Double Gamow–Teller transition studied by charge exchange reaction of (^{12}C, ^{12}Be(0^+_2)) at 250 MeV/nucleon

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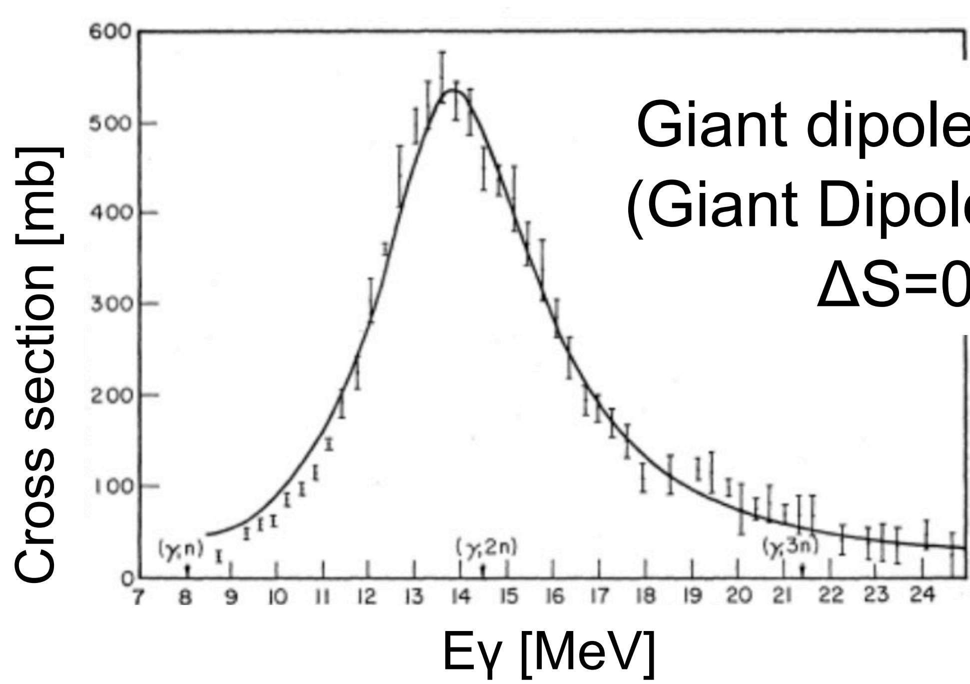
2025.08.21 NEWS colloquium

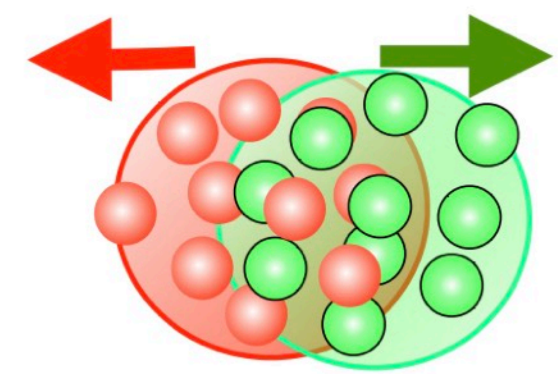
Giant resonance

- Giant resonance: collective excitation of nucleus
  - Ex > ~10 MeV
  - Oscillation of nucleus
  - Coherent excitation of 1p1h
  - Account for large fraction of sum rule value

Giant dipole resonance in ^{197}Au
(Giant Dipole Resonance, GDR)
$\Delta S=0, \Delta T=1, \Delta L=1$



S. C. Fultz et. al., Phys. Rev. Lett. 127, 1273 (1962)


Collective motion of protons/neutrons out of phase

- Observed in wide range of nucleus and in various mode (ΔS, ΔT, ΔL)

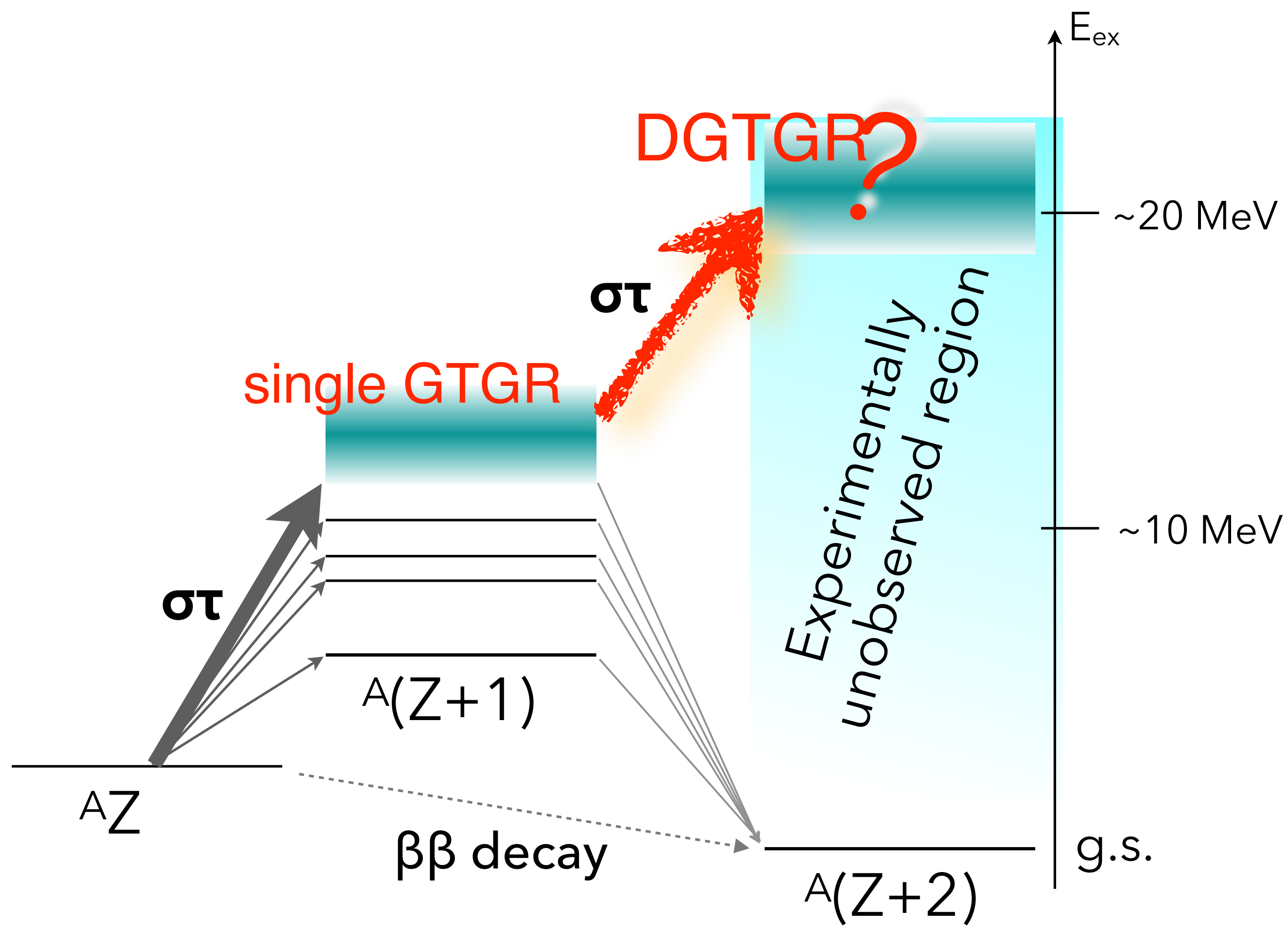
Double Gamow–Teller transition

- Gamow–Teller (GT) transition : spin ΔS=1, isospin ΔT=1, ΔL=0

  β decay : $^{A}Z \rightarrow {}^{A}(Z+1) + e^{-} + \bar{\nu}_e$ (β- decay)

- Double Gamow–Teller (DGT) transition : spin ΔS=1x2, isospin ΔT=1x2, ΔL=0

  Double β decay: $^{A}Z \rightarrow {}^{A}(Z+2) + 2e^{-} + 2\,\bar{\nu}_e$ (β-β- decay)



double β decay
~0.01% of sum rule value

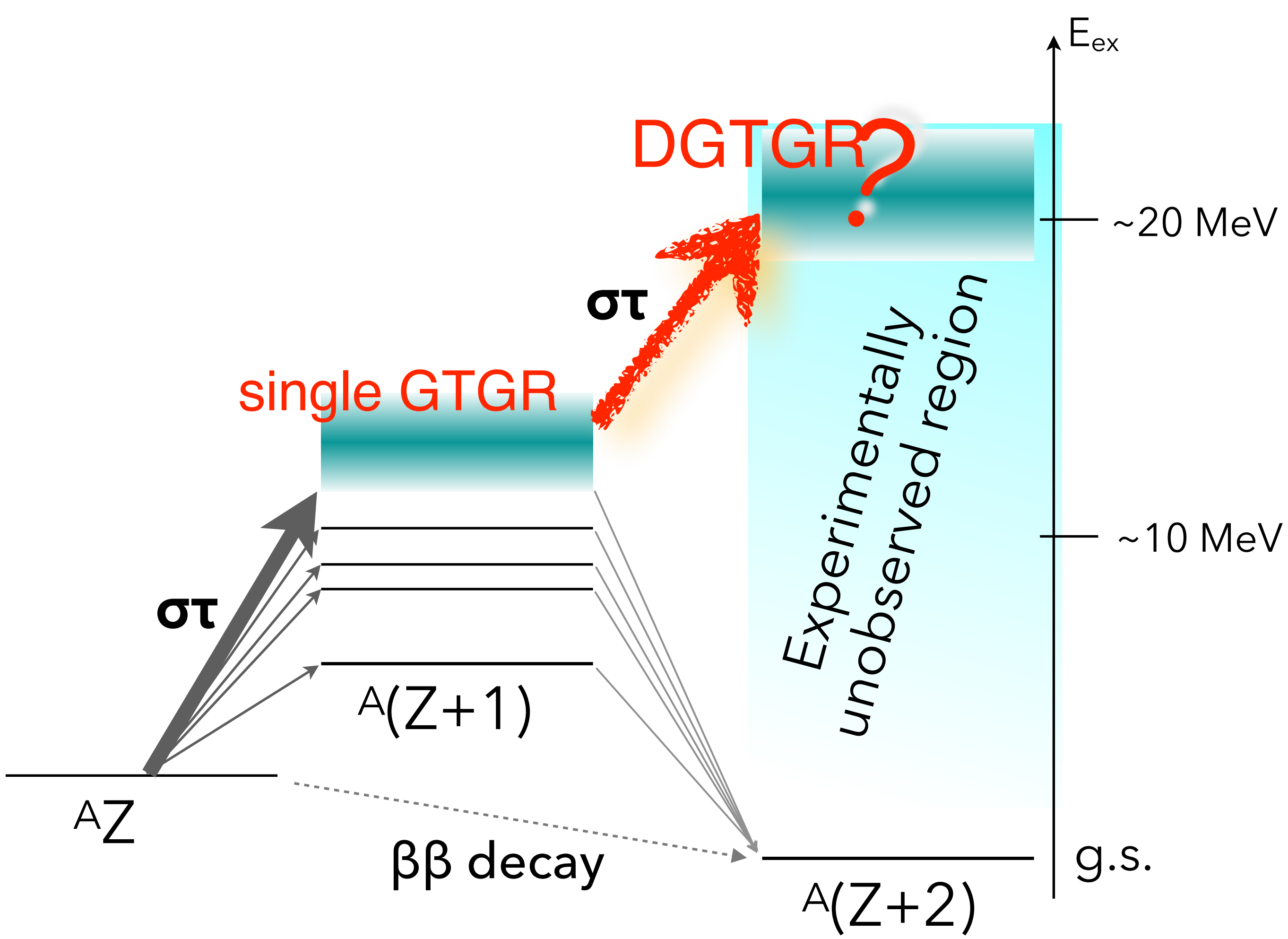
Other 99.9% is in **Ex > ~ 10 MeV**
Experimentally unobserved region

Especially, it is expected to exist giant resonance in DGT transition
DGT giant resonance (DGTGR)

Double Gamow–Teller Giant Resonance

Get DGT response in high Ex
Observation of DGTGR

The experimental information of DGTGR will provide various insight into nuclear nature:



- Understanding of collective excitation in the spin-dependent process
  - Ec, Γ, ... are the simple superposition of single GTGR?
- DGTGR has larger strength
  → provide information to double β decay : 0νββ

Neutrino-less double beta decay

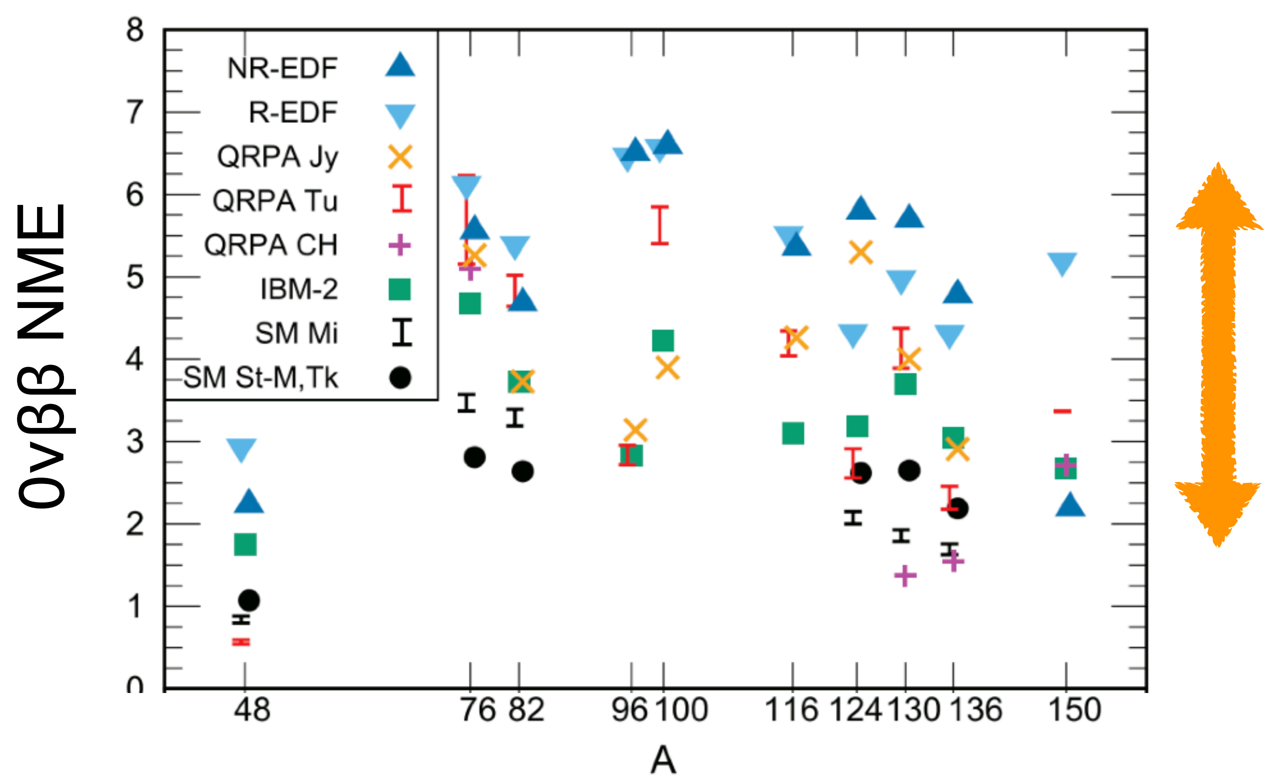
If neutrinos are Majorana particle, **neutrino-less double beta decay (0νββ)** can occur

