Nuclear Response and Gamma Emissivity Studied by Proton Inelastic Scattering

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Outline

1. IS/IV spin-M1 response in N=Z sd-shell nuclei

   Quenching in IS/IV spin-M1 transition strengths

2. Gamma Emissivity of the Giant Resonances in ^{12}C and ^{16}O

   NC ν-Reaction in Water Cherenkov Detector

IS/IV spin-*M1* responses and their quenching in *N*=*Z* *sd*-shell nuclei

H. Matsubara[1], A. Tamii[2]
and RCNP-E299 collaboration

[1]*National Institute of Radiological Sciences*
[2]*RCNP, Osaka University*

IS/IV spin-*M1* response

ν-opacity and ν-transportation in SNe and PNS

SNe dynamics, nucleosynthesis, cooling of a proton neutron star

- GT, IS/IV-spinM1 response of nuclear matter
- IS-spinM1 response of pure neutron matter

Spin (magnetic) susceptibility and response to a strong magnetic field

$$\frac{\chi_\sigma}{2n} = \frac{4}{3N}\sum_f \frac{1}{\omega}\left|\langle f|\sum_i \boldsymbol{\sigma}_i|0\rangle\right|^2$$

Inversely energy weighted sum-rule of spin-M1 transition strengths.

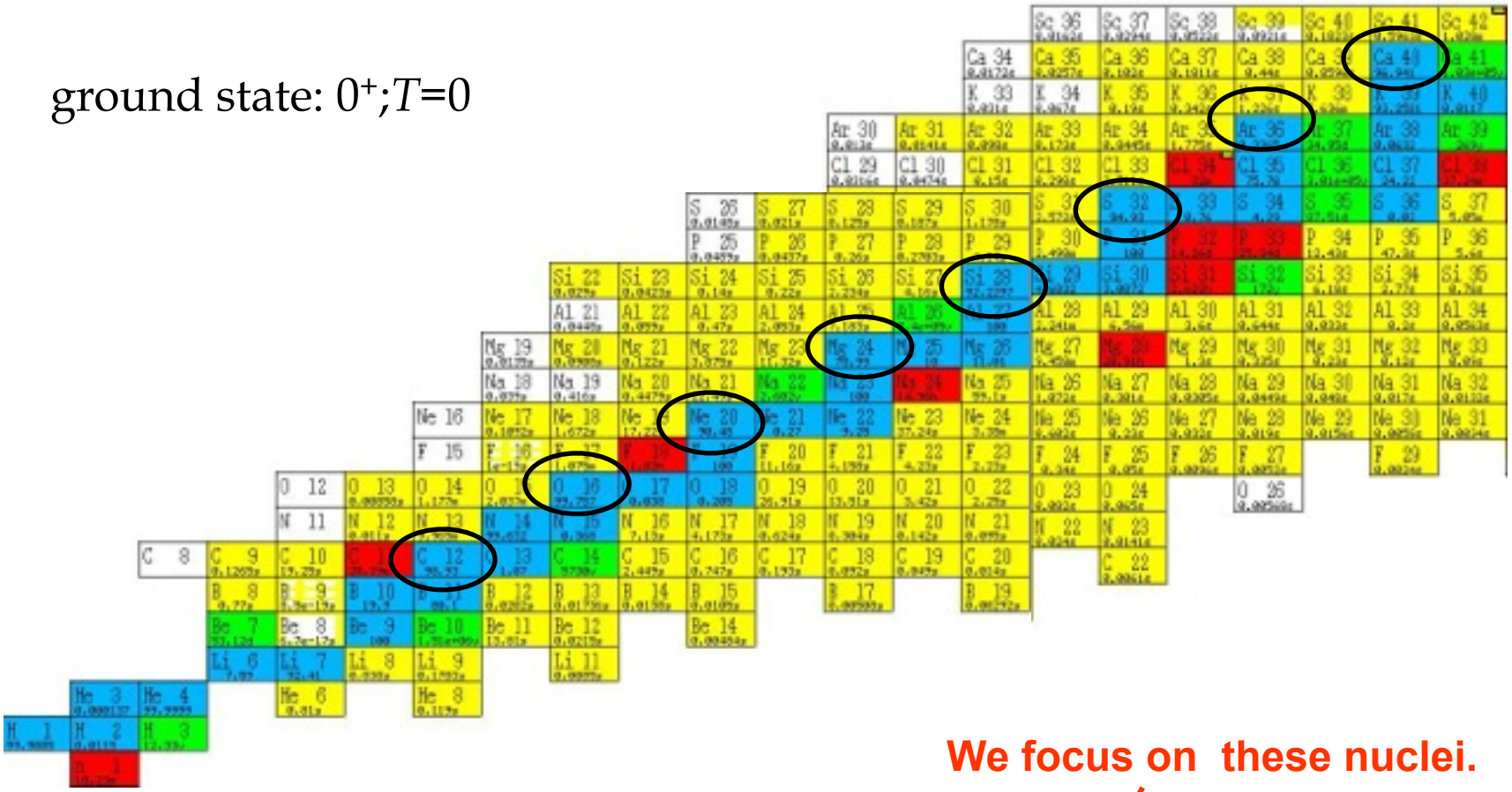
G. Shen et al., PRC**87**, 025802 (2013)

Magnetic response of nuclear matter in a magnetar

The mechanism of quenching need to be understood well.

Measurement of IS/IV spin-*M1* Transition Strengths in *N*=*Z* Nuclei

ground state: $0^+;T=0$



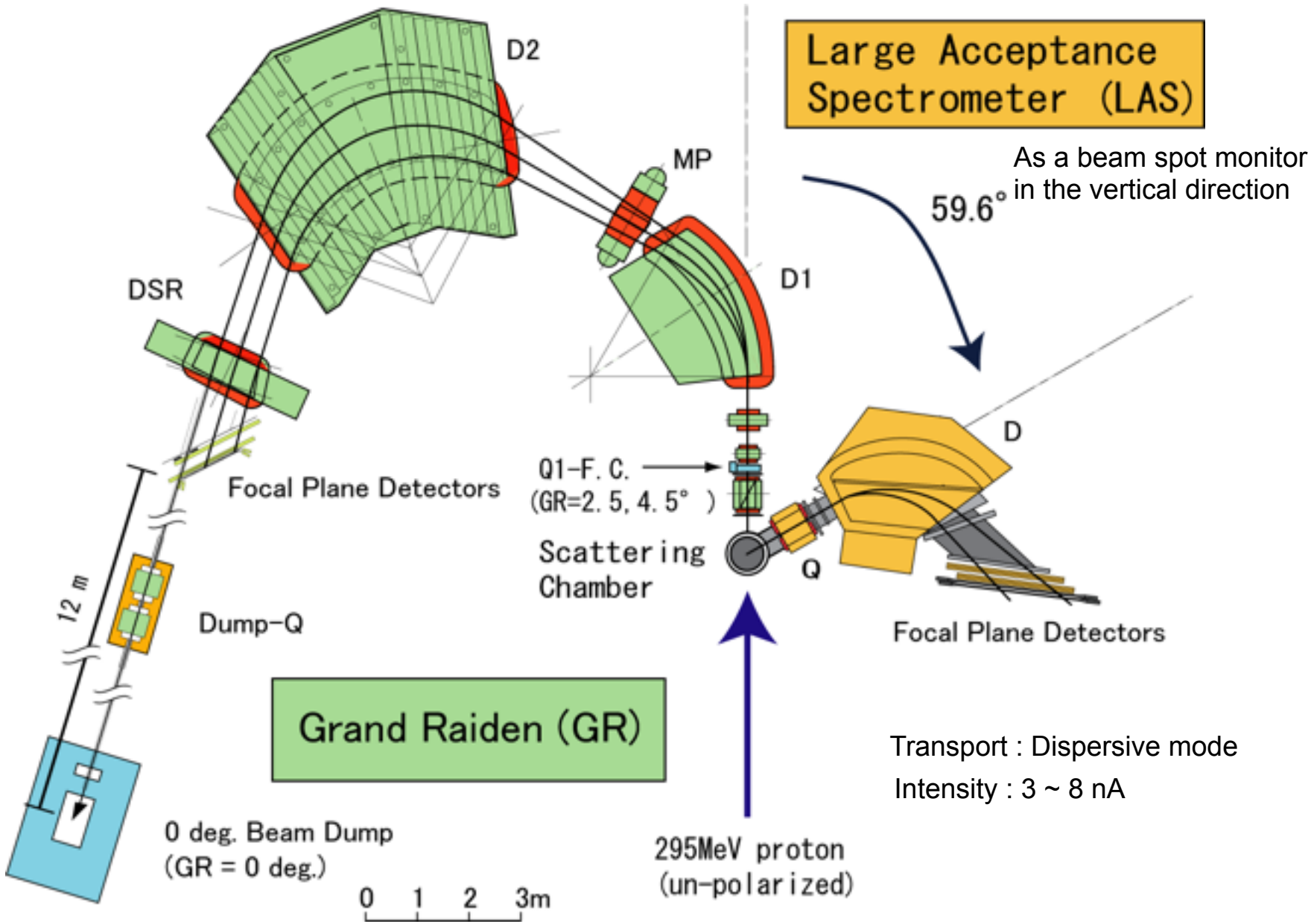
We focus on these nuclei.

Stable self-conjugate even-even nuclei:

$(^{4}\mathrm{He}),\ ^{12}\mathrm{C},\ ^{16}\mathrm{O},\ ^{20}\mathrm{Ne},\ ^{24}\mathrm{Mg},\ ^{28}\mathrm{Si},\ ^{32}\mathrm{S},\ ^{36}\mathrm{Ar},\ ^{40}\mathrm{Ca}$

We measured (p,p′) for all the above nuclei except ^{4}He.

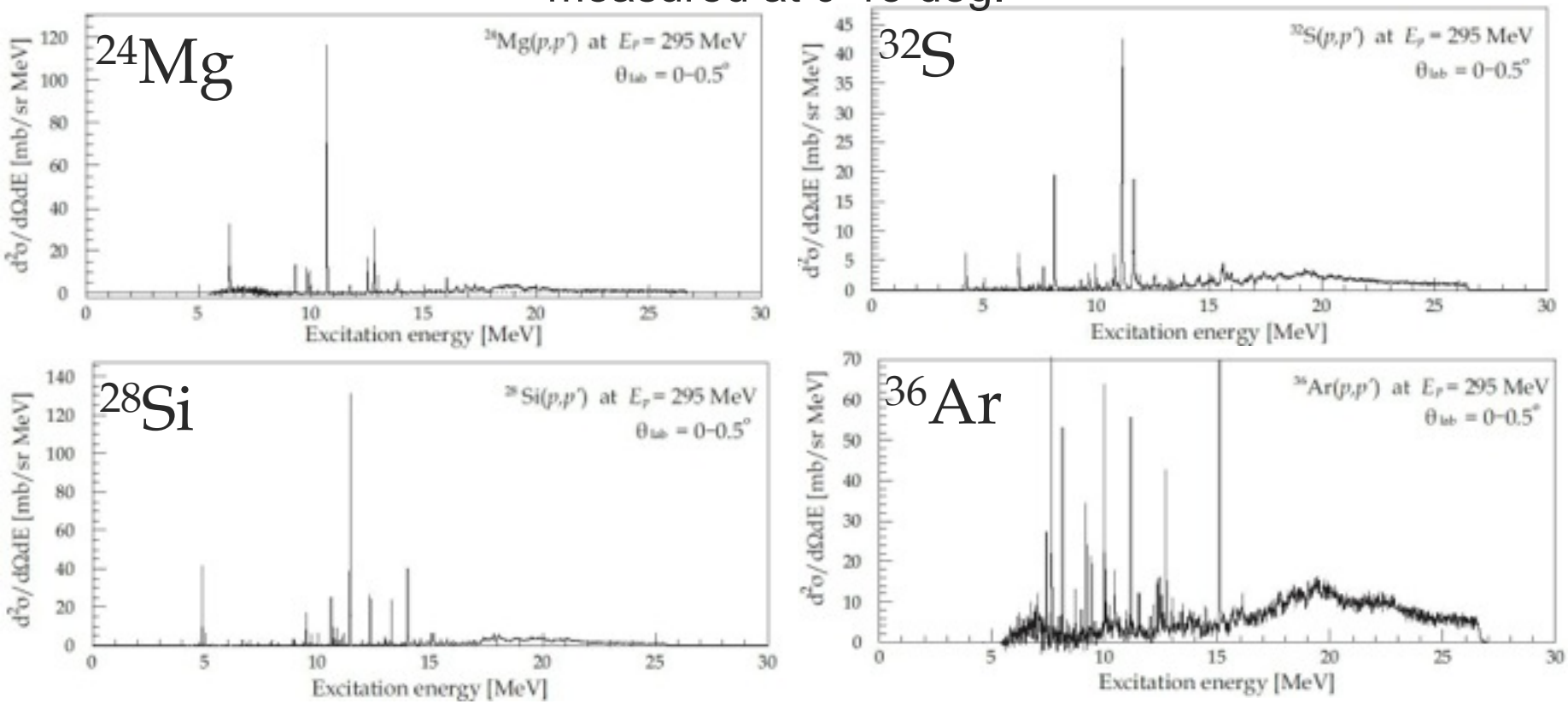
Spectrometer Setup for 0-deg (p,p') at RCNP



