# Neutrino-Nucleus Interactions From Elastic to Quasi-Elastic Region (1-100MeV)

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Outline

1. Neutrino Interactions for Neutrinos from Supernova
2. Form Factors (FF)
   - ✓ Nuclear FF (Electric and magnetic)
   - ✓ Nucleon FF
   - ✓ Hosstadter's results
   - ✓ Exercises
3. Neutrino Interactions in 10-100MeV
4. E398 $^{16}O$,$^{12}C$(p,p' $\gamma$) Experiment at RCNP
5. Summary

# Importance of Neutral-Current γ-production

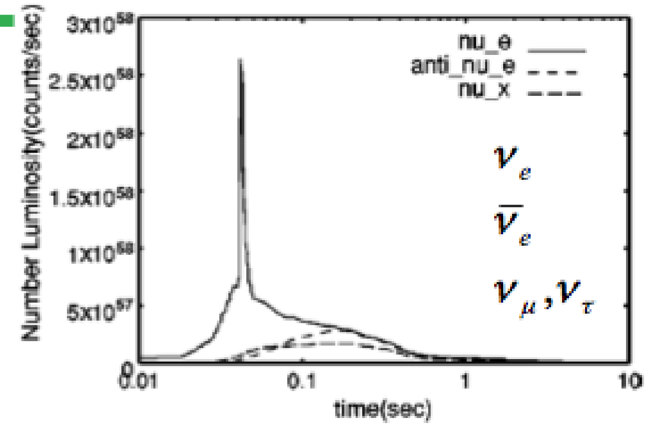
## ---Neutrinos from SN explosion@10kpc---

✦ The number of events observed in the detectors

- Super Kamiokande ($H_2$**O**)

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

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

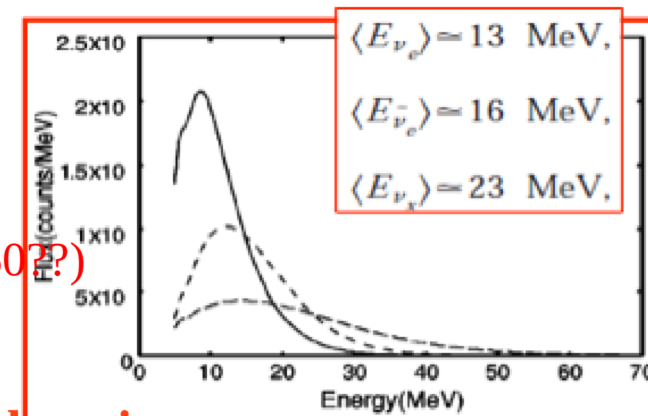



- KamLAND (**C**H)

$$\bar{\nu}_e + p \rightarrow e^+ + n \qquad \text{~300}$$

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

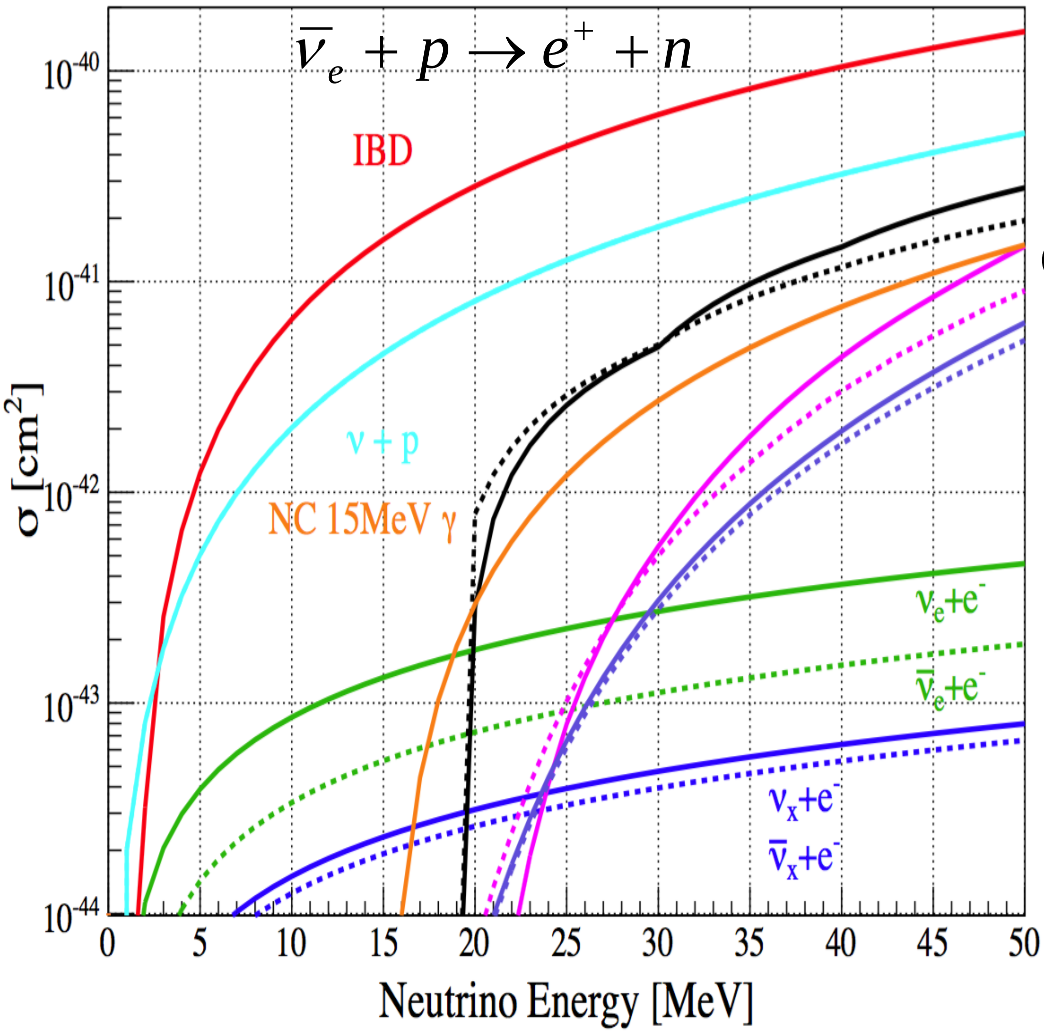
$$NC: \nu_x + {}^{12}C \rightarrow \nu_x + X + \gamma \ (E_X > 16 MeV \text{の巨大共鳴}) \qquad \text{(~50-60??)}$$




✦ **Importance of Neutral-Current events**

- **The 2nd most 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

# 1. νCH cross sections in the Supernova energy region



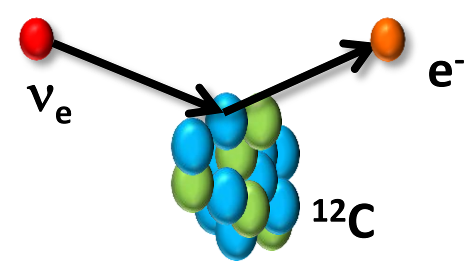

CCEL(ν,ν)

*NPA652,91 (1999)*

CCQE(ν,ν)

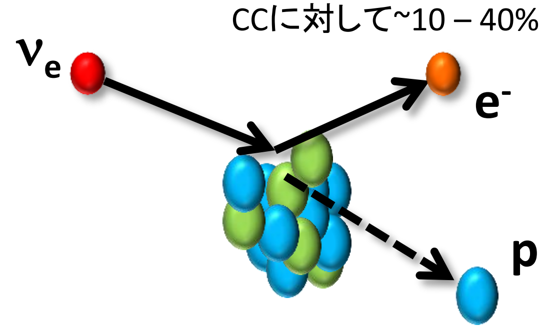
NCQE(ν,ν)

**Charged Current (CC)**




- CC Quasi-Elastic

CCに対して~10 – 40%との予測



# 2. Form Factors

- Many of you will participate in NuInt15 Workshop and you will hear a lot about words like ,"Form Factor (FF)", "Dipole", "Vector and Axial Vector Form Factor", etc, there. In NuSTEC News-Letters, there have been many hot e-mail discussions over "Form Factors" since last week.
- It is very instructive to review the definition of "Form Factor", though it is a clasical topics.

# Charge and Magnitization Density Distribution of the nucleons and nucleus –Form Factors

- Discovery of the structure of the nucleons---R.Hofstadter (Nobel Prize in 1961)
  - ✓ Rutherford started the study of nuclear size by studying deviations from Coulomb scattering of $\alpha$-particles in 1919. Nuclear Radius~$10^{-5}$ x (Atom).
  - ✓ Hofstadter et al used electron-nucleus elastic scattering, since (they thought) electron, or electromagnetic interaction, is "simpler" and better-understood than $\alpha$-particle. 1953-. $E_e$=190MeV. Later $E_e$=420MeV.

    De Broglie wavelength $\lambda$=hc/E=200MeV･fm/(E[MeV]) must be <1fm.
  - ✓ They started with meadium and heavy nuclei and and found,

    Radius $R=r_0 x A^{1/3}$. ($r_0$=1.1±0.1fm) and skin thickness t=2.4±0.3fm.
  - ✓ They also found that this method can be applied to nucleons (proton and neutrons) and discovered the charge and magnetic structure of the nucleons.

→Internal Structure $\rho(r) \approx$ Form Factor F(q) [Fourier Transform]

- The historical results are quoted by many textbooks. Let's look at the formalism and typical plots from the experiments, where Form Factors play a central role.
  - R.Hofstadter, Electron Scattering and Nuclear Structure, RMP.28,214-254(1956).
  - H.de Vries, C.W.de Jager and C.de Vries, Atom.Data Nucl.Data Tabl. 36,495 (1987).
  - T.W.Donnelly and I.Sick, RMP 56, 461(1984). For Updates.

