日本物理学会/山形大学/2008年9月20日

超新星爆発に関与する光核反応の実験的研究
Experimental Study of Photonuclear Reactions Relevant to Supernova Explosions

Tatsushi Shima

Research Center for Nuclear Physics, Osaka University

- Photonuclear reactions related to SNe
- Laser Compton-scattered γ-ray source
- Recent experiment; ex. ^{4}He
- Summary & Outlook

Photonuclear Reactions Related to Supernova Explosions

- He-burning ; $^{12}C(\alpha,\gamma)^{16}O \Leftrightarrow {}^{16}O(\gamma,\alpha)^{12}C$ (detailed balance)

- Photodisintegration of iron core ;

  (γ,α), $^{4}He(\gamma,p)^{3}H(\gamma,n)^{2}H(\gamma,n)^{1}H$, $^{4}He(\gamma,n)^{3}He(\gamma,p)^{2}H(\gamma,n)^{1}H$

- r-, p-, γ-processes ; (p,γ), (n,γ), (γ,n), (γ,p), (γ,α)

- ν-process ; $(\nu,\nu' x)$ (neutral current) $\Leftrightarrow$ (γ,x)

  --- nuclear responses to dipole excitation by τ_3, $\sigma\cdot\tau_3$

Photonuclear reactions

as a tool for nuclear astrophysics

- EM interaction; **well-know !**
- Sensitivity to **multi-body channels**;

  $X+Y+Z+\ldots \rightarrow A+\gamma \;\Leftrightarrow\; A+\gamma \rightarrow X+Y+Z+\ldots$

  ex. $2\alpha+n \rightarrow {}^{9}Be$, $3\alpha \rightarrow {}^{12}C$
- Enhancement of cross sections by

  phase space factor
- Analogy between **γ-A** and **ν-A** interactions

Low-energy γ-ray sources

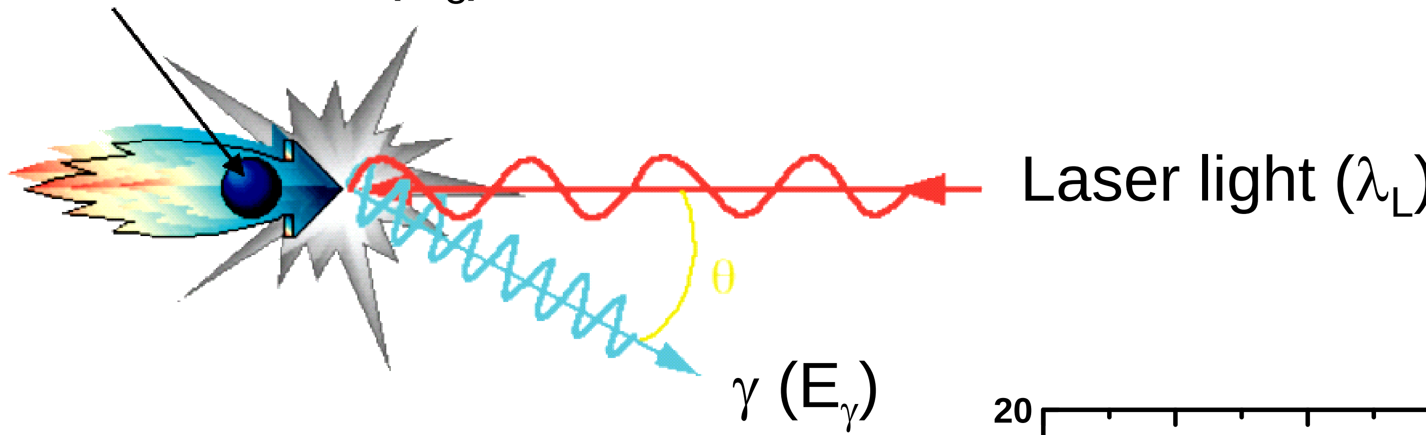
- Discrete γ-rays from radioisotopes
- Bremsstrahlung (continuous energy) / tagged photons
- e^+e^- pair annihilation in flight ; monoenergy γ + brems.
- **Laser Compton Scattered γ (LCS-γ)**
- Synchrotron photons from super-conducting wiggler

  --- quasi-Planck spectrum (Utsunomiya, Nucl. Phys. A777)

- Coulomb Dissociation (CD) ; virtual photons, application to RI

  ^{7}Be(p,γ)^{8}B, ^{14}C(n,γ)^{15}C, … **RIKEN, GSI**
- (p,p') ; probe for M1 excitation **RCNP**

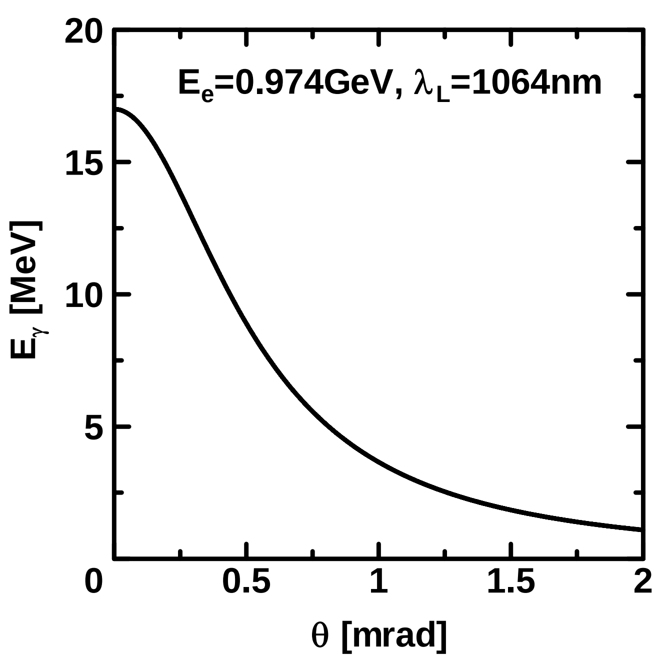
Laser Compton backscattering



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

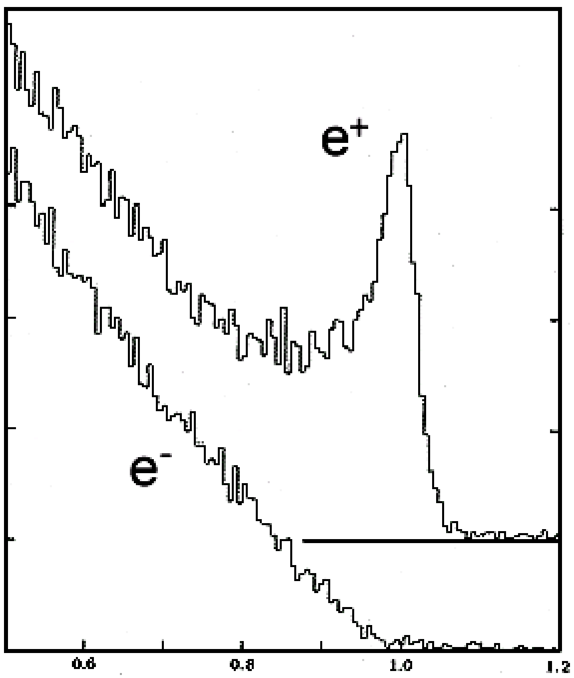
ex. λ_L=1.064μm, E_e=974MeV

⇒ E_γ = 17MeV



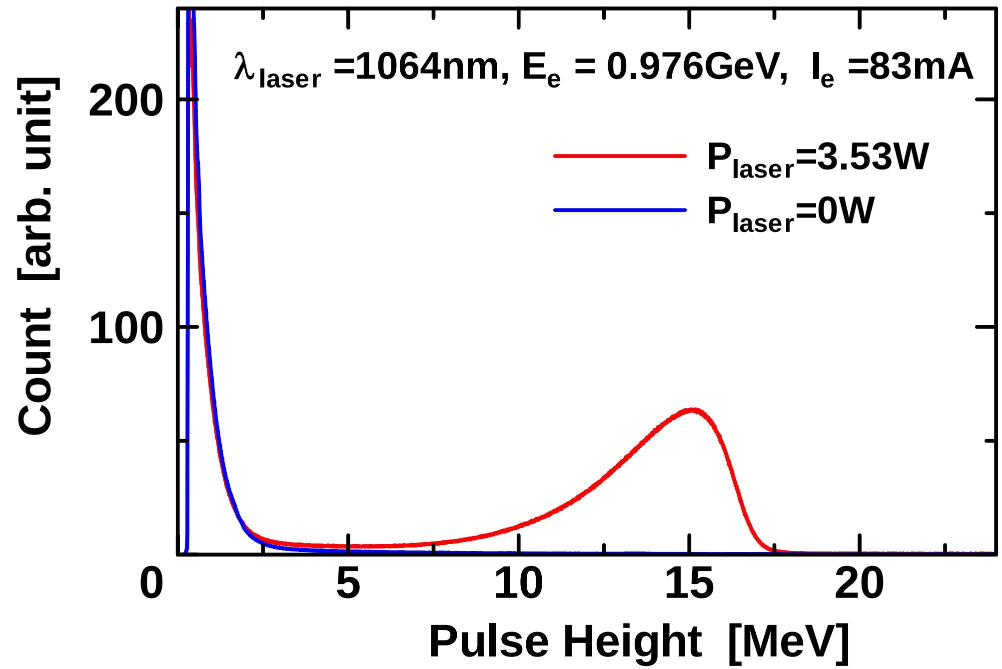
Energy distributions

Bremsstrahlung,
e^+e^- annihilation in flight



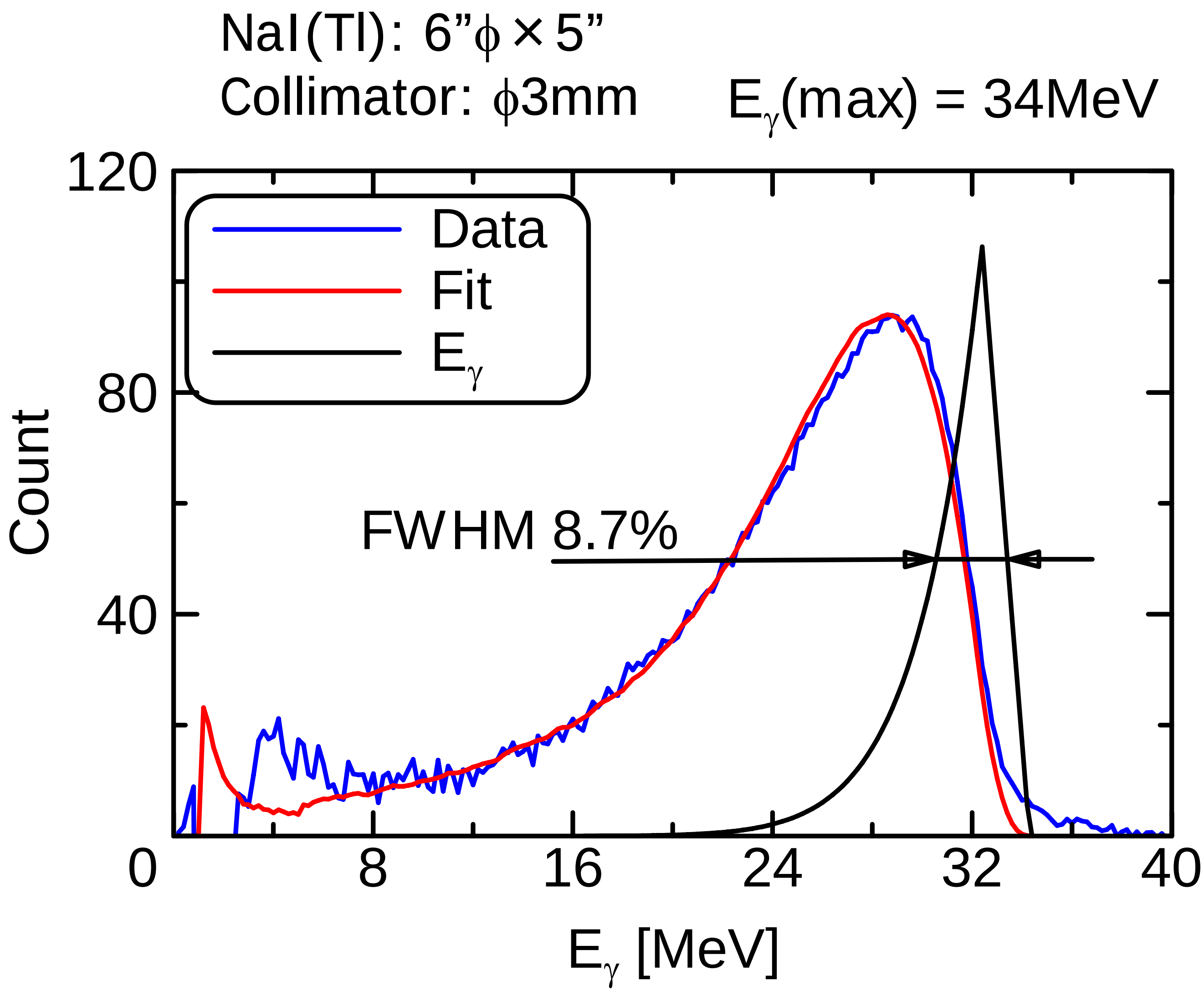
BG from low-energy component of brems.

