Exploring nuclear structure by double charge exchange reactions in Japan

CNNP2017, Catania, Oct17

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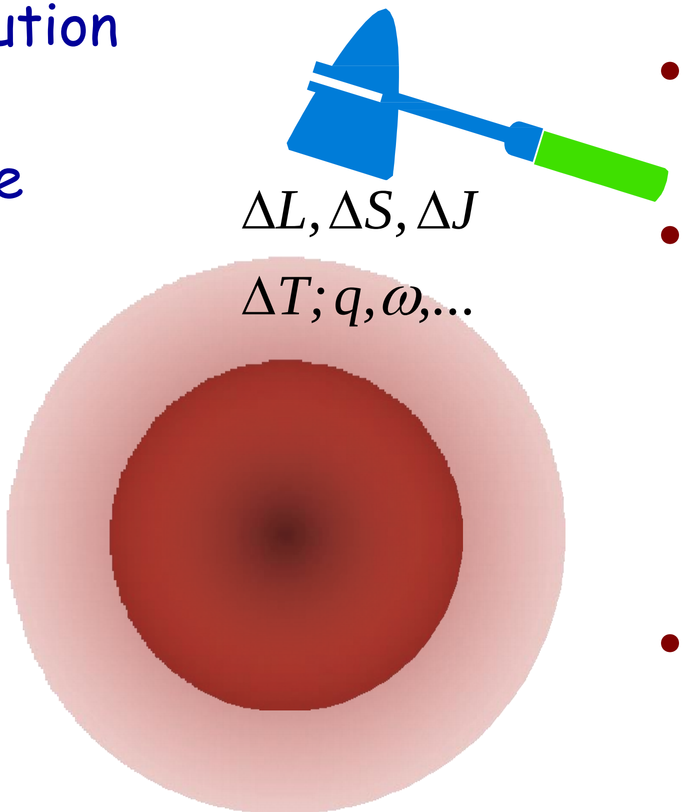
Studies of Nuclei via Direct reactions

- Size/ρ-distribution
  - Skin/Halo
- Shell Structure
  - New magic #
  - Isospin / Deformation
- New modes
  - IVE1
  - ISE0, ISE1
- etc.

Direct Reactions



- Size/ρ-distribution
  - σ_R, elastic scat.
- Shell Structure
  - Mass / S_n, S_{2n}
  - Inelastic scatt.
  - Low lying states
  - Knockout / Transfer
- New modes
  - Coulex
  - Inelastic scatt.
  - CEX
- etc.

"Hit and analyze the sound"

Single Charge Exchange reactions

Table 3.1 *Fermi and Gamow–Teller strengths, B(F) and B(GT), for several (p, n)-like and (n, p)-like reactions obtained from experimental β-decay log ft values (CHO93). The relative values $B(GT)_{rel}$ are normalized to the (p, n) and (n, p) reactions. Adapted from (ANN99).*

β^- whole → surface

β^+

	$J_i^\pi \rightarrow J_f^\pi$	B(F)	B(GT)	$B(\mathrm{GT})_{rel}$
(p, n)-like reactions				
(p, n)	$1/2^+ \rightarrow 1/2^+$	1.00	3.008 ± 0.014	100%
(^{3}He, t)	$1/2^+ \rightarrow 1/2^+$	1.00	2.685 ± 0.009	89%
(^{6}Li, ^{6}He)	$1^+ \rightarrow 0^+$		1.576 ± 0.005	52%
(^{12}C, ^{12}B)	$0^+ \rightarrow 1^+$		0.991 ± 0.011	33%
(n, p)-like reactions				
(n, p)	$1/2^+ \rightarrow 1/2^+$	1.00	3.008 ± 0.014	100%
(d, ^{2}He)[a]	$1^+ \rightarrow 0^+$		≈ 3	~100%
(t, ^{3}He)	$1/2^+ \rightarrow 1/2^+$	1.00	2.685 ± 0.009	89%
(^{6}He, ^{6}Li)	$0^+ \rightarrow 1^+$		4.727 ± 0.014	157%
(^{7}Li, ^{7}Be$_{g.s}$)	$3/2^- \rightarrow 3/2^-$	1.00	1.300 ± 0.004	43%
(^{7}Li, ^{7}Beγ)	$3/2^- \rightarrow 1/2^-$		1.122 ± 0.007	37%
(^{12}C, ^{12}N)	$0^+ \rightarrow 1^+$		0.877 ± 0.006	29%
(^{13}C, ^{13}N)	$1/2^- \rightarrow 1/2^-$	1.00	0.194 ± 0.004	6%

M. Harakeh & A. van der Woude, "Giant Resonances"

"Proportionality" in Single Charge-X reaction

Factorized form of cross section:

Idea: Taddeucci
NPA 469(1987)125.

$$d\sigma(q,\omega) = \hat{\sigma}_{GT}(E,A) F_{GT}(q,\omega) B_{P,GT} B_{T,GT}(\omega)$$

exp. cross section

reaction

Unit cross section

(q,ω) dependence

probe "efficiency"

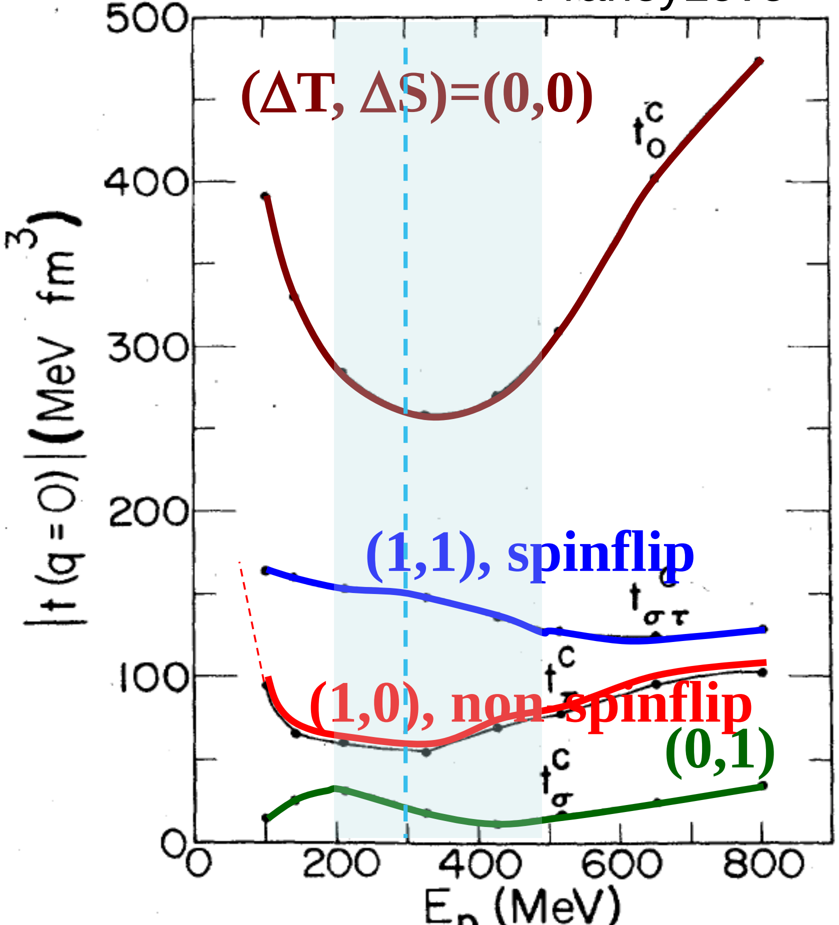
Structure info

<u>~300 MeV is good*</u> when studying spin-isospin modes like GT, SD,…

- distortion is smallest.
- spinflip interaction is large compared with non-spinflip int.
- tensor int. is reasonably small.

*) In many cases other factors dictate the measurement, such as resolution.

FraneyLove



Double Charge Exchange reactions

Factorized form of cross section:

Cappuzzello et al.
EPJ A(2015)51: 145

$$d\sigma(q,\omega) = \hat{\sigma}_{DGT}(E,A) F_{DGT}(q,\omega) B_{P,DGT} B_{T,DGT}(\omega)$$

exp. cross section

reaction

Structure info (transition strength)

Unit cross section

(q,ω) dependence

probe "efficiency": B(GT; i ->m)·B(GT; m ->f)

Reaction	Type	$B_{P,DGT}$	Q-valueP	Comments
(^{11}B,^{11}Li)	β-β-	?	-32 MeV	lightest, no exctd bound state in ^{11}Li
(^{18}O,^{18}Ne)	β+β+	3	-6 MeV	large $B_{P,GT}$, between mirror nuclei
(^{12}C,$^{12}Be(0^+_2)$)	β-β-	0.2	-27 MeV	good id of final state
(^{8}He,^{8}Be)	β-β-	(large)	+28 MeV	exothermic, RI beam

Recent Attempts in Japan

1. Search for Double GT Resonance by the $^{48}Ca(^{12}C, ^{12}Be(0^+_2))^{48}Ti$ reaction at 100 A MeV at RCNP
   Takaki, Uesaka et al.
2. Search for tetra-neutron bound state in the $^{4}He(^{8}He, ^{8}Be)4n$ reaction 190 A MeV at RIBF - SHARAQ
   Kisamori, Shimoura et al. PRL 116(2016)052501

Reaction	Type	$B_{P,DGT}$	Q-valueP	Comments
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1. Double Gamow-Teller Resonance

Motivation

Experimental information on nuclear
double GT / double spin-dipole (SD) responses
is limited.

