Critical Role of Nuclear Data in Nuclear Astrophysics

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Outline

- ♦ **Motive:**

  Nuclear-astrophysics & -physics view points

- ♦ **Experimental method:**

  photon-, α- and neutron-induced reactions with new methods

- ♦ **Results:**

- ♦ **Summary:**

Observing Universe with Nuclear Telescope

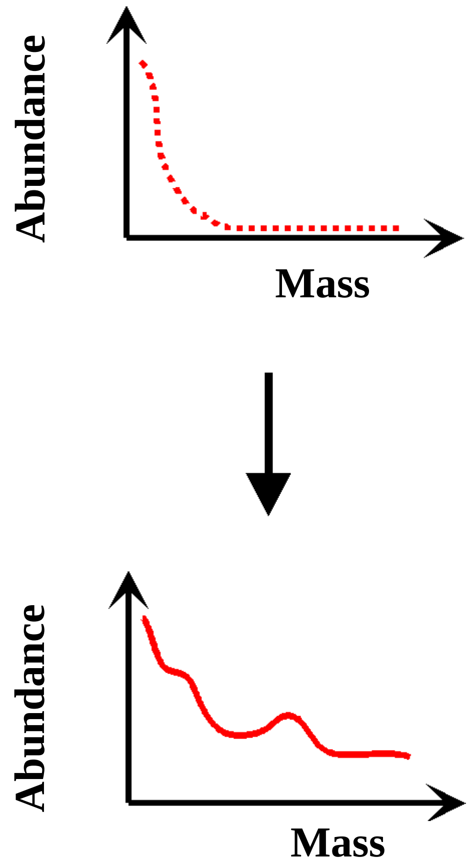
0.4 My

1 Gy

14 Gy

View of evolution of universe

Stellar Generation & Elemental Abundance



Observation

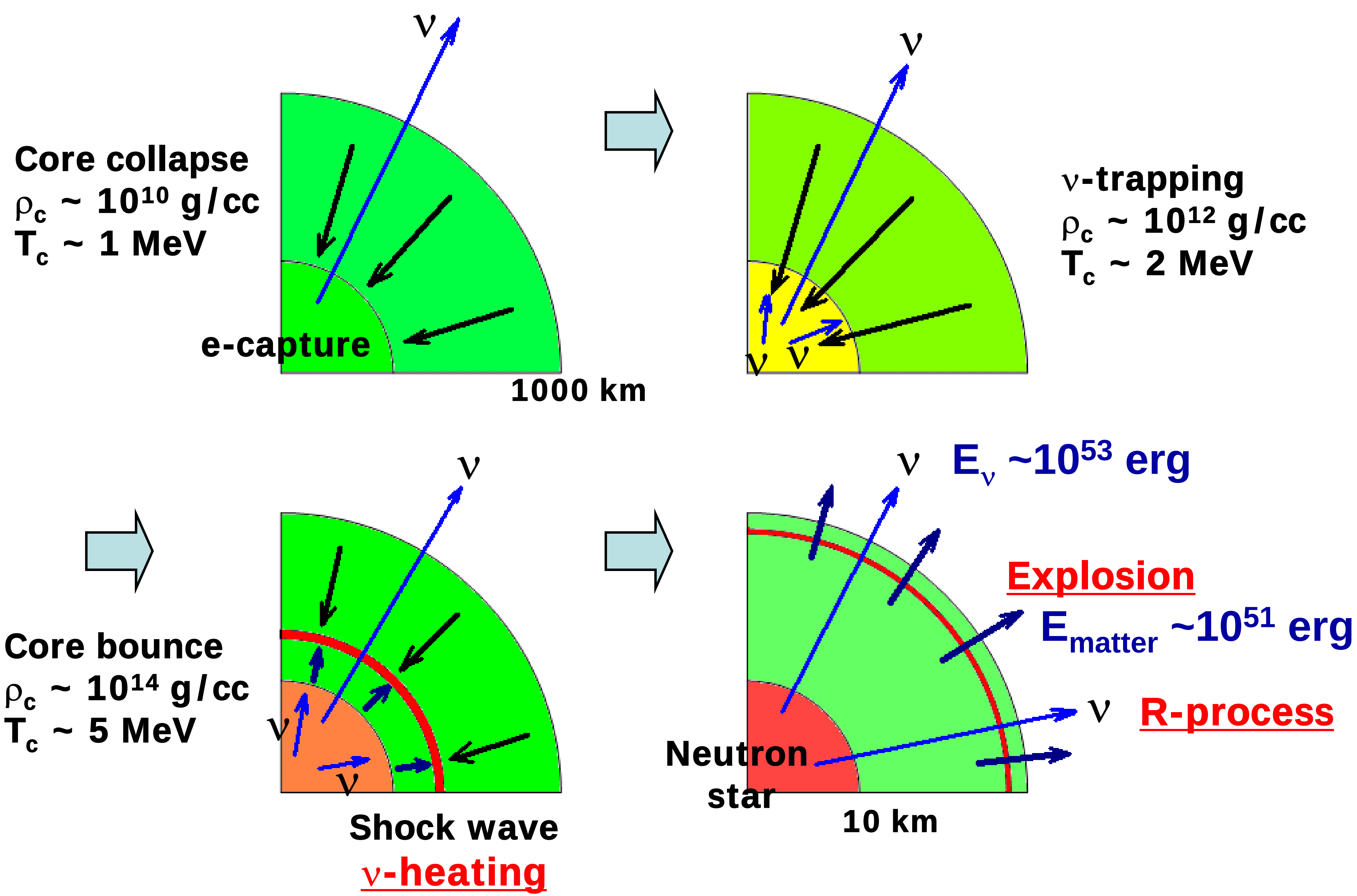
Stellar Evolution & Origin of Elements

Tool to trace the history of Galaxy

1) Photoreaction of D, ^{3}He & ^{4}He at threshold region

with a newly developed method (focus on ^{4}He)

Scenario of Super Nova Explosion



^{4}He: rapid Process & Supernovae Explosion

1) Astrophysical site for r-process: remain open question !

♦ r-process induced by *ν*-driven wind from a nascent neutron star

Woosley et al. ApJ. (1990)

