Double Gamow–Teller giant resonance in ^{48}Ca studied by (^{12}C, $^{12}Be(0^+_2)$) reaction at 250 MeV/u

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Based on "Candidate for the Double Gamow–Teller Giant Resonance in ^{48}Ca Studied by the (^{12}C, $^{12}Be(0^+_2)$) Reaction at 250 MeV/Nucleon"
A. Sakaue et al., PTEP 123D03 (2024) https://doi.org/10.1093/ptep/ptae174

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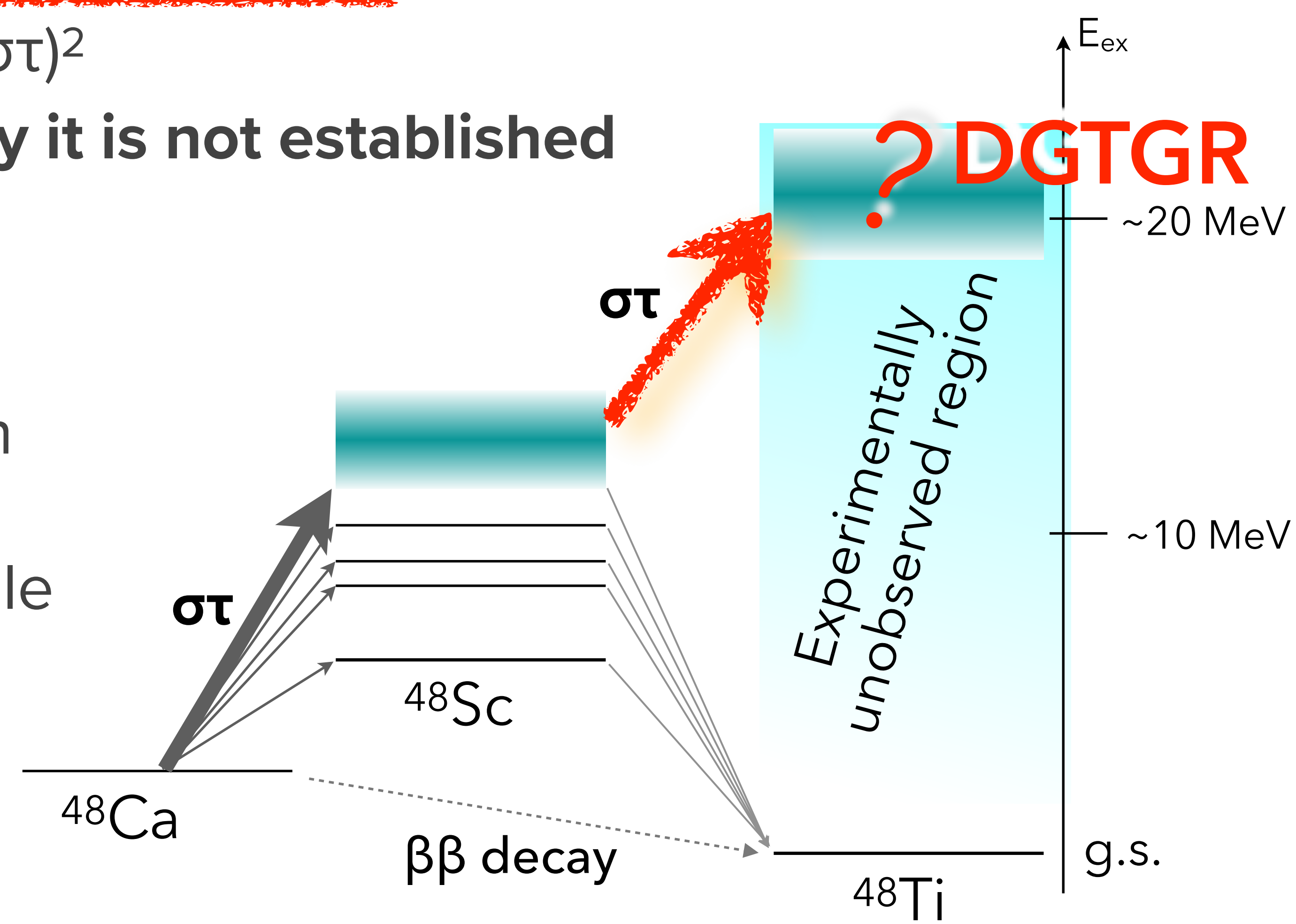
Double Gamow–Teller giant resonance

Double Gamow–Teller (DGT) transition - spin and isospin flip twice, ΔL=0 : $(\sigma\tau)^2$

- Double β decay: occupy ~ 0.01% of total strength of $(\sigma\tau)^2$
- **Double Gamow–Teller giant resonance (DGTGR)**
  : occupy most of total strength of $(\sigma\tau)^2$
  proposed in 1989 but **experimentally it is not established**
  Auerbach (Ann. Phys. 192, 77)



Observation of DGTGR is important

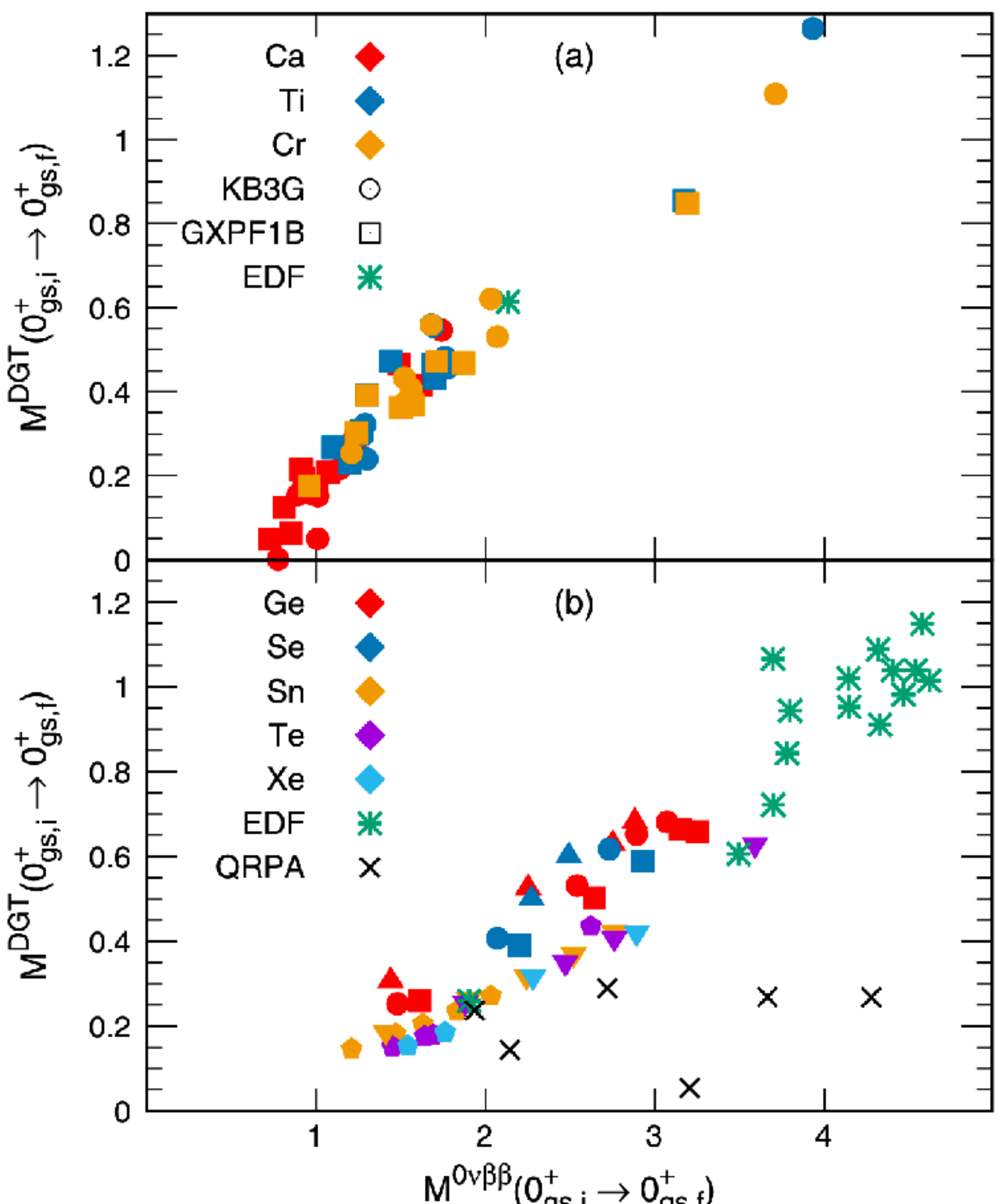
- Understanding of collective mode in spin-dependent space
  Ec, Γ, ... : simple superposition of sigle resonance?
- DGTGR is main component of DGT
  — provide information on
  nuclear matrix element (NME) of 0νββ

our aim : observe DGTGR experimentally

DGTGR↔0νββ NME

Observables of DGTGR is correlated with 0νββ NME

Matrix element of DGT ↔ 0νββ NME



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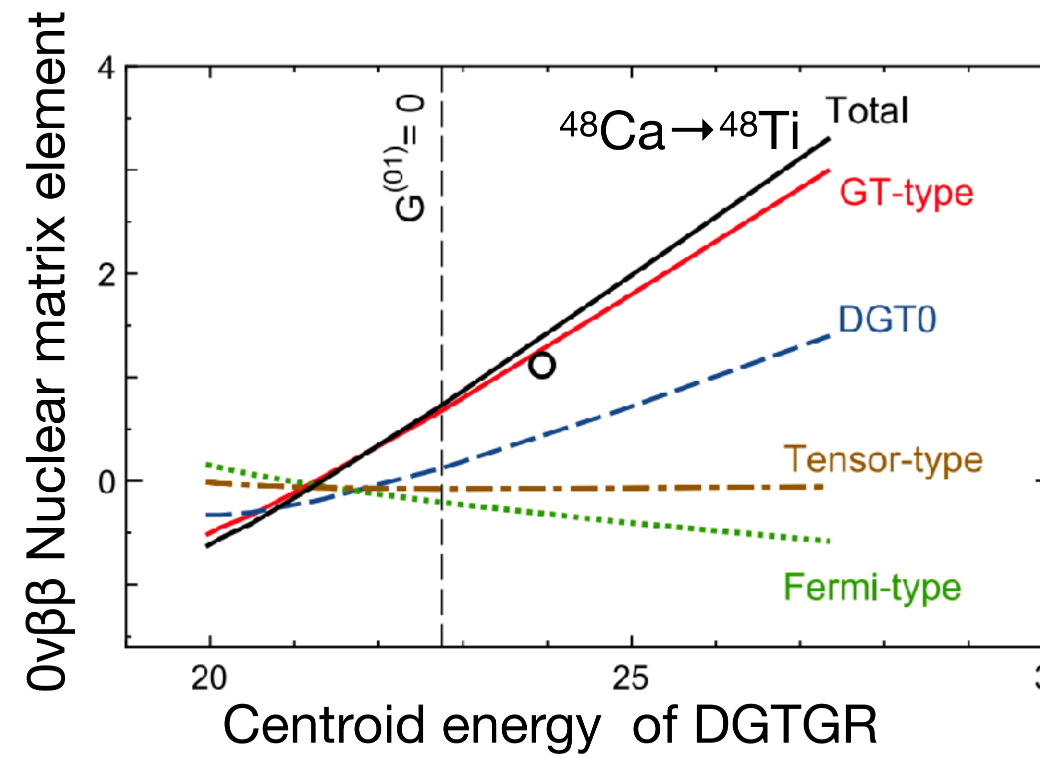
Centroid energy of DGTGR ↔ 0νββ NME



shell model calculation
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The experimental information of DGTGR will constrain the value of 0νββ NME

(^{12}C, ^{12}Be(0^+_2)) reaction

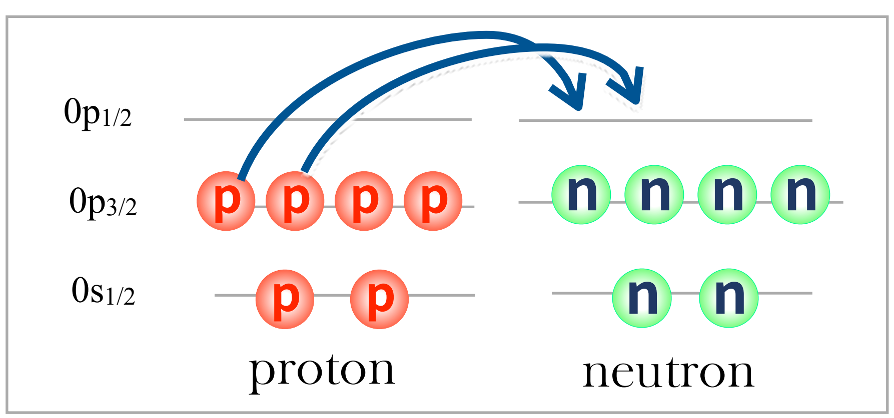
Observation of DGTGR

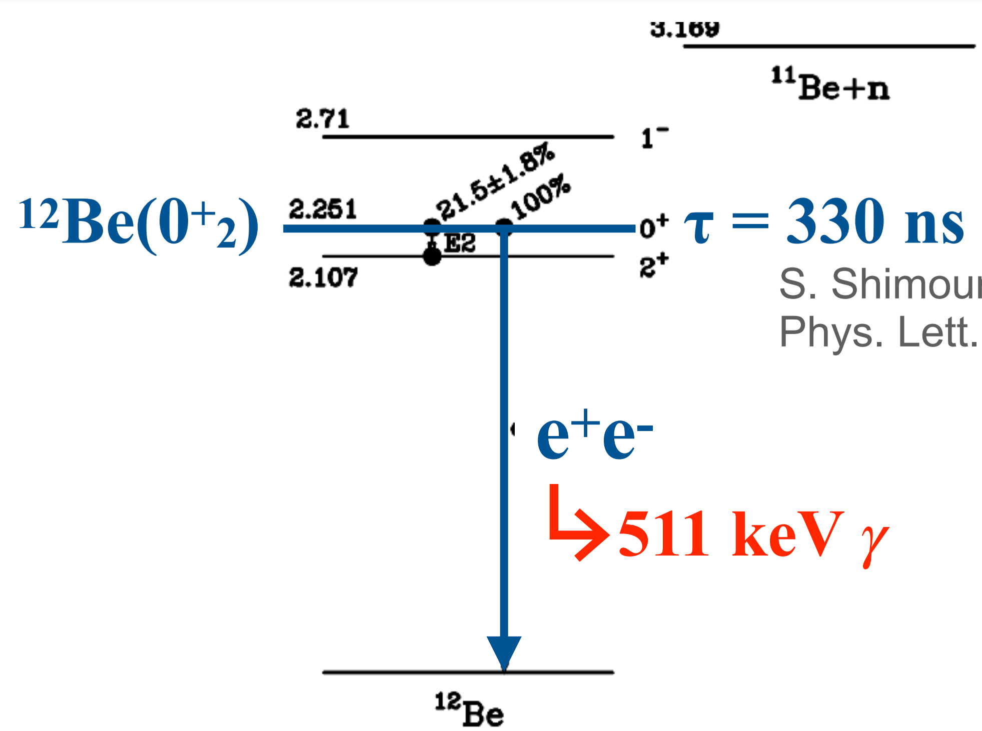
— Double charge exchange (DCX) reaction using heavy ion **(^{12}C, ^{12}Be(0^+_2))**

isomeric state
(E_{ex} = 2.3 MeV, τ = 330 ns)