Laser Compton-Scattered γ
(PH spectra of GSO scintillator)



No BG !!

Energy distribution



Advantages of LCS-γ

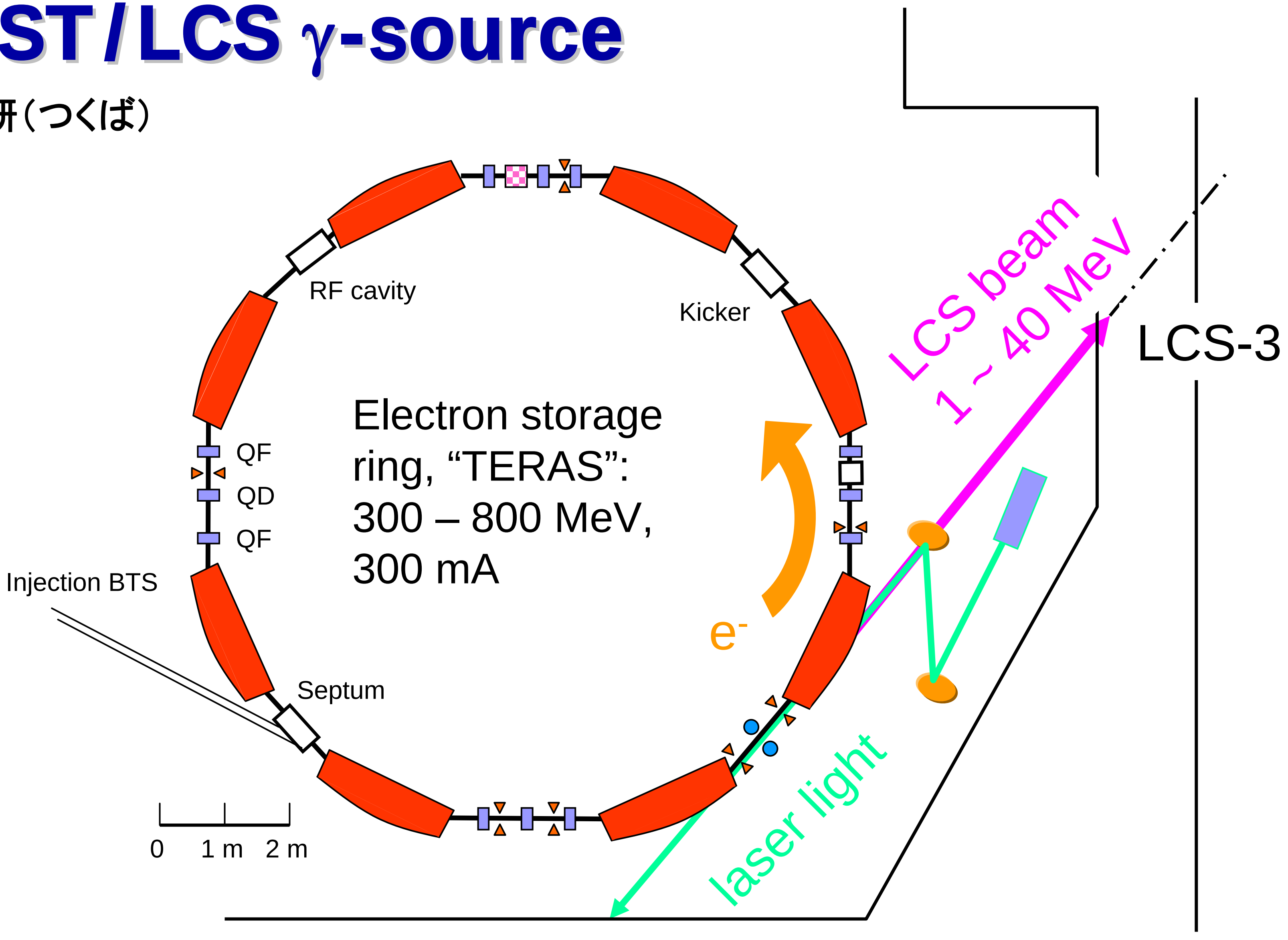
- Quasi-monochromatic; $\Delta E/E$ < ~10%, little BG
- Well-collimated; $\Delta\theta$ < 0.1 mrad
- Highly polarized; linear or circular, P ~ 100%
- Continuous or pulsed; Δt < 10ns

LCS γ-ray facilities in the world

Year	Facility	E_e [GeV]	Laser	E_γ [MeV]	Φ_γ [/sec/MeV]
1964	Lebedev	0.6	ruby	~10	$\sim 10^6$
1965	Harvard / CEA	6	ruby	~1000	5×10^4
1978	Frascati / LADON	1.5	Ar^+	5 - 80	$\sim 10^5$
1985	ETL(AIST) / TERAS	0.2-0.8	Nd-YAG	2 - 40	$10^3 \sim 10^5$
1990	BNL / LEGS	2.8	Nd-YAG	150 - 470	$10^4 \sim 10^5$
1996	Grenoble / GrAAL	6	Ar^+	1500	$\sim 4 \times 10^3$
1999	SPring-8 / LEPS	8	Ar^+	1500 - 3500	$\sim 10^4$
1999	TUNL(Duke) / HIγS	0.2-1.2	FEL	2 - 70	$\sim 10^7$
2004	LASTI(U. Hyogo) / NewSUBARU	1 - 1.5	$Nd\text{-}YVO_4$	16 - 40	$10^4 \sim 10^5$

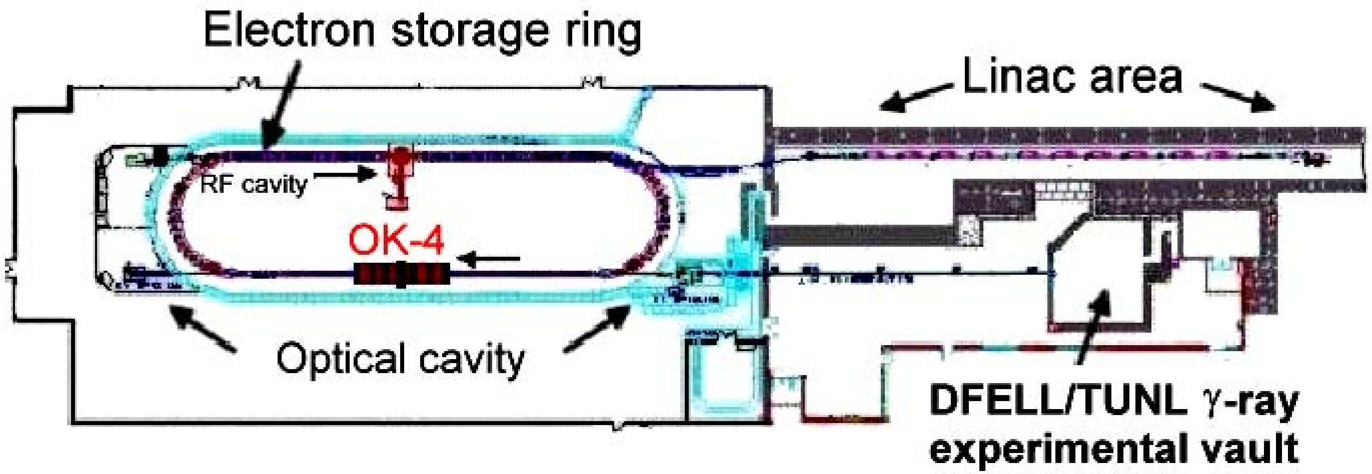
AIST/LCS γ-source

産総研（つくば）



Duke/HIgS (High Intensity γ-ray Source)

- Intra-cavity Compton Backscattering of FEL photons by electrons circulating in the 1.2GeV Duke Storage Ring



- E_γ = 2~70 MeV, $\Delta E_\gamma/E_\gamma$ ~ 1%, Φ_γ ~ 10^7 /MeV/s (→ 10^9)
- Time interval of γ-ray pulses ; 170ns