Lifetimes of $2\nu\beta\beta$ nuclei
→ limited to low lying states (mostly ground sates) for ~10 species.

Single GT / SD responses
→ rich data, constrains structure models.
Relationship to double GT/SD responses is not direct.
Exp -> B(GT), B(SD)
not the matrix element with sign.

Existing data: lifetimes of 2νββ decay nuclei

TABLE 1 Summary of experimentally measured $\beta\beta(2\nu)$ half-lives and matrix elements[a]

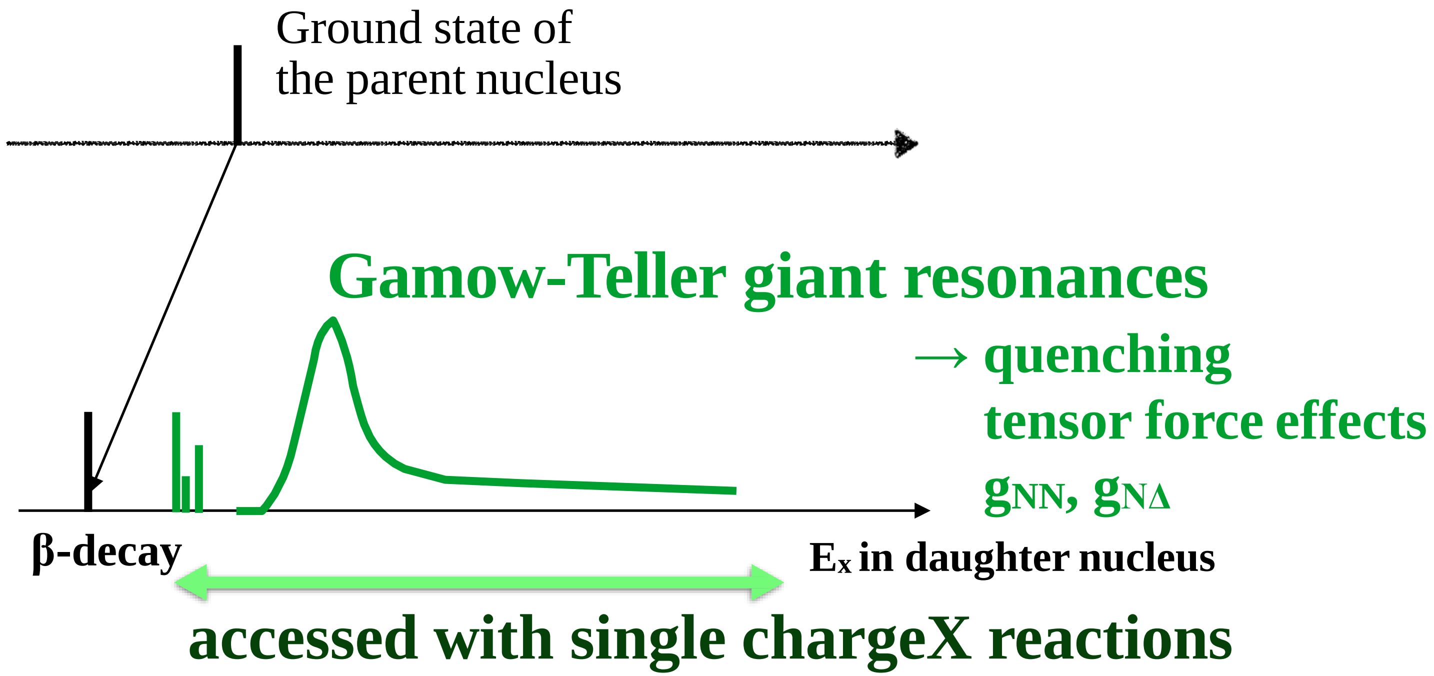
Isotope	$T^{2\nu}_{1/2}$ (y)	References	$M^{2\nu}_{GT}$ (MeV^{-1})
^{48}Ca	$(4.2 \pm 1.2) \times 10^{19}$	(55, 56)	0.05
^{76}Ge	$(1.3 \pm 0.1) \times 10^{21}$	(57–59)	0.15
^{82}Se	$(9.2 \pm 1.0) \times 10^{19}$	(60, 61)	0.10
^{96}Zr†	$(1.4^{+3.5}_{-0.5}) \times 10^{19}$	(62–64)	0.12
^{100}Mo	$(8.0 \pm 0.6) \times 10^{18}$	(65–70), (71)†	0.22
^{116}Cd	$(3.2 \pm 0.3) \times 10^{19}$	(72–74)	0.12
^{128}Te[b]	$(7.2 \pm 0.3) \times 10^{24}$	(75, 76)	0.025
^{130}Te[c]	$(2.7 \pm 0.1) \times 10^{21}$	(75)	0.017
^{136}Xe	$>8.1 \times 10^{20}$ (90% CL)	(77)	<0.03
^{150}Nd†	$7.0^{+11.8}_{-0.3} \times 10^{18}$	(68, 78)	0.07
^{238}U[d]	$(2.0 \pm 0.6) \times 10^{21}$	(79)	0.05

< 10^{-3} of sum rule values

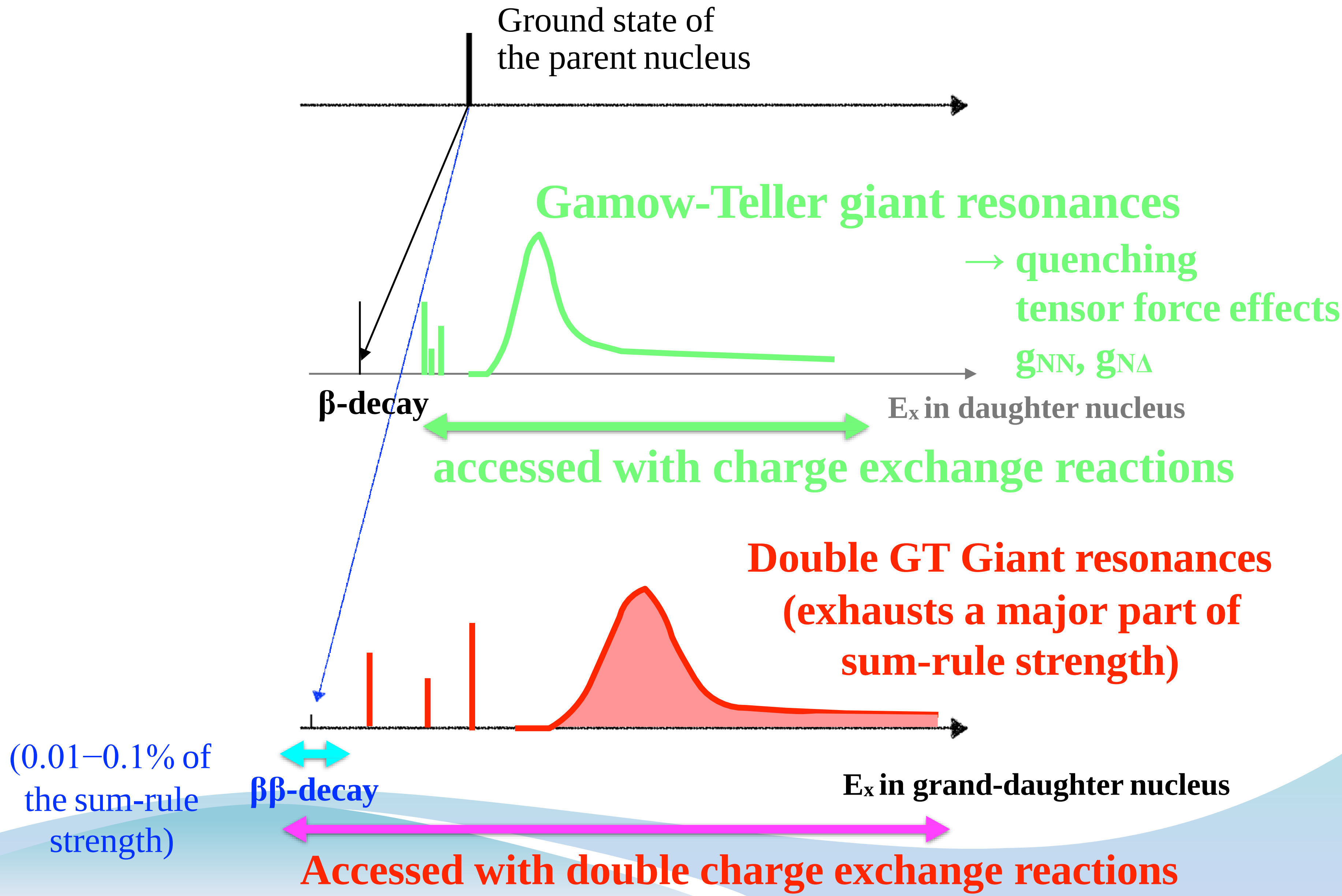
>99.9%: unobserved

Elliot & Vogel (2002)

