Study of γ production from giant resonances of carbon and oxygen in (p,p′) reactions

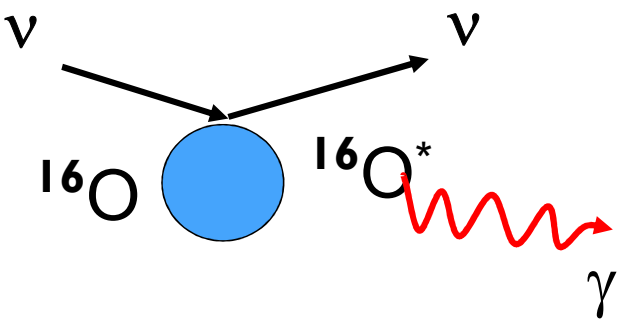
Makoto Sakuda (Okayama) @ NNR16

Outline

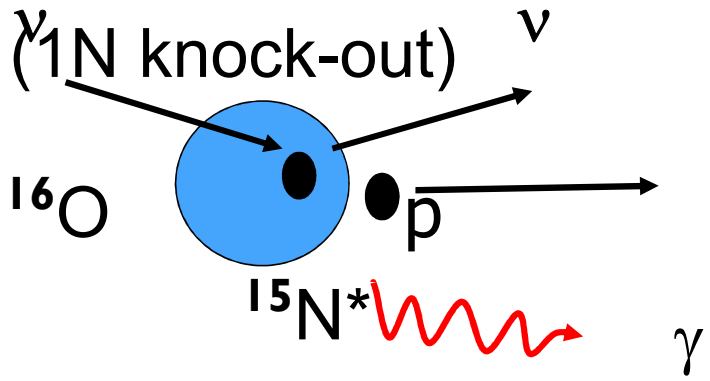
1. Why C,O(p,p′)? Feature of NC n-O,C g-production
2. RCNP E398 C,O(p,p′) experiment
3. Preliminary Result
4. Summary

1. Status of γ-ray production in NC ν-O (-C) reactions

1) E_ν<100MeV: Elastic and Inelastic



2) E_ν>100MeV: Quasi-elastic (1N knock-out)



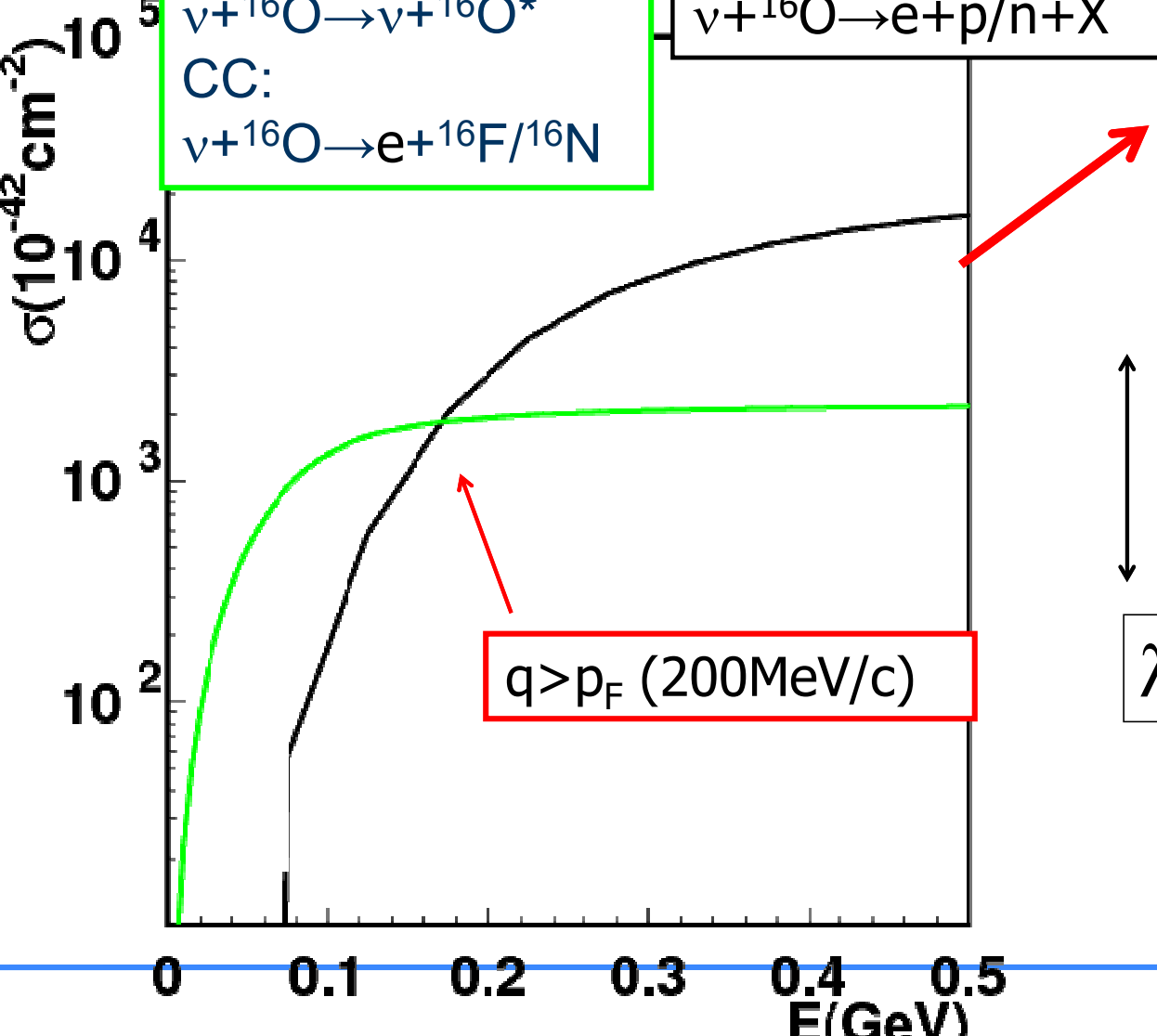
- Theoretical Calculations
  1) E_ν<100MeV: Langanke et al., *Phys.Rev.Lett.***76**(1996).
     - Inelastic scattering (Giant resonances):νO→νO* , O*→γ
  2) E_ν>100MeV: Ankowski,Benhar,Mori,Yamaguchi and MS, *Phys.Rev.Lett.***108**(2012)052505
     - Nucleon knockout: νO→ν+p/n+^{15}N*/^{15}O*(Excitation of residual nucleus)
- Experiments
  1) E_ν<100MeV:No experiments exists for Oxygen. Karmen for C*(15.1MeV) only → RCNP E398
  2) E_ν>100MeV: T2K →K.Abe et al.(T2K),PRD90,072012 (2014)

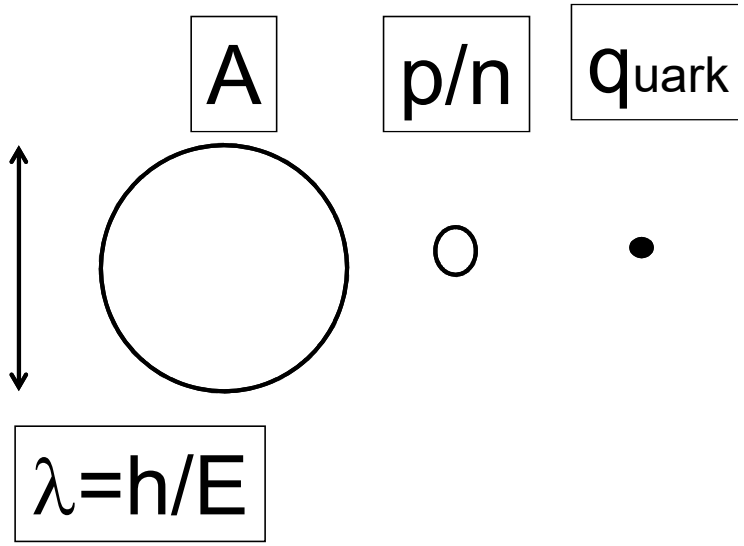
Overall Picture of the ν-A cross section

NC: Elastic
$\nu + {}^{16}O \rightarrow \nu + {}^{16}O$
Inelastic
$\nu + {}^{16}O \rightarrow \nu + {}^{16}O^*$
CC:
$\nu + {}^{16}O \rightarrow e + {}^{16}F/{}^{16}N$

NC quasi-elastic (QE)
$\nu + {}^{16}O \rightarrow \nu + p/n + X$
CC QE
$\nu + {}^{16}O \rightarrow e + p/n + X$