NewSUBARU

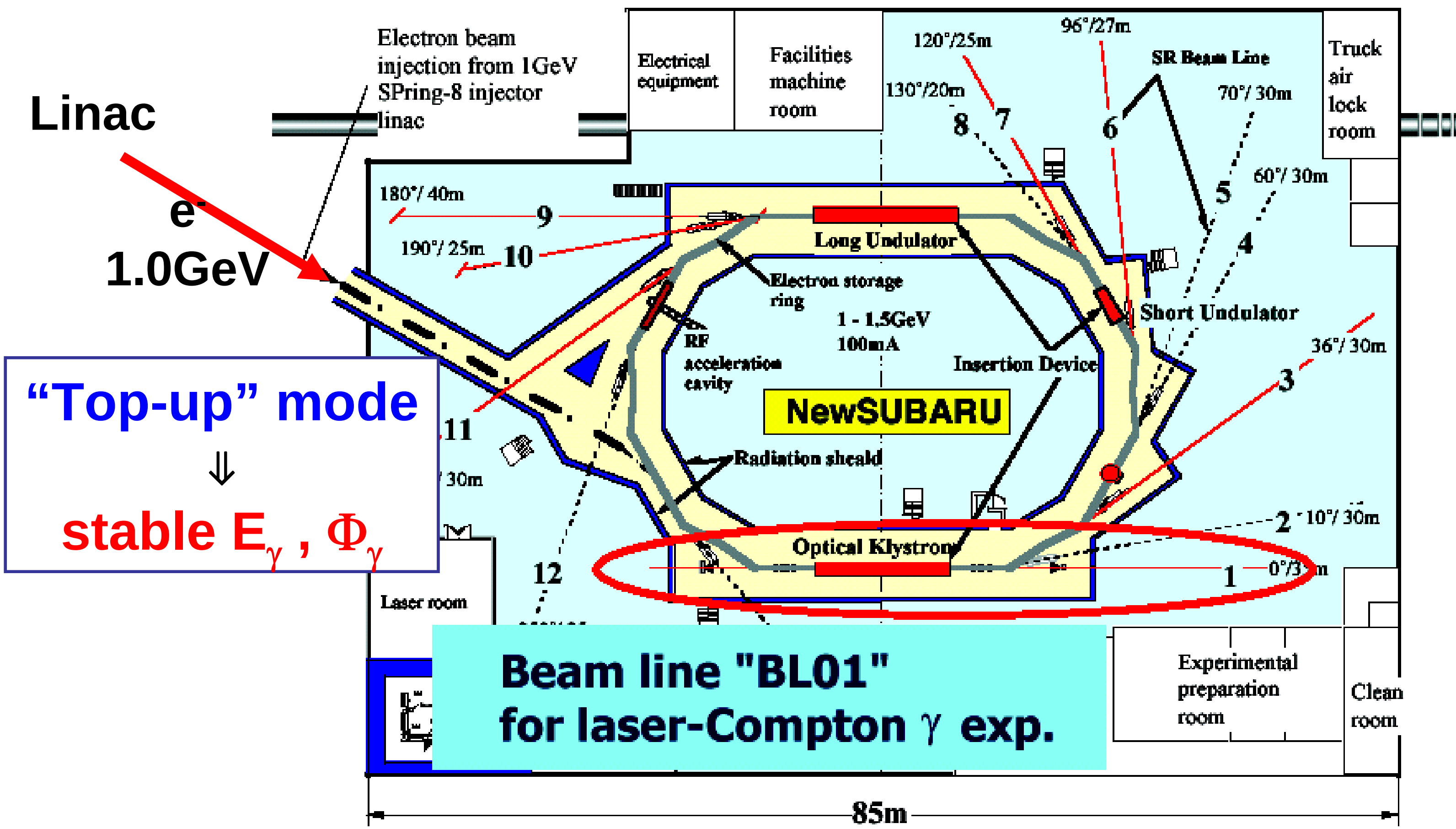
Lab. of Adv. Sci. and Tech. for Industry, University of Hyogo, Japan

Subaru is an old Japanese meaning “get together”, and also the Japanese name of the Pleiades Star Cluster.

	Subaru	NewSUBARU	SUBARU
Type	Telescope	SR facility	Automaker
Location	Mauna Kea, Hawaii	Hyogo, Japan	Gunma, Japan
Feature	8.2m single mirror with adaptive optics	Race-track shape isochronous ring	Boxer engine + symmetrical AWD
Memorial	First light 1999	First beam 1998	WRC first win 1993

NewSUBARU / LCS-γ source

K. Aoki, S. Miyamoto, et al. NIM A516 (2004) 228-236



E_γ = 16 - 40 MeV, Φ_γ = $10^{4\sim5}$ photons/MeV/s, $\Delta E_\gamma / E_\gamma$ = 3~10%

Merits of NewSUBARU LCS γ-source

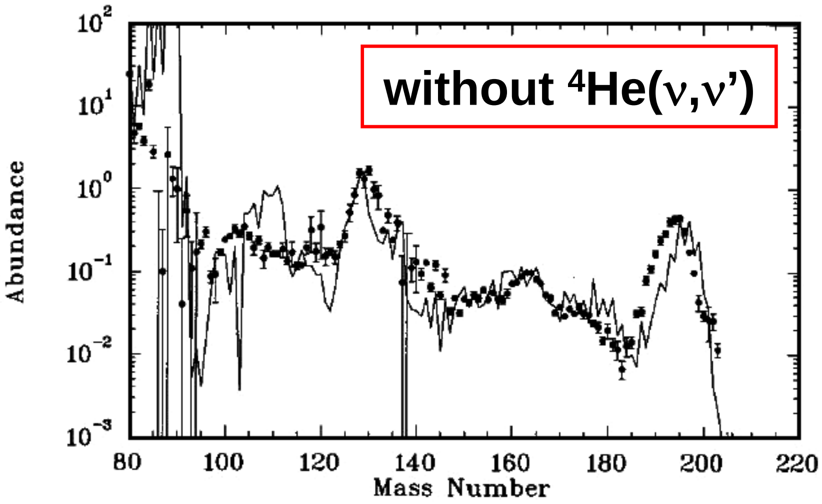
- Conventional lasers (Nd:YVO4, CO_2, etc.) are used.
  → Various kinds of lasers can be employed.
  Flexibility in energy range, pulse structure, polarization, etc.

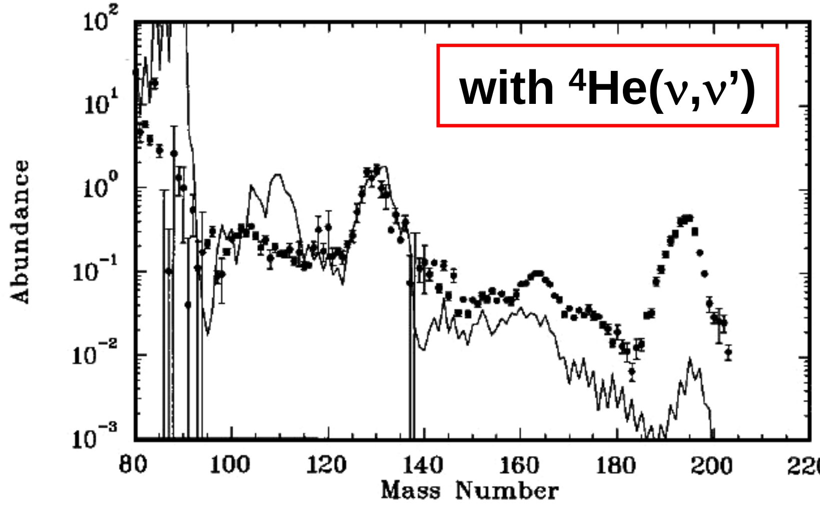
- Laser and electron beam collide in a straight section.
  → Little background from bremsstrahlung

- Top-up (top-loaded) operation is available.
  → High flux and excellent stability

$^4He(\gamma,X) \Leftrightarrow {}^4He(\nu,\nu')$

- Neutrino-heating effect ➡ needs CS with 10% accuracy
- R-process in neutrino-driven wind





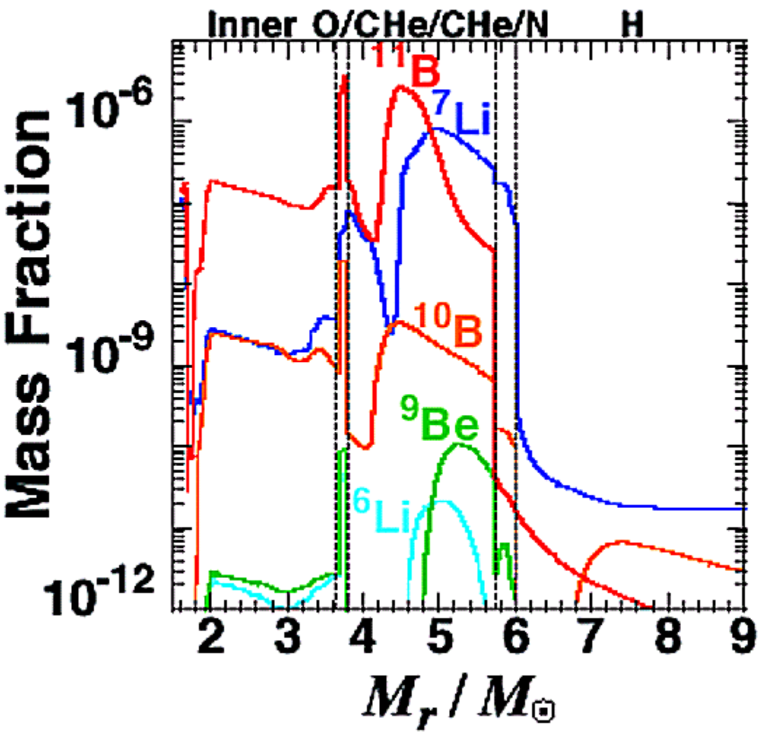
Meyer, ApJ449 (1995) L55

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

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

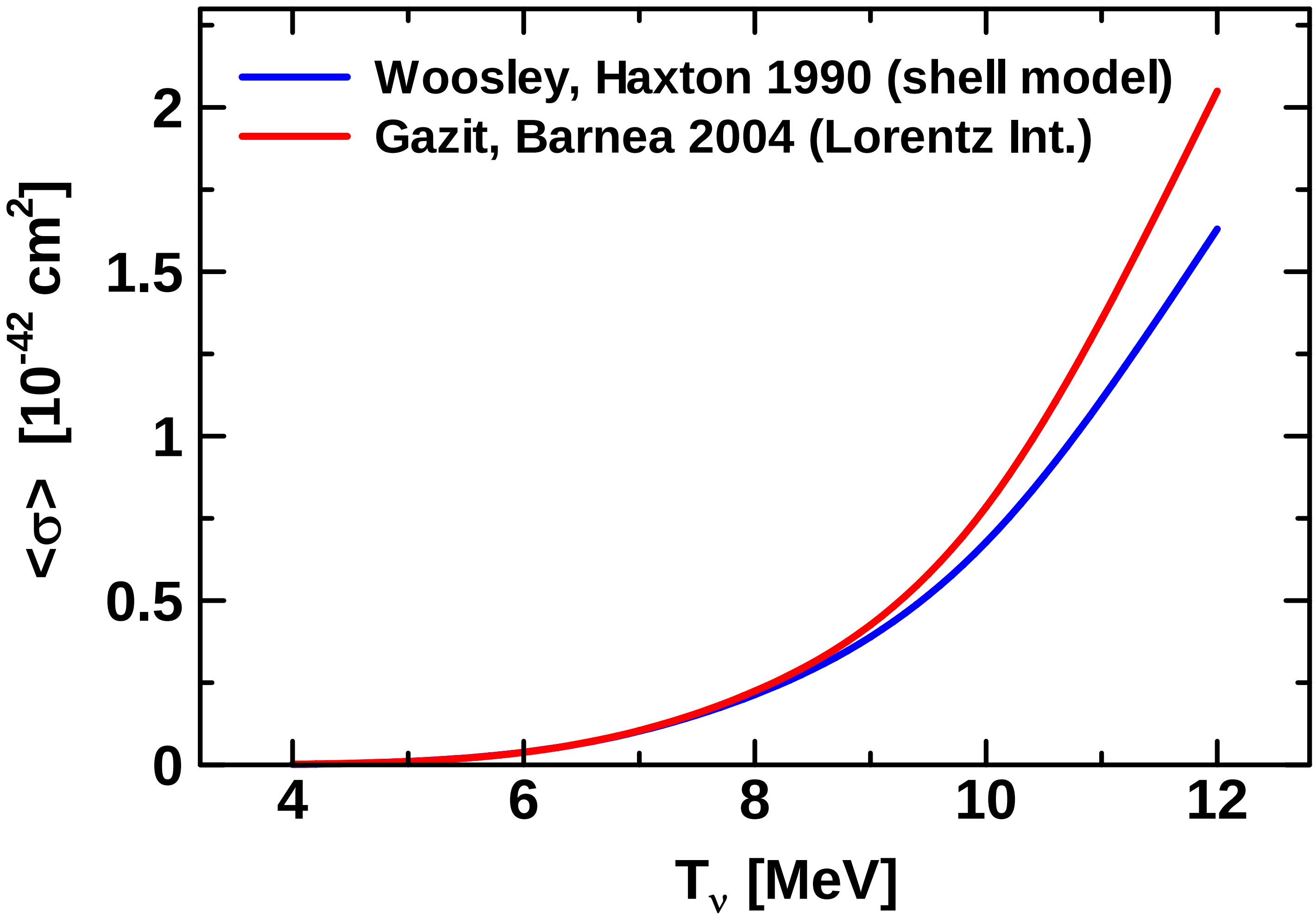
$^4He(\nu,\nu'p)^3H(\alpha,\gamma)^7\mathbf{Li}(\alpha,\gamma)^{11}\mathbf{B}$