- ^{12}C($0^+_{g.s.}$)→^{12}B($1^+_{g.s.}$)→^{12}Be(0^+_2) are all dominated by $0\hbar\omega$ states
  ⇒ **transition will be strong**

- ^{12}Be(0^+_2) decays into g.s. with emmiting e^+e^-
  ⇒ 511 keV γ ray deriving from annhilation of e^+ **serves as a tag of event**



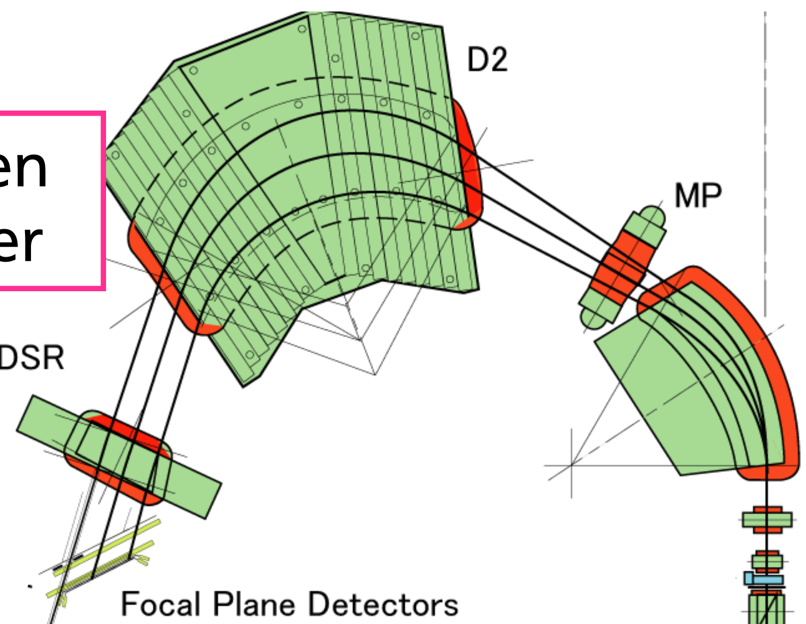


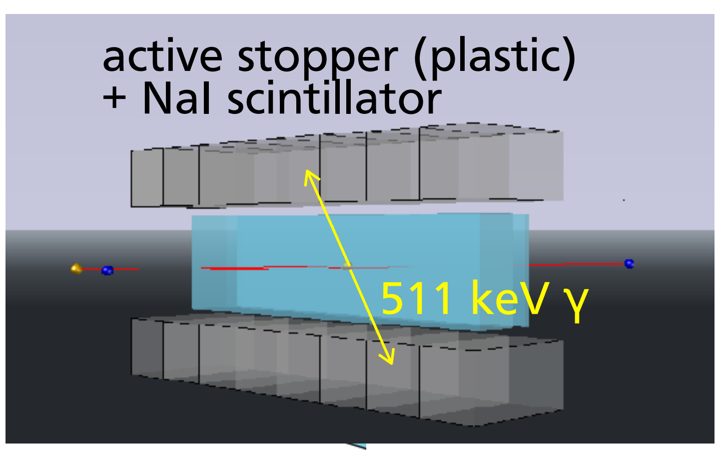
S. Shimoura et al.,
Phys. Lett. B **654,** 87 (2007)

Pilot experiment at RCNP

^{48}Ca(^{12}C, ^{12}Be(0^+_2)) @RCNP
(2015, M. Takaki et al.)

Grand Raiden spectrometer





10 mg/cm^2
^{48}Ca target

100 MeV/u,
16 pnA
^{12}C beam

Summary of the pilot experiment

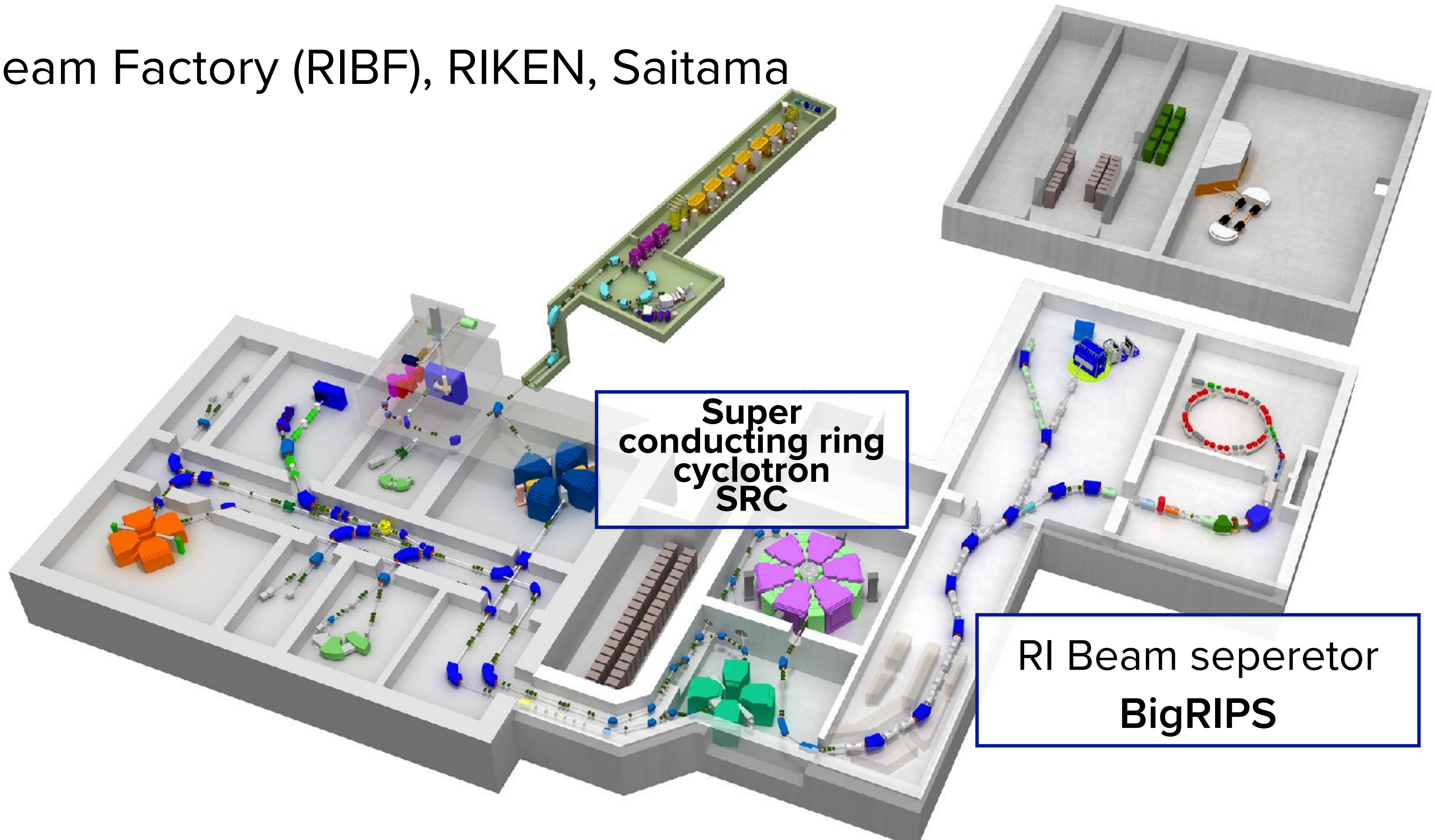
- ☑ Timing distribution of γ-rays reproduced lifetime of ^{12}Be(0^+_2): ID of ^{12}Be(0^+_2)
- ☑ In Ex distribution of cross section, forward peaking structure was observed around predicted region of DGTGR
- ☐ BG from stopper (^{12}C) —S:N=1:1
  ^{3}H+^{12}C→^{11}C (β+ decay, τ=20 min)
- ☐ Statistics was limited

Conclusive result was not obtained

Experiment at
RIKEN **RI Beam Factory (RIBF)**
- Intense beam
- stopper without BG source

Experiment at RIBF

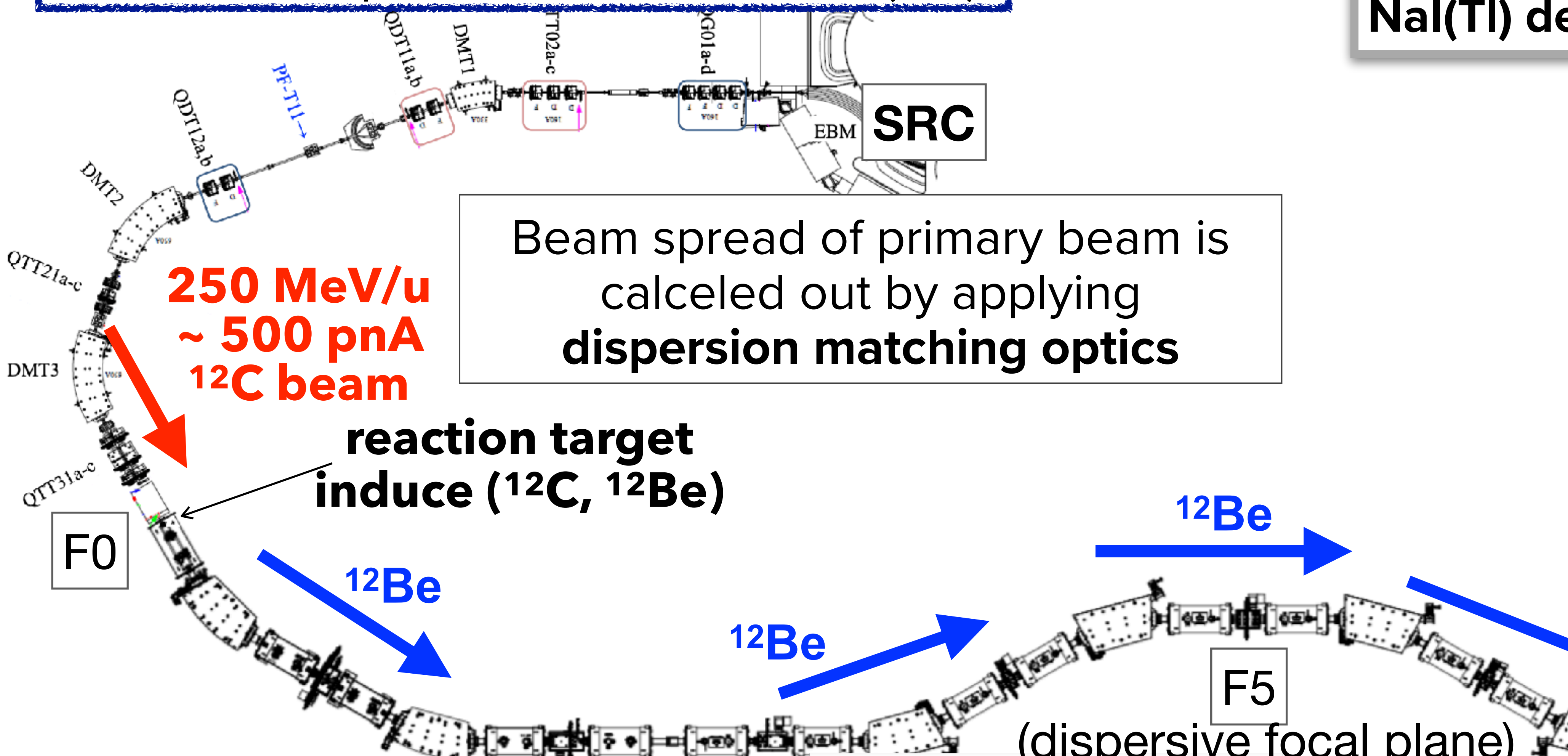
RI Beam Factory (RIBF), RIKEN, Saitama



We use BigRIPS as a spectrometer with BG separation

Measurement of (^{12}C, ^{12}Be(0^+_2)) at RIBF BigRIPS

F0–F5: momentum analyzation of ^{12}Be
F5–F8: BG separation and ID of ^{12}Be(0^+_2)



250 MeV/u
~ 500 pnA
^{12}C beam

Beam spread of primary beam is calceled out by applying **dispersion matching optics**

reaction target
induce (^{12}C, ^{12}Be)

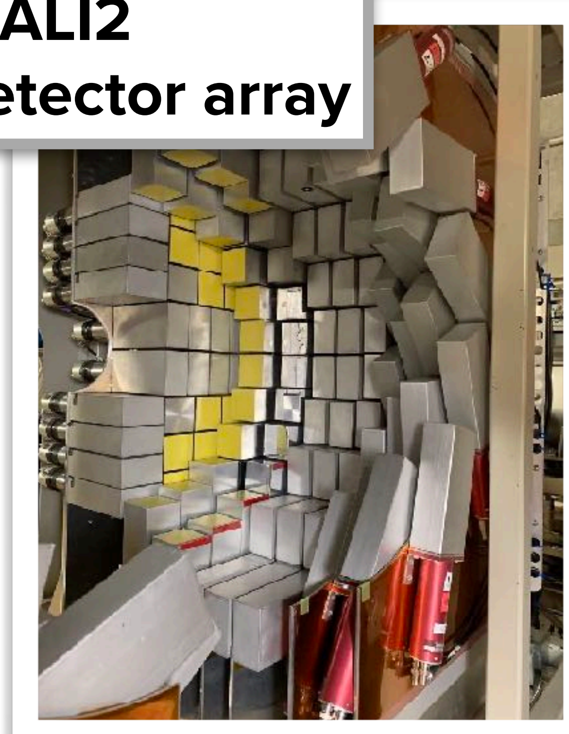
^{12}Be

^{12}Be

^{12}Be

F5 (dispersive focal plane)

