The 4th International Symposium on
Neutrinos and Dark Matter in Nuclear Physics (NDM12)
June 11-15th, 2012, Nara, Japan

Neutrino nuclear reactions by photon and lepton probes

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- Importance of n-A interactions in nuclear and particle astrophysics
- Photo-nuclear reaction experiment with monochromatic γ-rays
- μ-capture experiment with high-intensity μ source
- Summary

Neutrino-nucleus interactions play important roles in

- heating on SN shockwave by ν-spallation on D, ^{4}He, etc.
- r-process in neutrino-driven wind;
  free neutrons supplied by ν-spallation on light nuclei?
  post processing to original r-abundances?
- p-nucides; rare but unreachable by neither r- nor s-processes
  (p,γ)? (γ,n)? (ν,l)? $(\nu,\nu'n)$?
- detection of astronomical neutrinos ; D, ^{71}Ga, ^{100}Mo, etc.
- double beta decays with 0ν and 2ν emissions

Accuracy of better than ~10% is required.

Calculation needs information on

- weak form factors (f_V , f_A , f_M , f_P)

nuclear β-decay, μ-capture

- wave functions

nuclear potential

model (ChiPT, shell model, cluster, RPA, TDHF,...)

approximations (one-meson exchange,
long-wave approx., Siegert theorem, ...)

EM probes **---** **Photonuclear reactions**

Analogy between ν-A and γ-A interactions

Weak operators ;

$$T^{W}_{10\ LJ} = g^{W}_{10\ LJ} \cdot \tau \cdot \left[i^{L} r^{L} Y_{L} \right]_{J}$$

$$T^{W}_{11\ LJ} = g^{W}_{11\ LJ} \cdot \tau \cdot \left[i^{L} r^{L} Y_{L} \times \sigma \right]_{J}$$

$$\tau = \begin{cases} \tau_{\pm} & (\text{charged current}) \\ \tau_{3}\sqrt{2} & (\text{neutral current}) \end{cases}$$

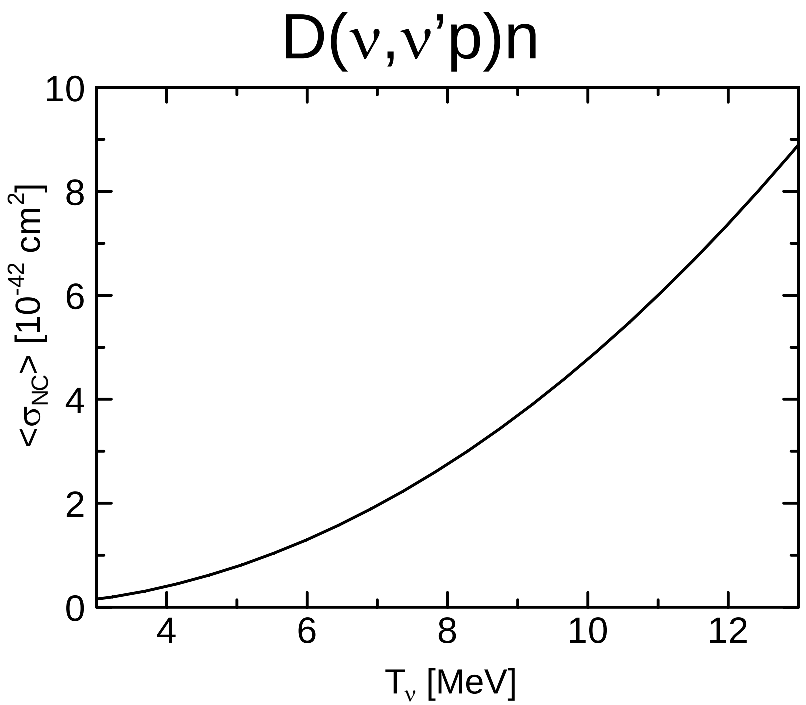
EM operators ;

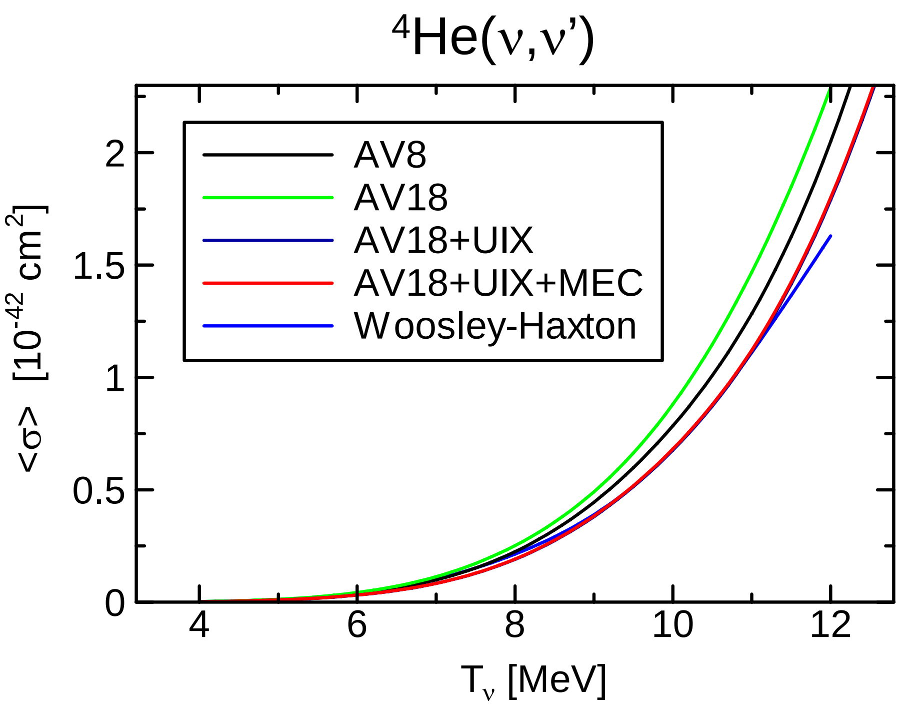
$$\boldsymbol{T^{EM}_{10\ LJ} = g^{EM}_{10\ LJ} \cdot \tau_{3}\sqrt{2} \cdot \left[i^{L} r^{L} Y_{L} \right]_{J}}$$

$$\boldsymbol{T^{EM}_{11\ LJ} = g^{EM}_{11\ LJ} \cdot \tau_{3}\sqrt{2} \cdot \left[i^{L} r^{L} Y_{L} \times \sigma \right]_{J}}$$

--- Photon is a useful probe for weak nuclear responses.