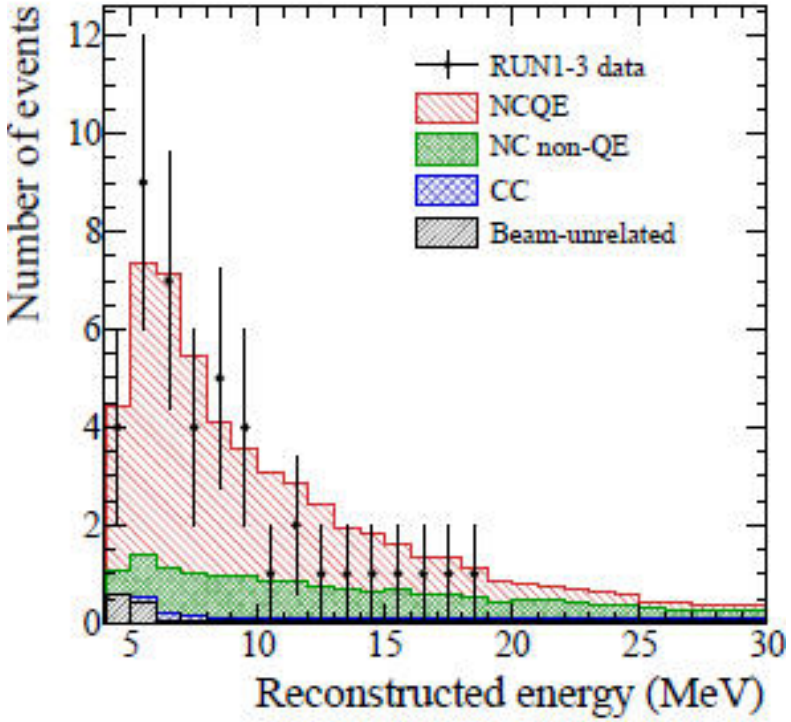
π-production and DIS



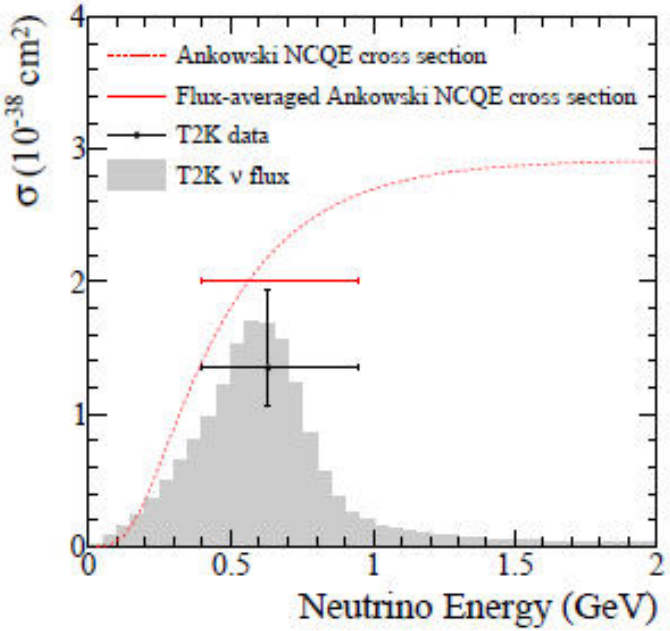


Experiments: T2K NC γ production and Karmen NC γ production

T2K 6MeV γ from $^{15}N/^{15}O$

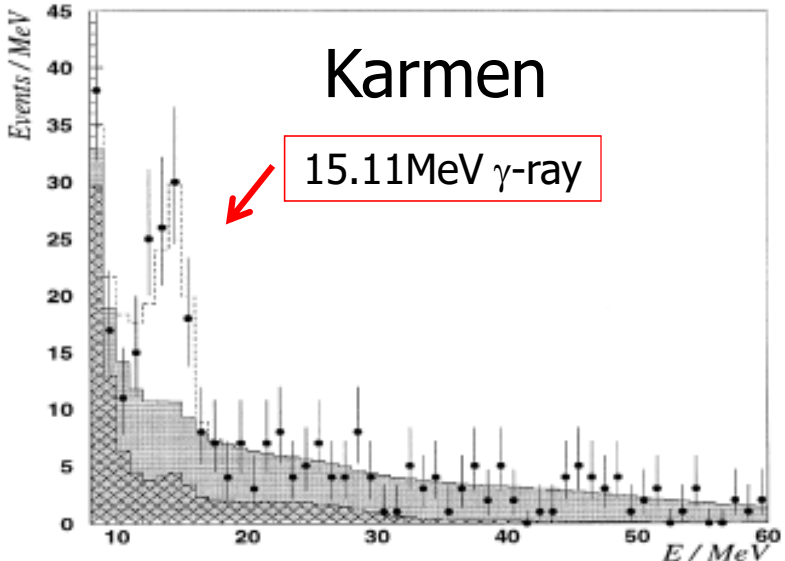


T2K and Ankowski et al, PRL108



- T2K data is consistent with Ankowski et al.

- KARMEN @E_ν=29.8MeV
  $(3.2\pm0.5\pm0.4)\times10^{-42}cm^2$
  In good agreement with the calculation,
  $2.8\times10^{-42}cm^2$.
- .



Quasi-Elastic (QE) Interaction

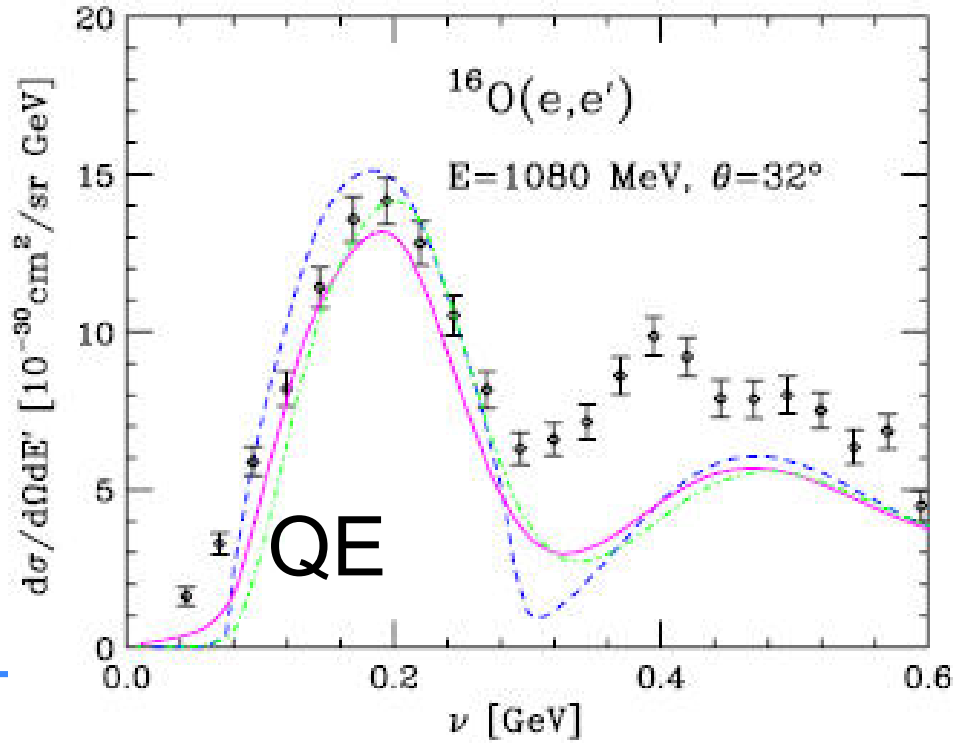
- We use Impulse Approximation approach with Spectral Function plus FSI to describe QE.

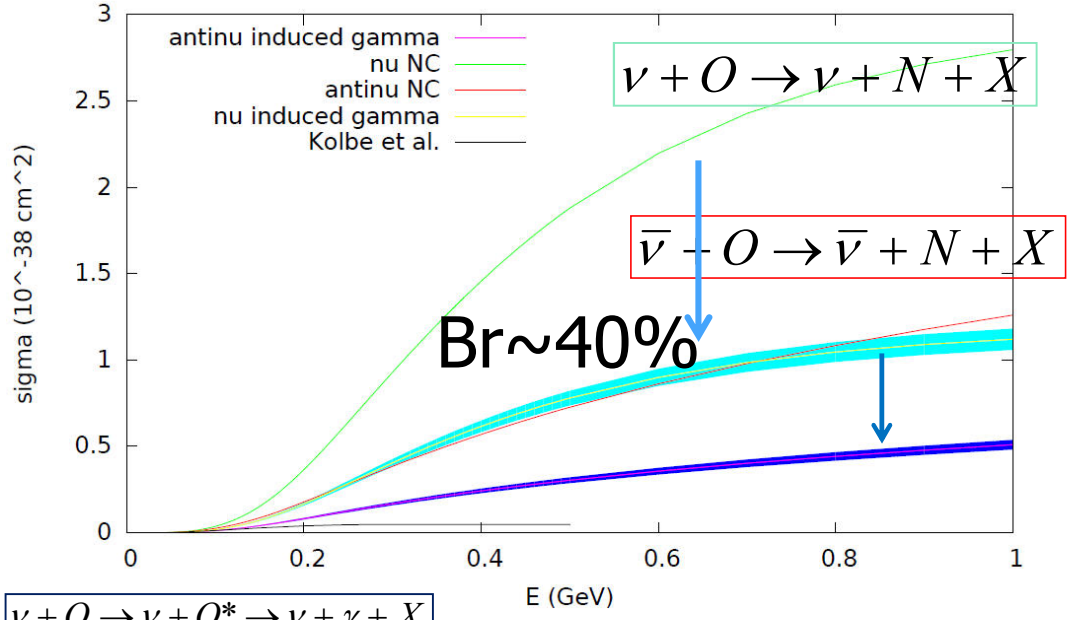
*Benhar,MS et al., PRD72,053005, '05; Ankowski,Benhar,MS:PRD91,033005,'15.

*SF is being used as a standard method by most neutrino experiments.

- Production of γ-rays (>5MeV) in NC/CC QE is significant (Br~ 40% for O). This makes a background to SRN search.

*Ankowski,MS et al, PRL 108,052505(2012).

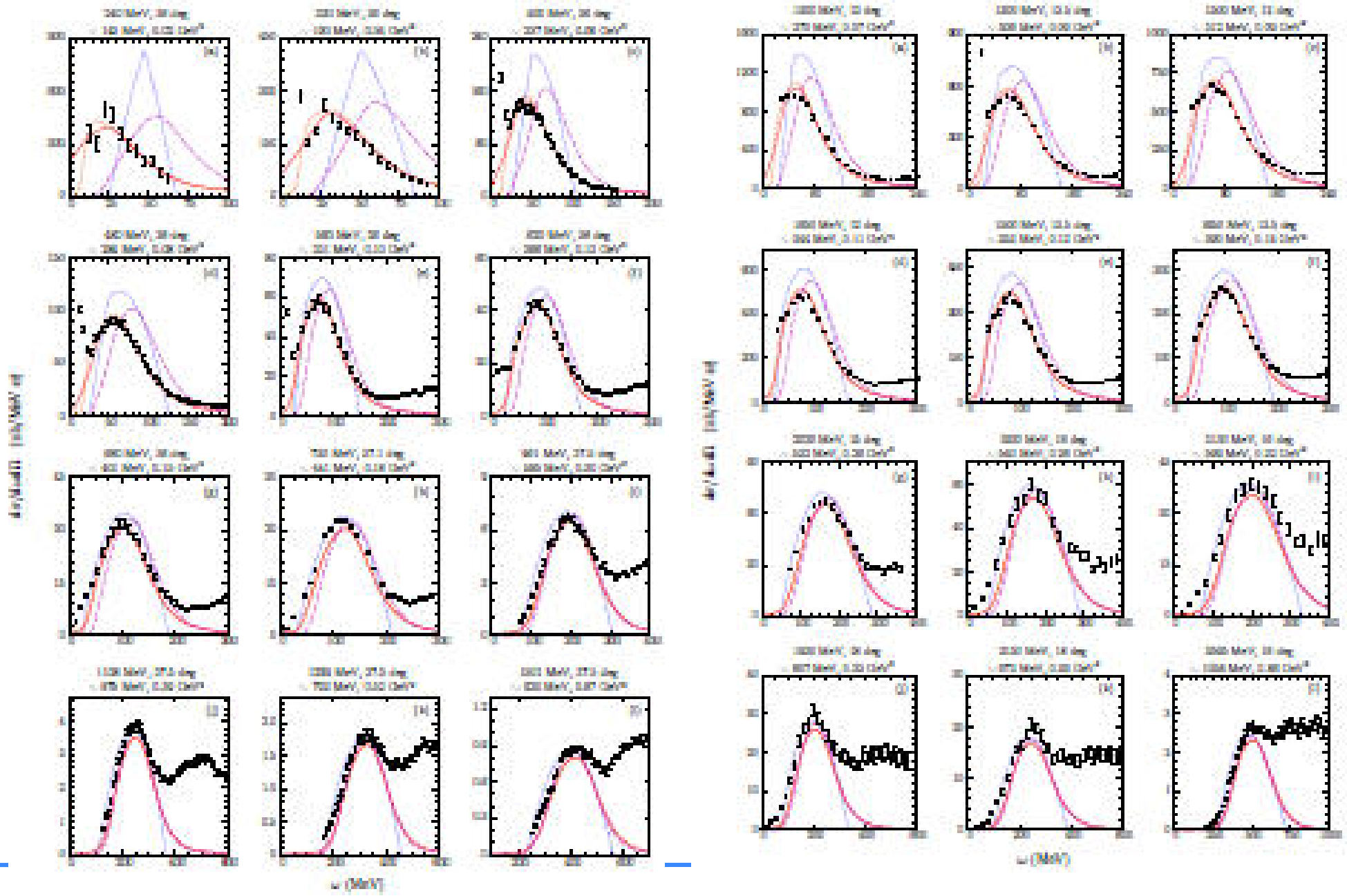




$\nu + O \rightarrow \nu + O^* \rightarrow \nu + \gamma + X$

by Kolbe etal.(NC Inelastic)

We compare our calculations with all existing C(e,e') data E=240-2000MeV Ankowski, Benhar, MS,PRD91,033005,'15.



