20 April, 2015

Beta decay as an absolute calibration probe for spin-isospin responses

H. Sakai

RIKEN Nishina Center

Today's concern

- GT strength and Spin dipole(SD) strength by charge-exchange reaction
- Extract B(GT) and B(SD)
- For that, needs calibration on reaction probe by β decay data.

β-decay & Nuclear Reaction

- **β-decay transition rate** $= \dfrac{1}{t_{1/2}} = f\,\dfrac{\lambda^2}{D}\,\mathrm{B}(J^\pi)$

  B(J^π) : reduced transition strength $\propto |M|^2$

  ☺ **Provide absolute value**
  △ **Q_β window**

- **Charge-exchange reaction cross-section**

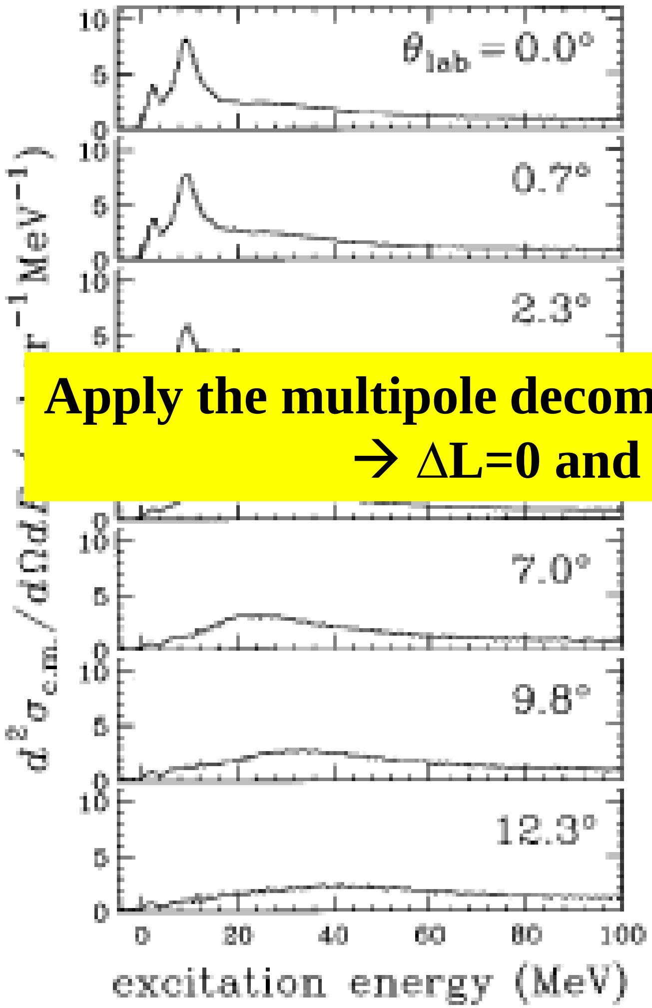
  $= K(E, A) * B(J^\pi)$

  △ **Needs calibration**
  ☺ **No Q_β window**

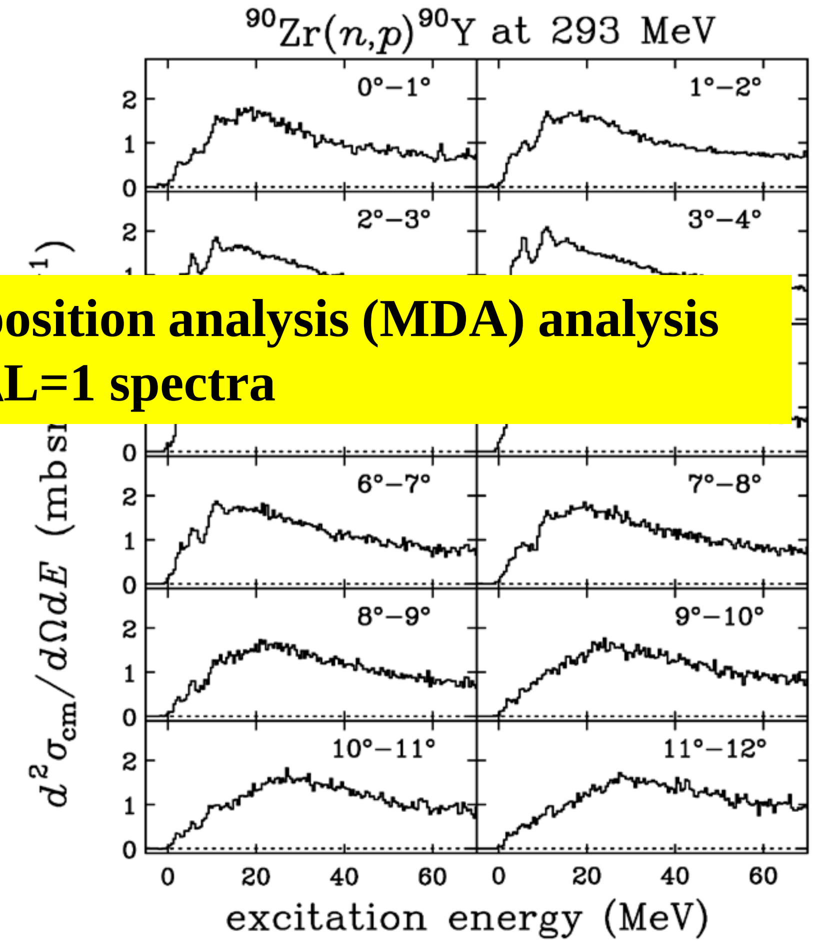
Reaction cross section can be calibrated by $B(J^\pi)$ of β decay.

$^{90}Zr(p,n)/(n,p)$ measurements

$^{90}Zr(p,n)^{90}Nb$ at 295 MeV



$^{90}Zr(n,p)^{90}Y$ at 293 MeV



Apply the multipole decomposition analysis (MDA) analysis
→ ΔL=0 and ΔL=1 spectra

Wakasa, Sakai, PRC55(1997)2909

Yako, Sakai, PLB615(2005)193

Gamow-Teller (Op: $t_{+/-}\sigma$) strength B(GT)

Model independent spin sum rule (Ikeda sum rule)

$$S_{\beta-} - S_{\beta+} = \frac{1}{2J_i+1}\sum_f \left| \left\langle f \left\| \sum_{i=1}^{A} t_-(i)\sigma_i \right\| i \right\rangle \right|^2 - \frac{1}{2J_i+1}\sum_f \left| \left\langle f \left\| \sum_{i=1}^{A} t_+(i)\sigma_i \right\| i \right\rangle \right|^2$$

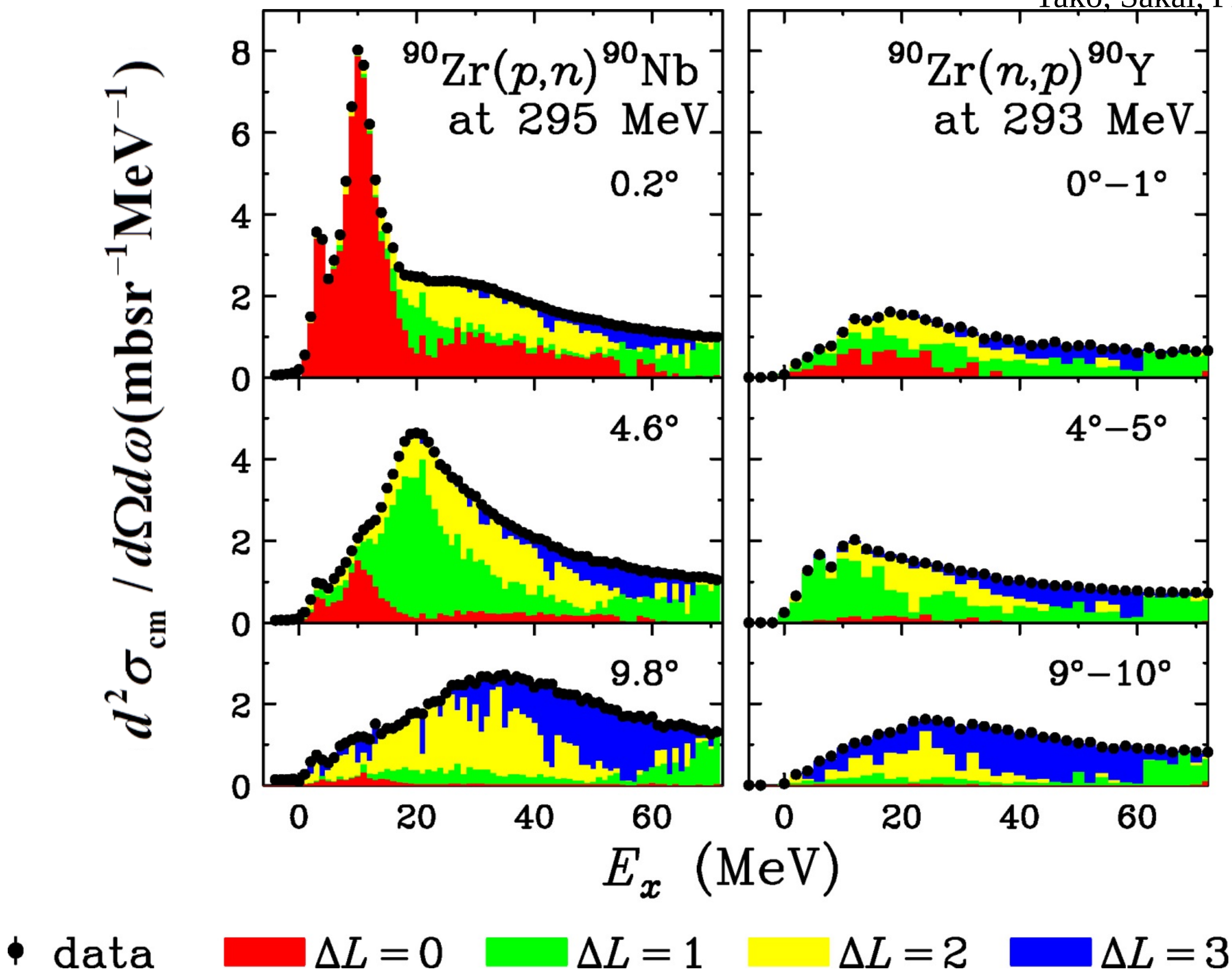
$$= \sum \mathrm{B(GT-)} - \sum \mathrm{B(GT+)}$$