0νββ: $^{A}Z \rightarrow {}^{A}(Z+2) + 2e^{-}$

lifetime of 0νββ and neutrino mass : $[T^{0\nu}_{1/2}]^{-1} = G_{0\nu}(Q,Z)\,|M_{0\nu}|^2 m^2_{\beta\beta}$

0νββ lifetime phase space factor **neutrino mass**

Nuclear Matrix Element (NME)



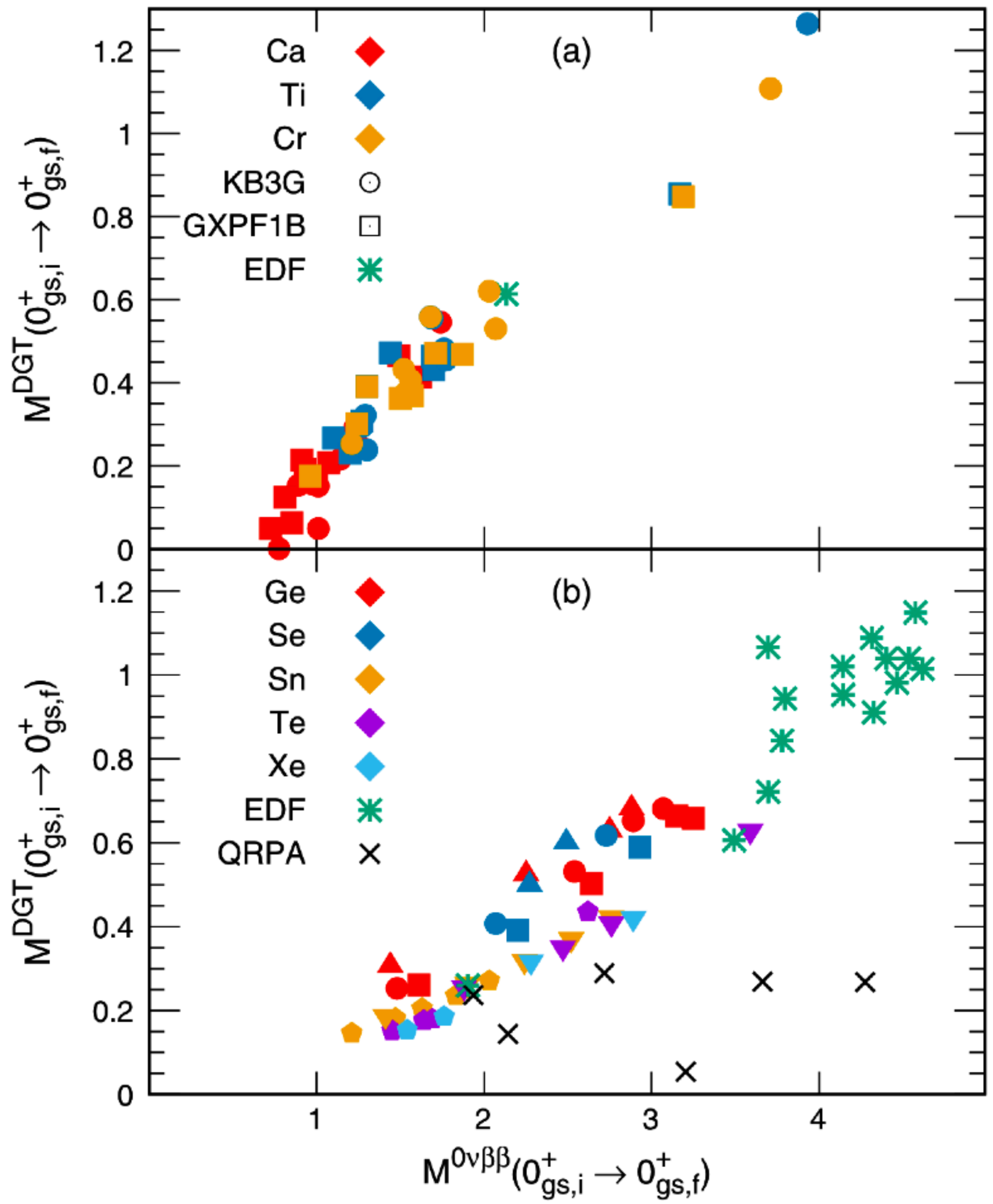
Calculated NME has uncertainty by factor of 2~3 depending on models

Information from experimental side is needed

DGT and 0vββ NME

information on DGT response will provide information on 0vββ

- DGT NME v.s. 0vββ NME in several calculation



Shimizu, Menéndez, Yako PRL120

- Shell model
  - KB3G
  - GXPF1B
- EDF
- QRPA

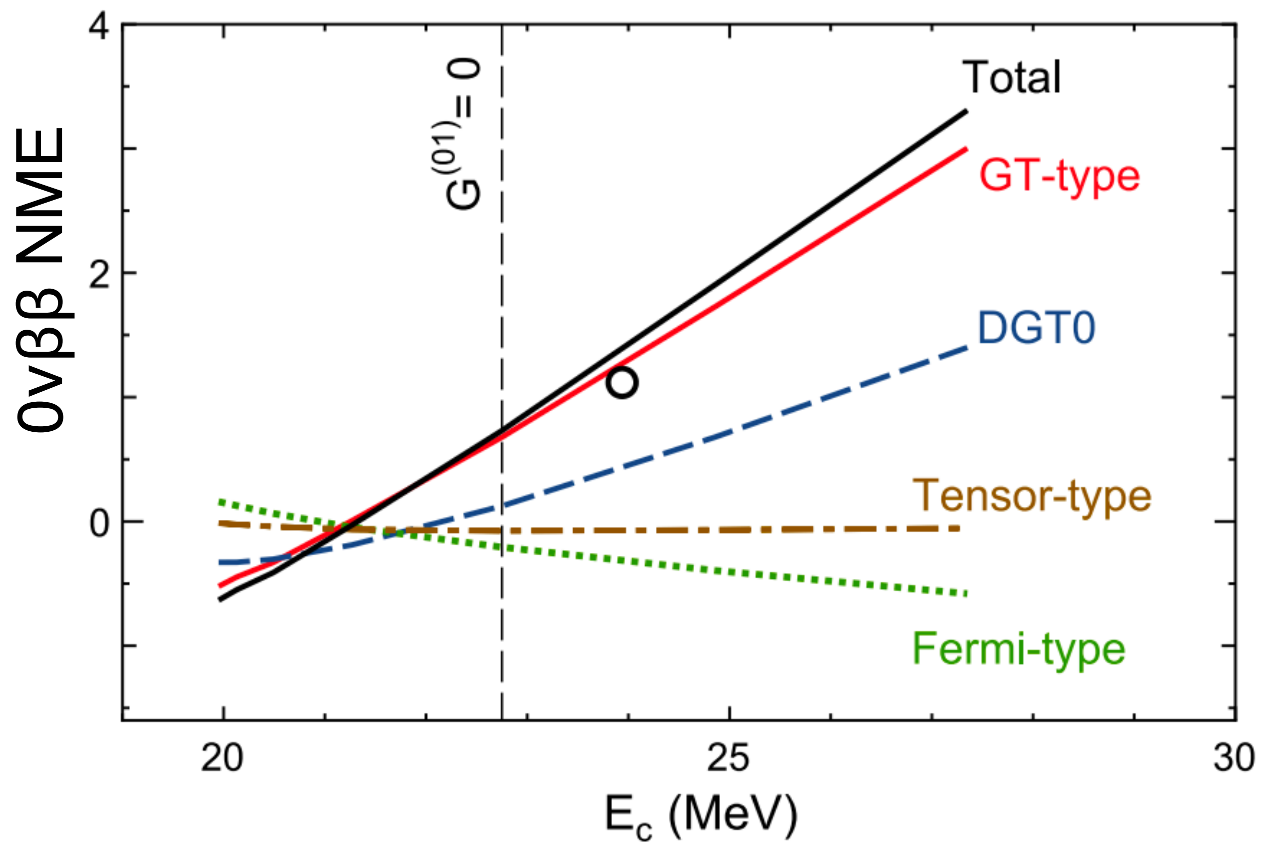
✓ <u>DGT NME is correlated to 0vββ NME</u>

DGT and 0νββ NME

information on DGT response will provide information on 0νββ

- 0νββ NME v.s. centroid energy of DGTGR Ec in shell model calc.

Shimizu, Menéndez, Yako PRL120



✓ <u>DGTGR Ec is correlated to 0νββ NME</u>

- 0νββ NME is sensitive to pairing
- Ec of DGTGR is sensitive to pairng

Observable of DGTGR will constrain 0νββ NME

Double charge exchange reaction

GT response in high excitation energy beyond β decay :
(single) Chrage Exchange reaction (SCX)

e.g. (p,n), (n,p), (^{3}He,t),…

DGT response in high excitation energy beyond ββ decay :
Double Chrage Exchange reaction (DCX)

previous studies:

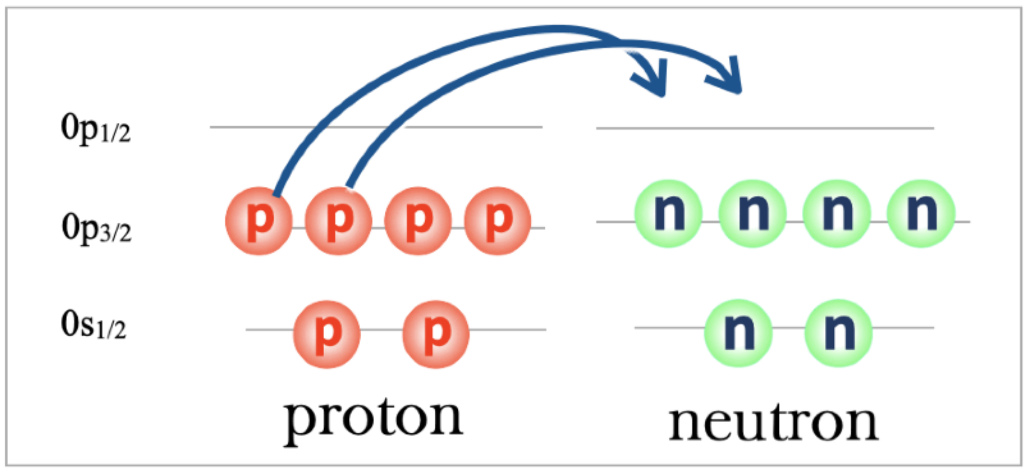
- (π^+, π^-) @292 MeV LAMPF S. Mordechai, PRL 60, 408 (1988)
- (^{18}O, ^{18}Ne) @76 MeV/u MSU J. Blomgren, PLB 362, 34 (1995)
- (^{11}B, ^{11}Li) @69 MeV/u RCNP H. Takahisa, AIP Proc. Conf. 915, 815 (2007)

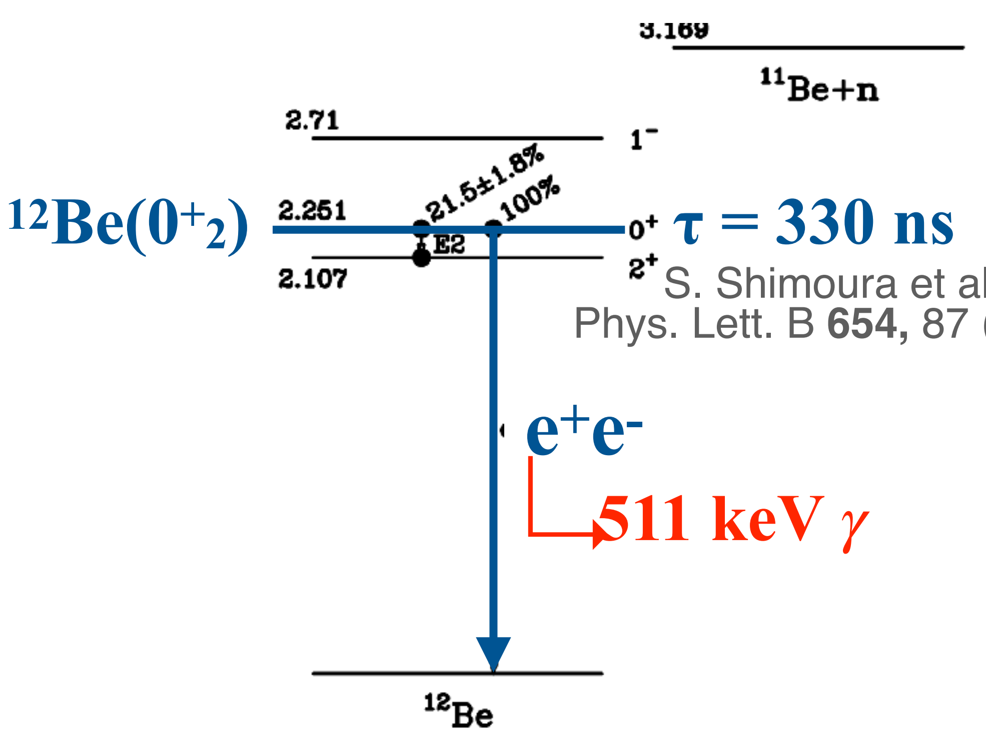
conclusive observation is not yet achieved

new probe

- **(^{12}C, ^{12}Be(0^+_2)) @~100 MeV/u**

New probe: (^{12}C, ^{12}Be(0^+_2))





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

^{12}**Be(0^+_2)**: isomeric state

Ex = 2.2 MeV, τ = 330 ns

- Transition between ^{12}C(0^+)→^{12}B(1^+)→^{12}Be(0^+_2) will be strong
- Spin flip transition ^{12}C(0^+)→^{12}B(1^+)→^{12}Be(0^+_2) will be main
  (cf.isobaric analogue partner of ^{12}Be(0^+_2) : ^{12}C(29 MeV))
- β$^-$ type in the target: less affected by Pauli blocking