DALI2
NaI(Tl) detector array



^{12}Be is stopped at ^{9}Be stopper

^{12}Be(0^+_2)→e$^+$e$^-$
↳ γ

track measurement at F5 :
Low-pressure MWDC

BGs (t, ^{6}He, ^{9}Li, …) are swept by degraders and magnets of F5-F7

identify ^{12}Be(0^+_2)

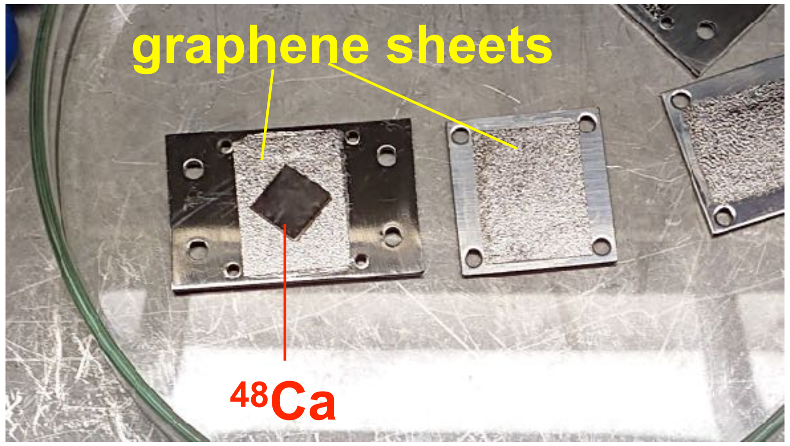
Experiment at RIBF in 2021

The first experiment of (^{12}C, $^{12}Be(0^+_2)$) at RIBF was performed in 2021

- Target : ^{48}Ca 10.3 mg/cm^2
  - Double β decaying nuclei —CANDLES exp.
  - Doubly magic nuclei: precise theoretical calculation is possible
  - Single GT resonance is well studied

^{48}Ca target is coated with graphene sheet (4 μm x2(up/downstream))

- Enhance thermal conductivity
- Prevent oxidation / nitrization



^{48}Ca target with graphene

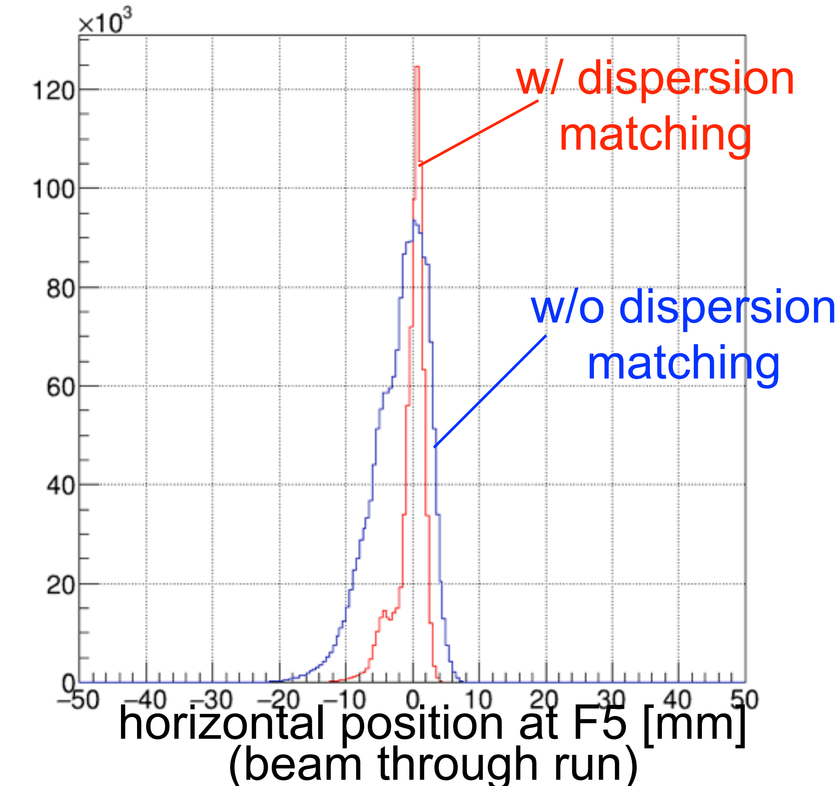
- Measurement of $^{48}Ca(^{12}C, ^{12}Be(0^+_2))$ for ~ 40 hours
  Intensity of primary beam ~ 600 pnA

Achievement of the first experment

Dispersion matching

Δp/p ~ **0.06%** (w/o DM) → **0.026%** (w/ DM)

☑ Sufficient excitation energy resolution (1.5 MeV) was achieved



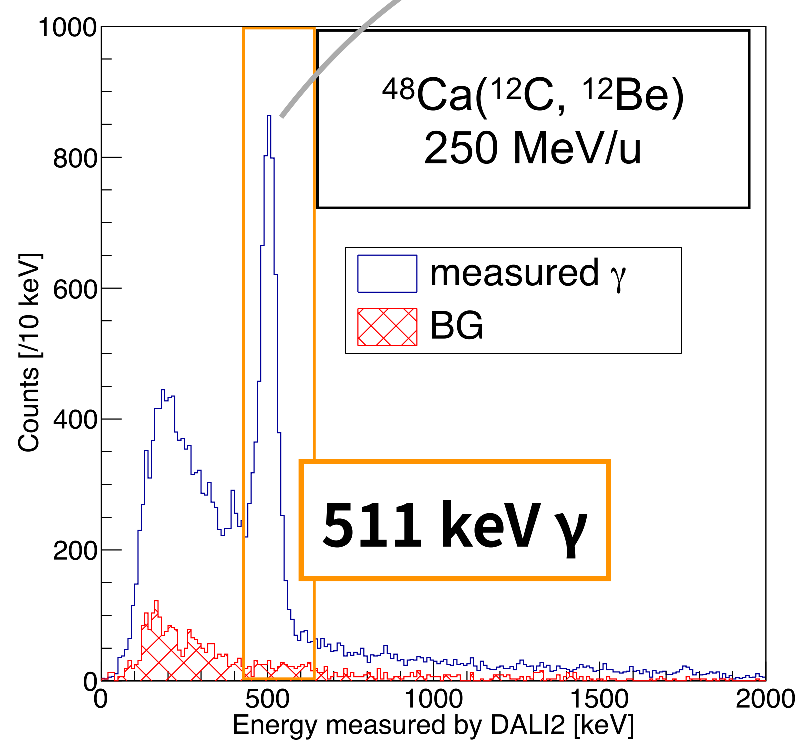
Detection of $^{12}Be(0^+_2)$ events

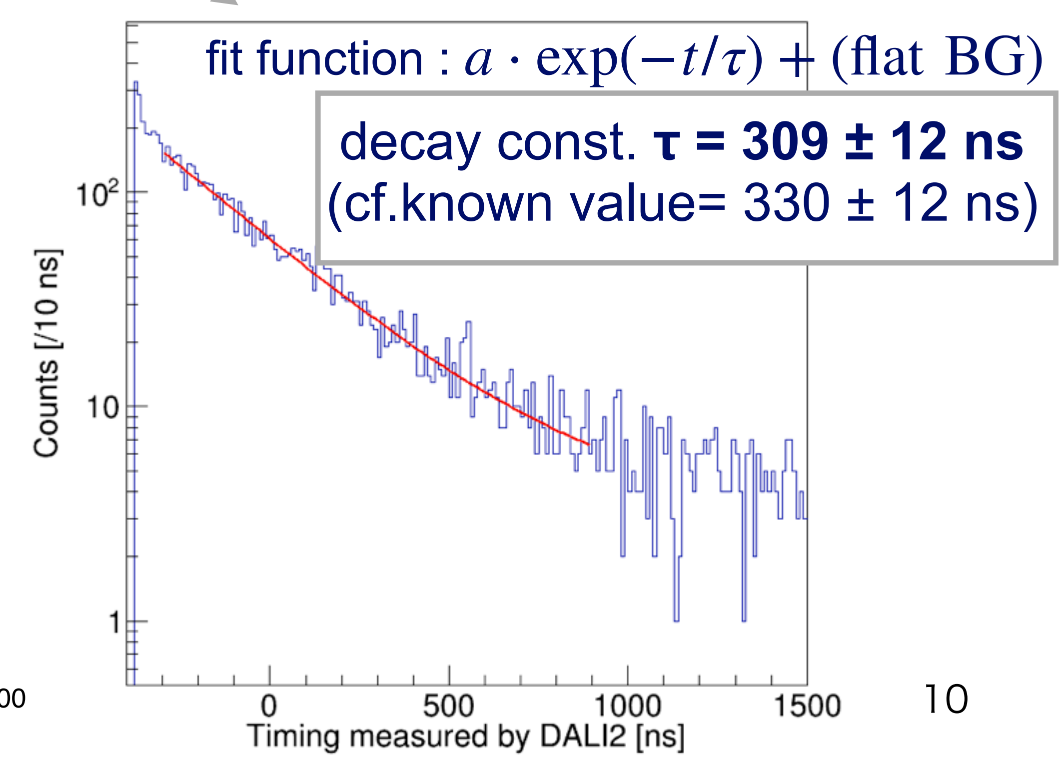
☑ Successfully identified $^{12}Be(0^+_2)$

☑ S:N ~ 9:1 **low BG**

cf. 1:1 at RCNP

BG : acc. coin of ^{12}Be and room BG γ



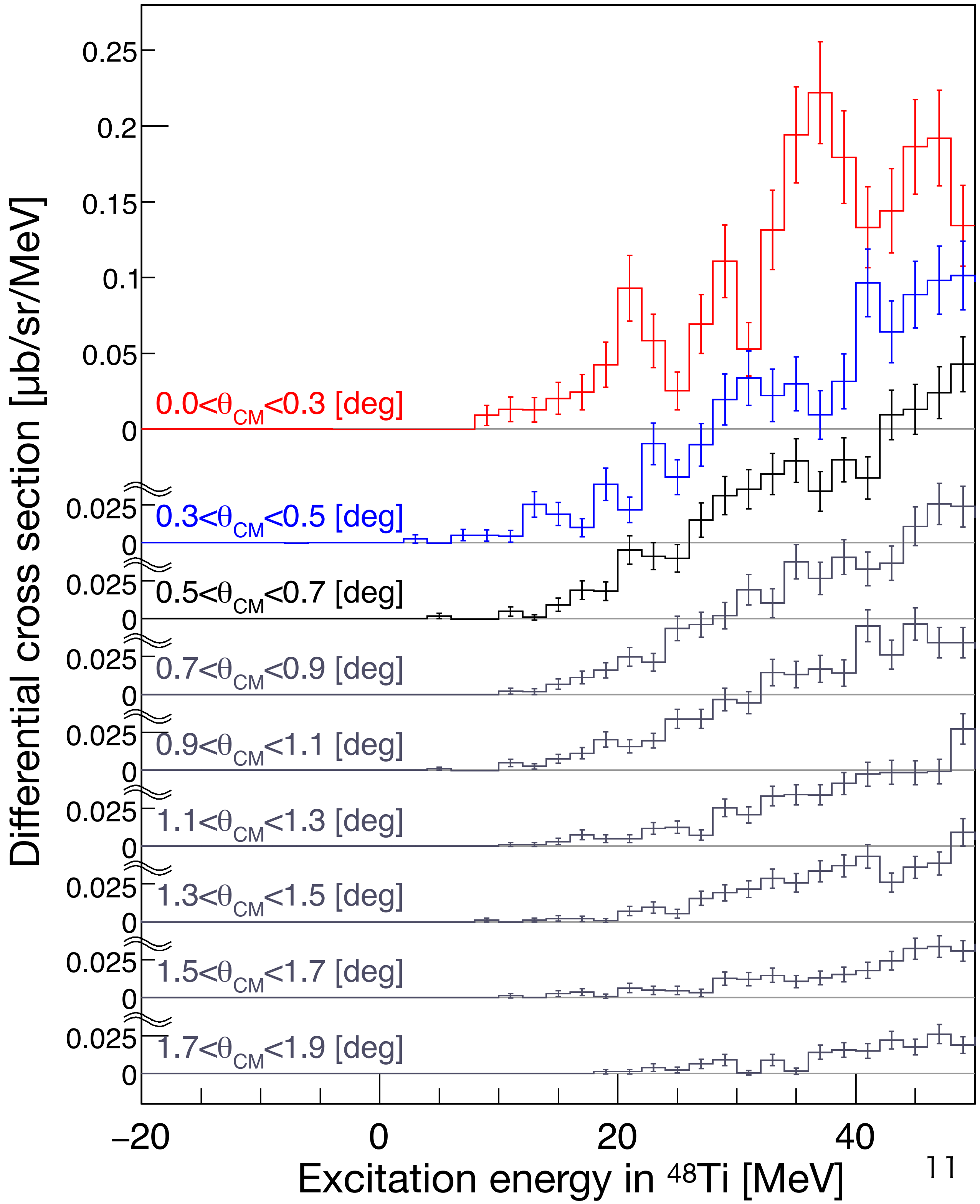


Results of $^{48}Ca(^{12}C, ^{12}Be(0^+_2))^{48}Ti$ measurement

Ex distribution of cross section for
$^{48}Ca(^{12}C, ^{12}Be(0^+_2))^{48}Ti$
at 0–0.3°, 0.3–0.5°, 0.5–0.7°, …

- $^{12}Be(0^+_2)$ events were selected by γ gate
- acc. coin events of ^{12}Be and room BG γ were subtracted
- ^{48}Ca target with graphene coating
  - events from $^{12}C(^{12}C, ^{12}Be(0^+_2))^{12}O$ contaminates at $E_x > 34$ MeV ~ 6±2%