$$= 3(\mathrm{N - Z})$$

If nucleus can be described in terms of nucleon degrees of freedom

Decomposed results

Yako, Sakai, PLB615(2005)193

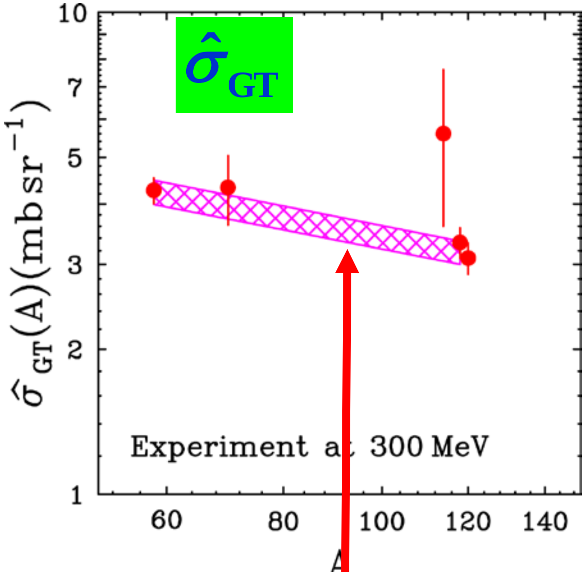


$$\left.\frac{d\sigma(0^\circ)}{d\Omega}\right)_{\Delta L=0} \Rightarrow \mathrm{B(GT)}$$

Proportionality assumption to extract B(GT)

$$\left.\frac{d\sigma(0^\circ)}{d\Omega}\right)_{\Delta L=0} = \hat{\sigma}_{GT}(E_p, A)\cdot F_{GT}(q,\omega)\cdot \mathrm{B(GT)}$$

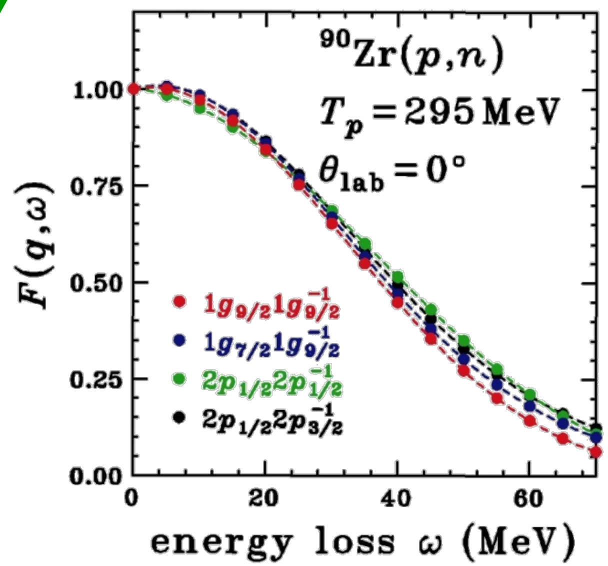
Unit cross section



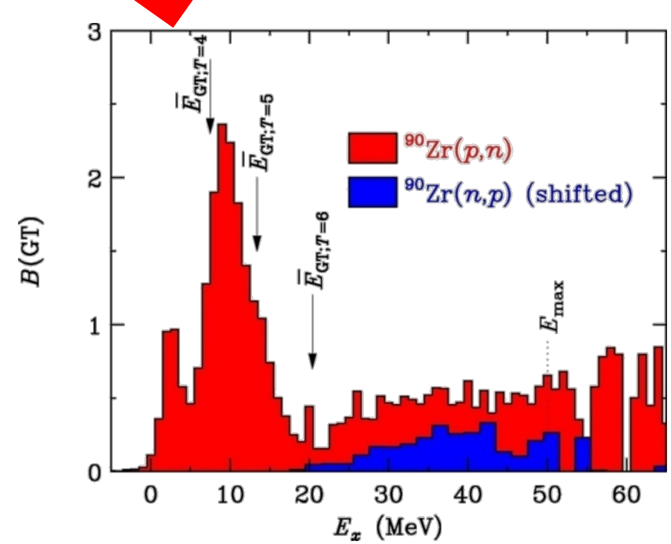
M. Sasano et al., PRC 79, 23602 (‘09)

$$\hat{\sigma}_{GT}(^{90}\mathrm{Zr}) = 3.6 \pm 0.2\ \ (\mathrm{mb/sr})$$

DWIA



B(GT)

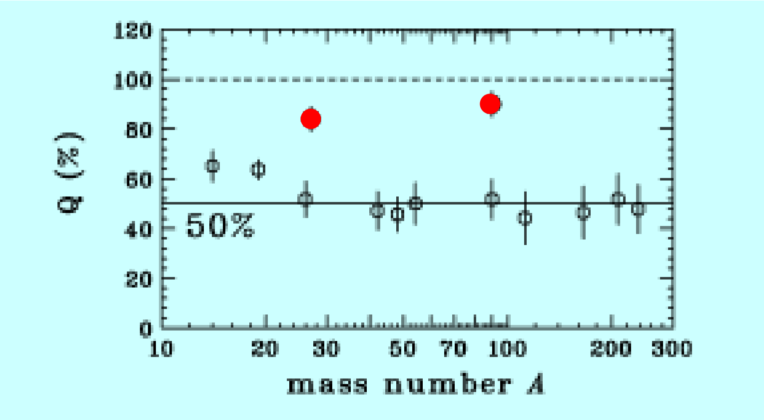


$$S_{\beta-} - S_{\beta+} = 27.6$$

For $0 \le \omega \le 50$ MeV

Quenching factor (^{90}Zr)

$$Q = 0.92 \pm 0.07$$



Wakasa et al., PRC **55**, 2909 (1997)

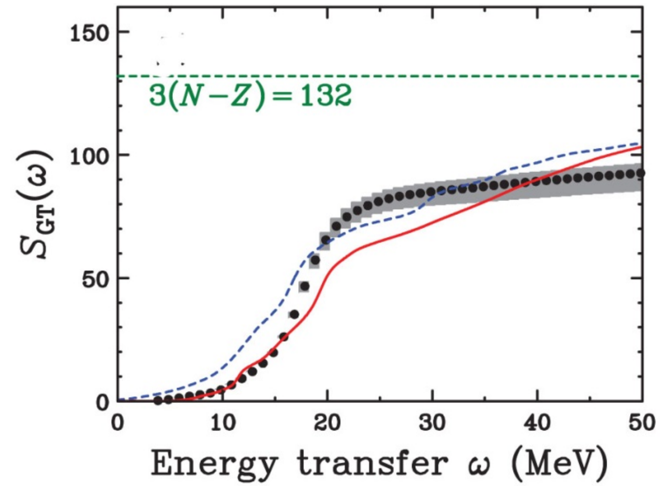
Strength spread into 2p2h coupled states

Small Δh^{-1} contribution

Quenching problem solved !