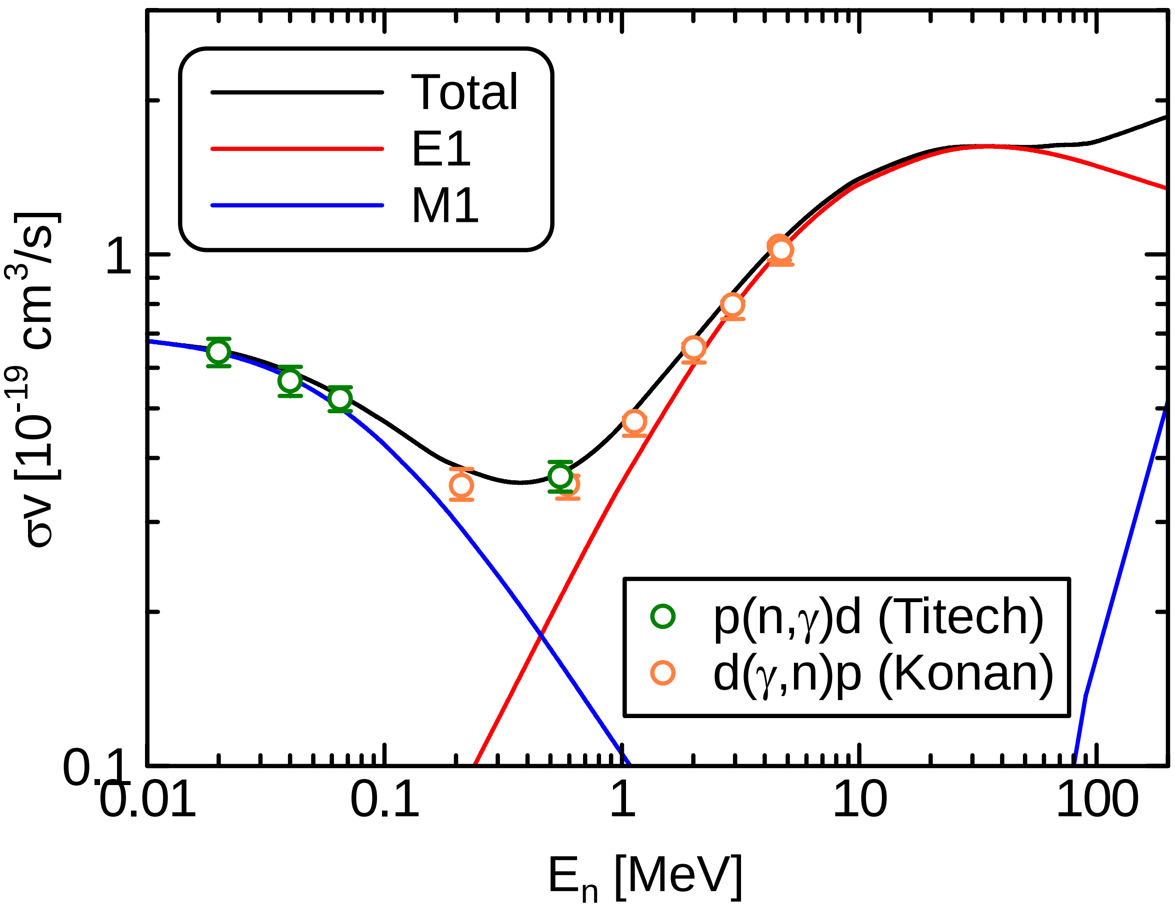
D, ^{4}He





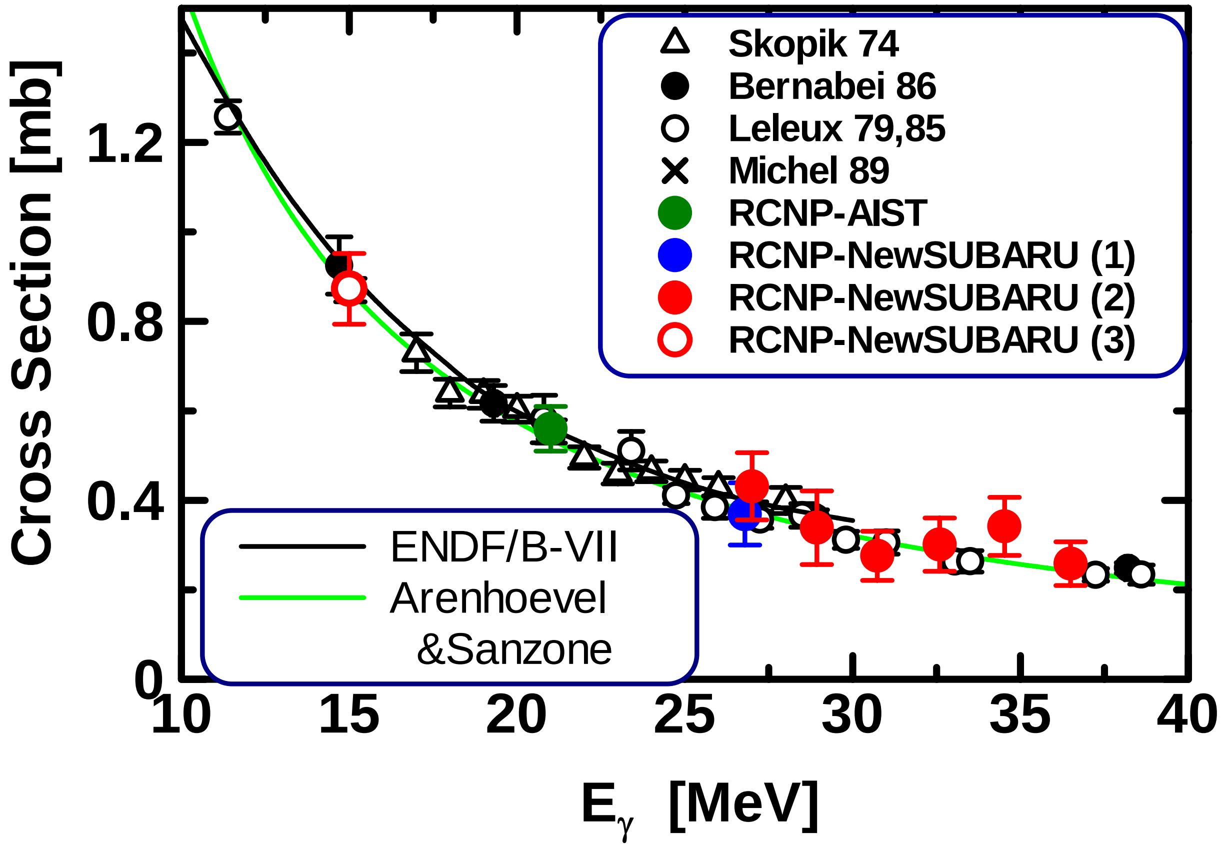
The abundance of the deuteron is ~±2 dex of α, and its (ν,ν') cross section is about one order of magnitude larger than that of α due to the low threshold energy.

p(n,γ)d; Theory v.s. Experiment



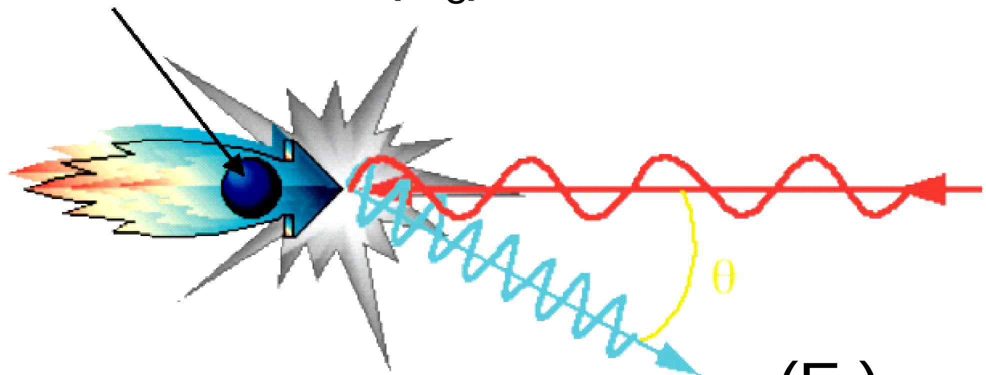
S.Nakamura, T.Sato, V.Gudkov, K.Kubodera, PRC63, 034617 (2001)

D(γ,p)n data



--- Good agreement with existing data
as well as theoretical calculations and fittings !

Laser Compton backscattering



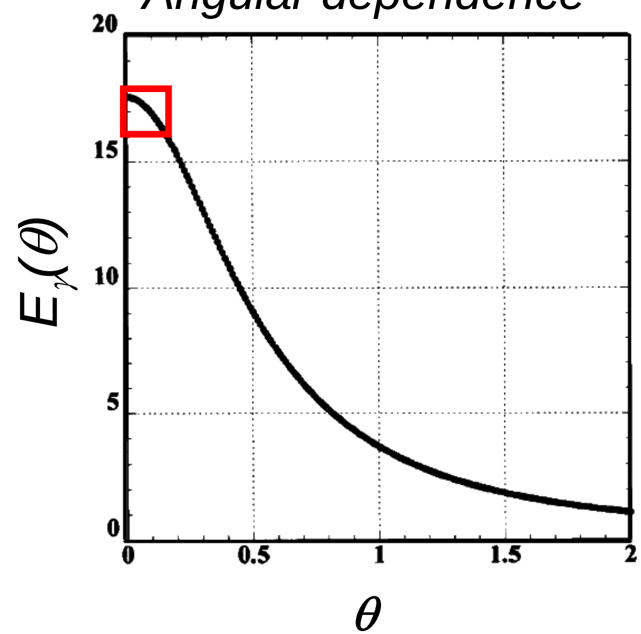
Klein-Nishina formula

$$E_\gamma = \frac{4hc}{\lambda_L} \cdot \frac{\gamma^2}{1+\gamma^2\theta^2}\ , \qquad \gamma = \frac{E_e}{m_e c^2}$$

ex. λ_L=1.064μm, E_e=800MeV

$\Rightarrow E_\gamma$ = 11MeV

Angular dependence



Advantages of LCS-γ

- Quasi-monochromatic; $\Delta E/E \sim$ a few %
- Little background γ-rays; tagging not necessary
- Well-collimated; $\Delta\theta < 0.1$ mrad
- Highly polarized; linear or circular, P ~ 100%