ν interact with ^{4}He: ^{4}He(ν,ν'n)^{3}He, 4He(ν,ν'p)^{3}H

2) *ν*-heating in Delayed Explosion in Type II Supernovae

Energy Transfer by ν-Nucleus Interaction:
Influence the explosion process

Janka-Müller, A&A 306 (1996) 167

Neutrino induced breakup cross section for ^{4}He:

Necessary to estimate the yield of the r-process elements & to study a role of the neutrino in the delayed supernovae explosion.

Point:

Woosley et al., Haxton et al.

***ν*-nucleus interaction & EM interaction with nuclei: similar**
first forbidden & electric dipole

^{4}He: Nuclear Physics Interest

- ^{4}He: Lightest self-conjugate nucleus with closed shell structure
- ^{4}He(γ,N) in the GDR region: Proceed mainly by electric dipole

⇓

1) Ideal testing ground for theory on NN, 3N, collective structure

Efros, Leidemann et al.

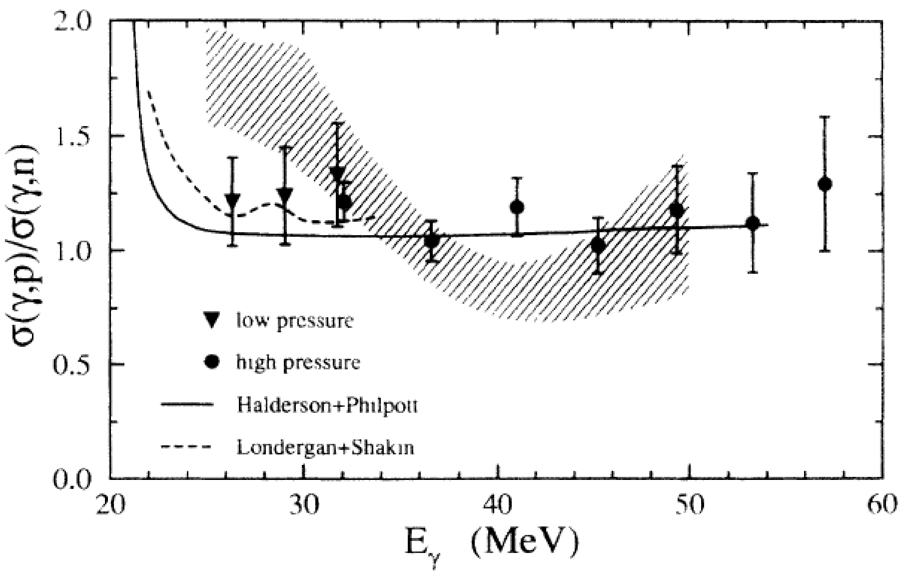
2) Charge symmetry:

Florizone et al. Phys. Rev. Lett.(1994)

Ratio of the σ(γ,p) to σ(γ,n):