2. Neutrinos from SN explosion@10kpc

✦The number of events observed in the detectors

▸Super Kamiokande (H_2O)

$$\bar{\nu}_e + p \rightarrow e^+ + n$$ ~8000 events

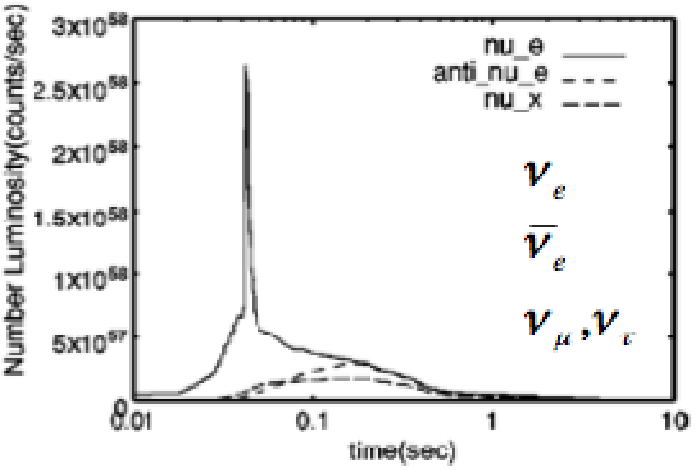
$$NC: \nu_x + {}^{16}O \rightarrow \nu_x + X + \gamma \ (\nu_x = \nu_\mu, \nu_\tau)$$ 400~600? events

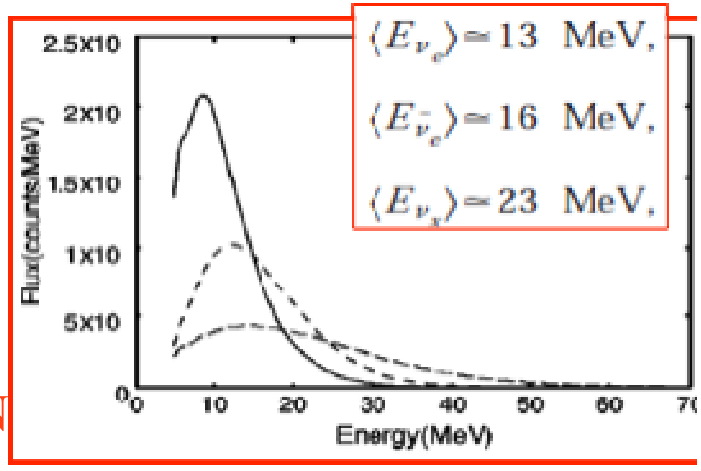
▸KamLAND (CH)

$$\nu_e + p \rightarrow e^+ + n$$ ~300

$$NC: \nu_x + {}^{12}C \rightarrow \nu_x + X + \gamma \ (15.1MeV)$$ ~60

$$NC: \nu_x + {}^{12}C \rightarrow \nu_x + X + \gamma \ (E_X > 16MeV)$$巨大共鳴(~50-60??)





✦**Importance of Neutral-Current events**

▸**The 2nd larget reaction and no one has measured them in SN bursts**

*Koshiba-san measured 11 CC events

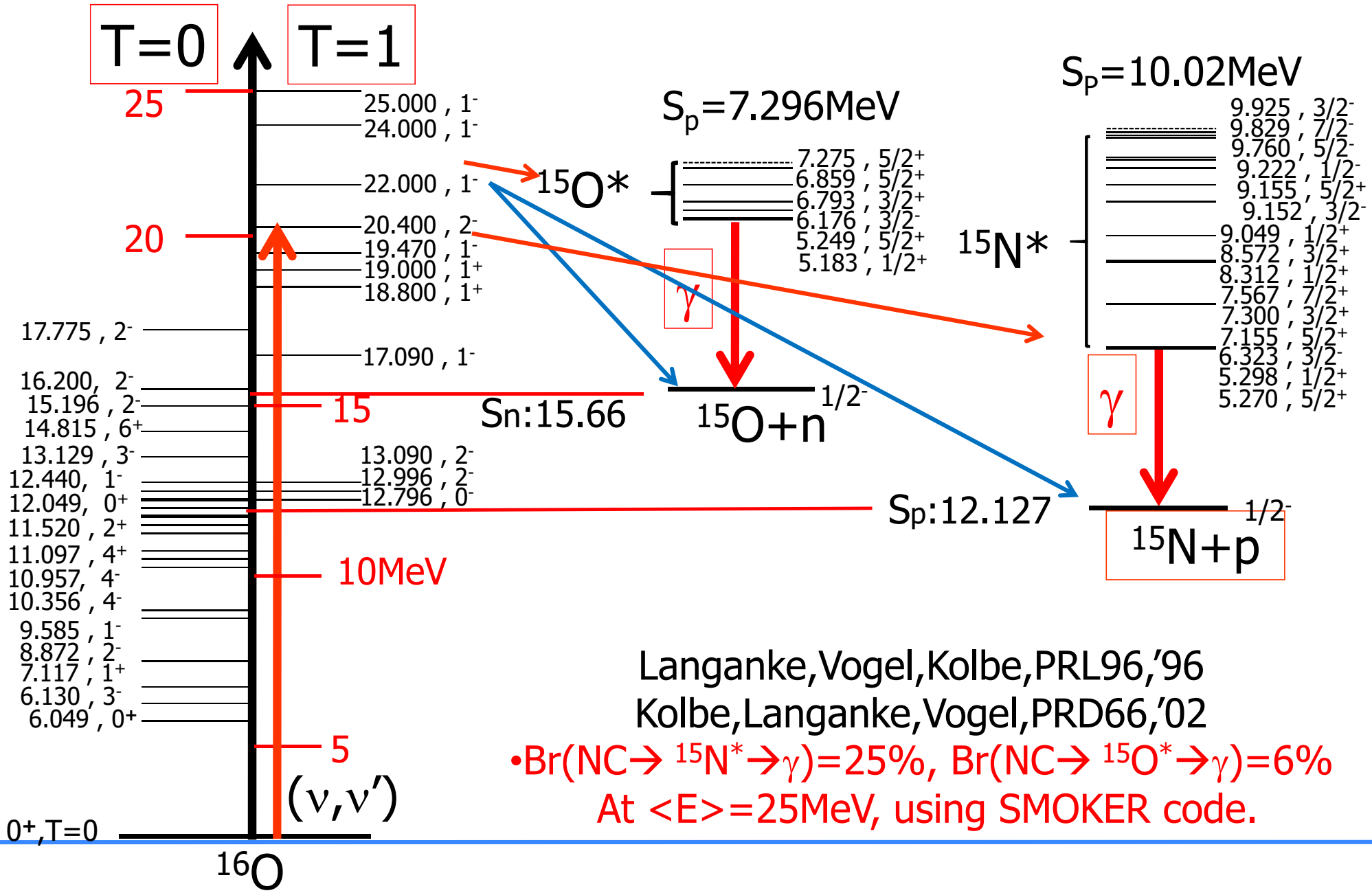
▸**μ,τ –type neutrino-induced events dominate NC reactions since energy (Temperature) is higher than e-type.**

▸Independent of neutrino oscillations

▸Let's Measure Br(C*,O*→γ) = Γγ/Γ (**E_x**). Purpose of RCNP E398.

NC ν-O γ-production (E<100MeV, Inelastic)

$\nu_x + {}^{16}O \rightarrow \nu_x + {}^{16}O^* \; ; {}^{16}O^* \rightarrow {}^{15}N^* + p, \; {}^{15}O^* + n \; ; \; {}^{15}N^*, {}^{15}O^* \rightarrow \gamma$

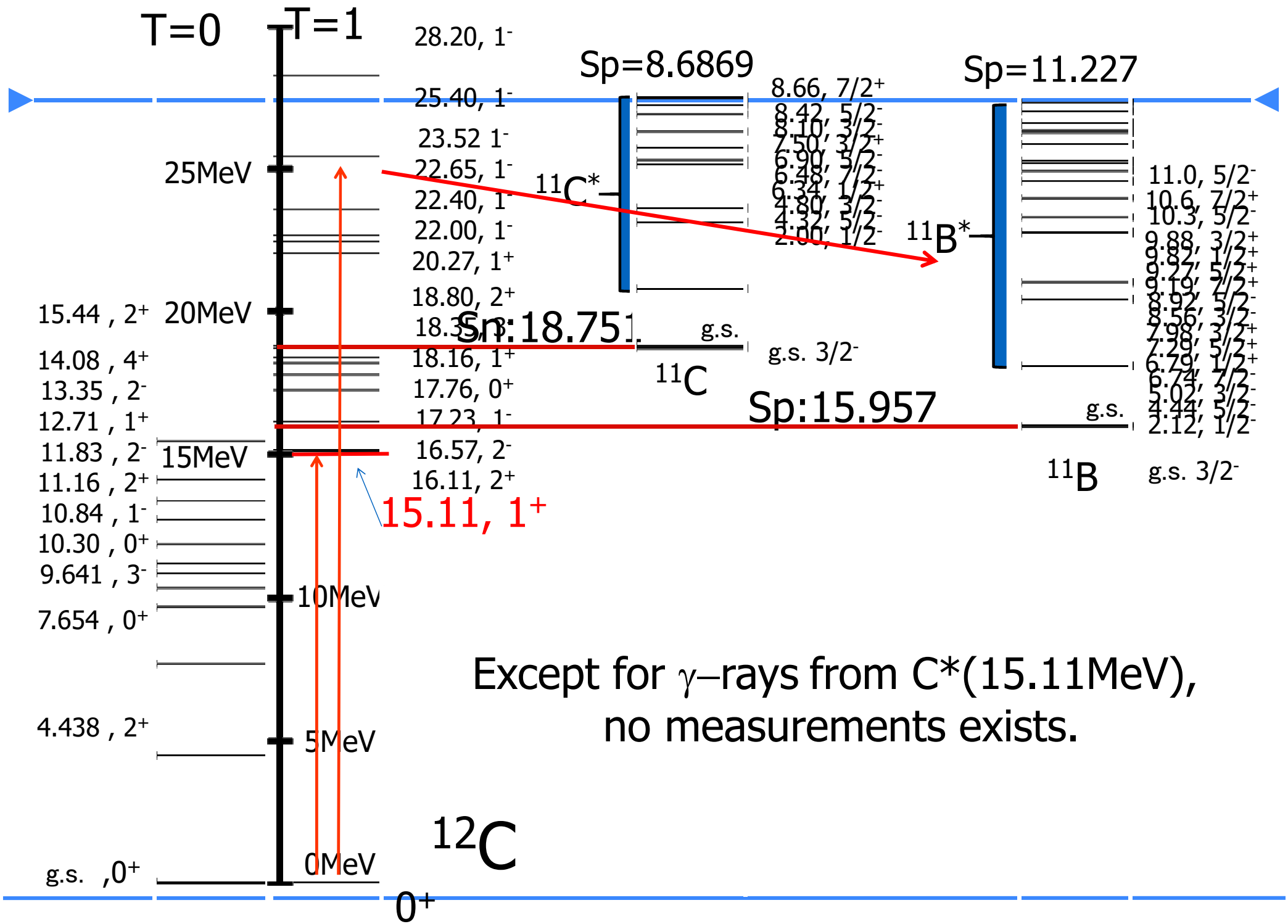


Langanke,Vogel,Kolbe,PRL96,'96

Kolbe,Langanke,Vogel,PRD66,'02

- Br(NC→ $^{15}N^*$→γ)=25%, Br(NC→ $^{15}O^*$→γ)=6%

At <E>=25MeV, using SMOKER code.