However . . .

208Pb(p,n) at 300 MeV



Wakasa et al., PRC 85, 064606 (2012)

Q~72 % !

Spin Dipole strength B(GT)

$$\hat{O}_{\mathrm{SD}\pm} = \sum_{im\mu} t_{\pm}^{i} \sigma_{m}^{i} r_i Y_1^{\mu}(\hat{r}_i)$$

Model independent spin sum rule

$$S_{-}(SD) - S_{+}(SD) = \frac{9}{4\pi}\left(N\left\langle r^2\right\rangle_n - Z\left\langle r^2\right\rangle_p\right)$$

(p,n)

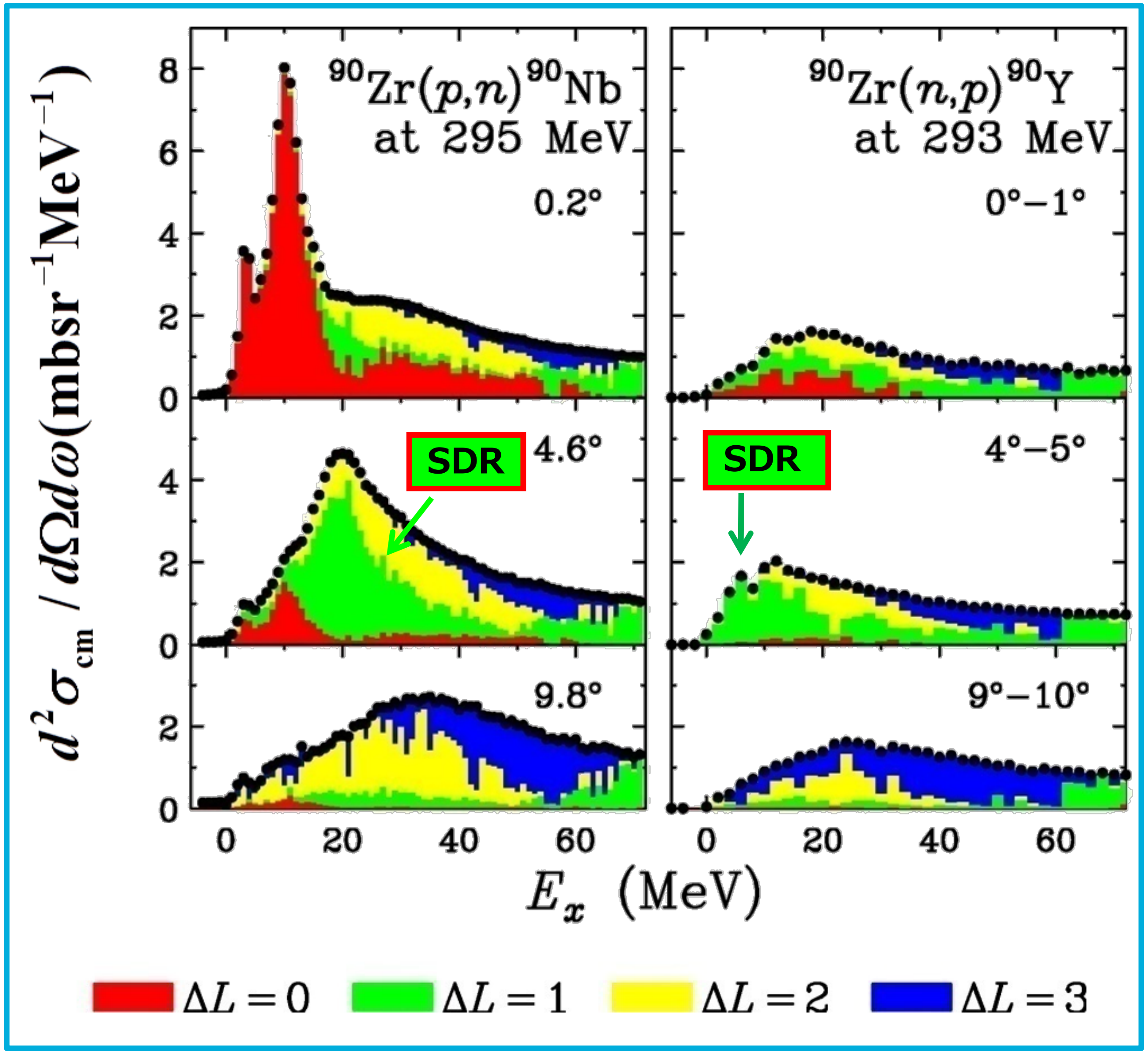
(n,p)

extract

e scatt.

$$\delta_{np} = \sqrt{\left\langle r^2\right\rangle_n} - \sqrt{\left\langle r^2\right\rangle_p}$$

Spin dipole strength



Extraction of B(SD)

- **Proportionality relation (assumption !)**

$$\sigma_{\Delta L=1,\pm}(q,\omega)=\hat{\sigma}_{SD\pm}(q,\omega)\cdot \mathrm{B(SD\pm)}$$

Characterized by ΔS=1, ΔL=1, ΔJ=0,1,2

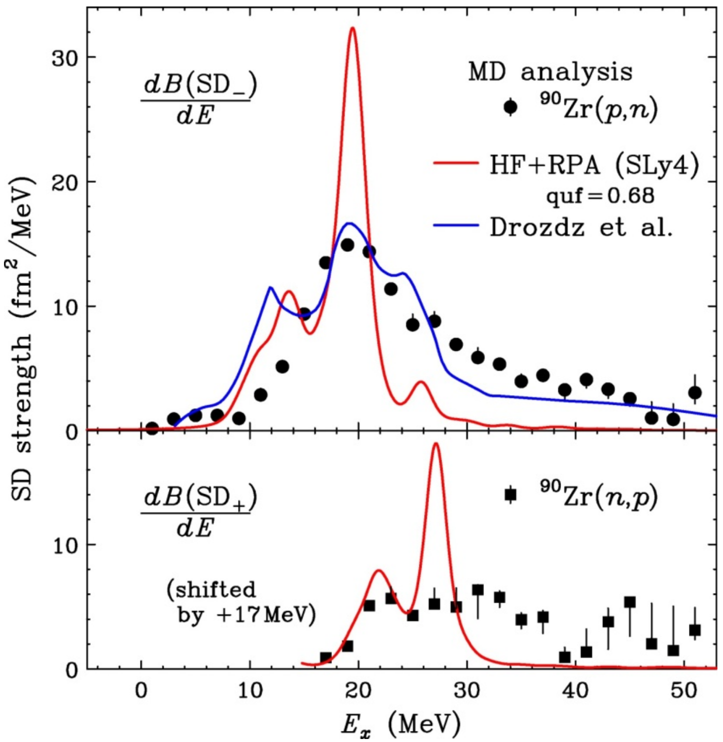
0+ → 0- first forbidden
0+ → 1- first forbidden
0+ → 2- unique first forbidden

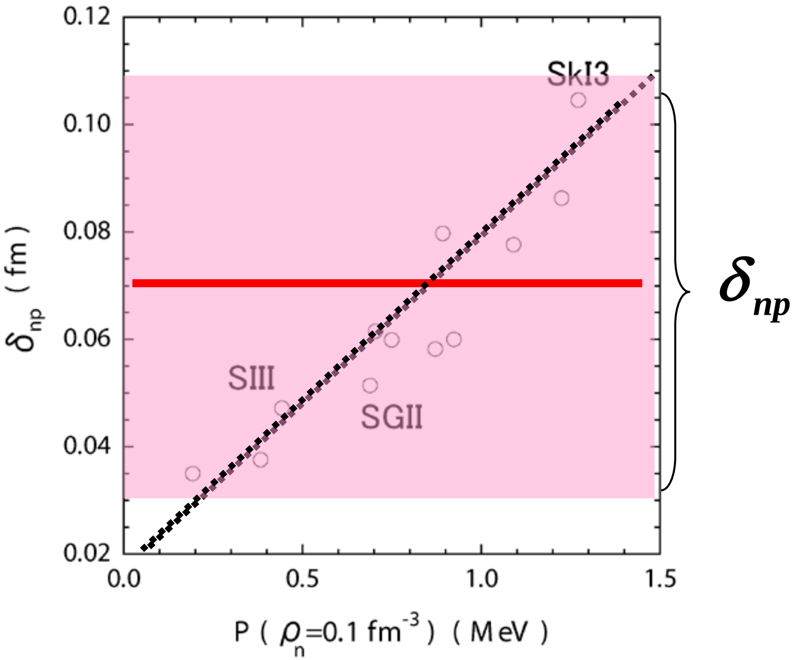
- **Unit cross section** $\hat{\sigma}_{SD\pm}(q,\omega)$