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



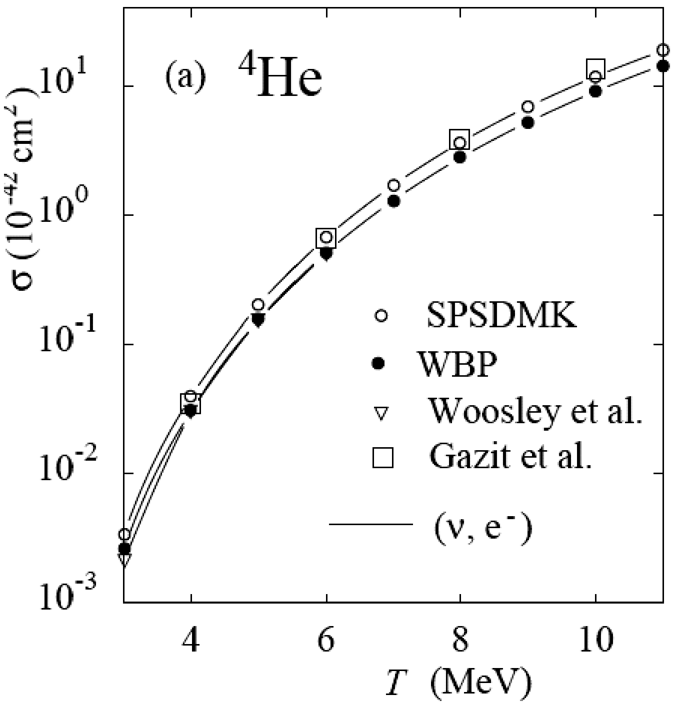
Yoshida, Kajino et al.,
PRL96, 091101 (2006)

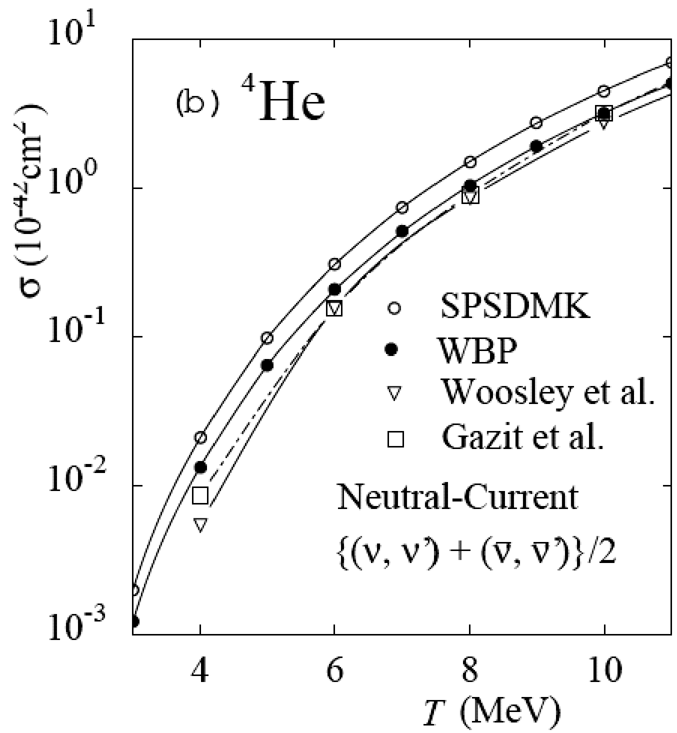
Neutrino neutral reaction rate on ^4He



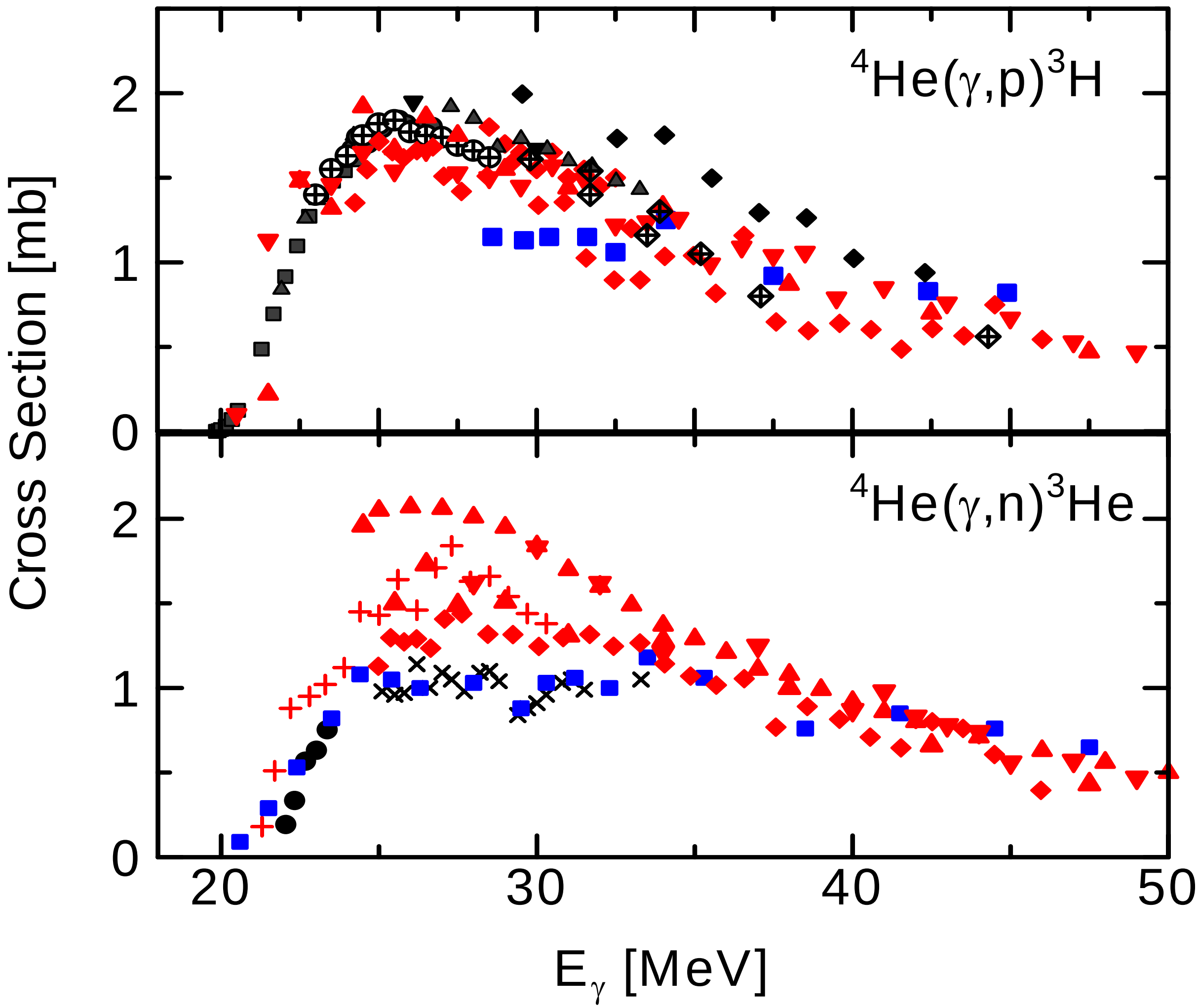
Shell-model calculation

T. Suzuki et al., PR C74 034307 (2006)



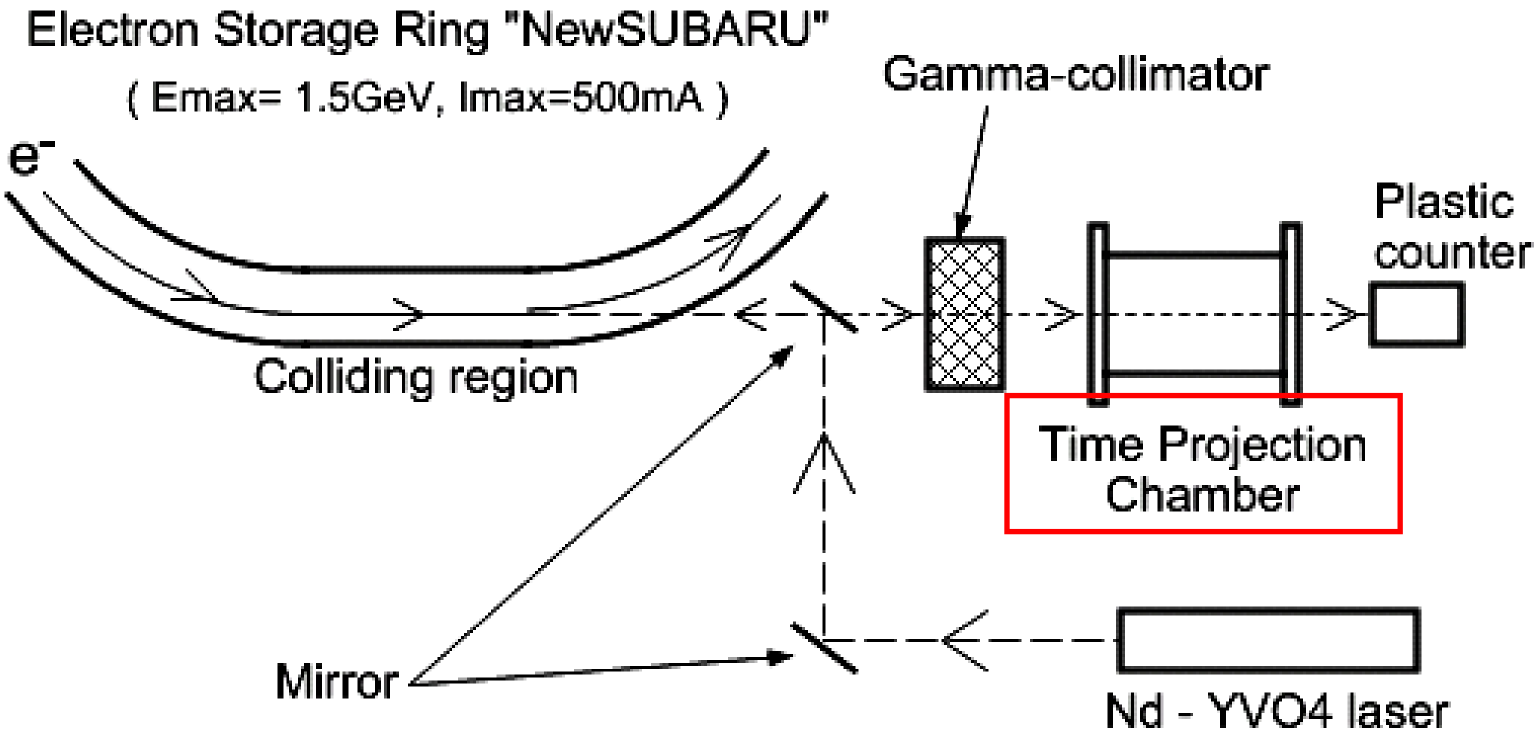


Photodisintegration of ^{4}He have been studied by means of monochromatic γ, bremsstrahlung, radiative capture...