Test the validity of charge symmetry

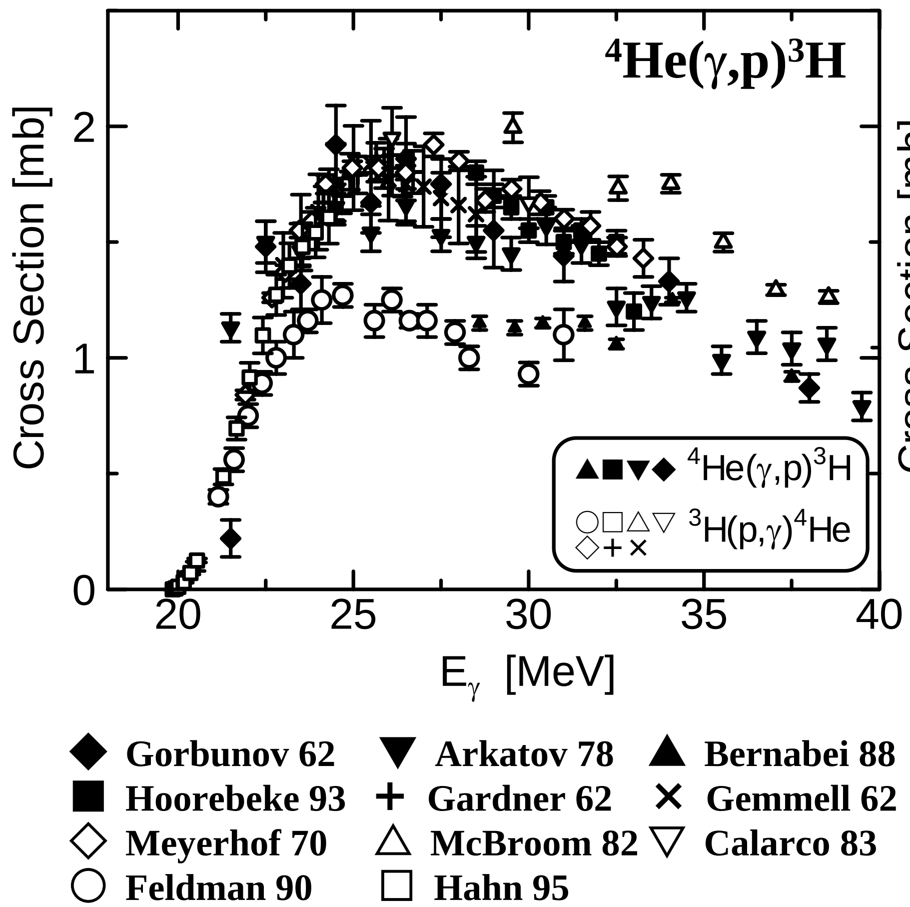
of the strong interaction

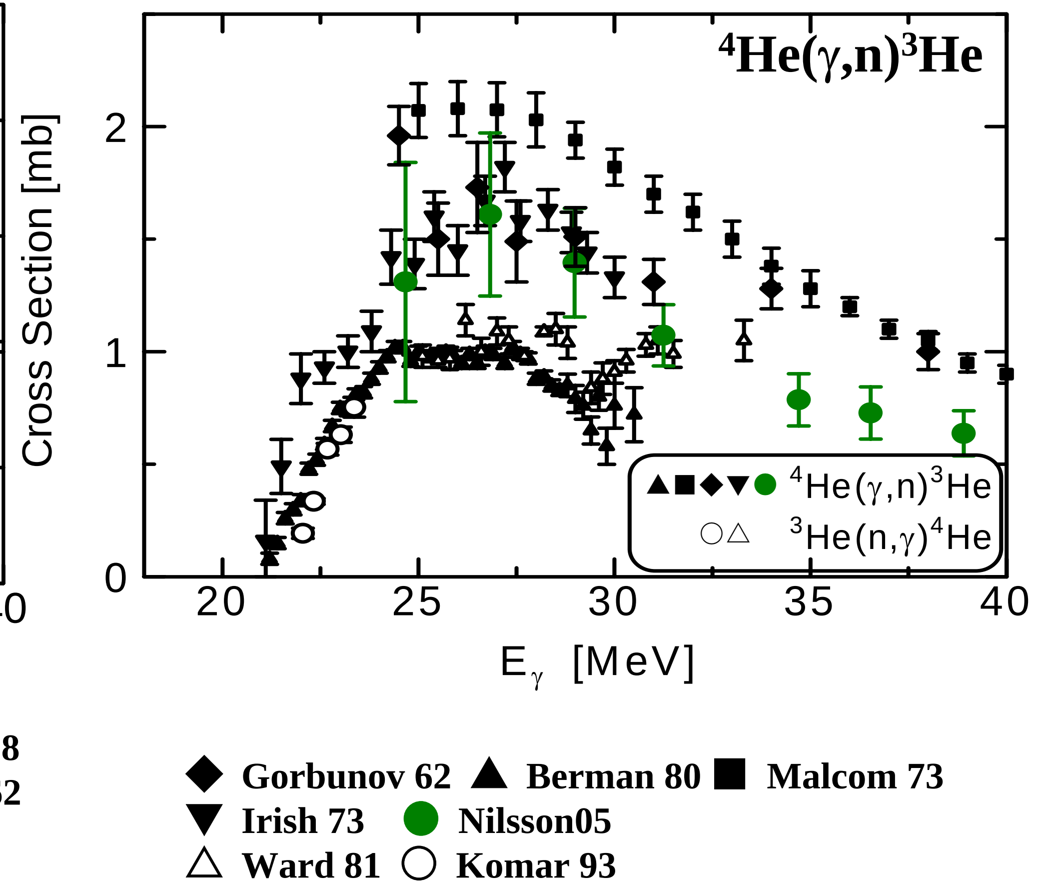


Shaded region: recommended ratio (Caralco et al.)

Experimental and theoretical situations on the photodisintegration of ^{4}He: Complicated, despite the progresses made by many researchers