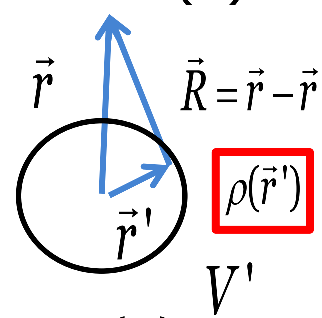
# Form Factor F(q) and Charge distribution ρ(r)

- How was it introduced?? → Matrix Element in a Born approximation:

$$U_{fi} = \langle f | U | i \rangle = \frac{1}{V}\int_V e^{-i\vec{p}_f\cdot\vec{r}} U(\vec{r}) e^{i\vec{p}_i\cdot\vec{r}} d^3\vec{r} = \frac{1}{V}\int_V U(\vec{r}) e^{i\vec{q}\cdot\vec{r}} d^3\vec{r}, \quad with\ \vec{q} = \vec{p}_i - \vec{p}_f . \qquad (1)$$

- If the nucleus has a finite (charge) density distribution ρ(r'), an interaction (potential) U(r) is the sum of point interaction (potential) V(r) over each charge at r'. V(R) is a Coulomb potential.

$$U(\vec{r}) = \int_{V'} V(\vec{r}-\vec{r}\,')\rho(\vec{r}\,')d^3\vec{r}\,' \qquad (2)$$




- Put U(r) into (1) and set $\vec{R} = \vec{r} - \vec{r}\,'$ , we obtain

$$U_{fi} = \frac{1}{V}\int_V U(\vec{r}) e^{i\vec{q}\cdot\vec{r}} d^3\vec{r} = \frac{1}{V}\int_V V(\vec{R}) e^{i\vec{q}\cdot\vec{R}} d^3\vec{R} \int_{V'} \rho(\vec{r}\,') e^{i\vec{q}\cdot\vec{r}\,'} d^3\vec{r}\,' = V_{fi} F(q)$$

- Where $F(q) = \int_V \rho(\vec{r}) e^{i\vec{q}\cdot\vec{r}} d^3\vec{r}$ (3) is called a nuclear form factor. Then, charge distribution is obtained by Fourier transformation.

$$\rho(\vec{r}) = \frac{1}{(2\pi)^3}\iiint F(q) e^{-i\vec{q}\cdot\vec{r}} d\vec{q} \qquad (4)$$

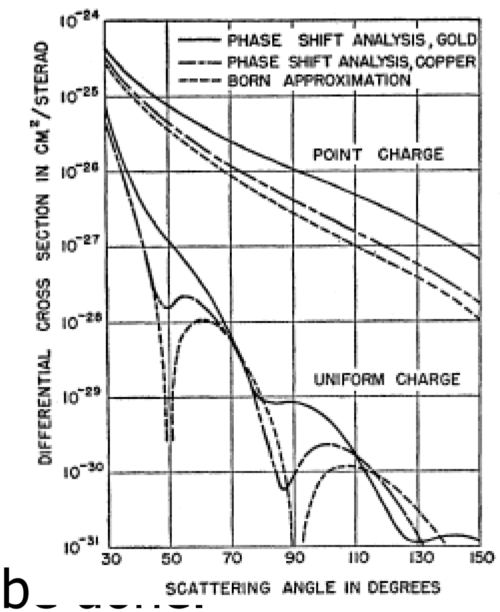
■ (Matric element)$^2$= $|U_{fi}|^2 = |V_{fi}|^2 |F(q)|^2$ →

$$\frac{d\sigma}{d\Omega} = \left[\frac{d\sigma}{d\Omega}\right]_{Point} |F(q)|^2$$

# Form Factor

- If the nucleus (nucleon) has a structure $\rho(r)$, then the cross section is reduced by $F(q)^2$, as compared to that for no structure ($F(q)^2$=1.).

$$\frac{d\sigma}{d\Omega} = \left[\frac{d\sigma}{d\Omega}\right]_{Point} |F(q)|^2$$




1) Point, 2) Exponential->Dipole, 3) Gauss,

4) Uniform

5) Fermi Type: two parameters (c , t),
   c=radius and t=skin.

$$\rho(\vec{r}) = \frac{\rho_0}{1+\exp[(r-c)/t]}$$

6) A Born approximation fails. A phase shift analysis must be done.

Formulas

$$F(q) = \int_V \rho(\vec{r}) e^{i\vec{q}\cdot\vec{r}} dV = \iiint_V \rho(\vec{r}) e^{i\vec{q}\cdot\vec{r}} dxdydz$$

$$F(q) = \int_0^\infty \frac{\sin(qr)}{qr} \rho(r) 4\pi r^2 dr$$

$$\iiint_V \rho(\vec{r}) dxdydz = 1$$

$$\rho(\vec{r}) = \frac{1}{(2\pi)^3} \iiint F(q) e^{-i\vec{q}\cdot\vec{r}} d\vec{q}$$

# Form Factor

- 4 basic distributions.

Normalized : $\iiint_V \rho(\vec{r})dxdydz = 1$

1) Point (=no structure)

$$\rho(\vec{r}) = \delta(x)\delta(y)\delta(z)\ ,\quad F(q) = 1.$$

2)

$$\rho(\vec{r}) = \frac{a^3}{8\pi}e^{-ar} \qquad F(q) = \frac{1}{(1+q^2/a^2)^2}$$

(Dipole)

3)

$$\rho(\vec{r}) = \frac{a^3}{(2\pi)^{3/2}}e^{-\frac{a^2r^2}{2}} \qquad F(q) = e^{-\frac{q^2}{2a^2}}$$

4)

$$\rho(\vec{r}) = \frac{1}{4\pi a^3/3}$$

(Uniform sphere *a*)

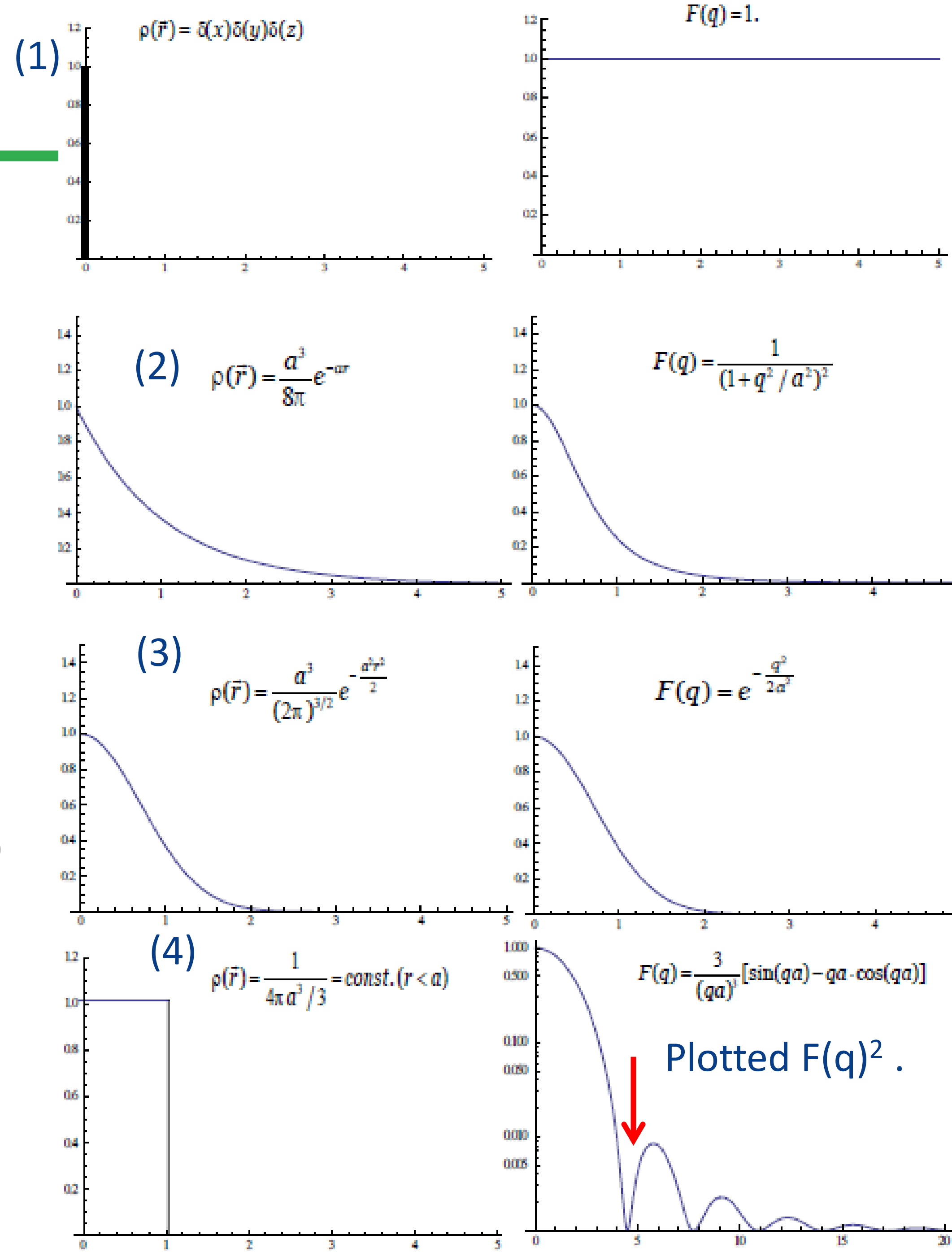
$$F(q) = \frac{3}{(qa)^3}[\sin(qa) - qa\cdot\cos(qa)]$$

■ Important feature

✓ 2),3) Smooth → F(q) smooth

✓ 4) ρ: uniform → Diffraction

F(q)=0 at qa=4.4~3π/2.