(p,p') Spectra at E_p=295 MeV

RCNP-E299

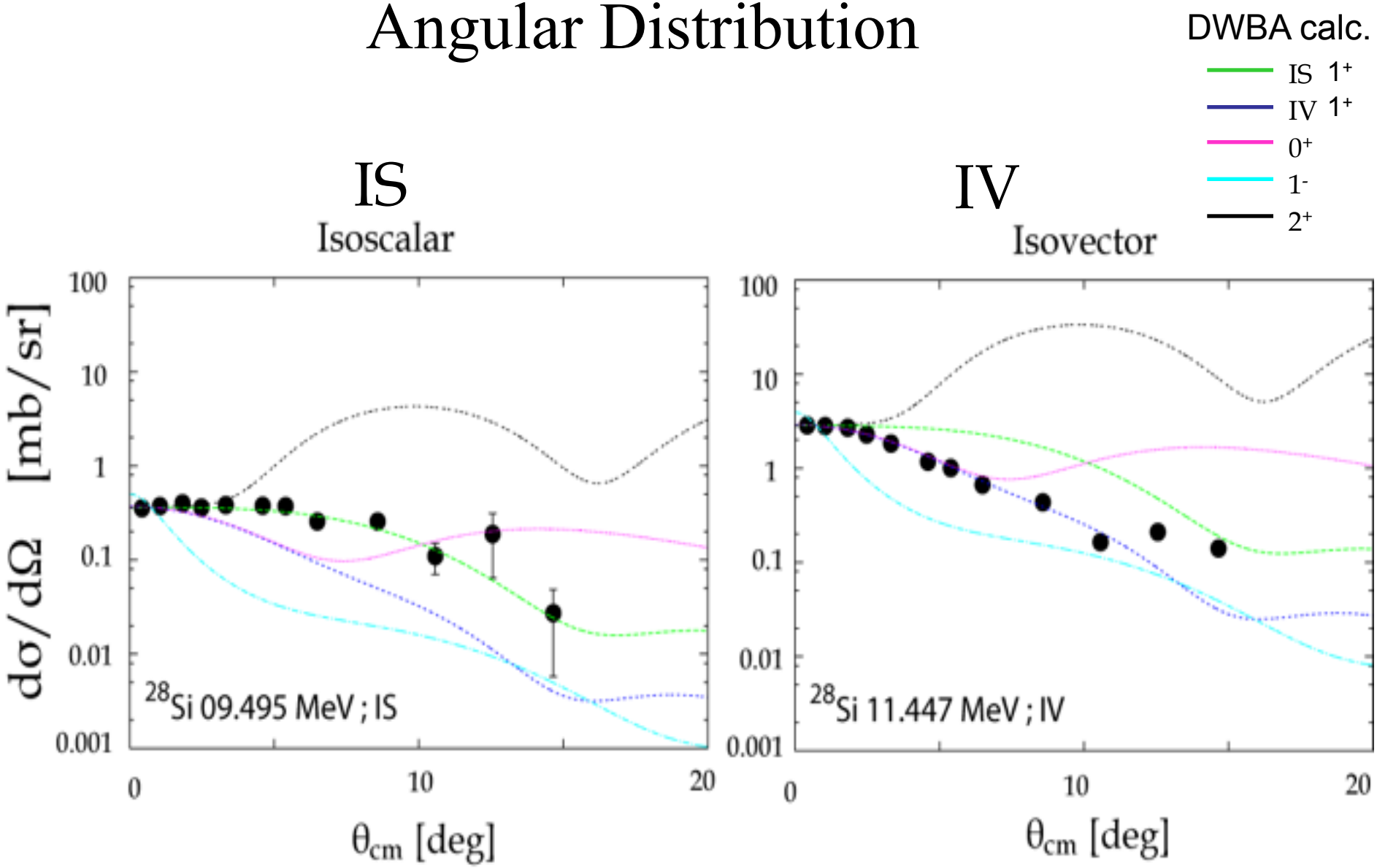
measured at 0-15 deg.



IS/IV 1^+ states were identified from angular distribution for each of IS and IV transitions.

The cross sections at the most forward angles have were converted to the spin-M1 strengths.

Angular Distribution



ΔT(IS or IV) has also been identified from angular distribution.

Unit cross section (UCS)

- Conversion factor from cross-section to Squared Nuclear Matrix Elements (SNME)
- Calibration from β andγ-decay measurements
  (on the assumption of the isospin symmetry).

$$\frac{d\sigma}{d\Omega}(0^\circ) = \hat{\sigma}_T F(q, E_x) |M_f(O)|^2$$

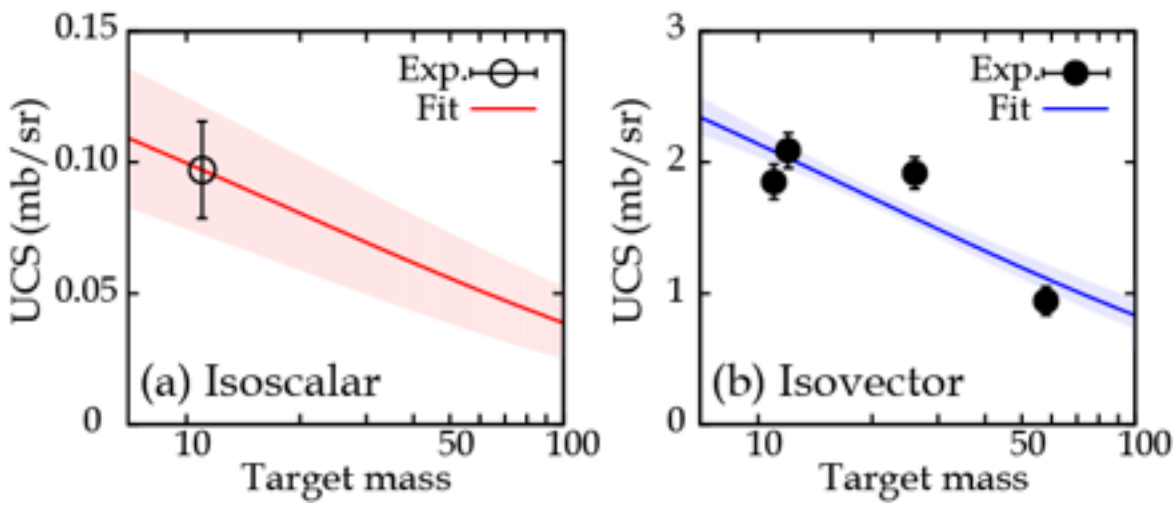
(*T*= IS or IV)

UCS Kinematical factor SNME

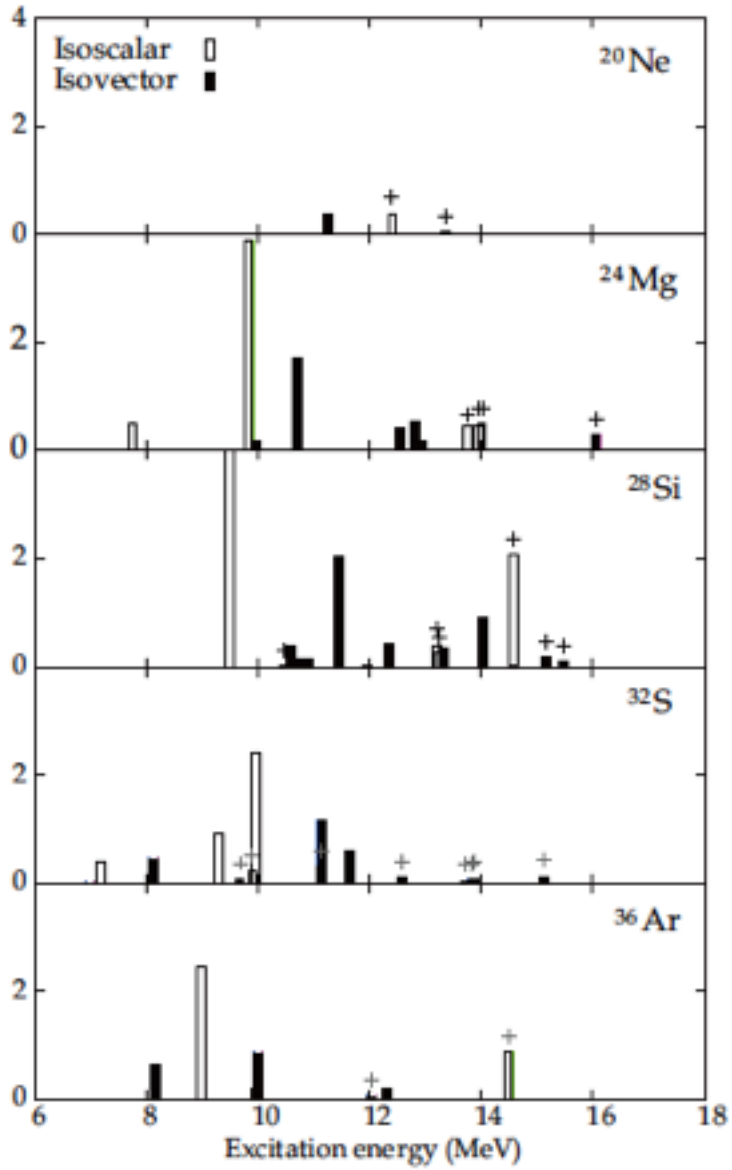
$$\hat{\sigma}_T(A) = N \exp\left(-xA^{1/3}\right)$$

- Function taken from the mass dependence of GT UCS

M. Sasano *et al.*, PRC**79**, 024602 (2009)



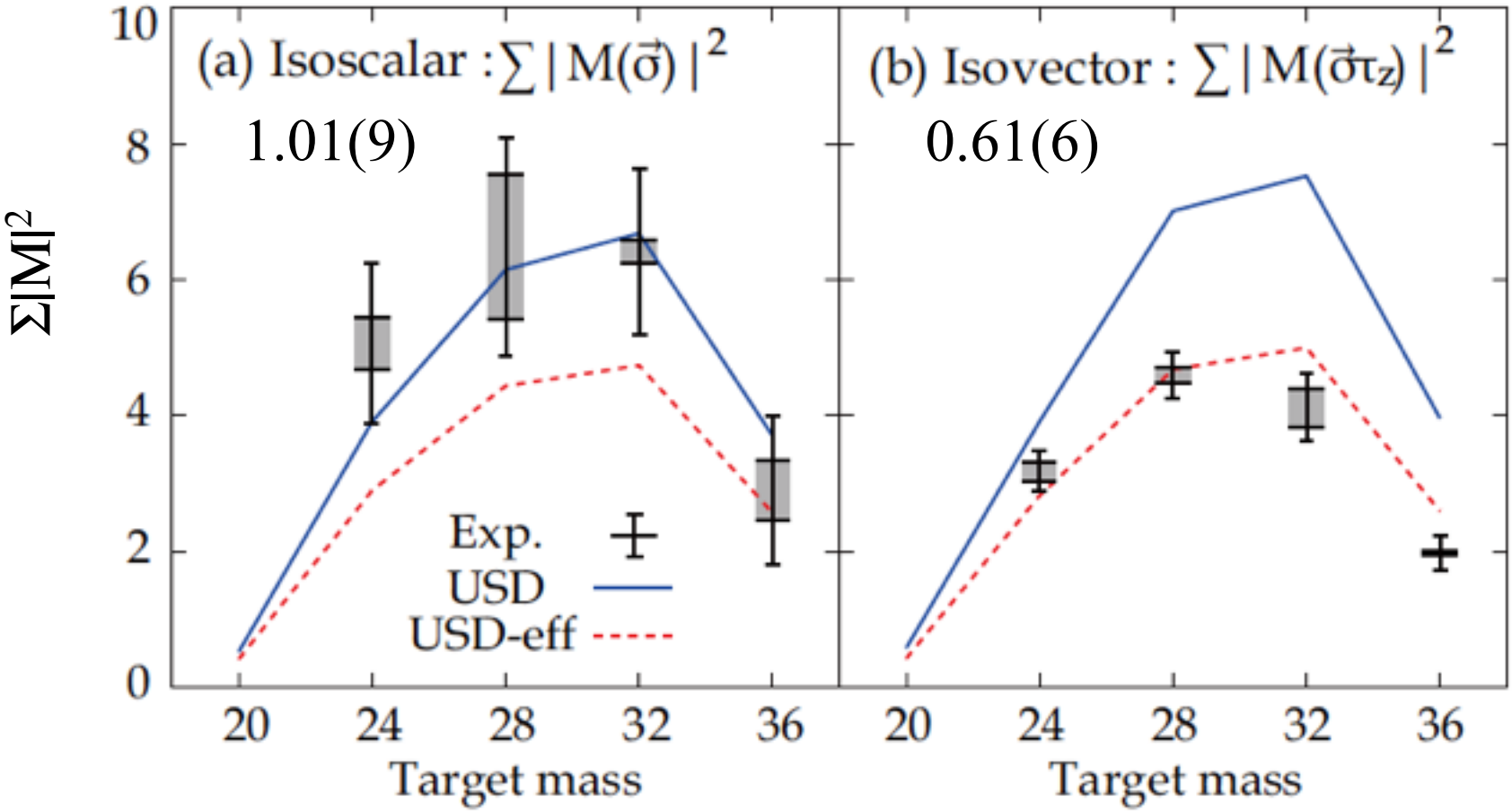
Spin-M1 Strength Distribution



Sum of the strengths is taken up to 16 MeV for each of IS and IV transitions.