(γ,p) & (γ,n) Data





1) Measurement: separately for (γ,p) & (γ,n). {except few}

2) Large discrepancy between different data sets

3) Systematic uncertainty >> Statistical uncertainty

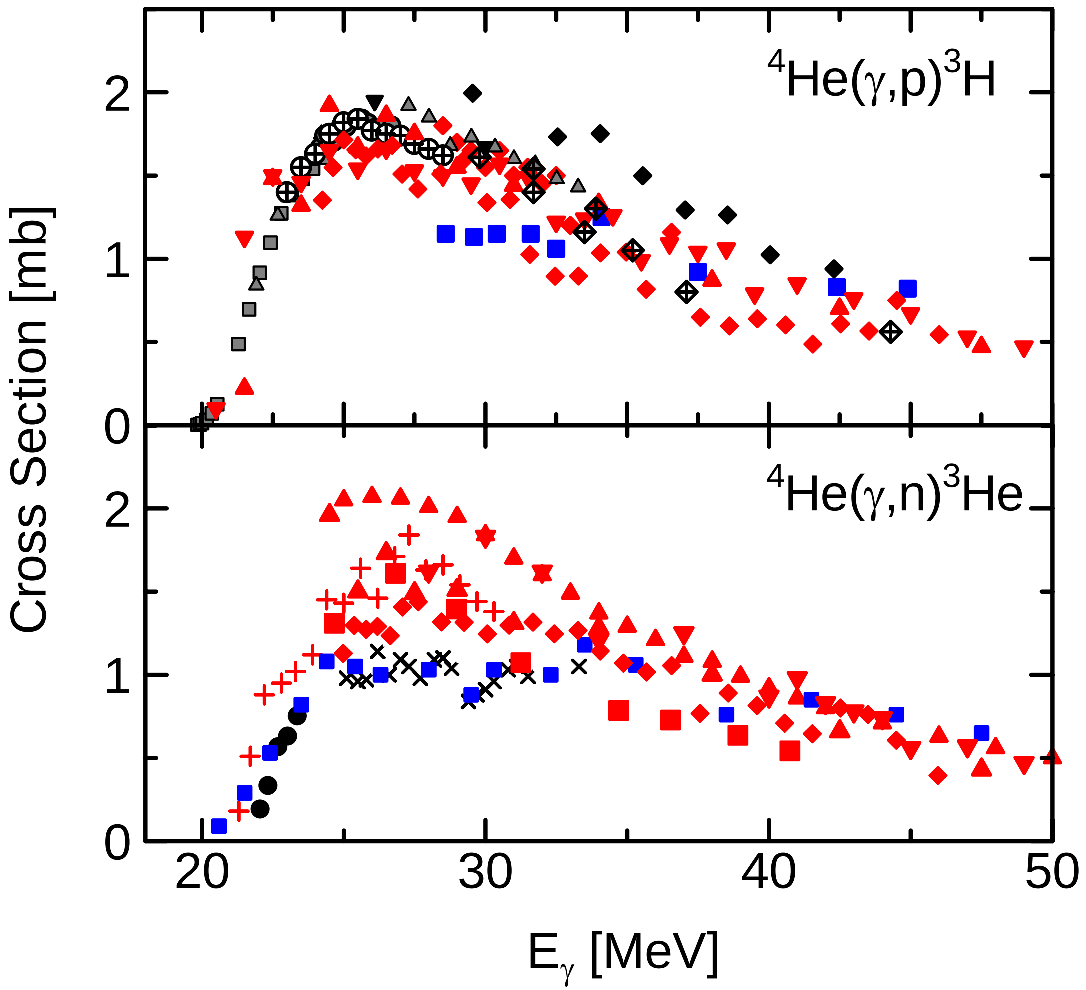
Develop a System with Small Systematic Uncertainty