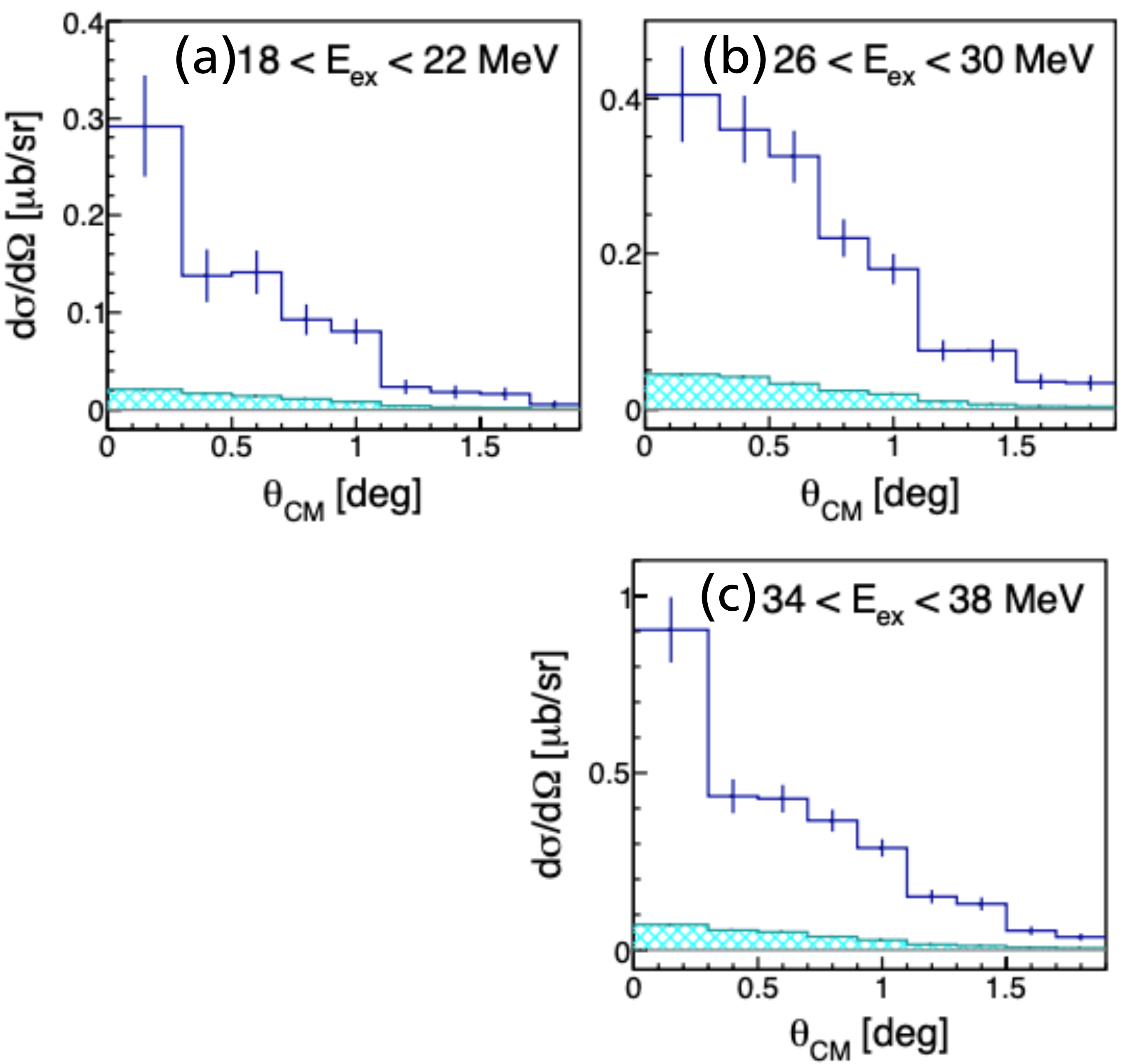
- ΔE=1.5 MeV, $\Delta\theta_{CM}$=0.2°
- cross section = 1.33 ± 0.12 μb/sr in $0 < E_{ex} < 34$ MeV, $0 < \theta_{CM} < 0.3°$
  - only statistical error is shown
  - overall uncertainty is ~ 40%

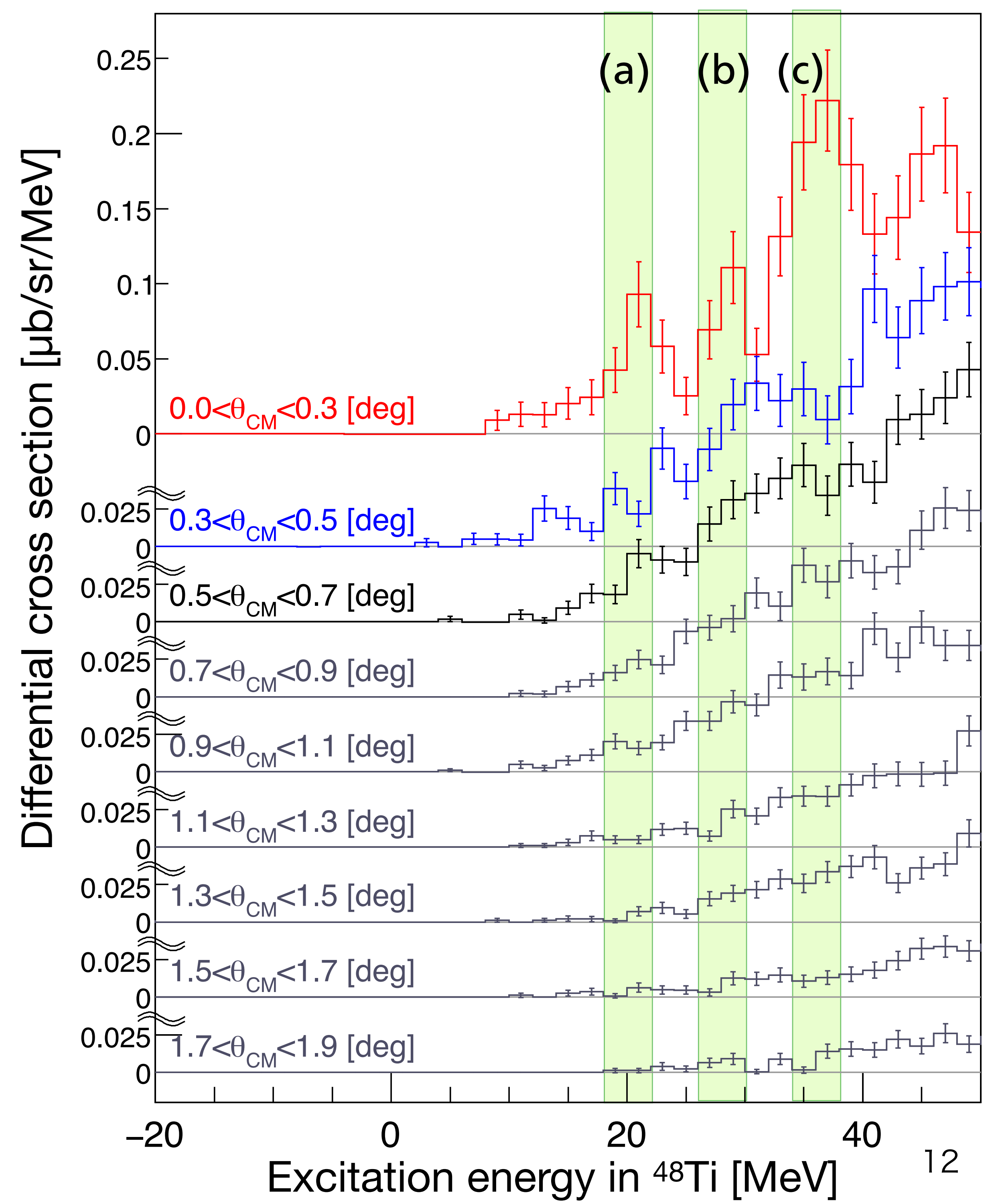


Results of $^{48}Ca(^{12}C, ^{12}Be(0^+_2))^{48}Ti$ measurement

forward peaking structrue
at Ex = 20, 28, 35 MeV

Candidate of DGTGR





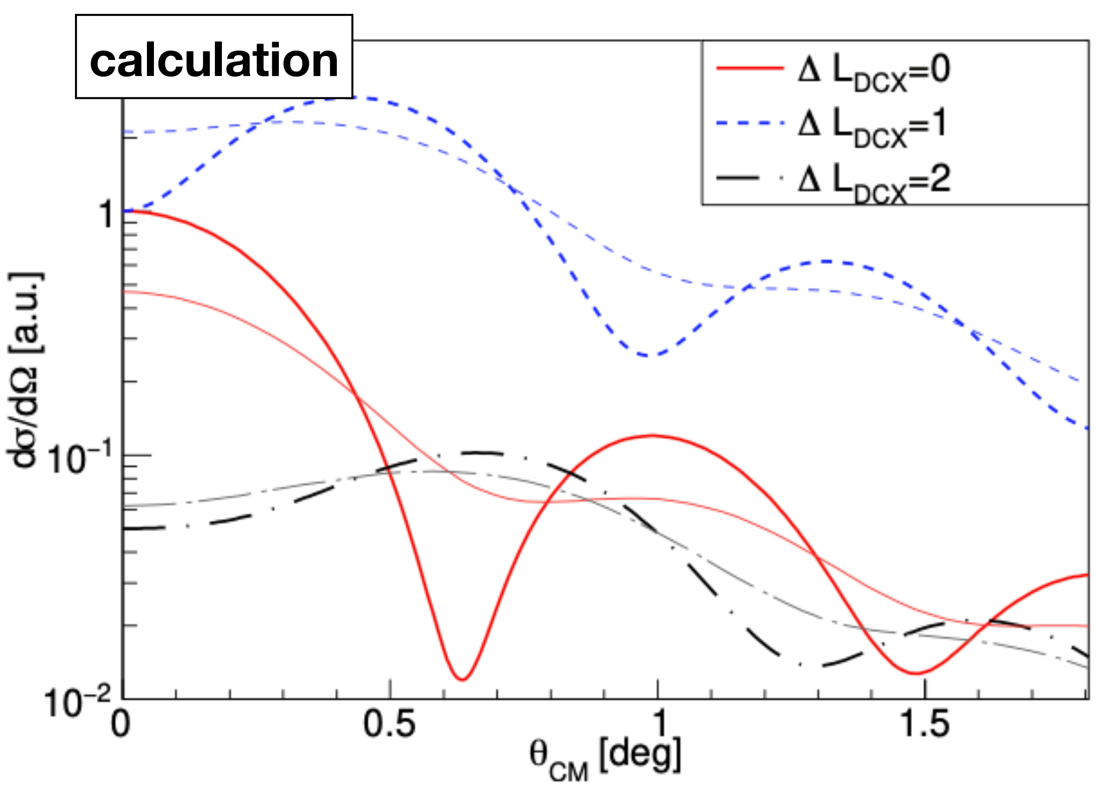
Expected angular distribution of DCX

In order to extract DGT components, angular disribution for DCX is estimated by **coupled channel calculation** with ECIS97

- intinal state: $^{12}C(0^+)+^{48}Ca(0^+)$
- intermediate state: $^{12}B(1^+)+^{48}Sc(1^+)$ are assumed to be each channel
- final state: $^{12}Be(0^+)+^{48}Ti(0^+)$

- Transition form factors are obtained by folding microscopic transition using FOLD
- Global optical potential by T. Furumoto

T. Furumoto et al., PRC 85, 044607 (2012).

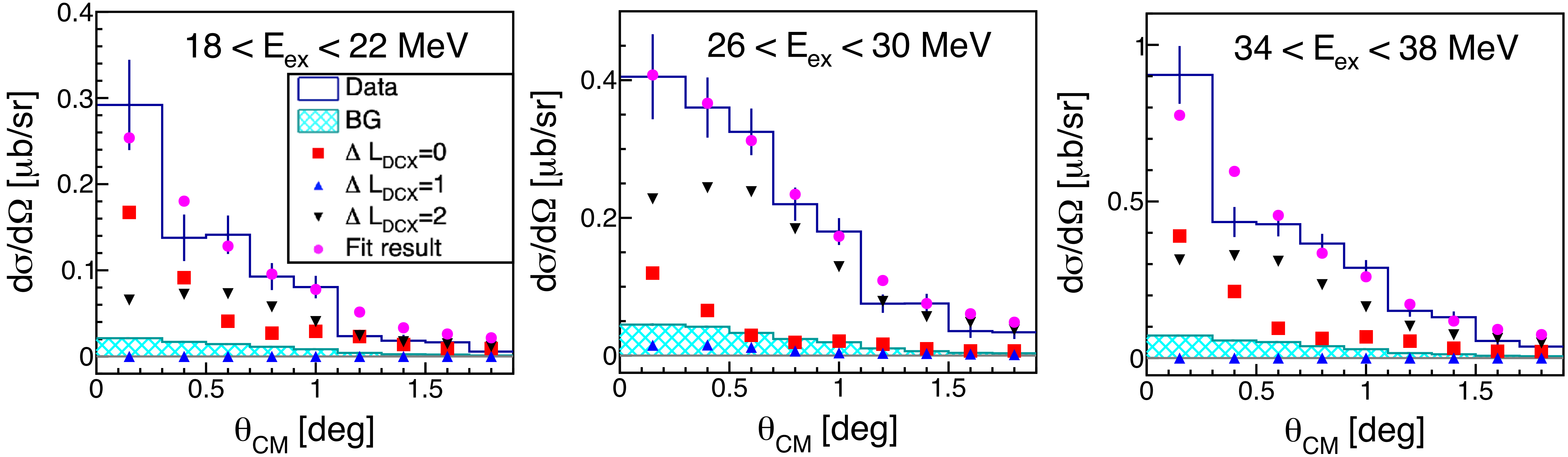


- $\Delta L_{DCX} = 0$: $[\Delta L=0]\otimes[\Delta L=0]$: DGT-like
- $\Delta L_{DCX} = 1$: $[\Delta L=1]\otimes[\Delta L=0]$
- $\Delta L_{DCX} = 2$: $[\Delta L=2]\otimes[\Delta L=0]$

