Study of Gd(n,γ) reaction and γ rays from giant resonances of ^{12}C and ^{16}O

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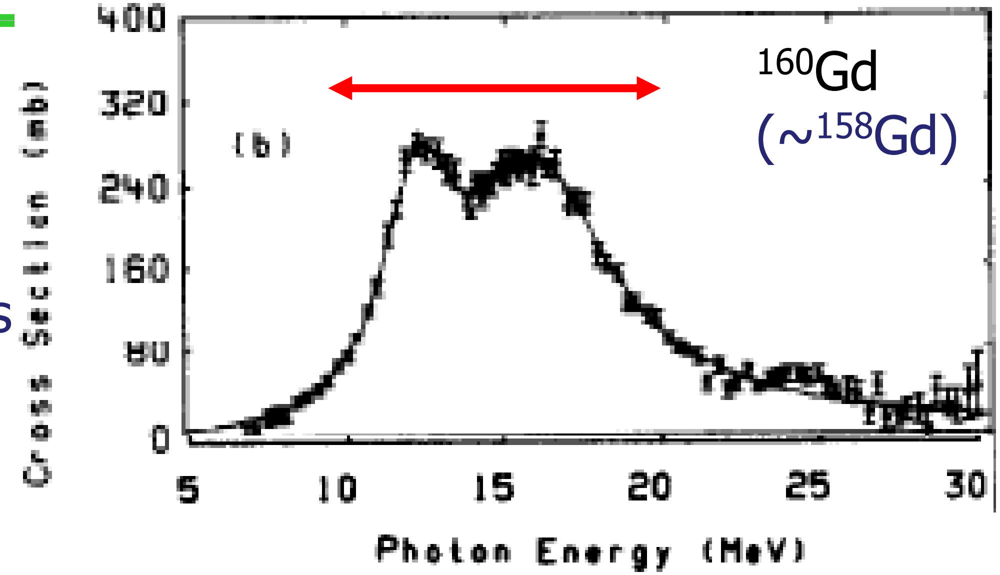
Outline:

1. γ-ray spectrum of Gd(n,γ) and ANNRI-Gd model for SK-Gd project
2. γ rays from giant resonances of ^{12}C and ^{16}O
3. Evaluation of O,C(ν,ν'γ) events for SN neutrinos (10kpc)
4. Summary

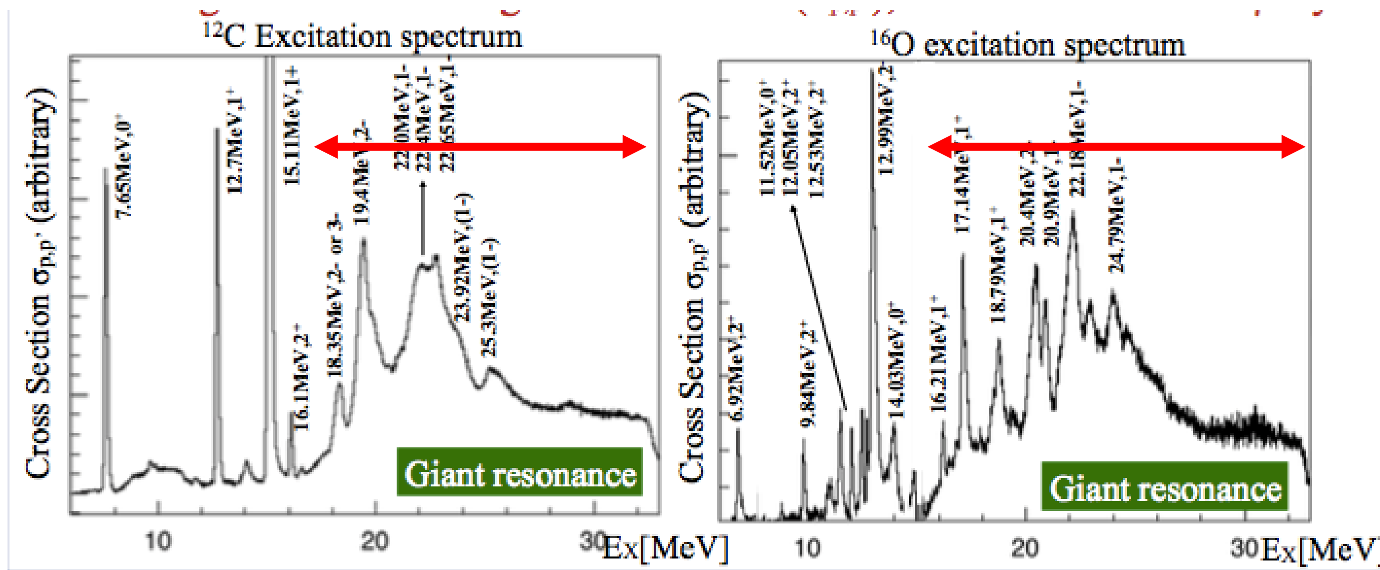
Giant Resonances (GR)

and γ rays from resonances ^{158,156}Gd, ^{12}C and ^{16}O.

- ^{160}Gd resonance seen in photo-absorption=Photon Strength Function f(E_γ) (PSF).
  -We study ^{157}Gd(n,γ)^{158}Gd and γ rays from ^{158}Gd.



- ^{12}C and ^{16}O GR in (p,p') reaction



1. Study of γ rays from $^{157,155,nat}Gd(n,\gamma)$ reaction and MC (ANNRI-Gd) Model for SK-Gd project

- We performed a series of measurements of $Gd(n,\gamma)$ reactions using high intensity pulsed neutron beam and ANNRI Germanium spectrometer.

1. γ-ray spectrum from thermal neutron capture on ^{157}Gd,
   K. Hagiwara, T. Yano, T. Tanaka, M.S. Reen, P.K. Das, S. Lorenz, I. Ou, T. Sudo, Y. Yamada, T. Mori, T. Kayano, R. Dhir, Y. Koshio, M. Sakuda, A. Kimura, S. Nakamura, N. Iwamoto, H. Harada, M. Wurm, W. Focillon, M. Gonin, A. Ali and G. Collazuol (ANNRI-Gd), PTEP 2019, 023D01 (29pages).

2. γ-ray spectrum from $^{155,\,nat}Gd(n,\gamma)$,
   A.Ali et al. (ANNRI-Gd), PoS (ICHEP2018) 120 (4 pages), in preparation for PTEP.

3. 2γ angular correlations in $^{155,\,157}Gd(n,\gamma)$ reaction

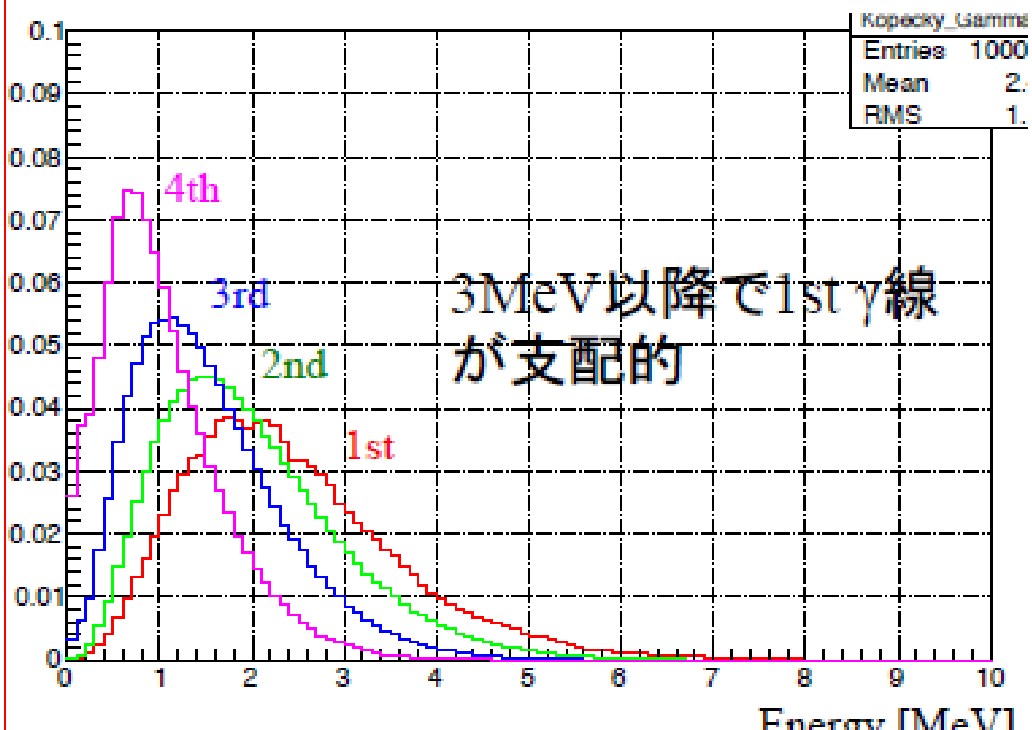
- β-version of MC (ANNRI-Gd) model is already being used in SK-Gd, XENONnT and NEOS (IBS, Korea).