Our understanding of GT response



Our understanding of Double GT response



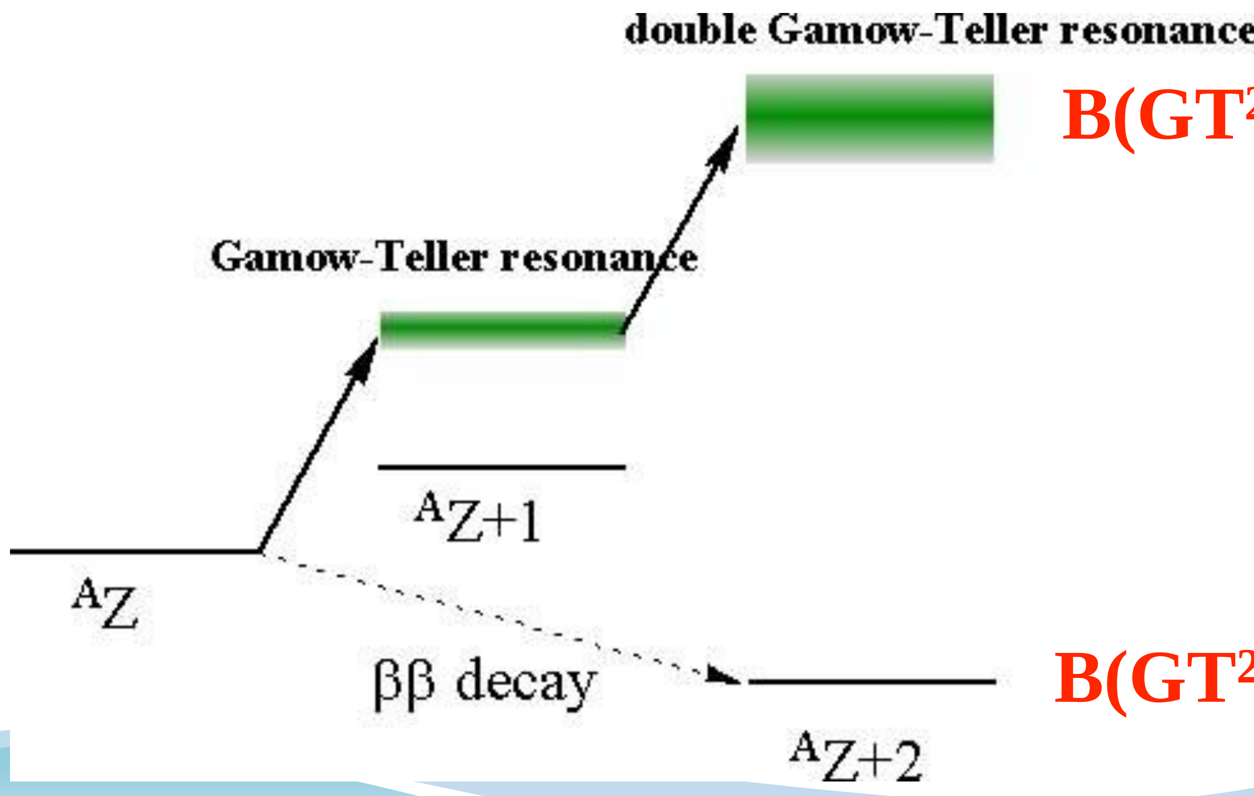
Double GT Giant Resonance

GT resonance built on a GT resonance

… exhausts a major part of the $(GT)^2$ strength

⇔ 2νββ decay

Auerbach, Zamick, Zheng, Ann. Phys. **192**, 77 (1989).



$B(GT^2) \sim 100$

$B(GT^2) \sim 0.1$

Issues on DGT responses

- Extending DGT study to
  to wider range of excitation energy
  (with no Q-value restriction)
  on any nuclei (not limited to ββ nuclei)

- Nature of DGTGR
  …simple superposition of single GTGRs?
  $E_{\mathrm{DGTGR}} = 2E_{\mathrm{GTGR}}$??
  $\Gamma_{\mathrm{DGTGR}} = \sqrt{2}\,\Gamma_{\mathrm{GTGR}}$??
  …Quenching of the GT^2 strength ?
  exp. sum rule value?

Previous attempt of DChX: (π⁺, π⁻)

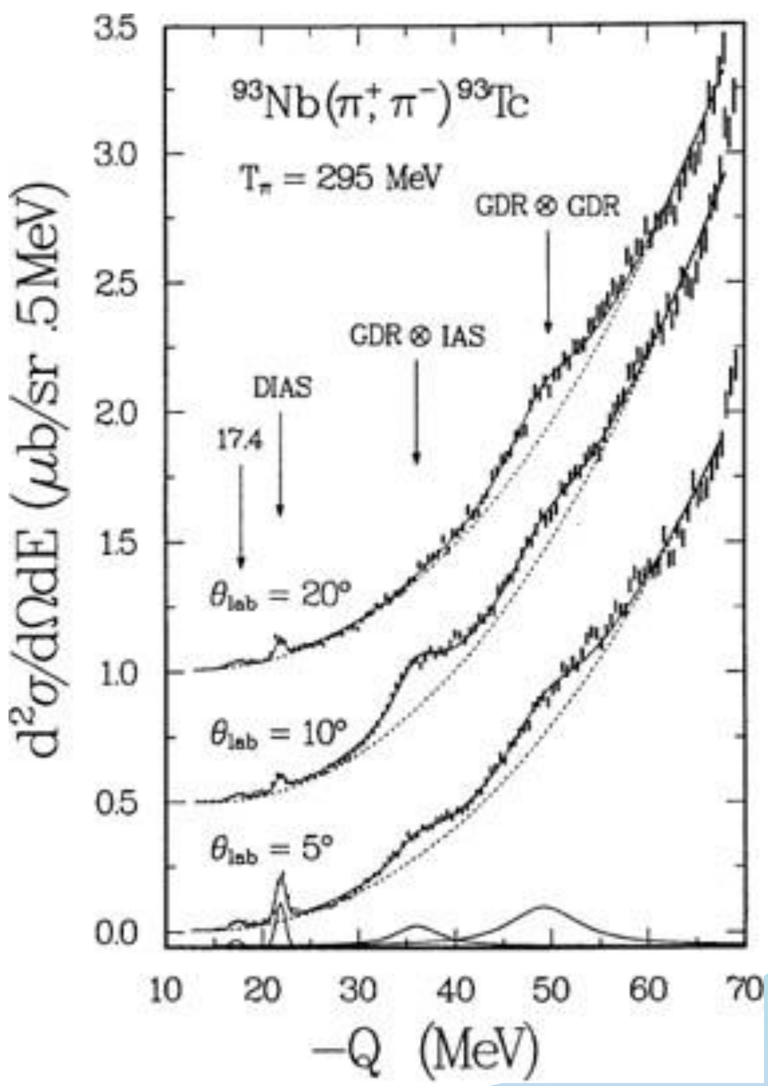
(π⁺,π⁻) @ 292 MeV LAMPF

S. Mordechai et al., PRL **60**, 408 (1988).

π⁻… clean id of final state

Double IAS & Double GDR ○

Double GT X



Previous attempts: (^{18}O, ^{18}Ne)