T=0
T=1
28.20, 1-
25.40, 1-
23.52 1-
22.65, 1-
22.40, 1-
22.00, 1-
20.27, 1+
18.80, 2+
18.35, 3-
18.16, 1+
17.76, 0+
17.23, 1-
16.57, 2-
16.11, 2+
15.11, 1+
25MeV
20MeV
15MeV
10MeV
5MeV
0MeV
15.44 , 2+
14.08 , 4+
13.35 , 2-
12.71 , 1+
11.83 , 2-
11.16 , 2+
10.84 , 1-
10.30 , 0+
9.641 , 3-
7.654 , 0+
4.438 , 2+
g.s. ,0+
Sp=8.6869
Sn:18.751
11C*
11C
g.s.
g.s. 3/2-
8.66, 7/2+
8.42, 5/2-
8.10, 3/2-
7.50, 3/2+
6.90, 5/2-
6.48, 7/2-
6.34, 1/2+
4.80, 3/2-
4.32, 5/2-
2.00, 1/2-
Sp=11.227
Sp:15.957
11B*
11B
g.s.
g.s. 3/2-
11.0, 5/2-
10.6, 7/2+
10.3, 5/2-
9.88, 3/2+
9.82, 1/2+
9.27, 5/2+
9.19, 7/2+
8.92, 5/2-
8.56, 3/2-
7.98, 3/2+
7.29, 5/2+
6.79, 1/2+
6.74, 7/2-
5.02, 3/2-
4.44, 5/2-
2.12, 1/2-
12C
0+
Except for γ–rays from C*(15.11MeV),
no measurements exists.

3. RCNP E398 experiment

Measurement of γ −rays from O(p,p′) and C(p,p′)

E398: I. Ou, Y. Yamada, D.Fukuda, T.Shirahige, T. Yano, T. Mori, Y. Koshio, M. Sakuda, (Okayama), A. Tamii, N.Aoi , M.Yosoi, E. Ideguchi, T. Suzuki, T. Hashimoto, C. Iwamoto, K. Miki, T. Ito, T. Yamamoto (RCNP), H. Akimune (Konan), T.Kawabata (Kyoto)

[Goal]: We measure the γ-decay probability($\Gamma\gamma/\Gamma$) (E_γ>5 MeV) from giant resonances of ^{16}O and ^{12}C, at ±1% stat. accuracy, as the functions of excitation energy (E_x).

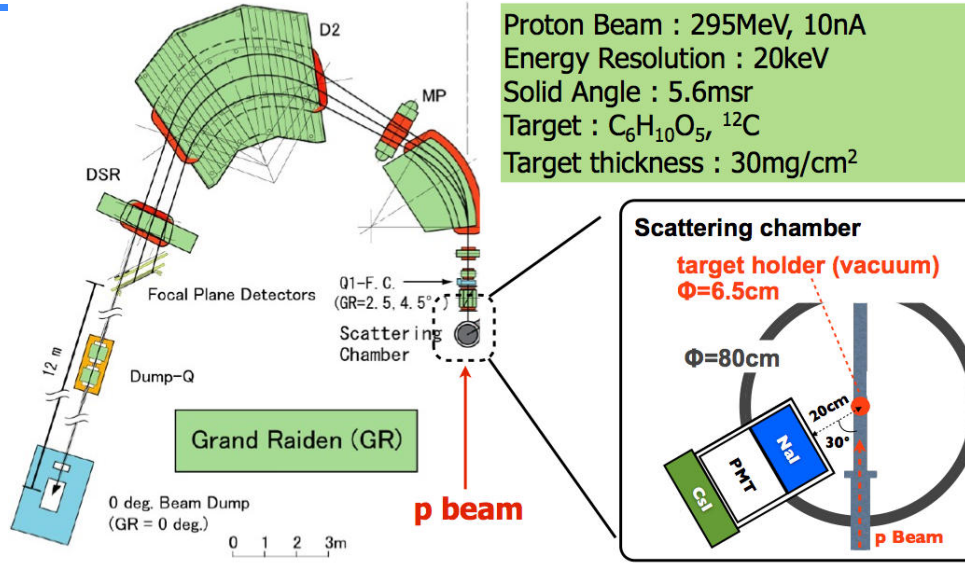
Definition: The γ-decay probability ($\Gamma\gamma/\Gamma$)(E_γ>5MeV)=
(Number of γ-rays observed for E_γ>5 MeV)/(Number of events excited in the range Ex=15-30 MeV, each Ex bin) →Fig.

[Importance]: Data for $\nu O \rightarrow \nu O^* \rightarrow \gamma$ and $\nu C \rightarrow \nu C^* \rightarrow \gamma$ do not exist and they are very important to neutrino physics. RCNP Grand-Raiden is the best place for this experiment.

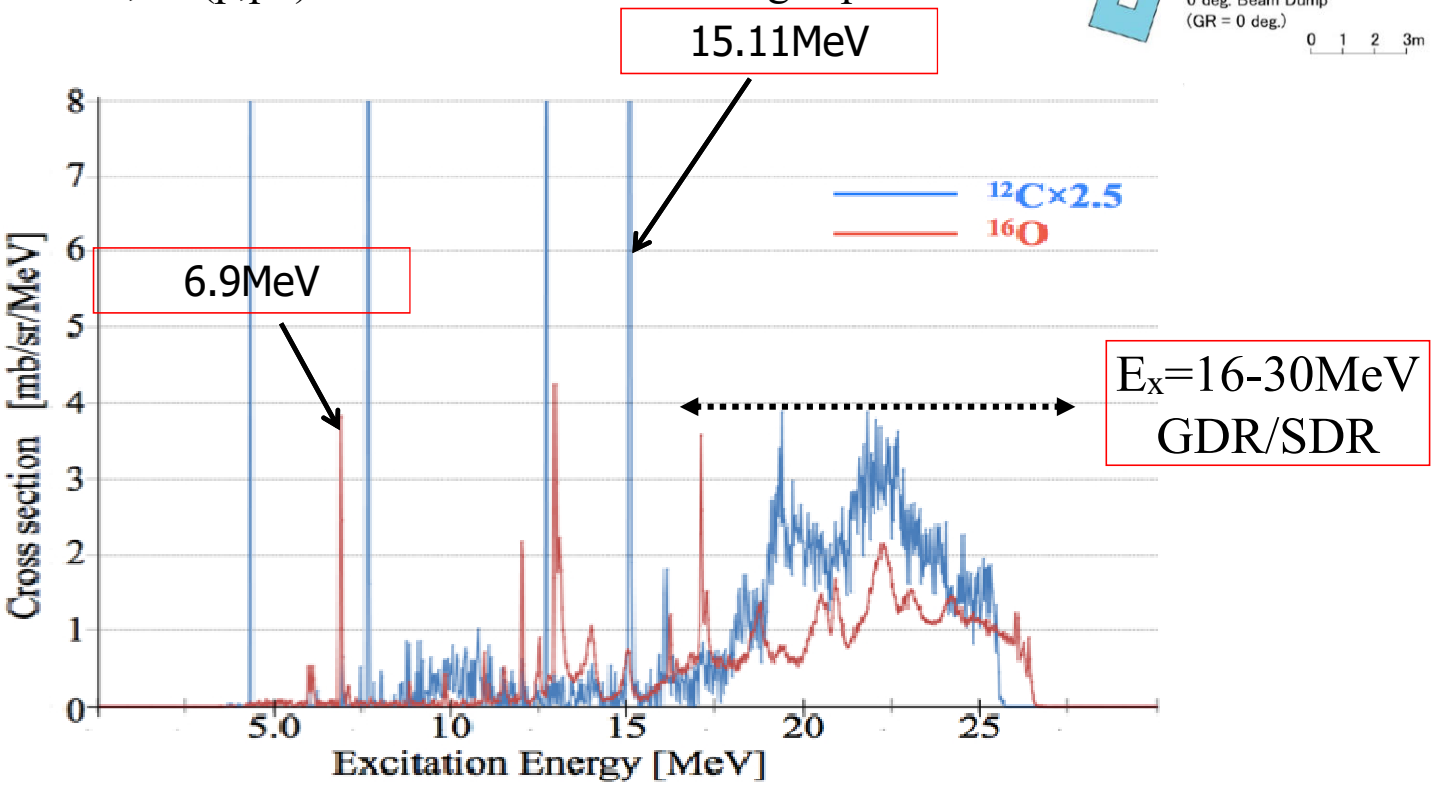
-Proposal was approved in March, 2013 and Experiment was finished in May, 2014.

RCNP Grand-Raiden Spectrometer O,C(p,p')