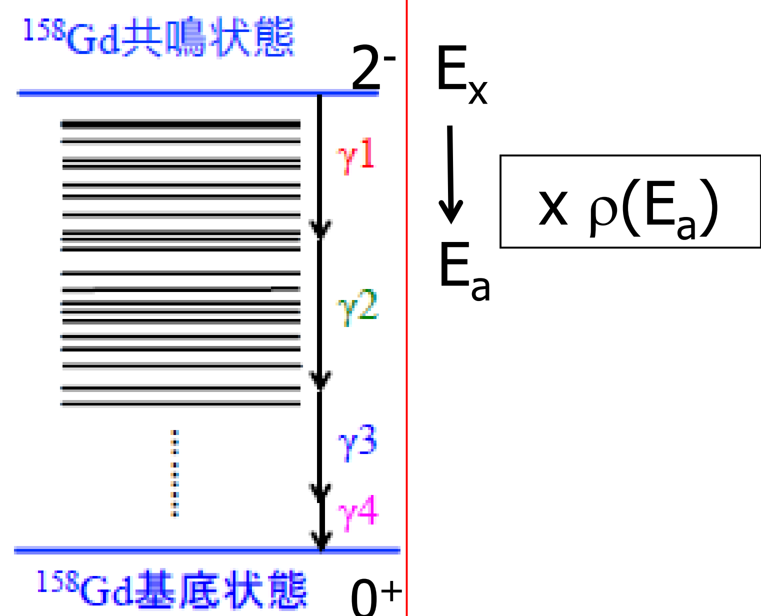
1. Feature of γ-ray spectrum from ^{157,155}Gd(n,γ)

- ~4γ rays/event (E_{tot}=8MeV)-

- Probability Distribution from $E_x \rightarrow E_a = E_x - E_\gamma$
  - ✓ Fermi Golden Rule: Probability=|Amptilude|^2*(Number of States)
  - ✓ $E_\gamma{}^3$ favors Large E_γ, $f(E_\gamma)$ favors Large E_γ, But $\rho(E_a)$ favors Very Small E_γ.

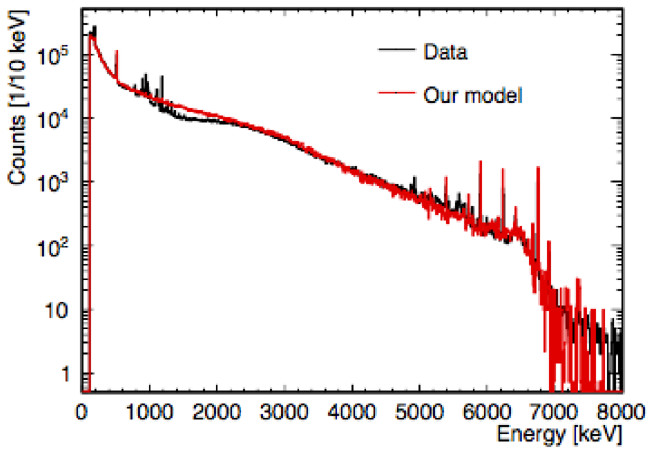
$$P(E_\gamma, E_x) = \frac{E_\gamma^3 f(E_\gamma)\rho(E_x - E_\gamma)}{\int_0^{Ex} E_\gamma^3 f(E_\gamma)\rho(E_x - E_\gamma)\mathrm{d}E_\gamma}$$

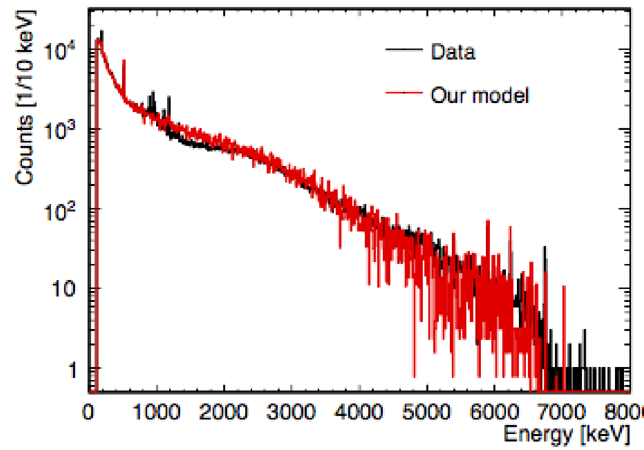




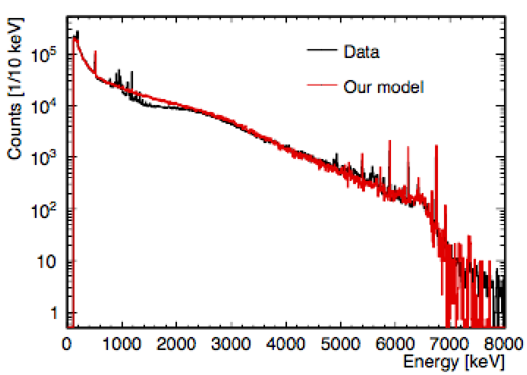
1-1) ^{157,155}Gd(n,γ) Eγ spectrum (Data) and MC(ANNRI-Gd model), Tested for multiplicity=1,2,3,4.

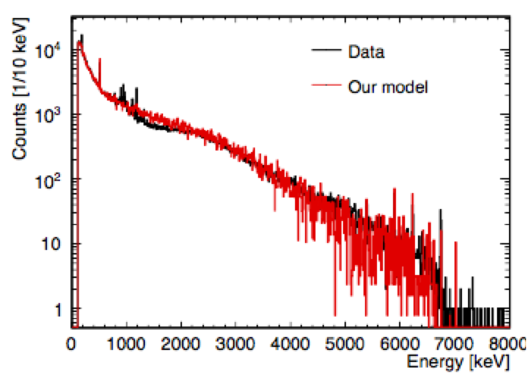
- ^{157}Gd(n,γ) Eγ (single) spectrum ^{155}Gd(n,γ) Eγ spectrum

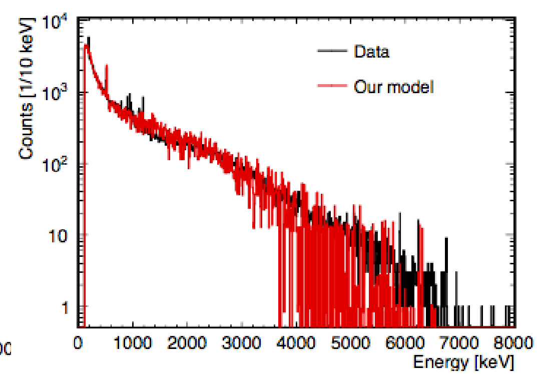




- ^{157}Gd(n,γ) Multiplicity=2,3,4 Eγ spectrum







- Data and MC in reasonable agreement.

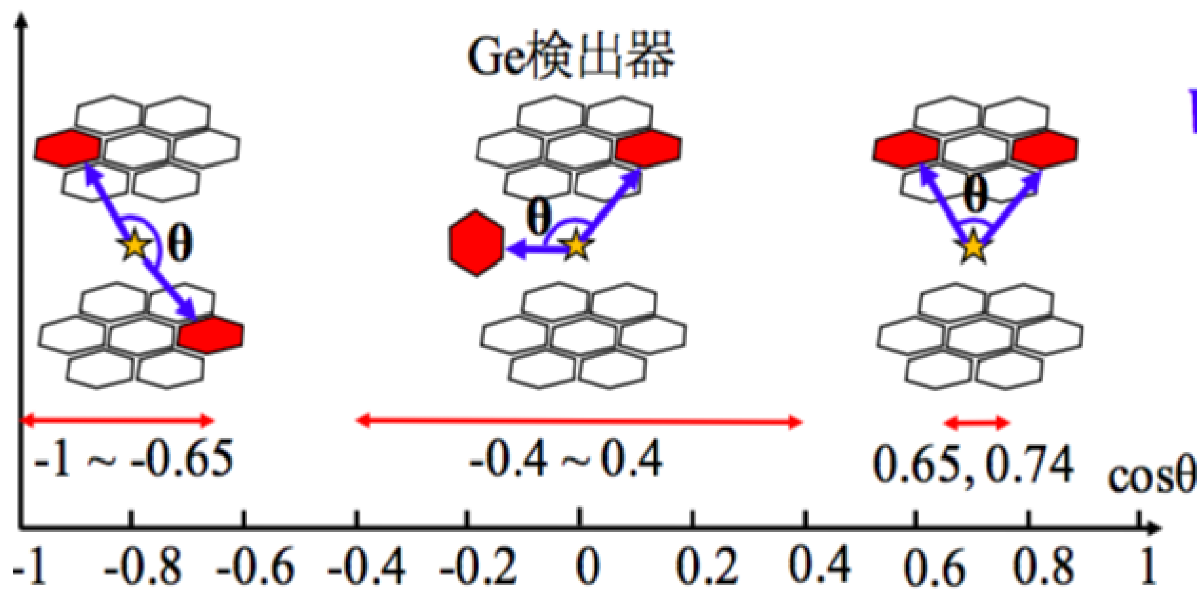
1-2) γ–γ angular correlation W(z) in ^{157,155}Gd(n,γ) (p6

- The definition of angular correlation W(z) for z=cosθ=[-1,1].
  - ✓ Select 2 γ–ray dataset (E_1 and E_2) and make z distribution.