⇒ Estimated with DWIA calculation at 4.5°

$$\sigma_{\Delta L=1,\pm}(4.5^{\circ},\omega)=\hat{\sigma}_{SD\pm}(4.5^{\circ},\omega)\cdot \mathrm{B(SD\pm)}$$

Spin dipole strength and sum rule value





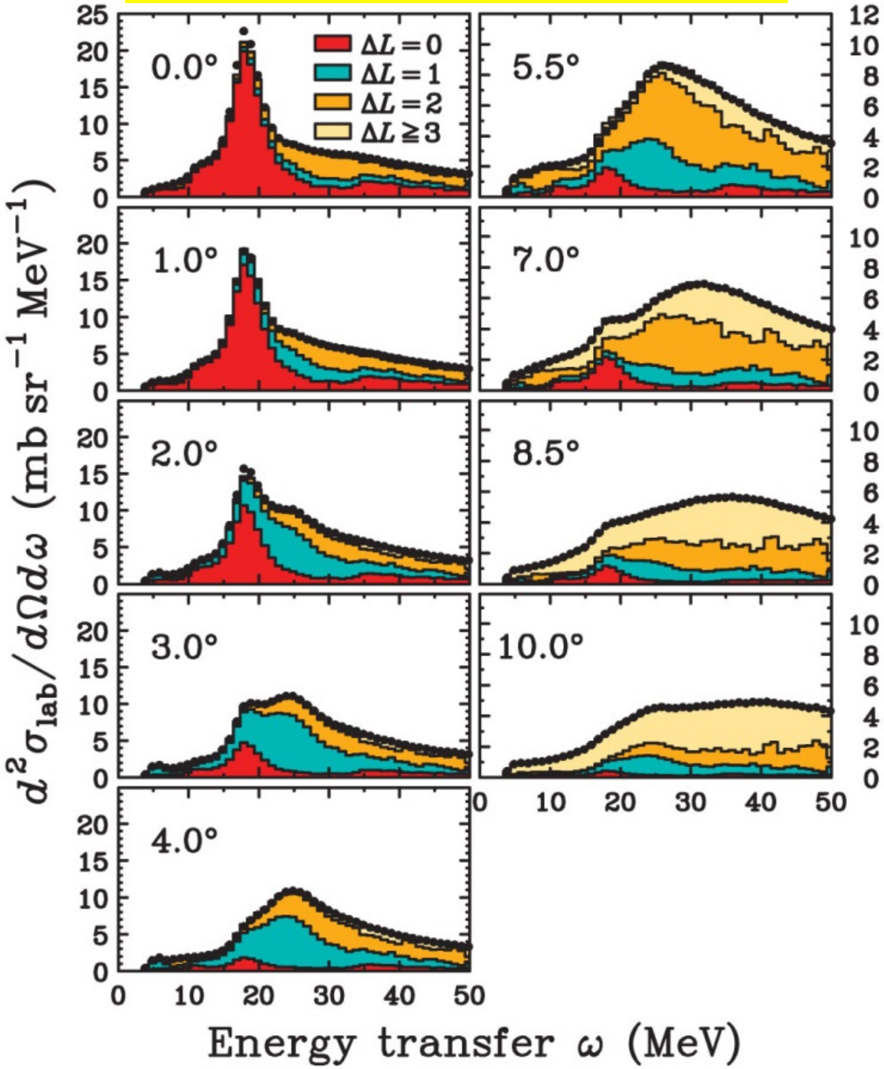
$$S_- - S_+ = 148 \pm 13 \text{ fm}^2$$
$$\sqrt{\langle r^2 \rangle_p} = 4.19 \text{ fm}$$

$$\sqrt{\langle r^2 \rangle_n} = 4.26 \pm 0.04 \text{ fm}$$
$$\delta_{np} = 0.07 \pm 0.04 \text{ fm}$$

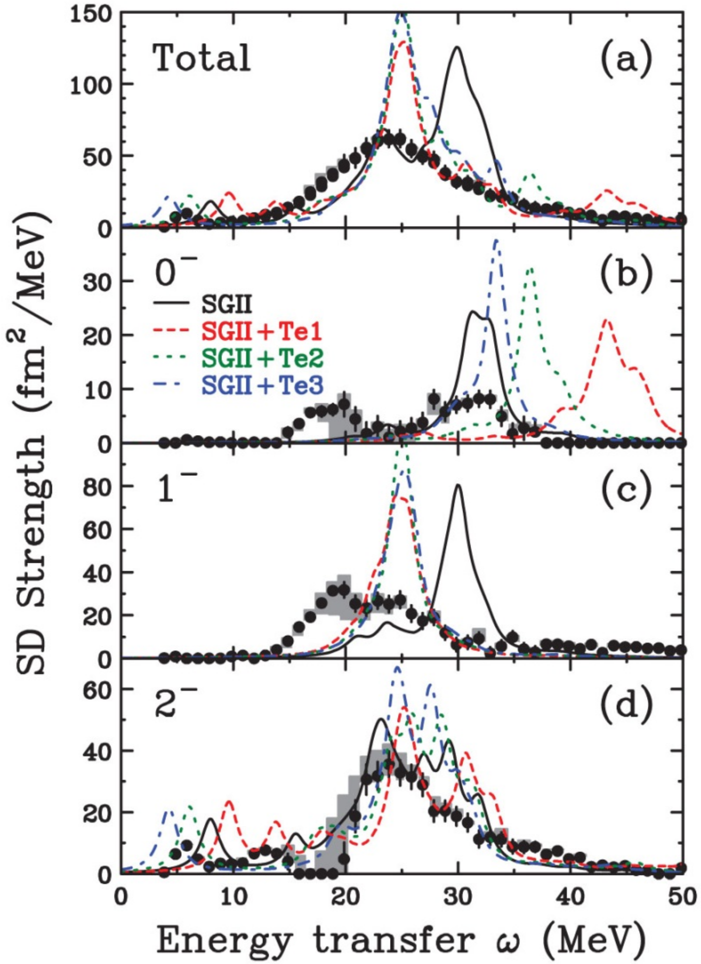
Spin dipole strength in ^{208}Pb by Wakasa (Kyushu U)

Wakasa et al., 85(2012)064606

Excellent experiment !



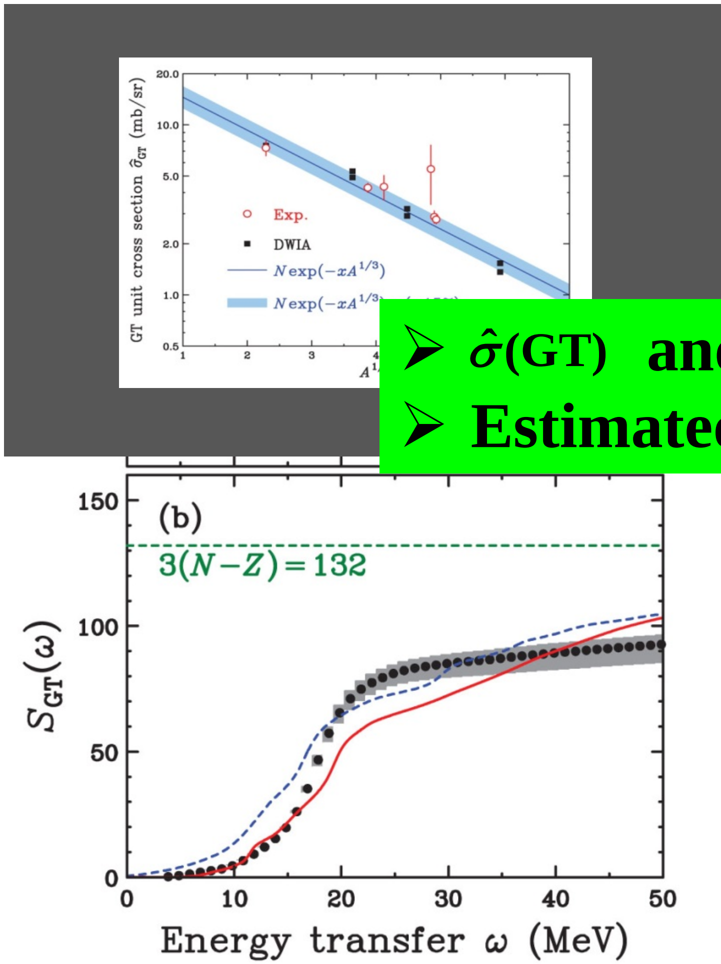
SD decomposed !