IS Spin-M1 Matrix Elements Are NOT Quenching

from the shell-model prediction with USD

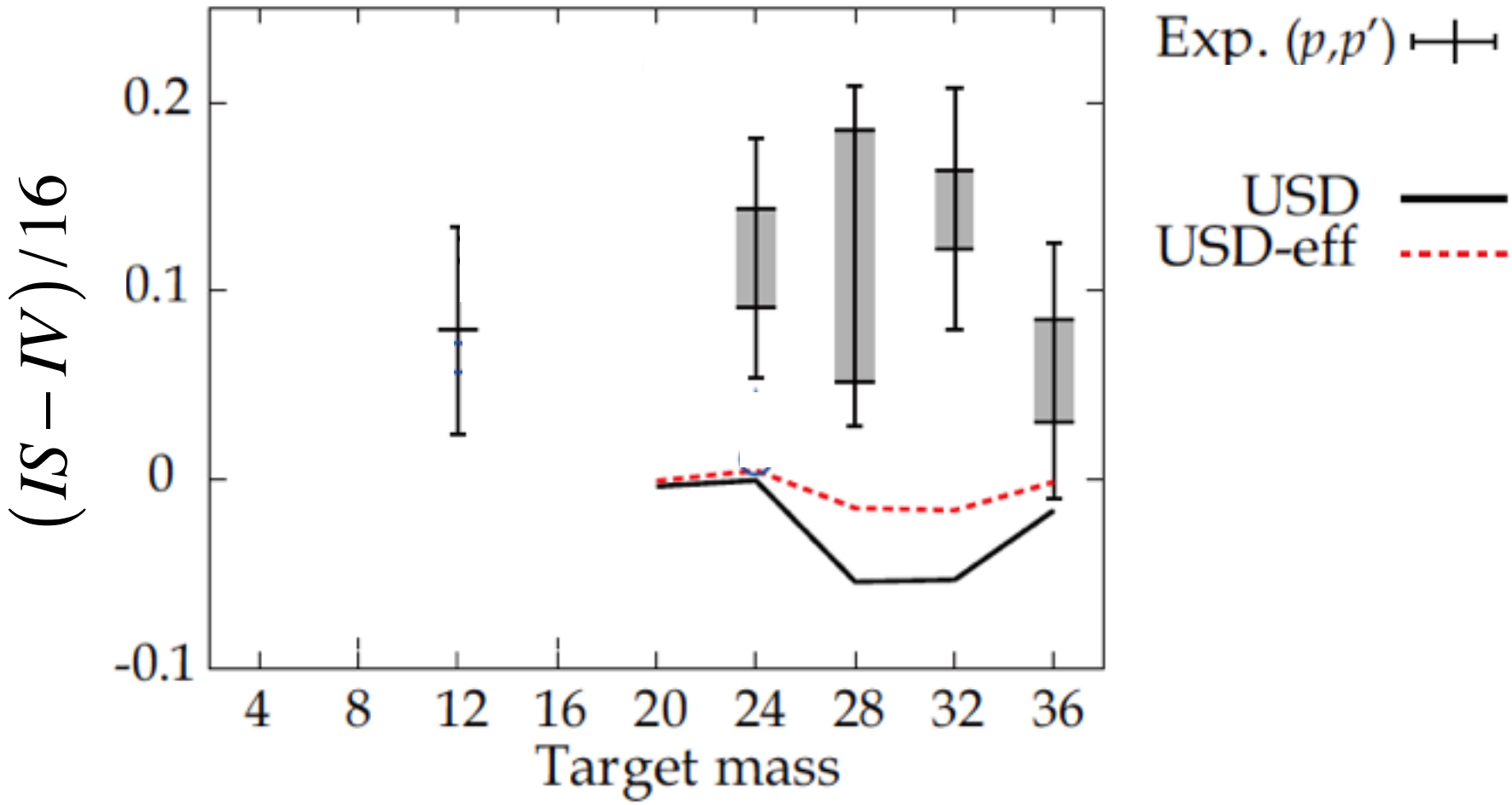


No quenching

Quenching similar to GT

Difference of IS and IV

Correlated Gaussian Method: W. Horiuchi
Non-Core Shell Model: P. Navratil
Shell-Model: USD interaction



np-spin correlation in the g.s. - IS/IV Spin-M1 Sum-Rule

$$\vec{S}_p \equiv \sum_{i=1}^{Z} \vec{s}_i = \sum_{i=1}^{Z} \frac{\vec{\sigma}_i}{2} \quad \text{for } p$$

$$\vec{S}_n \equiv \sum_{i=1}^{N} \vec{s}_i = \sum_{i=1}^{N} \frac{\vec{\sigma}_i}{2} \quad \text{for } n$$

$$\left\langle \left(\vec{S}_n - \vec{S}_p\right)^2 \right\rangle = \frac{1}{4}\left\langle \left(\vec{\sigma}\tau_z\right)^2 \right\rangle$$

$$= \frac{1}{4}\sum_f \langle 0|\vec{\sigma}\tau_z|f\rangle\langle f|\vec{\sigma}\tau_z|0\rangle$$

$$= \frac{1}{4}\sum_f \left|\langle f|\vec{\sigma}\tau_z|0\rangle\right|^2$$

closure

$$= \frac{1}{4}\sum \left|M\left(\vec{\sigma}\tau_z\right)\right|^2$$

IV spin-M1 transition matrix elements

$$\left\langle \left(\vec{S}_n + \vec{S}_p\right)^2 \right\rangle = \frac{1}{4}\sum \left|M\left(\vec{\sigma}\right)\right|^2$$

IS spin-M1 transition matrix elements

$$\left\langle \vec{S}_n \bullet \vec{S}_p \right\rangle = \frac{1}{4}\left\langle \left(\vec{S}_n + \vec{S}_p\right)^2 - \left(\vec{S}_n - \vec{S}_p\right)^2 \right\rangle$$

$$= \frac{1}{16}\left(\sum \left|M\left(\vec{\sigma}\right)\right|^2 - \sum \left|M\left(\vec{\sigma}\tau_z\right)\right|^2\right)$$

IS - IV

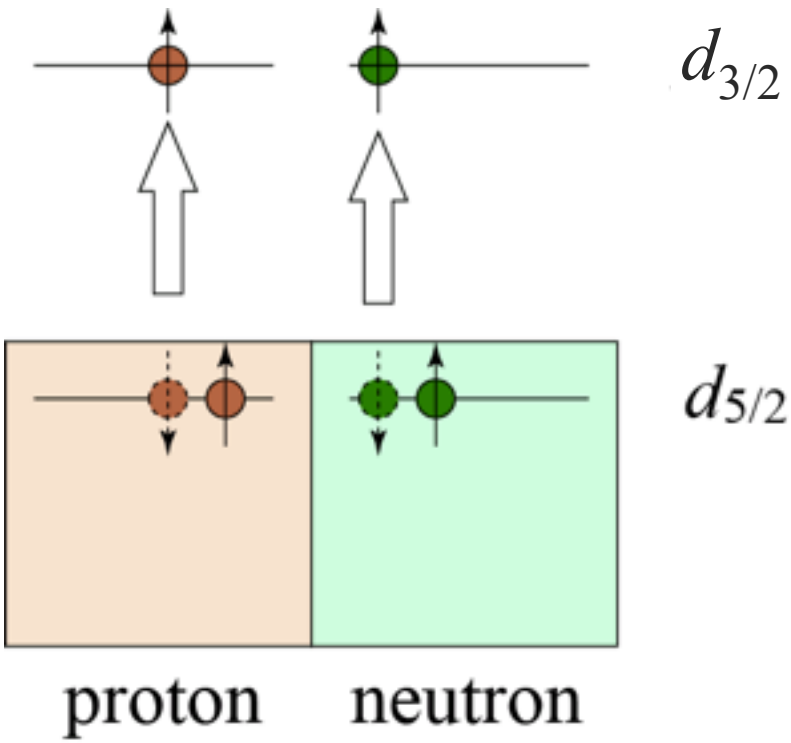
$$\left\langle \vec{S}_n^2 + \vec{S}_p^2 \right\rangle = \frac{1}{4}\left\langle \left(\vec{S}_n + \vec{S}_p\right)^2 + \left(\vec{S}_n - \vec{S}_p\right)^2 \right\rangle$$

$$= \frac{1}{16}\left(\sum \left|M\left(\vec{\sigma}\right)\right|^2 + \sum \left|M\left(\vec{\sigma}\tau_z\right)\right|^2\right)$$

The ground state expectation value can be extracted from the sum-rules of the IS/IV spin-M1 transition matrix elements.

np-Correlated 2p-2h Admixture in the ground state

induced by tensor-type
short-range correlation



$$\left\langle \vec{S}_n \bullet \vec{S}_p \right\rangle > 0$$

^{4}He with realistic *NN* interaction (Correlated Gaussian Method)

Spin matrix elements of the ^{4}He ground state

CG calc. by W. Horiuchi

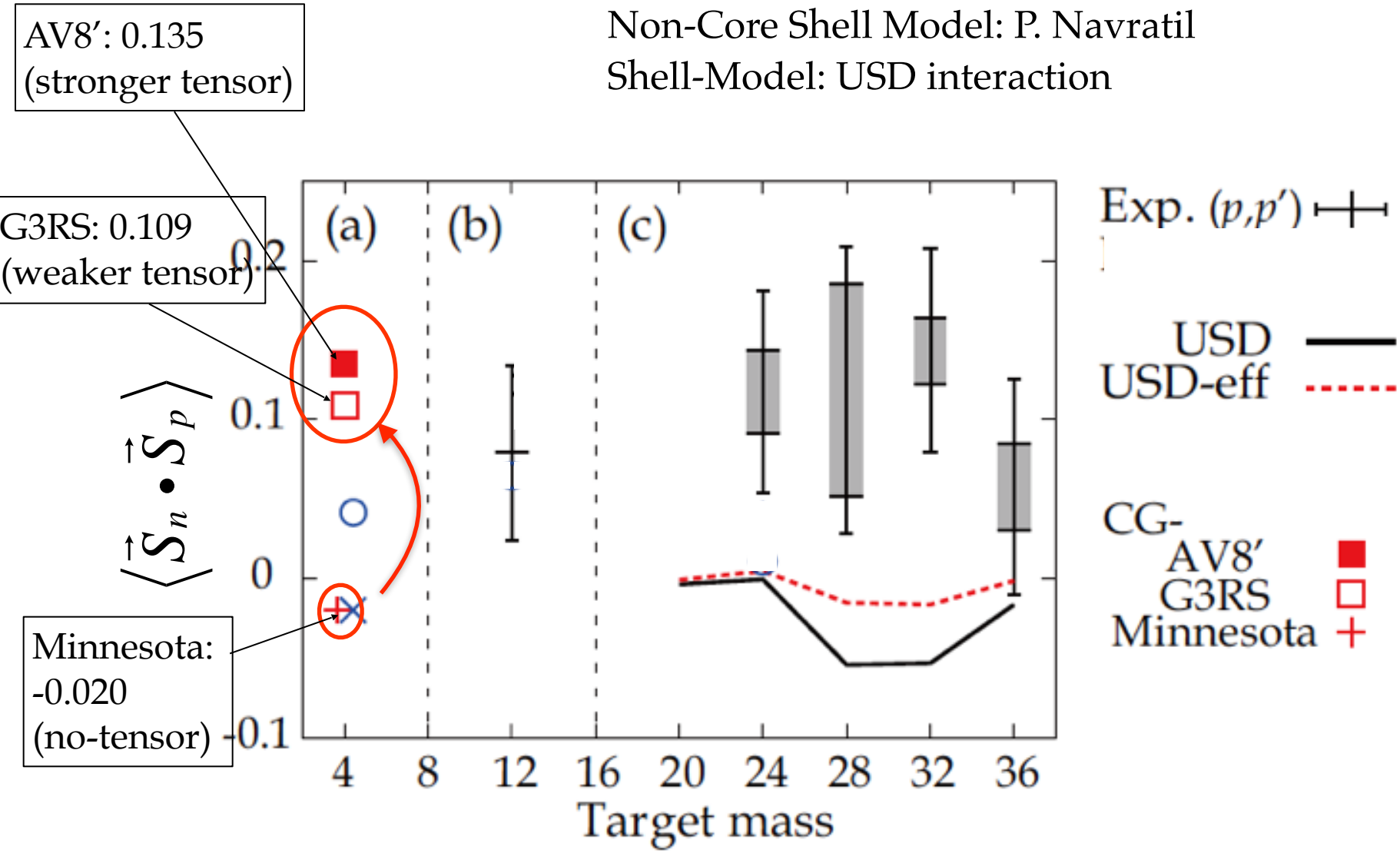
	$\langle \vec{S}_p^2 + \vec{S}_n^2 \rangle$	$\langle \vec{S}_p \cdot \vec{S}_n \rangle$	S=0	S=1	S=2
AV8' Stronger tensor int.	0.572	0.135	85.8%	0.4%	13.9%
G3RS Weaker tensor int.	0.465	0.109	88.5%	0.3%	11.3%
Minnesota No tensor int.	0.039	-0.020	100%	0%	0%