$$N_{ij} = N_0\, \varepsilon_i(E_1)\, \varepsilon_j(E_2)\, W(Z)$$

(Z = cosθ)

$$W(Z) \propto \frac{N_{ij}}{\varepsilon_i(E_1)\varepsilon_j(E_2)}$$

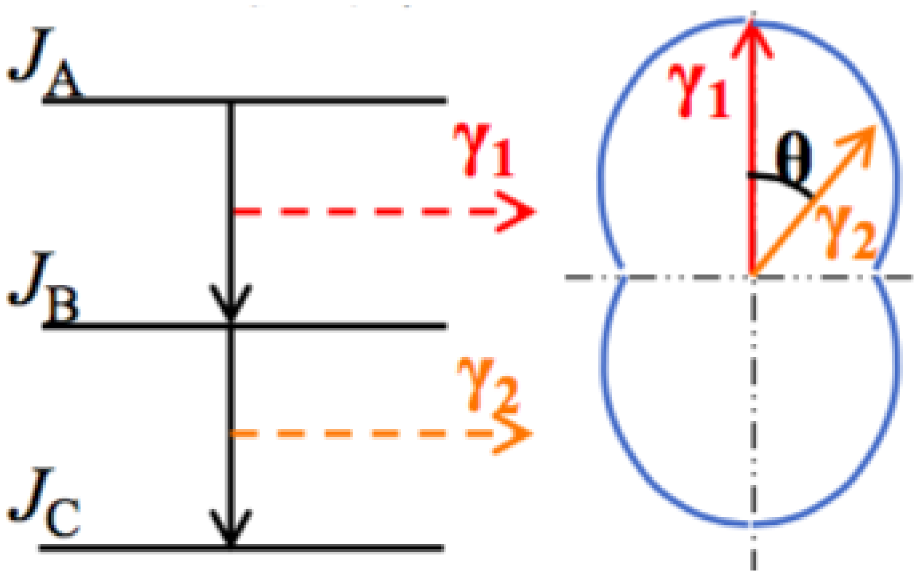


1-2) Angular correlation W(z) of 2 γ rays in cascade ($J_A \rightarrow J_B \rightarrow J_C$), z=cos$\theta$ (skip-7)

- For the angular momentum (j,m) of γ_1 in z-direction, only L=0 and m=+1 and -1 are allowed. Thus, the weight p(M) on M of (J,M) for γ_2 is restricted. Then, W(z) is not uniform.

$$W(\theta) \propto \sum_M p(M) \left| X_{JM}(\theta,\phi) \right|^2$$

$$\frac{dP}{d\Omega} \propto \left| \vec{X}_{JM}(\theta,\phi) \right|^2$$

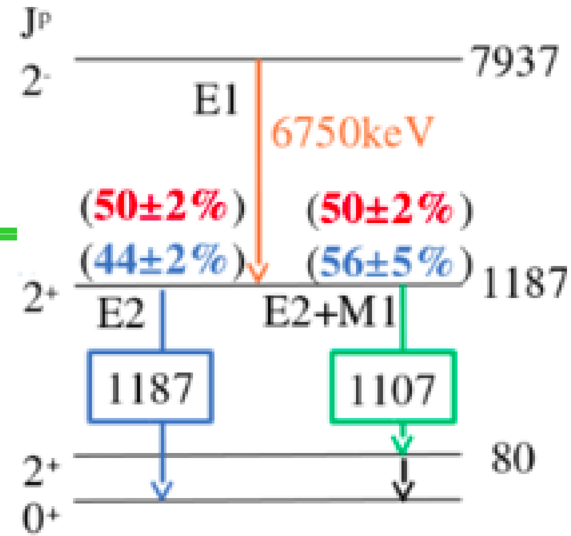


- BUT, If p(M)=1 for all M, W(z)=uniform, because

$$\sum_M \left| \vec{X}_{JM}(\theta,\phi) \right|^2 = \frac{2J+1}{4\pi}$$

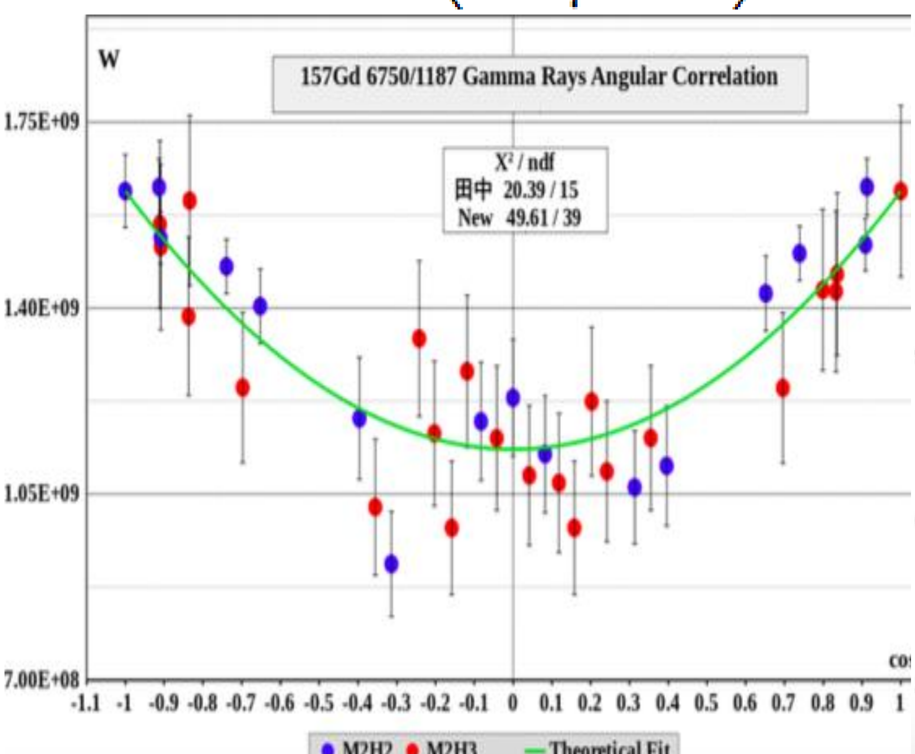
Angular correlation of 2γ rays for ^{157}Gd(n,γ) (specially chosen) cascades

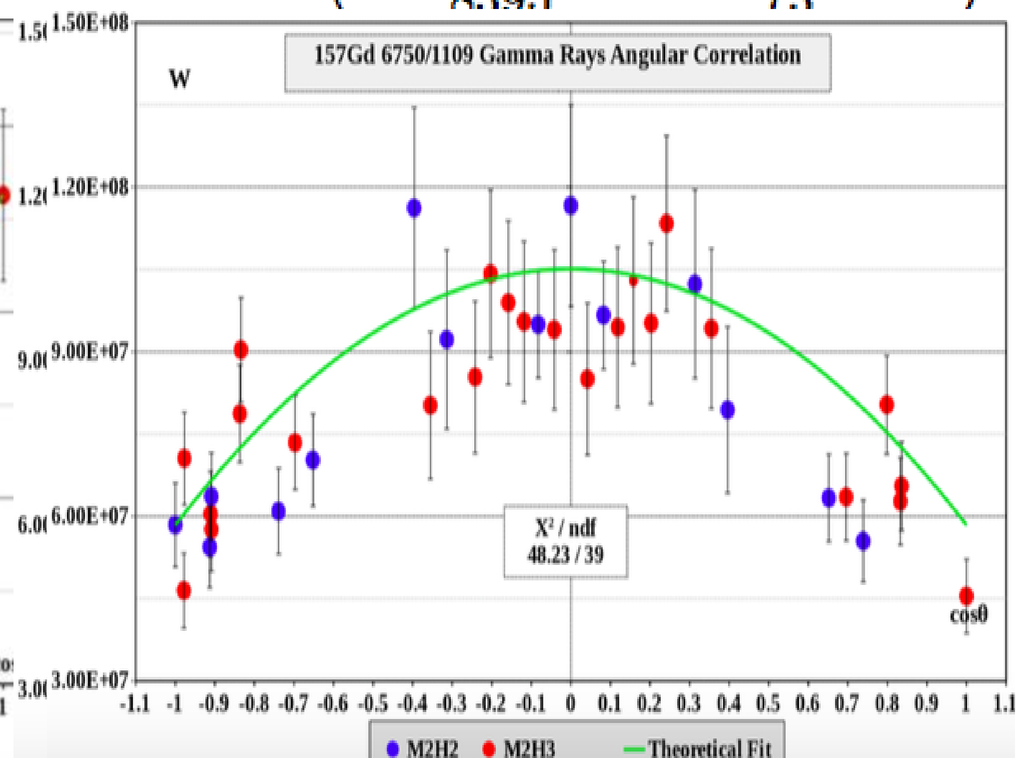
- We observe the expected angular correlations for $2^- \rightarrow 2^+ \rightarrow 0^+$ and $2^- \rightarrow 2^+ \rightarrow 2^+$ cascade transitions.