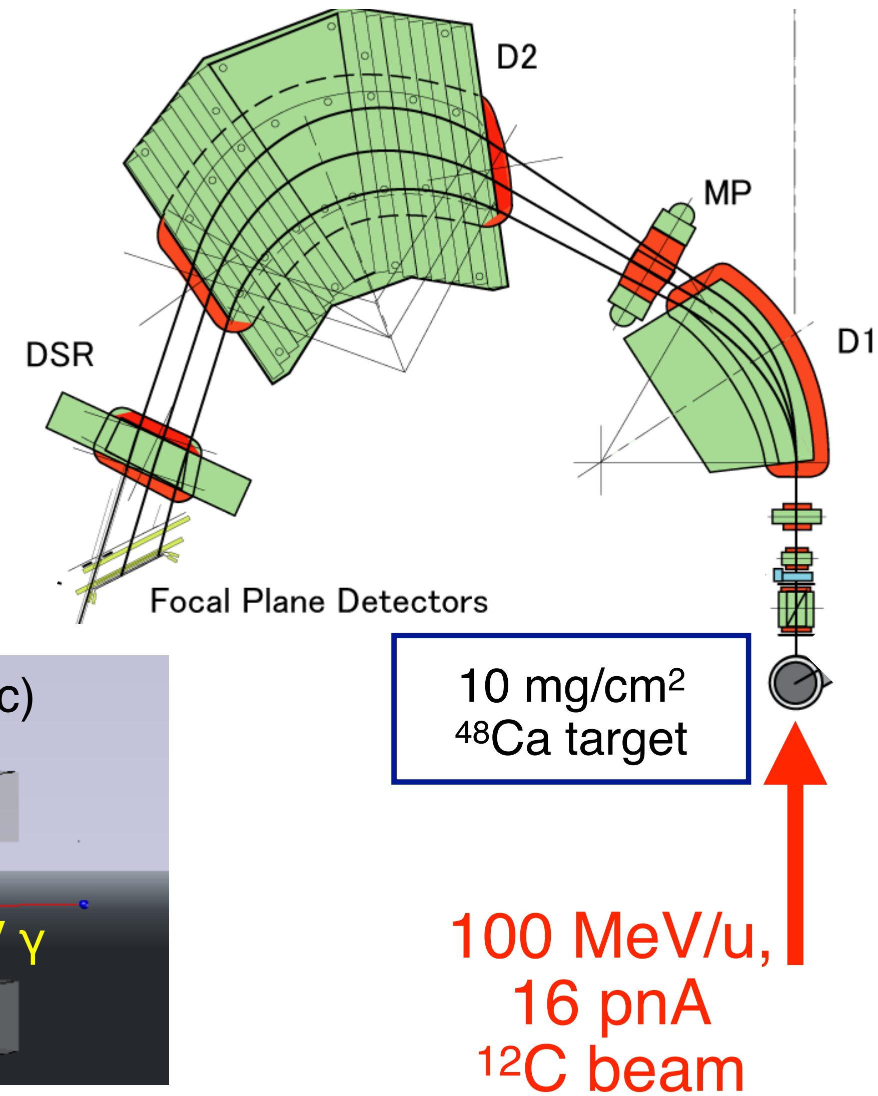
(^{12}C, ^{12}Be(0^+_2)) at ~200 MeV/u
mainly excite spin isospin flip

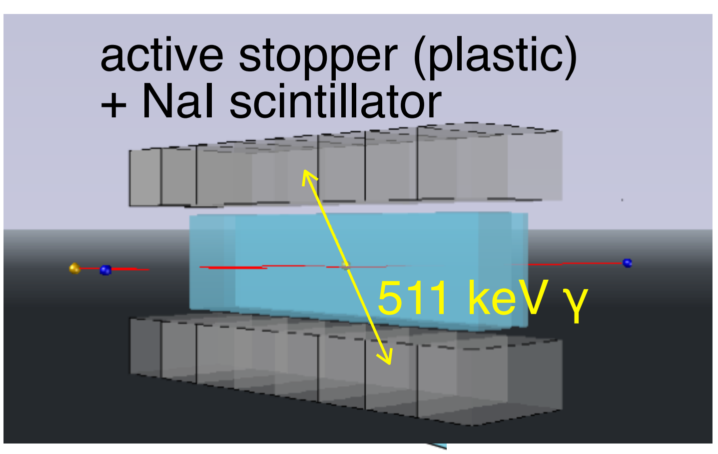
- De-excite with emitting e$^+$e$^-$
  → 511 keV delayed γ-ray

ID of final state is possible by
detectiong γ-ray

Pilot experiment at RCNP

$^{48}Ca(^{12}C, ^{12}Be(0^+_2))$ at RCNP (2014, Takaki et al.)

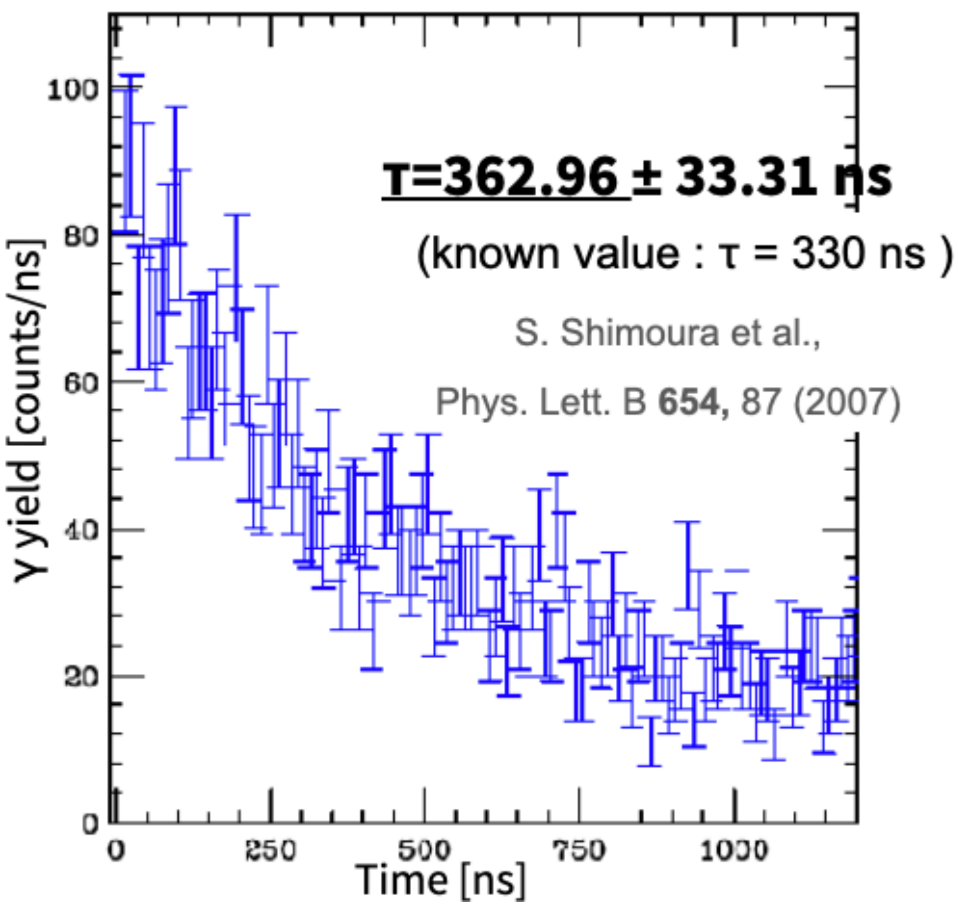


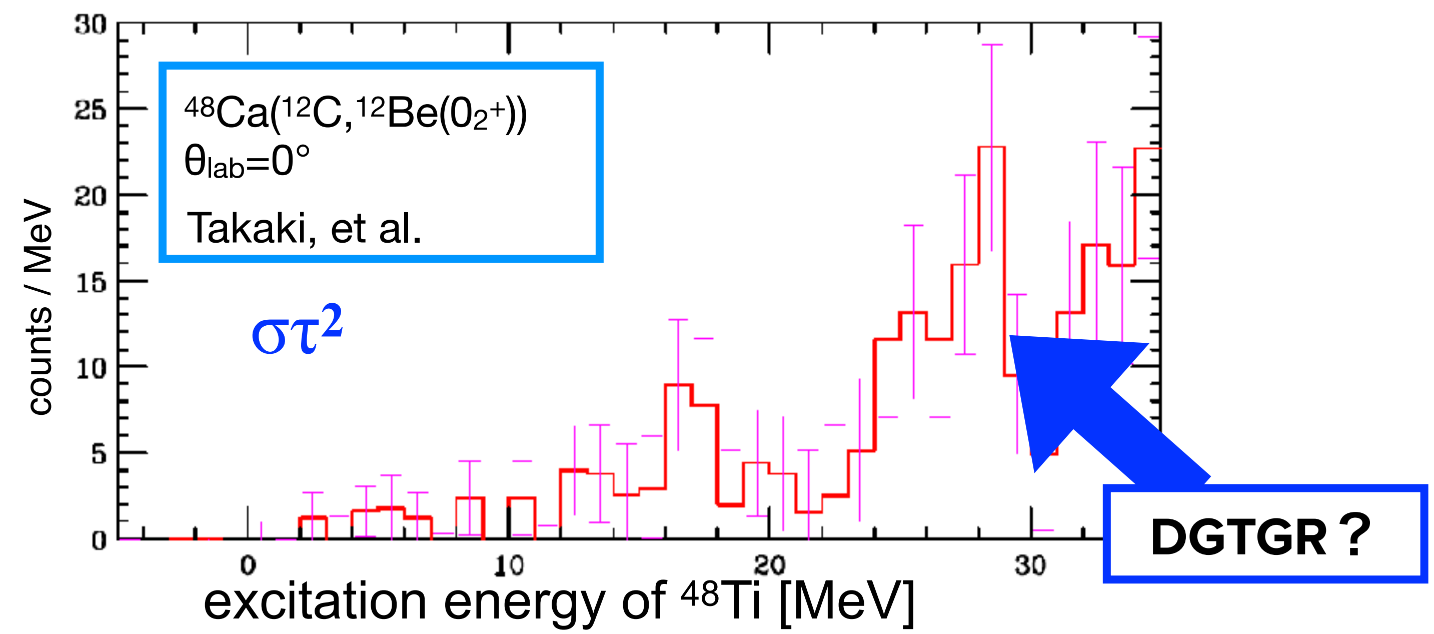


- 100 MeV/u, 16 pnA ^{12}C beam was irradiated to ^{48}Ca target
- emitted ^{12}Be was momentum analyzed by Grand Raiden spectrometer
- ^{12}Be was stopped at the active stopper (plastic scintillator)
- 511 keV γ-ray were detected by NaI scintillator array

Pilot experiment at RCNP

^{48}Ca(^{12}C, ^{12}Be(0^+_2)) at RCNP (2014, Takaki et al.)





- γ-ray timing reproduces the life time of ^{12}Be(0^+_2)→ ID of ^{12}Be(0^+_2) is possible
- Enhancement in the expected region in the observed cross section
- BG was serious: S:N=1:1
  - Active stopper (^{12}C) reacted with t and produced ^{11}C (β^+ emitter)
- Statistics is not enough