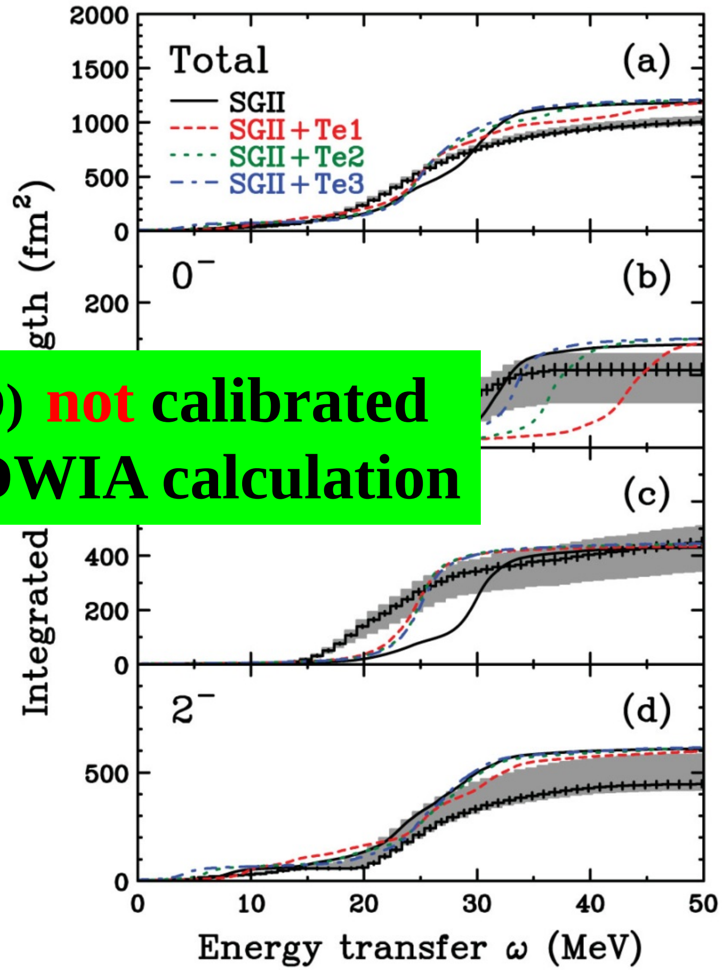
Spin dipole strength in ^{208}Pb by Wakasa (Kyushu U)

Wakasa et al., 85(2012)064606

GT quenched by 30% !



0- and 2- quenched by 30% !



- ➢ $\hat{\sigma}$(GT) and $\hat{\sigma}$(SD) **not** calibrated
- ➢ Estimated by DWIA calculation

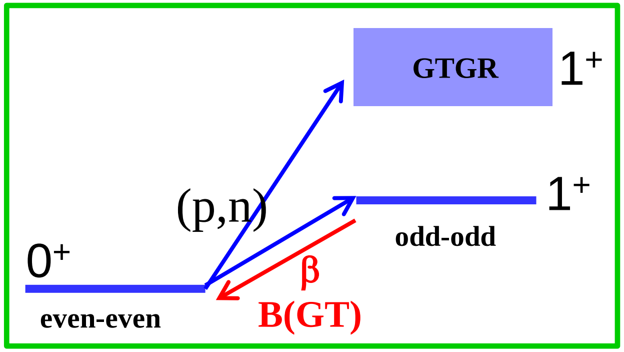
Probe calibration by β-decay B(GT/SD) values

- **Rely on proportional relation**

$$\left.\frac{d\sigma(\theta)}{d\Omega}\right)_{\Delta L=0} = \hat{\sigma}_{\mathrm{GT}}(E_p, A)\cdot F_{GT}(q,\omega)\cdot \mathrm{B(GT)}$$

$$\left.\frac{d\sigma(\theta)}{d\Omega}\right)_{\Delta L=1} = \hat{\sigma}_{\mathrm{SD}}(E_p, A)\cdot F_{SD}(q,\omega)\cdot \mathrm{B(SD)}$$

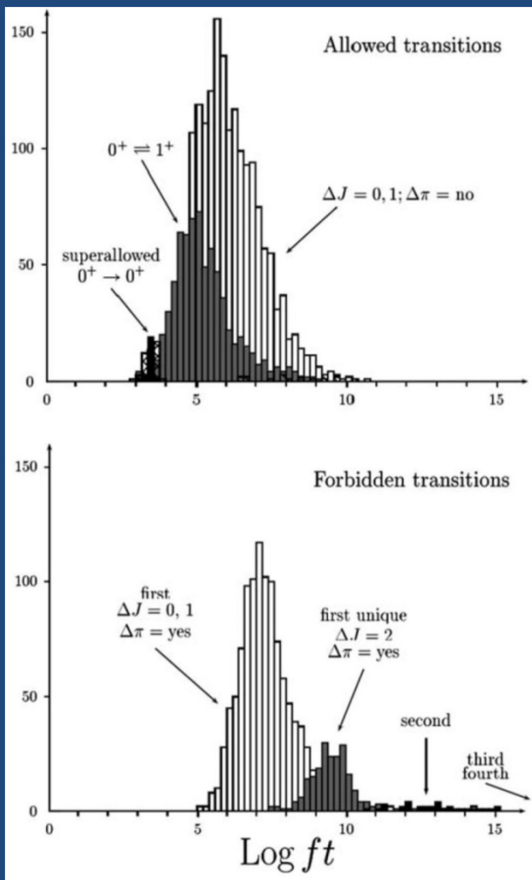
- **Unit cross section should be calibrated using known B(GT/SD) by β decay !**



- **Calibration is NOT available**
  - $\hat{\sigma}_{\mathrm{GT}}$ for A>130
  - $\hat{\sigma}_{\mathrm{SD}}$ for A> 1 (nothing)

- **Why no calibration ?**
  - No good candidate with stable target

β-decay matrix elements for GT state

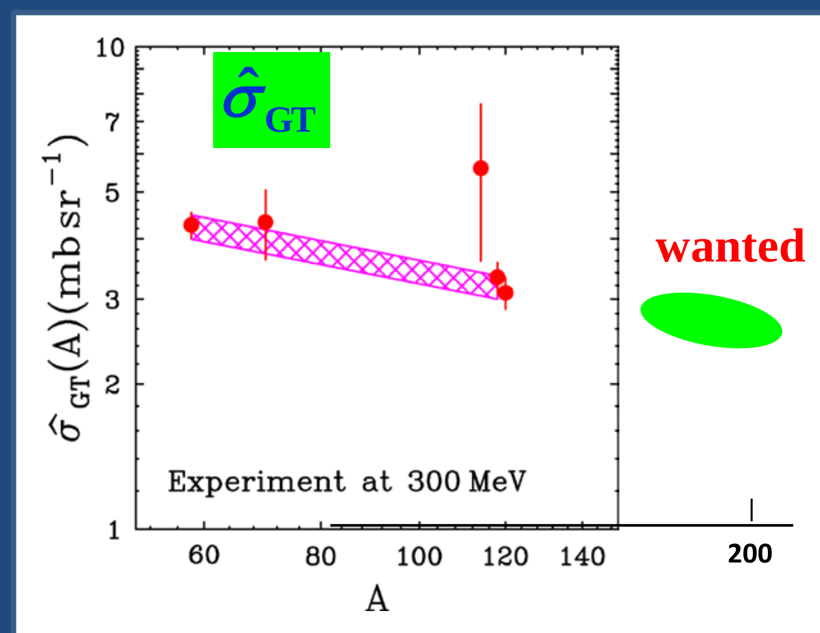


- **GT moment**

Bohr-Mottelson

$$\mathscr{M}(j_A, \kappa = 0, \lambda = 1, \mu) = \frac{g_A}{(4\pi)^{1/2}} \sum_k t_-(k)\sigma_\mu(k) \qquad \text{(3D-42)}$$

- **Operator is similar to reaction probe**
- **need unit σ(GT) for A~200**

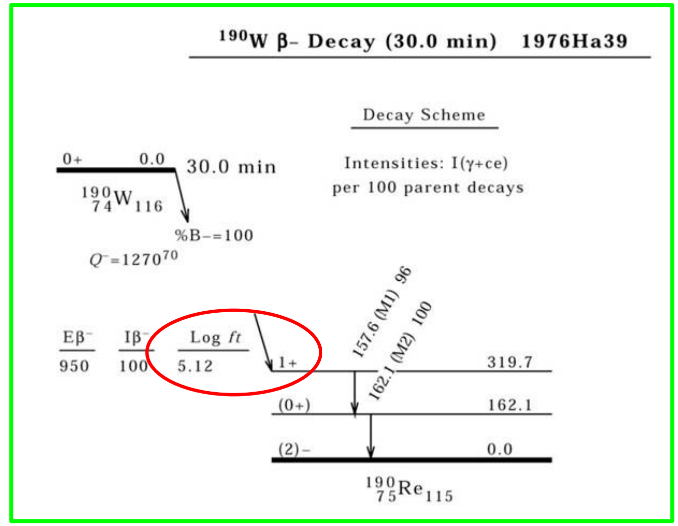


Feasibility of σ(GT) calibration for A>160

- Possible case ? ^{190}W(p,n)
  - log *ft* = 5.12 ⇒B(GT)=0.03
  - Isolated : ?
  - Why No F-trans. to 162 keV ?
  - Isomer involvement ?
  - Unstable beam exp.