$$W(\theta) \propto \left(1 + \frac{3}{7}\cos^2\theta\right)$$

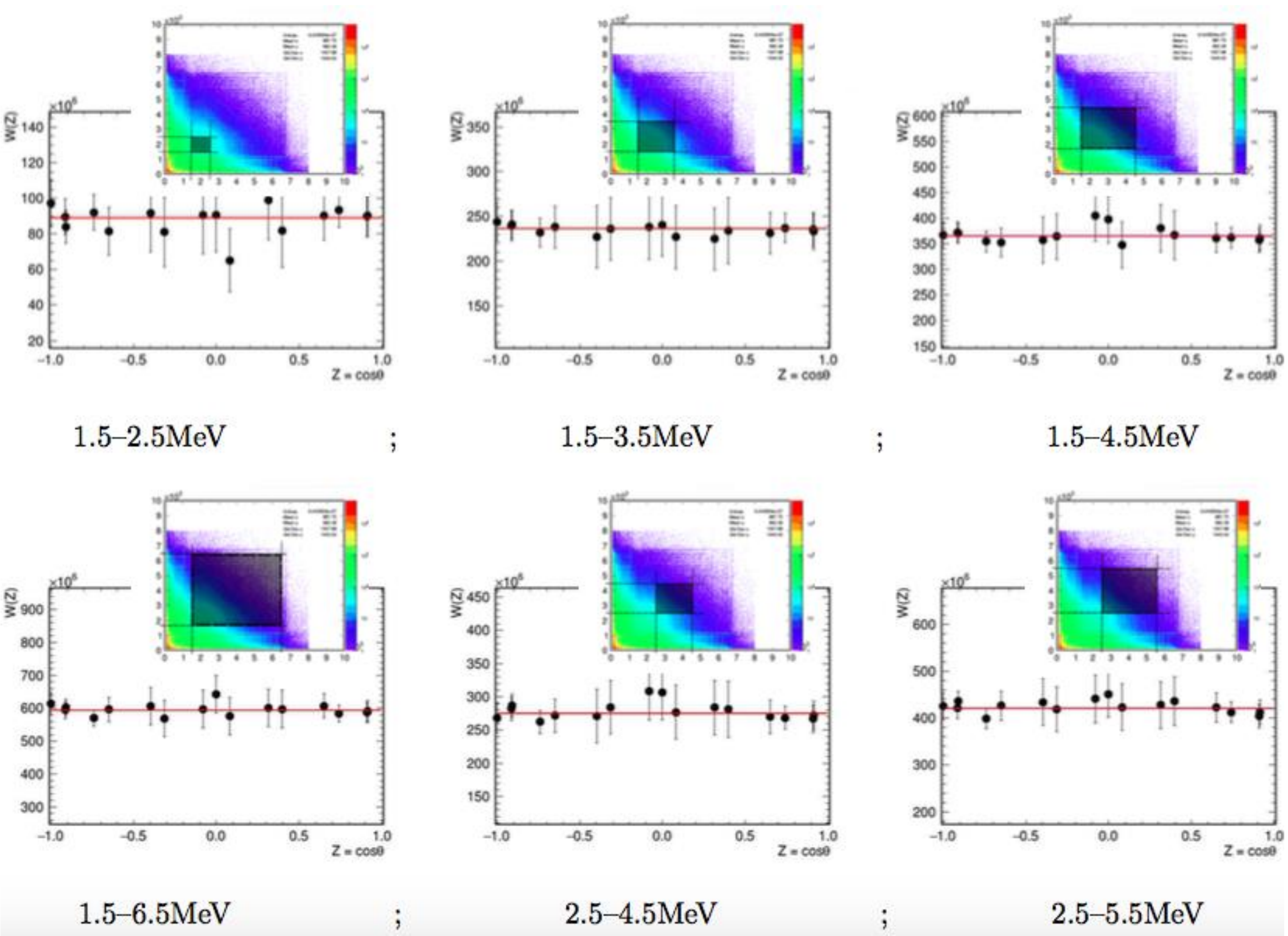
$$W(\theta) \propto \left(1 - \frac{3729}{8395}\cos^2\theta - \frac{21}{73}\cos^4\theta\right)$$





No angular correlations of 2 γ rays from continuum (bulk) of ^{157,155}Gd(n,γ)

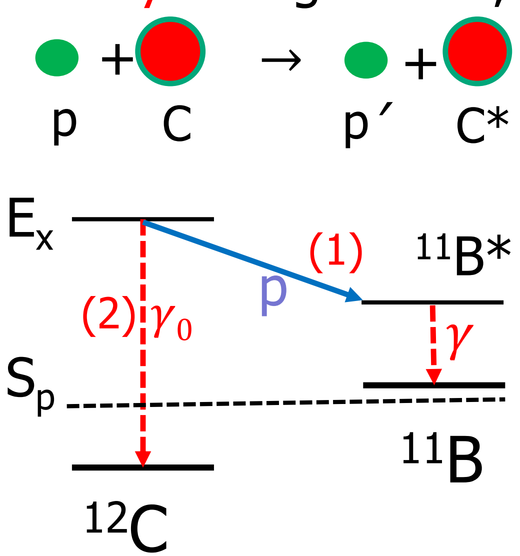
- We observe no correlations for bulk of 2γ rays from continuum.

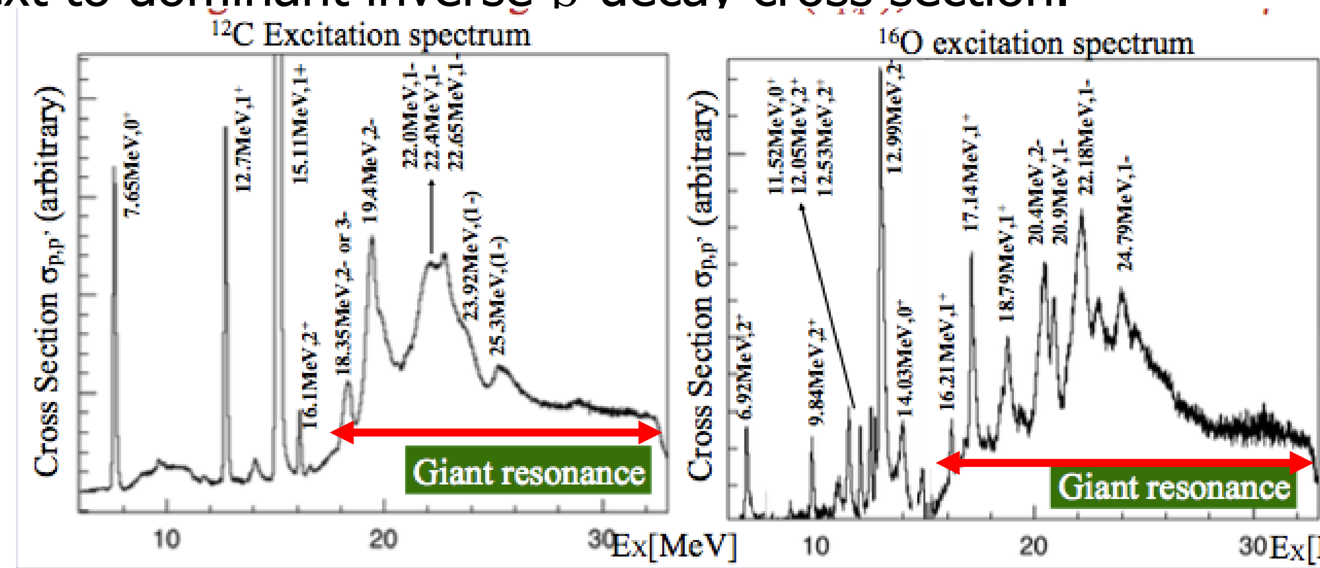


2. RCNP E398 $^{12}C,^{16}O(p,p'\gamma)$

-Study of γ emission rate $R_\gamma(E_x)$ from Giant Resonance-

- ^{12}C and ^{16}O are being used as a target material in large scale neutrino experiments, since they are abundant (cheap).
- [Nulcear Physics] No systematic measurements of γ rays from giant resonance region (E_x=16-35MeV).
  - (1) Hadronic decay
  - (2) Electromagnetic decay
- [Supernova Detection] Neutral-Current γ production cross sections ν-$^{12}C/^{16}O$ may be significant, next to dominant inverse β-decay cross section.





2-1) E398 Experiment at RCNP(Osaka)

- Magnetic Spectrometer (E_x) and NaI array (E) –

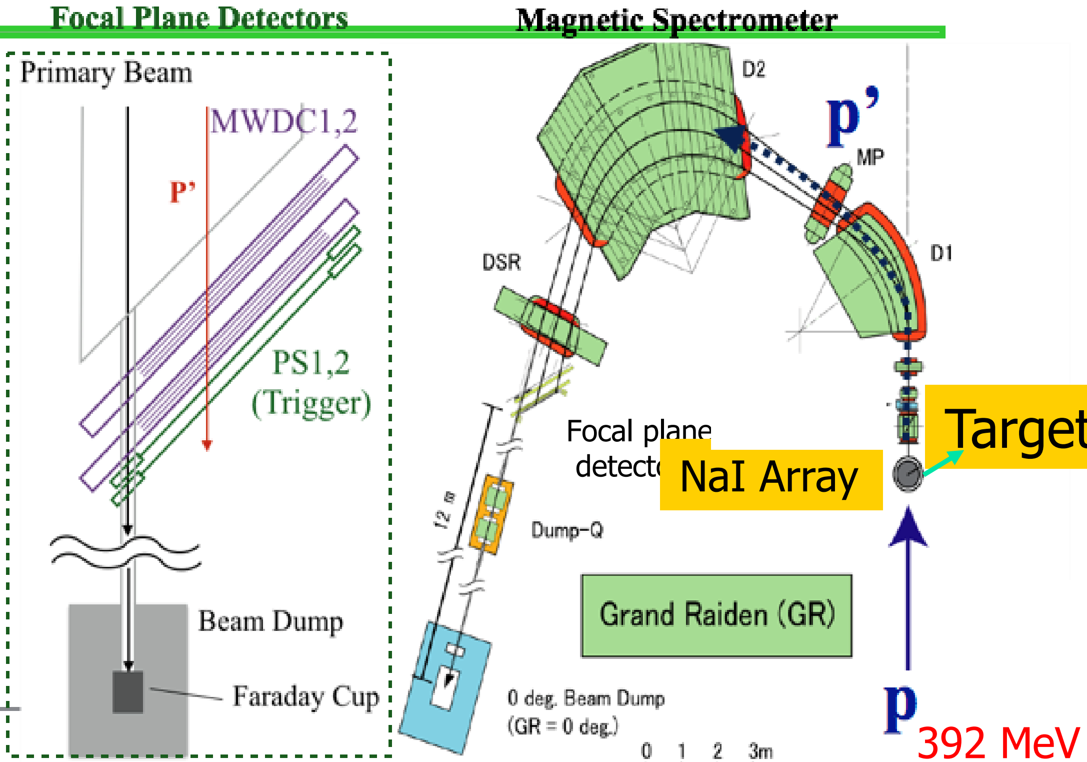
Excitation Energy

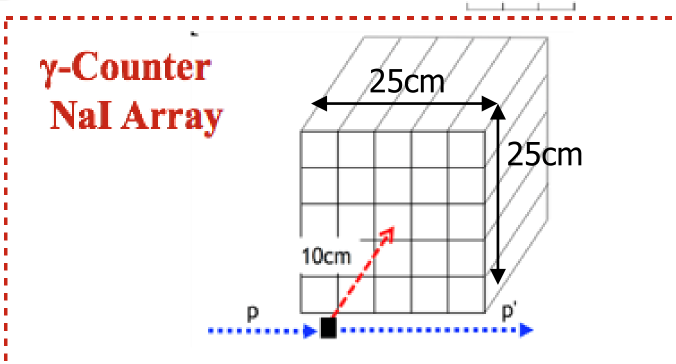
* Proton Beam: 392MeV, 0.5~1.5nA
* Target: ^{nat}C (36.3 mg/cm^2)
  $C_6H_{10}O_5$(Cellulose, 28.2mg/cm^2)
* Magnetic Spectrometer “**Grand Raiden**”