Experiment at NewSUBARU LCS-γ facility

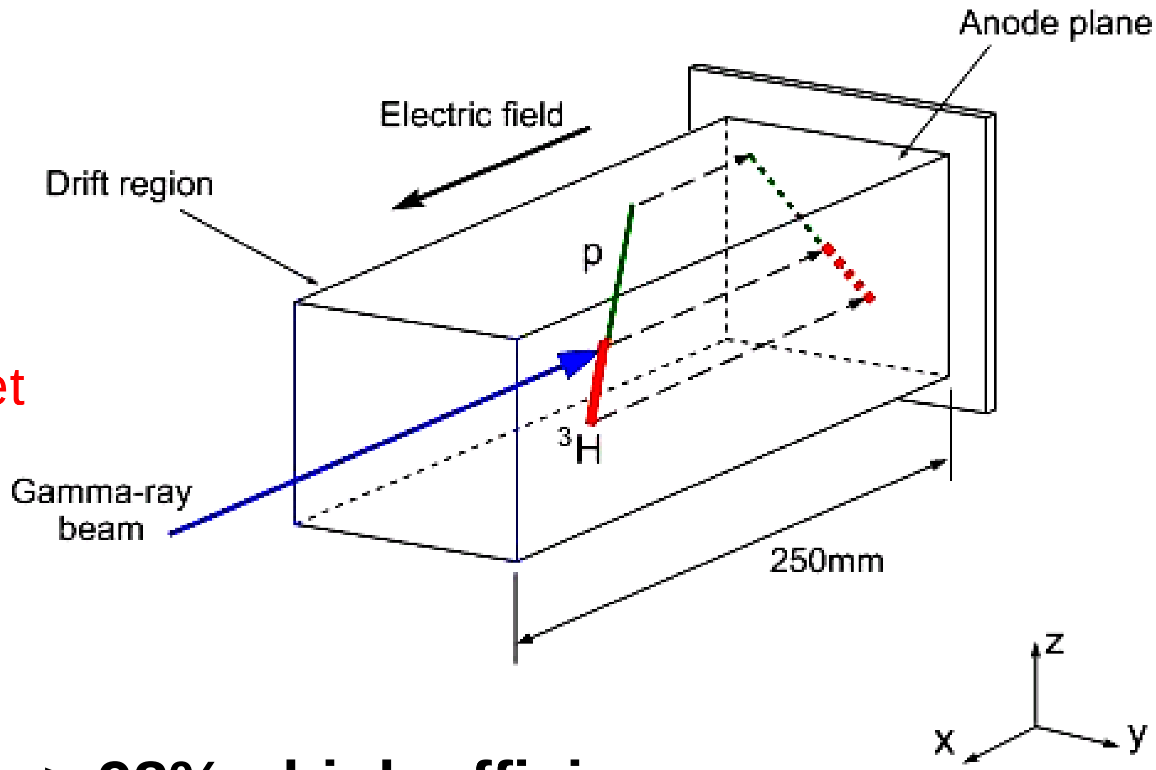
E_γ = 16 ~ 40MeV, Φ_γ =2~4×10^4 /sec, FWHM~9%, P~100%



Time Projection Chamber

T. Kii, T. Shima, T. Baba, Y. Nagai, NIM A552 (2005) 329

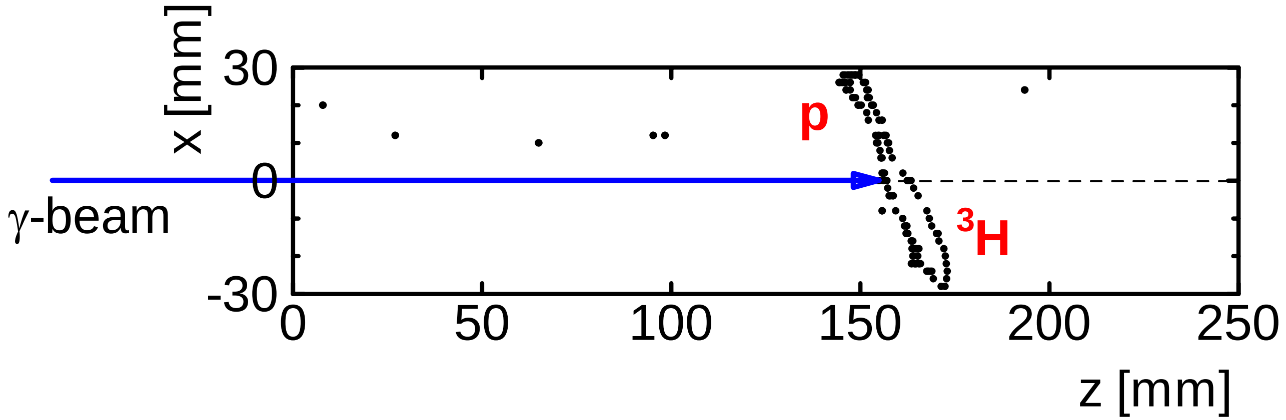
Target gas :
He + CD_4
--- active target



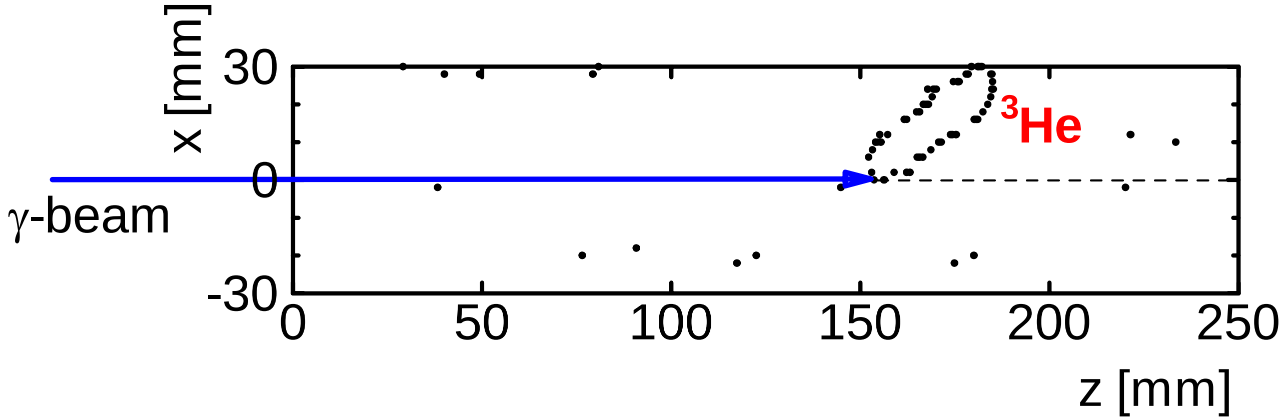
- $\Omega \sim 4\pi$, $\varepsilon > 98\%$; **high efficiency**
- **track shape, dE/dx** $\Rightarrow$ **event ID,** $d\sigma/d\Omega$**, asymmetry**