  → useful to separate E1 (vector) and M1 (axial-vector)
- Continuous or pulsed; $\Delta t < 10$ns
- Considerable intensity; $\Phi_\gamma = 10^4 \sim 10^8$ γ/s/MeV

NewSUBARU

Lab. of Adv. Sci. and Tech. for Industry, University of Hyogo, Japan

N
SPring-8/NewSUBARU
Osaka Univ./RCNP
100km
You are here !
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Toyooka
Maizuru
Obama
Tsuruga
Mino
Ikeda
Gifu
Ogaki
Ichinomiya
Fukuchiyama
Nagoya
Tsuyama
Yamasaki
Sasayama
Kyoto
Kusatsu
Yatomi
Kameoka
Yokkaichi
Tokai
Nishiwaki
Himeji
Minakuchi
Seki
Suzuka
Ueno
Ako
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Kobe
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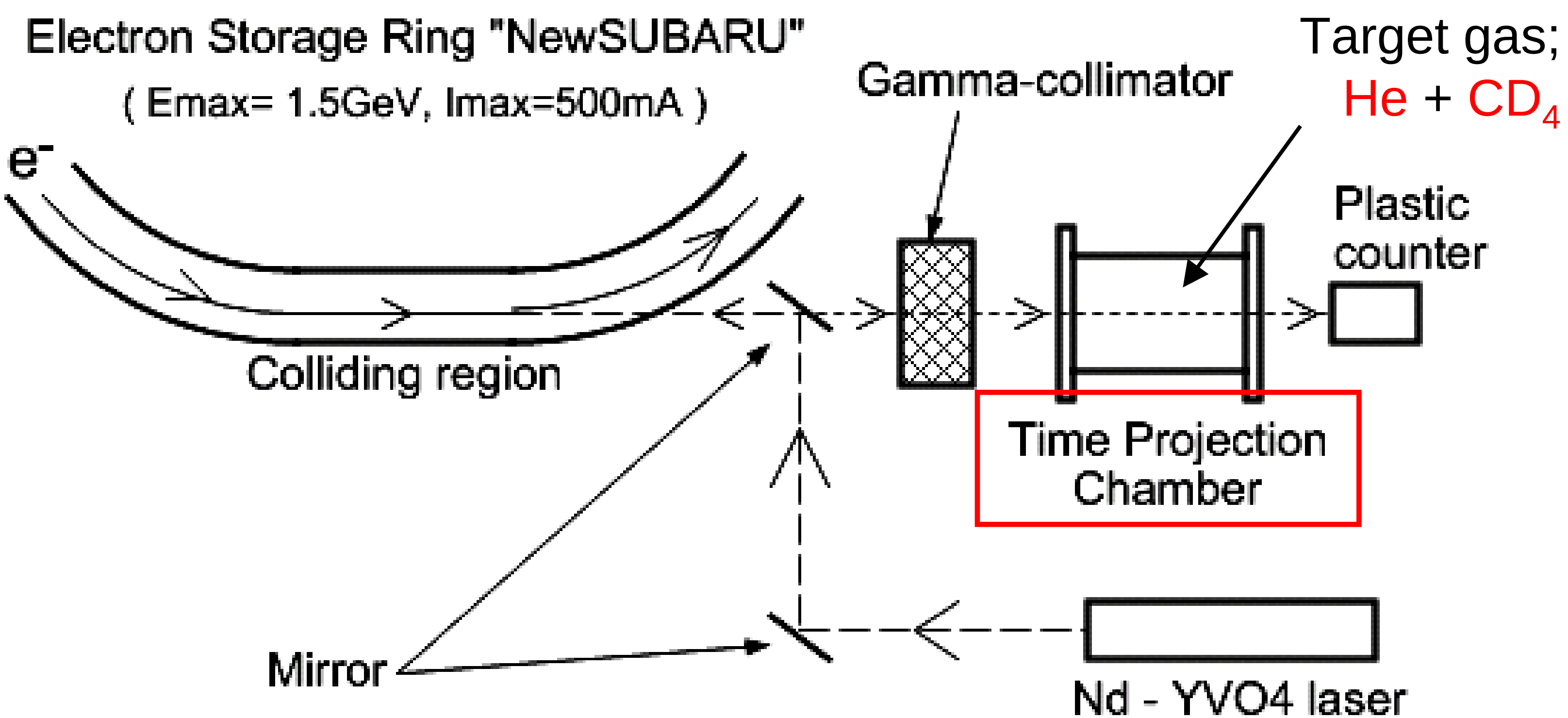
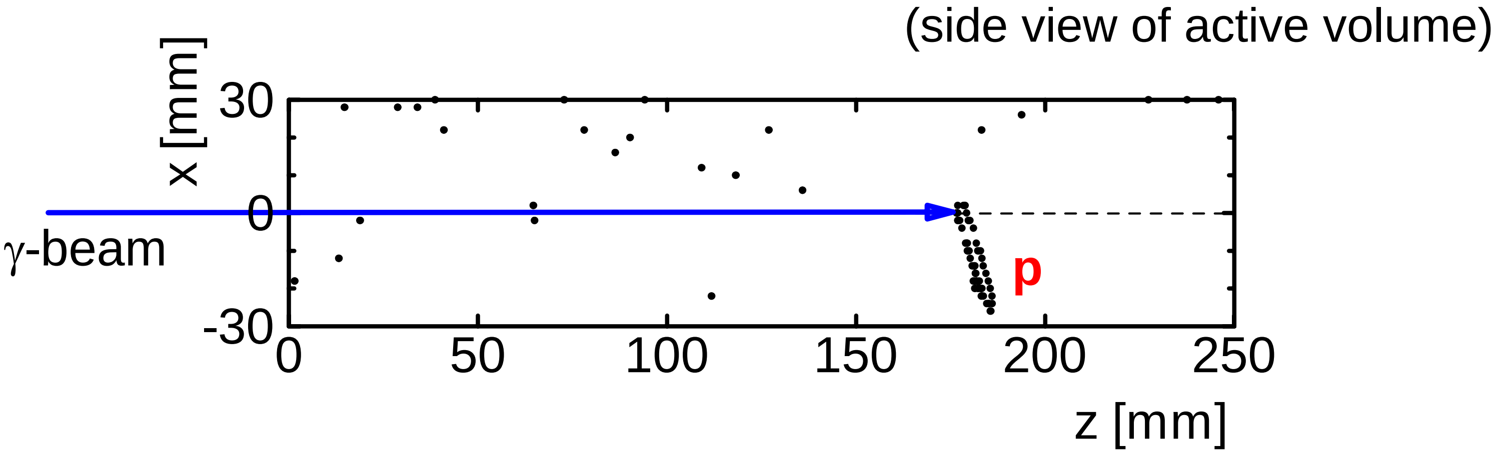
Experiment with quasi-monochromatic γ at NewSUBARU

Laser Compton-scattered γ-ray :

E_γ = 1.6 ~ 40MeV, Φ_γ ~4×10^4 /sec, FWHM=4~5%, P~100%



Candidate of D(γ,n)p event



Event ID:

- Single track
- Vertex on beam axis
- Pulse height corresponding to proton dE/dx