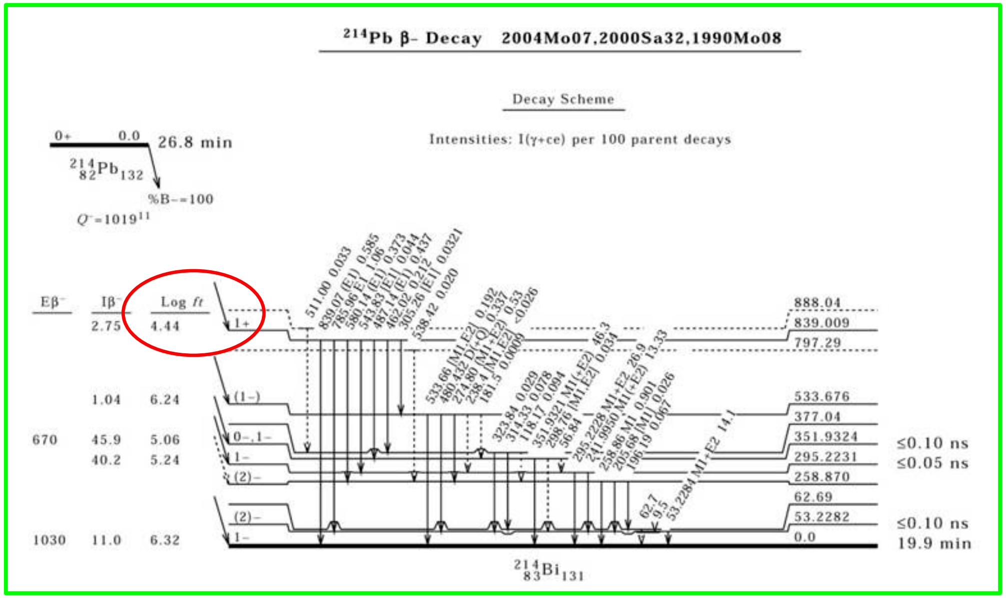
Cf. Sasano
^{118}Sn, ^{120}Sn : B(GT)=0.34

Too small !



- Possible case ? ^{214}Pb(p,n)
  - log *ft* = 4.44⇒B(GT)=0.14
    ⇒effective B(GT)~0.07
  - Isolated : many states around
  - Isomer involvement ?
  - Unstable beam exp.

Still too small !



Need isolated GT decay with B(GT)>0.5 for A~200.

β-decay matrix elements of SD states

◆ SD moment

Bohr-Mottelson

$$\left.\begin{aligned}\mathcal{M}(\rho_A, \lambda=0) &= (4\pi)^{-1/2}\frac{g_A}{c}\sum_k t_-(k)(\boldsymbol{\sigma}(k)\cdot\mathbf{v}_k) \\ \mathcal{M}(j_A, \kappa=1, \lambda=0) &= g_A\sum_k t_-(k)r_k(Y_1(\hat{\mathbf{r}}_k)\sigma(k))_0\end{aligned}\right\}\lambda\pi = 0-$$

$$\left.\begin{aligned}\mathcal{M}(\rho_V, \lambda=1, \mu) &= g_V\sum_k t_-(k)r_k Y_{1\mu}(\hat{\mathbf{r}}_k) \\ \mathcal{M}(j_V, \kappa=0, \lambda=1, \mu) &= (4\pi)^{-1/2}\frac{g_V}{c}\sum_k t_-(k)(v_k)_{1\mu} \\ \mathcal{M}(j_A, \kappa=1, \lambda=1, \mu) &= g_A\sum_k t_-(k)r_k(Y_1(\hat{\mathbf{r}}_k)\sigma(k))_{1\mu}\end{aligned}\right\}\lambda\pi = 1- \qquad (3D\text{-}43)$$

$$\mathcal{M}(j_A, \kappa=1, \lambda=2, \mu) = g_A\sum_k t_-(k)r_k(Y_1(\hat{\mathbf{r}}_k)\sigma(k))_{2\mu} \qquad \lambda\pi = 2-$$

Unique FF !

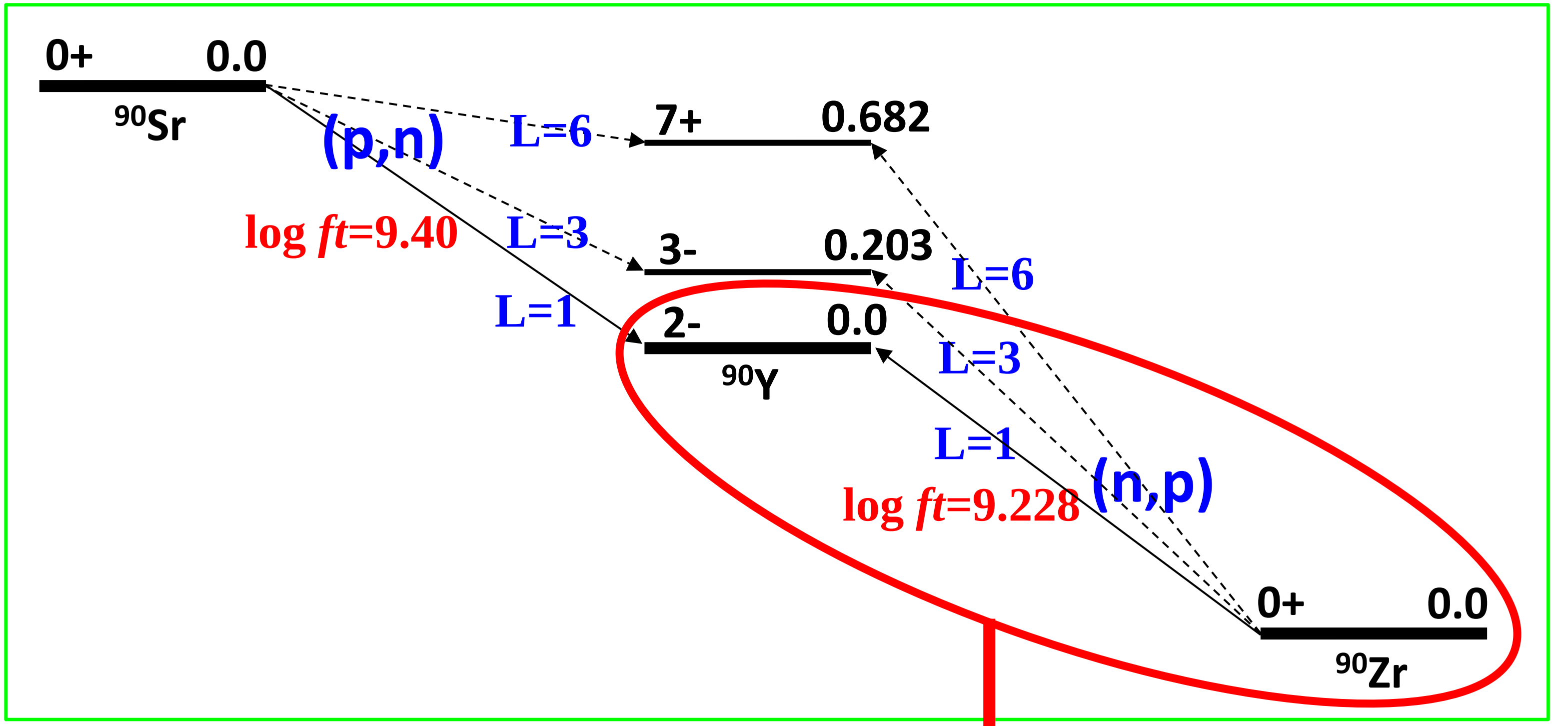
Operators are NOT necessarily similar to reaction probe operator $t_{\pm}\sigma r Y_1$

Calibration of 2^- SD at A=90

$$\mathcal{M}(j_A, \kappa=1, \lambda=2, \mu) = g_A \sum_k t_-(k) r_k (Y_1(\hat{\mathbf{r}}_k)\sigma(k))_{2\mu}$$

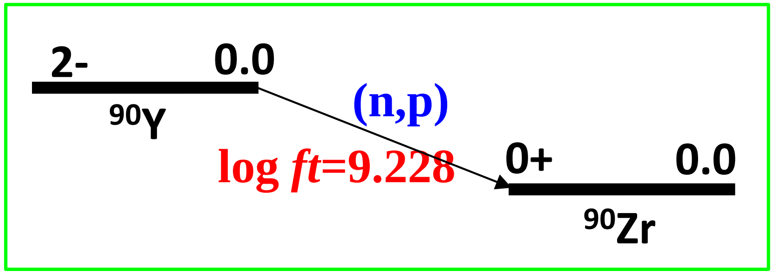
$[\sigma \times r]^2$

Similar to reaction probe $t_-\sigma r Y_1$



I realized we have measured !