$$\vec{S} = \vec{S}_p + \vec{S}_n$$

Y. Suzuki, W. Horiuchi et al., FBS42, 33(2007)
H. Feldmeier, W. Horiuchi et al., PRC84, 054003(2011)

Difference of IS and IV

Correlated Gaussian Method: W. Horiuchi
Non-Core Shell Model: P. Navratil
Shell-Model: USD interaction



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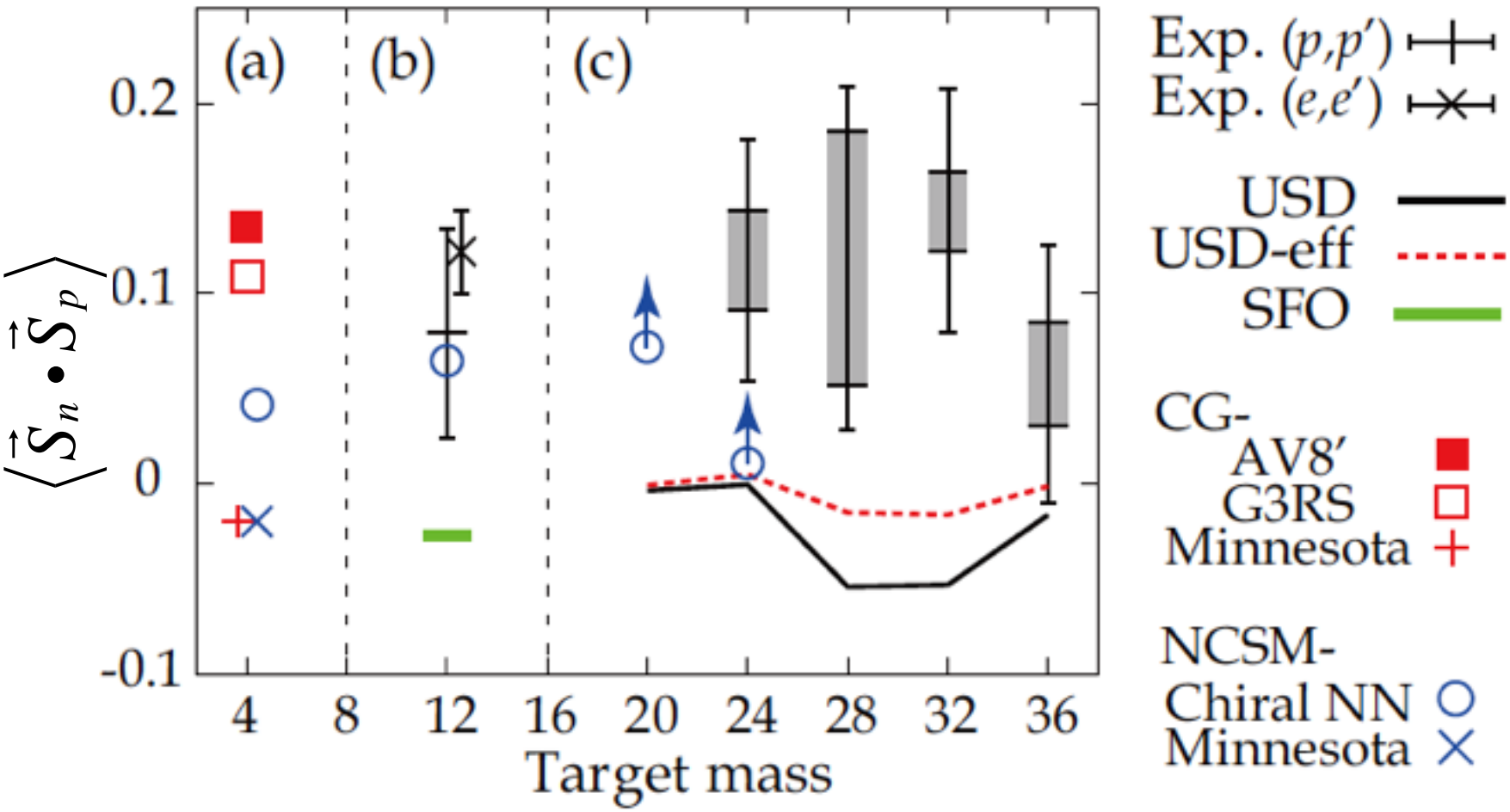

# of IS and IV

Correlated Gaussian Method: W. Horiuchi
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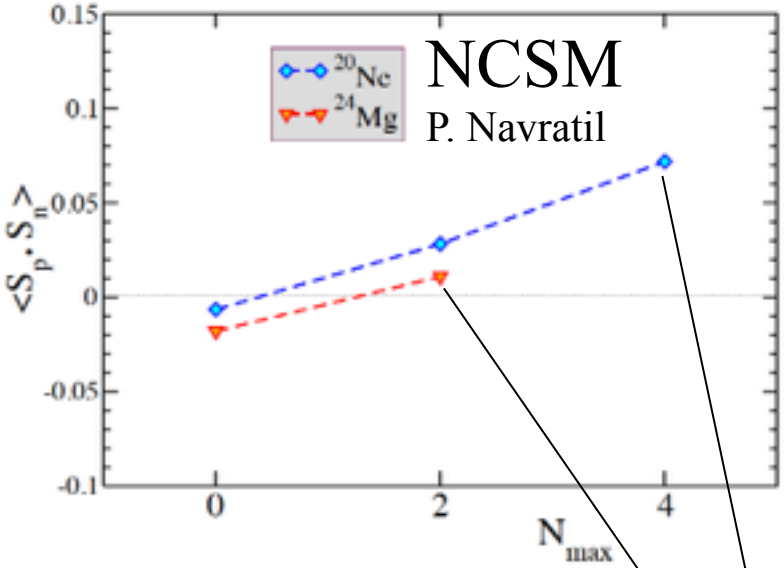
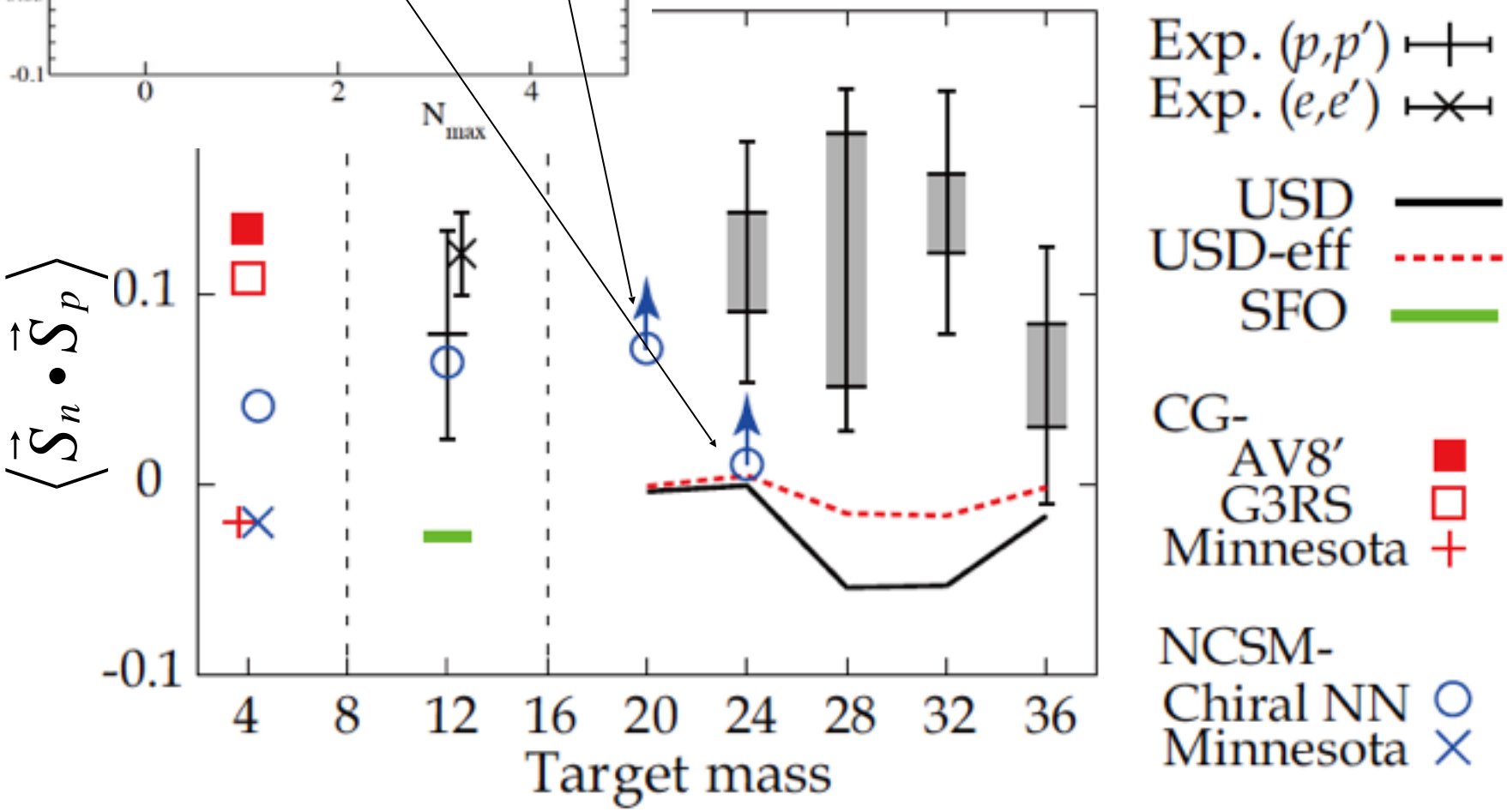




Summary of the 1st Part

- Study of the spin-M1 responses in nuclei and their quenching mechanism is important for the ν-transportation in SNe or in PNS.

- The IS spin-M1 SNME in *N*=*Z* sd-shell nuclei are NOT quenching from the shell model prediction with USD int, while the IV spin-M1 SNMEs are quenching as is the case of GT.

- The positive values of the IS-IV SNMEs hint the *np*-correlated 2p2h admixture in the gourd state, and are supported by the CG calculation of ^{4}He with realistic tensor interaction and by NCSM calculations.

Gamma Emissivity of the Giant Resonances in ^{12}C and ^{16}O

I. Ou and M. Sakuda (Okayama Univ.)

and

A. Tamii (RCNP, Osaka Univ.)

for the RCNP-E398 Collaboration

Supernova Neutrino Detection by NC Neutrino Reactions

✳ Expected number of events
by a core-collapse supernova explosion @10kpc

- Super Kamiokande (H_2**O**)

  Beacom-Vogel,PRD58,053010(1998)

  $CC: \bar{\nu}_e + p \rightarrow e^+ + n$ ~8000 ev.