Intermediate-mass nuclei

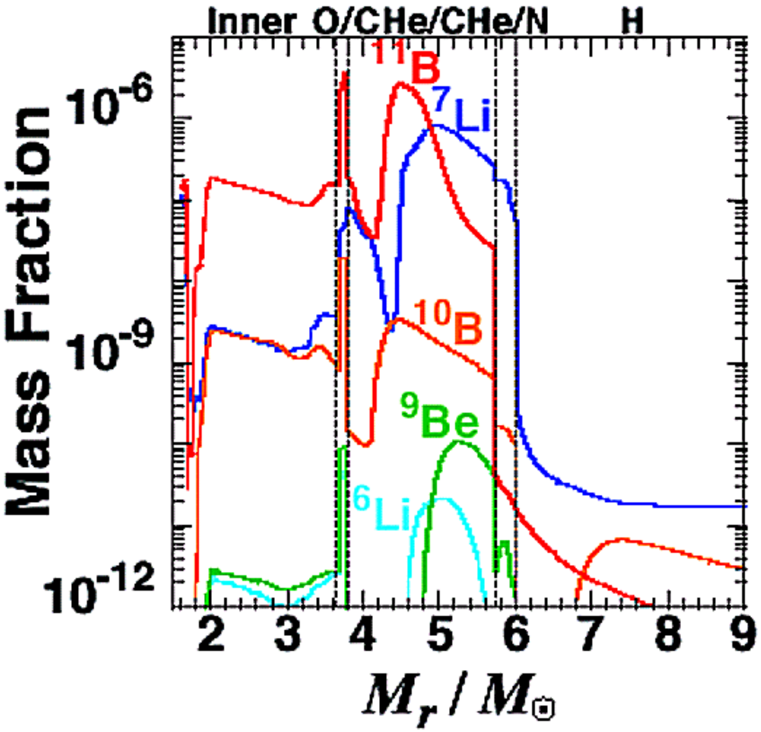
^{7}Li, ^{11}B production by ν-spallations

Woosley et al., Woosley & Weaver, Rauscher et al., Yoshida et al.

$\underline{^{4}\mathrm{He}(\nu,\nu'p)^{3}\mathrm{H}}(\alpha,\gamma)\mathbf{^{7}Li}(\alpha,\gamma)\mathbf{^{11}B}$

$\underline{^{4}\mathrm{He}(\nu,\nu'n)^{3}\mathrm{He}}(\alpha,\gamma)^{7}\mathrm{Be}(e^{-},\nu_e)\mathbf{^{7}Li}$

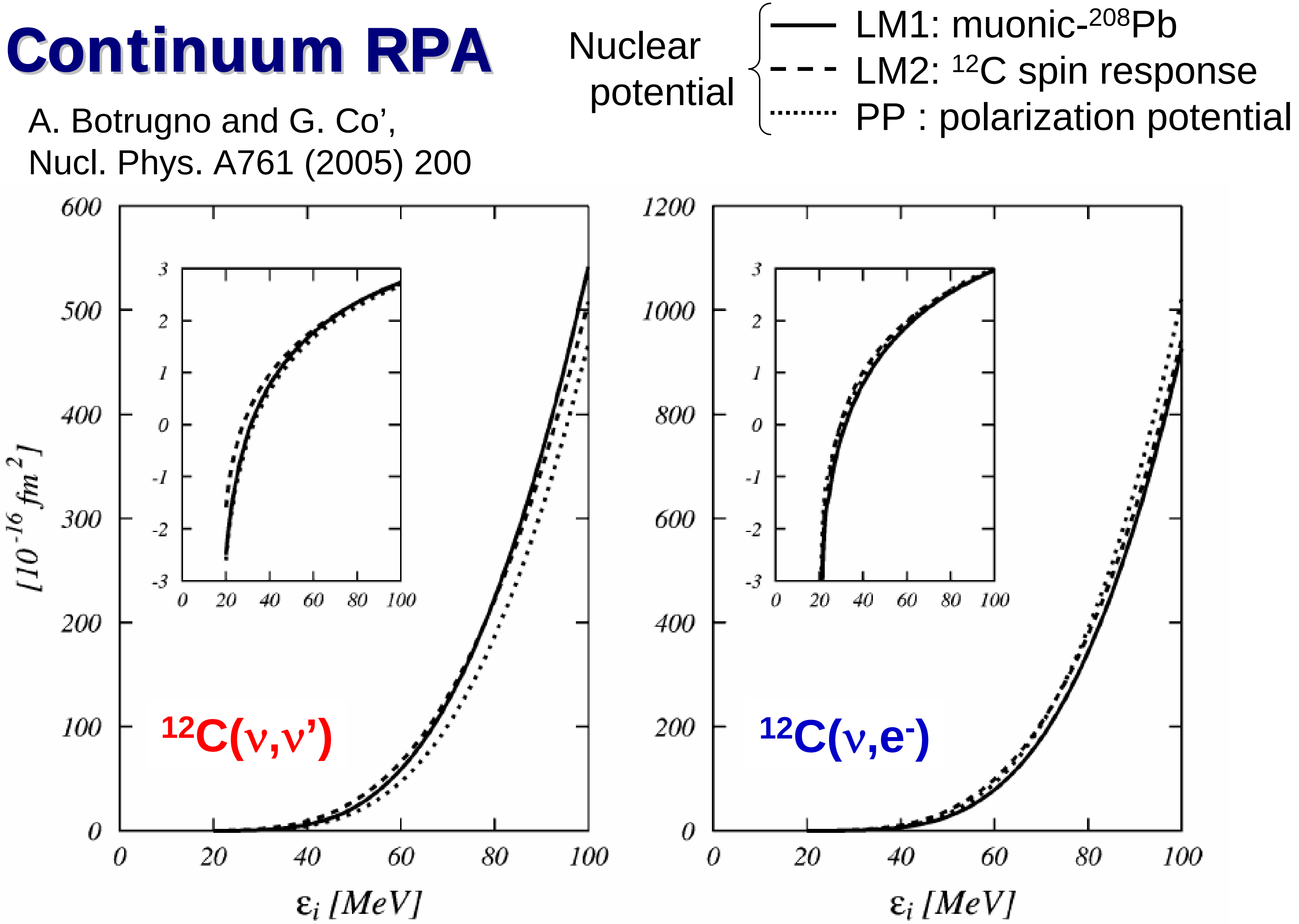
$\boxed{\begin{array}{l} \underline{^{12}\mathrm{C}(\nu,\nu'p)\mathbf{^{11}B}} \\ \underline{^{12}\mathrm{C}(\nu,\nu'n)^{11}\mathrm{C}}(e^{-},\nu_e)\mathbf{^{11}B} \end{array}}$



Yoshida, Kajino et al., PRL96, 091101 (2006)