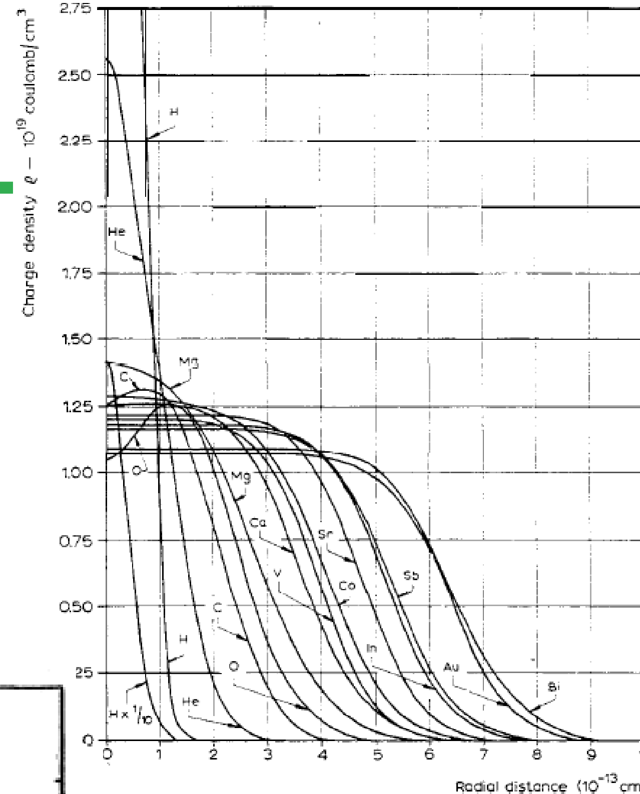


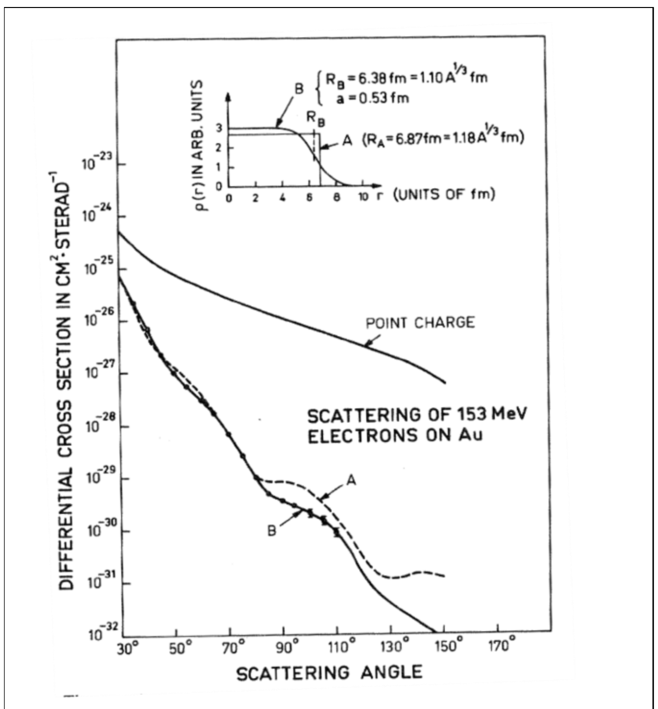
# Exercises

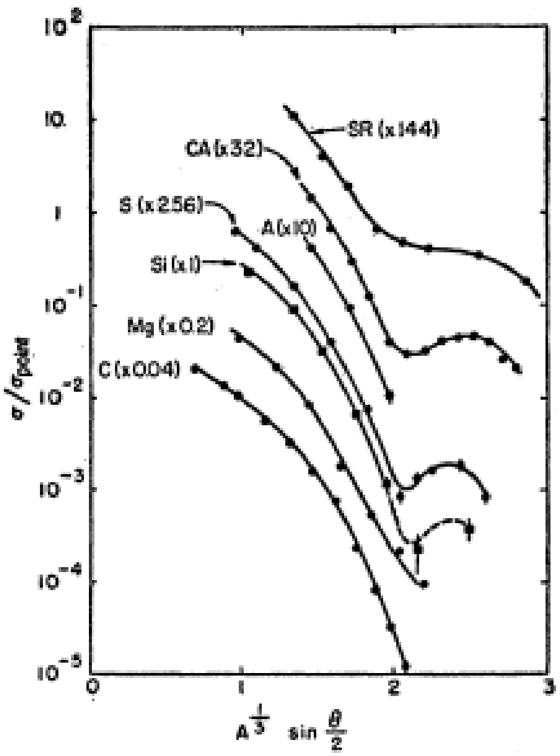
- Calculate F(q) for typical 1-4) distributions.

# Hofstadter's results

- For medium and heavy nuclei, (c,t) were obtained.
  - C=(1.07+-0.02) fm
  - t=2.4+-0.3 fm

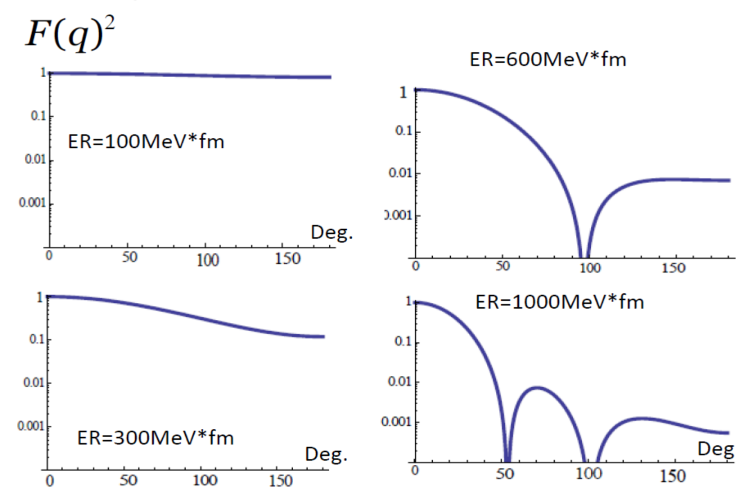


# Size of the nucleus and the cross section

- If a is the size, FF is a function of qa.
- $qa=2Ea\sin(\theta/2)$
- To look for a finite structure $\{|F(q)|<1\}$, the region, $qa<1$, contributes to the cross section.
  - De Broglie wavelength $\lambda=hc/E=200\text{MeV}\cdot\text{fm}/(E[\text{MeV}])$ must be <1fm.
  - If E is low, q=0, then, F(0)=1. It looks like a point.
  - $qa=2Ea\sin(\theta/2)<2$ contributes.
  - If E becomes very large, Ea>>1, then, only forward angle $\theta\sim 0$, contributes to the cross section. The cross section saturates.



# Review of the formula

1) e-p (Point Charge)

-Rutherford Scattering

$$\left(\frac{d\sigma}{d\Omega}\right)_{Rutherford} = \frac{\alpha^2}{4E^2\sin^4(\theta/2)}$$

2) e-p (e:Dirac, p:point charge)

-Mott Scattering

$$\left(\frac{d\sigma}{d\Omega}\right)_{Mott} = \frac{4\alpha^2}{q^4}E_e'^2\cos^2\frac{\theta}{2} = \left(\frac{d\sigma}{d\Omega}\right)_{Rutherford}\cos^2\frac{\theta}{2}$$

3) e-p (e:Dirac, p:Dirac)

-No Name. Still, interacion is point.

$$\frac{d\sigma}{d\Omega} = \frac{4\alpha^2E_e'^2}{q^4}\frac{E_e'}{E_e}\cos^2\frac{\theta}{2}\left[1+2\tau\tan^2(\theta/2)\right] = \left(\frac{d\sigma}{d\Omega}\right)_{Mott}\frac{E_e'}{E_e}\left[1+2\tau\tan^2(\theta/2)\right]$$

4) e-p (e:Dirac, p:Dirac)

-Proton has charge and magnetic distributions (Form Factors, $F_1$, $F_2$/$G_E$,$G_M$).

→Rothenbluth Formula

$$\frac{d\sigma_{eN}}{d\Omega} = \frac{4\alpha^2E_e'^2}{q^4}\frac{E_e'}{E_e}\cos^2\frac{\theta}{2}\left[F_1^2+\tau\chi^2F_2^2+2\tau(F_1+\chi F_2)^2\tan^2(\theta/2)\right]$$

Note:

*Gordon Decomposition for Dirac Current :

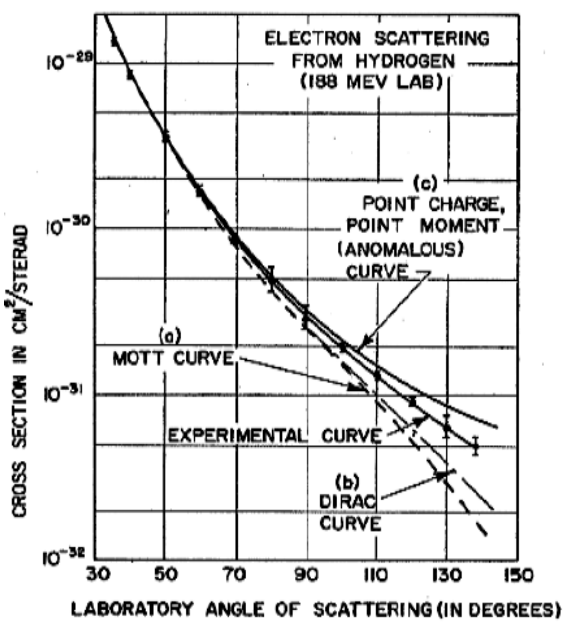
$$\bar{u}_f\gamma^\mu u_i = \frac{1}{2m}\bar{u}_f((p_f+p_i)^\mu + i\sigma^{\mu\nu}(p_f-p_i)_\nu)u_i$$

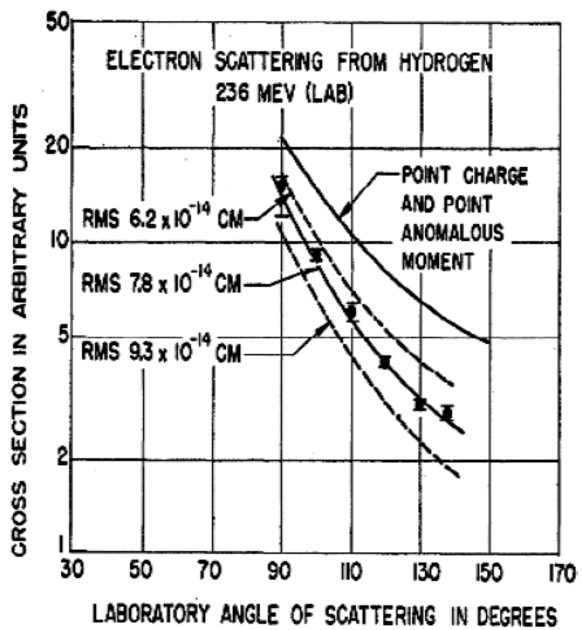
*Consider "structure" (Form Factors):

$$J_\alpha = \bar{u}_f\left[F_1(q^2)\frac{(p_f+p_i)_\alpha}{2M} + \frac{F_1(q^2)+\chi F_2(q^2)}{2M}i\sigma_{\alpha\beta}q^\beta\right]u_ie^{i(p'-p)x}$$
$$= \bar{u}_f\left[F_1(q^2)\gamma_\alpha + \frac{\chi F_2(q^2)}{2M}i\sigma_{\alpha\beta}q^\beta\right]u_ie^{i(p'-p)x}$$

# Hofstadter's results

- He started e-p scattering in 1954.
  - Consider magnetic scattering. Rothenbluth Formula.
  - Found the structure of nucleon.
  - Latest (2005)




| Observable | Value ± error |
| --- | --- |
| $\langle (r_E^p)^2 \rangle^{1/2}$ | $0.895 \pm 0.018$ fm |
| $\langle (r_M^p)^2 \rangle^{1/2}$ | $0.855 \pm 0.035$ fm |
| $\langle (r_E^n)^2 \rangle$ | $-0.119 \pm 0.003$ fm$^2$ |
| $\langle (r_M^n)^2 \rangle^{1/2}$ | $0.87 \pm 0.01$ fm |