  $NC: \nu_x + {}^{16}O \rightarrow \nu_x + X + \gamma \; (\nu_x = \nu_\mu, \nu_\tau)$ ~700 ev.

  and antil-neutrinos

- KamLAND (**C**H)

  A. Suzuki,NPB-Suppl 77, 171(1999)

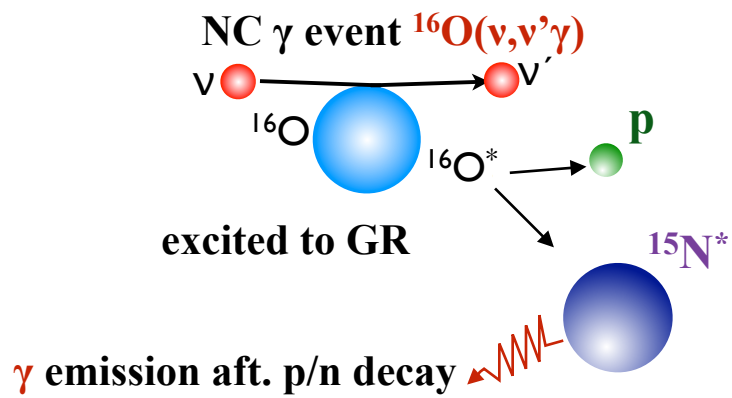
  $CC: \bar{\nu}_e + p \rightarrow e^+ + n$ ~ 300 ev.

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

  $NC: \nu_x + {}^{12}C \rightarrow \nu_x + X + \gamma \; (E_X > 16 MeV$ ~ 60 ev.

  and antil-neutrinos

✳ **SN 1987A** @50kpc



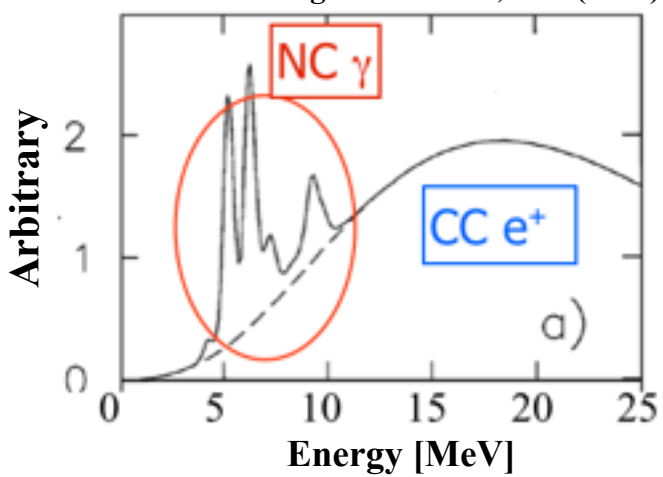
NC events can be detected by γ-rays

Importance of the **NC** Reactions in ^{16}O

- **The 2nd most type of events.**
- **μ,τ–ν events dominate NC.**
  → $T_{\nu\mu}, T_{\nu\tau} > T_{\nu e}$ Info. on equilibrium temp
- **Effect of the ν-oscillation**

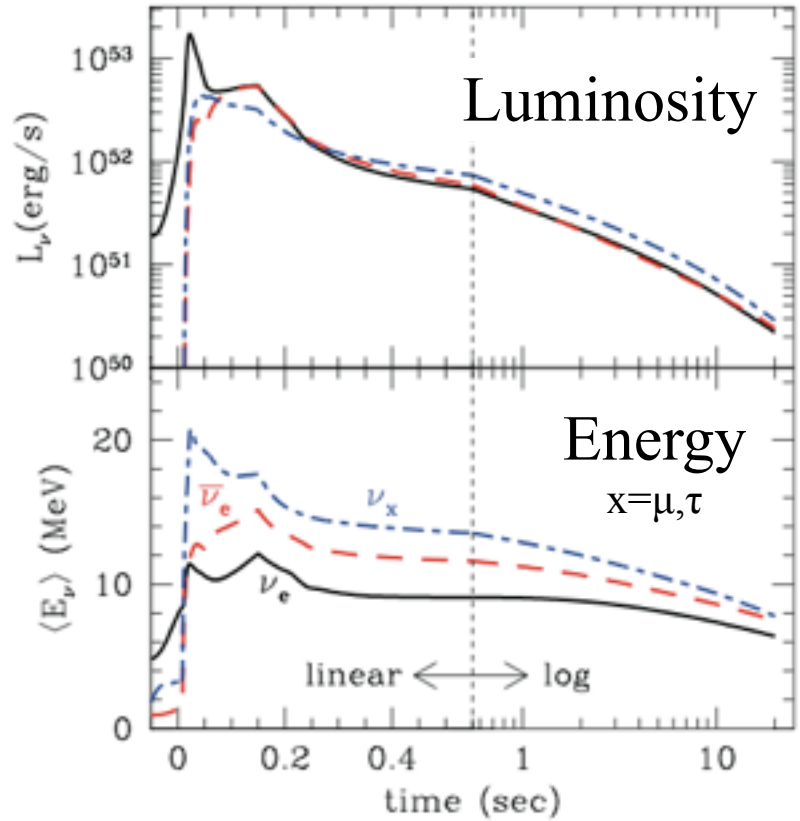
Estimated signal in SK

K. Langanke PRL76, 2629(1996)



Numerical simulations of Supernova

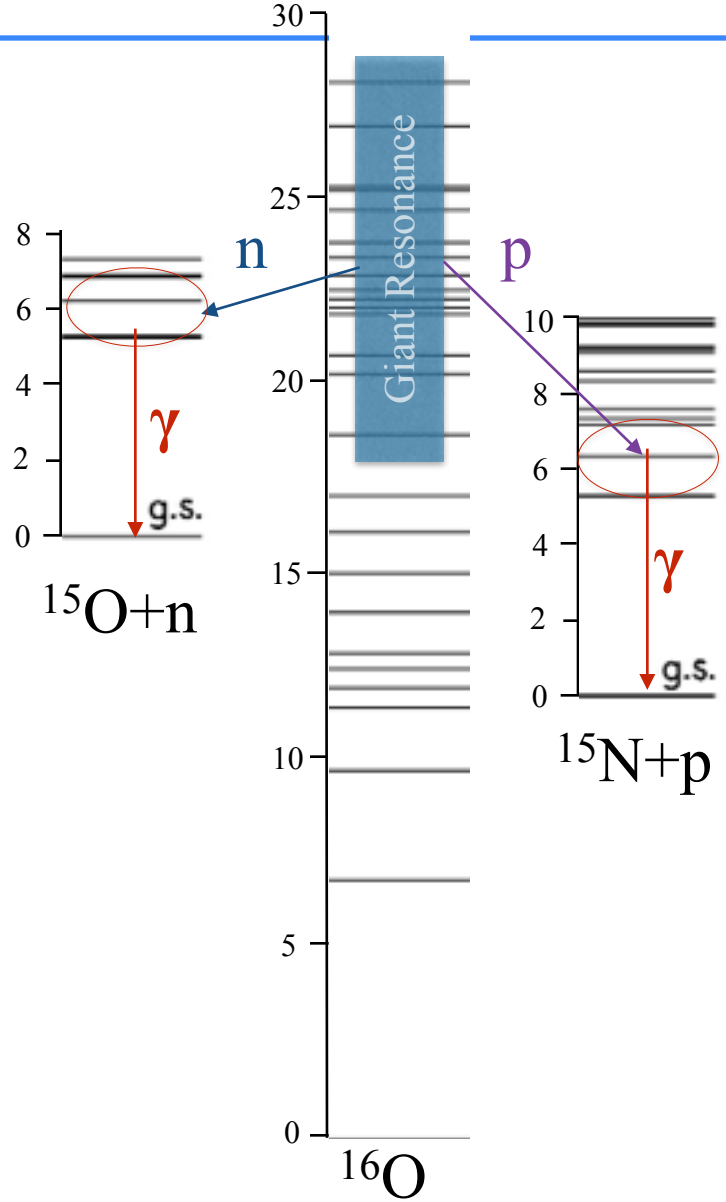
K. Nakazato ApJS205:2(2013)



Essentially no data exist on γ-ray emissivity from giant resonances

→RCNP-E398: measurement of the γ-ray emission probability(Pr) and the energy from GDR and SDR.

γ-Emission from Giant Resonances in ^{16}O

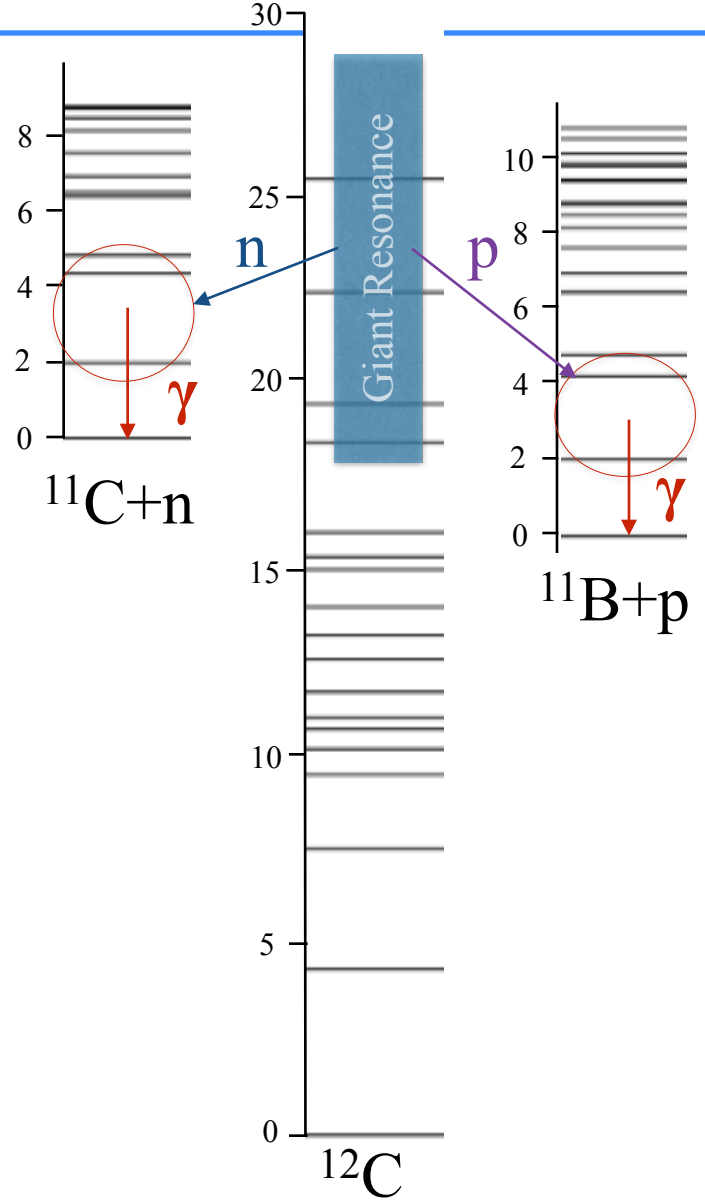


$\Sigma E_\gamma > 5$ MeV

Statistical cal. (SMOKER)
@ $\langle E_x \rangle = 25$MeV
$Pr(NC\ ^{15}N^*\gamma) = 25\%$
$Pr(NC\ ^{15}O^*\gamma) = 6\%$

Langanke PRL76, 2629(1996)
Kolbe PRD66,013007(2002)

γ-Emission from Giant Resonances in ^{12}C



$\Sigma E_\gamma > 2$ MeV

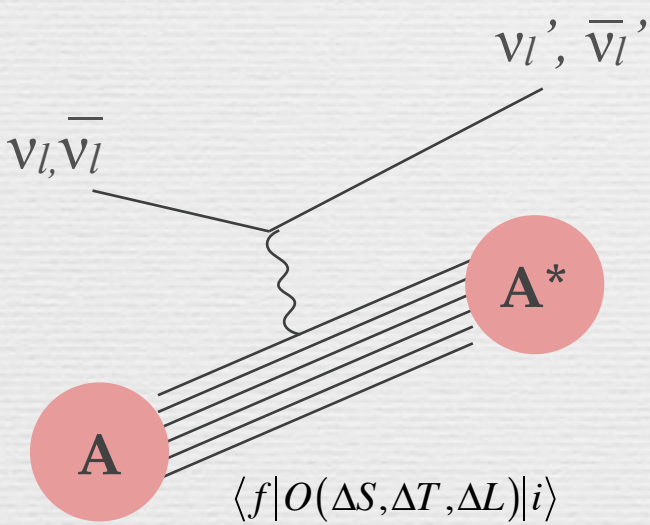
Probing Nuclear Matrix Elements by a Light-Ion (Hadronic) Reaction