Continuum RPA

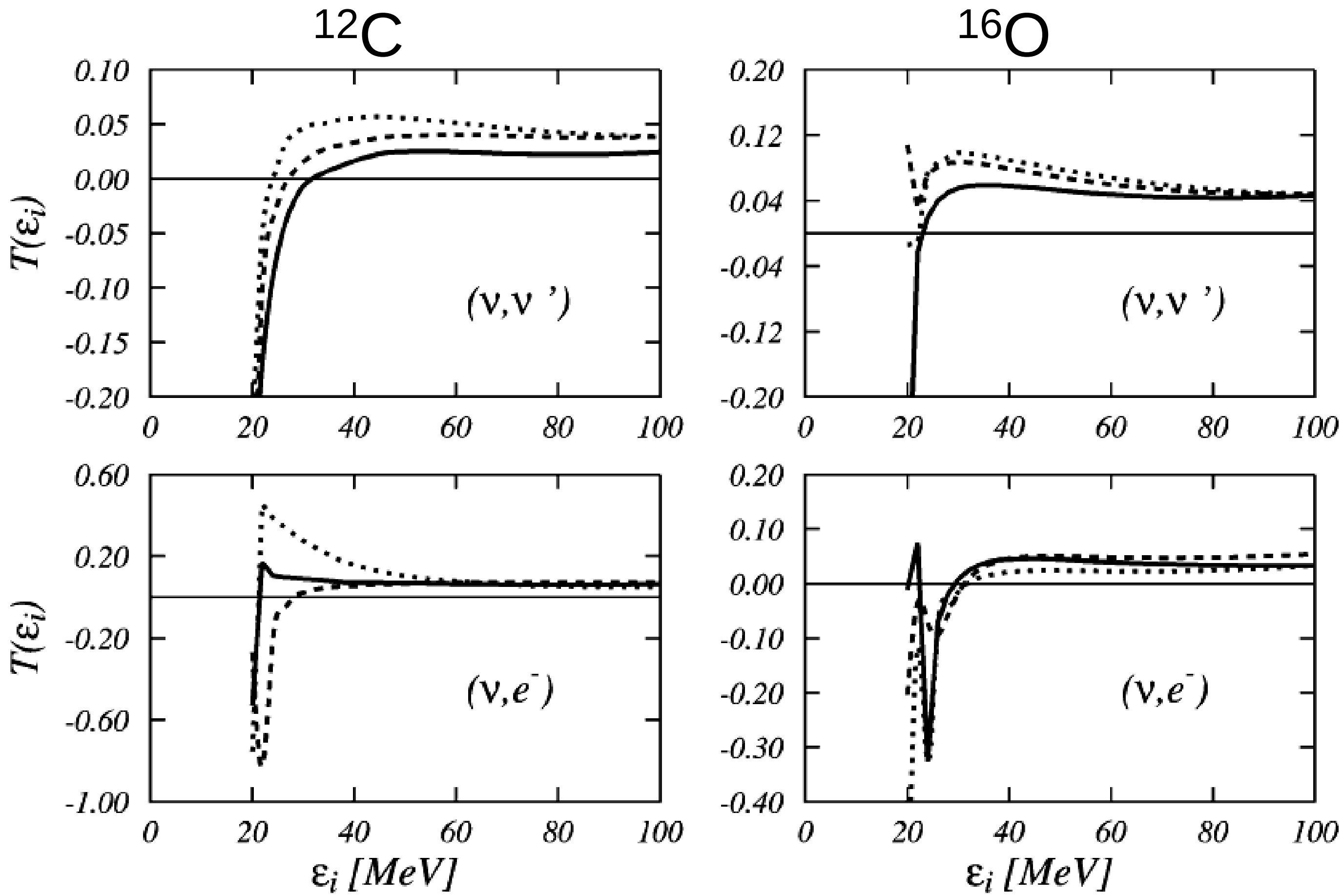
A. Botrugno and G. Co',
Nucl. Phys. A761 (2005) 200



CRPA with Final State Interaction

Relative magnitude of FSI effect: $$T(\varepsilon_i) = \frac{\sigma^{CRPA}(\varepsilon_i) - \sigma^{CRPA+FSI}(\varepsilon_i)}{\sigma^{CRPA}(\varepsilon_i) + \sigma^{CRPA+FSI}(\varepsilon_i)}$$

= 3 ~ 10 %



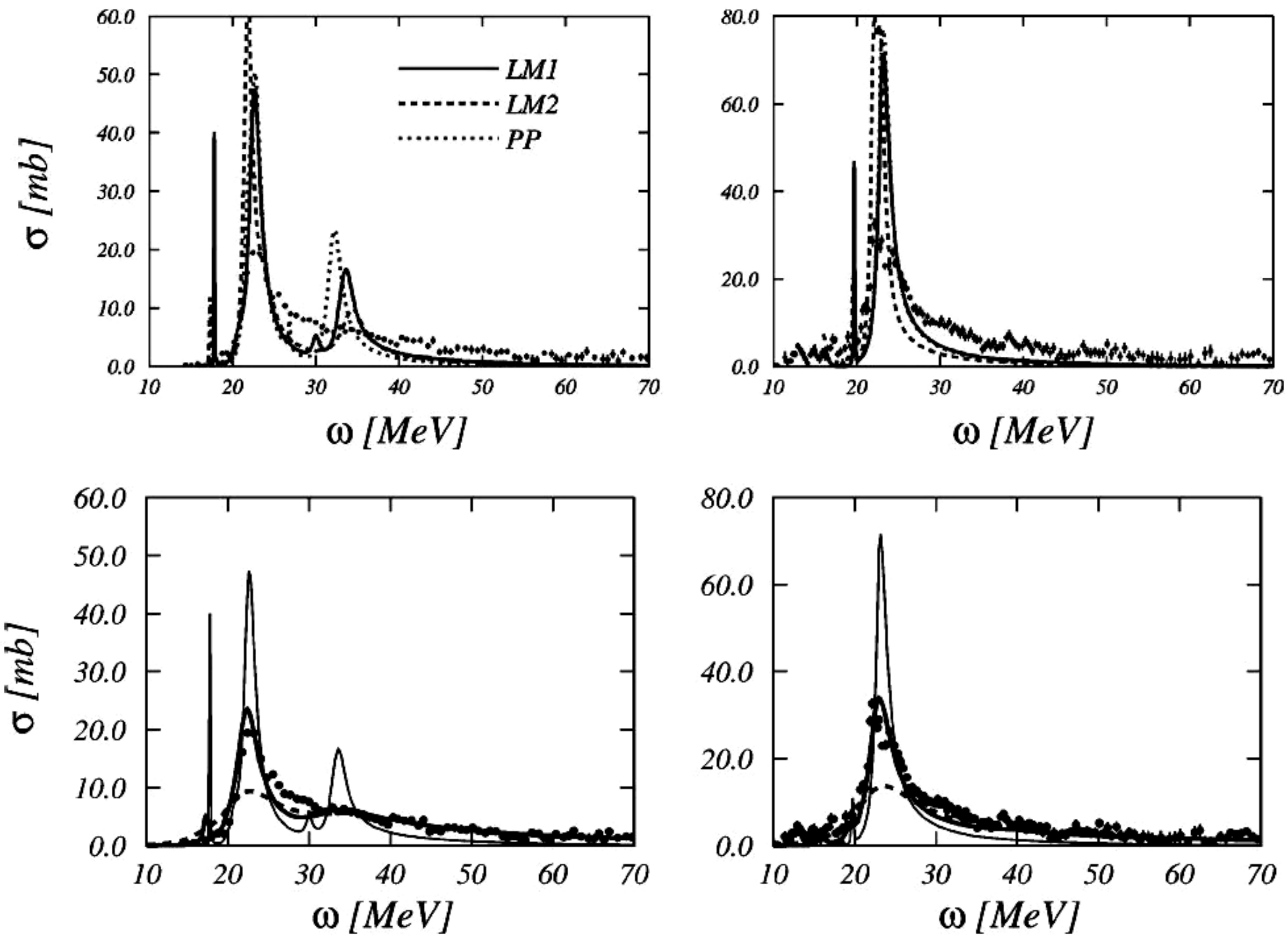
Photoabsorption

Nuclear potential
- LM1: muonic-^{208}Pb
- LM2: ^{12}C spin response
- PP : polarization potential