See excellent Energy Resolution
Ex=Ep-Ep', ΔEx~20keV

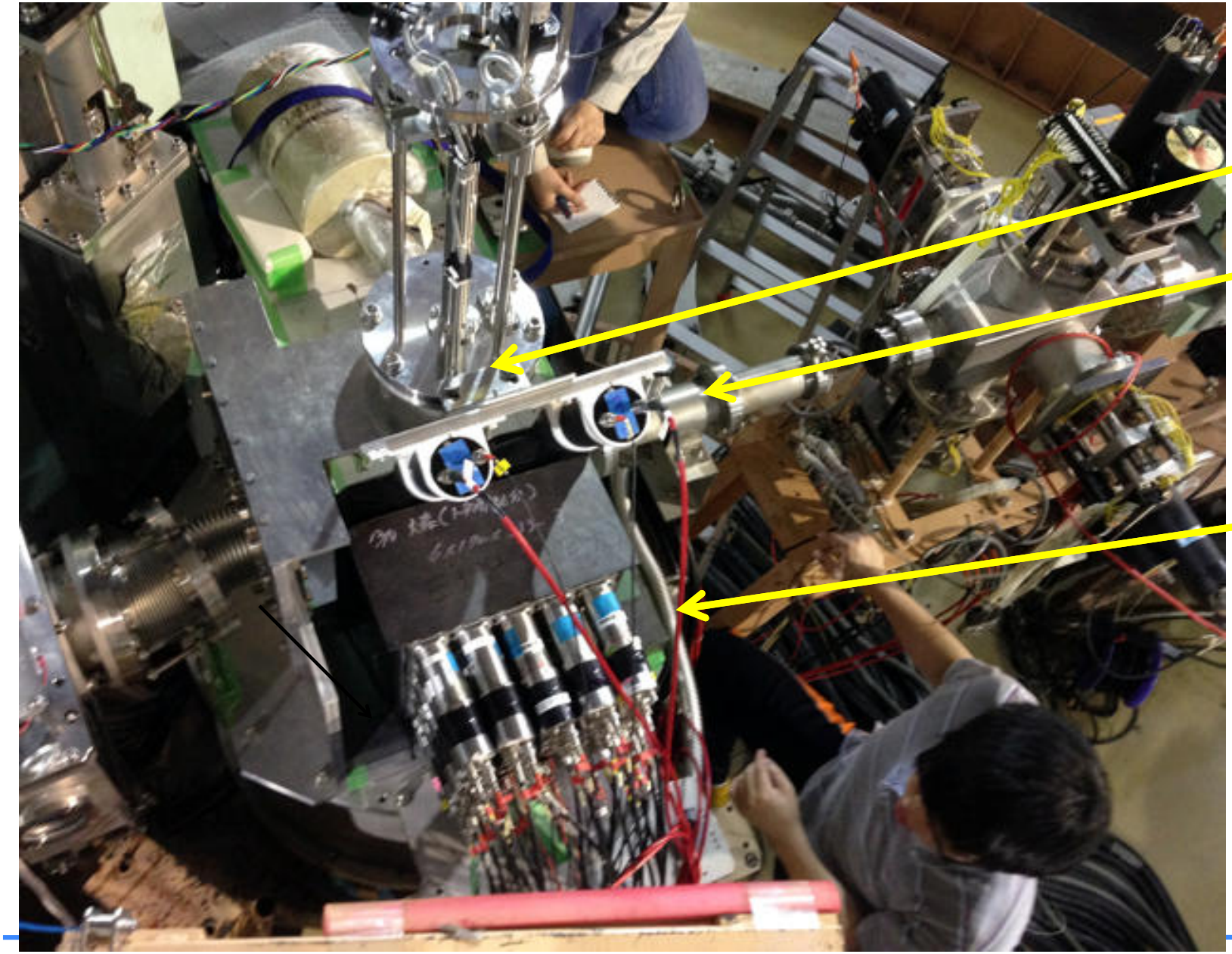


$^{16}O,^{12}C(p,p')$ cross section at θ=0.4 deg. Ep=295MeV



Ref. A. Tamii, H. Matsubara, et al.RCNP E249 & E299 Collaboration, 5-JAN-2011.

E398 (May 16-27, 2014)



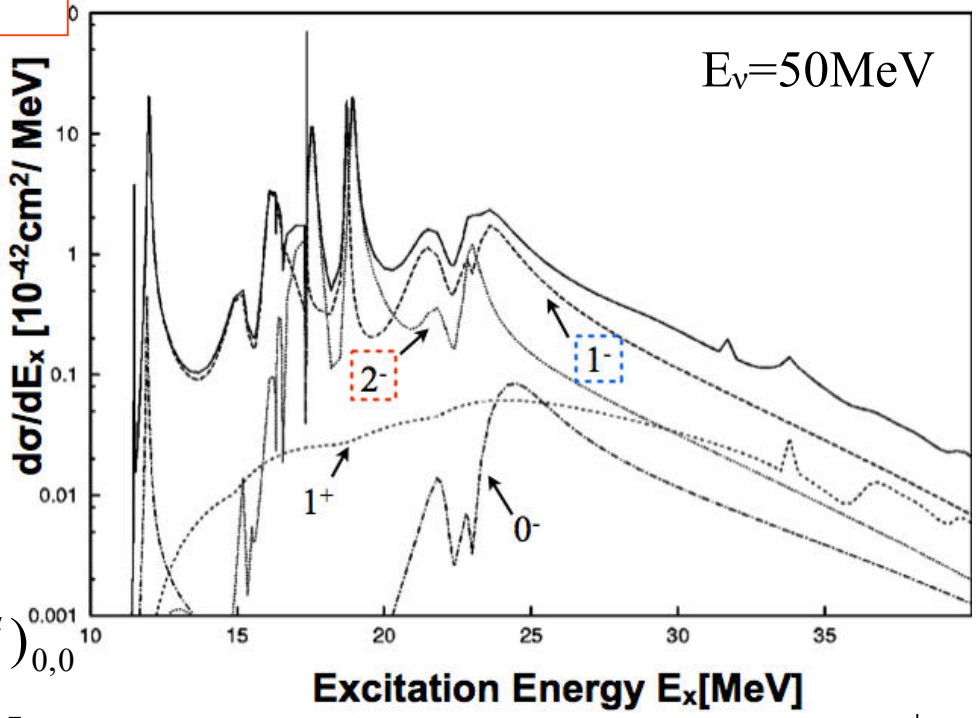
NC ν-^{16}O,^{12}C reaction

Ref. Jachowicz et al .,PRC59('99), Botrugno, Co', NPA761('05)

Axial Current Dominant:

Especially, Spin Dipole Resoance : $J^P = 2^-, 1^-(T=1)$ Domiant. (1^+,15.1MeV for C)

^{16}O(ν,ν') Cross Section



✦NC Neutrino-Nucleus Cross Section :

ν+A→**ν**+A' : Nuclear Matrix Element

✦

$$J^{\mu}_{em} = (J^{\mu}_{V})_{1,0} + (J^{\mu}_{V})_{0,0}$$

$$J^{\mu}_{CC} = (J^{\mu}_{V})_{1,\pm1} + (J^{\mu}_{A})_{1,\pm1}$$

$$J^{\mu}_{NC} = \beta^{1}_{V}(J^{\mu}_{V})_{1,0} + \beta^{1}_{A}(J^{\mu}_{A})_{1,0} + \beta^{0}_{V}(J^{\mu}_{V})_{0,0} + \beta^{0}_{A}(J^{\mu}_{A})_{0,0}$$

$$= (J^{\mu}_{V})_{1,0} + (J^{\mu}_{A})_{1,0} - 2\sin^{2}\theta_{W} J^{\mu}_{em} \qquad [+(J^{\mu}_{A})_{0,0}]$$

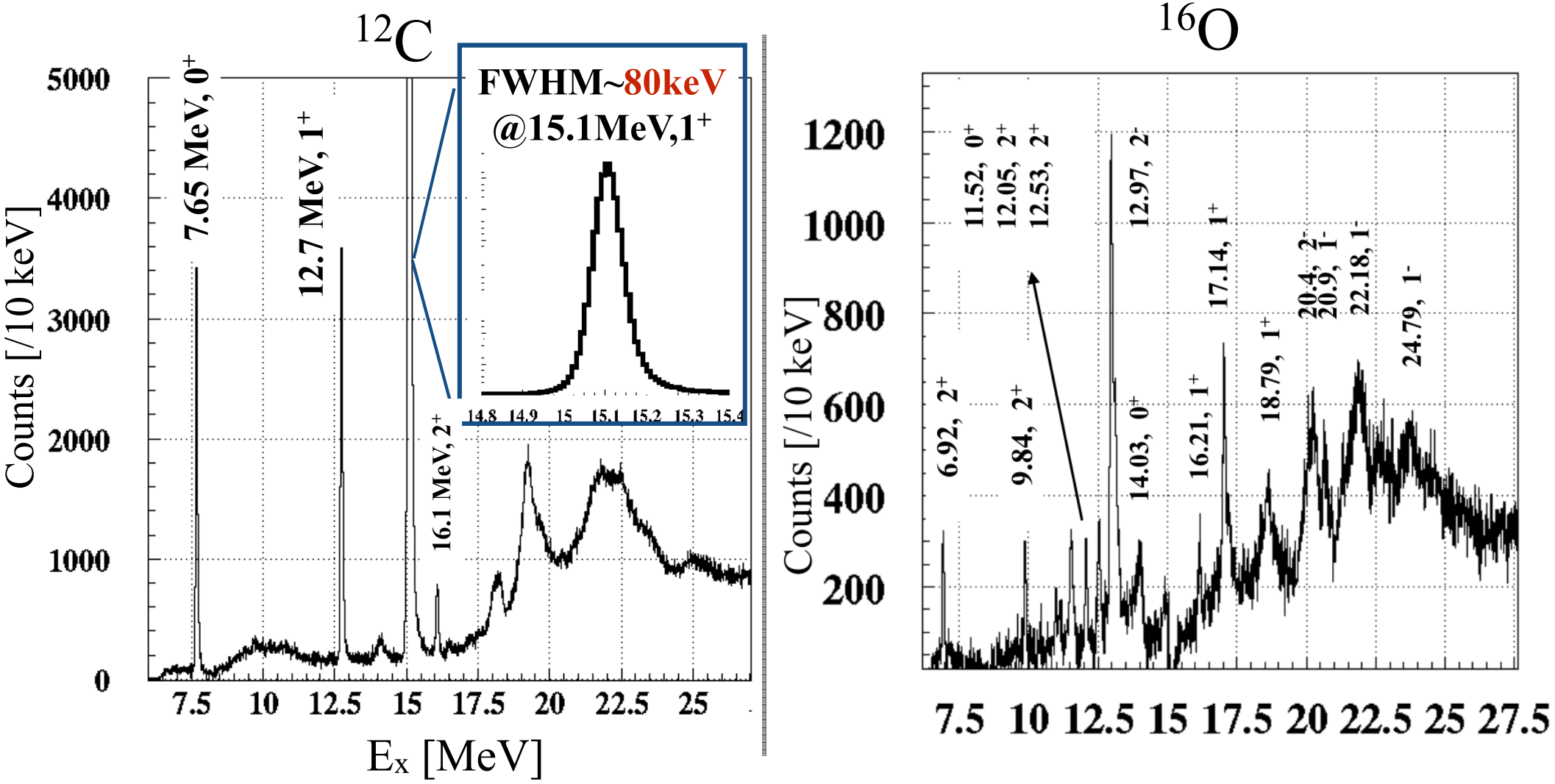
✦GDR ($J^p=1^-,\Delta T=1,\Delta S=0,\Delta L=1$): $f_1(r)Y_1^m\tau_3$

Spin Dipole R ($J^p=0^-,1^-,2^-$, $\Delta T=1,\Delta S=1,\Delta L=1$): $\vec{\sigma} f_1(r)Y_1^m\tau_3$