(Cross Section) ~ (Kinematical Factor)×[(Interaction)×(Matrix Element)]^2

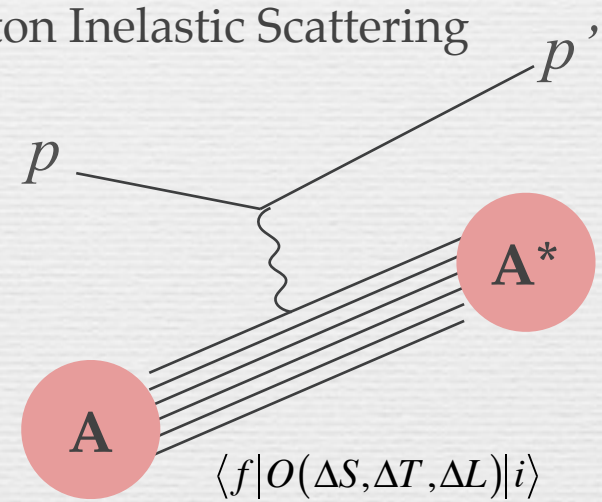
Requires calibration

Common between the hadronic reaction and the neutrino reaction

Neutral Current ν Reaction



Proton Inelastic Scattering



IVGDR: ΔS=0, ΔT=1, ΔL=1
IVSDR: ΔS=1, ΔT=1, ΔL=1
(spin-M1, IS, …)

Probing Nuclear Matrix Elements by a Light-Ion (Hadronic) Reaction

(Cross Section) ~ (Kinematical Factor)×[(Interaction)×(Matrix Element)]^2

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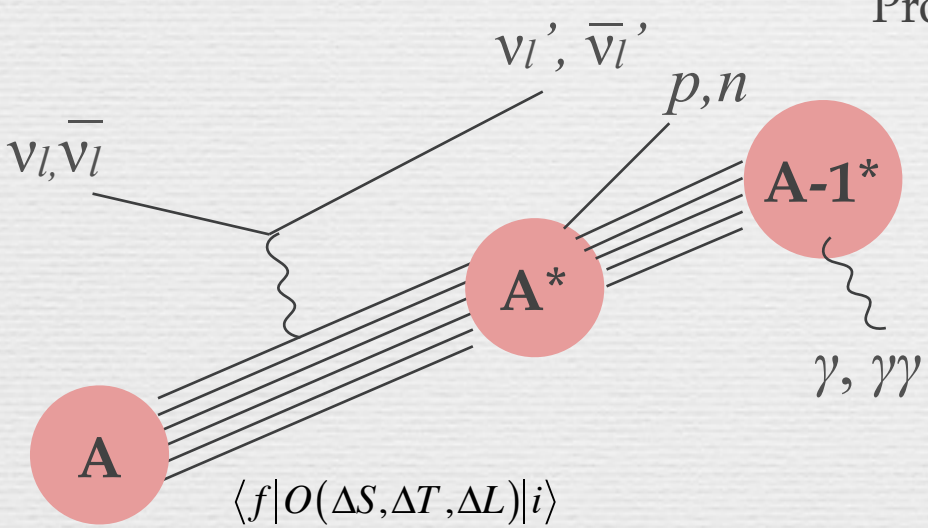
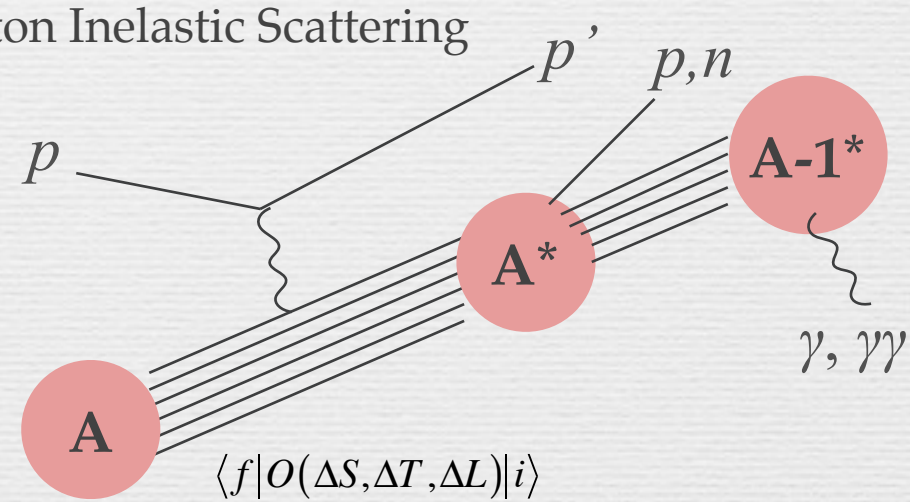
Neutral Current ν Reaction



Proton Inelastic Scattering

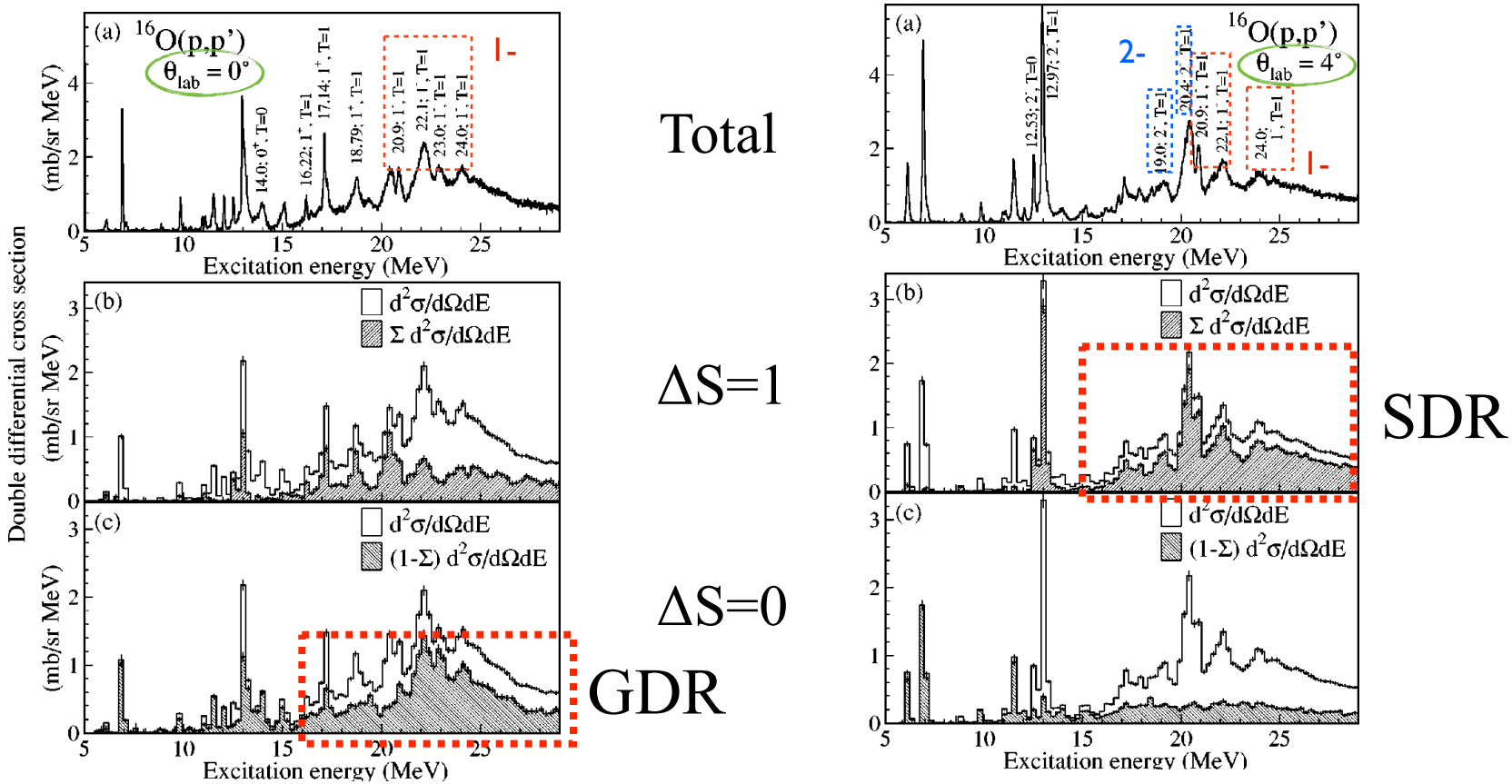


IVGDR: ΔS=0, ΔT=1, ΔL=1
IVSDR: ΔS=1, ΔT=1, ΔL=1
(spin-M1, IS, …)

$^{16}O(p, p')$ at small angles

- O(ν,ν'): SDR(2^-,1^-) dominant. C(ν,ν'): SDR & 1^+(15.11MeV) dominant
- **O,C(p,p'): SDR(1^-,2^-) shows up at θ=3°~5°**

^{16}O(p,p') at E_p=392 MeV Kawabata PRC65, 064316(2012)



0°: GDR dominant (ΔL=1,ΔS=0,ΔT=1) **4°: SDR dominant (ΔL=1,ΔS=1,ΔT=1)**

E398 experiment: $^{16}O,^{12}C(p,p'\gamma)$ experimental setup

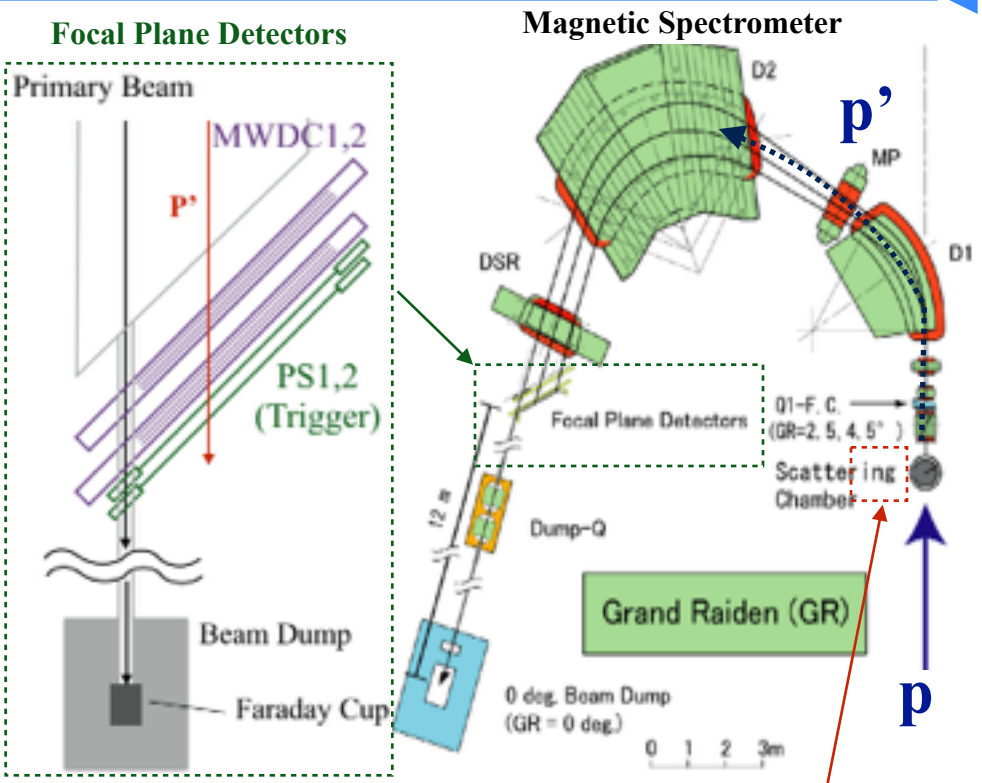
RCNP Cyclotron Facility, Osaka Univ.