(π^+,π^-) @ 292 MeV LAMPF

no spin-flip resonances

S. Mordechai et al., PRL **60**, 408 (1988).

(^{18}O,^{18}Ne) @76MeV/A MSU, GANIL

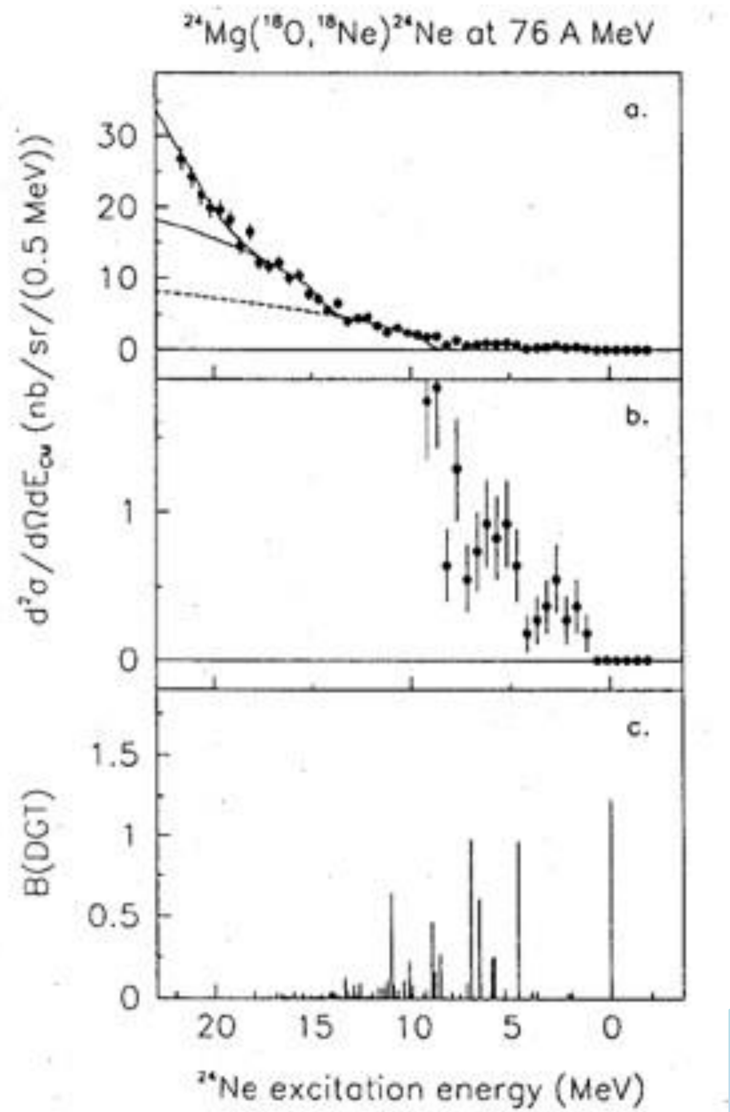
J. Blomgren et al., PLB **362**, 34 (1995).

(^{18}O,^{18}Ne): $\beta^+\beta^+$ type

24Mg -> 24Ne:

no strong DGT transition

probe is ineffective to study DGTR



Previous attempts: (^{11}B, ^{11}Li)

(π^+,π^-) @ 292 MeV LAMPF

no spin-flip resonances

S. Mordechai et al., PRL **60**, 408 (1988).

(^{18}O,^{18}Ne) @76MeV/A MSU, G

J. Blomgren et al., PLB **362**, 34 (

(^{18}O,^{18}Ne): $\beta^+\beta^+$ type

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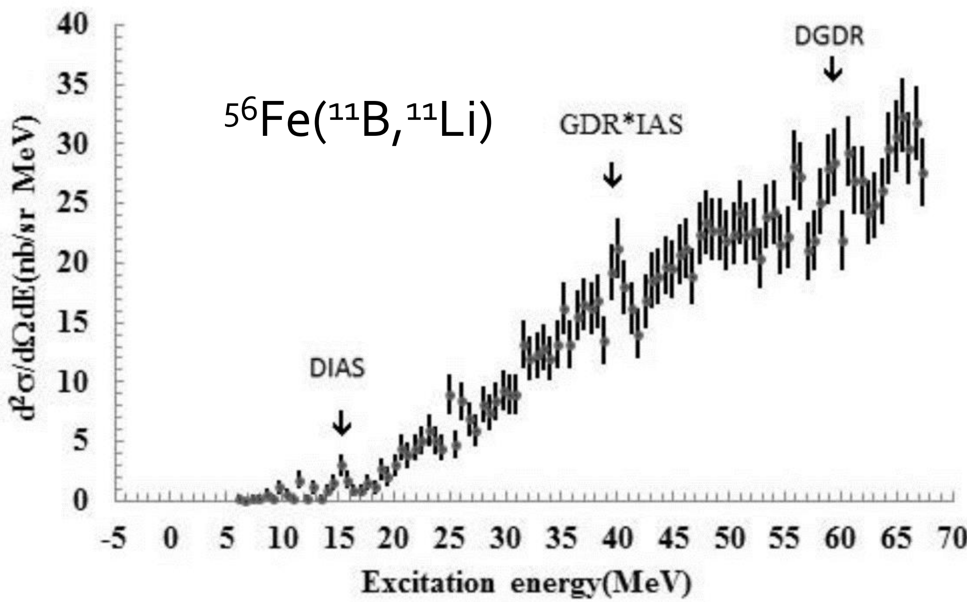


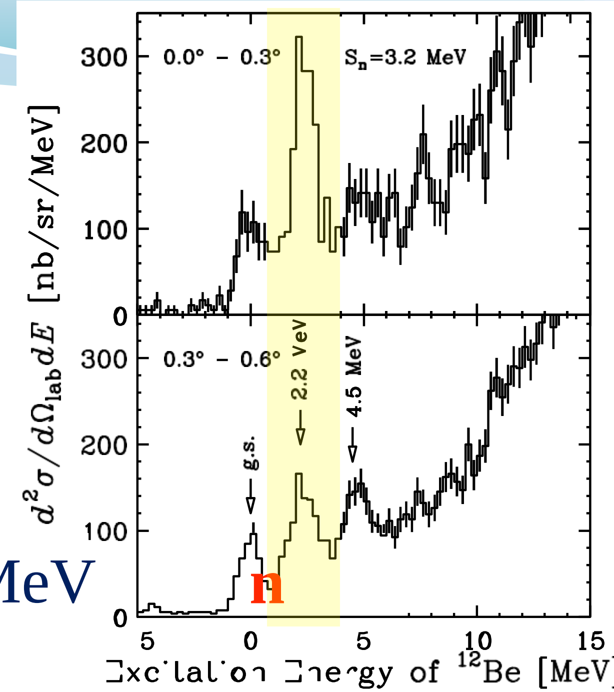
(^{11}B, ^{11}Li) @80 A MeV RCNP

Lightest probe

Takahisa, Ejiri et al., arXiv:1703.08264 (2017)

Identifying DIAS, and finding some structure.

Use of (^{12}C,^{12}Be(0^+_{2nd}))



^{12}C(gnd)→^{12}Be(0_2^+) transition is reasonably strong.

$B_{P,DGT}$ ~ 0.2

^{12}C(^{18}O,^{18}Ne)^{12}Be experiment →

dominance of transition to 0^+_2 state at 2.2 MeV

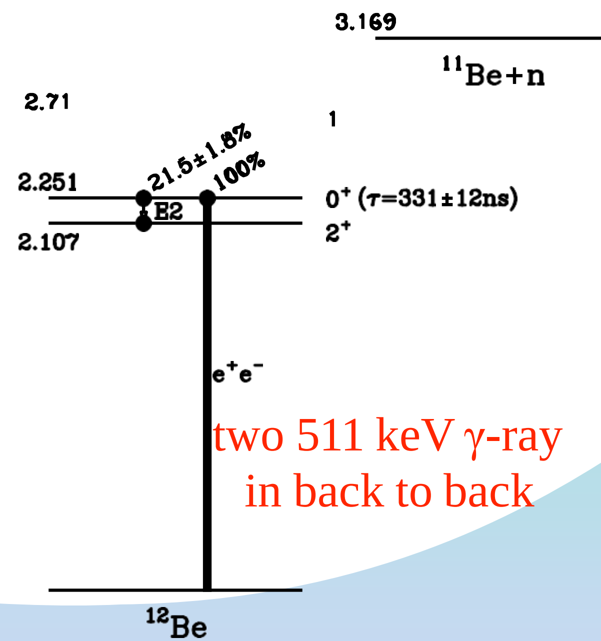
Matsubara, Takaki, et al., Few-Body Syst. **54**, 1433 (2013).

Delayed-γ tagging enables clear event identification.

- τ(^{12}Be(0_2^+)) = 331 ns

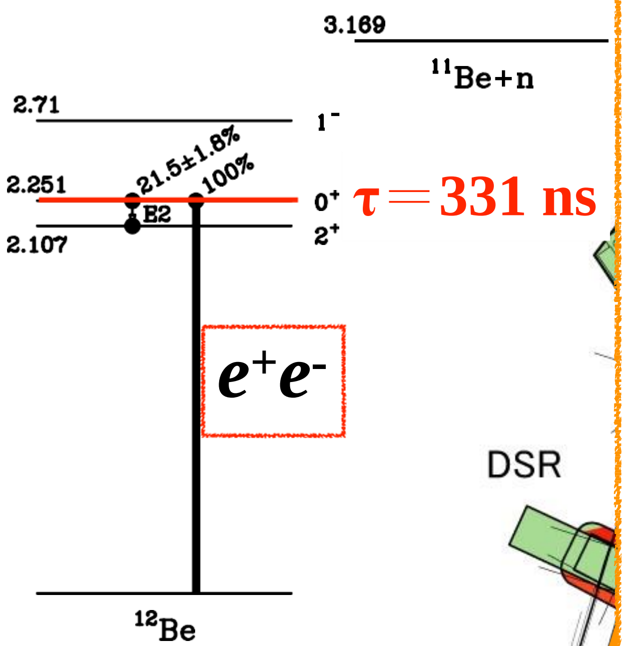
  ≫TOF ~ 150 ns (Grand Raiden)

- ~ 70% of the ^{12}Be(0^+_2) survive and reach the focal plane.