M1 ($J^p=1^+,\Delta T=1,\Delta S=1,\Delta L=0$): $\vec{\sigma} f_0(r)\tau_3$

3. Results: (1) Excited States ($E_x=E_p-E_{p'}$) (C and O)

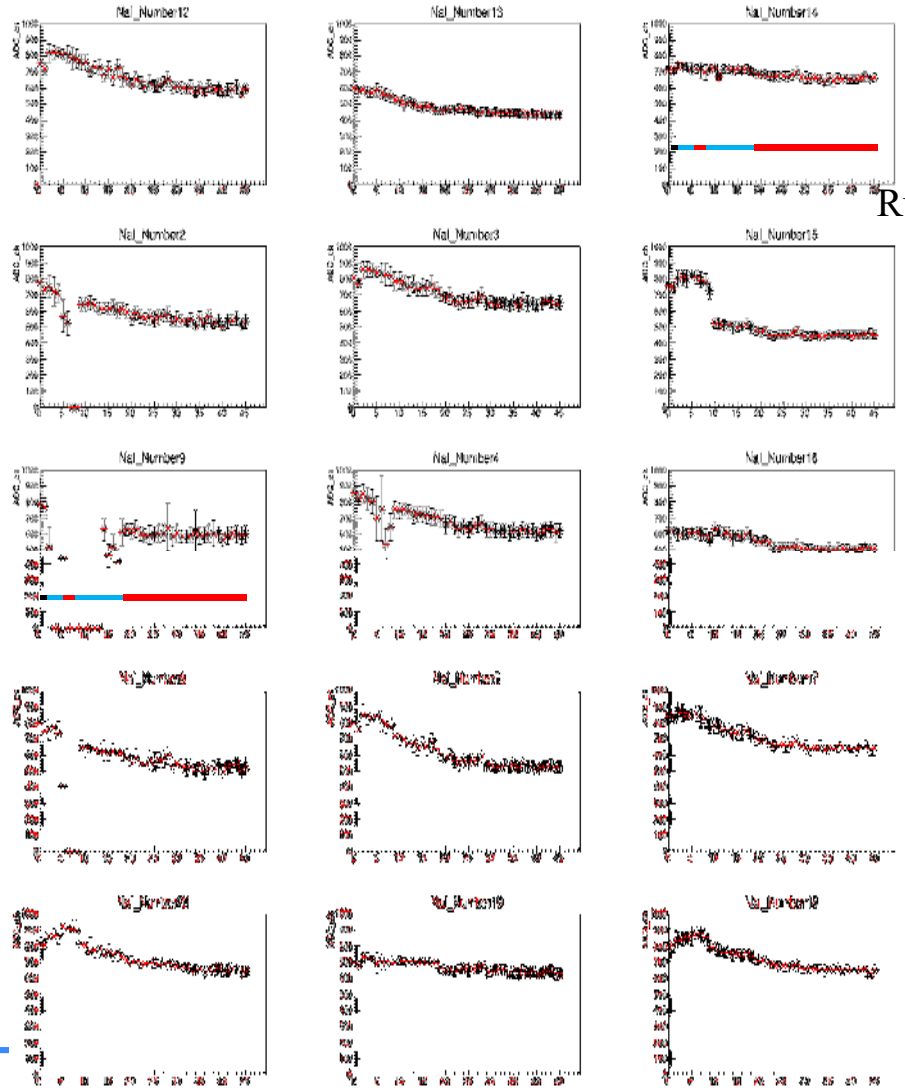
Each observed peak is consistent with existing data (Table of Isotopes, 8th ed**).**



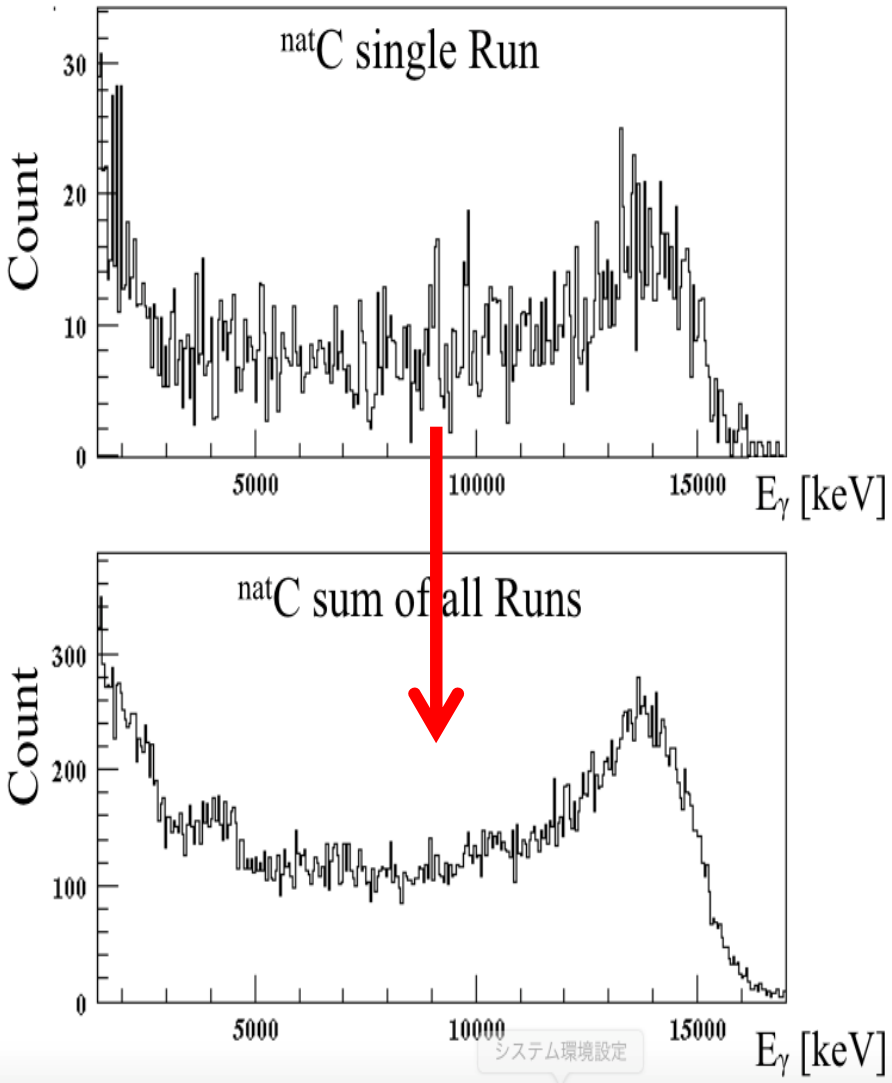
Data :C target, 0.5nA, 2hrs & $C_6H_{10}O_5$ target, 0.5nA, 2hrs

In-situ Gain Calibration using C(15.1MeV) during the experiment (May 16-27, 2014)

The pulse-height of NaI counters decreased during the experiment. We corrected it on run-by-run basis so that the



Run number



Results: Gamma Spectrum (I.Ou (E398), presented at NuInt15)

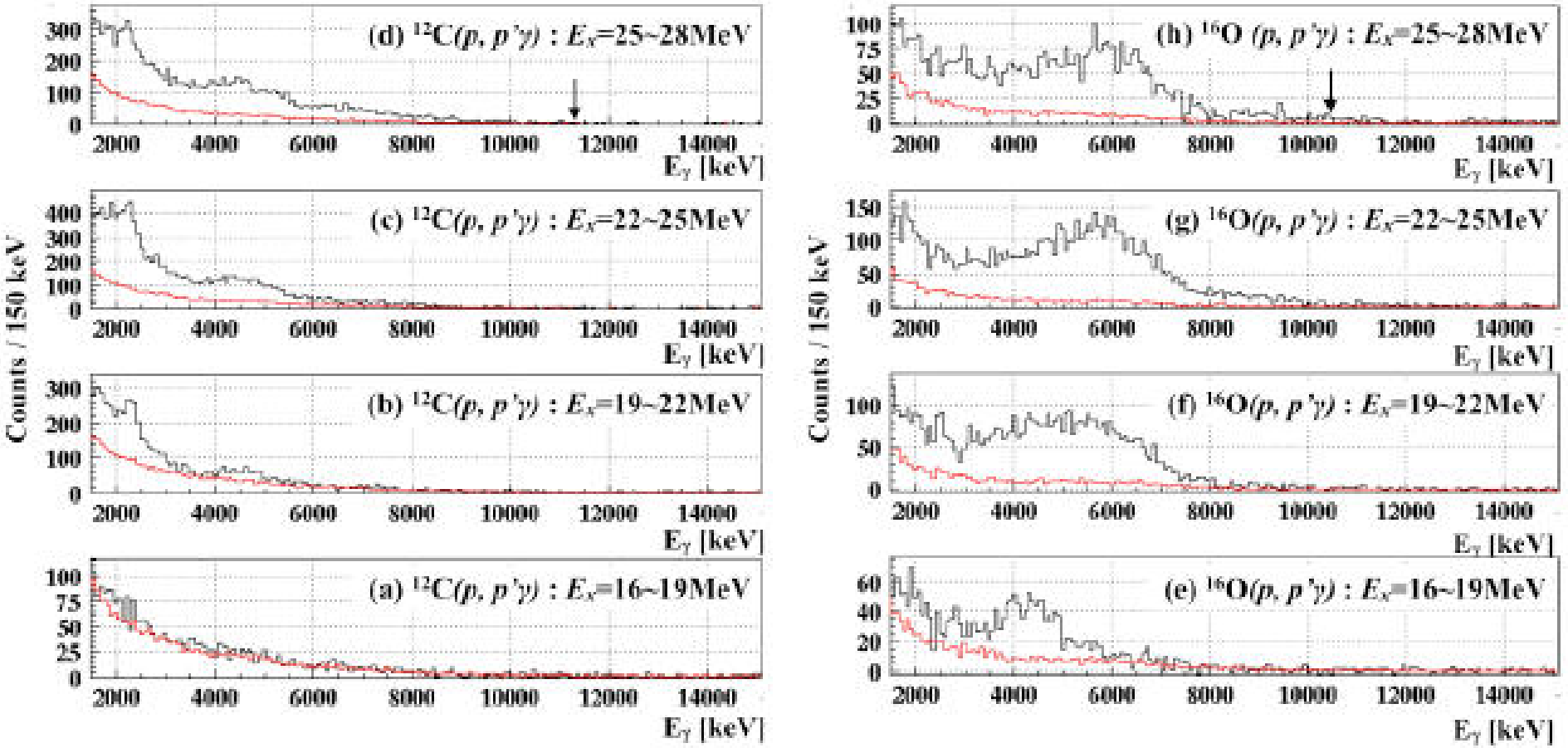
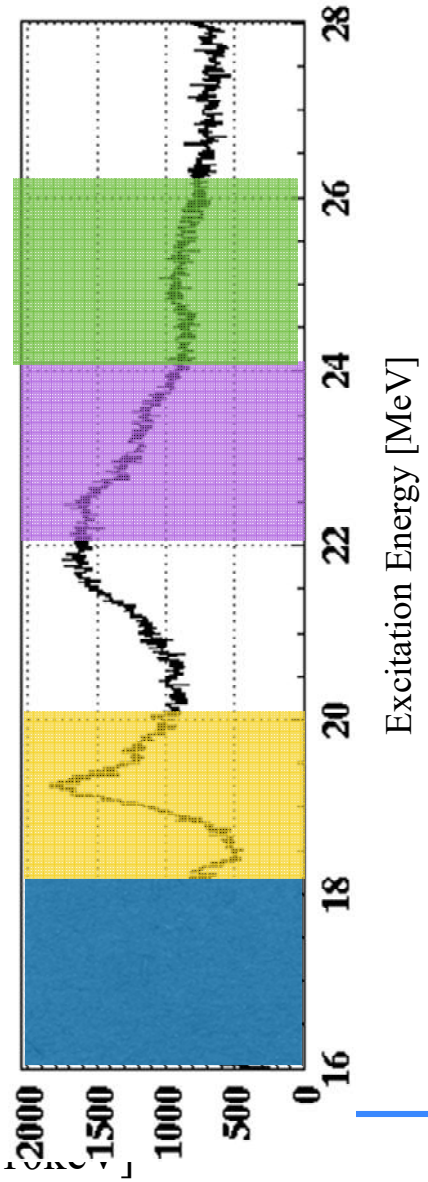