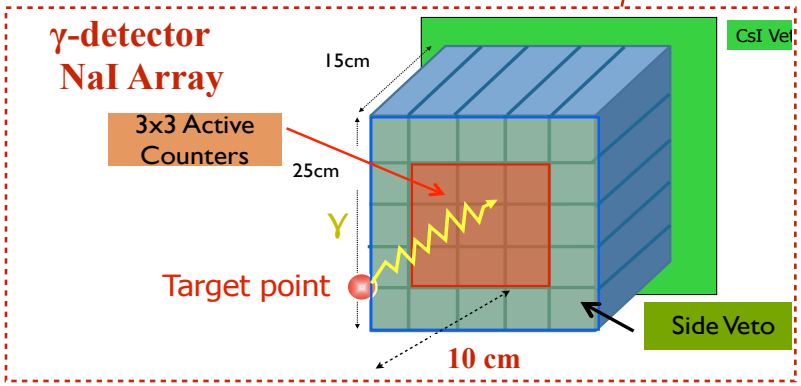
Excitation

- Proton Beam: 392 MeV, 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**"
  - $\theta_{scat} = 0°$ (covers 0° ~ 3°)
  - Solid Angle = 5.6 msr
  - $\Delta E_x \sim 100$ keV

Gamma-ray

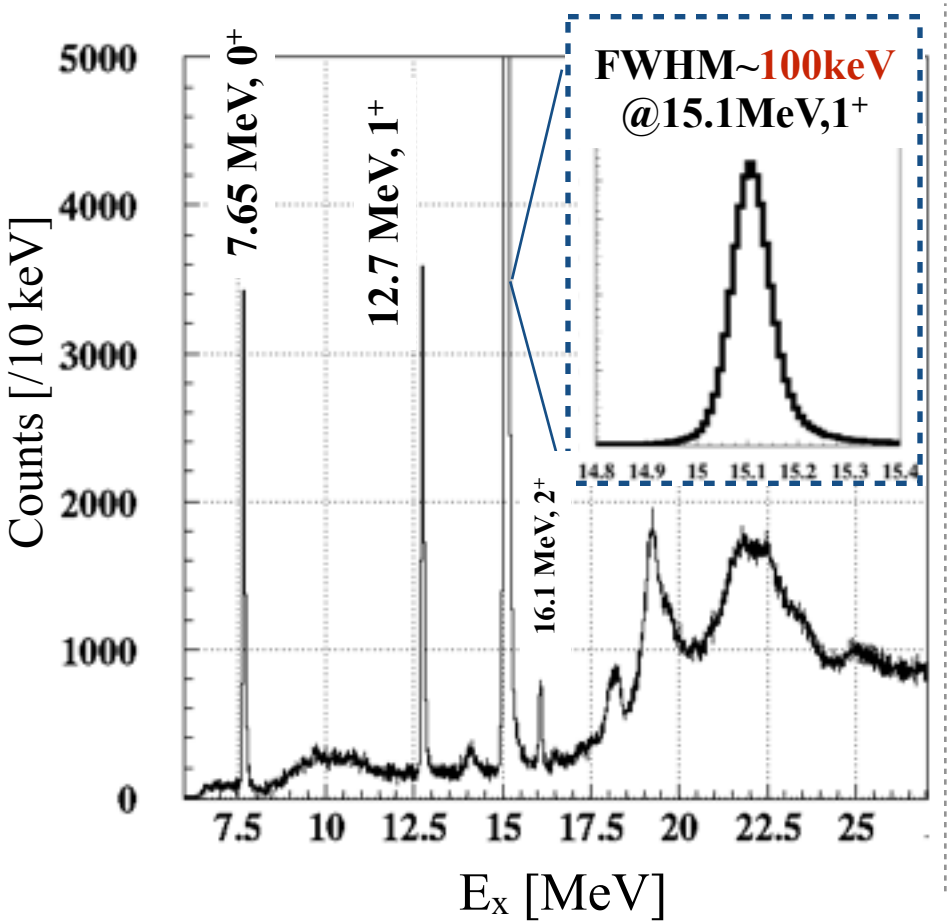
- γ-detector：NaI(Tl) ×25 Array
  - Solid Angle × Detection Efficiency ~ 2% @6MeV (GEANT4)
  - each NaI: 25×25×15 cm, ΔE~5%@1.33MeV
  - Front : Plastic Scintillator Veto (3mm thick)





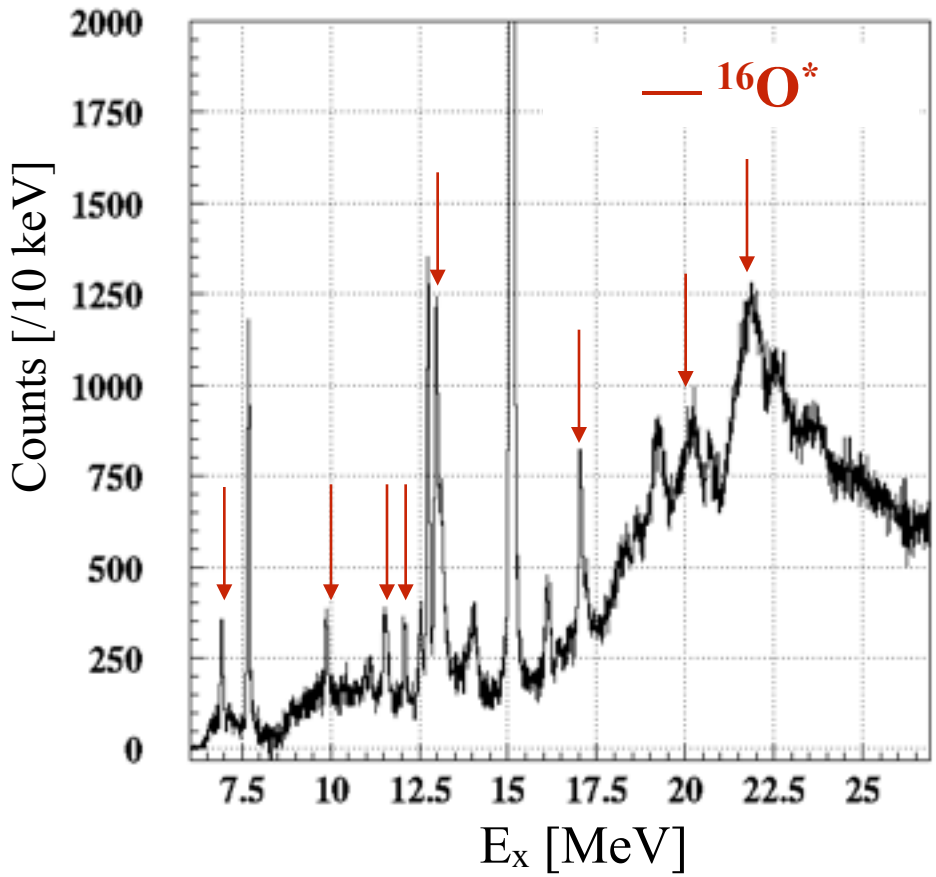
Excitation Energy Spectra

C 0.5nA, 2hrs



0.5nA, 2hrs

$C_6H_{10}O_5$(Cellulose)

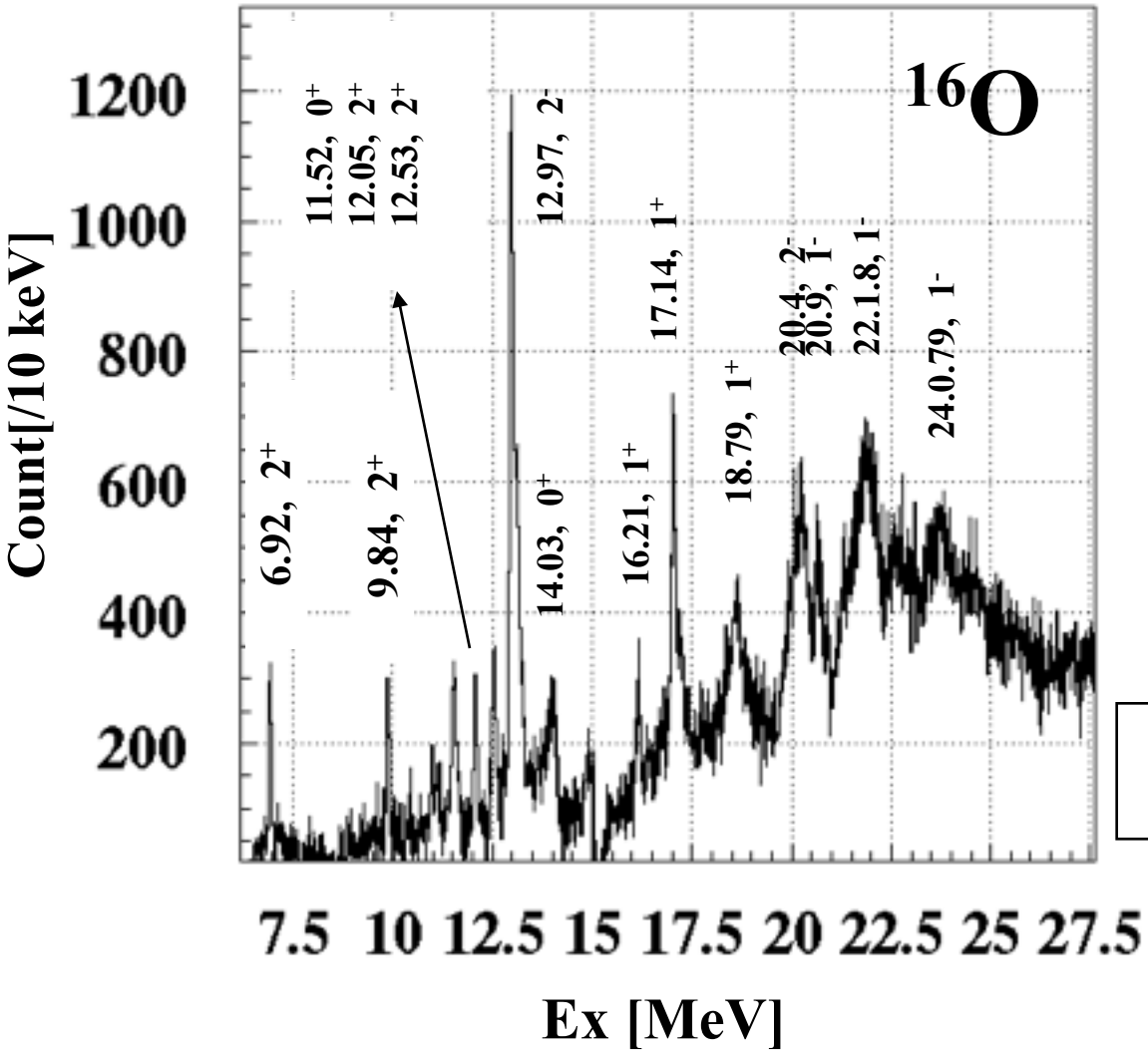


The peak energies agreed with the known values in ~40 keV.

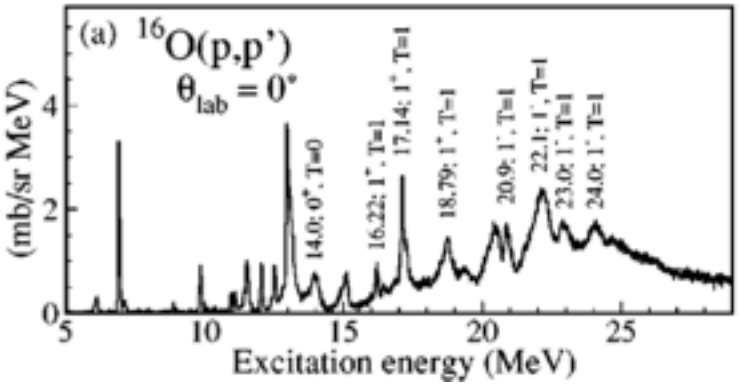
Table of Isotopes, 8th ed.

^{16}O Spectrum after subtraction of ^{12}C

***Subtraction with normalization to $^{12}C(1^{+;}$ 15.1MeV)**



Reference: H_2O(Ice) target



T. Kawabata PRC65, 064316 (2002)

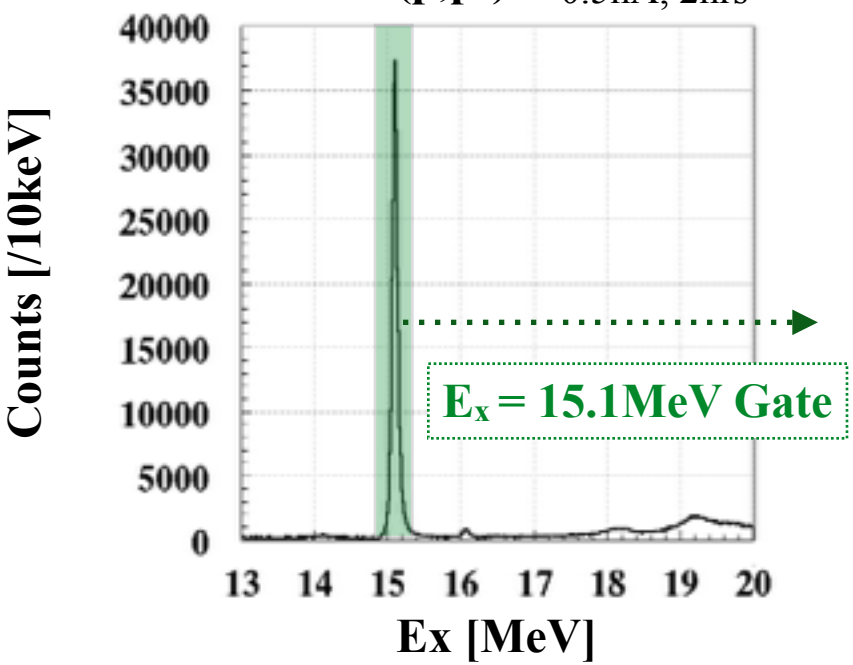
Subtraction worked good.
GRs in ^{16}O were clearly observed.