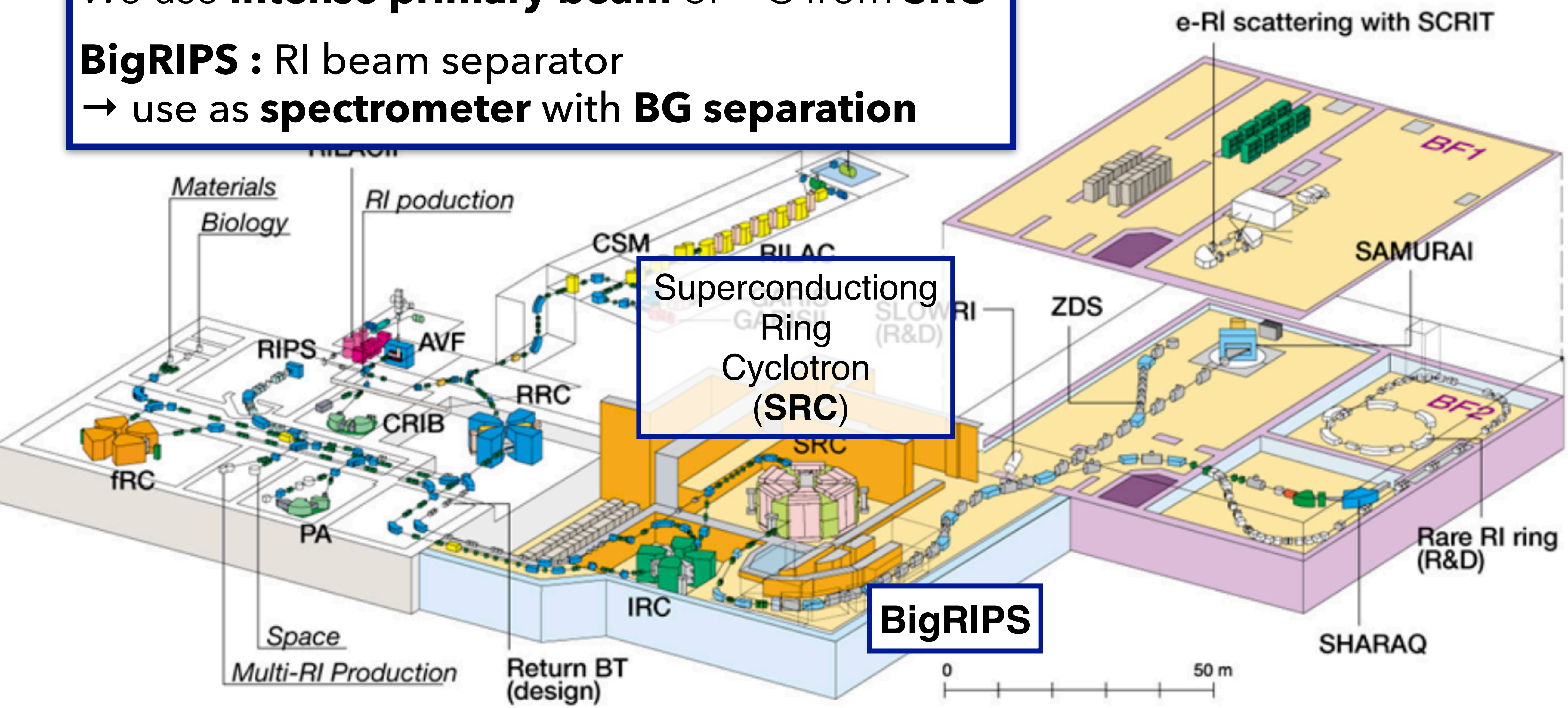
→ **improved experiment at RIBF**

Experiment at RIBF BigRIPS

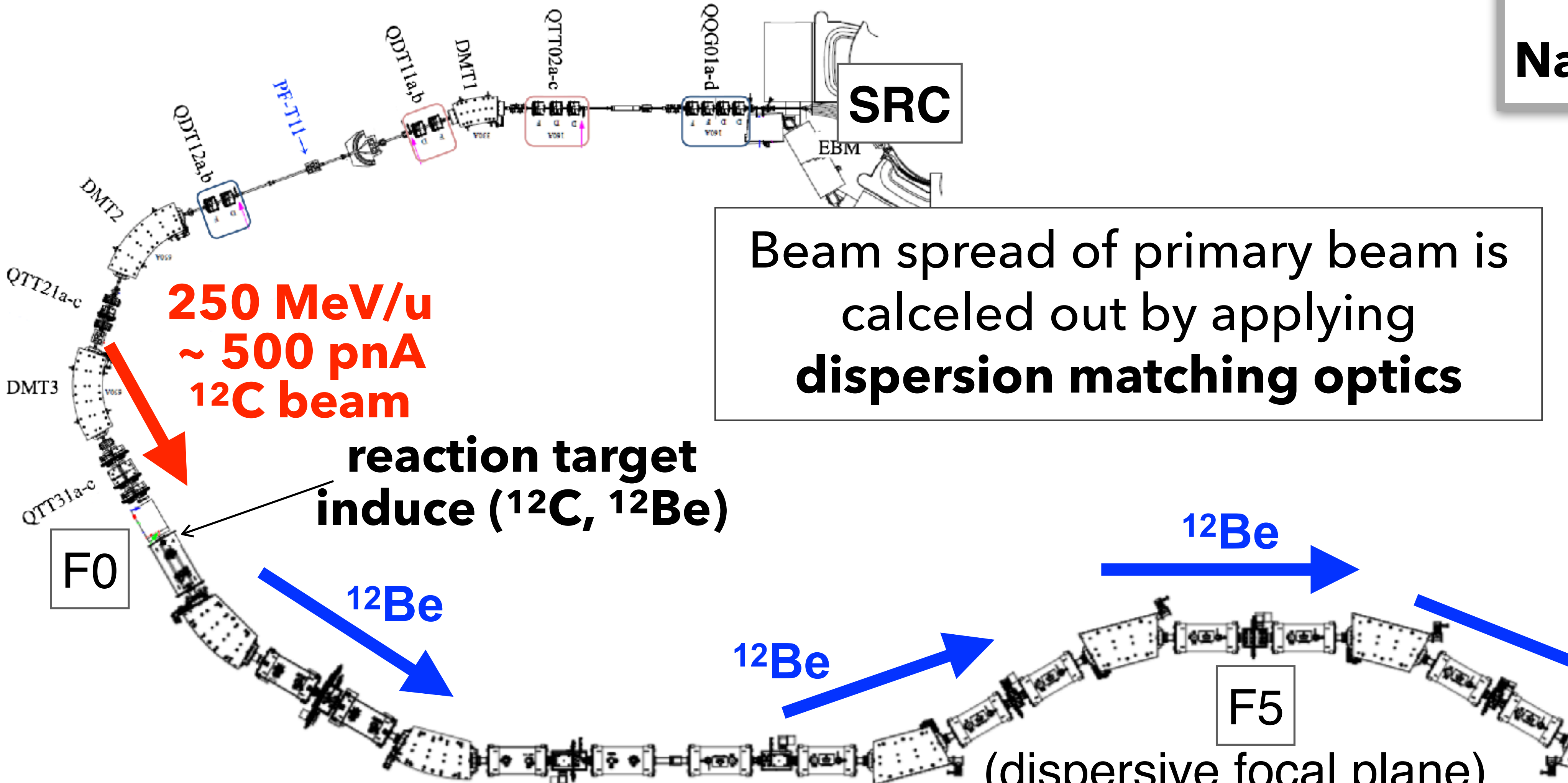
DCX measurement is performed at RI Beam Factory (RIBF), Saitama, Japan

We use **intense primary beam** of ^{12}C from **SRC**

BigRIPS : RI beam separator
→ use as **spectrometer** with **BG separation**



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

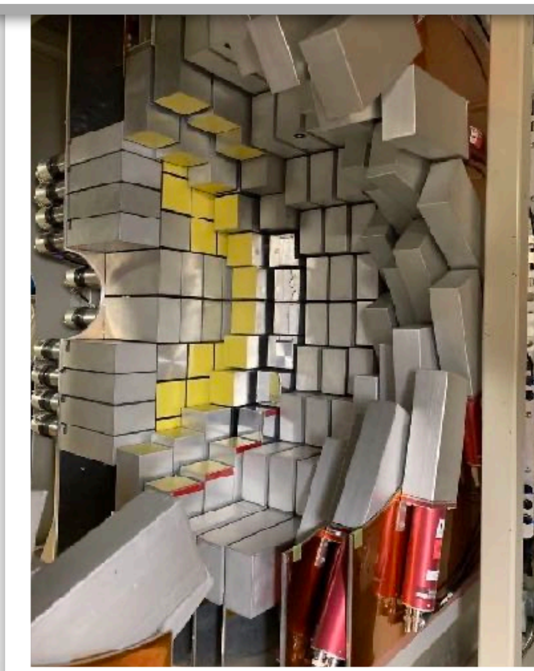


250 MeV/u
~ 500 pnA
^{12}C beam

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

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

DALI2
NaI(Tl) detector array



(dispersive focal plane)

track measurement at F5 :
Low-pressure MWDC

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

Stopped at ^{9}Be stopper

^{12}Be(0^+_2)⟶ ^{12}Be$_{g.s.}$+e^+e^-

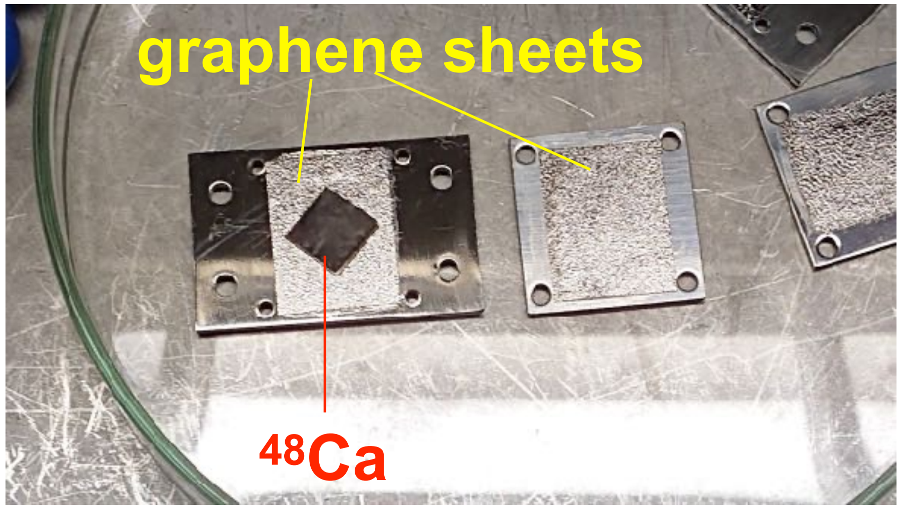
511 keV γ

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

First experiment at RIBF

- **The first experiment at RIBF was performed in 2021**
  - Target : **^{48}Ca** (10 mg/cm^2 foil)
    - Double magic nucleus
    - Double beta decaying nucleus (cf. CANDLES experiment)
    - Information of single GT resonance is available

  - The target was protected with graphene sheets
    - Thermal conductivity is enhanced → reduce the damage due to irradiation
    - Prevent from oxidation and nitrization when installing

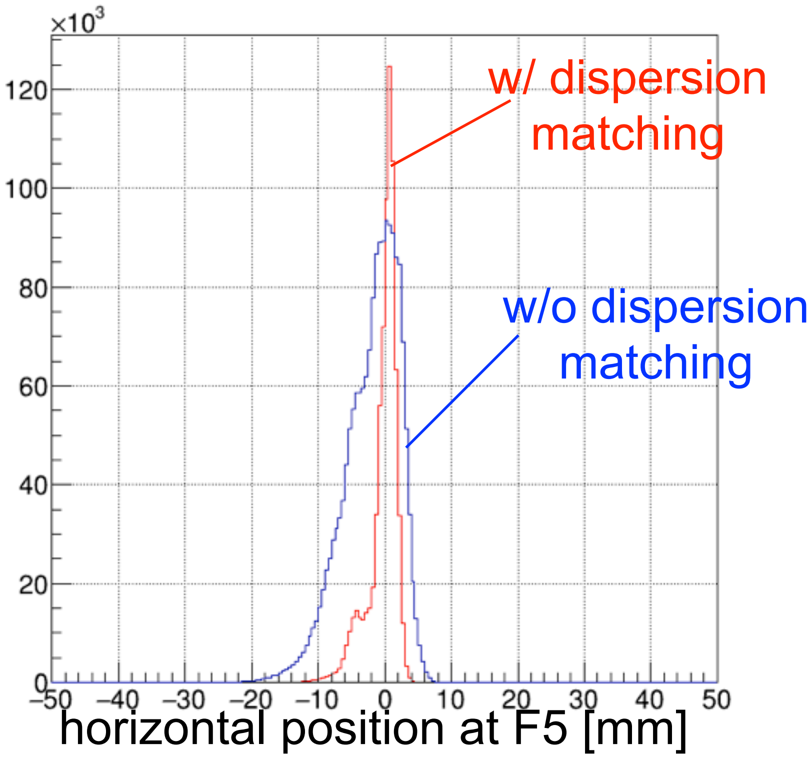


^{48}Ca target

Achievement in the first experiment

✓ Dispersion matching

$\Delta p/p \sim$ **0.06%** (w/o DM) → **0.026%** (w/ DM)
Sufficient excitation energy resolution (1.5 MeV) was achieved