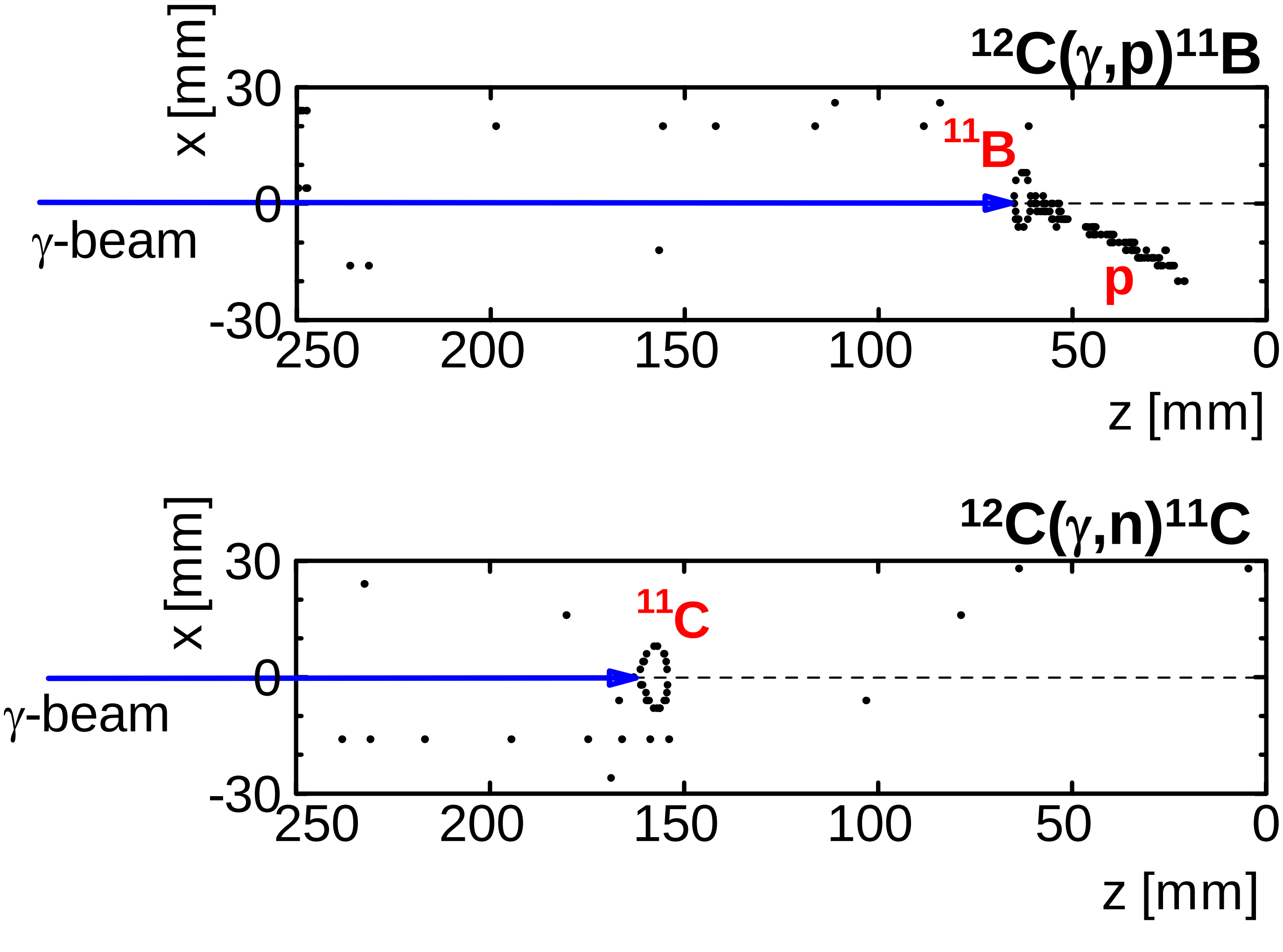
^{12}C(γ,abs) | ^{16}O(γ,abs)

CRPA

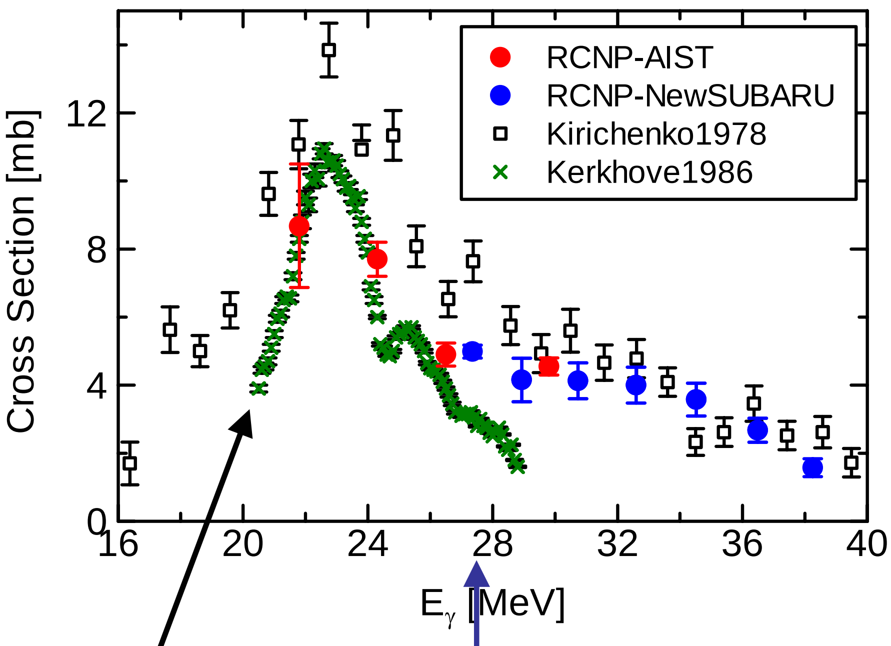
CRPA+FSI

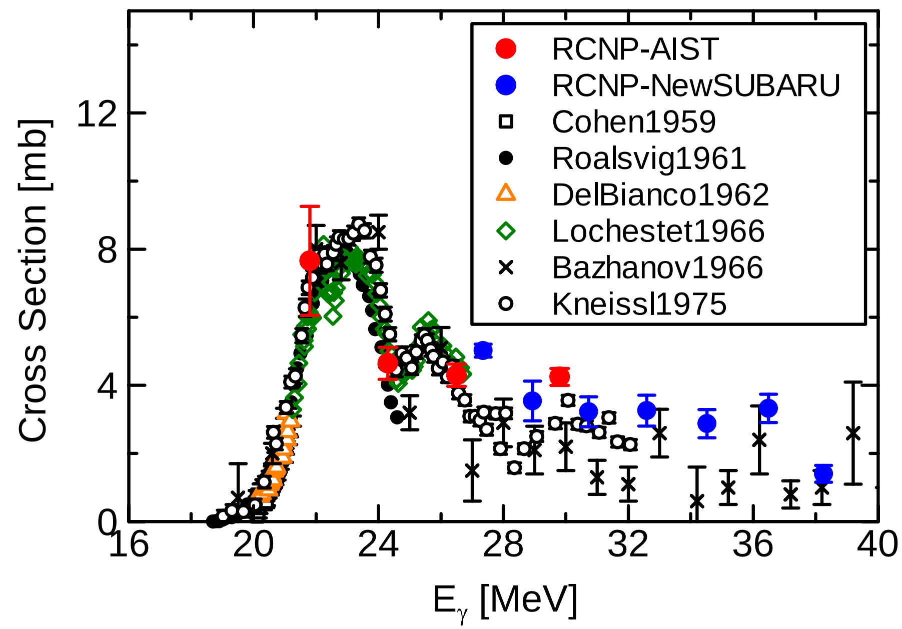


^{12}C photodisintegration



$^{12}C(\gamma,p)^{11}B$ $\quad$ $^{12}C(\gamma,n)^{11}C$





$^{11}B(p,\gamma)^{12}C$
(detailed balance)

$^{12}C(\gamma,pn)^{10}B$ threshold

--- Systematic errors are reduced due to use of monochromatic γ and active target (TPC).