# Hofstadter's results

Table VI. This table gives the radial parameters for the nuclei of column 1 and the appropriate charge (and magnetic) distributions. All quantities used in the table are defined in the text, except the parameters of the Hill model (used only for $_{82}Pb^{208}$). All distances are given in units of $10^{-13}$ cm (one fermi unit). The accuracy in surface thickness parameter is about ±10% and may be somewhat poorer for the lighter elements where it is less well defined. The accuracy of the radial parameters is about ±2% except, possibly, in the case of Ta. The accuracy for gold is better than ±2%. $\rho_U$ in column 9 is the charge density in proton charge per cubic fermi for the equivalent uniform model and may be compared with Fig. 1 (b). The results for lithium and beryllium are to be considered preliminary.

| Nucleus (1) | Type of charge distribution (see Table I) (2) | rms radius (3) | Radius of equivalent uniform model ($R$) (4) | $r_0 = \frac{R}{A^{1/3}}$ (5) | Skin thickness (6) | Half-density Radius $c$ (7) | $r_1 = \frac{c}{A^{1/3}}$ (8) | $\rho_U$ (9) | $A^{1/3}$ (10) | Comments (11) | Reference number (12) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $_{1}H^{1}$ | III, IV, VI, VII magnetic distribution similar | 0.77±0.10 | 1.00 | 1.00 | ··· | ··· | ··· | 0.239 | 1.00 | The charge distributions in column 2 are equivalent to each other. The rms radius is a mean value for all. The magnetic distribution is the same as that of the charge. The fact that $R=1.00$ in column 4 is accidental. | 42, 55, 68 |
| $_{1}D^{2}$ | Charge distribution calculated from deuteron wave function for Hulthèn, etc., potentials. | 1.96 | 2.53 | 2.01 | ··· | ··· | ··· | 0.0147 | 1.26 | ··· | 71 |
| $_{2}He^{4}$ | III | 1.61 | 2.08 | 1.31 | ··· | ··· | ··· | 0.053 | 1.59 | ··· | 42, 49 |
| $_{3}Li^{6}$ | XII | 2.78 | 3.59 | 1.98 | ··· | ··· | ··· | 0.0153 | 1.82 | ··· | 75 |
| $_{3}Li^{7}$ | XII | 2.71 | 3.50 | 1.83 | ··· | ··· | ··· | 0.0167 | 1.19 | ··· | 75 |
| $_{4}Be^{9}$ | XII | 3.04 | 3.92 | 1.89 | ··· | ··· | ··· | 0.0157 | 2.08 | ··· | 75 |
| $_{6}C^{12}$ | XI | 2.37 | 3.04 | 1.33 | ~2.0 | ~2.3 | 1.00 | 0.051 | 2.29 | $\alpha=4/3$ | 77 |
| $_{12}Mg^{24}$ | $gU$ | 2.98 | 3.84 | 1.33 | 2.6 | 2.85 | 0.99 | 0.051 | 2.88 | ··· | 46 |
| $_{14}Si^{28}$ | $gU$ | 3.04 | 3.92 | 1.29 | 2.8 | 2.95 | 0.97 | 0.056 | 3.04 | ··· | 46 |
| $_{16}S^{32}$ | $gU$ | 3.19 | 4.12 | 1.30 | 2.6 | 3.28 | 1.03 | 0.055 | 3.18 | ··· | 46 |
| $_{20}Ca^{40}$ | Fermi | 3.52 | 4.54 | 1.32 | 2.5 | 3.64 | 1.06 | 0.052 | 3.42 | ··· | 33 |
| $_{23}V^{51}$ | Fermi | 3.59 | 4.63 | 1.25 | 2.2 | 3.98 | 1.07 | 0.055 | 3.71 | ··· | 33 |
| $_{27}Co^{59}$ | Fermi | 3.83 | 4.94 | 1.27 | 2.5 | 4.09 | 1.05 | 0.0662 | 3.89 | ··· | 33 |
| $_{49}In^{115}$ | Fermi | 4.50 | 5.80 | 1.19 | 2.3 | 5.24 | 1.08 | 0.0605 | 4.87 | ··· | 33 |
| $_{51}Sb^{122}$ | Fermi | 4.63 | 5.97 | 1.20 | 2.5 | 5.32 | 1.07 | 0.0572 | 4.96 | ··· | 33 |
| $_{73}Ta^{181}$ | Fermi plus quadrupole | 5.50 | ~7.10 | ~1.25 | ~2.8 | ~6.45 | ~1.14 | 0.0491 | 5.65 | The radial distances should be considered "effective" radii in view of the quadrupole effects. | 61, 88 |
| $_{79}Au^{197}$ | Fermi | 5.32 | 6.87 | 1.180 | 2.32 | 6.38 | 1.096 | 0.0581 | 5.82 | ··· | 33 |
| $_{82}Pb^{208}$ | Hill *et al.* (reference 9) $n=10$, $s=0$ | ~5.42 | ~7.0 | 1.18 | ~2.3 | ~6.5 | ~1.09 | 0.057 | 5.93 | The model of Hill *et al.* is similar to the Fermi model | 9 |
| $_{83}Bi^{209}$ | Fermi | 5.52 | 7.13 | 1.20 | 2.7 | 6.47 | 1.09 | 0.054 | 5.935 | ··· | 33 |

# Proton, Neutron form factors (BBBA5@NuInt05)

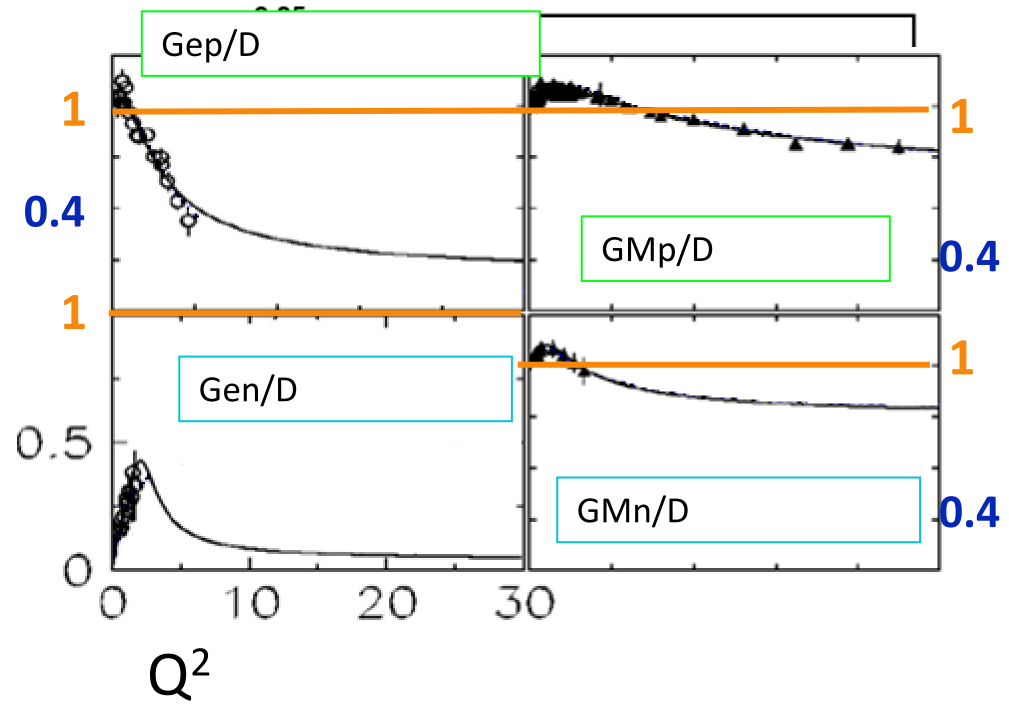
- FFs (GE, GM) are not a simple dipole.

$$G(Q^2) = \frac{\sum_{k=0}^{2} a_k \tau^k}{1 + \sum_{k=1}^{4} b_k \tau^k}$$

R.Bradford et al., Nucl. Phys. Proc. Suppl.159:127–132 (2006).