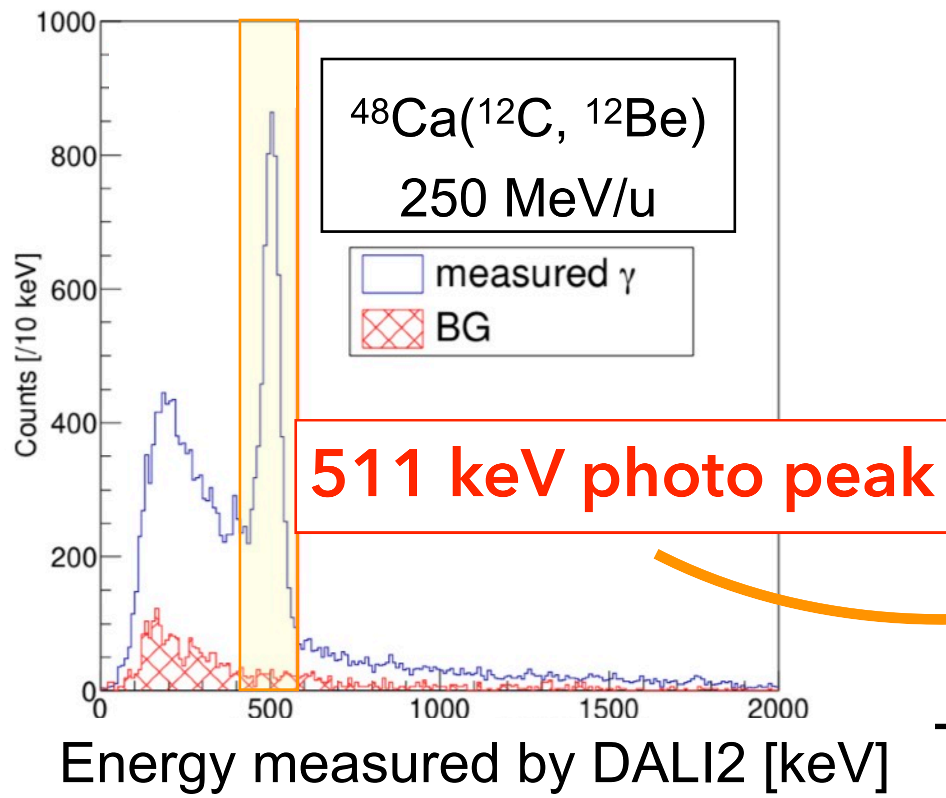


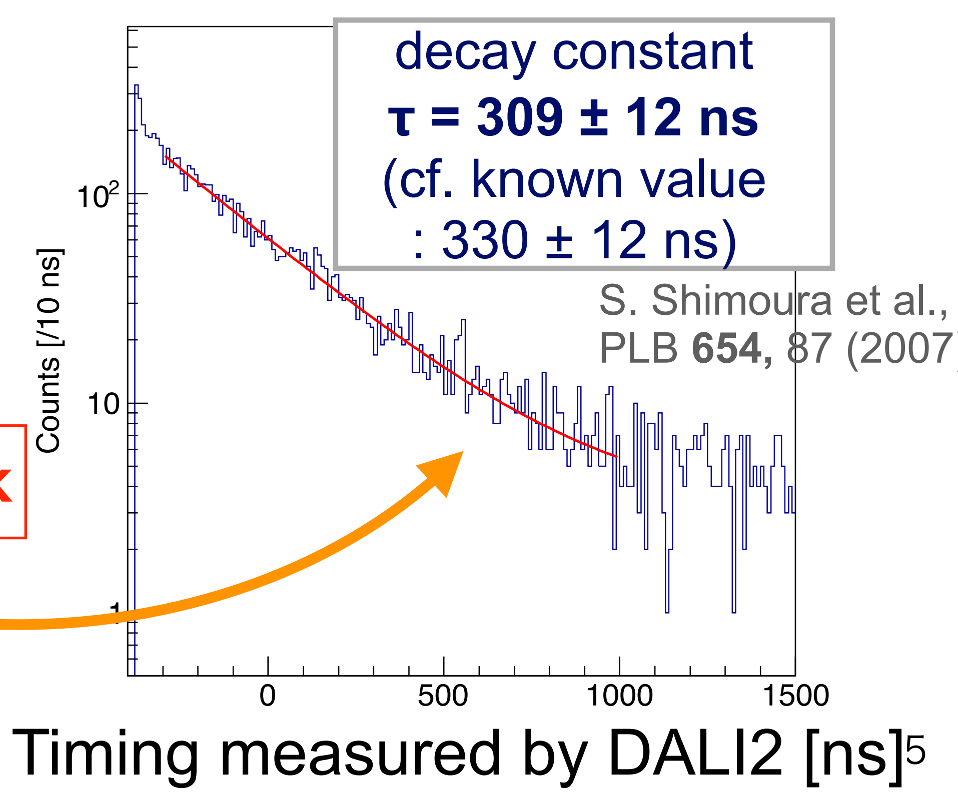
✓ Detection of ^{12}Be(0^+_2) events

successfully identified ^{12}**Be(0^+_2)**

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

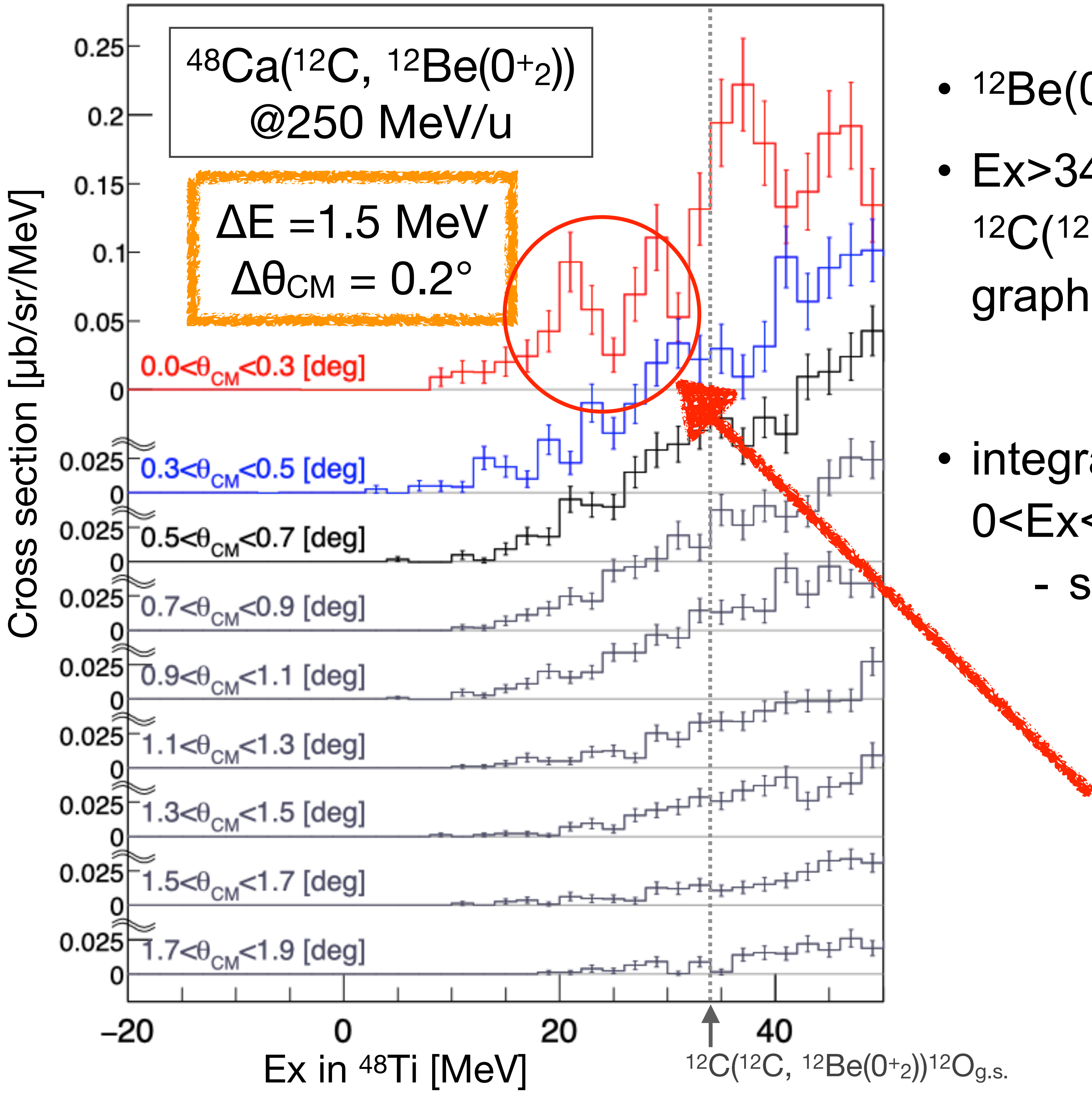
- S:N ~ 9:1
low BG
(cf. 1:1 at RCNP)





Energy spectra of $^{48}Ca(^{12}C,\ ^{12}Be(0^+_2))^{48}Ti$

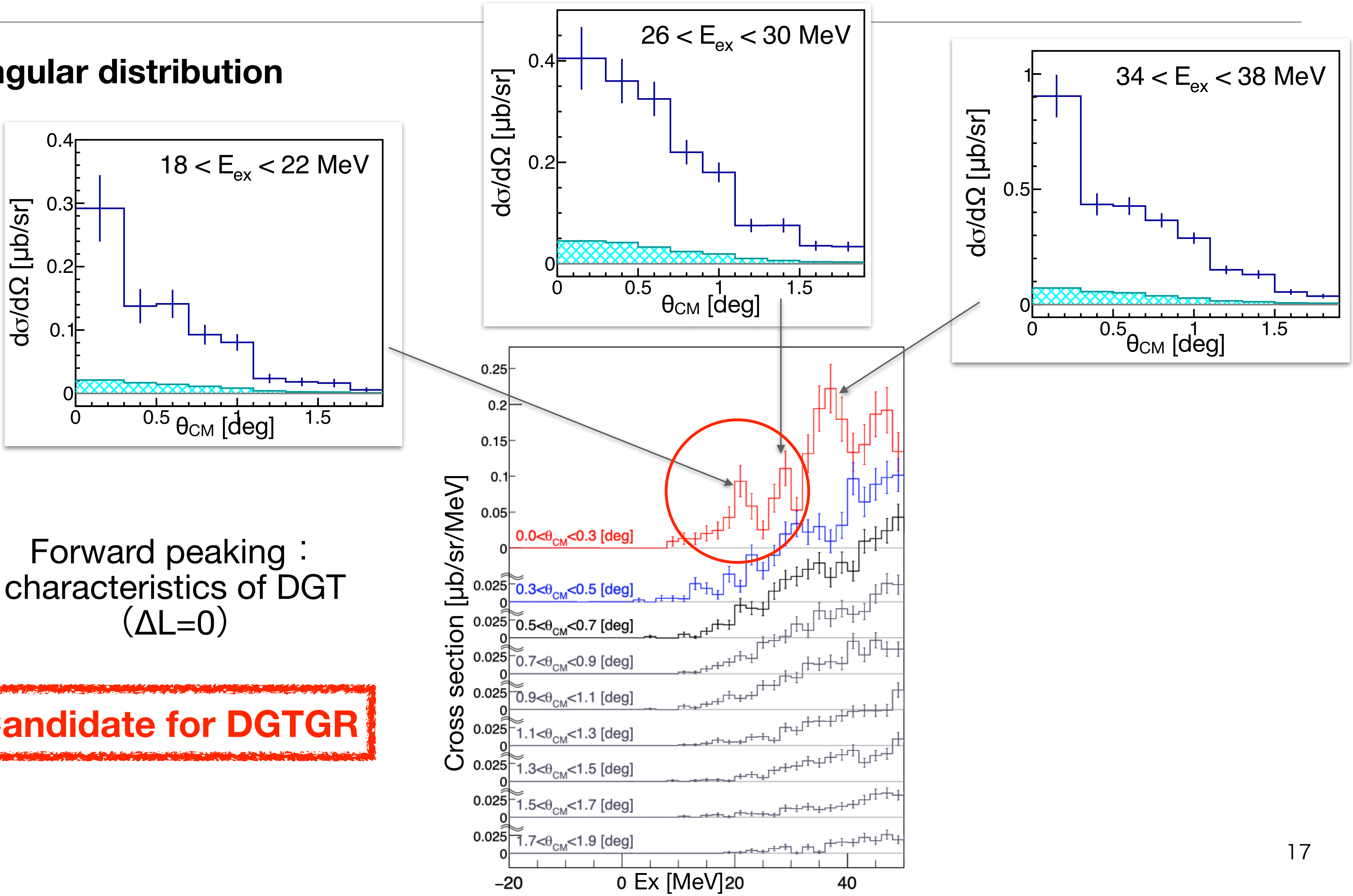
Ex distribution of cross section



- $^{12}Be(0^+_2)$ events are selected by gating γ-data
- Ex>34 MeV is contaminated by $^{12}C(^{12}C,\ ^{12}Be(0^+_2))^{12}O$ event coming from graphene sheet on the target (~6±2%)
- integrated cross section in $0<\theta_{CM}<0.3°$, 0<Ex<34 MeV: 1.33±0.12 (stat.) μb/sr
  - systematical error ~ 40%

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

Angular distribution



Forward peaking：
characteristics of DGT
(ΔL=0)

Candidate for DGTGR

Calculation of DCX

Angular disribution for DCX is estimated by **coupled channel calculation** with ECIS97

- intinal state: $^{12}C(0^+)+^{48}Ca(0^+)$
- intermediate state: $^{12}B(1^+)+^{48}Sc(1^+)$
- final state: $^{12}Be(0^+)+^{48}Ti(0^+)$

are considered as each channel

outline of the calculation :

- transition form factor is obtained by folding microscopic transition using FOLD
- global optical potential by T. Furumoto

3 types of ΔL :

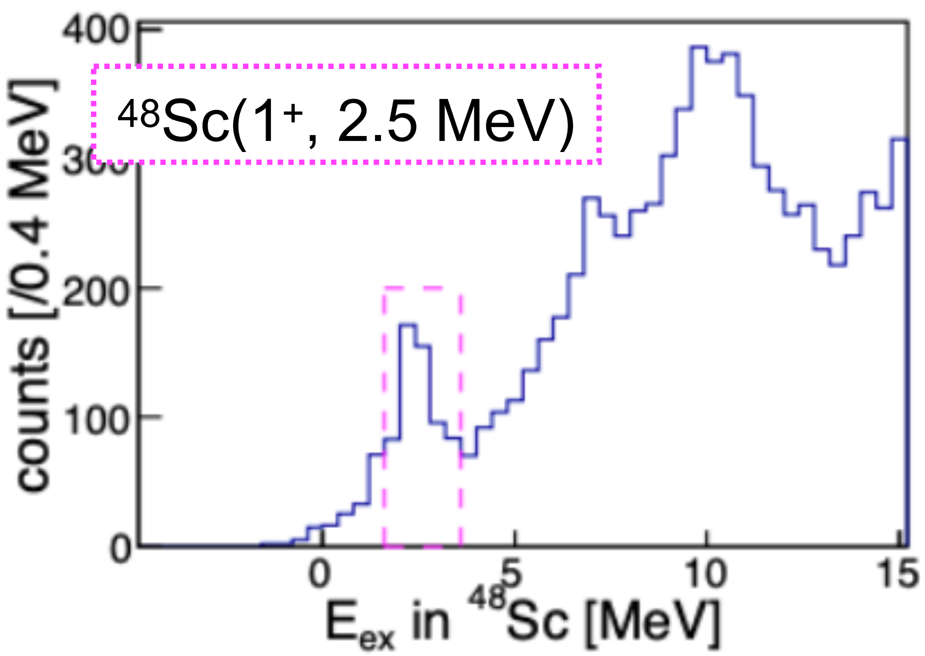
- $\Delta L_{DCX}=0$: $[\Delta L=0]\otimes[\Delta L=0]$ **DGT-like**
- $\Delta L_{DCX}=1$: $[\Delta L=1]\otimes[\Delta L=0]$
- $\Delta L_{DCX}=2$: $[\Delta L=2]\otimes[\Delta L=0]$