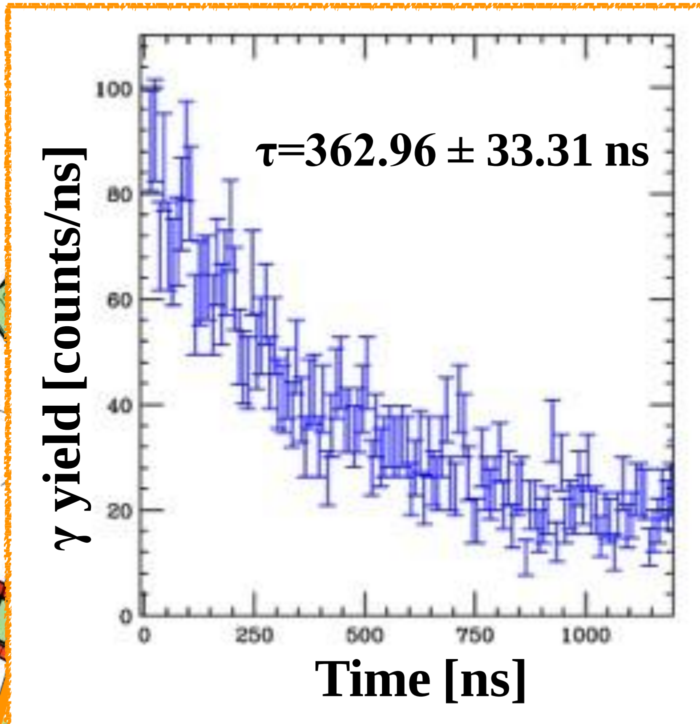
Experiment @ Grand Raiden (RCNP)

Takaki et al.

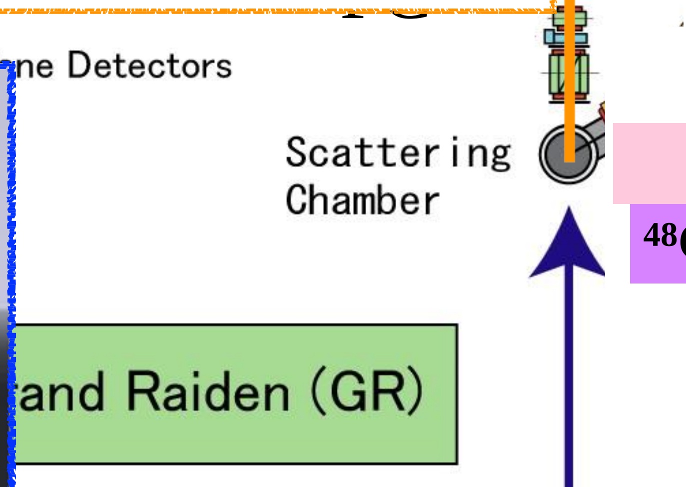


$\tau = 331$ ns

e$^+$e$^-$



Condition:
- $\Delta t_{\gamma\gamma}$ =10 ns
- back-to-back
- E_γ=400–600 keV
- ^{11}C-BG subtracted



Target

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

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

Active stopper (plastic)
+ NaI scintillators

2×511 keV γ-ray
in back-to-back

Excitation energy spectra in ^{48}Ti

Forward peaking (⇔ monopole) structures

arb. unit

$^{48}Ca(^{12}C,^{12}Be(0_2^+))$
E = 100 MeV/u

Unpublished spectra deleated

Comparison with (π^+,π^-) spectrum

Unpublished spectra deleated

analysis is ongoing…

Summary of part 1

Double Gamow-Teller Resonances

will open research opportunity on GT$\times$GT excitations

can serve as a test case for nuclear models of $0\nu\beta\beta$

Experimental access has been quite limited.

New idea: (^{12}C,$^{12}Be(0^+_2)$) reaction

Strong transition in the projectile ($^{12}C \rightarrow ^{12}Be(0_2^+)$)

Event identification capability via delayed-γ tagging

The first physics case : ^{48}Ca

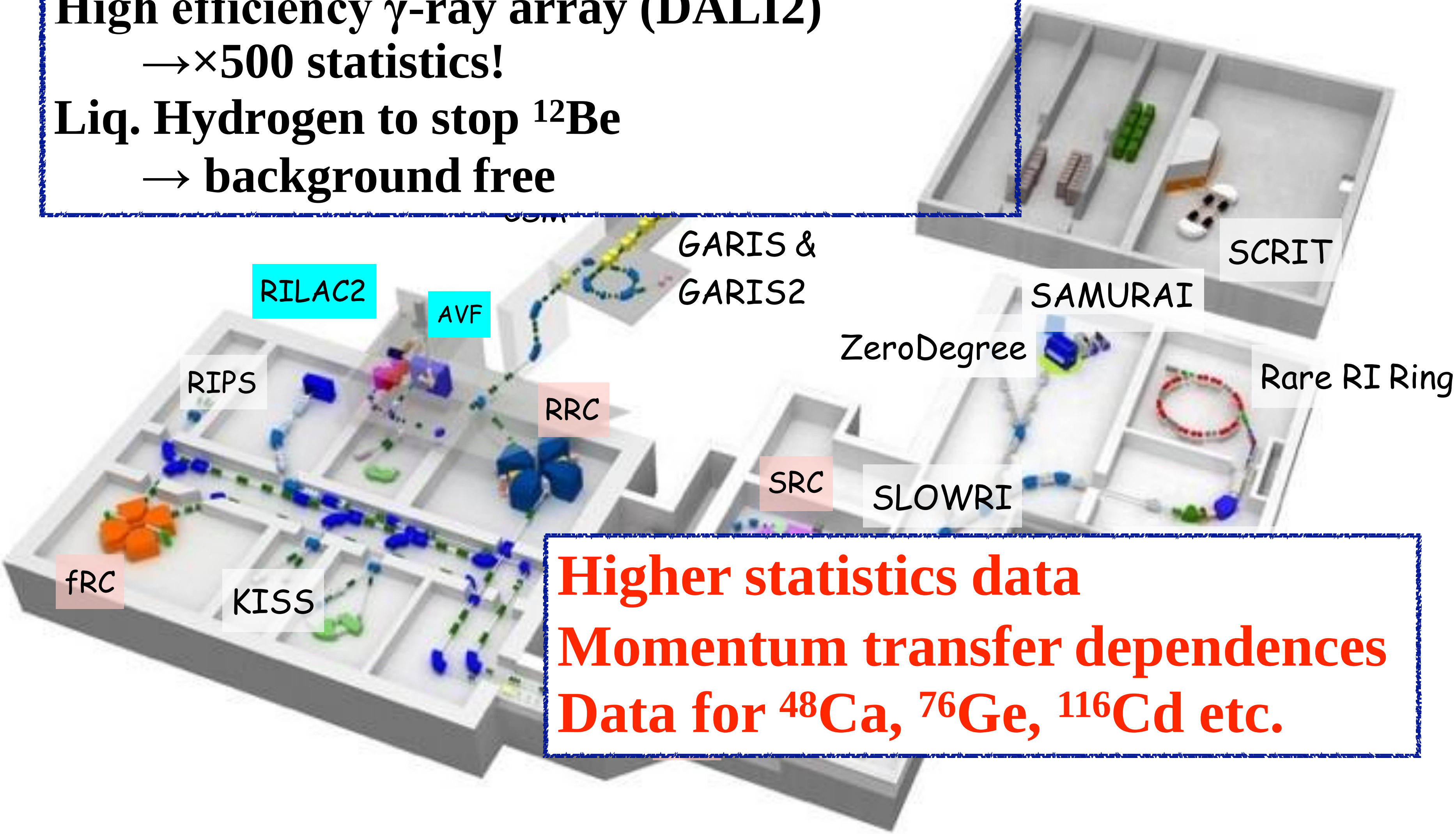
Structures at 17.4 MeV, 30 MeV and higher excitation energies.

Candidate of DGTR

➔Applications to other $\beta\beta$-decay nuclei

Future experiment @RI Beam Factory, RIKEN

High intensity 200 A MeV ^{12}C beam (<1pμA)
High efficiency γ-ray array (DALI2)
→×500 statistics!
Liq. Hydrogen to stop ^{12}Be
→ background free



Higher statistics data
Momentum transfer dependences
Data for ^{48}Ca, ^{76}Ge, ^{116}Cd etc.

2. Tetra-neutron

~ DCX with RI beam
…exothermic reaction ~

Historical Review

~ search for a bound state of 4n~

1960s

fission of Uranium

- No evidence for particle stable state of tetra-neutron

J. P. Shiffer Phys. Lett. 5, 4, 292 (1963)

1980s

$^4He(\pi^-, \pi^+)$ reaction

- Only upper limit of cross section was decided.