calculation / smeared with experimental resolution $\Delta\theta$

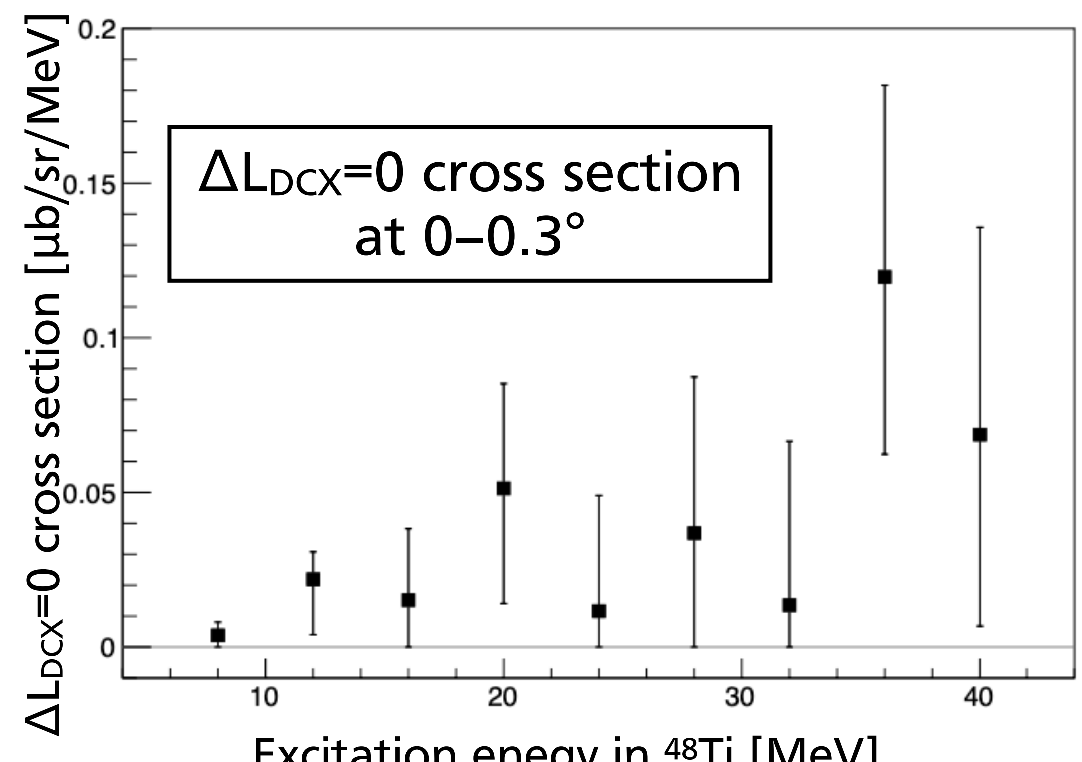
Extraction of ΔL$_{DCX}$=0

Experimental angular distributions are decomposed by **ΔL$_{DCX}$ = 0, 1, 2**



■ : ΔL$_{DCX}$ = 0
● : Fit result

extracted cross section of ΔL$_{DCX}$=0
at 0–34 MeV, 0–0.3° : $0.50^{+0.35}_{-0.11}$ μb/sr
(38^{+26}_{-8}% of observed cross section)



Extraction of B(DGT)

DGT transition strength $B(\mathrm{DGT}) = \frac{1}{2J_i+1}\left|\langle f\|(\sigma\tau)^2\|i\rangle\right|^2$ was deduced from the extracted ΔL_{DCX}=0 components under assumptions:

① ΔL_{DCX}=0 components are all attributed to DGT transition

② DGT cross section at 0° is proportional to B(DGT)

$$\frac{d\sigma}{d\Omega}(0^\circ) = \hat{\sigma}_{\mathrm{DGT}} F(q,\omega)\, B_{\mathrm{target}}(\mathrm{DGT})\, B_{\mathrm{projectile}}(\mathrm{DGT})$$

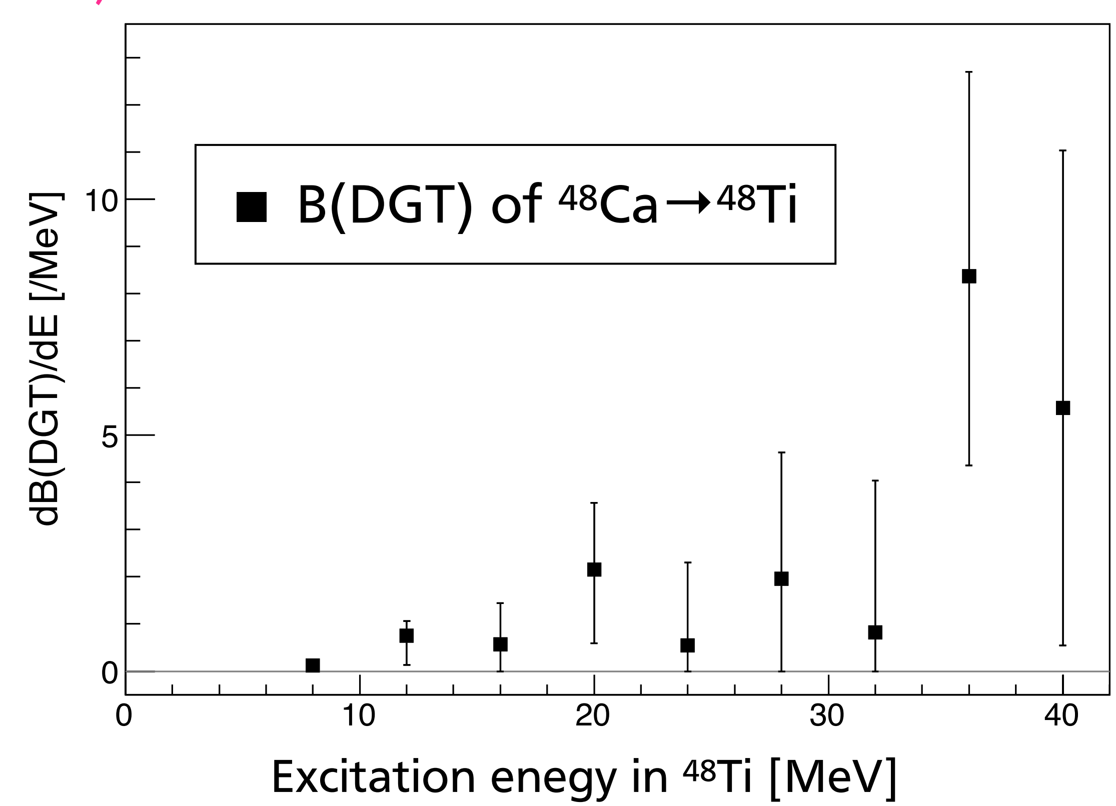
ΔL_{DCX}=0 cross section at 0°

Transition strength of target ($^{48}Ca \rightarrow {}^{48}Ti$)

$B_{projectile}$(DGT): transition strength of projectile ($^{12}C \rightarrow {}^{12}Be$)

($B_{12C\rightarrow 12B}(GT)$ * $B_{12B\rightarrow 12Be}(GT)$)

($\hat{\sigma}_{DGT}$: proportional coefficient
F(q,ω) : momentum transfer dependent term)
: obtained by reactcion calculation



Other possibility than DGT transition

In the extraction of ΔL_{DCX}=0 components,
other transitions with similar angular distribution to the DGT are not excluded

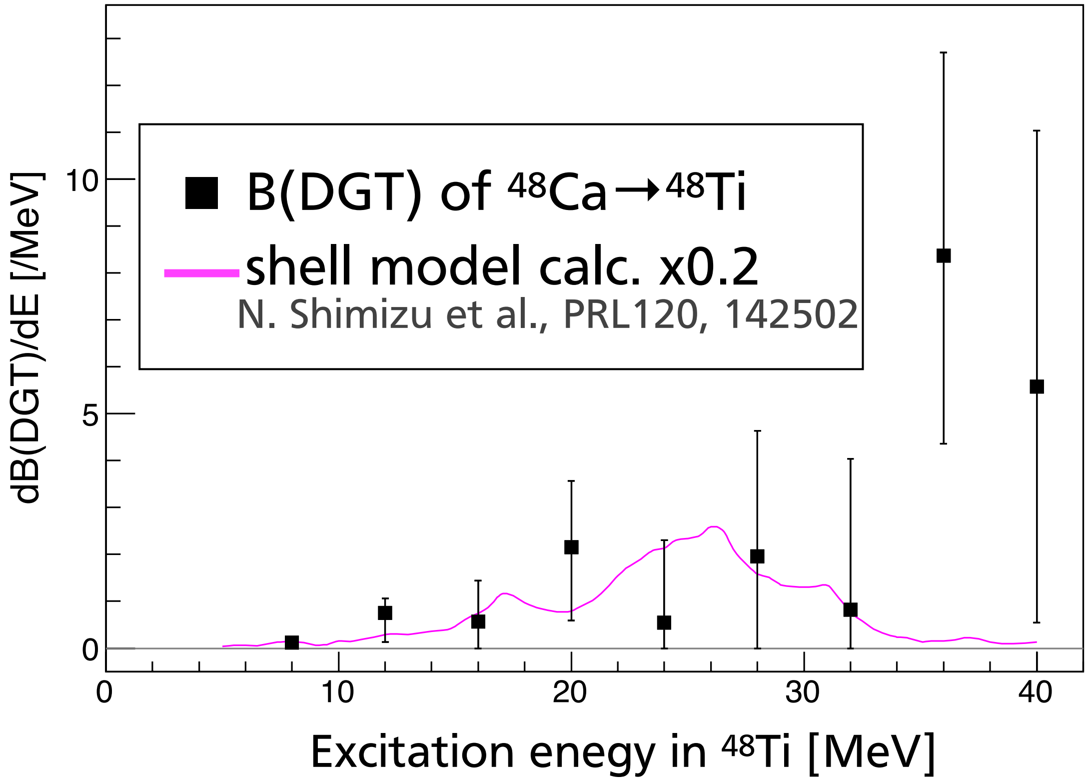
e.g. IsoVector Spin Monopole (IVSM) $(\hat{O}^{\pm}_{\mathrm{IVSM}} = \sum_i \sigma_i \tau_i^{\pm} r_i^2)$ → IVSM⊗GT, IVSM⊗IVSM,...

Consider the expected energy where these modes emerges

- Energy expected by adding E in single resonances
  - DGTGR : E~28 MeV
  - $E_{\mathrm{IVSM \otimes GT}}$~ 39 MeV
  - $E_{\mathrm{IVSM \otimes IVSM}}$~ 50 MeV

- Prediction by shell model is distributed at Ex < 35 MeV

- 0<E<34 MeV
  ➔DGT
- E>34 MeV
  ➔IVSM⊗GT, DIVSM?
  or DGTGR is pushed out to higher E?



Further study is needed for decisive conclusion

Extraction of B(DGT) of $^{48}Ca \rightarrow ^{48}Ti$

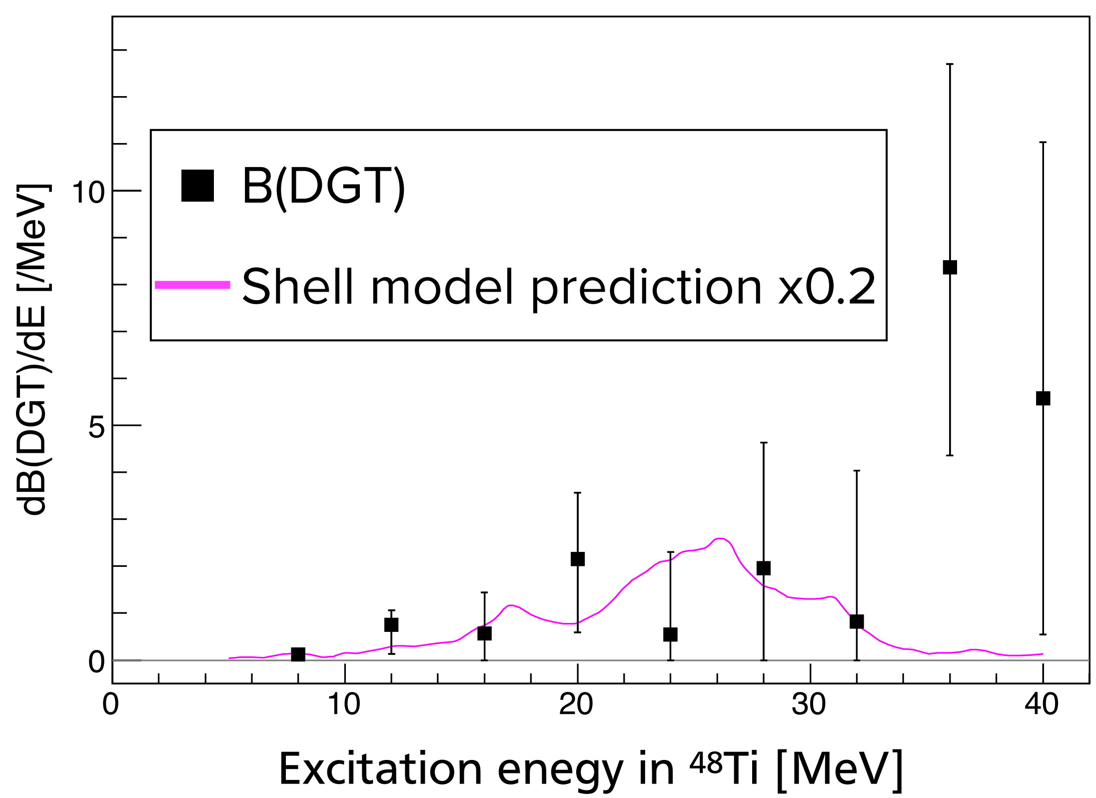
- We regard the structure at $0<E<34$ MeV as the DGTGR

integrated strength, centroid energy, width for $0<E<34$ MeV

$S=28^{+22}_{-7}$, E_c = 23±3 MeV, Γ = 6±1 MeV

(22^{+17}_{-6}% of sum rule)

$$S = \sum_i B_i(\mathrm{DGT}) \quad E_c = \frac{\sum_i E_i B_i(\mathrm{DGT})}{\sum_i B_i(\mathrm{DGT})} \quad \Gamma = \frac{\sum_i (E_i - E_c) B_i(\mathrm{DGT})}{\sum_i B_i(\mathrm{DGT})}$$