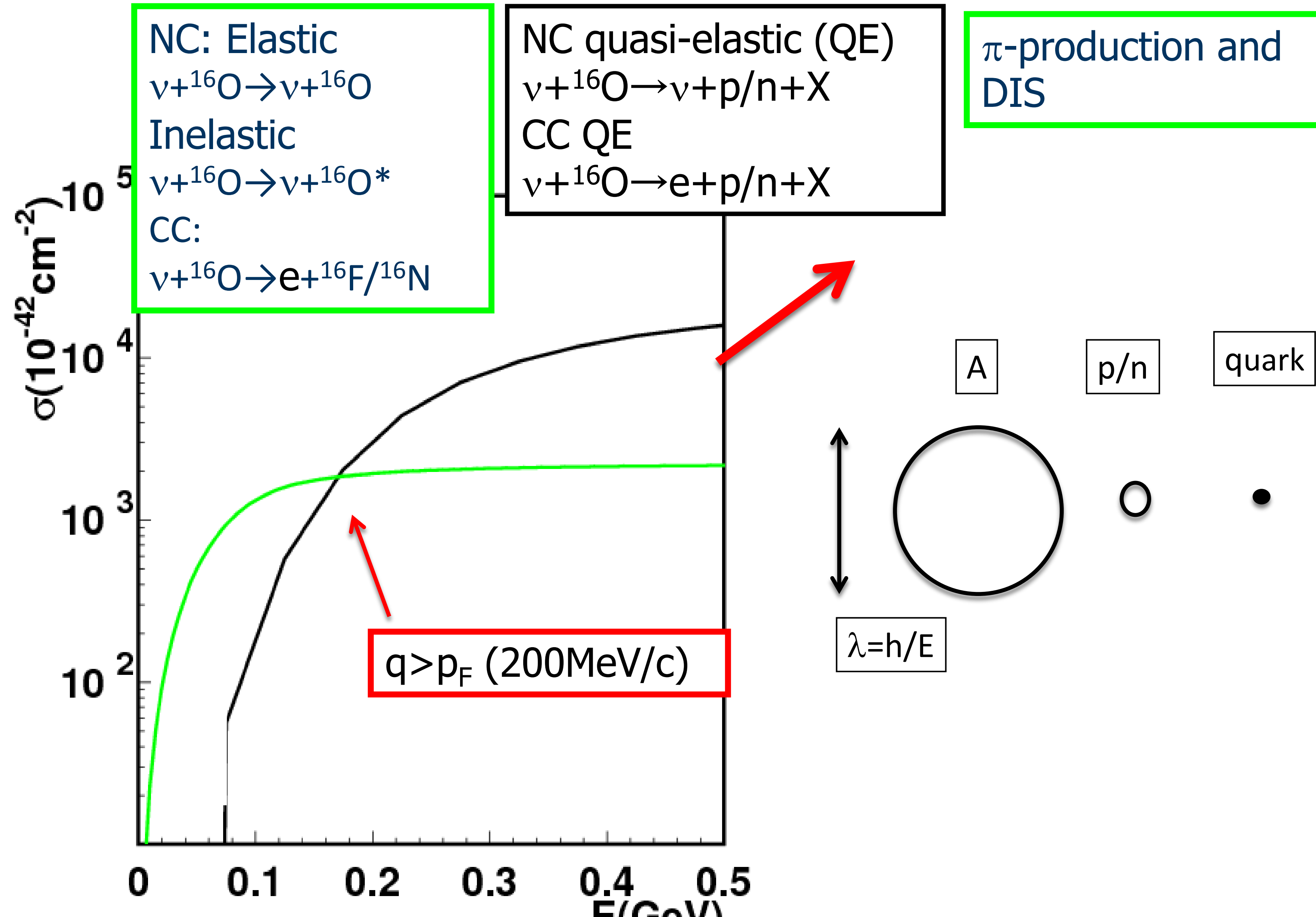
**BBBA05/ Dipole (G/D)**

$$D = \frac{1}{(1 + Q^2 / \Lambda^2)^2} \quad (\Lambda = 0.71\,GeV^2)$$

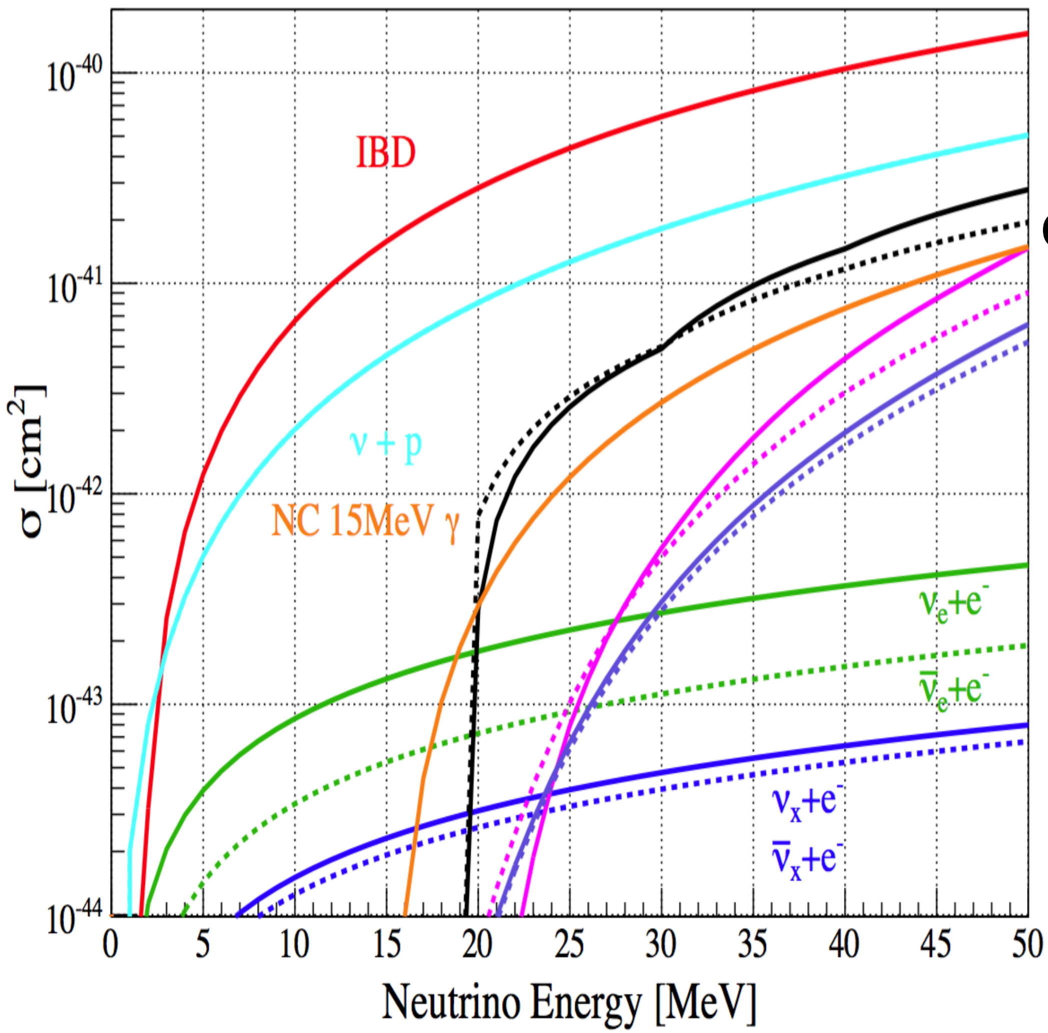



$$\tau = \frac{Q^2}{4M^2}$$

# 2. Overall Picture of the ν-A cross section



# 3. νC cross sections in the SN energy region

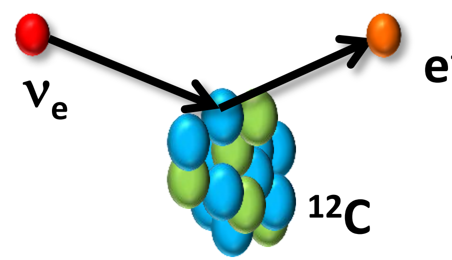



**CCEL(ν,$\bar{\nu}$)** *NPA652,91 (1999)*

**CCQE(ν,ν)**

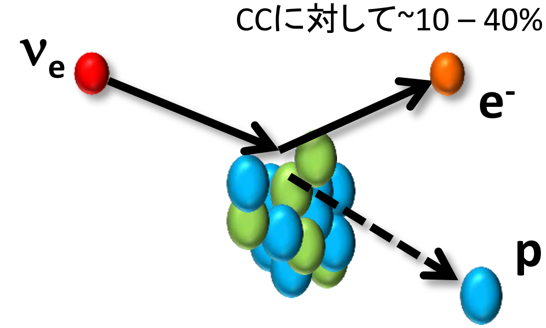
**NCQE(ν,ν)**

**Charged Current (CC)**




- CC Quasi-Elastic

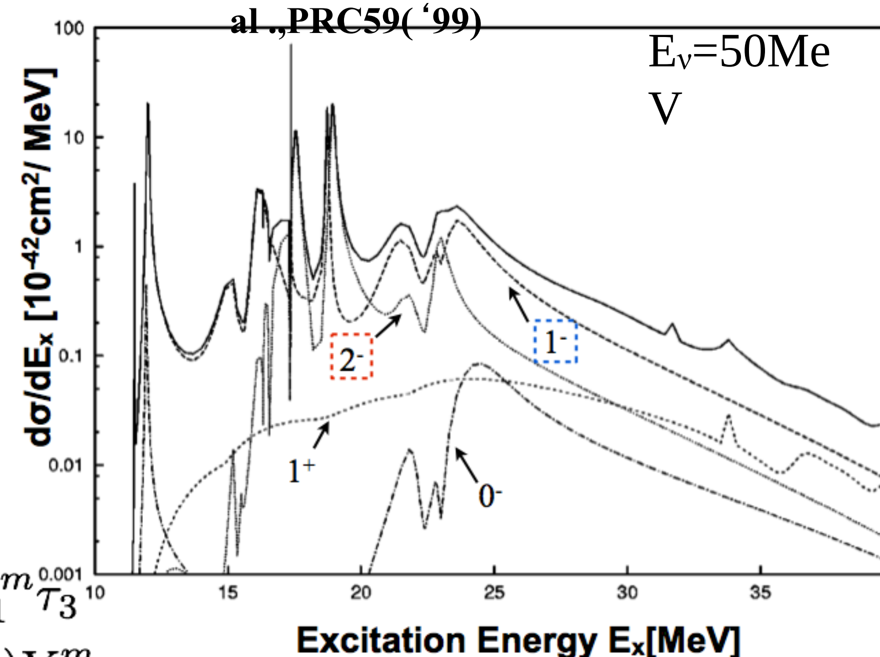
CCに対して~10 – 40%との予測



# Axial Vector is dominant in low energy nuclear excitations in Both CC and NC $\nu$-$^{16}O$,$^{12}C$ reactions

$^{16}O(\nu,\nu')$ Cross Section

**Ref. Jachowicz et al.,PRC59('99)**




✦NC Neutrino-Nucleus Cross Section :

ν-

$$< A'|J_W^\mu|A> = < A'|(J_V^\mu - J_A^\mu)\tau_3|A> = (M_W^\mu \tau_3)_{fi}$$

$$M_W^0 = F_1^V + F_A \frac{\vec{P}\cdot\vec{\sigma}}{M}$$

Vector　　Axial

$$\vec{M_W} = F_1^V \frac{\vec{P}}{M} - i\frac{\ldots}{2M}(F_1^V + \kappa F_2^V) + F_A\vec{\sigma}$$

✦GDR ($J^p=1^-$,ΔT=1,ΔS=0,ΔL=1) : $f_1(r)Y_1^m\tau_3$

SDR ($J^p=0^-,1^-,2^-$, ΔT=1,ΔS=1,ΔL=1) : $\vec{\sigma}f_1(r)Y_1^m\tau_3$

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

✦CC reactions too.