Event Identification

^{4}He photodisintegrations

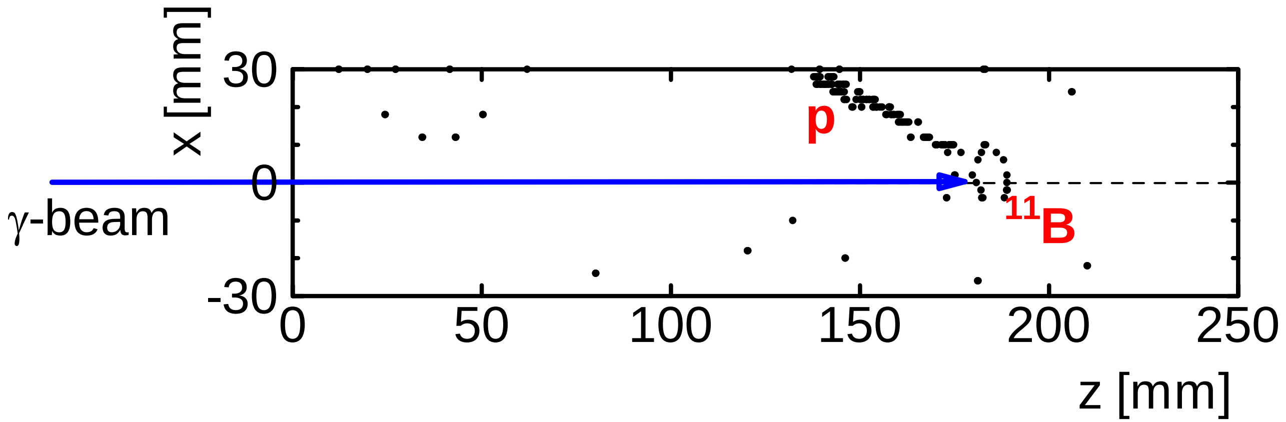


$^4He(\gamma,p)^3H$

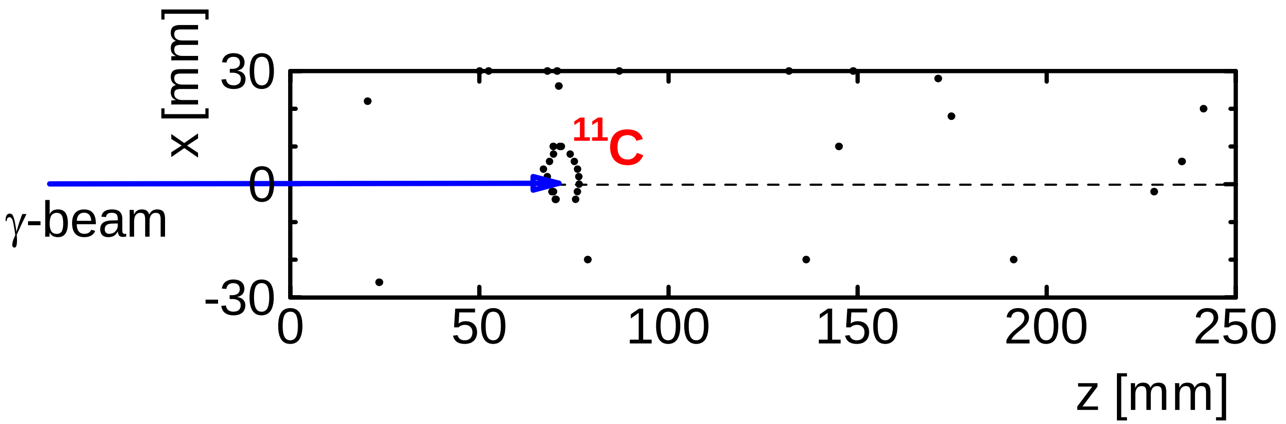


$^4He(\gamma,n)^3He$

^{12}C photodisintegrations

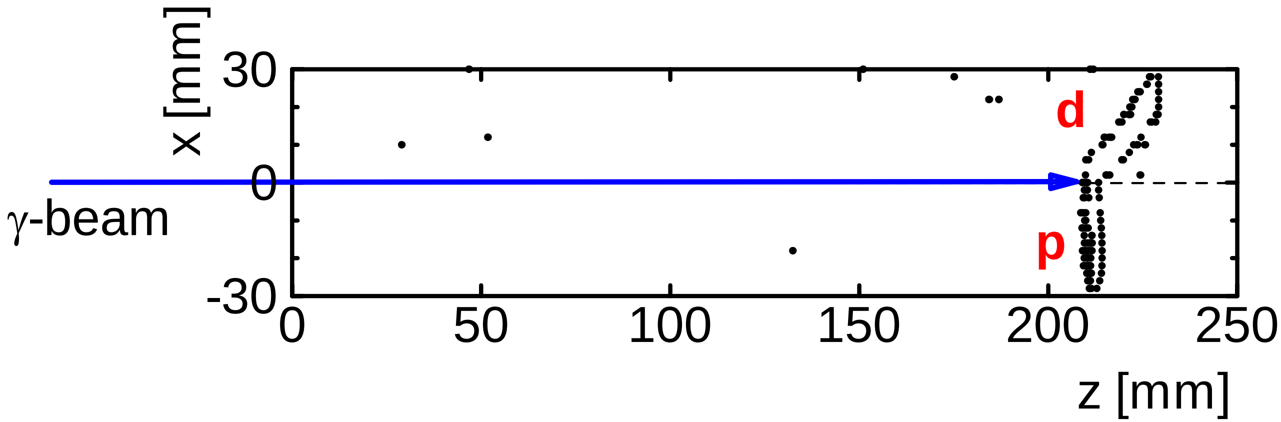


$^{12}C(\gamma,p)^{11}B$

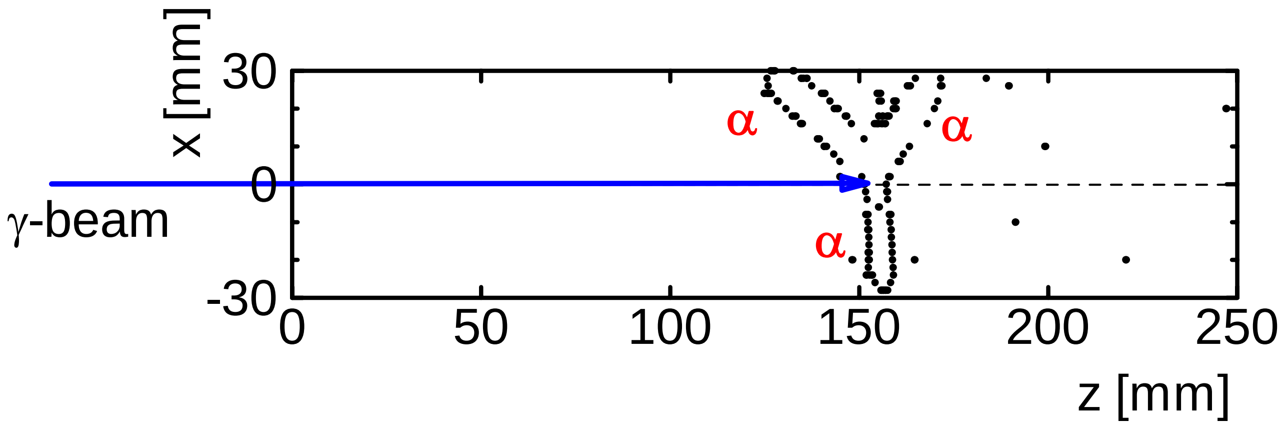


$^{12}C(\gamma,n)^{11}C$

Three-body decays

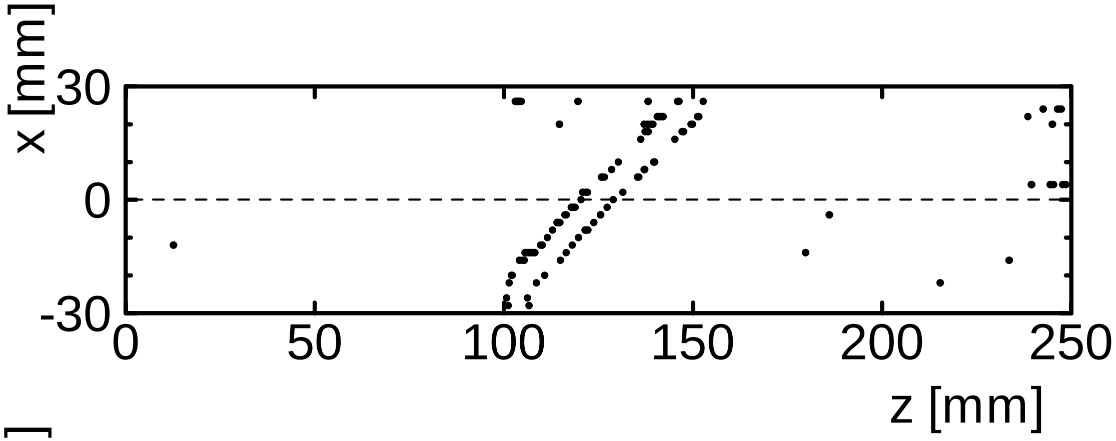


$^4He(\gamma,pn)^2H$

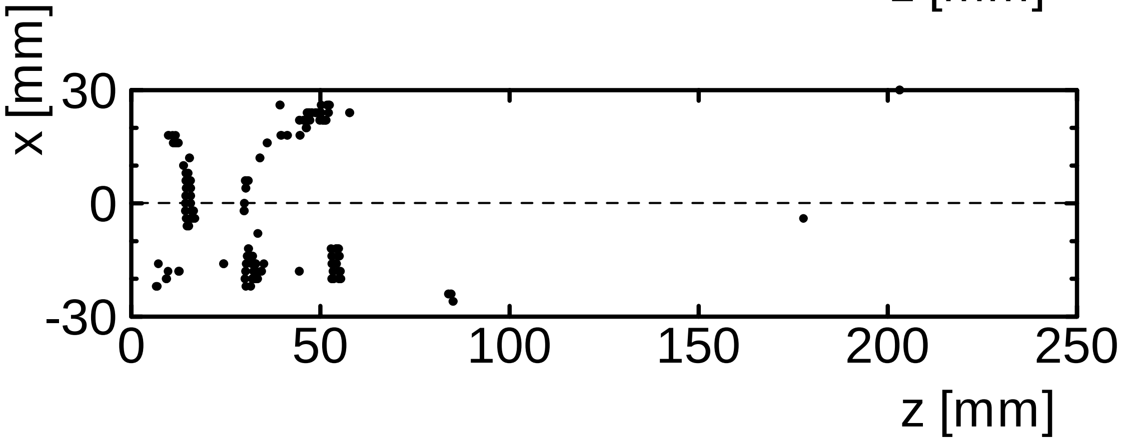


$^{12}C(\gamma,2\alpha)^4He$

Backgrounds

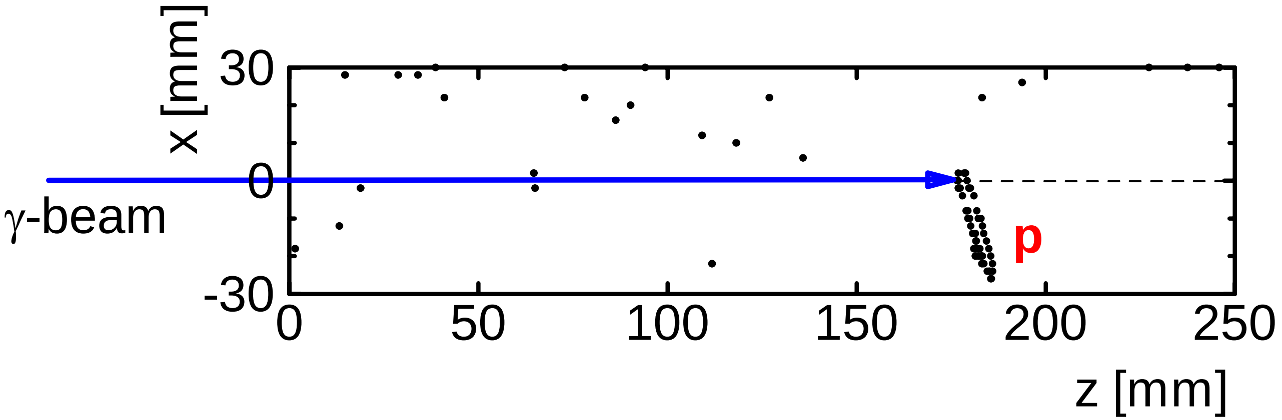


α from natural RI

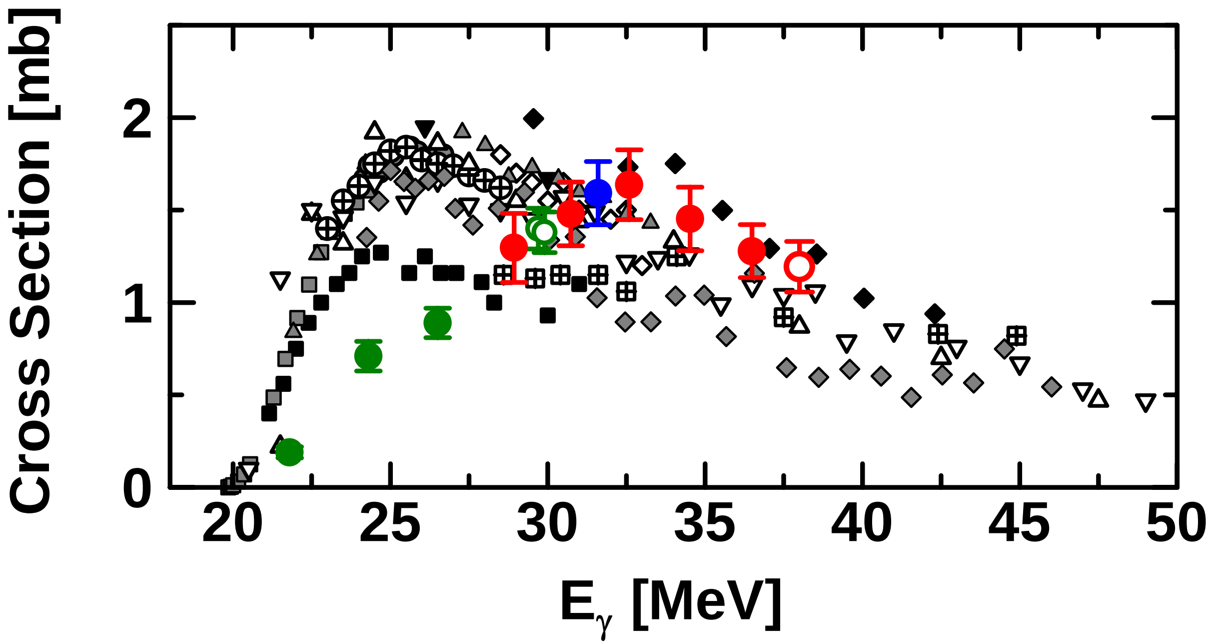


Photoelectrons

D(γ,p)n



$^4He(\gamma,p)^3H$ (preliminary)