Heavy nuclei

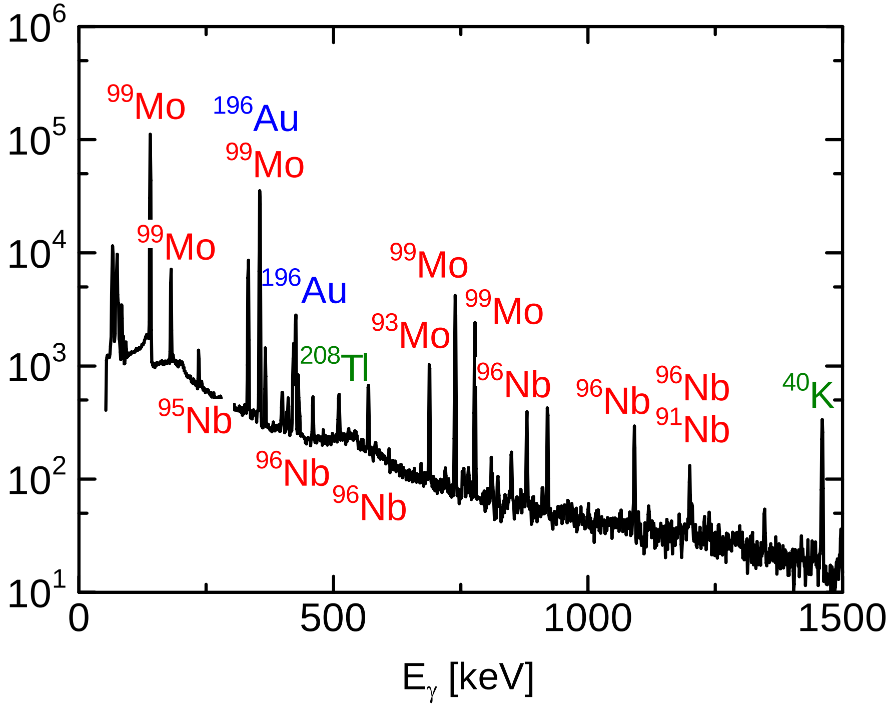
Ru93 59.7 s (9/2)+ * EC	Ru94 51.8 m 0+ EC	Ru95 1.643 h 5/2+ EC	Ru96 0+ 5.52	Ru97 2.9 d 5/2+	Ru98 0+ 1.88	Ru99 5/2+ 12.7	Ru100 0+ 12.6	Ru101 5/2+ 17.0	Ru102 0+ 31.6	Ru103 39.26 d 3/2+ * β^-
Tc92 4.23 m (8)+ EC	Tc93 2.75 h 9/2+ * EC	Tc94 293 m 7+ * EC	Tc95 20.0 h 9/2+ * EC	Tc96 4.28 d 7+ * EC	Tc97 2.6E6 y 9/2+ * EC	Tc98 4.2E+6 y (6)+ β^-	Tc99 2.111E+5 y 9/2+ * β^-	Tc100 15.8 s 1+ β^-	Tc101 14.22 m (9/2)+ β^-	Tc102 5.28 s 1+ * β^-
Mo91 15.49 m 9/2+ * EC	Mo92 0+ 14.84	Mo93 4.0E+3 y 5/2+ * EC	Mo94 0+ 9.25	Mo95 5/2+ 15.92	Mo96 0+ 16.68	Mo97 5/2+ 9.55	Mo98 0+ 24.13	Mo99 65.94 h 1/2+ β^-	Mo100 1.2E19 y 0+ $\beta^-\beta^-$ 9.63	Mo101 14.61 m 1/2+ β^-
Nb90 14.60 h 8+ * EC	Nb91 680 y 9/2+ * EC	Nb92 3.47E+7 y (7)+ * EC,β^-	Nb93 9/2+ * 100	Nb94 2.03E+4 y (6)+ * β^-	Nb95 34.975 d 9/2+ * β^-	Nb96 23.35 h 6+ β^-	Nb97 72.1 m 9/2+ * β^-	Nb98 2.86 s 1+ * β^-	Nb99 15.0 s 9/2+ * β^-	Nb100 1.5 s 1+ * β^-
Zr89 78.41 h 9/2+ * EC	Zr90 0+ * 51.45	Zr91 5/2+ 11.22	Zr92 0+ 17.15	Zr93 1.53E+6 y 5/2+ β^-	Zr94 0+ 17.38	Zr95 64.02 d 5/2+ β^-	Zr96 3.9E19 y 0+ β^- 2.80	Zr97 16.91 h 1/2+ β^-	Zr98 30.7 s 0+ β^-	Zr99 2.1 s (1/2+) β^-

^{100}Mo; pure r-process isotope, candidate for $0\nu\beta\beta$

^{92}Mo; p-nuclide with largest inconsistency between obs. and calc.

Photo-activation with laser-backscattered γ

γ-rays from daughter nuclei of photonuclear reactions are measured with a low-BG Ge detector.



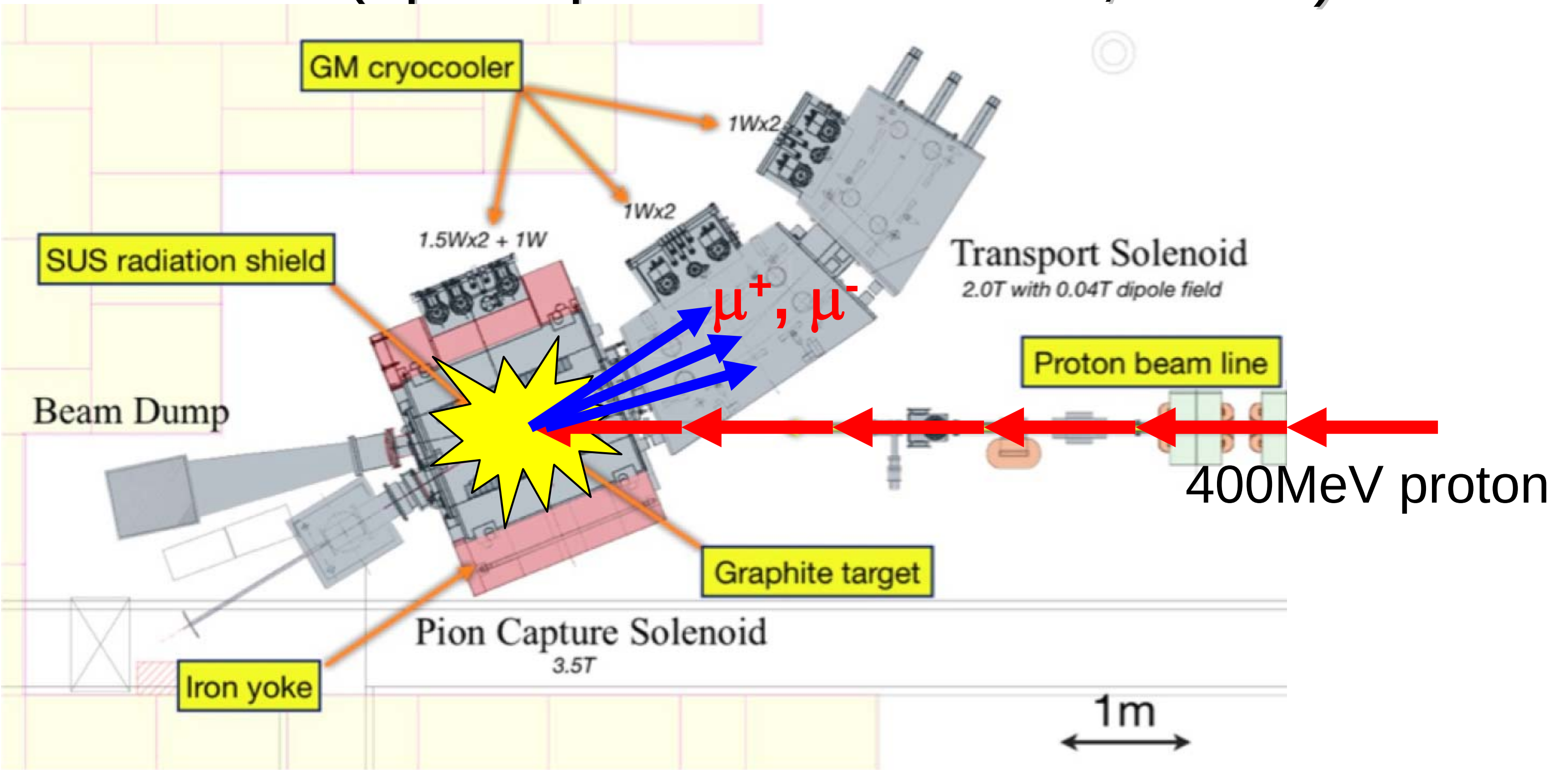
H.Ejiri & TS,
Phys. Rev. ST
Acc. And Beams
15 (024701) 2012.