Constrain to 0νββ NME

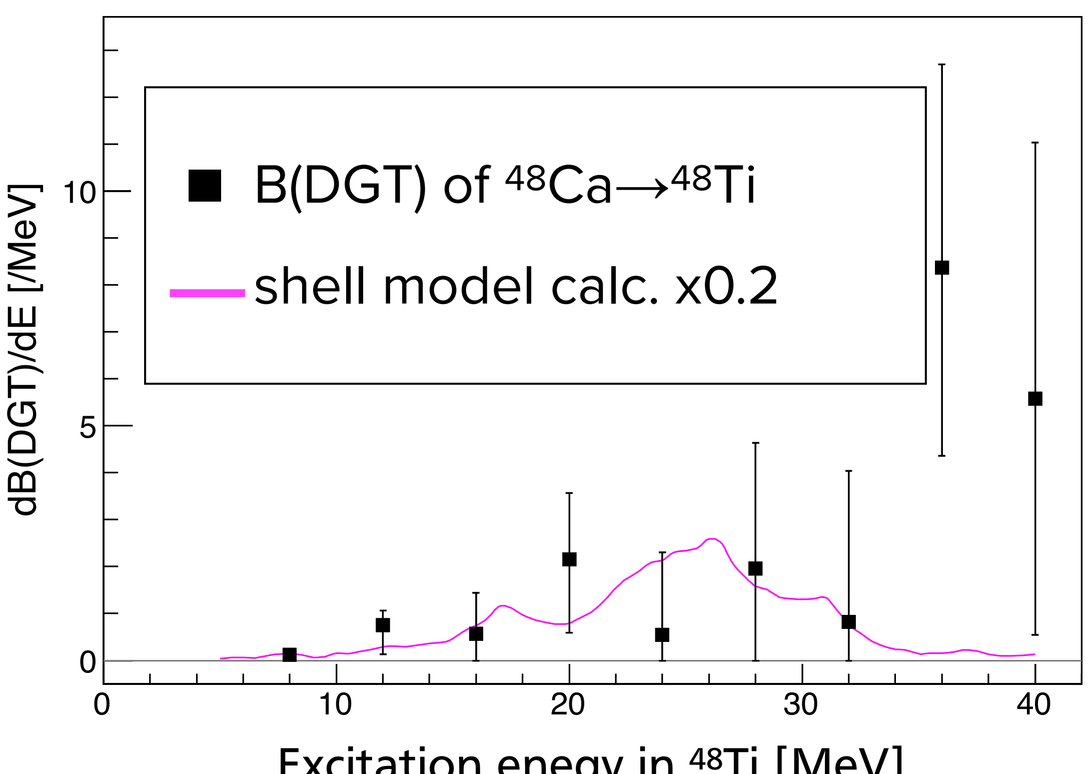
integrated strength, centroid energy, width for 0<E<34 MeV

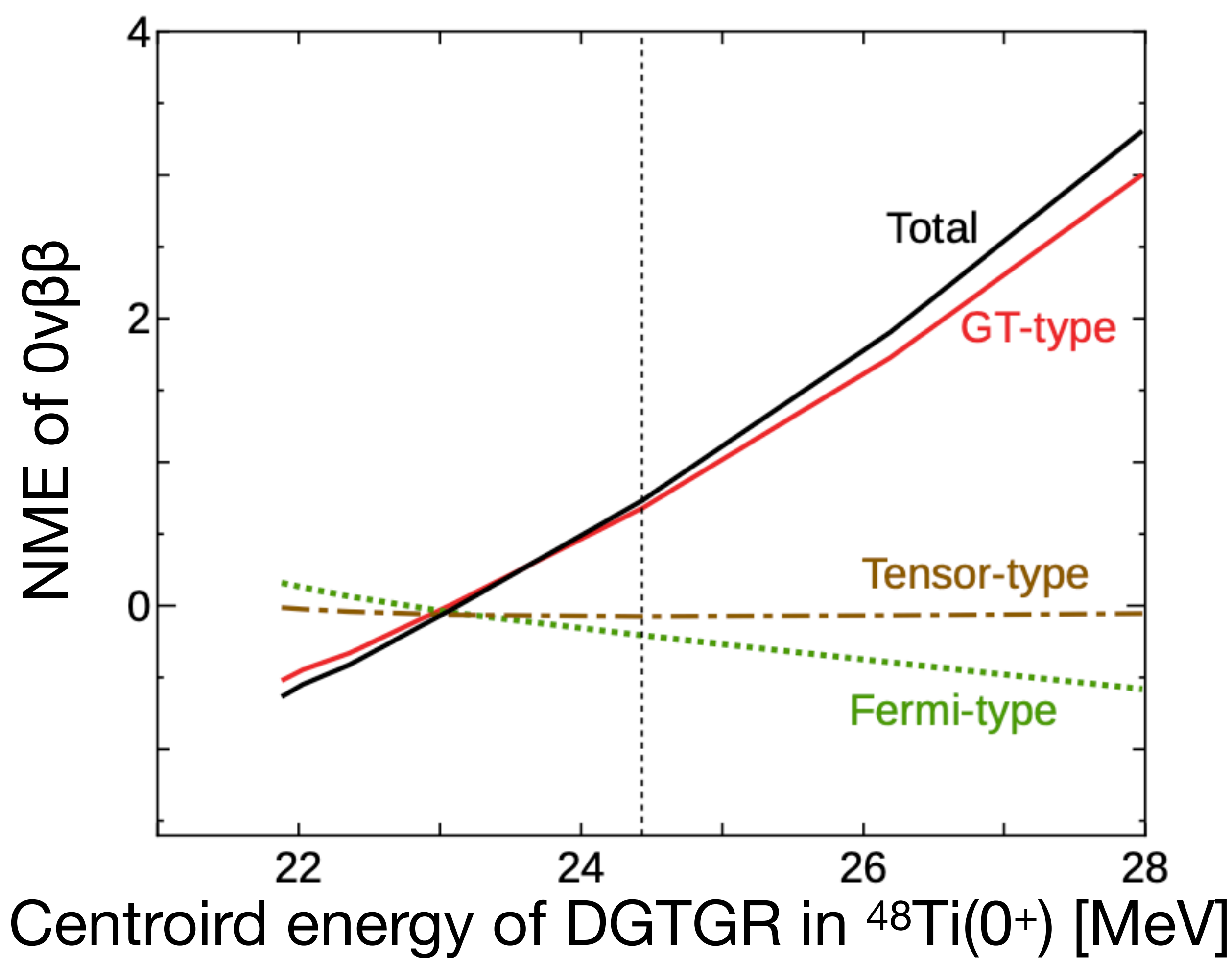
$S=28^{+22}_{-7}$, E_c = 23±3 MeV, Γ = 6±1 MeV

(22^{+17}_{-6}% of sum rule)

apply to the relation of “E_c ↔ 0νββ NME”

✓E_c=23±3 MeV





N. Shimizu, J. Menéndez, K. Yako Phys. Rev. Lett. 120, 142502
N. Shimizu, Private communication

Constrain to 0νββ NME

integrated strength, centroid energy, width for 0<E<34 MeV

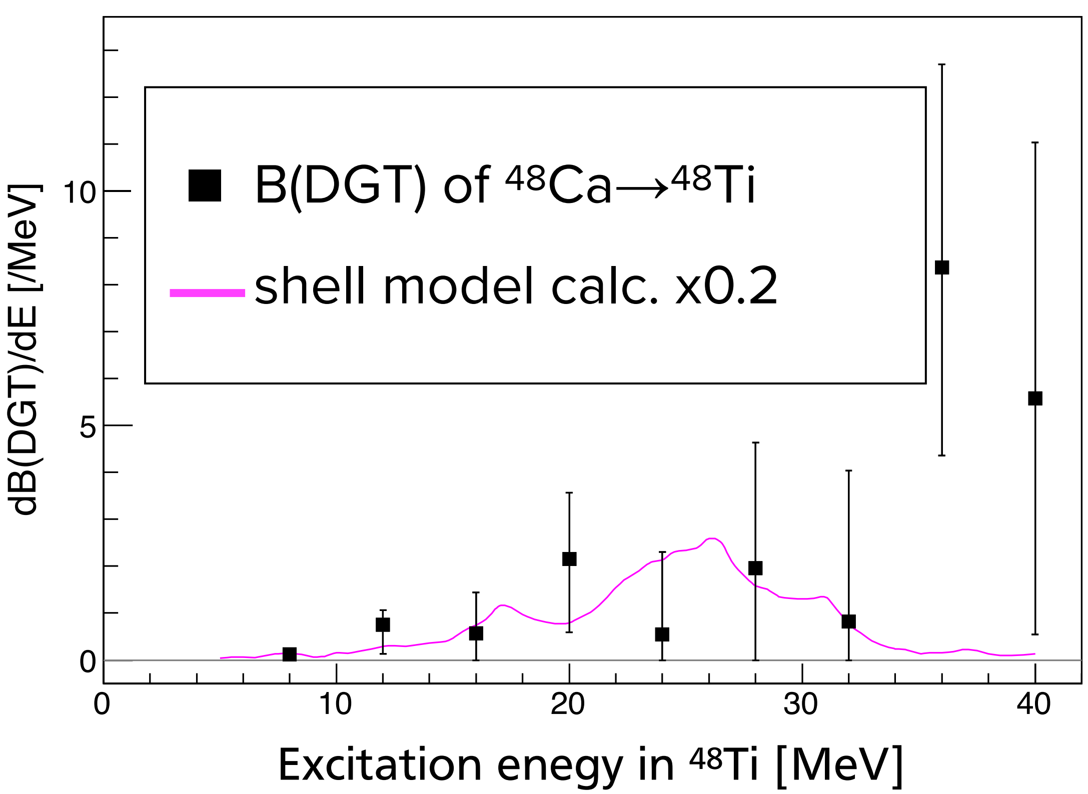
$S=28^{+22}_{-7}$, E_c = 23±3 MeV, Γ = 6±1 MeV

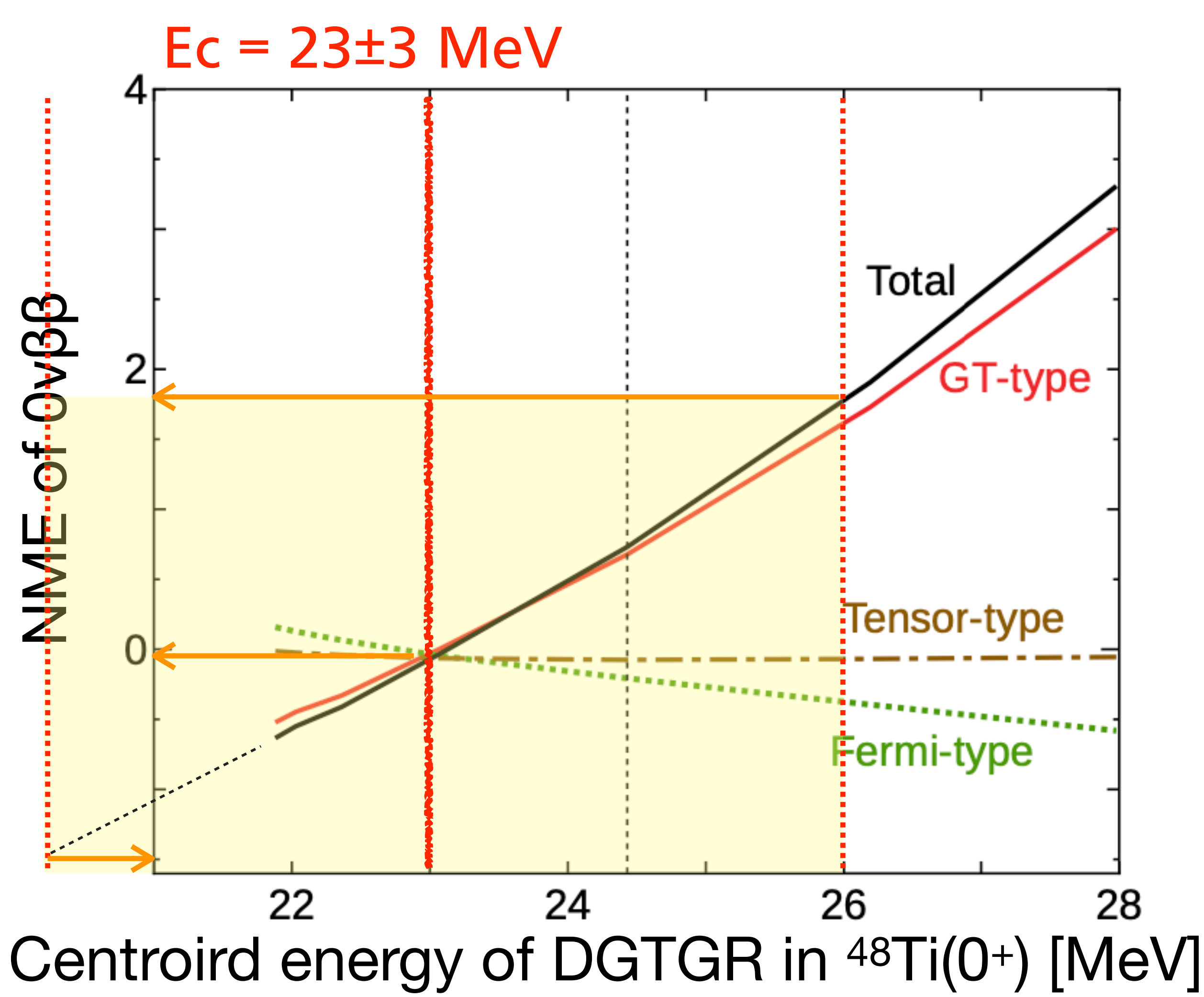
(22^{+17}_{-6}% of sum rule)

apply to the relation of "E_c ↔ 0νββ NME"

✓E_c=23±3 MeV → NME=0±2

Possiblity to constrain NME
by experiment of DCX





N. Shimizu, J. Menéndez, K. Yako Phys. Rev. Lett. 120, 142502
N. Shimizu, Private communication

Future prospects

Higher statistics will make the situation clear and make possible detailed discussion

statistics x40 ➜ ΔE_c = 0.8 MeV

- Upgrade of setup

  Current setup: The loss due to lifetime of $^{12}Be(0^+_2)$ is large

  make close the position of γ-ray detection to reaction point (F8 → F5, for example)

  yield x2

- Target choice

  ^{136}Xe : ββ decaying nucleus (KamLAND-Zen, PandaX)