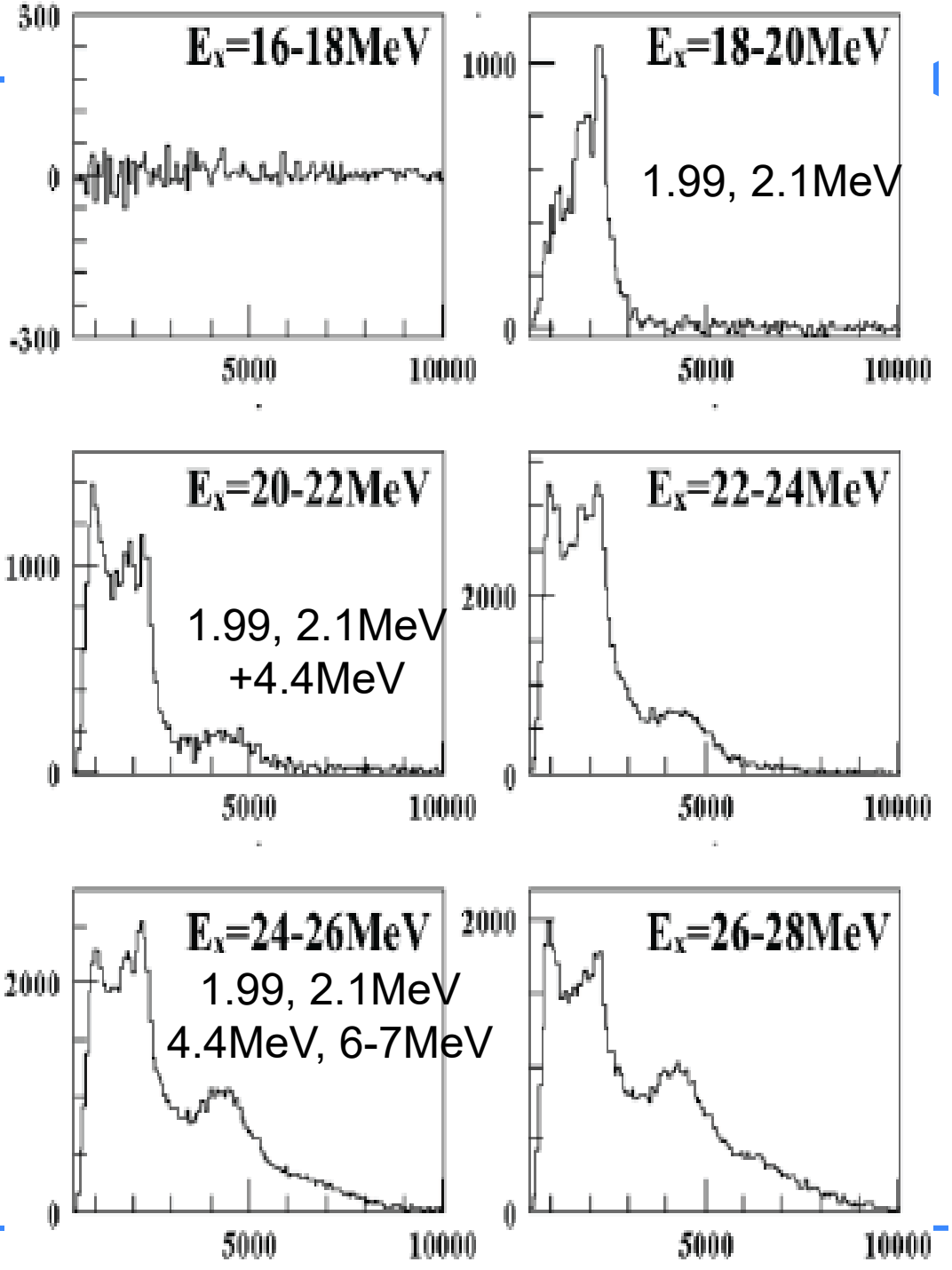
Figure 4. Coincidence γ-ray spectra (black line) with the 3 × 5 NaI array from giant resonances of ^{12}C (left) and ^{16}O (right) for different excitation energy region along with accidental coincidence γ-ray spectra (red line). Allows denote the separation energies of daughter nuclei.

γ-ray from giant resonance: ^{12}C (Using all data corrected for the gain shift.)

(P20

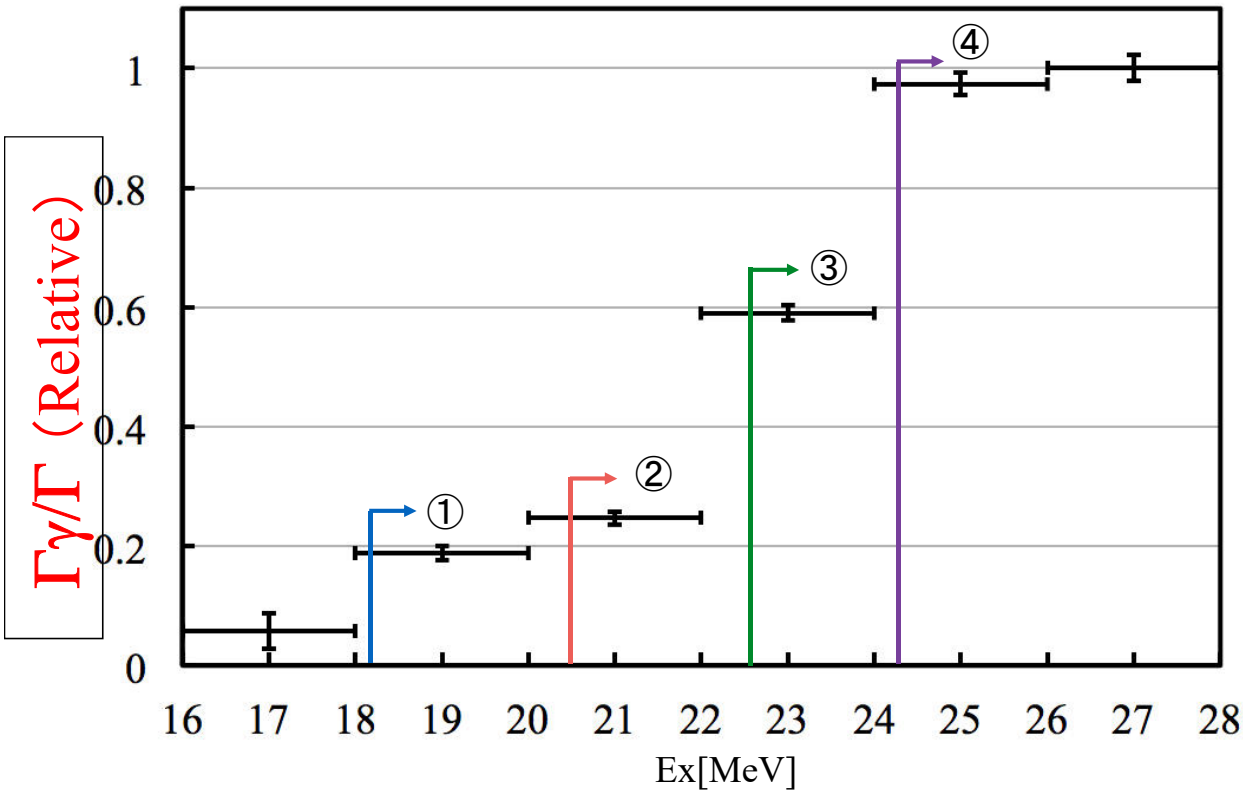
- Left: Excitaion energy of ^{12}C (Ex)
- Right: r-ray specrum for each Ex bin.

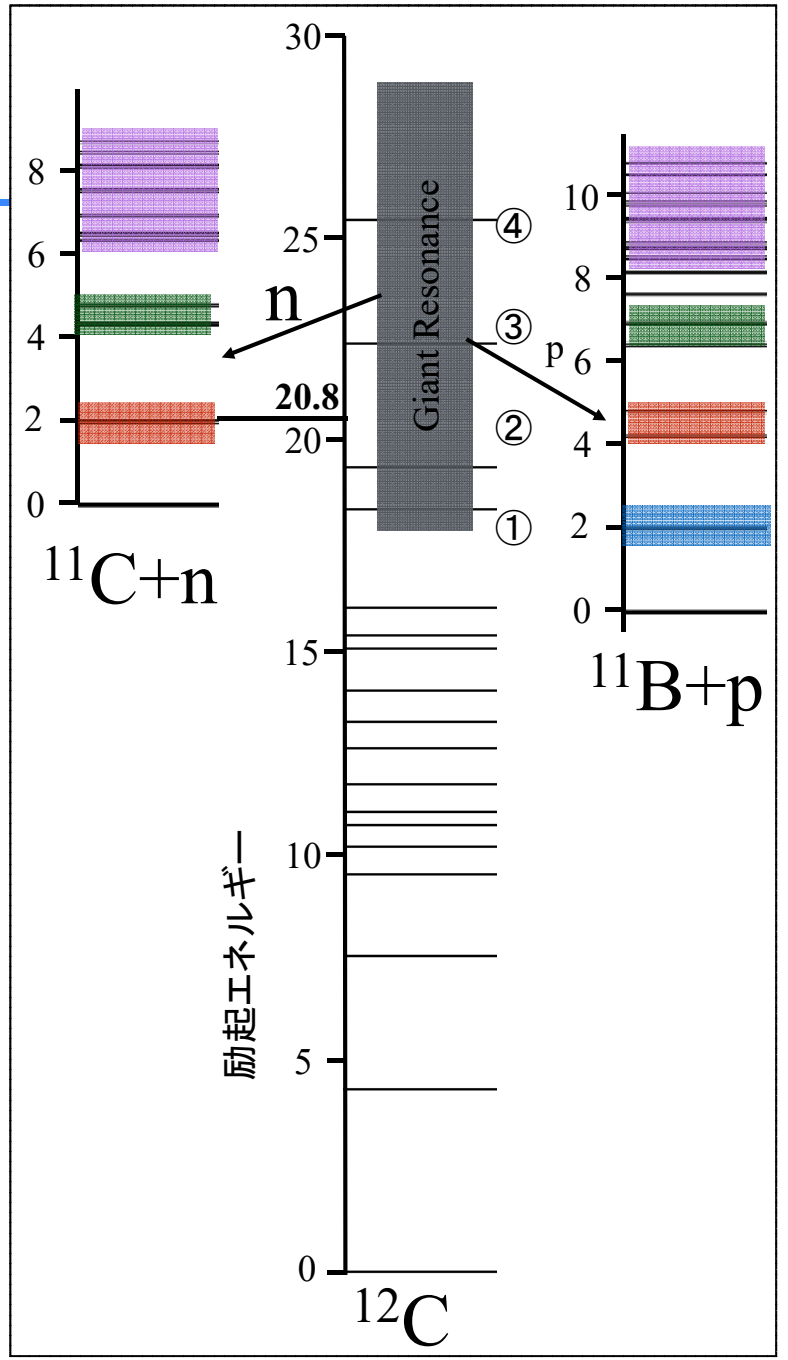




4. ^{12}C γ-decay probability (Γγ/Γ)

$$\Gamma\gamma/\Gamma = \frac{\text{Number of } \gamma\text{-rays detected}(1.5\text{MeV}<E\gamma<12\text{MeV})}{\text{Number of excited states (Ex)}}$$