# NC ν-$^{16}$O,$^{12}$C reaction

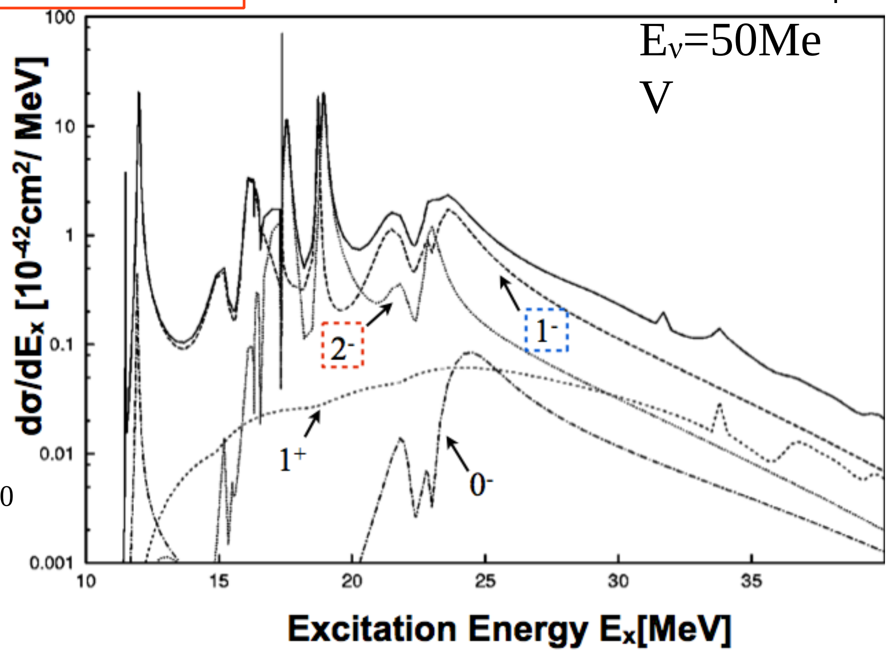
Ref. Jachowicz et al .,PRC59( '99), Botrugno, Co', NPA761('05)

xial Current Dominant:

specially, Spin Dipole Resoance : $J^P = 2^-, 1^-$(T=1) Dominant

( $1^+$,15.1MeV for C)

$^{16}$O(ν,ν' ) Cross Section




♦ NC Neutrino-Nucleus Cross Section :

**ν**+A→**ν**+A' : Nuclear Matrix Element

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

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

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

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

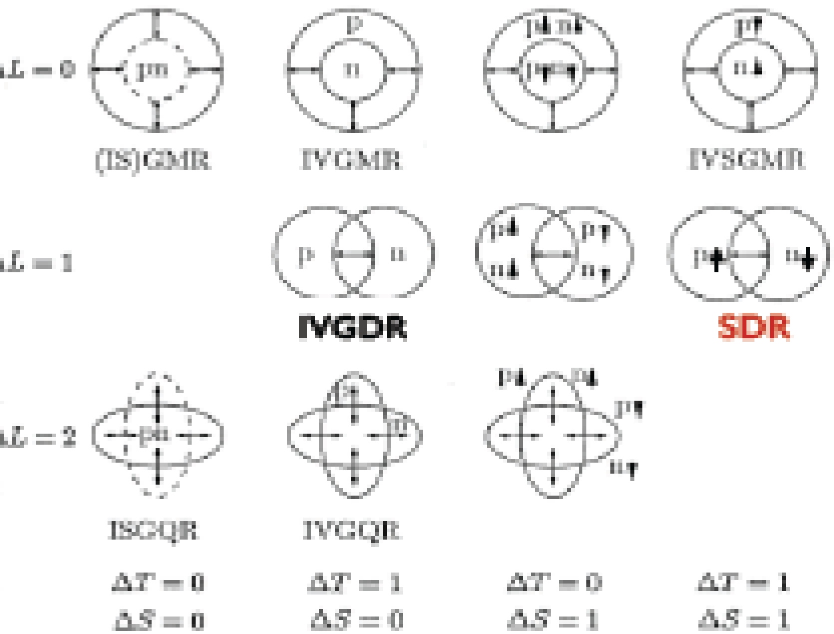
♦ Vector: GDR ($J^p=1^-$,ΔT=1,ΔS=0,ΔL=1) : $f_1(r)Y_1^m\tau_3$

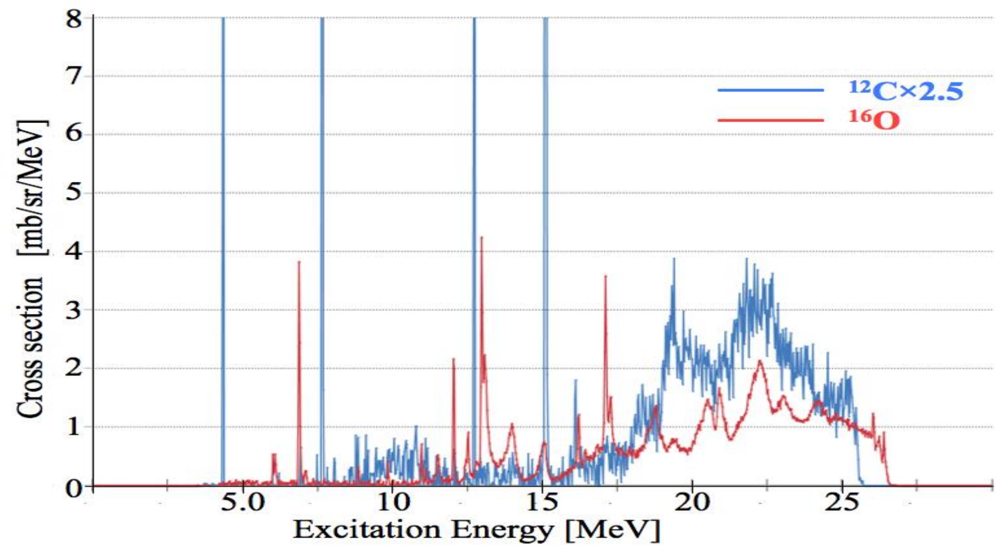
♦ Axial: **Spin Dipole R** ($J^p=0^-,1^-,2^-$, ΔT=1,ΔS=1,ΔL=1) : $\vec{\sigma} f_1(r)Y_1^m\tau_3$

**M1** ($J^p=1^+$,ΔT=1,ΔS=1,ΔL=0) : $\vec{\sigma} f_0(r)\tau_3$

# Emergence of Giant Resonances

巨大共鳴状態：量子数による分類



# NC $\nu$-$^{16}O$,$^{12}C$ reaction

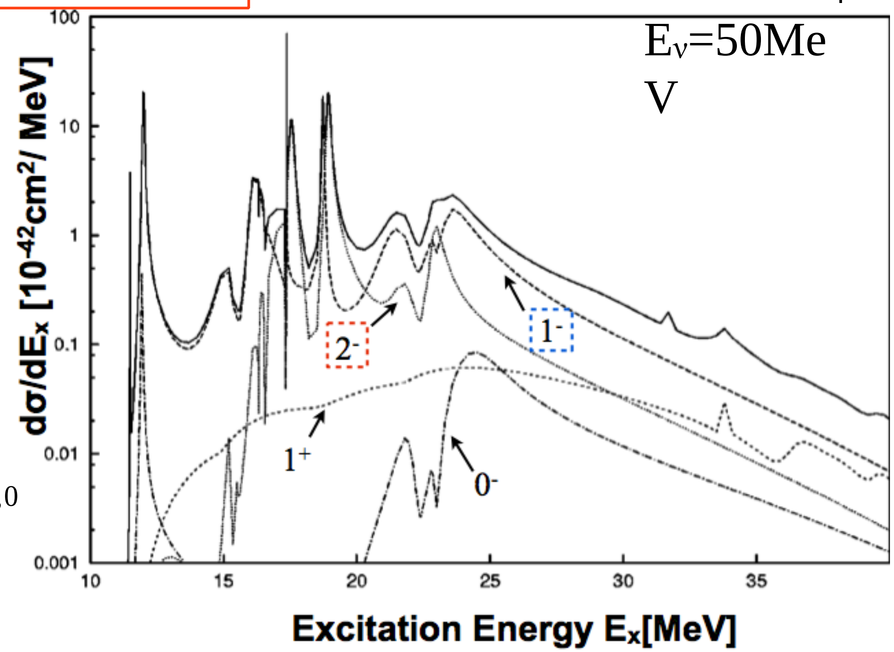
.Ref. Jachowicz et al .,PRC59( '99),
Botrugno, Co', NPA761('05)

xial Current Dominant:

specially, Spin Dipole Resoance : $J^P$ =2$^-$,1$^-$(T=1) Dominant

( $1^+$,15.1MeV for C)

$^{16}O(\nu,\nu')$ Cross Section




♦ NC Neutrino-Nucleus Cross Section :

$\boldsymbol{\nu}$+A→$\boldsymbol{\nu}$+A' : Nuclear Matrix Element

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

$$^{\mu}_{CC} = (J_V^{\mu})_{1,\pm1} + (J_A^{\mu})_{1,\pm1}$$

$$^{\mu}_{NC} = \beta_V^1 (J_V^{\mu})_{1,0} + \beta_A^1 (J_A^{\mu})_{1,0} + \beta_V^0 (J_V^{\mu})_{0,0} + \beta_A^0 (J_A^{\mu})_{0,0}$$

$$= (J_V^{\mu})_{1,0} + (J_A^{\mu})_{1,0} - 2\sin^2\theta_W J^{\mu}_{em} \quad [+(J_A^{\mu})_{0,0}]$$

♦ Vector: GDR ($J^p$=$1^-$,ΔT=1,ΔS=0,ΔL=1) : $f_1(r)Y_1^m\tau_3$

♦ Axial: **Spin Dipole R** ($J^p$=$0^-$,$1^-$,$2^-$, ΔT=1,ΔS=1,ΔL=1) : $\vec{\sigma} f_1(r)Y_1^m\tau_3$

**M1** ($J^p$=$1^+$,ΔT=1,ΔS=1,ΔL=0) : $\vec{\sigma} f_0(r)\tau_3$

# 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 probability of γ-ray emission ($E_\gamma$>2 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-ray emission probability ($E_\gamma$>2MeV)=
  - (Number of γ-rays observed for $E_\gamma$>2 MeV)/(Number of events excited in the range Ex=15-30 MeV, each Ex bin) →Fig.
  -

- [Importance]: Data for νO→νO*→ γ and νC→νC*→γ 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.