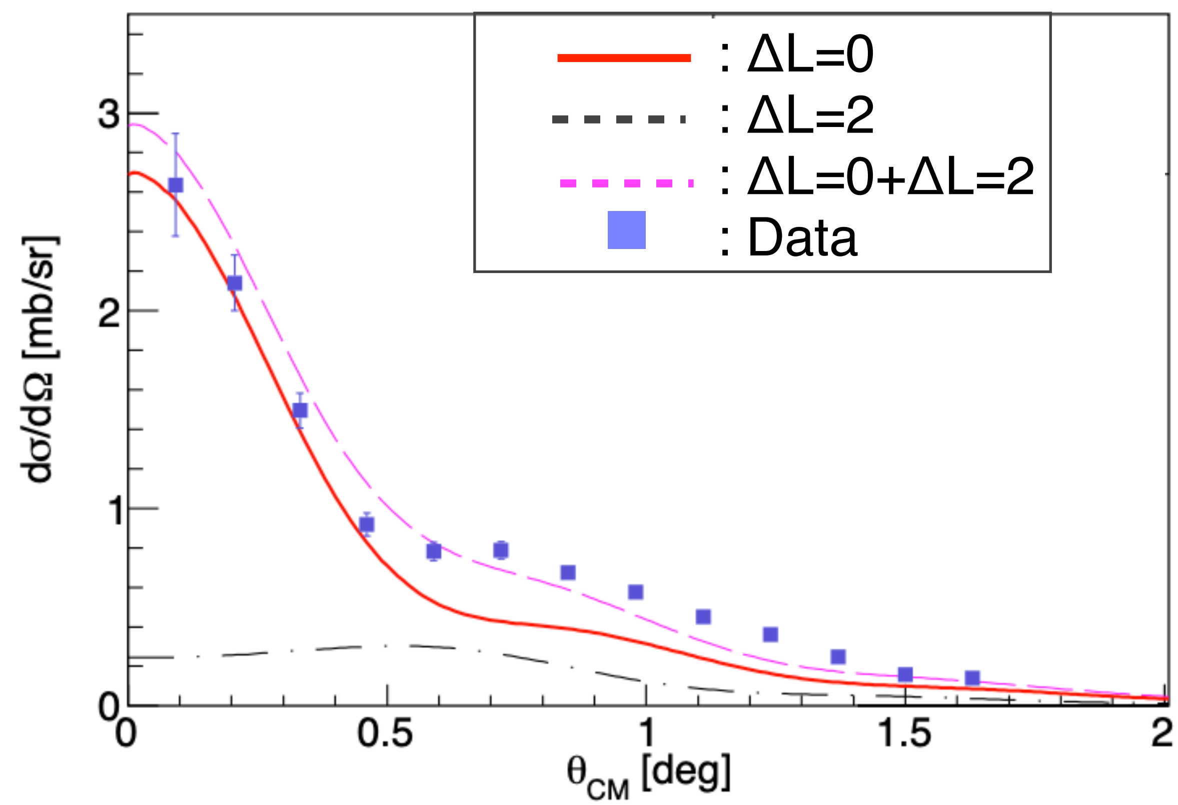
Angular distribution of SCX & DCX

single charge exchange

The consistency of the calculation was checked with SCX data

obsereved data of SCX
$^{48}Ca(^{12}C, ^{12}B)$





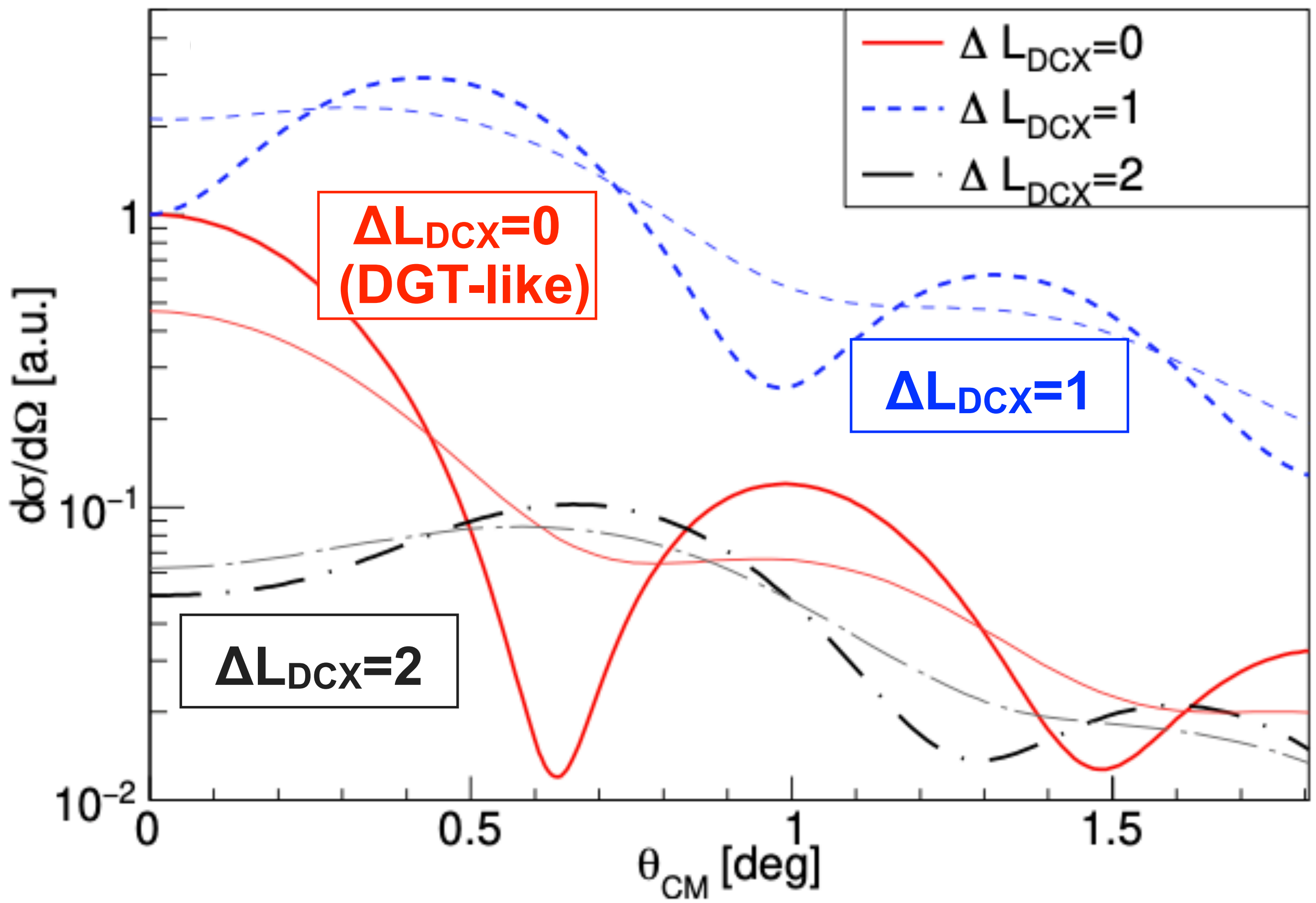
observed distribution is well described with
$\Delta L=0+\Delta L=2$
B(GT)=1.4 (known value: 1.09±0.01)

E.-W. Grewe et al., PRC 76, 054307 (2007)

– absolute value of cross section is reproduced within ~30%

Angular distribution of SCX & DCX

Double charge exchange



(Thin line: smeared by angular resolution)

✓ $\Delta L_{DCX}=0$ is forward-peaking

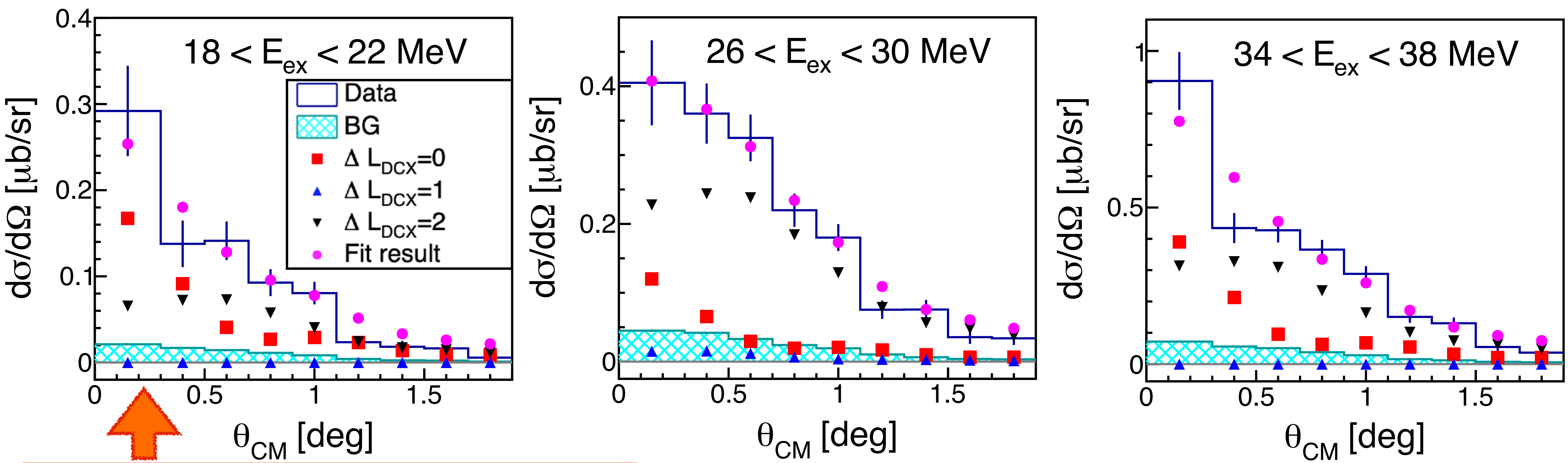
Decomposition of measured angular distribution

Observed angular distributions are decomposed by linear combinations of ΔL_{DCX}=0, 1, 2

Example of decomposition in several energy bins:

■ : $\Delta L_{DCX} = 0$

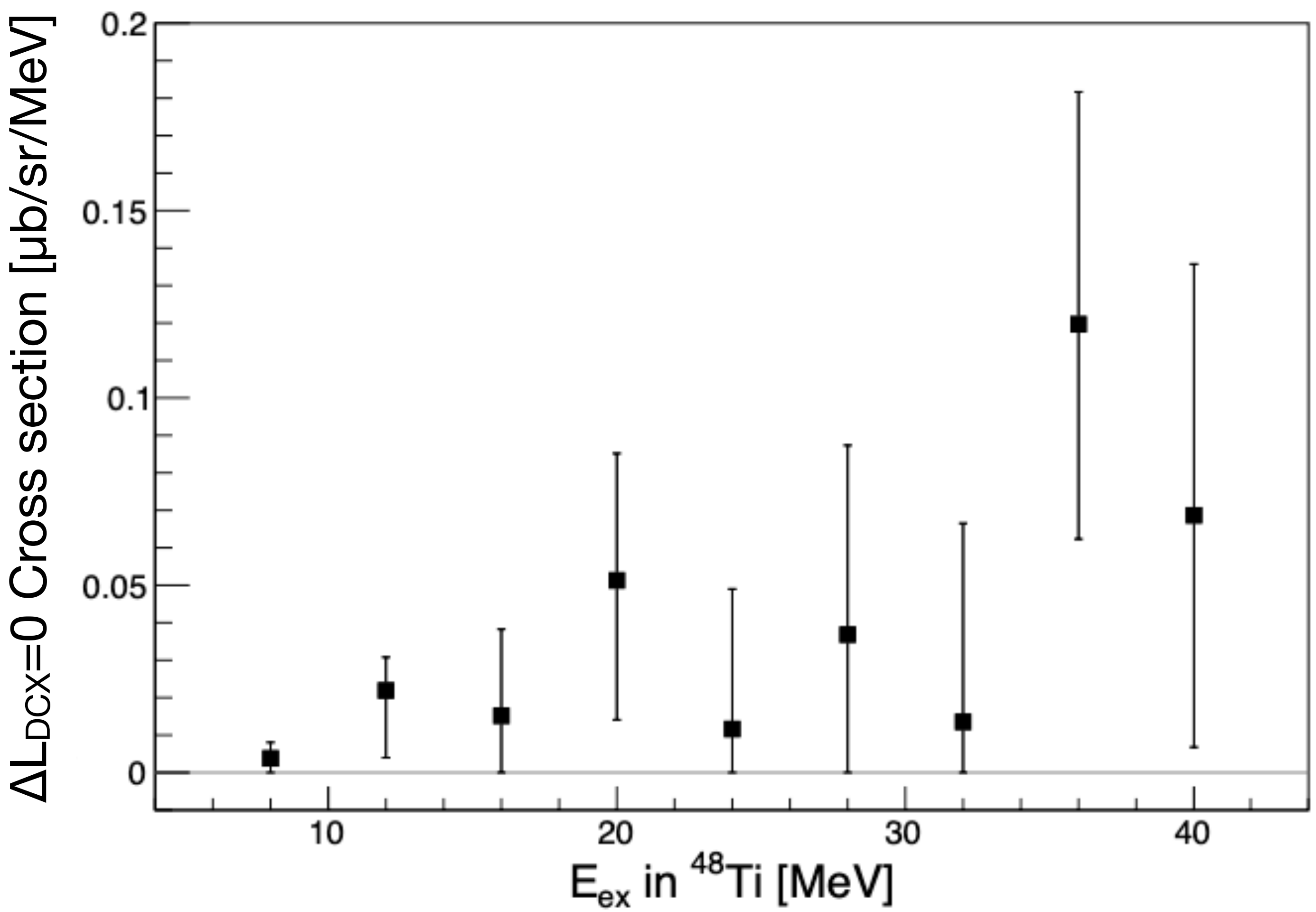
● : Fit result



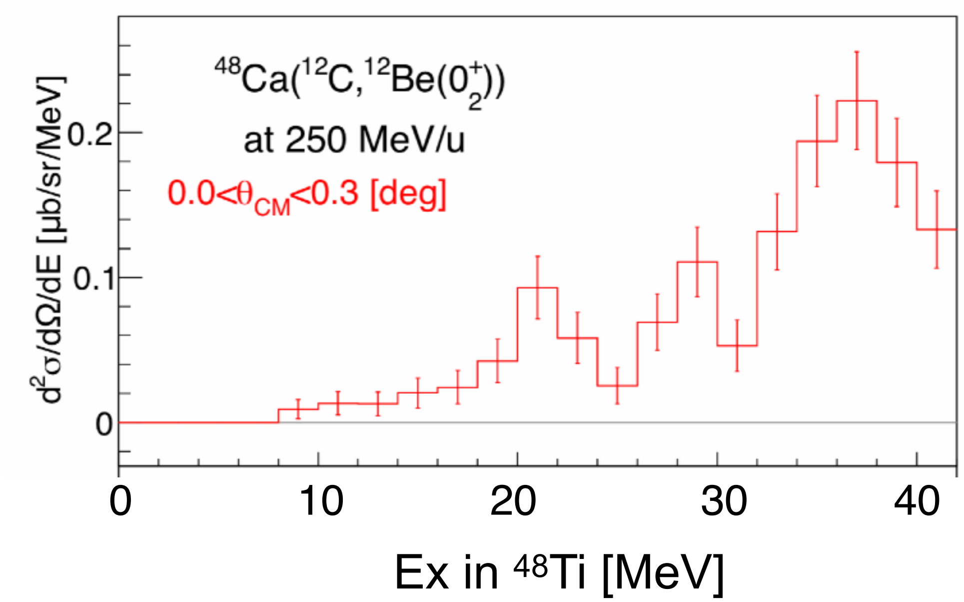
60±50% of observed cross section is ΔL_{DCX}=0

Extracted cross section of ΔL_{DCX}=0

Energy distribution of extracted ΔL_{DCX}=0 cross section at 0-0.3°



Observed cross section at 0-0.3°



ΔL_{DCX}=0 cross section is $0.50^{+0.35}_{-0.11}$ μb/sr in 0-34 MeV

38^{+26}_{-8}% of observed cross section is ΔL_{DCX}=0

Double Gamow–Teller transition strength

- Proportionality relation between cross section at 0 deg and B(GT)

$$\sigma(0^\circ) = \hat{\sigma}_{\mathrm{GT}} F(q,\omega)\ B(\mathrm{GT})$$

Gamow-Teller transition strength $B(\mathrm{GT}) = \frac{1}{2J_i + 1} \left| \langle f \| \sigma\tau \| i \rangle \right|^2$

($\hat{\sigma}_{\mathrm{GT}}$ (unit cross section) : proportional coefficient
F(q,ω) : kinematical dependence

- Proportionality relation betweenn cross section at 0 deg and B(DGT) is assumed :

$$\sigma(0^\circ) = \hat{\sigma}_{\mathrm{DGT}} F(q,\omega)\ B(\mathrm{DGT})$$

Double Gamow-Teller transition strength $B(\mathrm{DGT}) = \frac{1}{2J_i + 1} \left| \langle f \| (\sigma\tau)^2 \| i \rangle \right|^2$

Extraction of B(DGT) from the data

Proportional relation is assumed: $\sigma(0^\circ) = \hat{\sigma}_{\mathrm{DGT}} F(q,\omega)\ B(\mathrm{DGT})$

B(DGT) is factorized on the heavy ion reaction : $B(\mathrm{DGT}) = B_{\mathrm{target}}(\mathrm{DGT}) * B_{\mathrm{projectile}}(\mathrm{DGT})$

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

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

$^{12}C \rightarrow {}^{12}Be$ (projectile)

$\Delta L_{DCX}=0$ cross section at 0°

- $B_{\mathrm{projectile}}(\mathrm{DGT})$ is deduced by assuming single intermediate state:

$$B_{^{12}C(0+)\rightarrow {}^{12}Be(0+2)}(\mathrm{DGT}) = B_{^{12}C(0+)\rightarrow {}^{12}B(1+)}(\mathrm{GT}) * B_{^{12}B(1+)\rightarrow {}^{12}Be(0+2)}(\mathrm{GT})$$