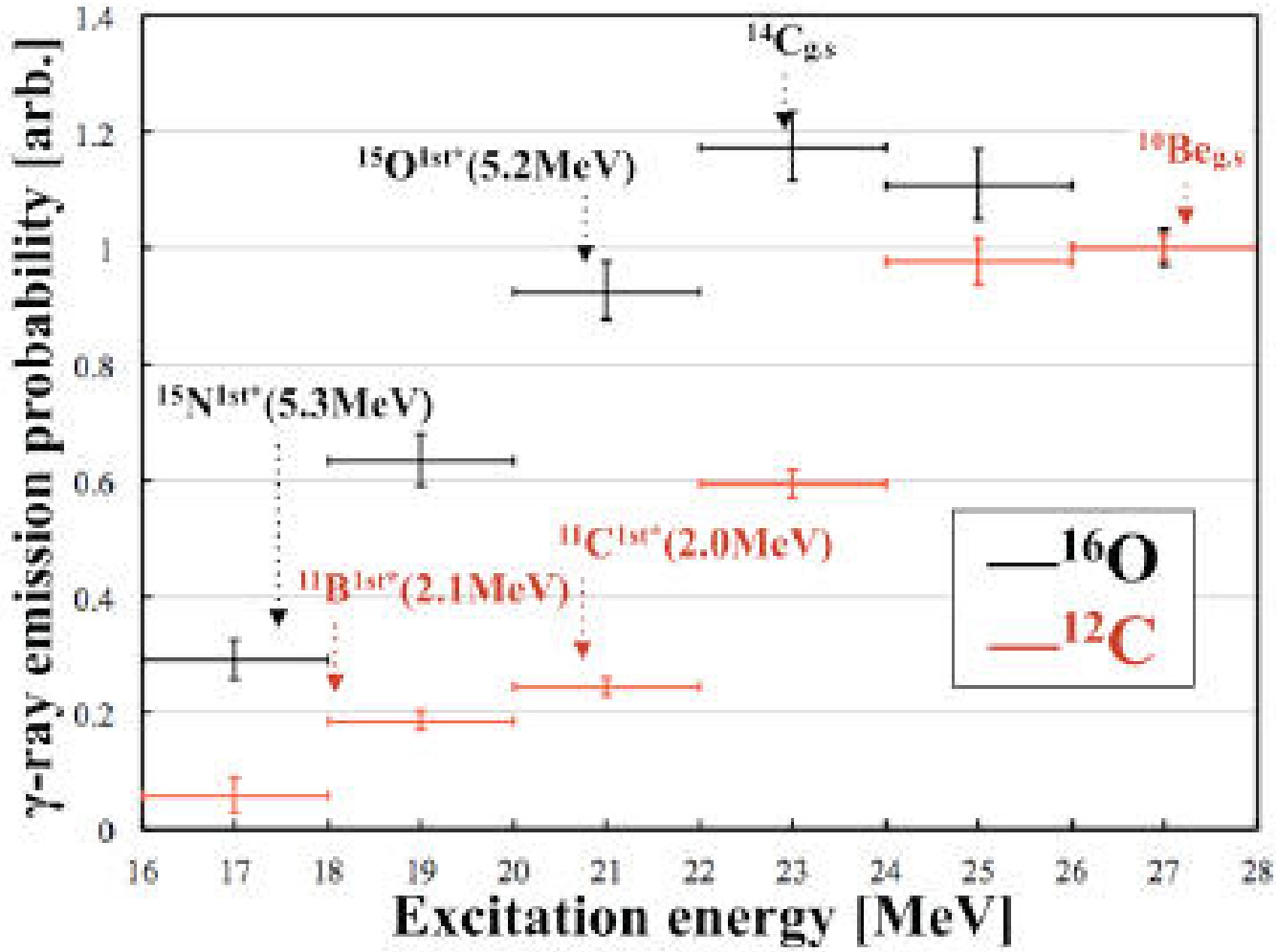


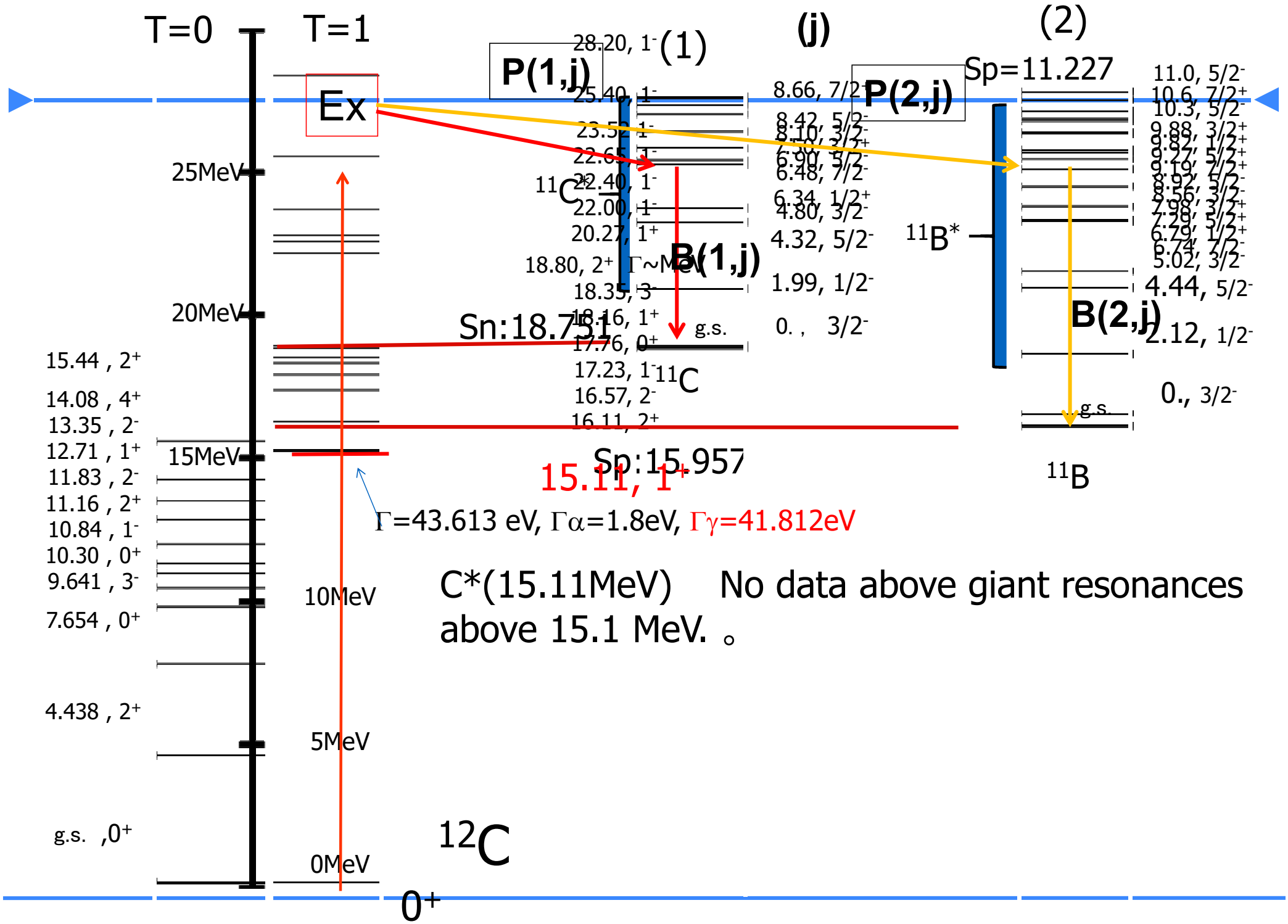
The observed rate is consistent with Langanke's prediction qualitatively. We will determine the decay probability (20%) after we estimate the γ-ray detection efficiency.

^{12}C and ^{16}O: γ-decay probability (Γγ/Γ)

(I.Ou (E398), presented at NuInt15)

The observed rate is consistent with Langanke's prediction qualitatively.




T=0
T=1
Ex
25MeV
20MeV
15MeV
10MeV
5MeV
0MeV
15.44 , 2+
14.08 , 4+
13.35 , 2-
12.71 , 1+
11.83 , 2-
11.16 , 2+
10.84 , 1-
10.30 , 0+
9.641 , 3-
7.654 , 0+
4.438 , 2+
g.s. ,0+
12C
0+
P(1,j)
(1)
(j)
11C
28.20, 1-
25.40, 1-
23.52, 1-
22.65, 1-
22.40, 1-
22.00, 1-
20.27, 1+
18.80, 2+ Γ~MeV
18.35, 3-
18.16, 1+
17.76, 0+
17.23, 1-
16.57, 2-
16.11, 2+
g.s.
Sn:18.731
Sp:15.957
15.11, 1+
Γ=43.613 eV, Γα=1.8eV, Γγ=41.812eV
B(1,j)
8.66, 7/2-
8.42, 5/2-
8.10, 3/2+
6.90, 5/2-
6.48, 7/2-
6.34, 1/2+
4.80, 3/2-
4.32, 5/2-
1.99, 1/2-
0. , 3/2-
P(2,j)
(2)
Sp=11.227
11B*
11B
B(2,j)
11.0, 5/2-
10.6, 7/2+
10.3, 5/2-
9.88, 3/2+
9.82, 1/2+
9.27, 5/2+
9.19, 7/2+
8.92, 3/2-
8.56, 3/2-
7.98, 3/2+
7.29, 5/2+
6.79, 1/2+
6.74, 7/2-
5.02, 3/2-
4.44, 5/2-
2.12, 1/2-
0., 3/2-
g.s.
C*(15.11MeV) No data above giant resonances above 15.1 MeV. 。

CASCADE

CASCADE Code (Puhlhofer('77), Harakeh('87))

➢Decay: nucleus-1 (E_1, J_1)→x + nucleus-2 (E_2, J_2)

x=p,n,d,α,t

$$R_x d\varepsilon_x = \frac{1}{\hbar}\Gamma_x(\varepsilon_x) = \frac{1}{2\pi\hbar}\frac{\rho_2(E_2, J_2, \pi_2)}{\rho_1(E_1, J_1, \pi_1)} \sum_{S=|J_2-S_x|}^{J_2+S_x} \sum_{L=|J_1-S|}^{J_1+S} T_L^x(\varepsilon_x) d\varepsilon_x$$

$\varepsilon x = E_1 - E_2$ -Separation Energy, $S = J_2 + S_x$, is the channel spin

Summary

- We took data of the excitation energy and γ-ray energy spectrum from giant resonances in C, O(p,p') reactions in 2014.
- Data are qualitatively consistent with Langanke et al.'s prediction in which the giant resonances above particle threshold decay to the ground state or excited states of daughter nuclei, and the latter emits γ-rays.]
- Hope to obtain the first measurements of Br(C,O, Ex=16-30MeV $\rightarrow\gamma$) at 10-20% level.
- Need to calculate NC ν+O,C (1-,2-,1+) and combine Br(C*,O*$\rightarrow\gamma$) , and finally obtain NC γ production cross section in the SN region.
- GR Forward Beamline has been improved. It accepts scattered protons at larger angles >4deg.
- After finishing off the first results, we like to propose an extension of the experiment to RCNP.