- Excitation energy $E_x = E_p - E_{p'}$
- ΔE_x = 100-200 keV
- θ_{scat} = 0°(covers 0°~3°)

γ-ray Energy

* γ-counter: NaI(Tl) ×25 Array
  - Solid Angle × Detection Efficiency ~ 6% @15.1MeV
  - NaI Array:25×25×15 cm, ΔE~2.7%@15.1MeV
  - Threshold : 1.5MeV, Time resolution : 5ns

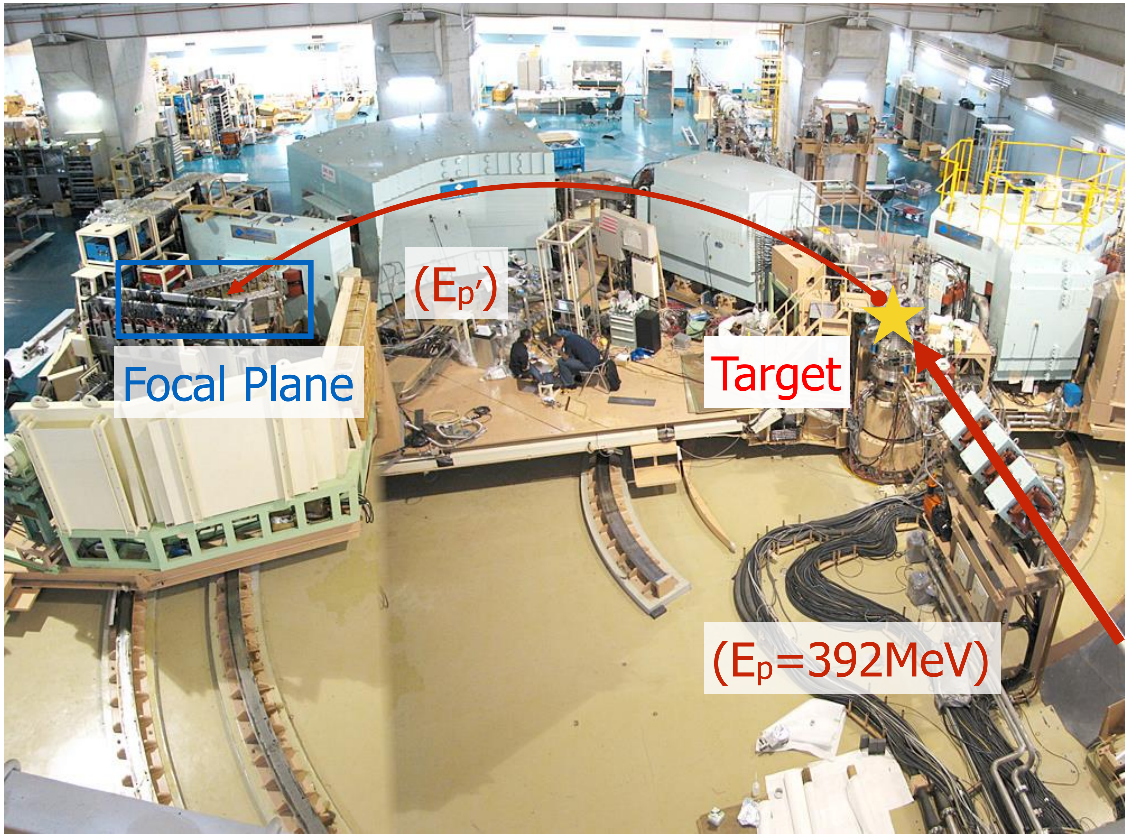




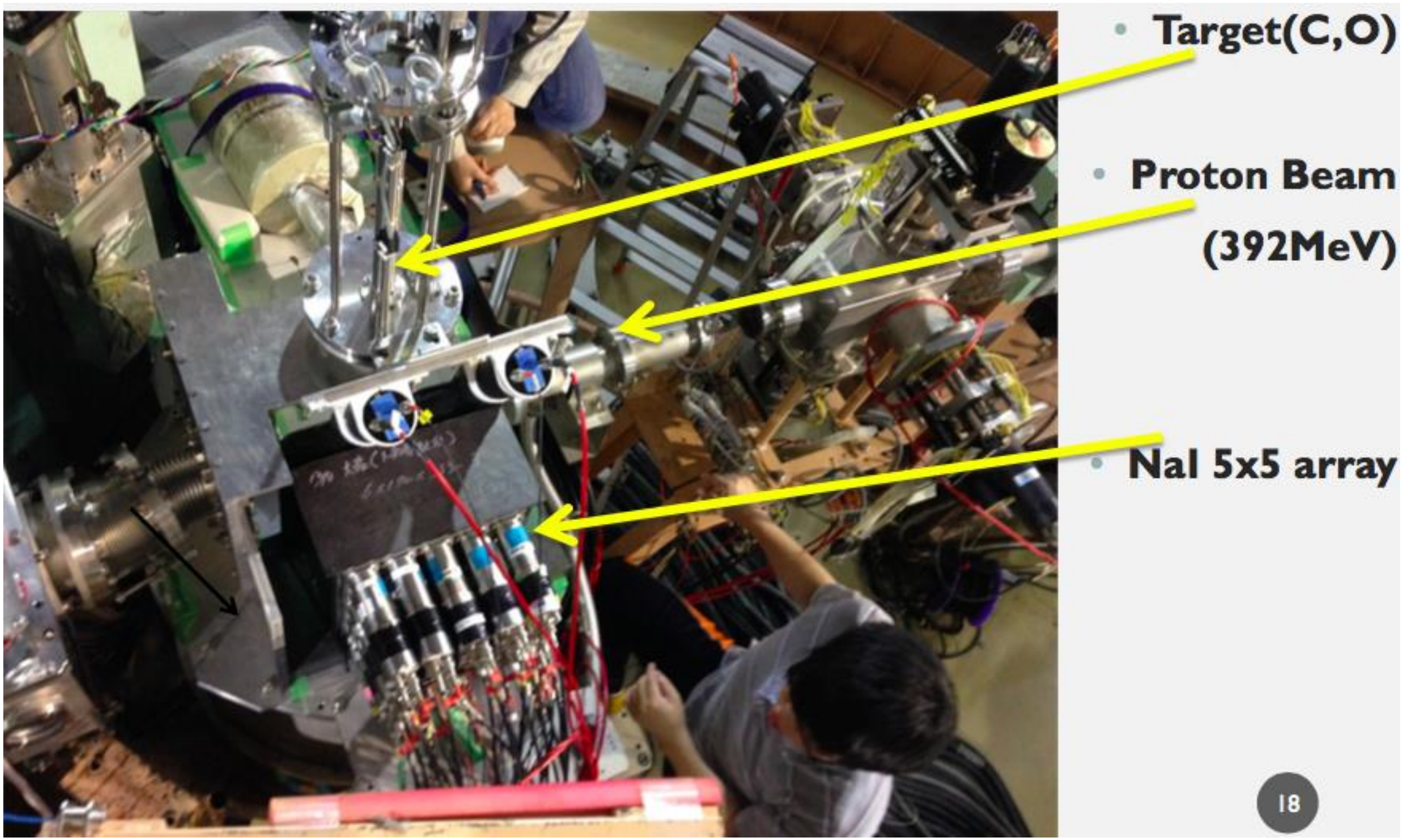
RCNP Magnetic Spectrometer "Grand Raiden"

- E_x = 392MeV - $E_{p'}$, ΔE_x=100keV -

Grand Raiden Spectrometer



γ ray detector(NaI)