F. Ajzenberg-Selove, Nucl. Phys. A 506, 1 (1990)
R. Meharchand et al., Phys. Rev. Lett. 108, 122501 (2012).

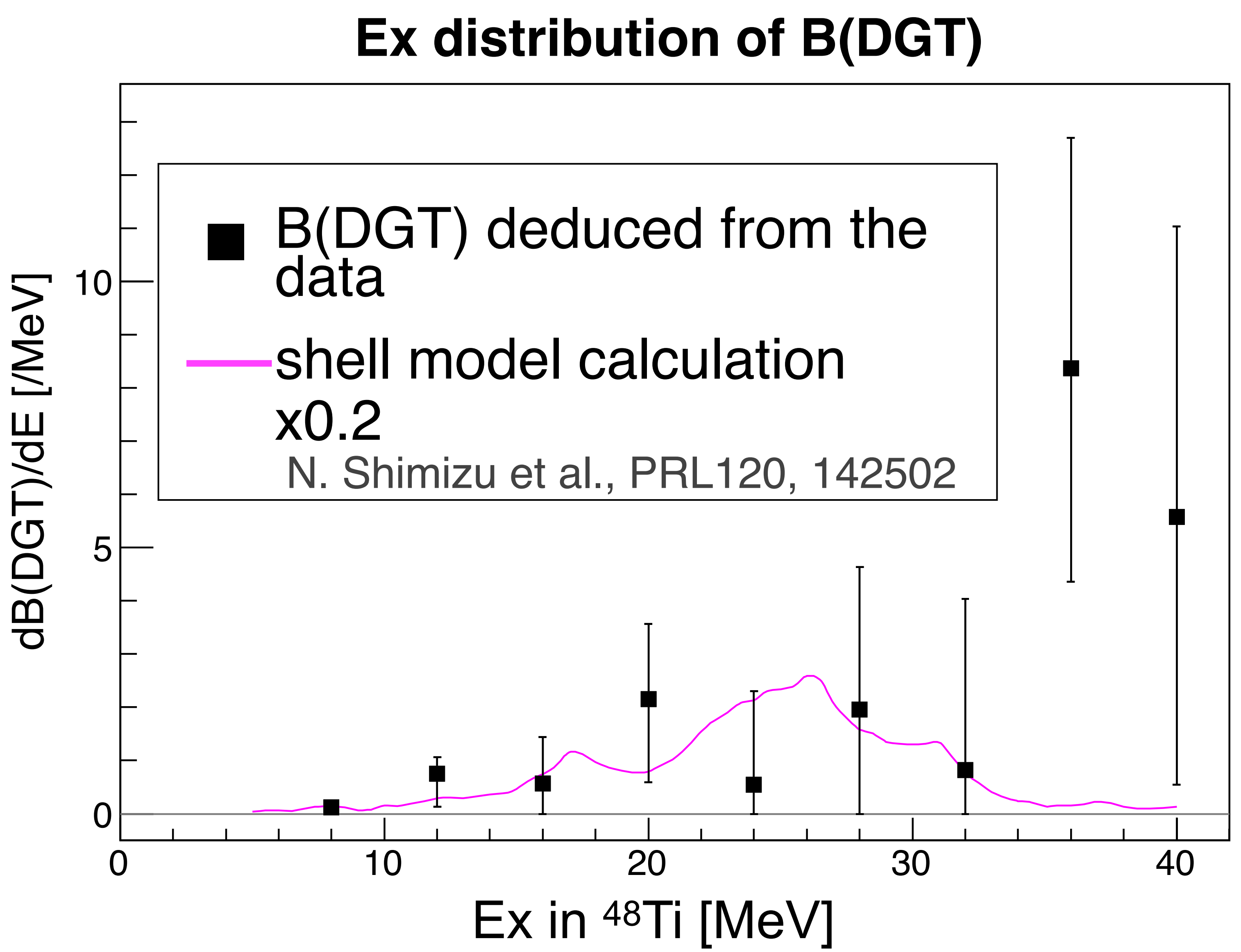
- σ_{DGT} and $F(q,\omega)$ are obtained by ECIS

Extraction of B(DGT) from the data

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

ΔL_{DCX}=0 cross section at 0°

$^{48}Ca \rightarrow {}^{48}Ti$



Other possibility than DGT transition

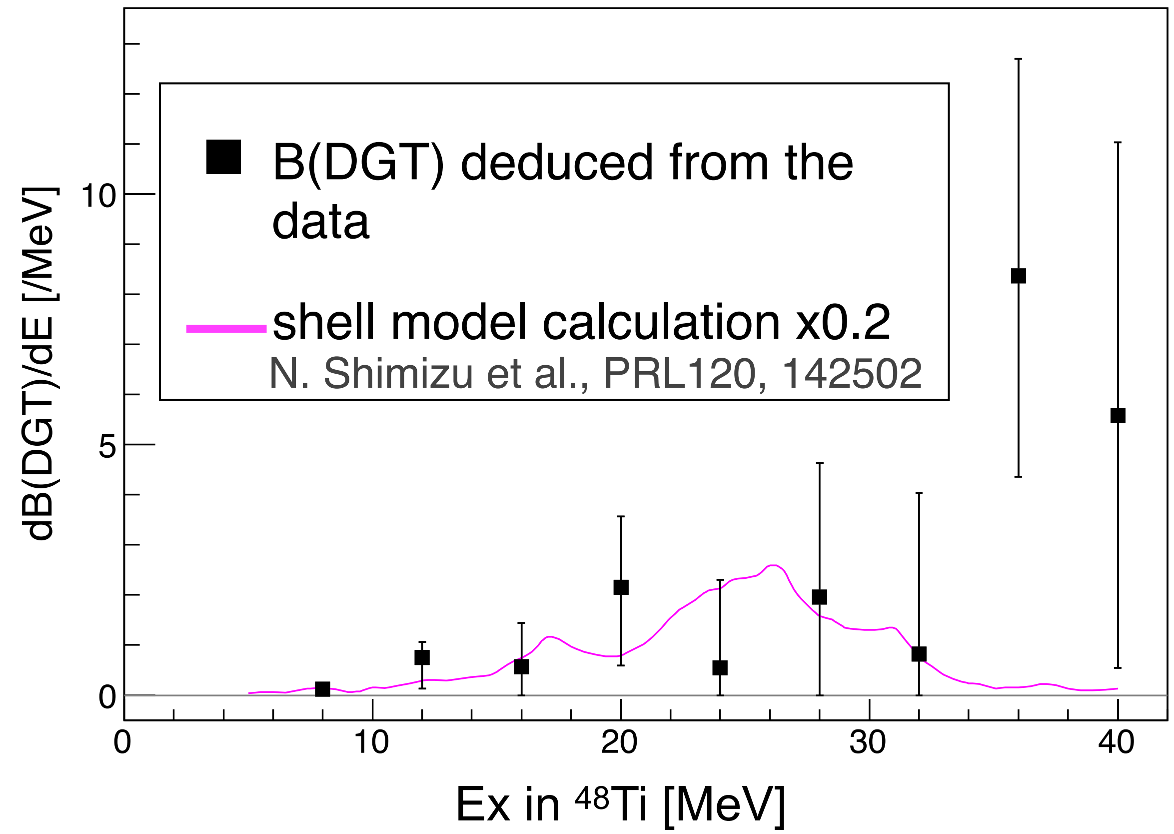
In the extraction of $\Delta L_{DCX}=0$ components,
other transitions with similar angular distribution to the DGT are not excluded