γ-Detector (in-situ 15.1MeV γ-ray calibration)

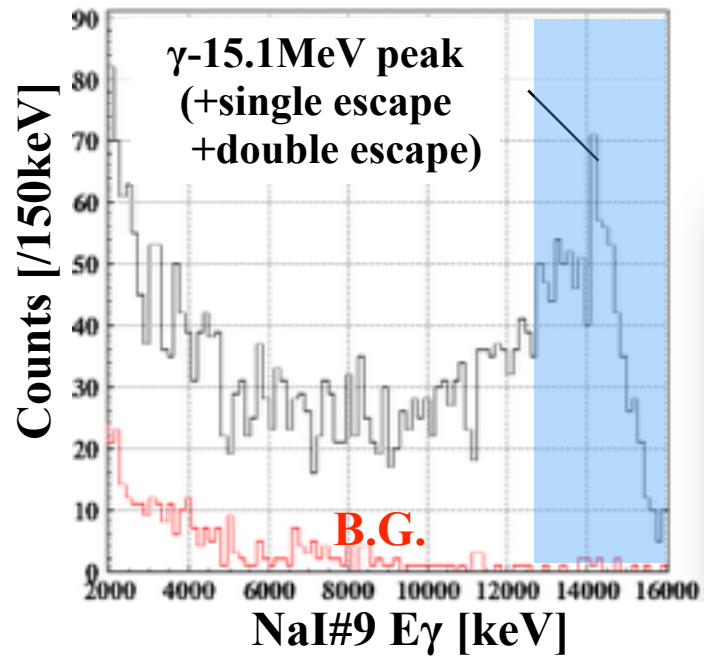
In situ γ-rays from $^{12}C(15.1MeV,1^{+}, Pr_{\gamma\text{-}15.1} = 88\% \pm 3\%)$ are used to **calibrate** the energy scale and the efficiency of the NaI-Array.

The γ-ray emission probability can be calibrated precisely

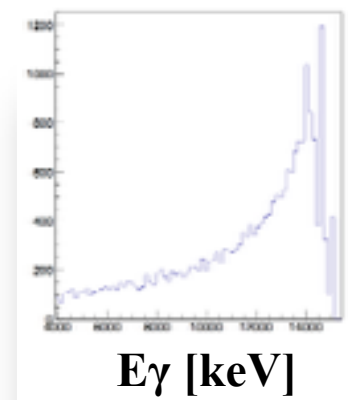
$^{12}C(p,p')$ 0.5nA, 2hrs



Eγ Spectrum

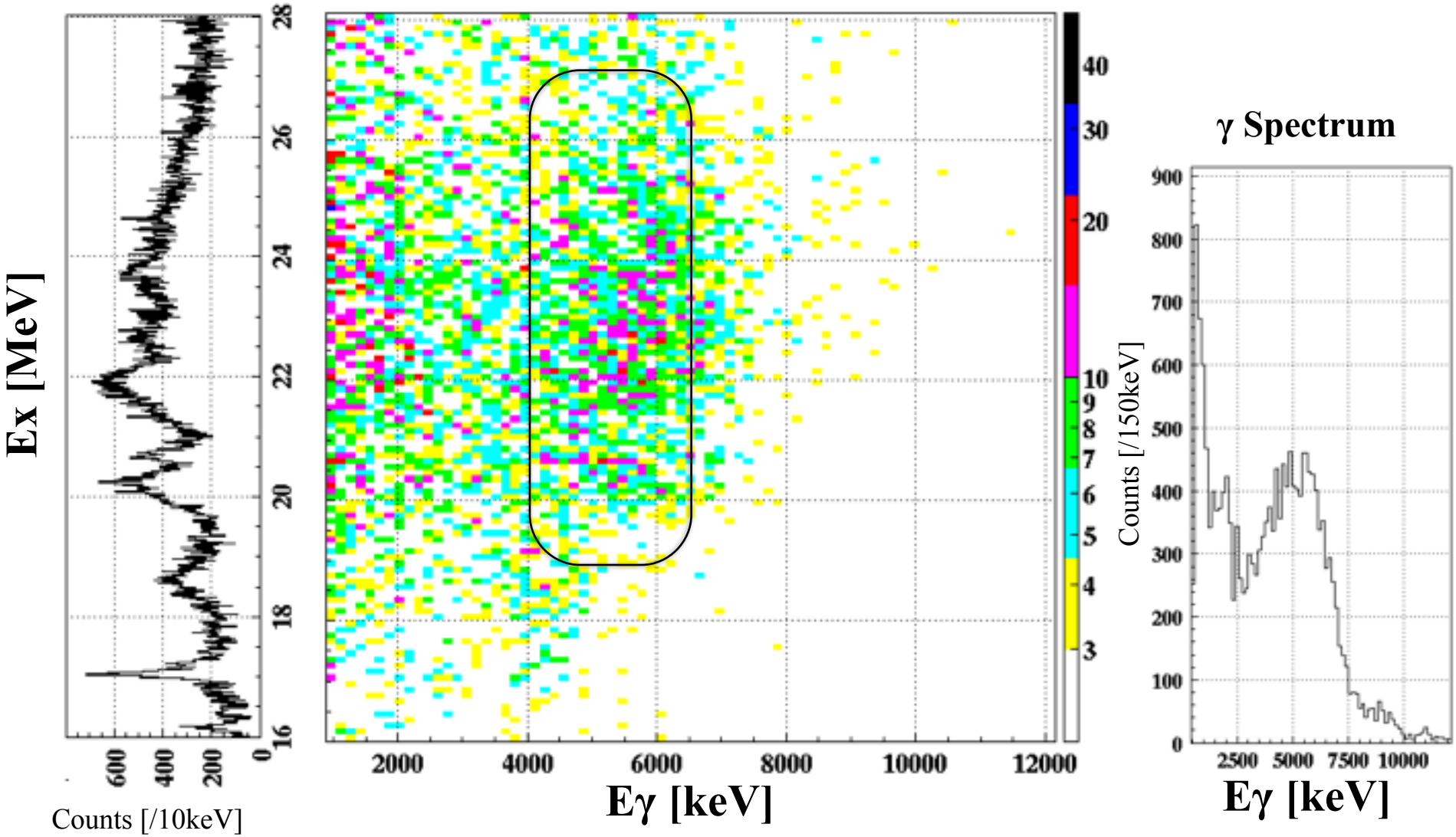


Simulation(GEANT4)



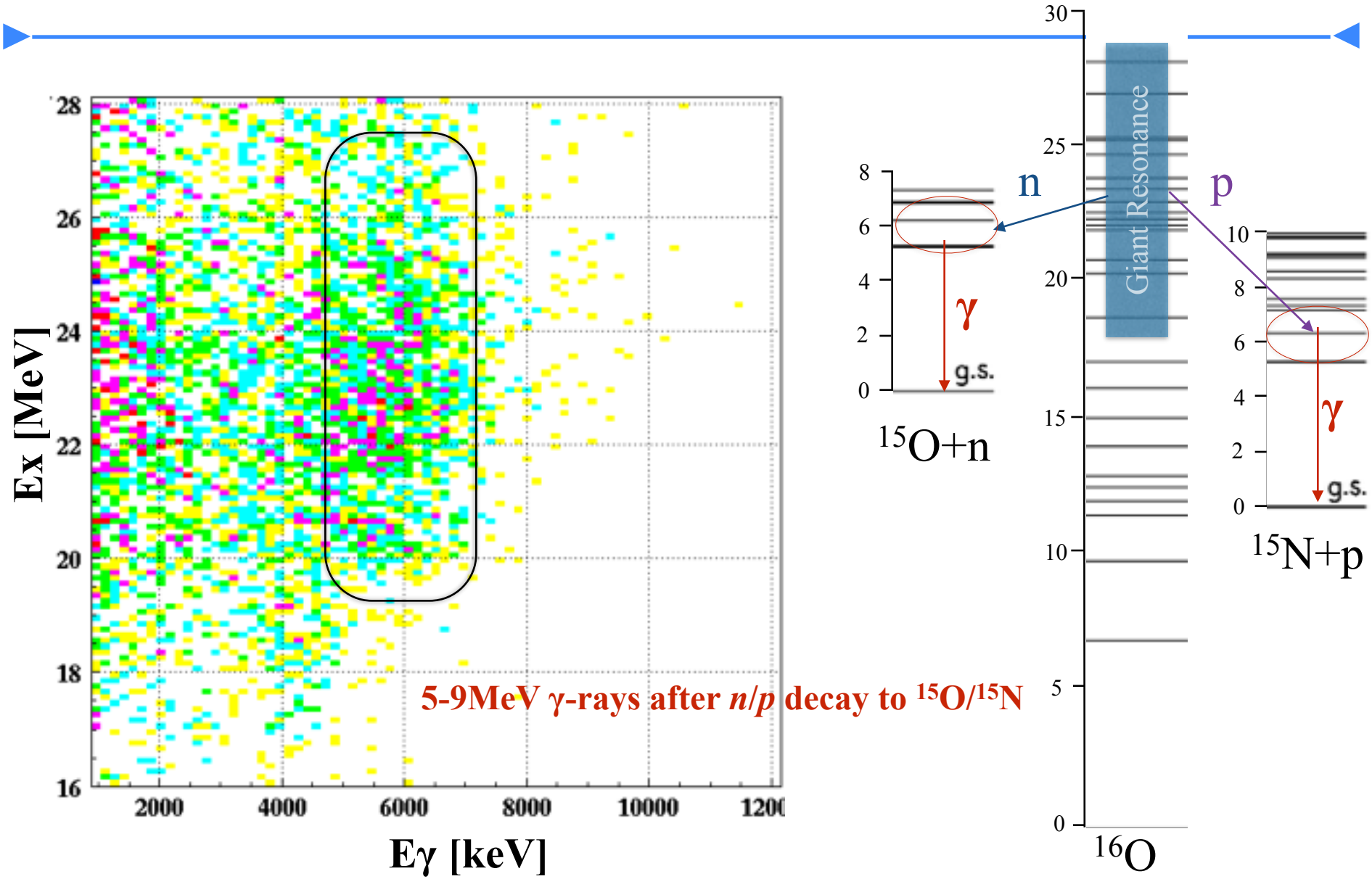
Solid Angle × Detection efficiency (Single NaI) =817/($3.9\times10^{5}\times0.88$)
*Angular correlation is not include yet. **= 0.24%**

Gamma-Rays from ^{16}O Giant Resonances



γ-rays from GRs in ^{16}O were observed

Gamma-Rays from ^{16}O Giant Resonances



Estimated Number of γ Events from Giant Resonances

✳ **Number of γ-ray events in 2hrs run (analyzed)**

	ΔT	Ex=16~27MeV	Ex=16~21MeV	Ex=21~27MeV
12	2hrs	20359	2129	18230
16	2hrs	11164	2797	8367

✳ **Estimated γ-ray events in total run**

	ΔT	Ex=16~27MeV	Ex=16~21MeV	Ex=21~27MeV
12	40hrs	**4.1×10**	4.3×10	3.6×10
16	30hrs	**1.7×10**	4.2×10	1.3×10

Gamma emission probabilities will be determined with an accuracy (Stat. + Sys.) of ~10% in 1 MeV Ex bin.

Expected systematic uncertainties

- Detection efficiency < ~10% ← under analysis
- Subtraction of ^{12}C from $C_6H_{10}O_5$ < ~5%

Summary of the 2nd Part

✳γ-ray from giant resonances in ^{12}C & ^{16}O are important for SN neutrino Physics.

ν-Flux × σ_{NC} × Pr (E398 Data) → Estimation for NC-γ events from SN

✳E398: Measurement of γ-rays from Giant Resonances

✳Data Analysis

- Excitation Energy Spectrum ✔
- Demonstration of In-situ γ-ray Calibration ✔

✳**γ-rays from giant resonances of ^{12}C and ^{16}O have been measured**

Next Step

✳Analysis of the γ-ray emission probability.

✳Correlation P_γ and θ_{scat} (0~1°, 1~2°, 2°~3°) → decomposition of GDR & SDR

→Pr($^{16}O^*$->$^{15}O^*$+n/$^{15}N^*$+p->5-10MeV-γ) is expected to be determined with ~ 10% accuracy in 1 MeV E_x bin)