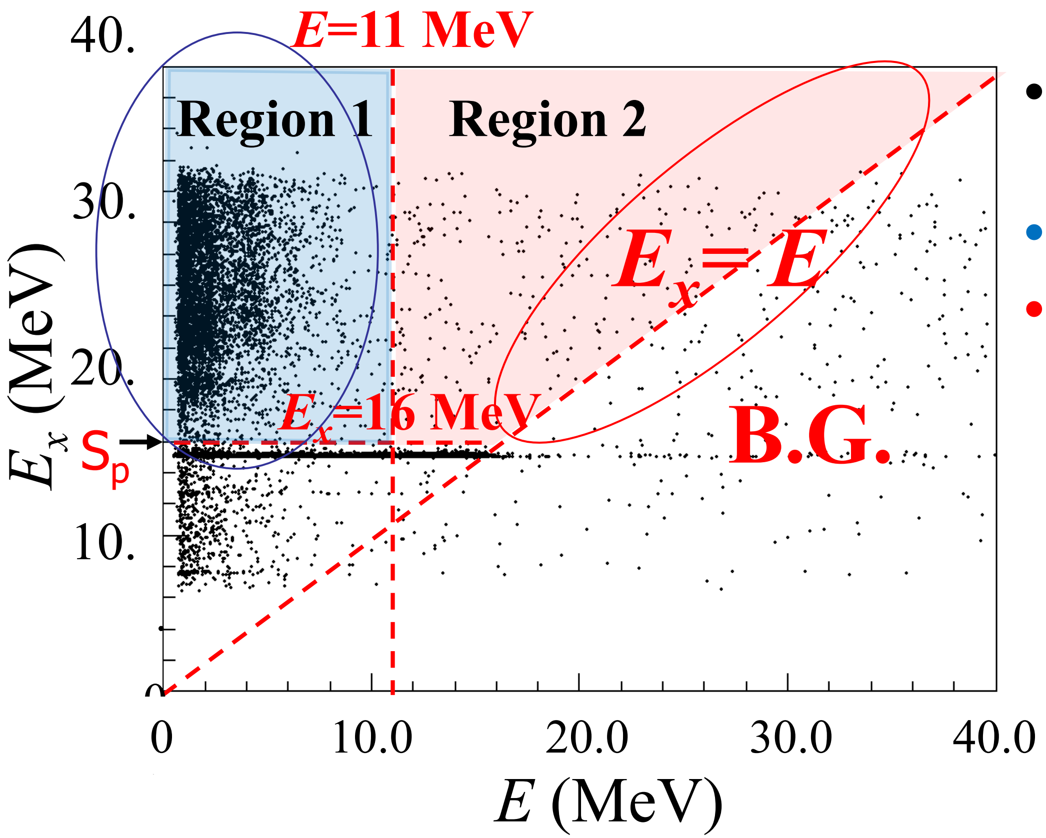


Analysis Method: E_x and E (NaI)

For each event, we measure:

(1) E_x (Excitation energy)

(2) E (γ-ray energy deposited in NaI detectors)

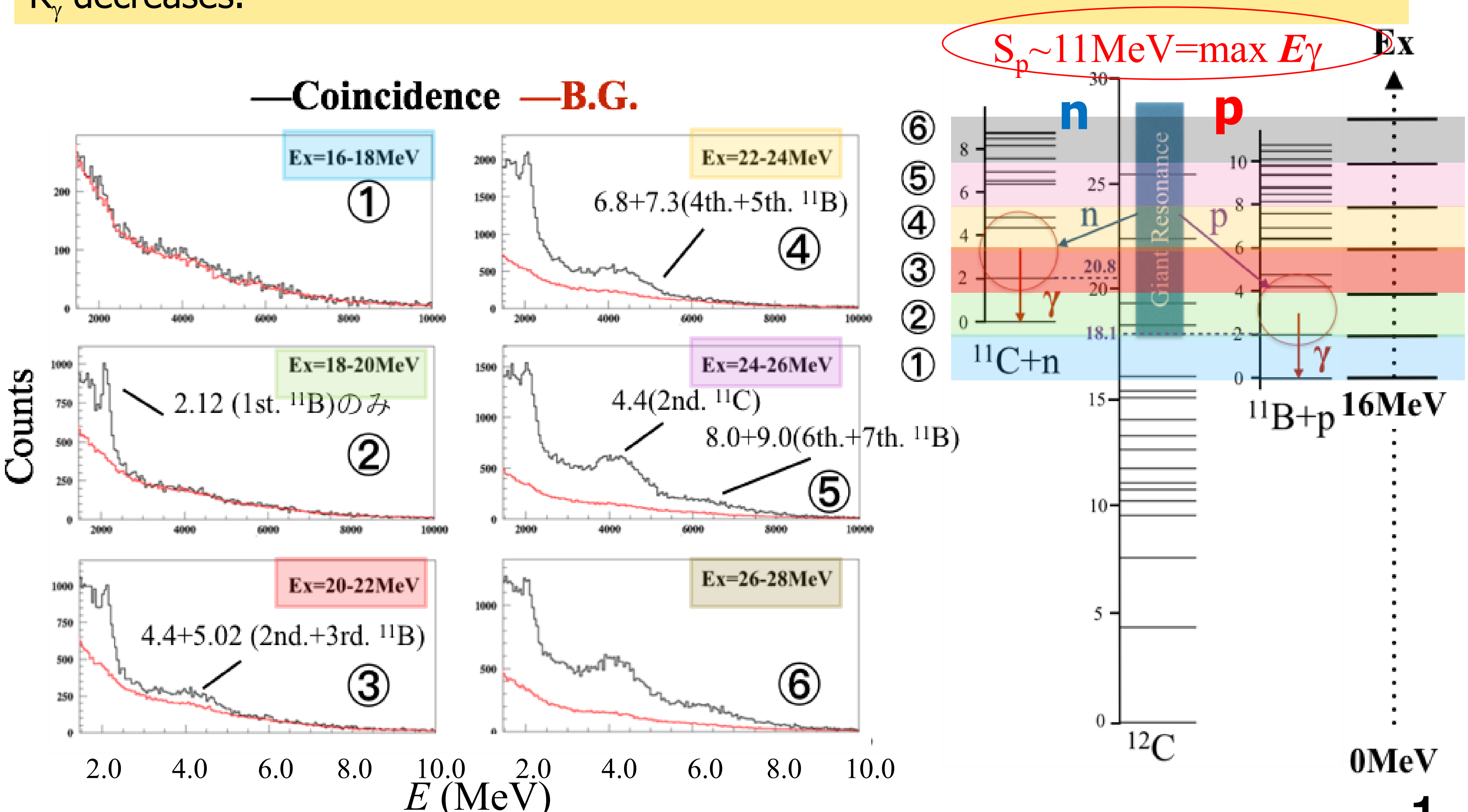


- E_x > 16 MeV:Giant resonance

- **Region 1** : Hadronic Decays
- **Region 2** : Electromagnetic Decays

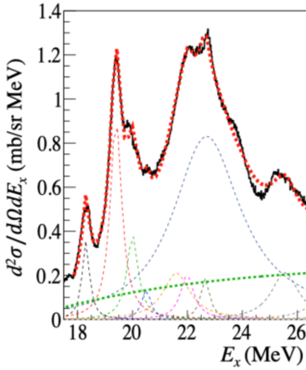
[Region 1] γ rays from hadronic decays

■ γ-rays are emitted from the excited states of ^{11}B and ^{11}C after hadronic decay. As E_x increases, R_γ increases. For E_x>27MeV, GR cross section becomes small and R_γ decreases.



γ-ray emission rate $R_\gamma(E_x)$ from hadronic decay

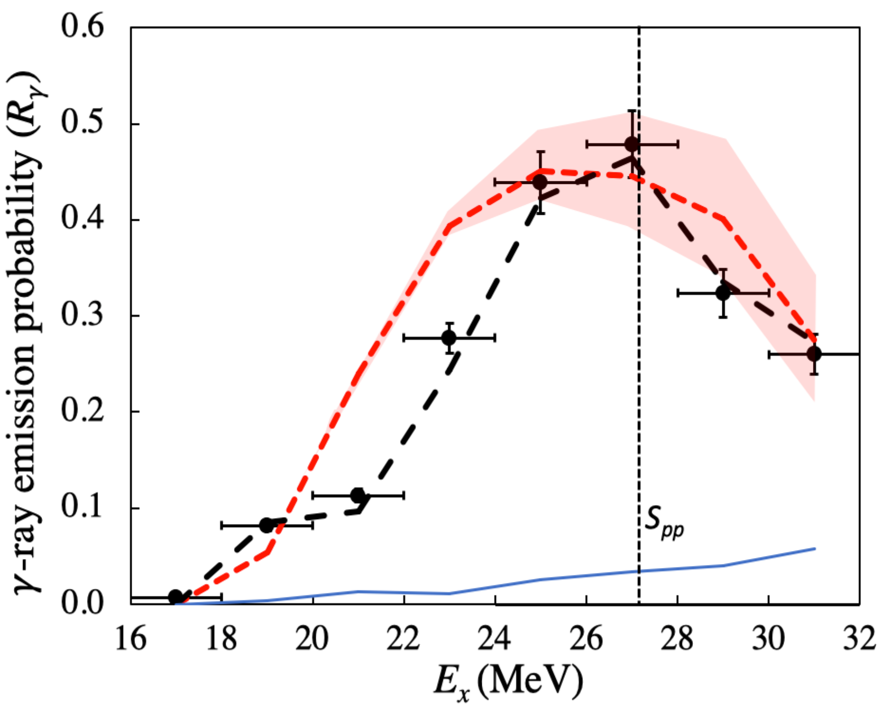
- R_γ~45% (^{12}C) and 60% (^{16}O) at max. -