Extraction of unit cross section for 2-



$$B(SD2\text{-})\uparrow = 5\frac{9}{4\pi}\frac{D}{ft}\left(\frac{g_V}{g_A}\right)^2 C^2$$

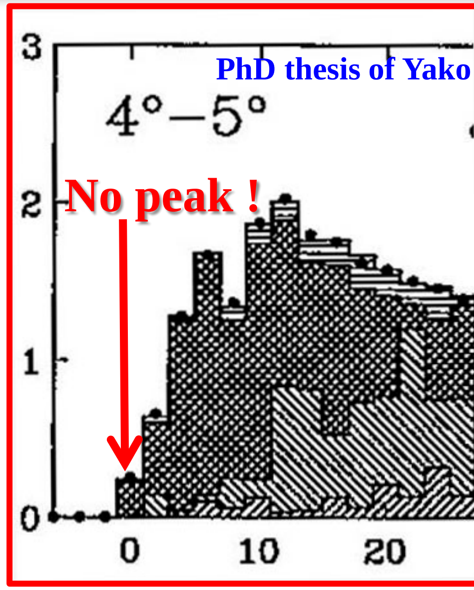
D=6143 s, C=386 fm

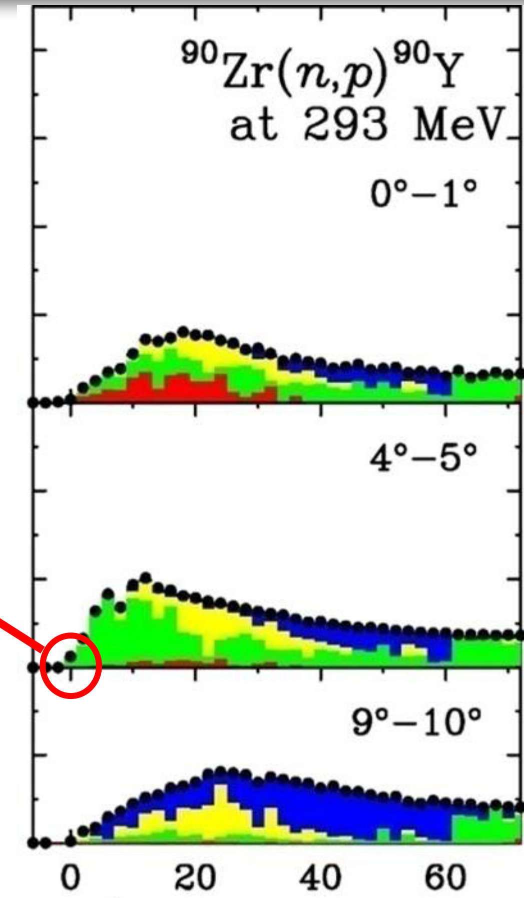
$$\Rightarrow B(SD2\text{-})\uparrow = 0.74\,\text{fm}^2$$

$$\sigma(\text{exp}) = \hat{\sigma}(SD2\text{-})\cdot B(SD2\text{-})$$

$$0.25\left(\frac{\text{mb}}{\text{sr}}\right) = \hat{\sigma}(SD2\text{-})\cdot 0.74\,\text{fm}^2$$

$$\Rightarrow \hat{\sigma}(SD2\text{-}) = 0.34\left(\frac{\text{mb/sr}}{\text{fm}^2}\right)$$



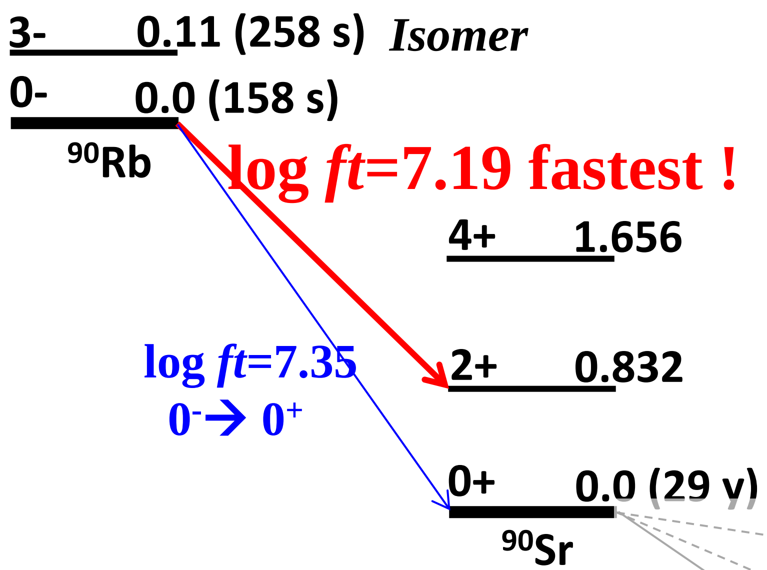


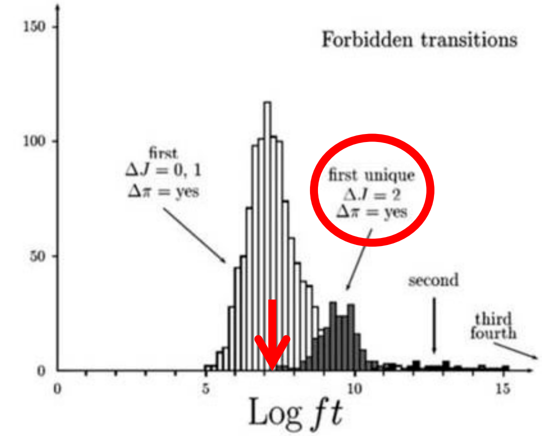
Reasonable

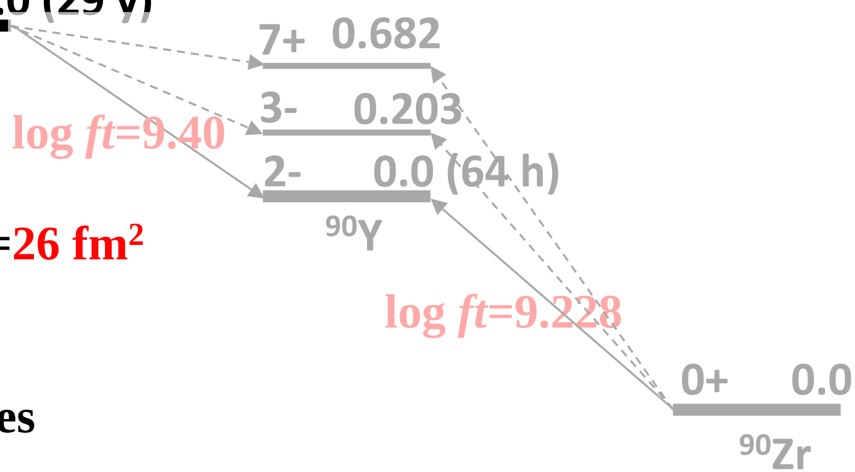
DWIA estimation by Yako

$$\hat{\sigma}(SD2\text{-}) = 0.29\left(\frac{\text{mb/sr}}{\text{fm}^2}\right)$$

Most favorable case unit-$\sigma_{SD}(2^-)$







- Possible case ? ^{90}Rb(p,n)
  - log ft = 7.19 $\Rightarrow$B(SD2-)=26 fm^2
  - Moderately isolated
  - Unstable beam exp.
  - Isomer involvement : Yes

$$\sigma(\text{exp}) = \hat{\sigma}(\text{SD2-}) \times \text{B(SD2-)} = 0.34 \times 26 = 8.8 \left(\frac{\text{mb}}{\text{sr}}\right)$$

Maybe measurable ?