# 2. $^{16}$O,$^{12}$C(p,p’ γ) experimental setup

Experiment was done at RCNP (Osaka Univ.)
in May 19-28, 2014

## Excitation Energy

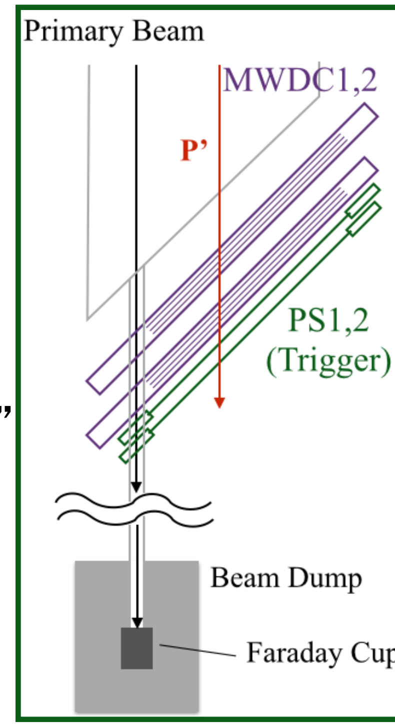
- Proton Beam: 392MeV, 0.5~1.5nA
- Target: $^{nat}$C (36.3 mg/cm$^2$)

  $C_6H_{10}O_5$(Cellulose, 28.2mg/cm$^2$)
- Magnetic Spectrometer “**Grand Raiden**”
  - $\theta_{scat} = 0°$ (covers 0° ~ 3° )
  - Solid Angle = 5.6 msr
  - $\Delta E_x$ ~ 100 keV

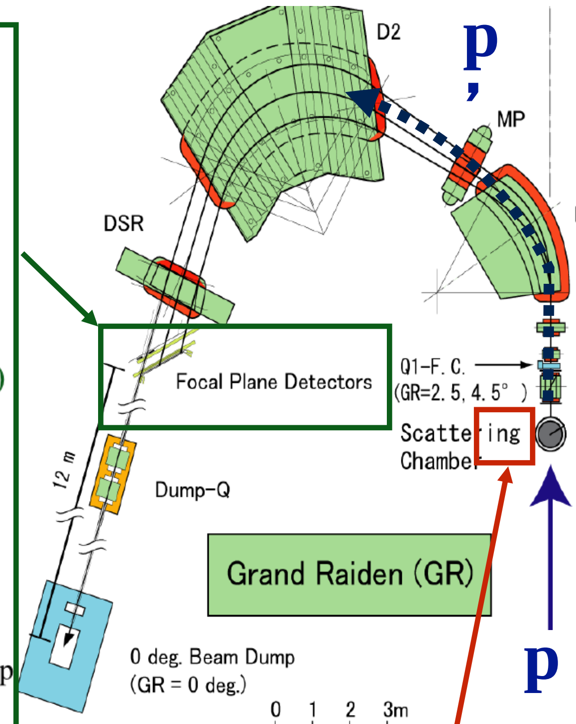
## Gamma-ray Energy

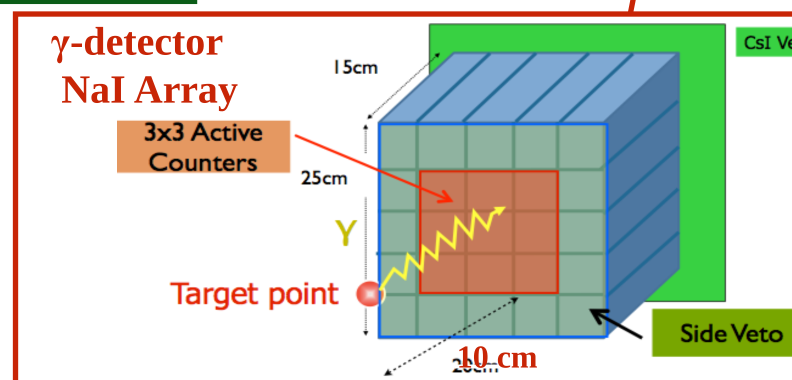
- γ-detector : NaI(Tl) ×25 Array
  - Solid Angle × Detection Efficiency ~ 2% @6MeV (GEANT4)
  - each NaI: 25×25×15 cm, ΔE~5%@1.33MeV