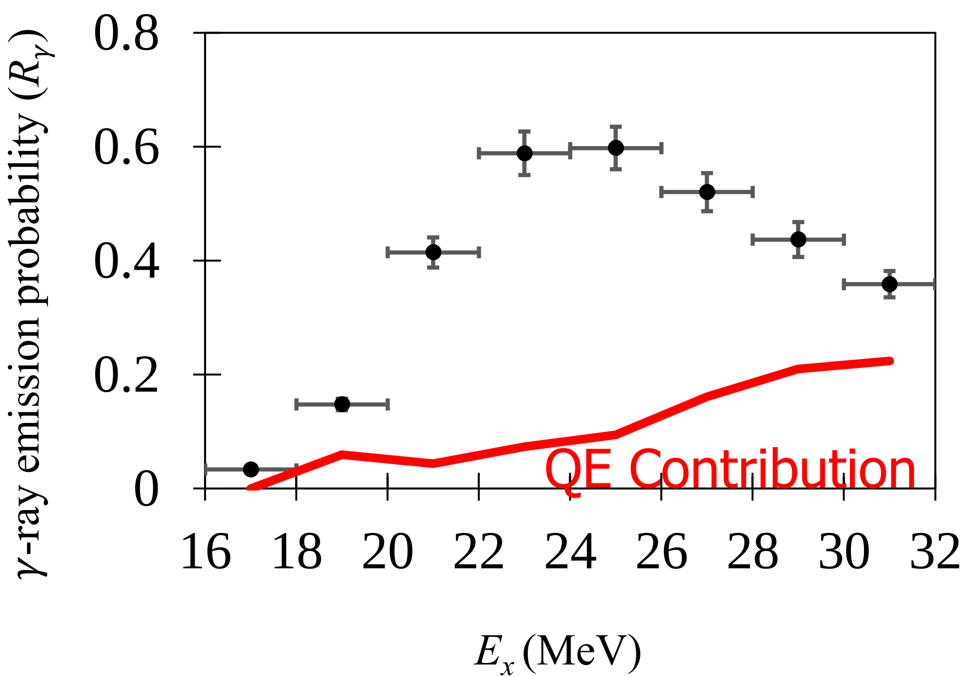
- Data (---) are lower by 20-30% than the simple transmission calculations using optical potential (---).

$$T(E_x \to a + (A,i)) = \sum_{S=|J_A^i - s_a|}^{J_A^i + s_a} \sum_{L=|J_x - S|}^{J_x + S} T_L^a(\epsilon_a),$$

^{12}C

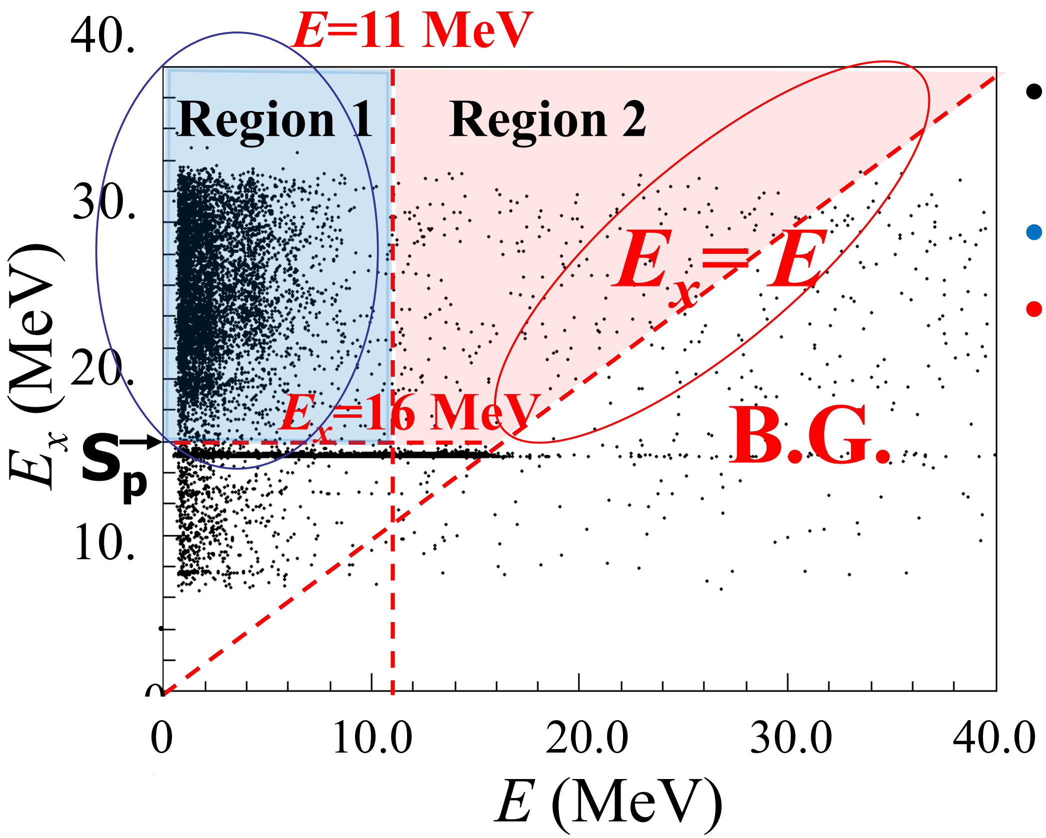


^{16}O



(Region 2): Search for Electromagnetic decays

-Make E_x-E plot -



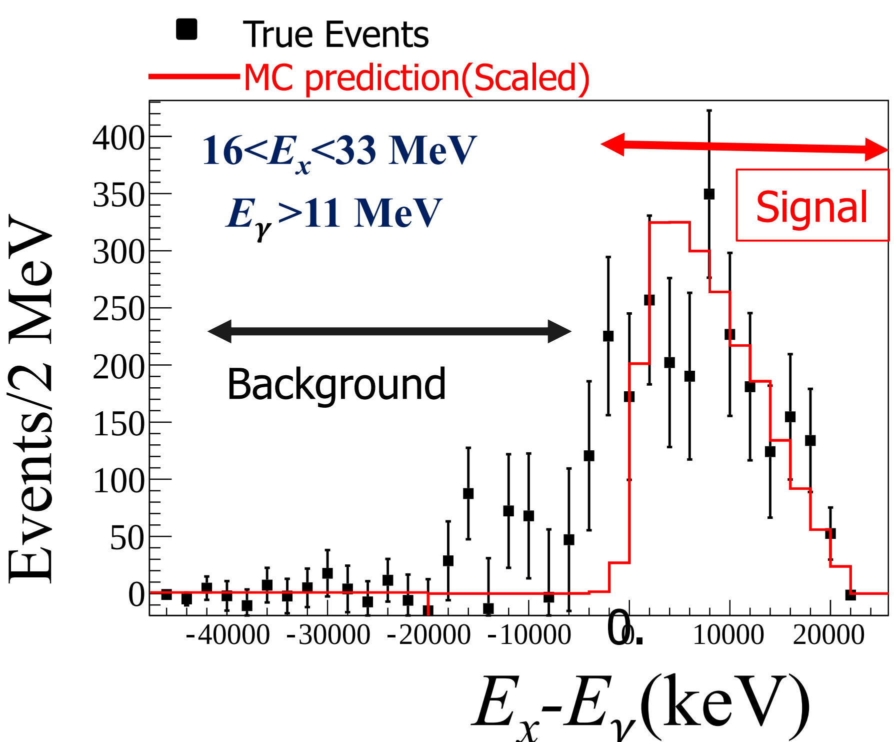
- E_x > 16 MeV:Giant resonance

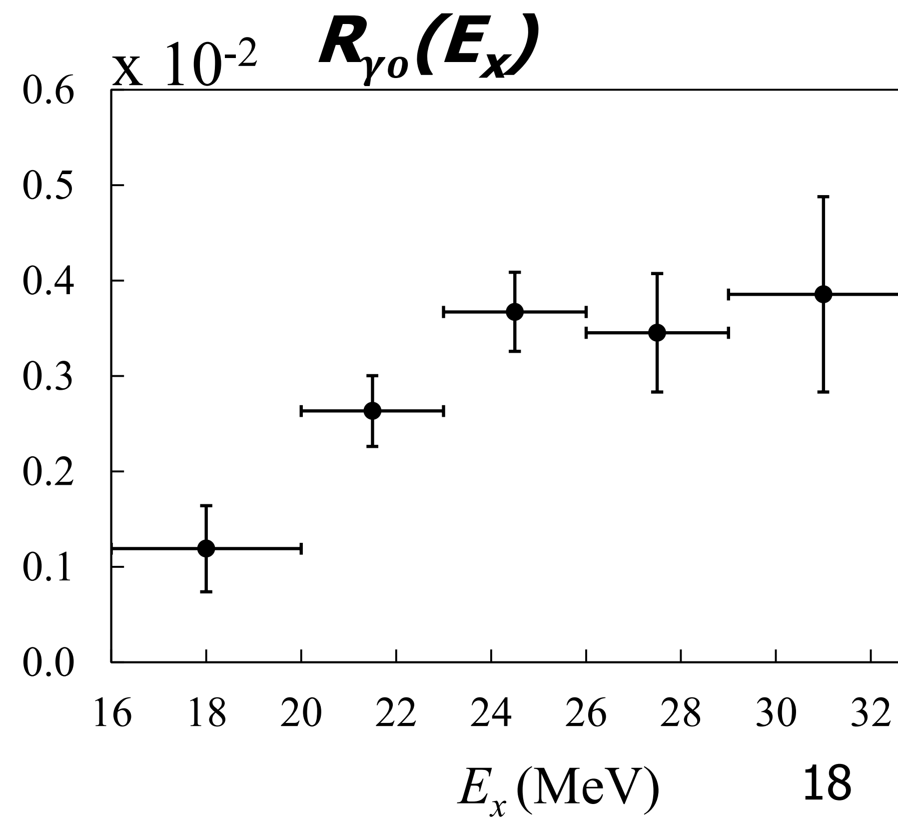
- **Region 1** : Hadronic Decays
- **Region 2** : Electromagnetic Decays

[Region 2] γ rays from Direct Electromagnetic Decay

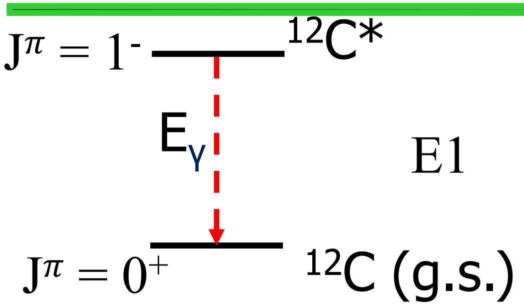
(p19

- We are beginning to observe the high energy γ rays (E=11-33MeV) from direct electromagnetic decay at $R_{\gamma 0}$=(0.37± 0.04± 0.04)%. To establish the result, we must work on the systematic errors.



