-PARC.

Check if the κ(J) is not zero.

Validity of neutron optical description should be checked by observing the spin behaviors in T-conserving terms.

Domestic consolidation finished.
Proposals to be submitted.

more alternative possibilities are also existing (La, Br, Sn, ...)