**Focal Plane Detectors**

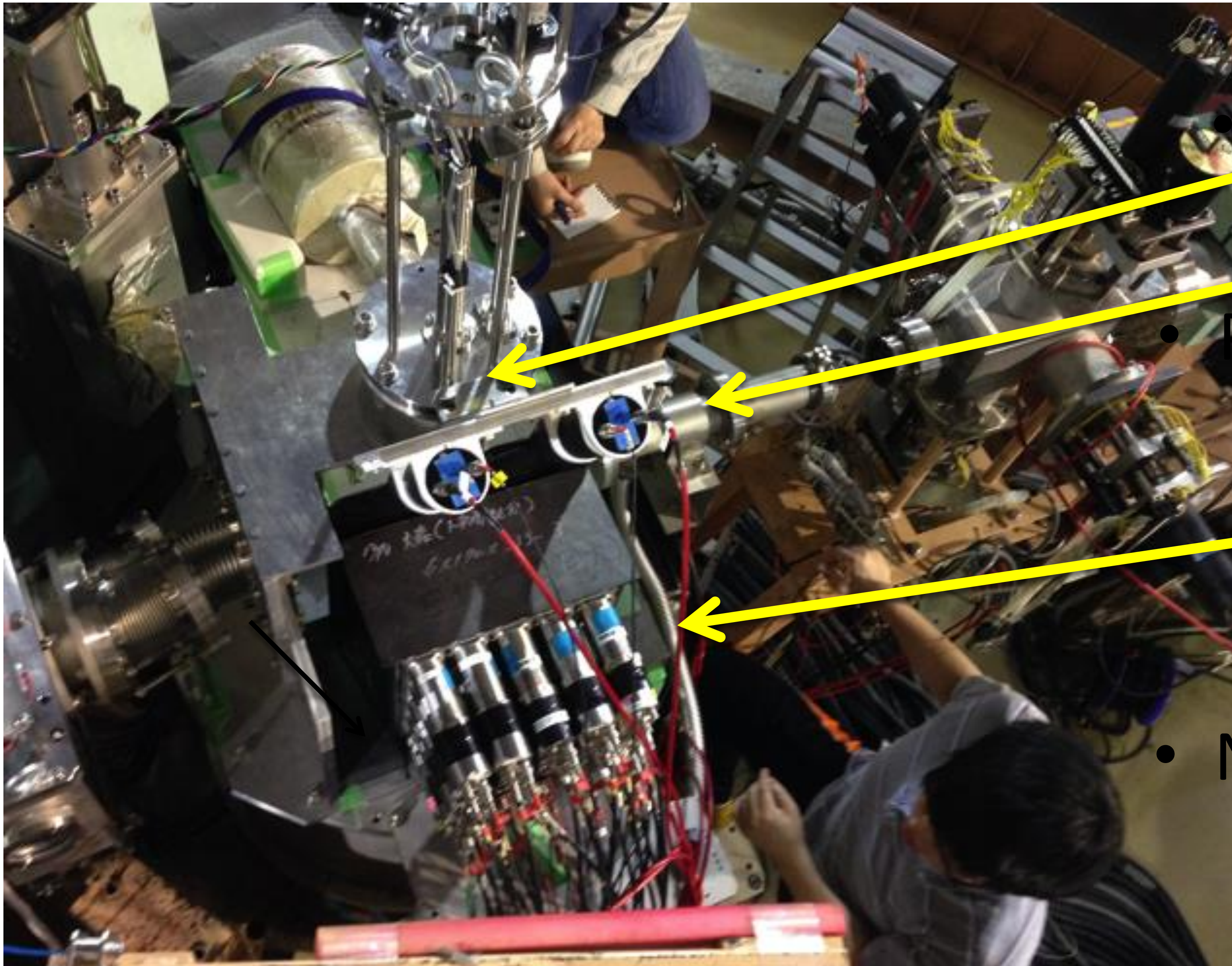



**Magnetic Spectrometer**



# E398 (May 16-27, 2014)

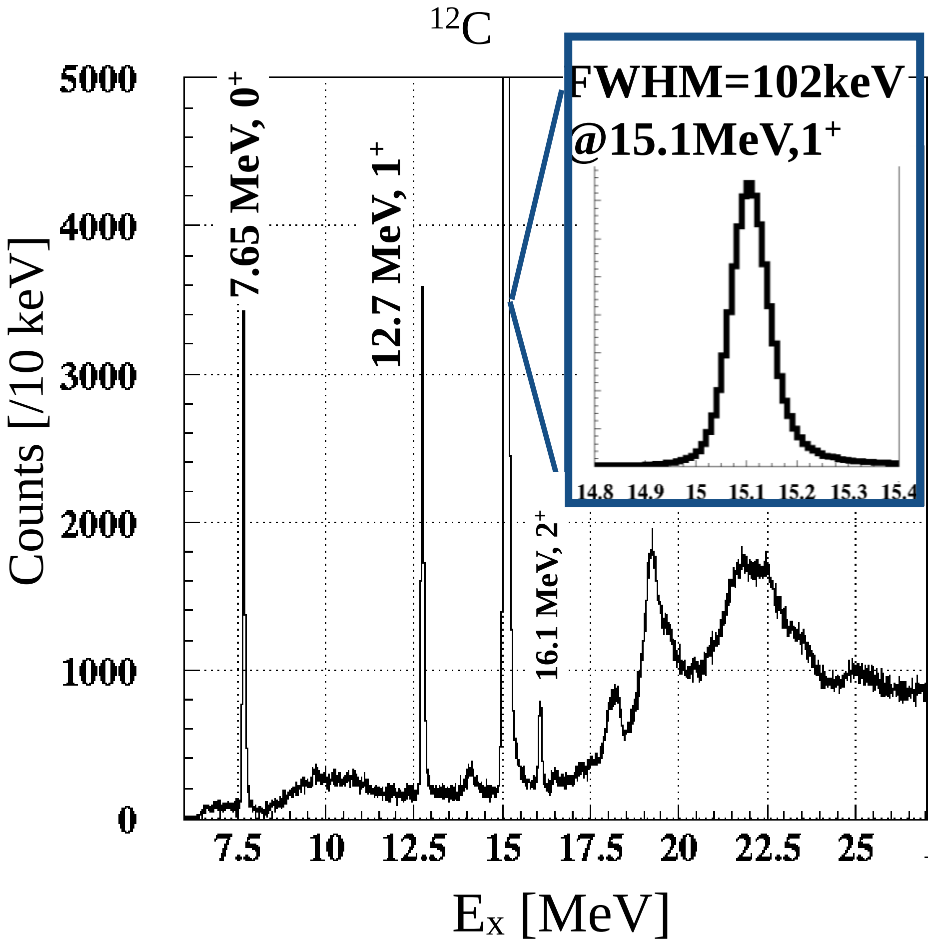


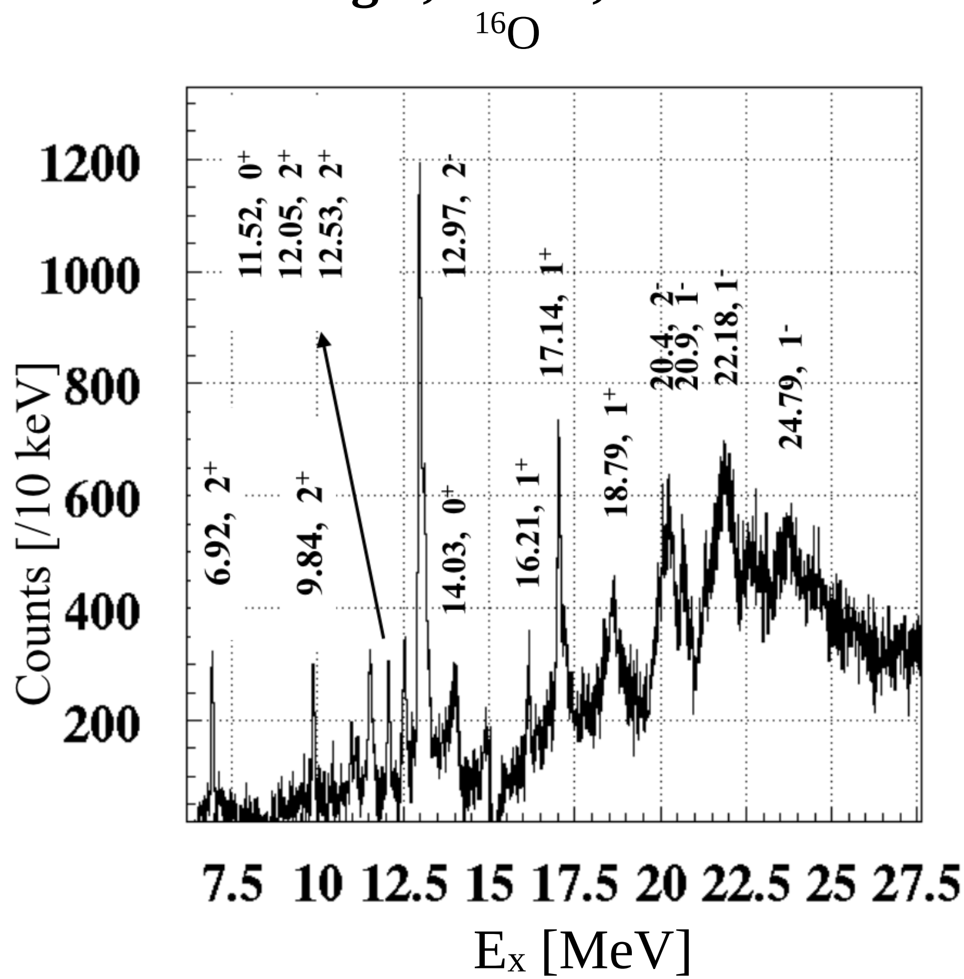
- Target(C,O)
- Proton Beam
  - 390MeV
- NaI 5x5 array

# (1) Analysis of Grand Raiden: Excitation Energy Spectrum

-I.Ou (Okayama)@JPS 2015.09.27

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



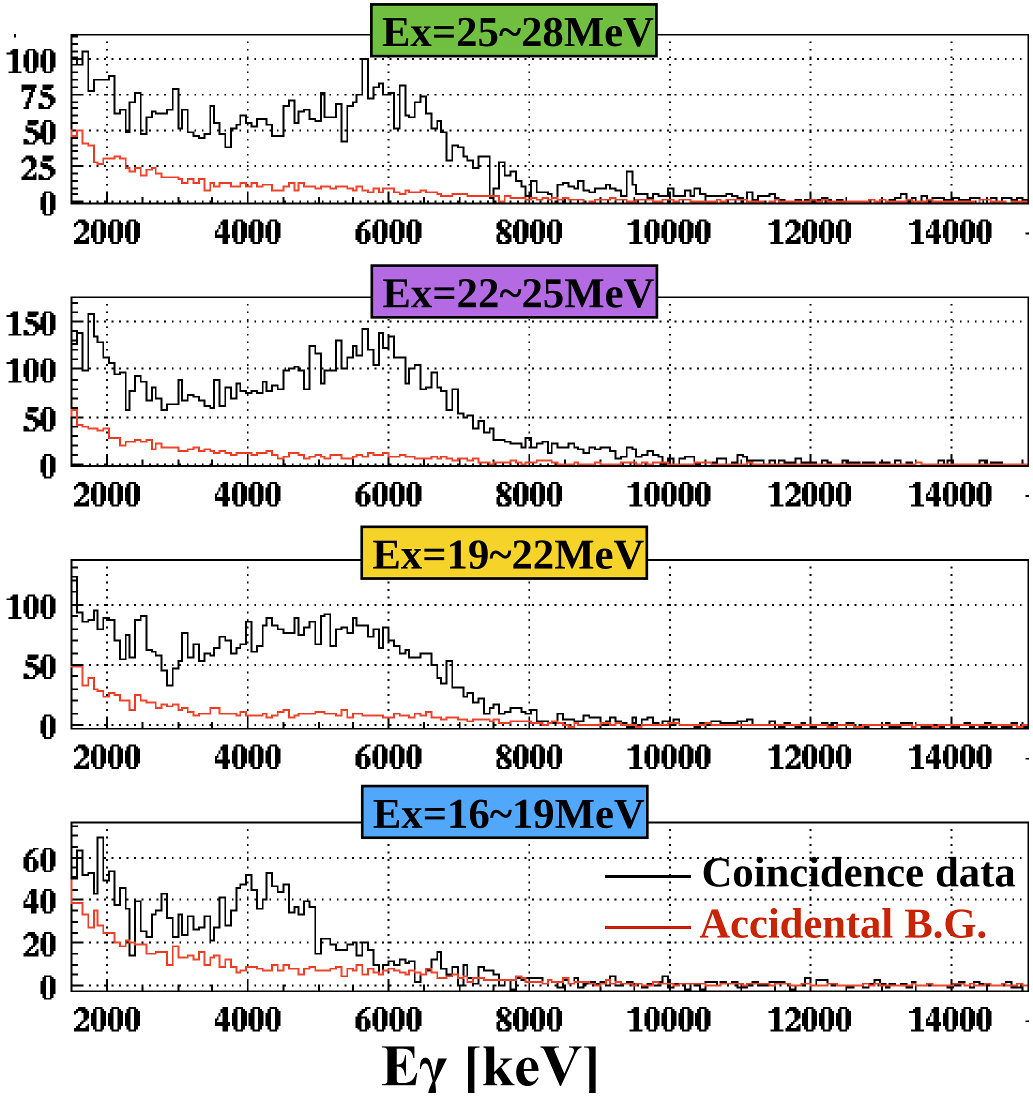



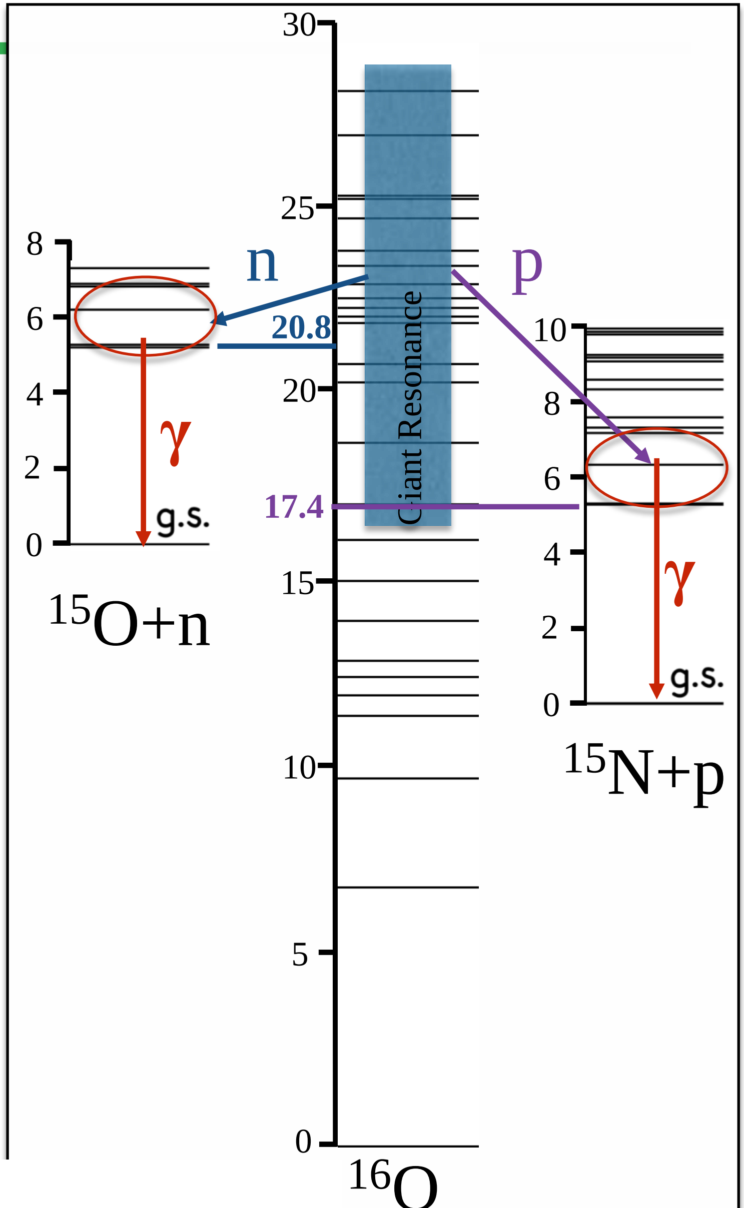

**Values of peak energy agree with the known levels within calibration error (~40 keV).**



**Ref.** Table of Isotopes, 8th ed.

# (2)γ-rays from giant resonance are seen :$^{16}$O




**after p/n decay, daughter nucleus $^{15}$O/$^{15}$N emit 5~9MeV-γ rays agree with statistical calc by Langanke.**

# (5) Status of E398

✶ **Quick look at γ-ray spectrum from giant resonances (1/10 of the total data used)**

- **Our data agree qualitativly with theoretical picture by Langanke et. al. "γ-rays are emitted from daughter nuclei after p/n decay"**
- **Next Step: Quantitative determination of emission probability(Pr)**
- **Future: After we publish the result, we would like to do an experiment at GRFBL (4-15 Degrees).**

# Summary

- Form Factors –Charge and Magtetization density distributions
  - H.de Vries, C.W.de Jager and C.de Vries, Atom.Data Nucl.Data Tabl. 36,495 (1987).
  - T.W.Donnelly and I.Sick, RMP 56, 461(1984). For Updates.
  - Nucleon FF – Recent NuInt Proceedings
  - R.Hofstadter, Electron Scattering and Nuclear Structure, RMP.28,214-254(1956).
- Neutrino  Interactions in 110-100 MeV
- We would like  to finilise our analysis and give new experimental data on O*/C*->gamma  emission probability.