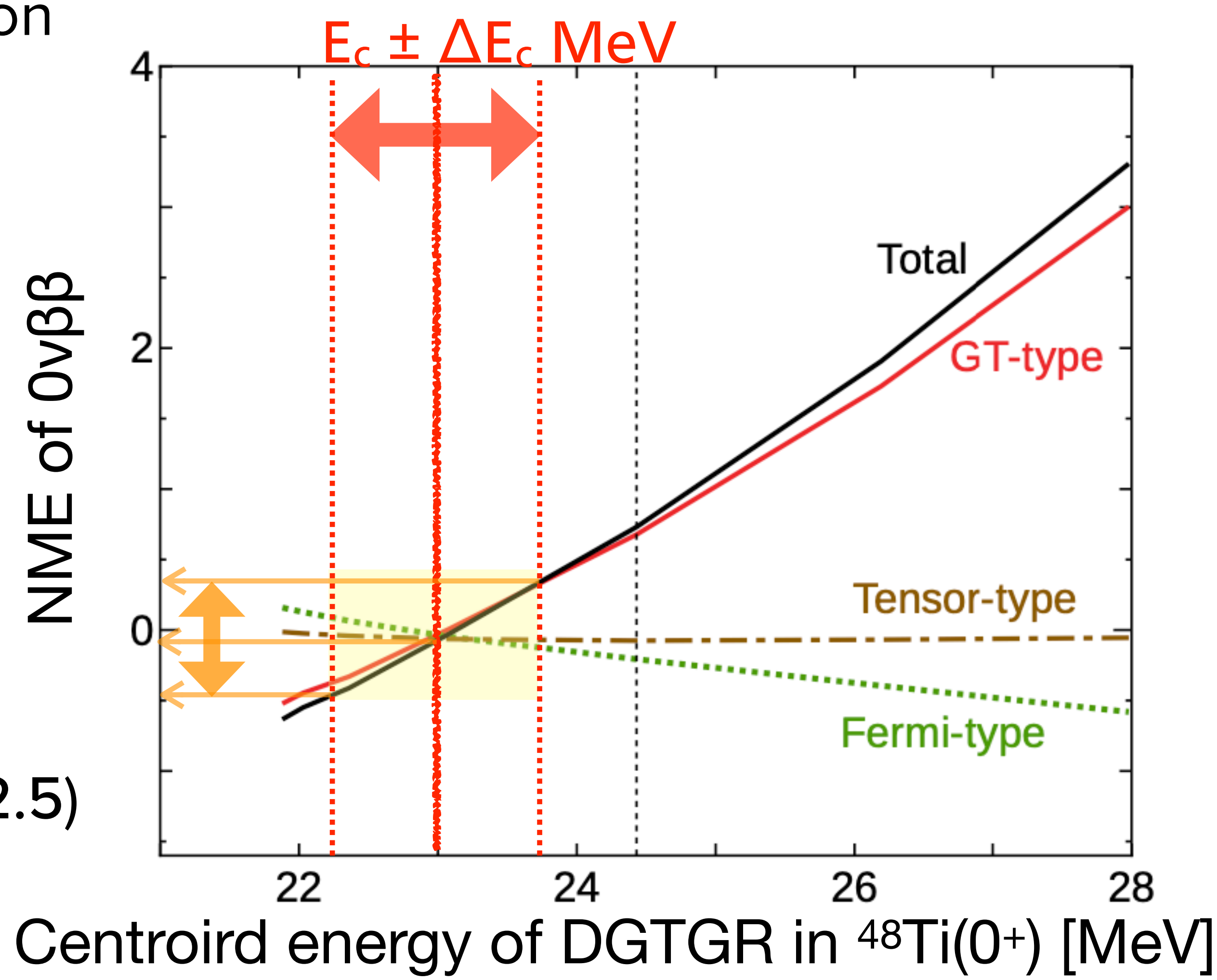
  strength ∝ 2(N-Z)(N-Z-1)

  ➜ cross section~**x4**

  target thickness can be thicker (~**yield x2.5**)

- **Beam time x2**

x40 in total



N. Shimizu, J. Menéndez, K. Yako Phys. Rev. Lett. 120, 142502
N. Shimizu, Private communication

Summary

- We are aiming at the observation of **Double Gamow–Teller Giant Resonance (DGTGR)**

- Heavy ion double charge exchange reaction of **(^{12}C, ^{12}Be(0^+_2))**

- Experiment at **RIBF BigRIPS**
  - use BigRIPS as a spectrometer with dispersion matching
  - γ ray detection by DALI2 for ID of ^{12}Be(0^+_2)

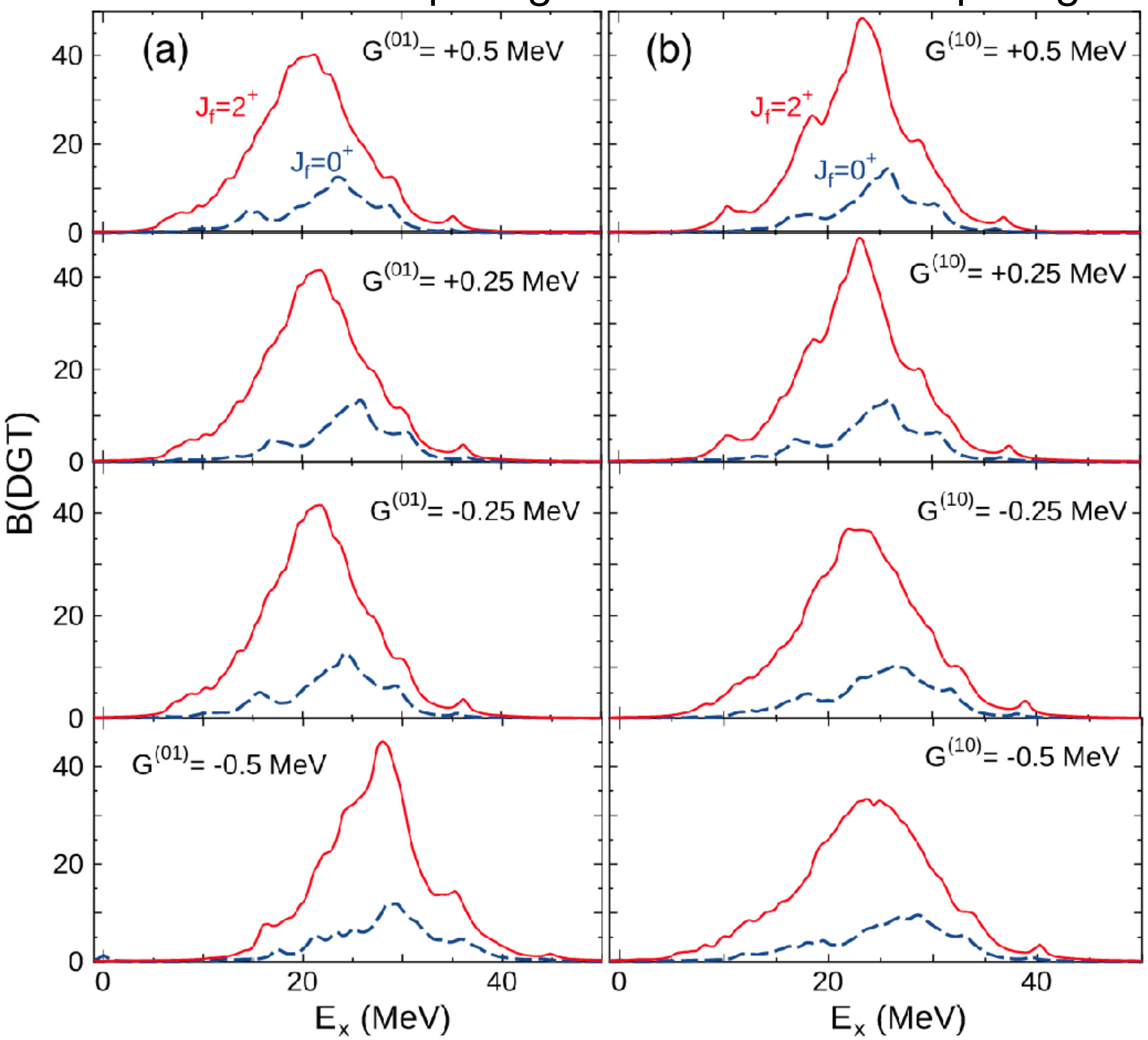
- **First experiment on ^{48}Ca** target
  - We have obtained E_{ex} spectra with ΔE=1.6 MeV and Δθ = 0.17°
  - low BG measurement : S/N ~ 9:1
  - forward peaking at Ex ~ 20 MeV : **Candidate of DGTGR**
  - Extract DGT-like components : E_c=23 MeV, width=7 MeV, ΣB(DGT)=22% of sum rule value
  - Possibility of constraining NME

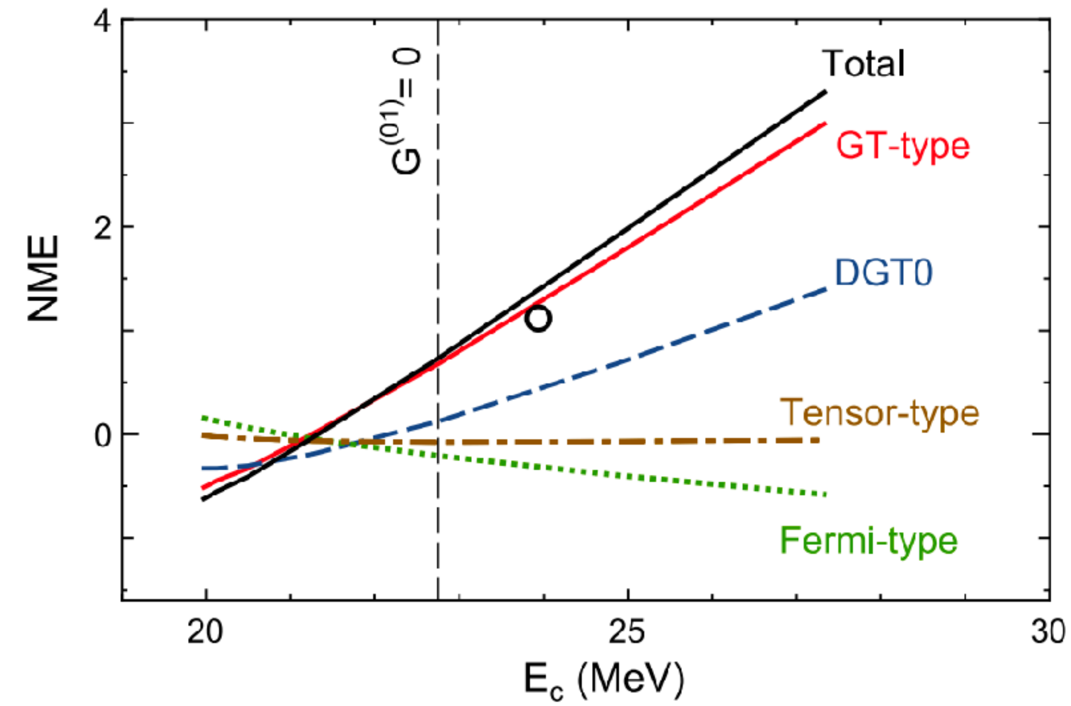
BACK UP

0νββ ↔ DGTGR

shell model calc $^{48}Ca \rightarrow ^{48}Ti$ Shimizu, Menéndez, Yako PRL120

$G^{(01)}$: isovector paring $G^{(10)}$: isoscalar paring





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Centroid E of DGTGR ↔ isovector pairing
Width of DGTGR↔ isoscalar pairing

0νββ NME is sensitive to pairing

Observables of DGTGR will constrain 0νββ NME

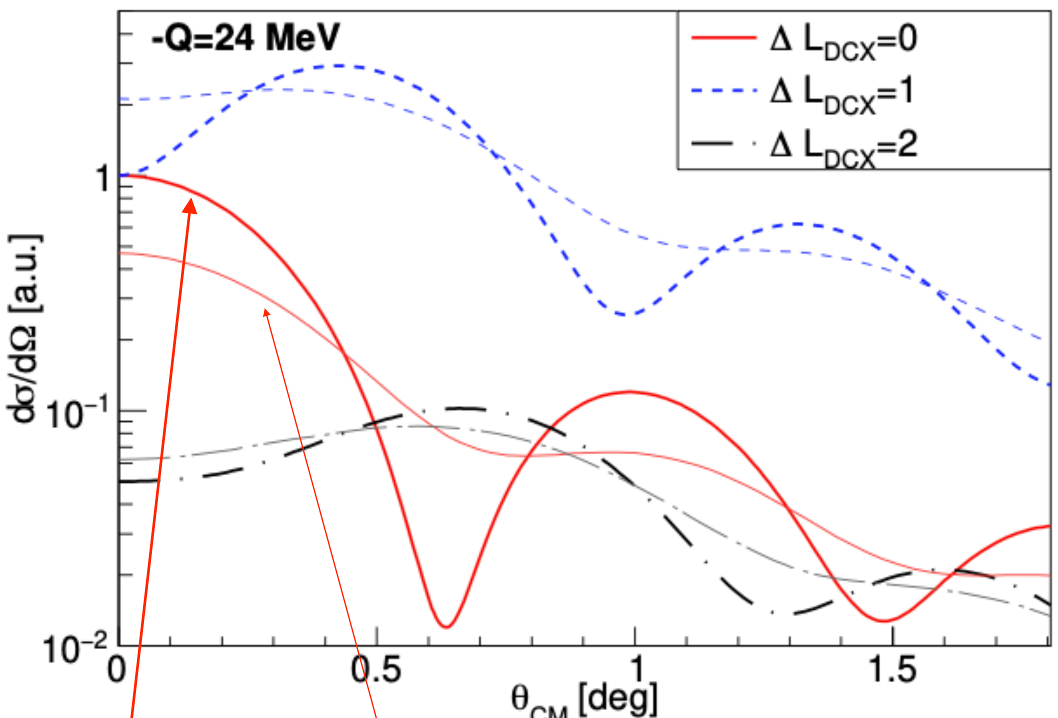
Compare RCNP and RIBF

	RCNP	RIBF
beam intensity	16 pnA	600 pnA
data taking time	5 days?	1.5days
eff. of γ detection	10%	70%
DAQ, tracking eff.	~100%?	60%
$^{12}Be(0^+_2)$ survival ratio	70%	25%
transmission	~100%	20%
S:N	1:1	9:1