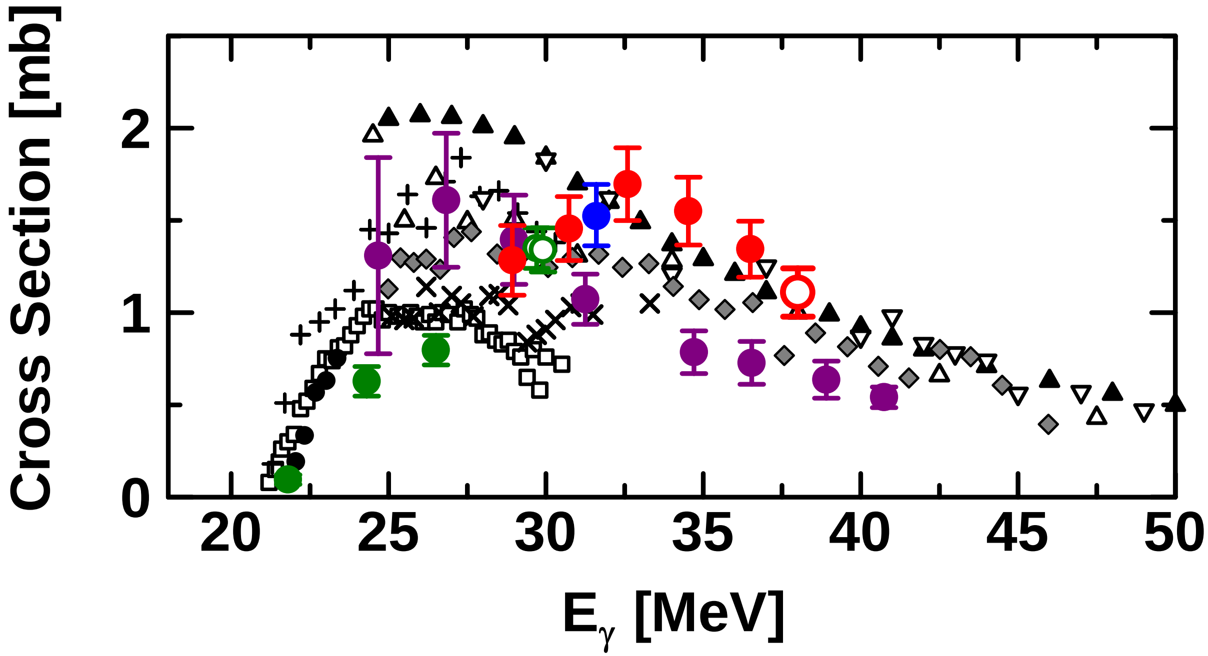
●○ RCNP-AIST (PRC72, 044004) ; λ=351nm (3rd), E_e=0.8GeV

● RCNP-NewSUBARU; λ=532nm (2nd), E_e=0.97GeV

● RCNP-NewSUBARU; λ=1064nm (fund.), E_e≤1.46GeV

○ RCNP-NewSUBARU; λ=532nm (2nd), E_e=1.06GeV

$^4He(\gamma,n)^3He$ (preliminary)



- ●○ RCNP-AIST (PRC72, 044004) ; λ=351nm (3rd), E_e=0.8GeV
- ● RCNP-NewSUBARU; λ=532nm (2nd), E_e=0.97MeV
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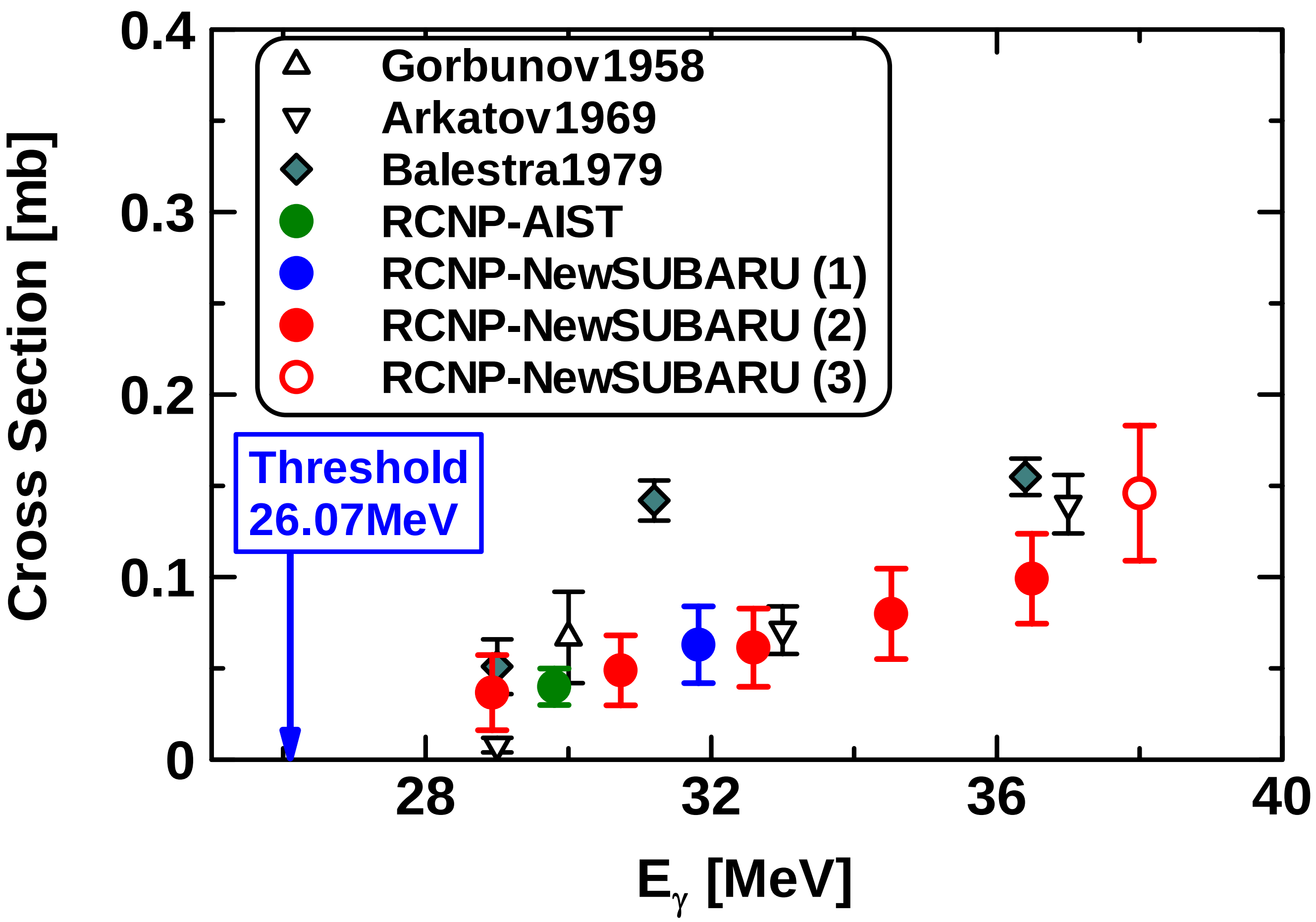
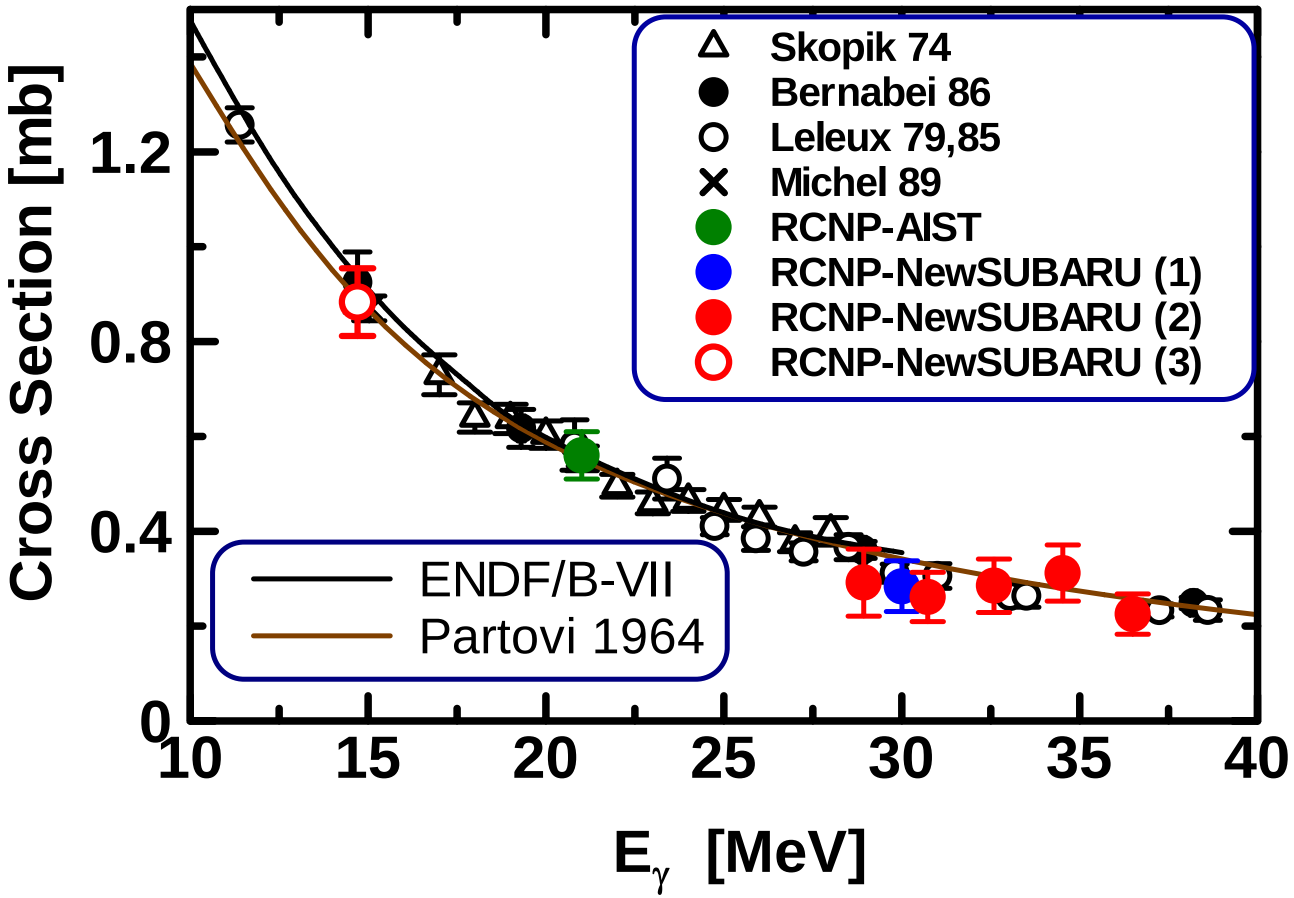
- ○ RCNP-NewSUBARU; λ=532nm (2nd), E_e=1.06GeV
- ● Lund 2005-2007 (PRC75, 014007) ; tagged photons

$^4He(\gamma,pn)d$ (preliminary)



D(γ,n)p



Skopik 74
Bernabei 86
Leleux 79,85
Michel 89
RCNP-AIST
RCNP-NewSUBARU (1)
RCNP-NewSUBARU (2)
RCNP-NewSUBARU (3)
ENDF/B-VII
Partovi 1964
Cross Section [mb]
0
0.4
0.8
1.2
10
15
20
25
30
35
40
Eγ [MeV]

Summary

- Laser Compton Scattered γ, combined with new detector techniques, provides a useful tool for high-precision studies of nuclear reactions induced by photons and also neutrinos.
- Complementary to radiative capture, CD, (p,p'), …
- The LCS γ-source at NewSUBARU is now in operation, and several works for nuclear astrophysics have been performed successfully.
- ^{4}He: excitation functions are measured up to 37MeV.
  Small cross sections below 30MeV were confirmed.
  GDR peak was found to locate at ~32.5MeV.
  → → → p-n, 1p1h, 3NF
- Other light nuclei and heavier p-nuclei are planned to be studied.