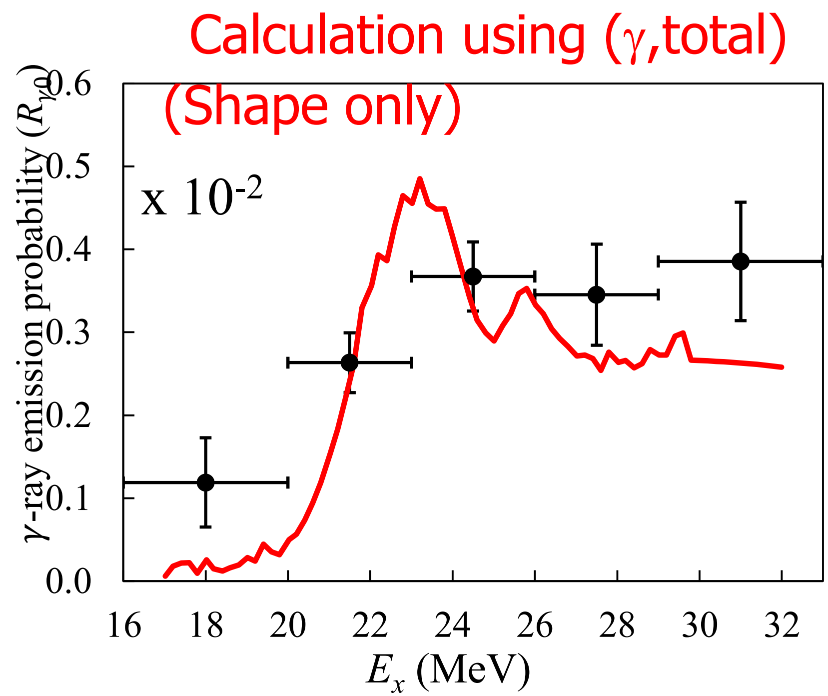


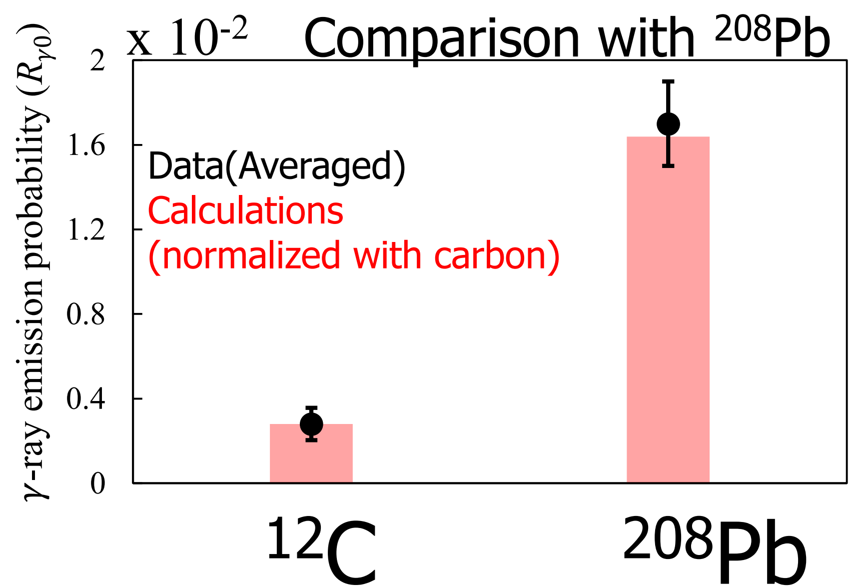
Interpretation of Direct EM decay (^{12}C and ^{208}Pb) in terms of E1 transition



$$R_{\gamma 0} \propto \Gamma_{\gamma 0} \propto E_{\gamma 0}^{3}\, B(E1)$$

$E_{\gamma 0}$ = Energy of emitted γ-ray





- Only one result on direct EM decay of a heavy nucleus ^{208}Pb is reported. Beene et al., Phys.Rev C 41, 920(1990).
- ^{12}C rate is 5 times smaller, due to the small B(E1) = coupling of the photon to the giant resonance for ^{12}C w.r.t. ^{208}Pb.

3. Estimation of O,C(ν,ν′γ) events for SN (10kpc)

- SN ν flux $d\Phi/dE_\nu$: we use MB/FD or Nakazato Flux
  - ✓ MB/FD T=3MeV (ν_e), 5 MeV (ν_e) and T=8MeV (ν_μ,ν_τ).
  - ✓ Nakazato flux (Nakazato,Suzuki et al., ApJS.205,2(2013)).

Supernova ν flux	$\langle E_{\nu_e} \rangle$ (MeV)	$\langle E_{\bar{\nu}_e} \rangle$ (MeV)	$\langle E_{\nu_x} \rangle$ (MeV)
F.D.	11.0	16.0	25.0
Nakazato	7.7	8.8	9.1

Table 5.3 Mean energies of the neutrinos from supernova explosion.

- Cross sections $d\sigma(E_\nu)/dE_x$: we use ^{12}C [T.Yoshida et al., ApJ686,448(2008)] and ^{16}O[T.Suzuki et al. PRC98,034613(2018)]. Shell Model calculation.
- The γ-ray emission rate $R_\gamma(E_x)$: we use our own data.

$$N_\gamma^{NC} = n_{tar.} \int_0^{E_\nu^{max}} dE_\nu \frac{d\Phi}{dE_\nu}(E_\nu) \left[\int_{E_x=16\text{ MeV}}^{E_x=32\text{ MeV}} dE_x \frac{d\sigma(E_x,E_\nu)}{dE_x} \times R_\gamma(E_x) \right]$$

SN rate evaluation: ^{12}C and ^{16}O targets

- Expected number of neutrino events from a core-collapse supernova at 10 kpc to be detected at JUNO (20 kton). [Very preliminary]

Reaction	Present work MB	FD	NK1	NK2	Laha *et al.* (MB) (JUNO collab.)
$p(\bar{\nu}_e, e^+)n$	4933	5378	2194	1974	4857
$^{12}C(\nu,\nu')^{12}C^*(15.1\ MeV)$	382	426	169	161	398
$^{12}C(\nu,\nu')^{12}C^*(E_x>16\ MeV)$	144	180	21	20	-

For NC events MB and FD, T = 8 MeV

For CC events MB and FD, T = 5 MeV

- Expected number of neutrino events from a core-collapse supernova at 10 kpc to be detected at Super-K (32.8kton). [Very preliminary]

Reaction	Present work MB	FD	NK1	NK2	Beacom *et. al.* FD	Nakazato *et. al.* NK1
$p(\bar{\nu}_e, e^+)n$	7685	7632	3257	2931	8300	3199
$^{16}O(\nu,\nu')^{16}O^*(E_x>16\ MeV)$	354	456	57	52	710	-

- Charged-current scattering off ^{16}O nucleus as a detection channel for supernova neutrinos, K.Nakazato, T.Suzuki, MS, PTEP 2018,123E02.

reaction	ordinary supernova no osc.	normal	inverted	black hole formation no osc.	normal	inverted
$^{16}O(\nu_e, e^-)X$	41	178	134	2482	2352	2393
$^{16}O(\bar{\nu}_e, e^+)X$	36	58	103	1349	1255	1055
electron scattering	140	157	156	514	320	351
inverse β-decay	3199	3534	4242	17525	14879	9255
total	3416	3927	4635	21870	18806	13054

Summary

- Measurement of γ-ray spectrum from $^{157, 155, nat}Gd(n,\gamma)$ and ANNRI-Gd Model
  - $^{157}Gd(n,\gamma)$ data and model: PTEP2019,023D01.
  - $^{155,nat}Gd(n,\gamma)$ and 2γ correlation, papers in preparation.
  - Download Web Page in preparation.

- Measurement of γ emission probabability $R_\gamma(E_x)=\sigma_{p,p'\gamma}/\sigma_{p,p'}$ from Giant Resonance in ^{12}C,$^{16}O(p,p'\gamma)$ reaction
  - We measure $R_\gamma(E_x) = \sigma_{p,p'\gamma}/\sigma_{p,p'}$ for the first time for ^{12}C for E_x = 16-32 MeV for the hadronic decay mode. $R_\gamma(E_x)$ starts from zero at E_x = 16 MeV and increases to $R_\gamma(E_x)$= 47.9 $\pm$ 0.5 $\pm$ 3.5% at E_x =27 MeV and then decreases. The paper for $^{12}C(p,p'\gamma)$ was submitted for publication.
  - We are beginning to observe the high energy γ rays (E=16-33MeV) from electromagnetic decay with $R_\gamma(E_x)$=(0.37$\pm$ 0.04$\pm$ 0.04)%. To establish the result, we must work on the systematic errors.
  - We have similar result on ^{16}O.
- We use $d\Phi/dE_\nu$(Nakazato et al.)+$d\sigma/dE$(T.Suzuki)+ $R_\gamma(E_x)$ (our hadronic decay rate) to evaluate NC γ production rate from SN neutrinos. (Ongoing)

Future

- We hope to extend E398 experiment by replacing a NaI array by Clover (Ge) Array (on-going at RCNP), and obtain a comprehensive understanding of both the hadronic and electromagnetic decay of ^{12}C and ^{16}O giant resonances.
- We can evaluate the NC γ production rate for SN neutrinos very precisely.