J. E. Unger, et al., Phys. Lett. B 144, 333 (1984)

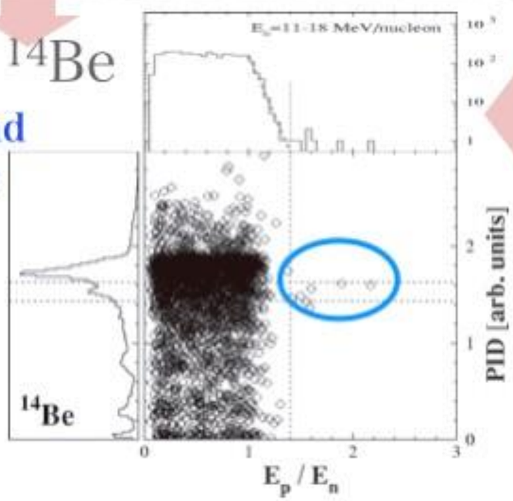
Bound state: No clear evidence.

2000s

Breakup of ^{14}Be

- Candidates of **bound tetra-neutron** were observed.

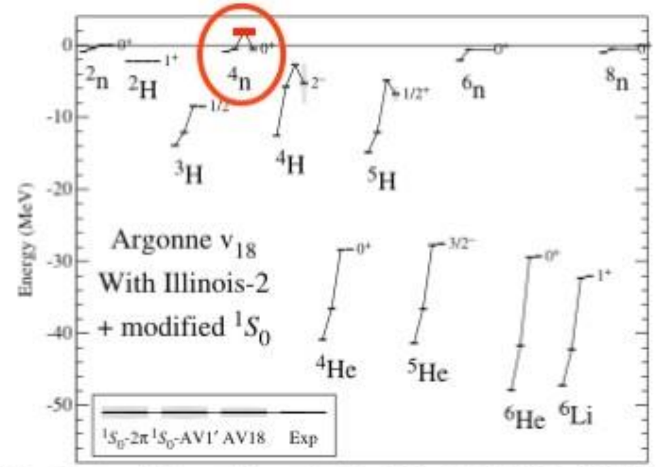
F. M. Marques, et al, Phys. Rev. C 65, 044006 (2002)



2000s

Theoretical work

- ab-initio calculation
  NN, NNN interaction

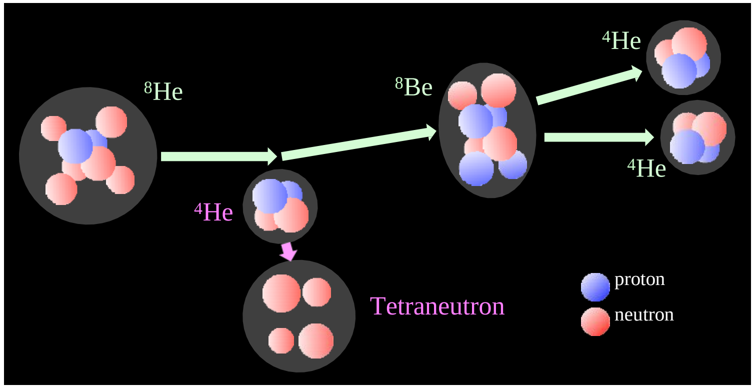


S. C. Piper, Phys. Rev. Lett. 90, 252501 (2003)

- **Bound ^4n cannot exist**
- **Possible resonance state ~2 MeV**

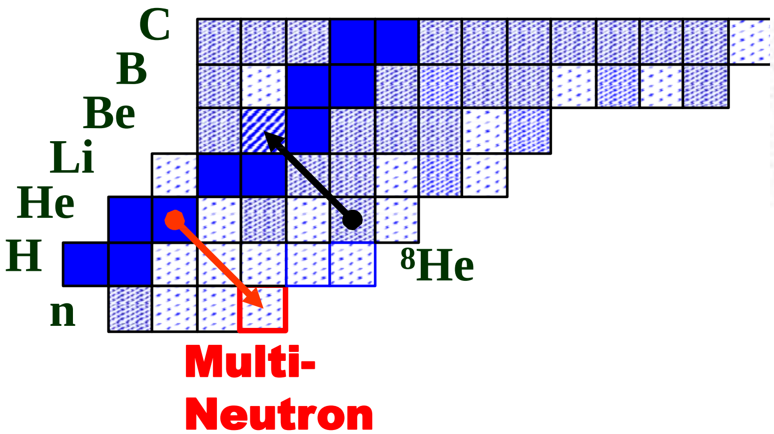
Resonance state : Possibility of the state is still an open and fascinating question.

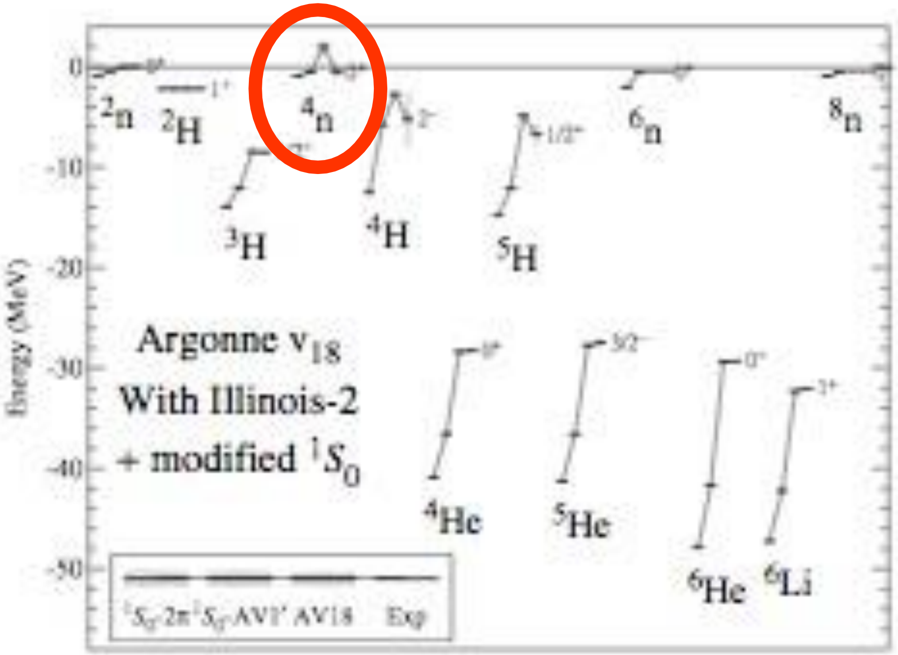
Tetra-neutron system produced by exothermic double-charge exchange reaction



Recoil-less 4n system via DCX using internal energy of ^{8}He

Almost recoil-less condition with ^{4}He(^{8}He,^{8}Be)4n reaction at 200 A MeV





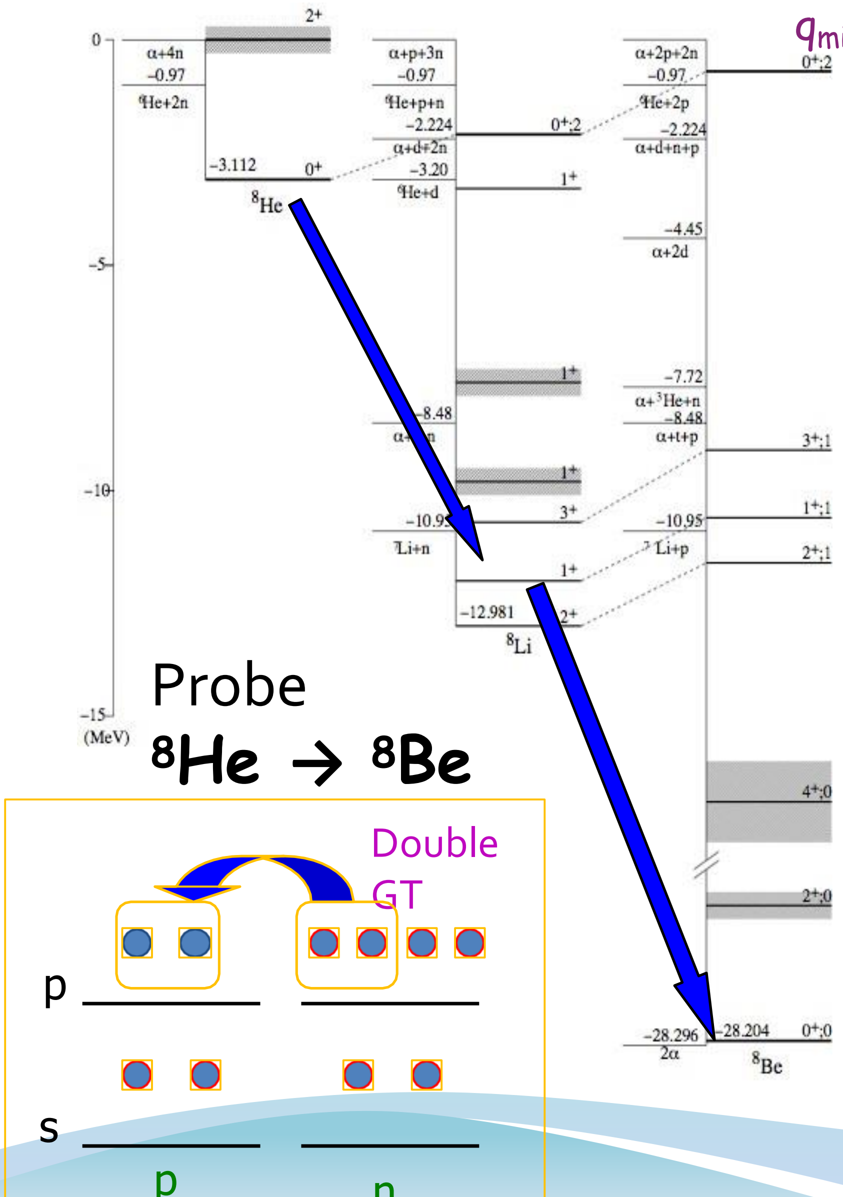
S.C. Pieper et al., PRL 90, 252501 (2003)