Outlook

- (γ,n) cross sections of long-lived radioactive nuclide ;

  $\Phi_{\gamma} = 10^4$ /s $\Rightarrow$ 10^6 /s ; target: 1g $\Rightarrow$ 10mg

- (γ,p), (γ,a) cross sections of p-nuclei ;

  for noble gases --- TPC

  for others --- activation method

- Reference data for indirect methods ; CD, (p,p'), …

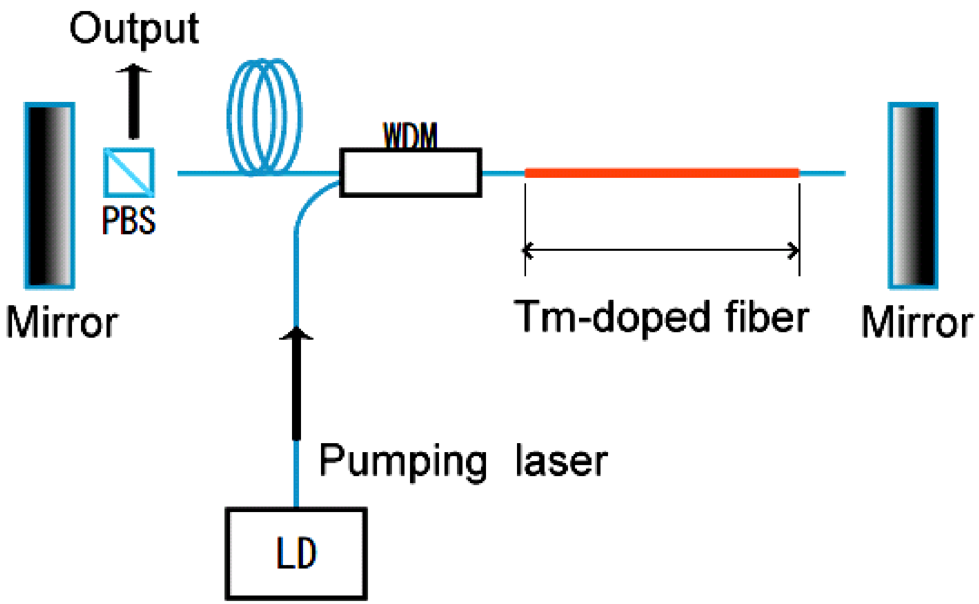
- Technical hint for experiment with other neutral beams ; n, ν

Present; Nd:YVO_4 laser (1.06μm), 1W

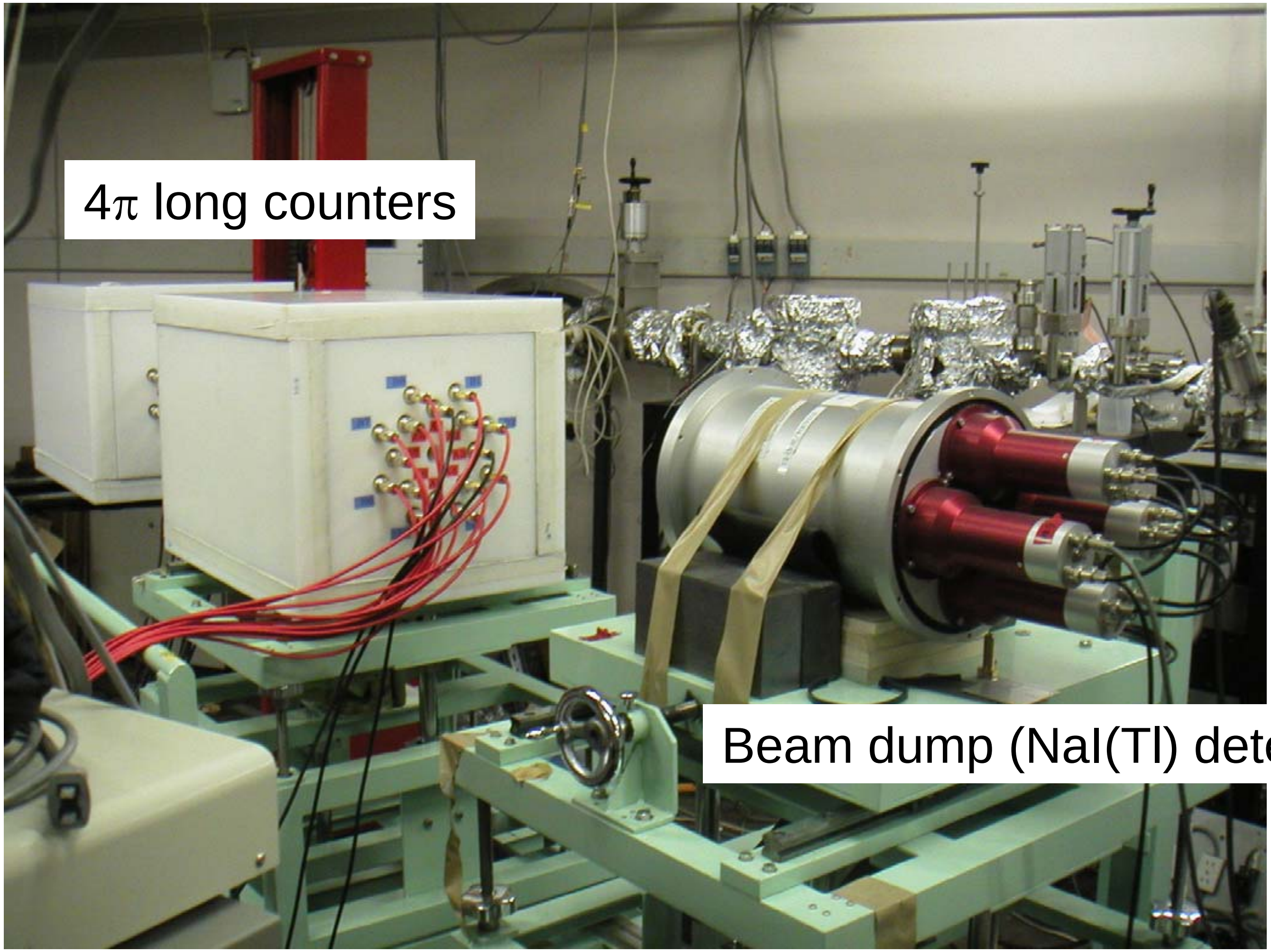
$\Rightarrow E_\gamma = 16.5$MeV, $\Phi_\gamma \sim 3 \times 10^4$ photons/s

Plan; Tm-doped fiber laser (2.05μm), 100W

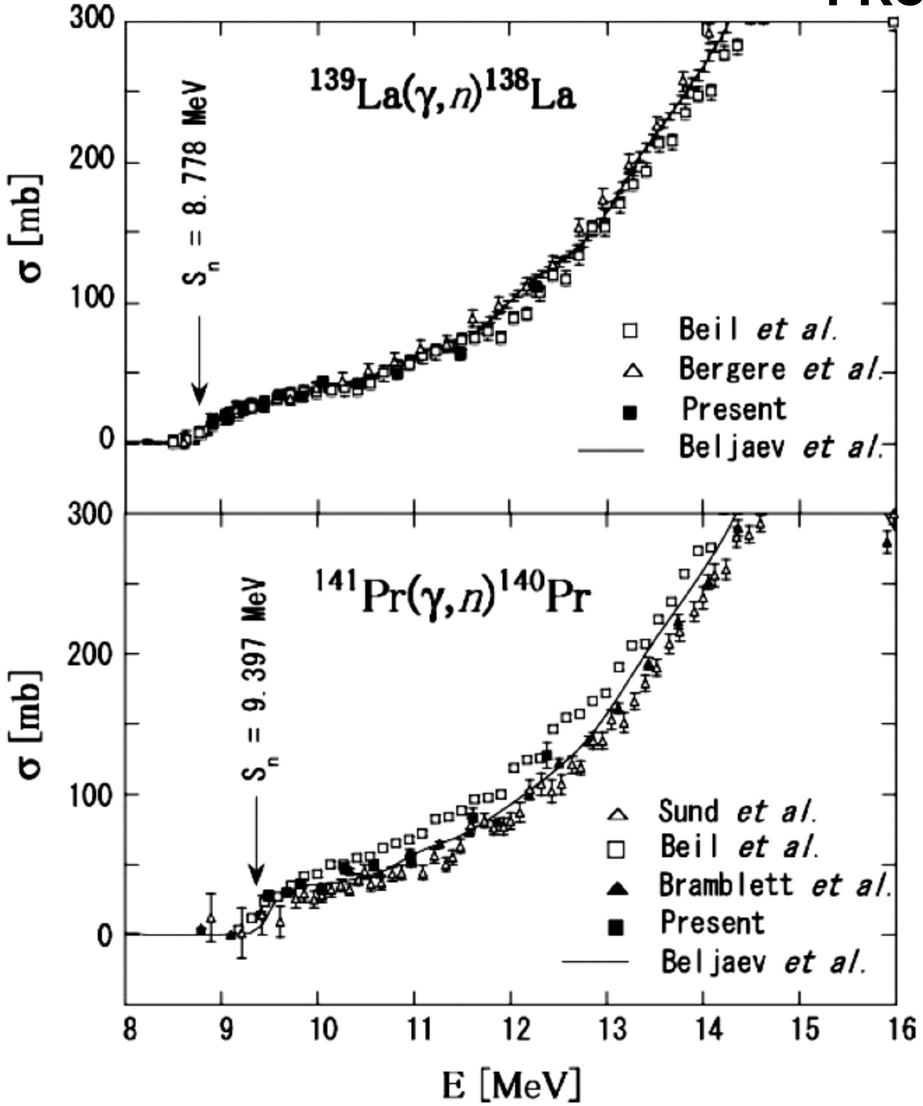
$\Rightarrow E_\gamma = 8.5$MeV, $\Phi_\gamma > 10^6$ photons/s



Neutron detector for (γ,n) (Konan Univ.)



Utsunomiya et al., PRC74 025806 (2006)



Radioactivity < 1MBq, 100μmol ⬌ $T_{1/2}$ > ~10000yr

$\beta^{\pm}$-γ, $T_{1/2}>10^4$y (15 nuclides) ;

^{10}Be, ^{26}Al, ^{36}Cl, ^{40}K, ^{59}Ni, ^{79}Se, ^{93}Zr, ^{92}Nb, ^{98,99}Tc, ^{107}Pd, ^{135}Cs, ^{138}La, ^{186}Re, ^{208}Bi

EC, no γ, $T_{1/2}>100$d (12 nuclides) ;

^{41}Ca, ^{49}V, ^{53}Mn, ^{55}Fe, ^{93}Mo, ^{97}Tc, ^{109}Cd, ^{137}La, ^{179}Ta, ^{178}W, ^{193}Pt, ^{205}Pb

α-γ, $T_{1/2}>10^4$y (16 nuclides) ;

^{210}Bi, ^{230,232}Th, ^{231}Pa, $^{233\text{-}236,238}$U, ^{236,237}Np, ^{239,242,244}Pu, ^{247,248}Cm

α, no γ, $T_{1/2}>100$d (4 nuclides) ; ^{146}Sm, ^{148,150}Gd, ^{154}Dy

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- Technical hint for experiment with other neutral beams ; n, ν

Collaborators

H. Utsunomiya, H. Akimune

Department of Physics, Konan University

T. Mochizuki, S. Miyamoto, K. Horikawa

Laboratory for Advanced Science and Technology for Industry, University of Hyogo

T. Hayakawa, T. Shizuma

Kansai Photon Science Institute, Japan Atomic Energy Agency

M. Fujiwara

Research Center for Nuclear Physics, Osaka University

Y. Nagai

Nuclear Science and Engineering Directorate, Japan Atomic Energy Agency