Sensitivity: 5μmol/cm^2 with Φ_γ =10^5 γ/s @GDR (σ~0.17b)

$\Leftrightarrow$ σ~ 1.7μb with 0.5mol/cm^2 and Φ_γ =10^5 γ/s

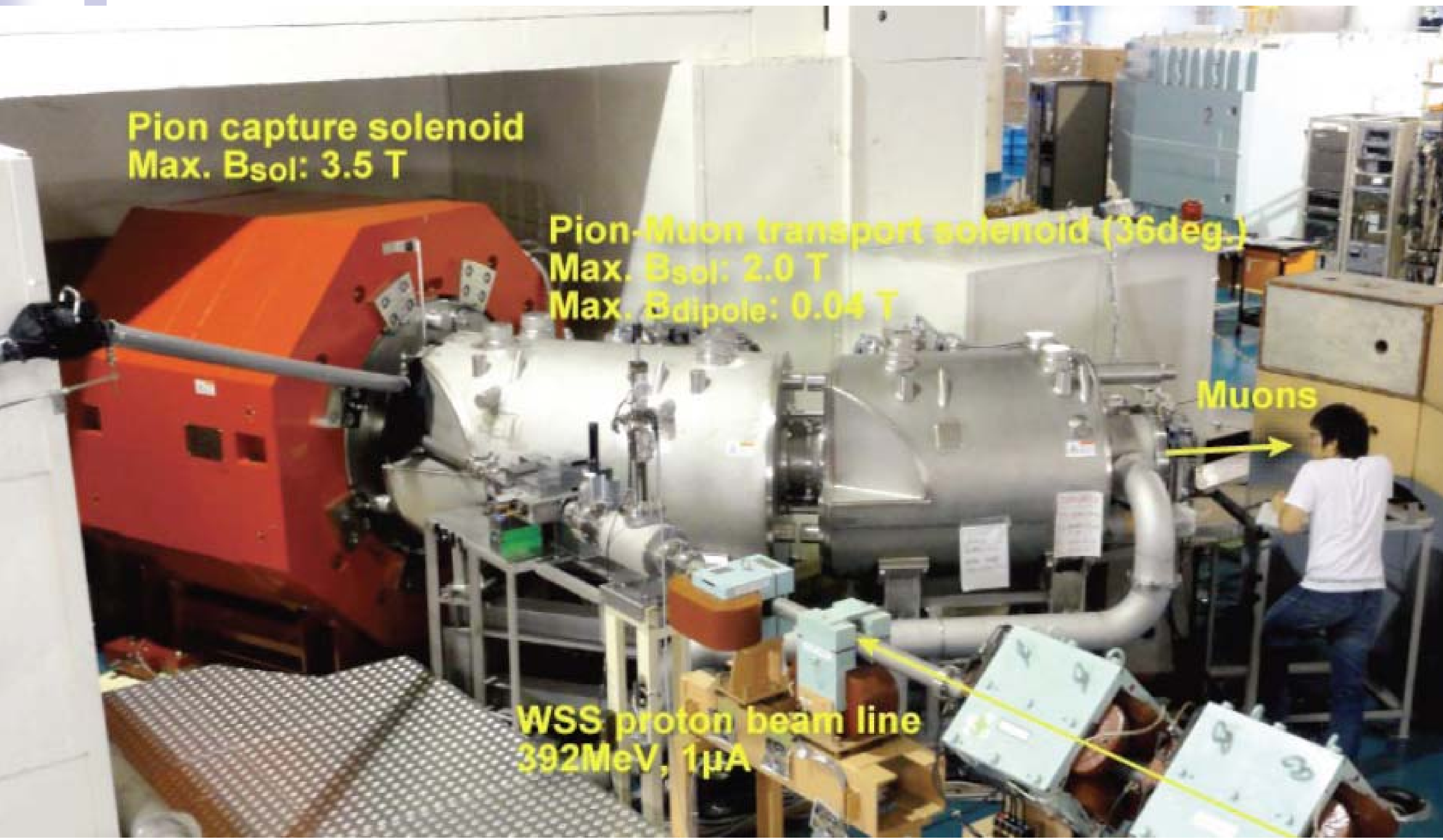
μ-capture experiment with high-intensity μ source

MuSIC High-intensity muon source at RCNP, Osaka
(Spokesperson: Prof. Kuno, Osaka)



Stopped μ rate ~3×10^8 /s@400W

--- comparable to J-PARC/MUSE@1MW



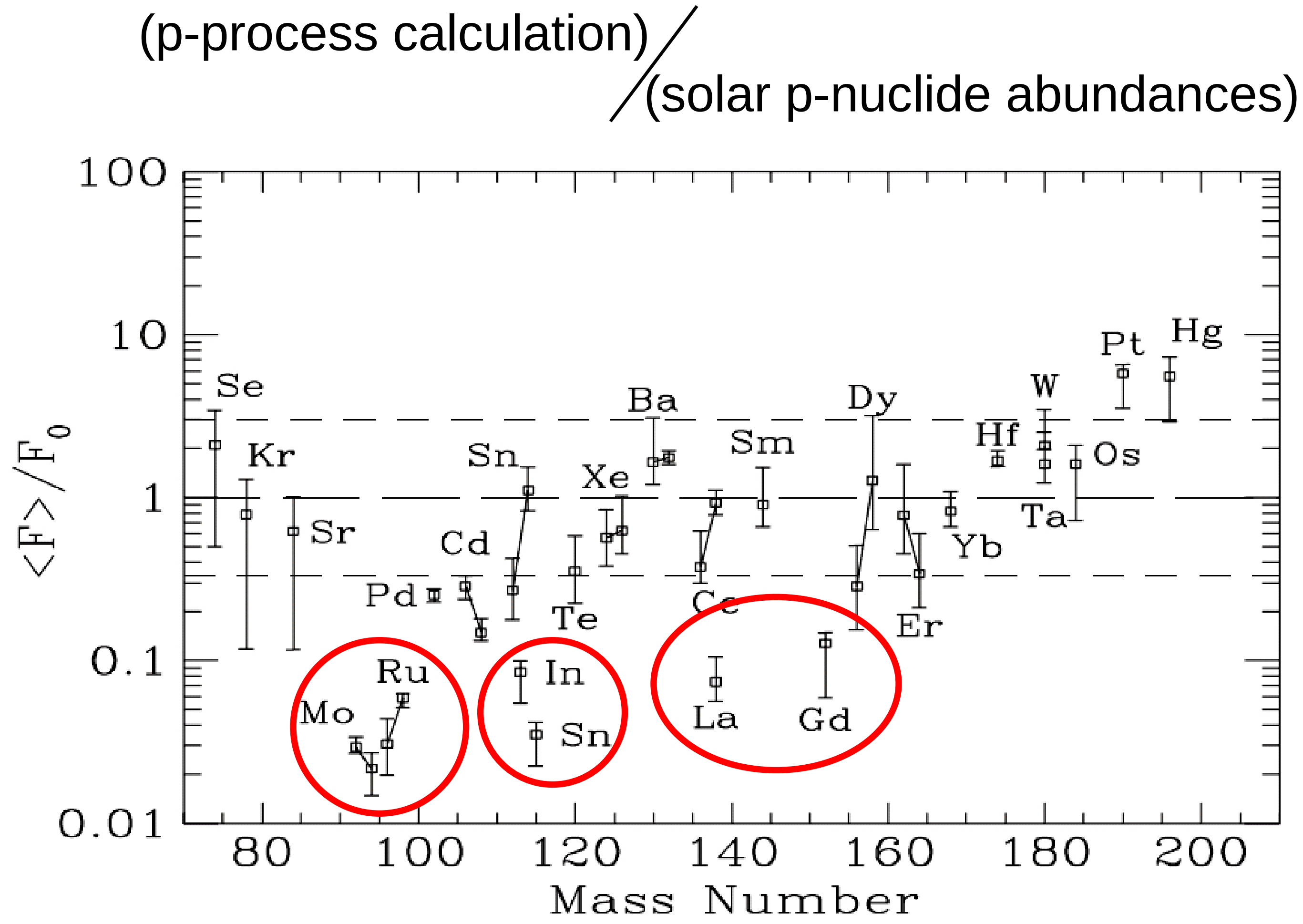
μ-capture experiment on Mo isotopes is scheduled in next week.

For detail, please visit the poster presented by Dr. H.I. Hashim.

Summary

- Data of photo-nuclear reaction cross sections up to ~80MeV are useful to test theoretical models for neutrino-nucleus reactions with neutral current.
- LCS γ-ray has a small (a few %) energy spread and high (~100%) polarization, and therefore provides a good tool to measure cross sections for E1 and M1 excitations separately.
- A new high-intensity (>10^8 /s) muon source will provide good opportunity to obtain direct information about highly excited states produced by weak interaction.

Observation vs Theory



Rayet, Arnould, Hashimoto, Prantzos, Nomoto, A&A 298, 517 (1995)