observed yield(signal) was twice by at RCNP
error for cross section has been 1/2

Calculated angular distribution

Calculated angular distribution of DCX

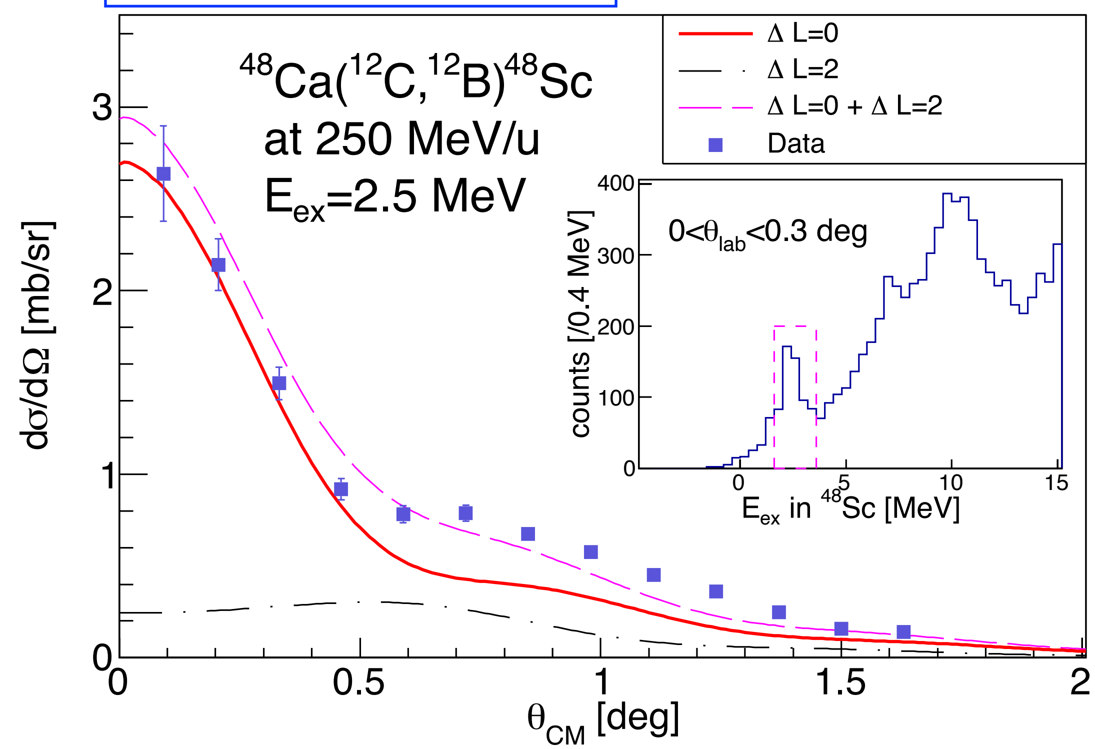


ΔL_DCX=0

ΔL_DCX=0 (Smeared by Δθ)

ΔL_{DCX}=0 : peak at 0°
ΔL_{DCX}=1, 2 : peak at 0.4°, 0.7°

Check of validity



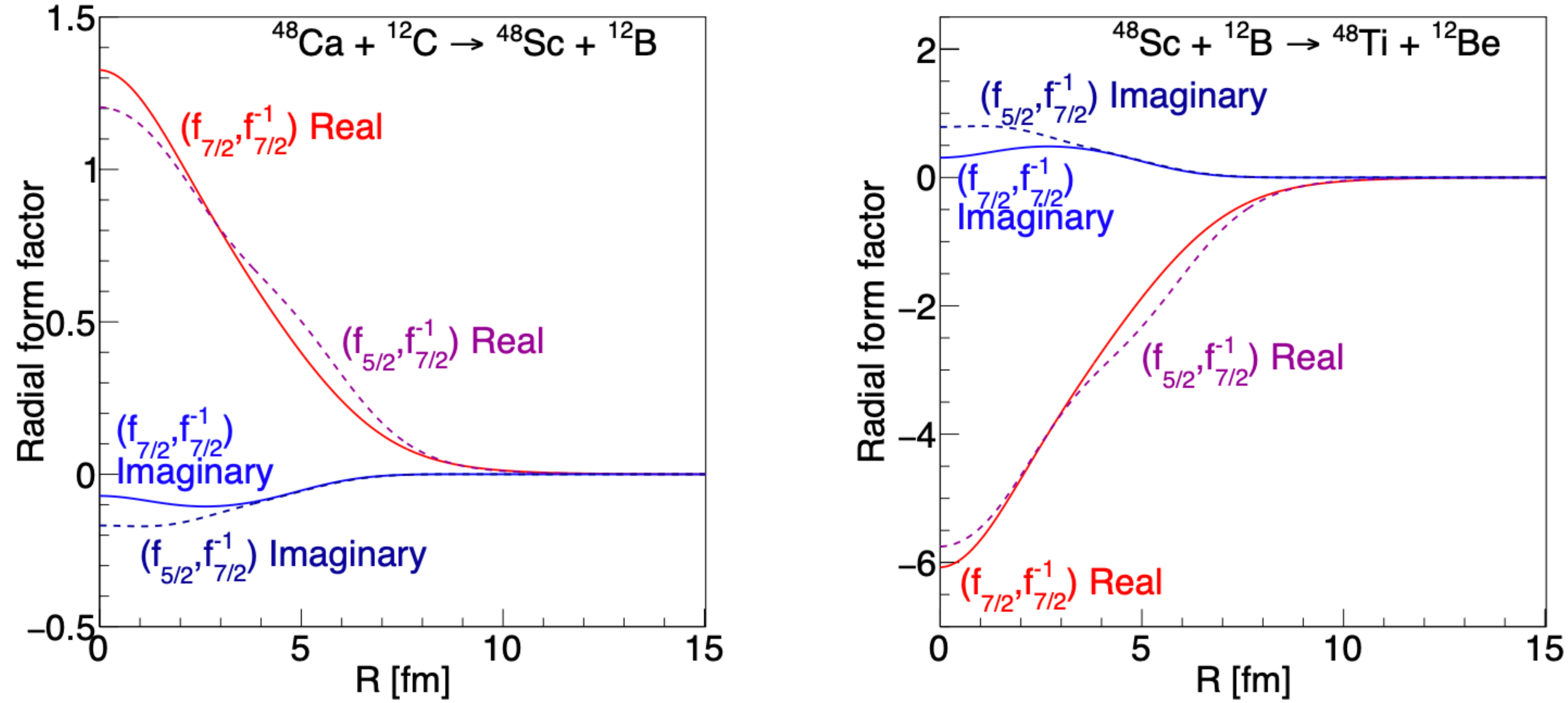
Calculated $^{48}Ca+^{12}C \rightarrow ^{48}Sc+^{12}B$ is compared to the data of $^{48}Ca(^{12}C, ^{12}B)^{48}Sc$(2.5 MeV)

$B(GT)_{48Ca \rightarrow 48Sc}$=1.4 in this normalization
cf. $B(GT)_{48Ca \rightarrow 48Sc}$ = 1.09±0.01 (^{3}He,t) measurement
E. W. Grewe et al., Phys. Rev. C 76. 054307 (2007)

reproduces up to ~1°
Absolute value reproduces ~30%

Transition form factor

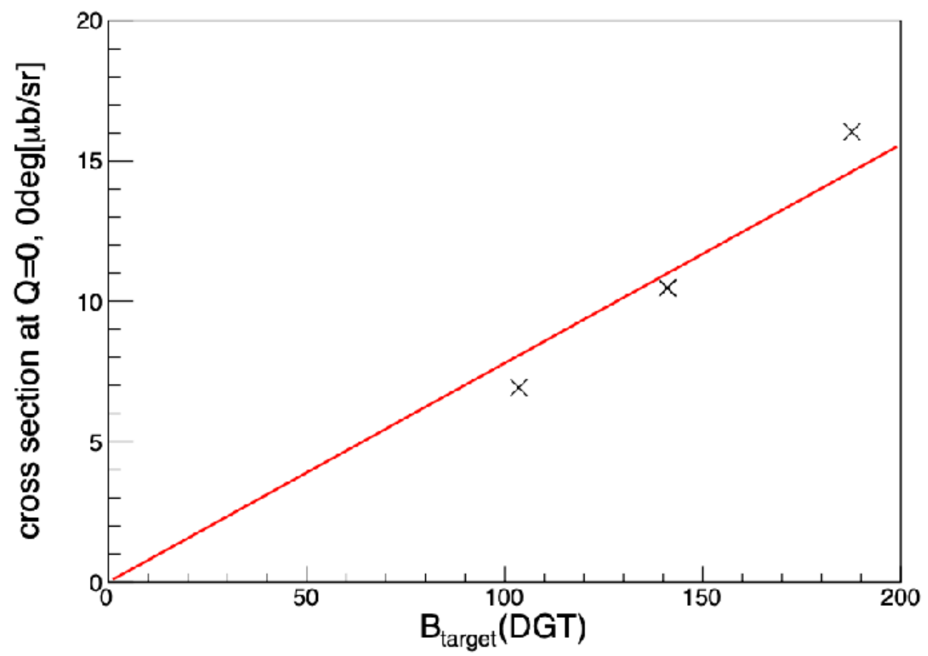
- One body transition densities for projectile system were obtained by NuSHellX
- OBTD for target system were settled arbitrary vale (Z=1) for each combination of the configurations of (f7/2, f7/2-1) and (f5/2, f7/2-1)



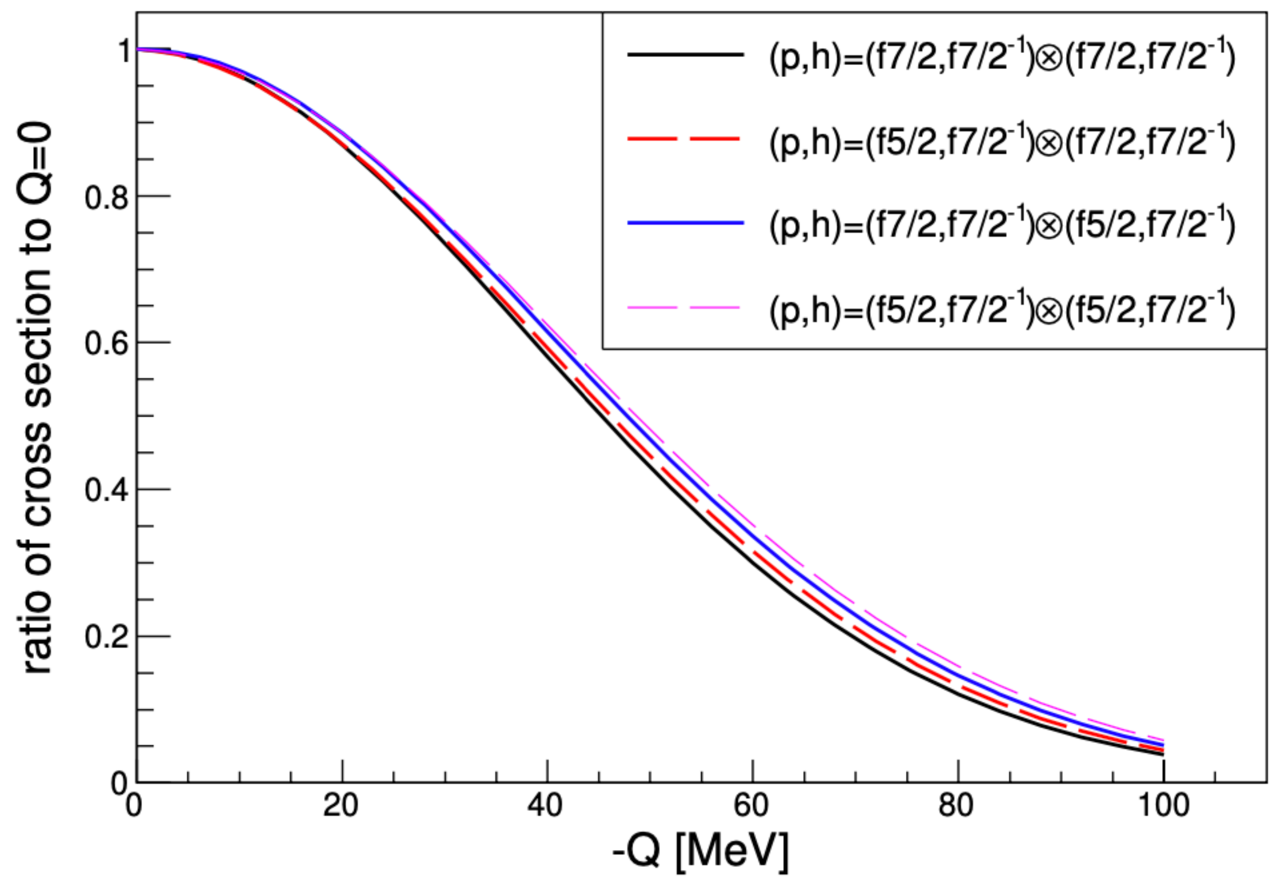
σ_{DGT}

Table 4.1: (p,h) configuration and B(DGT)

$(p,h)_{^{48}Ca\to^{48}Sc}$	$(p,h)_{^{48}Sc\to^{48}Ti}$	$B(GT)_{^{48}Ca\to^{48}Sc}$	$B(GT)_{^{48}Sc\to^{48}Ti}$	B_{target}(DGT)	Calculated cross section [μb/sr]
$(f_{7/2}, f_{7/2}^{-1})$	$(f_{7/2}, f_{7/2}^{-1})$	10.3	10.3	106	6.92
$(f_{7/2}, f_{7/2}^{-1})$	$(f_{5/2}, f_{7/2}^{-1})$	10.3	13.7	141	10.46
$(f_{5/2}, f_{7/2}^{-1})$	$(f_{7/2}, f_{7/2}^{-1})$	13.7	10.3	141	10.49
$(f_{5/2}, f_{7/2}^{-1})$	$(f_{5/2}, f_{7/2}^{-1})$	13.7	13.7	188	16.04



F(q,ω)



ratio of cross section to Q=0
-Q [MeV]
(p,h)=(f7/2,f7/2⁻¹)⊗(f7/2,f7/2⁻¹)
(p,h)=(f5/2,f7/2⁻¹)⊗(f7/2,f7/2⁻¹)
(p,h)=(f7/2,f7/2⁻¹)⊗(f5/2,f7/2⁻¹)
(p,h)=(f5/2,f7/2⁻¹)⊗(f5/2,f7/2⁻¹)
0
0.2
0.4
0.6
0.8
1
0
20
40
60
80
100