Calibration of 0⁻ and 1⁻ SD

Not necessarily similar to reaction probe $t_{-}\sigma r Y_1$

0⁻

$$\mathcal{M}(\rho_A, \lambda=0) = (4\pi)^{-1/2} \frac{g_A}{c} \sum_k t_-(k)(\boldsymbol{\sigma}(k)\cdot \mathbf{v}_k)$$

$$\mathcal{M}(j_A, \kappa=1, \lambda=0) = g_A \sum_k t_-(k) r_k (Y_1(\hat{\mathbf{r}}_k)\sigma(k))_0$$

$\lambda\pi = 0-$

hadronic weak current timelike comp. γ_5

$[\sigma\times r]^0$

- Two terms tend to cancel.

1⁻

$$\mathcal{M}(\rho_V, \lambda=1, \mu) = g_V \sum_k t_-(k) r_k Y_{1\mu}(\hat{\mathbf{r}}_k)$$

$$\mathcal{M}(j_V, \kappa=0, \lambda=1, \mu) = (4\pi)^{-1/2} \frac{g_V}{c} \sum_k t_-(k)(v_k)_{1\mu}$$

$$\mathcal{M}(j_A, \kappa=1, \lambda=1, \mu) = g_A \sum_k t_-(k) r_k (Y_1(\hat{\mathbf{r}}_k)\sigma(k))_{1\mu}$$

$\lambda\pi = 1-$

Non-spinflip !

hadronic weak current α

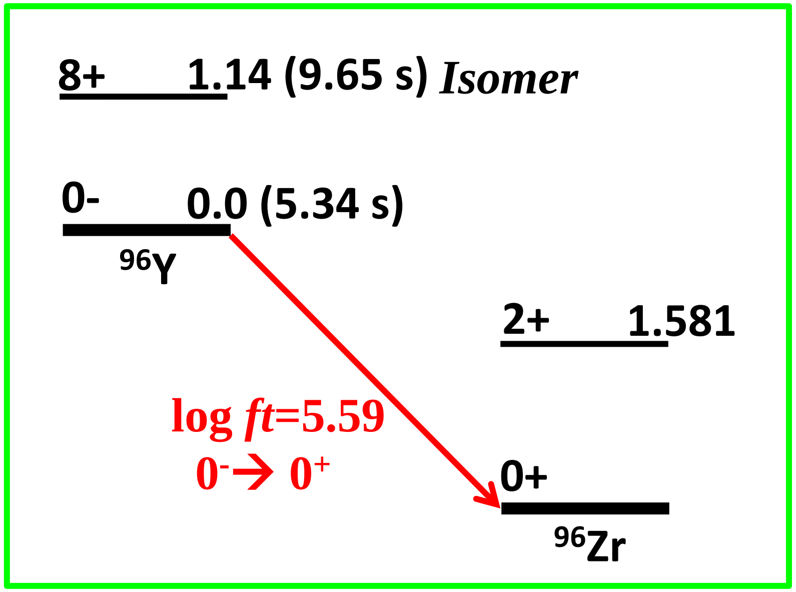
$[\sigma\times r]^1$

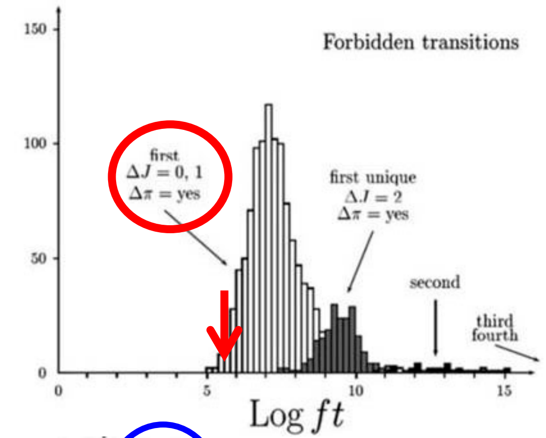
- Involves non-spinflip.

Probably B(0⁻/1⁻) of β decay is unable to use as a probe calibration purpose.

Candidate of 0- SD calibration

- **Possible case ? ^{96}Y(p,n)**
  - log *ft* = 5.59 ⇒B(SD0$^-$)=1,125 fm^2 !
  - Isolated
  - Unstable beam exp.
  - Isomer involvement : Yes





$$O(0^-) = g_A\left[\frac{\vec{\sigma}\cdot\vec{p}}{M_N} + \xi i\vec{\sigma}\cdot\vec{r}\right]t_-$$

~ 2 enhancement due to MEC

(p,n)

- Assume: B(SD0-;SF)=0.1×B(SD0-)

$$\sigma(\text{exp}) = \hat{\sigma}(\text{SD2-}) \times \text{B(SD0-;SF)} \approx 10\left(\frac{\text{mb}}{\text{sr}}\right)$$

- **Feasible with RI beam exp.**
- **Proportionality ???**

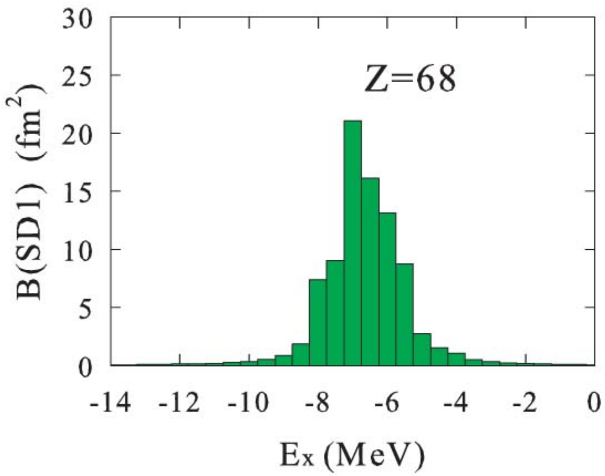
Difficulty of 1⁻ SD calibration

- **Shell model estimate of 1^- SD**

PHYSICAL REVIEW C **85**, 015802 (2012)

β decays of isotones with neutron magic number of $N = 126$ and r-process nucleosynthesis

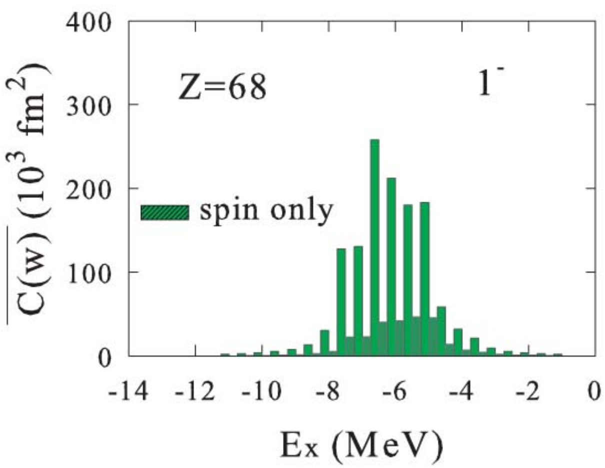
Toshio Suzuki,[1,2,3] Takashi Yoshida,[4] Toshitaka Kajino,[3,4] and Takaharu Otsuka[5,6]



$$B(SD\lambda) = \frac{1}{2J_i + 1} |\langle f || r[Y^{(1)} \times \vec{\sigma}]^{\lambda} t_- || i \rangle|^2 \quad (7)$$

$$O(1^-) = \left[g_V \frac{\vec{p}}{M_N} - \xi(g_A \vec{\sigma} \times \vec{r} - i g_V \vec{r}) \right] t_-,$$

(p,n)



- **Strong non-spinflip strength**
- **log *ft* is large**
- **Small branching ratio**

⇒ **Probably non-realistic to use β B(1⁻) for calibration**

Summary

1. GT and SD : important spin-isospin responses
   - (p,n) reaction could provide B(GT) and B(SD)
2. (p,n) reaction must be calibrated by β B(GT/SD)
   - No B(GT) for A>160
   - Nothing for B(SD)
3. RI beam is now available → open new possibilities
4. GT:
   - B(GT) > 0.5 is needed for A>160
5. SD: with 0- or 1-
   - B(2-) : ^{90}Rb(p,n) may be feasible with log *ft*=7.19
   - B(1-) : Maybe essential difficulty with non-spinflip
   - B(0-) : ^{96}Y(p,n) may be with log *ft*=5.59 but γ_5 term ?
6. SPES project
   - B(GT)/B(SD) are always precious for structure study
   - β decay measurement ?