Level diagrams

$q_{min} \sim 10MeV/c$

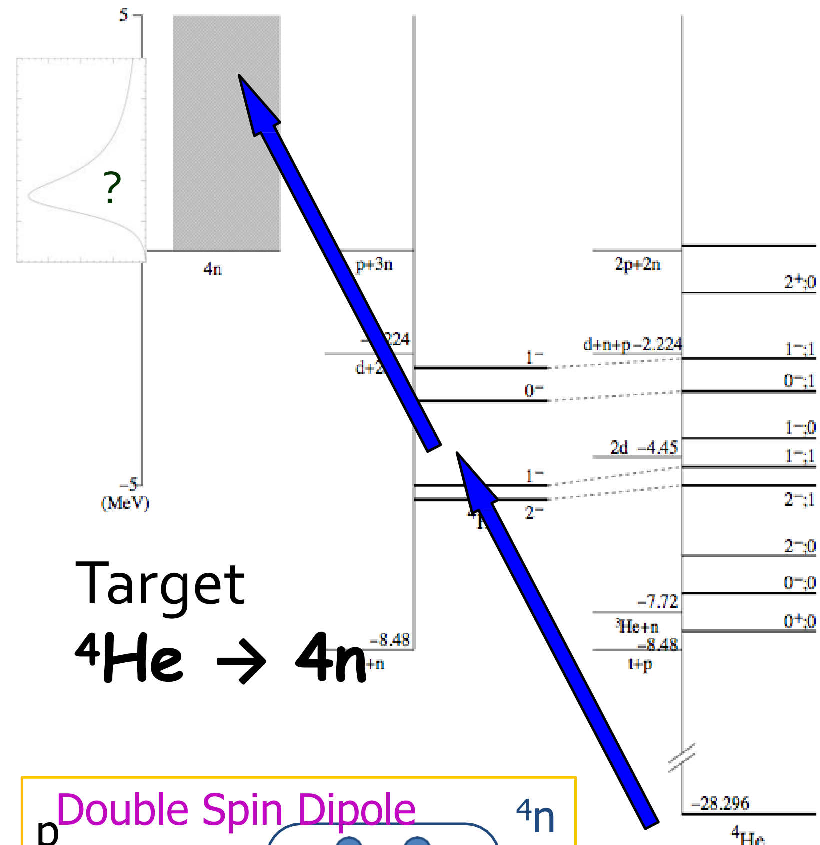
Probe

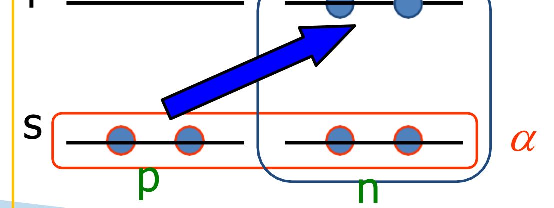
$^8He \rightarrow {}^8Be$



Target

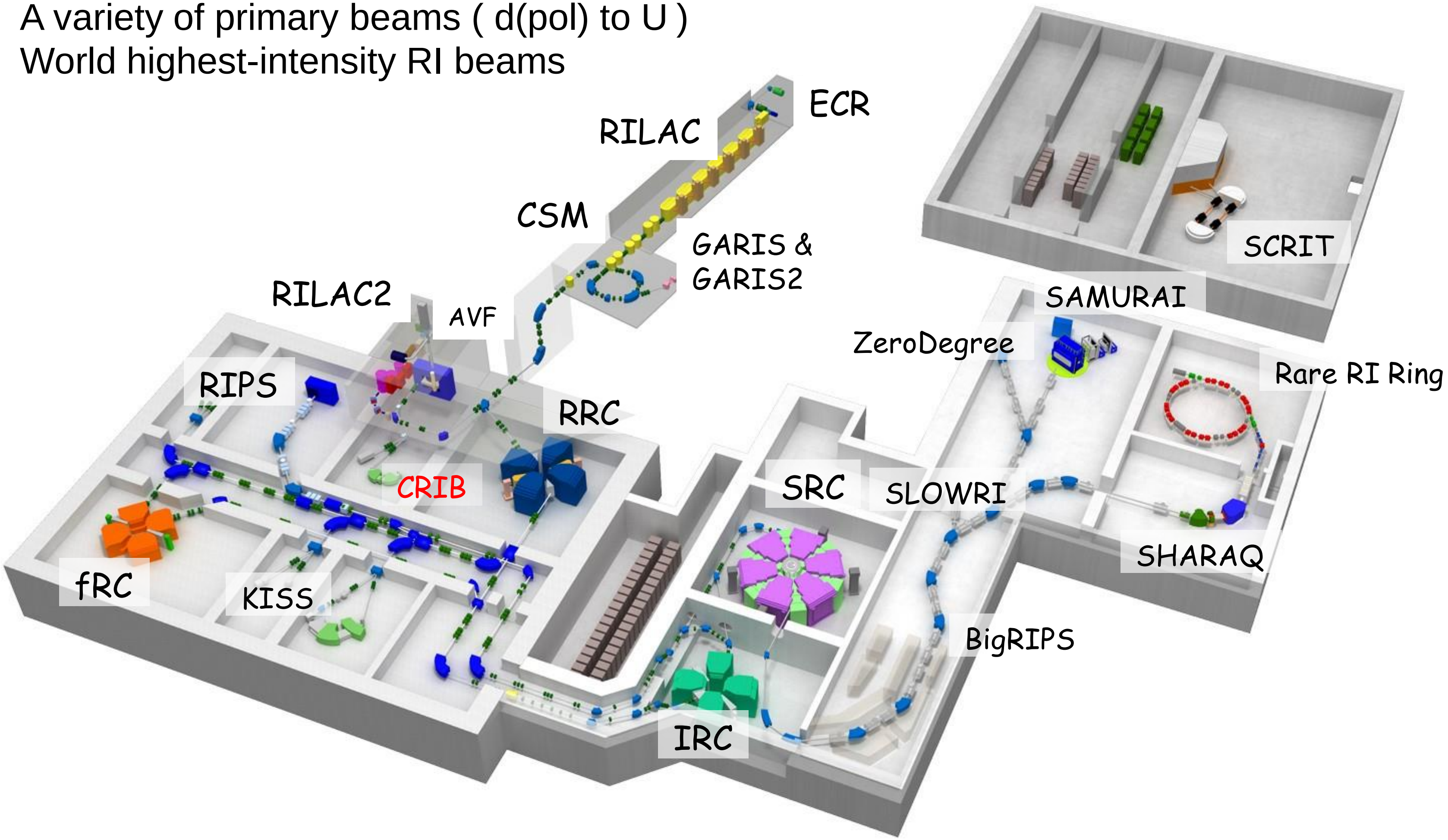
$^4He \rightarrow 4n$





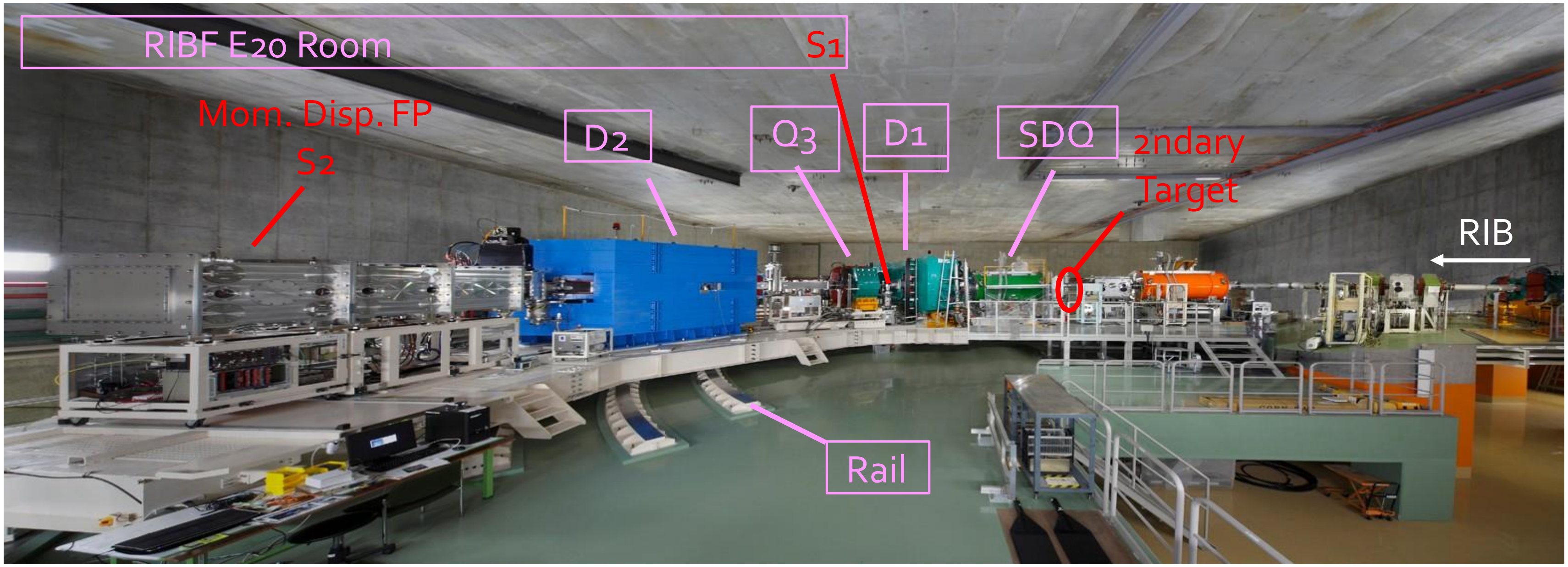
RI Beam Factory at RIKEN

3 injectors + cascade of 4 cyclotrons
~ several to 345 MeV/nucleon
A variety of primary beams (d(pol) to U)
World highest-intensity RI beams



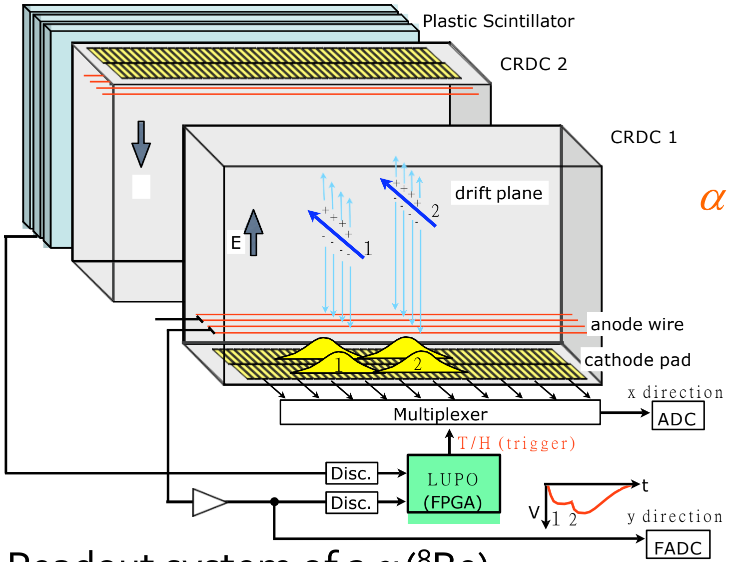
SHARAQ spectrometer

T. Uesaka et al.,
NIMB B **266** (2008) 4218.
PTEP 2012, 03C007 (2012)



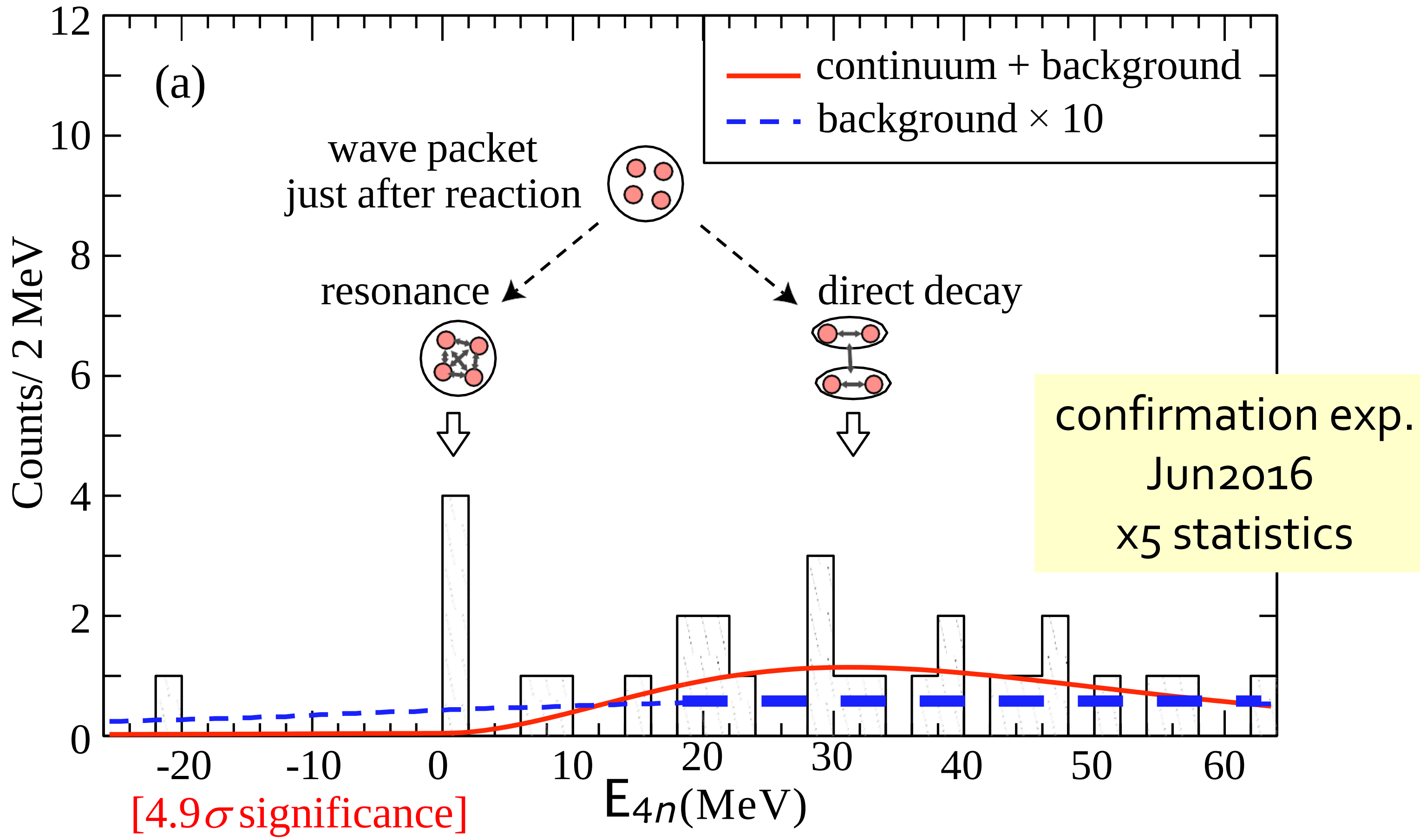
Maximum rigidity	**6.8 Tm**
Momentum resolution	**d*p*/*p* = 1/14700**
Angular resolution	**~ 1 mrad**
Momentum acceptance	**± 1%**
Angular acceptance	**~ 5 msr**

ICHOR



Readout system of 2α (^{8}Be)

Results



A possible resonance at 0.83 ± 0.65(stat.) ± 1.25(sys.) MeV with width < 2.6 MeV.

Integ. cross section θ_{cm}< 5.4deg: $3.8^{+2.9}_{-1.8}$ nb

Strong attractive 3-body force in T=3/2 system?: Lazauskas PTEP 2017, 073D03

Summary of part2

- $^{4}He(^{8}He,^{8}Be)4n$ was measured at 190 A MeV at RIBF-SHARAQ.
- Missing mass spectrum with few background
- Although statistics is low (27 evs), spectrum looks two components (continuum + peak).
- Continuum is consistent with direct breakup process from $(0s)^2(0p)^2$ wave packet.
- Four events just above 4n threshold is statistically beyond prediction of continuum + background (4.9 σ significance)

  → candidate of 4n resonance

  at $0.83 \pm 0.65(stat.) \pm 1.25(sys.)$ MeV; $\Gamma < 2.6$ MeV
- New experiment was done in June 2016.

Final words

- Double charge exchange reactions give us new opportunities to study nuclear structure.
- Two examples from Japan were introduced:
  - $^{48}Ca(^{12}C,^{12}Be(0^+_2))$ -> seeing *something* … candidate of DGTGR?
  - $^{4}He(^{8}He,^{8}Be)4n$ -> candidate of 4n resonance
- Reaction mechanism is considerably more complicated than single chargeX
  -> help from theorists is important.
  Data for establishing proportionality?