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

Consider the expected energy where these modes emerges

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

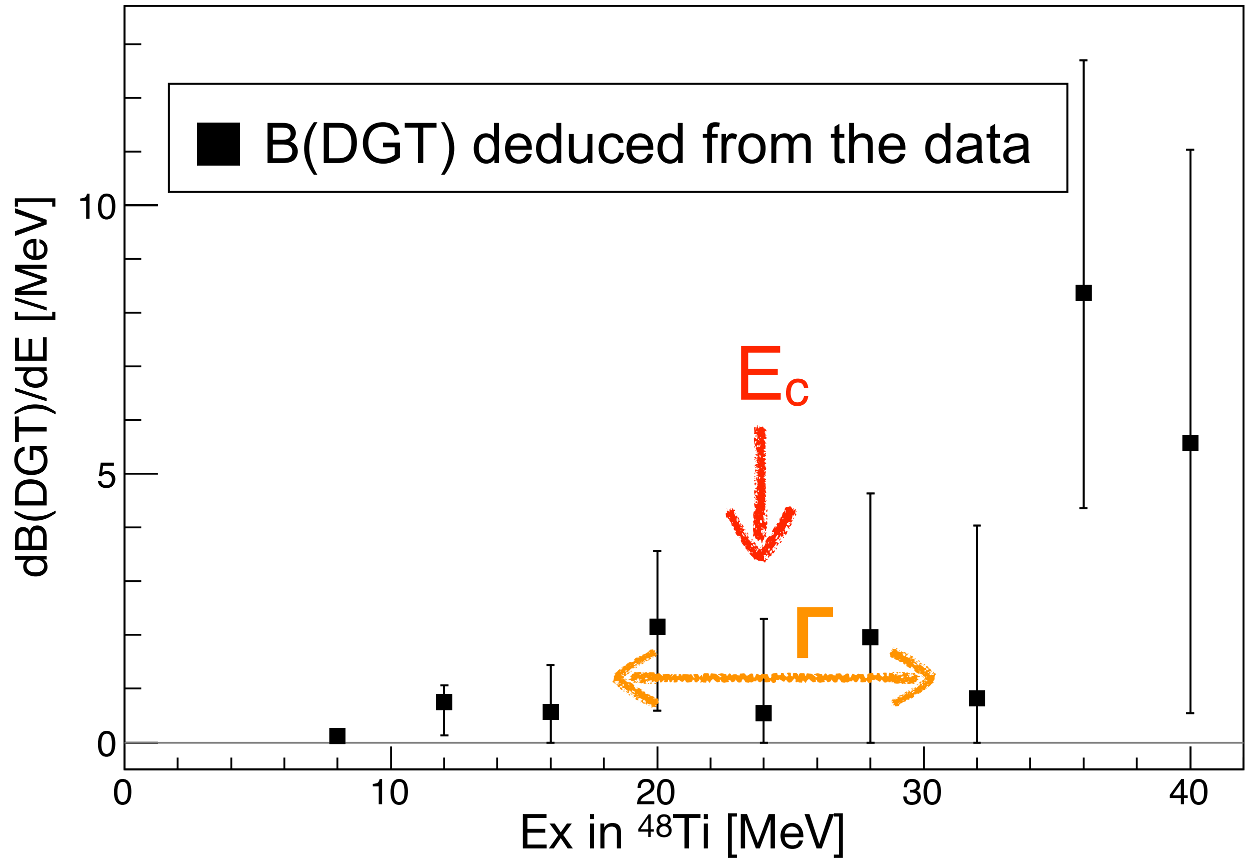
DGT transition strength in Ex=0–34 MeV

Sum, centroid energy, width of B(DGT) in 0<Ex<34 MeV is evaluated

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

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

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



B(DGT) has been first evaluated in high Ex region

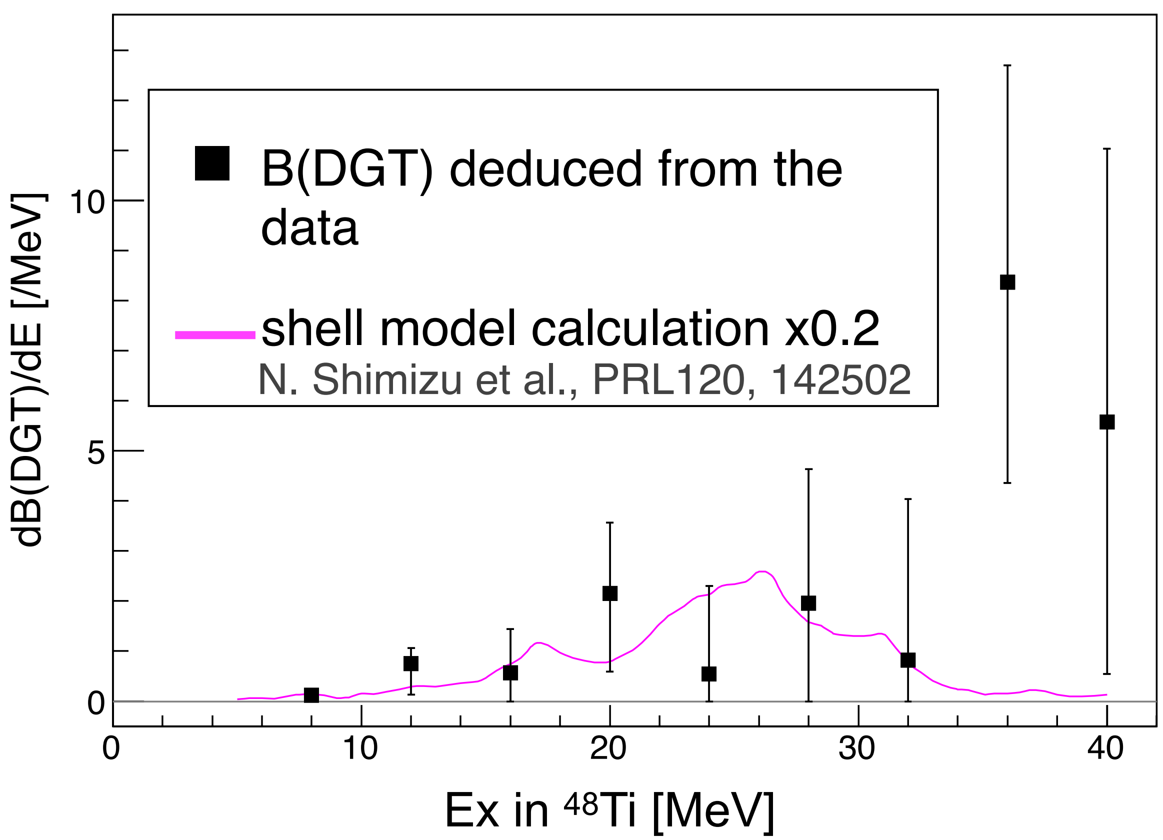
Ec of DGTGR and NME

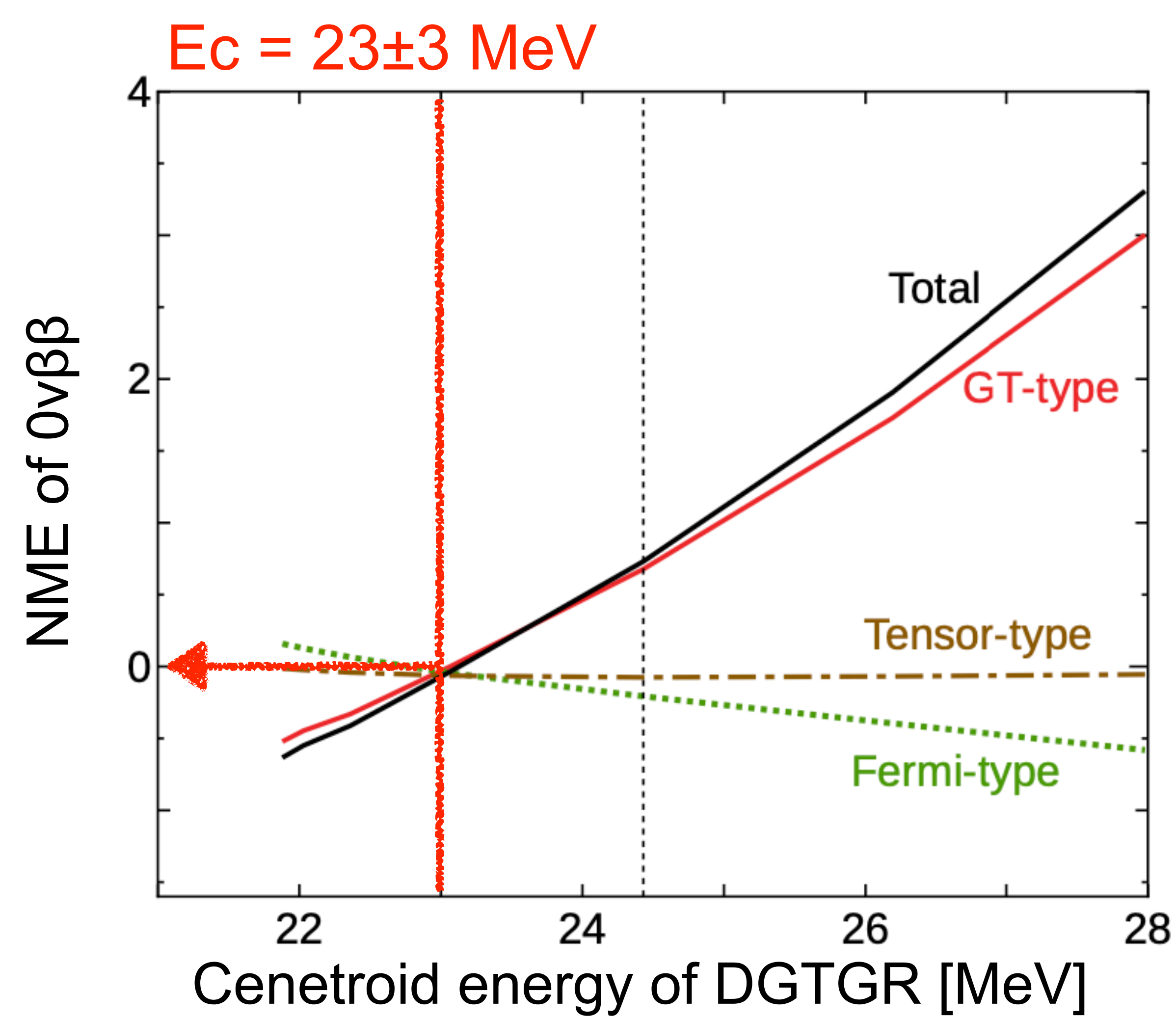
Sum, centroid energy, width of B(DGT) in 0<Ex<34 MeV is evaluated

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

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

Centroid energy of DGTGR E_c ↔ NME of 0νββ





✓NME=0±2

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

N. Shimizu, Private communication

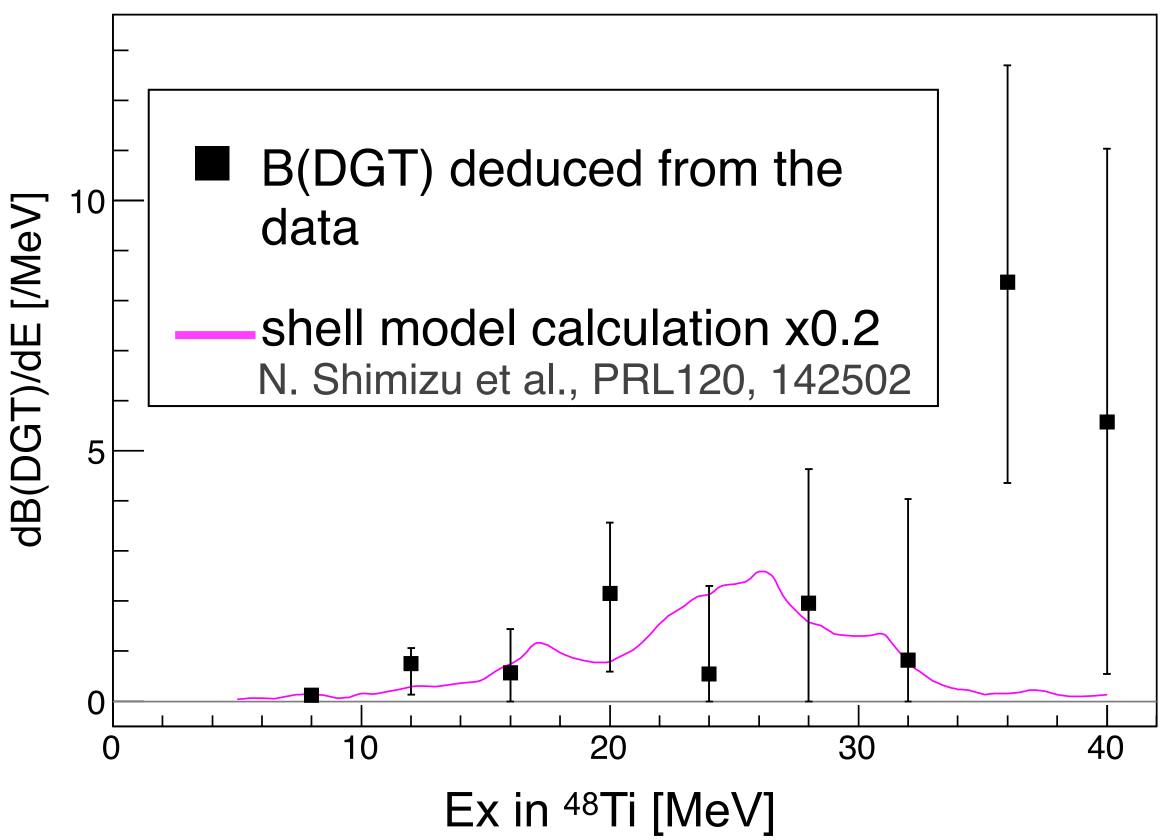
Ec of DGTGR and NME

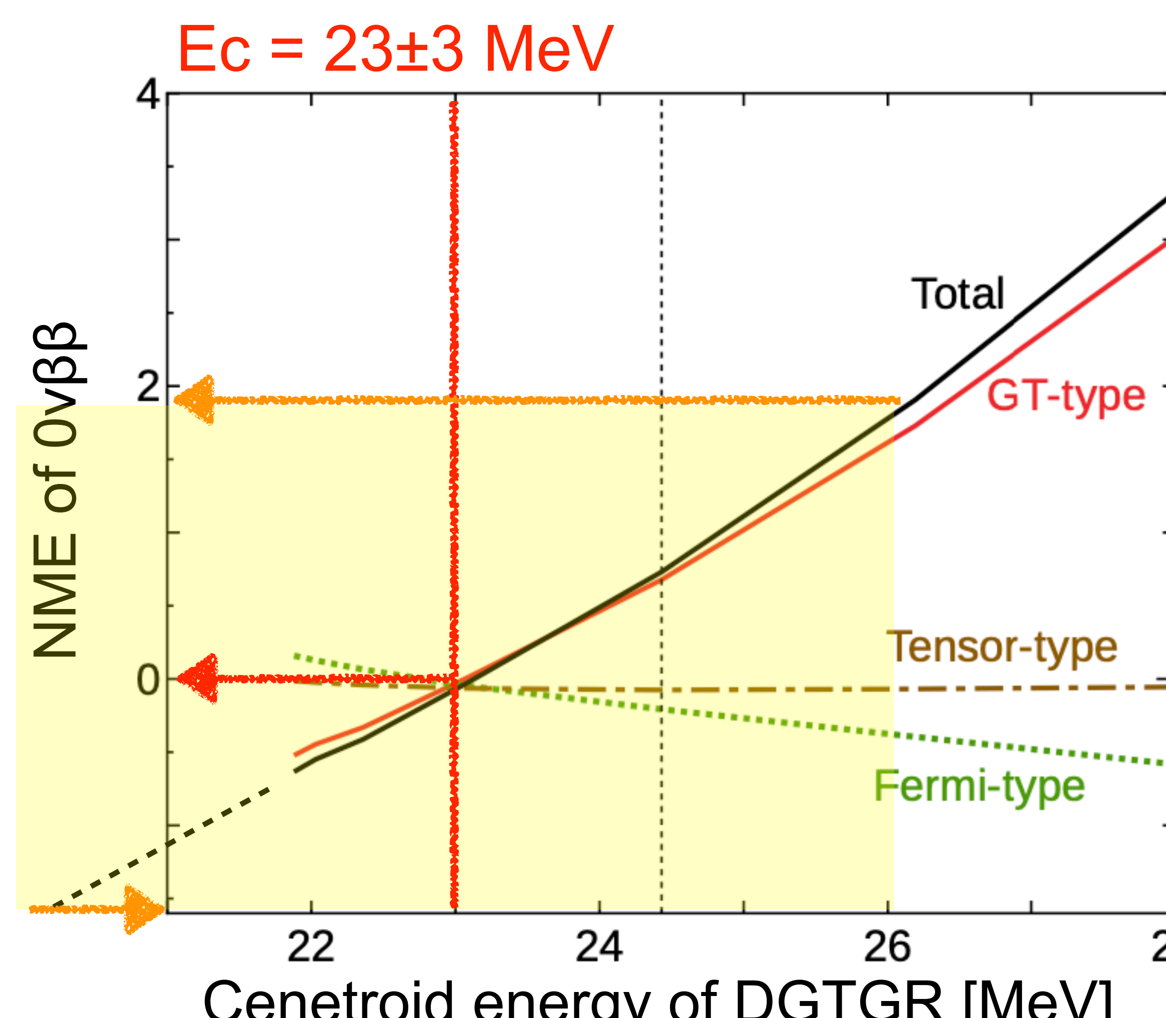
Sum, centroid energy, width of B(DGT) in 0<Ex<34 MeV is evaluated

$S=28^{+22}_{-7}$, $E_c = 23\pm3$ MeV, $\Gamma = 6\pm1$ MeV

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

Centroid energy of DGTGR $E_c \leftrightarrow$ NME of $0\nu\beta\beta$





✓NME=0±2

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

N. Shimizu, Private communication

Possible to constrain NME by experiment of DCX

Future plan

The first (^{12}C, $^{12}Be(0^+_2)$) experiment at RIBF for ^{48}Ca

- DGT at Ex > 10 MeV was measured with high resolution and low BG
- Candidate for the DGTGR was observed
- DGT strength was evaluated
- statistics is not enough - specific discussion is not yet achieved

High statistics experiment will provide more clear information on DGT

- Next plan: Using target with large cross section
  - Transition strength ∝ 2(N-Z)(N-Z+1)

    H. Sagawa and T. Uesaka, PRC 94, 064325 (2016)

→ **Next target: ^{136}Xe**

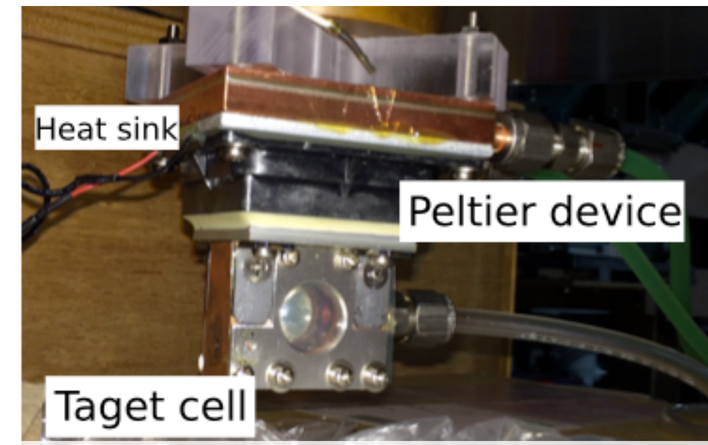
- Transition strength ~ ^{48}Ca x13, cross section ~ x4 considering distortion
- Magic neutron number
- Target nucleus of KamLAND-Zen

nuclide	2(N-Z)(N-Z+1)
^{48}Ca	112
^{76}Ge	264
^{82}Se	364
^{96}Zr	480
^{100}Mo	480
^{116}Cd	760
^{128}Te	1104
^{130}Te	1300
^{136}Xe	1512
^{150}Nd	1740
^{238}U	5724

Future plan - ^{136}Xe target

In order to realize ^{136}Xe measurement,
Gas target is to be installed in F0

- Gas is filled in the cell with window
- develop in collaboration with pionic atoms group (Itahashi et al.)



example of the gas target
(developed at RCNP)

Gain comparing ^{48}Ca experiment:

- cross section x4
- optimization of setup x2 yeild
- thick target x2.5 yield

➡ **20 times statistics**

- If data taking time x2
(cf. ^{48}Ca measurement ~ 1.5days)

➡ **40 times statistics → ΔEc = 0.8 MeV**

Plan： FY2025 submit proposal
FY2026 complete development of gas target
FY2027- ^{136}Xe measurement

F0 chamber and target holder
(for solid target)

Summary

- Double Gamow–Teller giant resonance (DGTGR) will provide various insight to the nuclear nature, including NME of $0\nu\beta\beta$

- DGT in high Ex is examined by double charge charge reaction of (^{12}C, $^{12}Be(0^+_2)$)

- The first experiment at RIBF was performed in 2021 for ^{48}Ca target
  - DCX was measured with ΔEx=1.5 MeV, $\Delta\theta_{CM}$=0.2° with low BG: 1.33±0.12 μb/sr in 0-34 MeV at the most forward angle
  - Forward peaking structure was observed around Ex=20 MeV
    Candidate for DGTGR
  - DGT strength was evaluated by using angular distribution
    - Sum of the strength = 22^{+17}_{-6}% of sum rule value, Ec = 23±3 MeV, Γ = 6±1 MeV
  - The result shows the possibility of constraining $0\nu\beta\beta$ NME by experiment of DCX

- Next plan: ^{136}Xe target
  - Development of gas target is now ongoing
  - Higher statistics experiment → ΔEc = 0.8 MeV
  - We will get more clear information on DGT response