Photon Probes and Measured Cross Sections

Monochromatic γ

Bremsstrahlung

Radiative capture



Data by Bremss. larger than data by monochro. below ~35 MeV

Remarks of the (γ,N) Reaction Study at Low Energy

1) γ-ray flux: low, ~10^4/s ⇒ pulsed photons to discriminate true events from beam uncorrelated events

2) Energy of emitted particles: low, < a few MeV ⇒ active target, to detect particles with 100 % efficiency

3) Cross section: small, a few mb ⇒ 4π detector

Our Method

1) Monoenergetic pulsed laser Compton backscattering photon

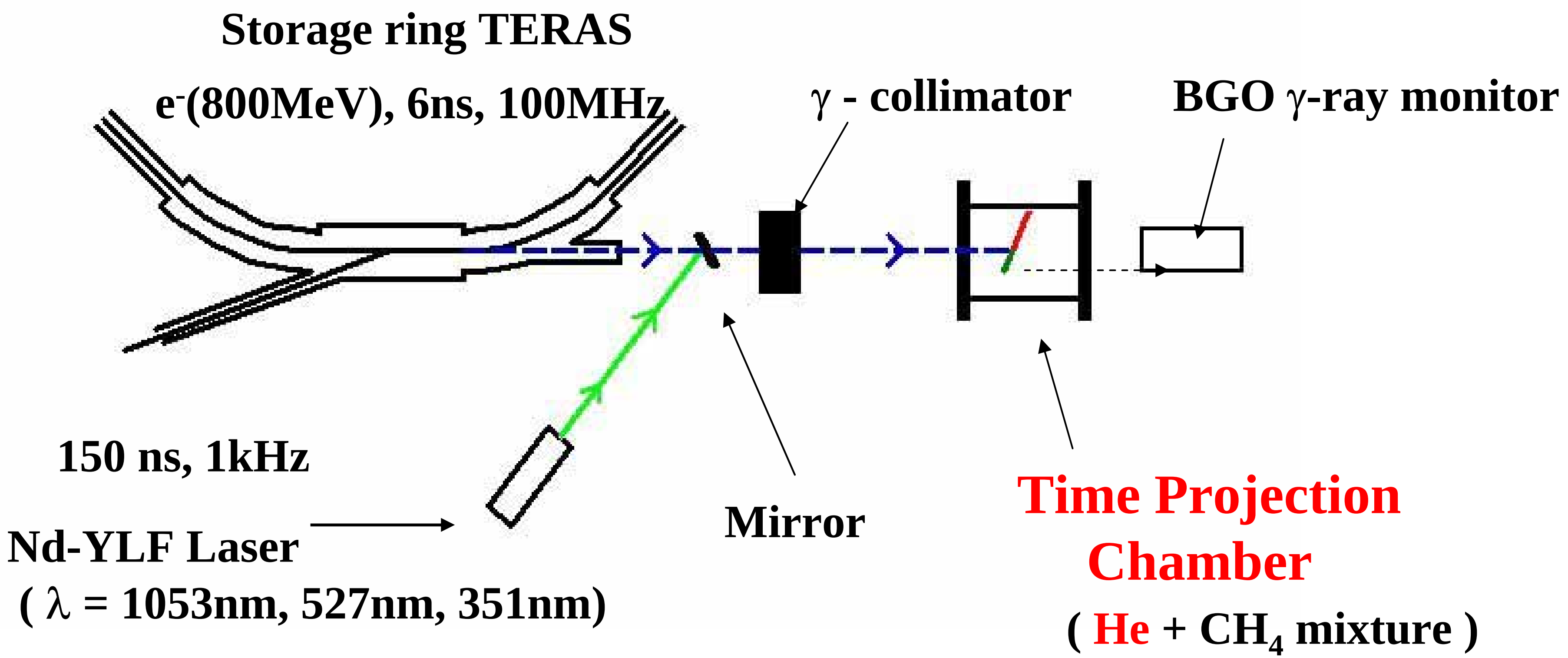
2) Time projection chamber with active ^{4}He gas target

3) Simultaneous measurement for ^{4}He{(γ,p) & (γ,n)}:

Essential to determine the ratio of σ(γ,p)/σ(γ,n)

Experiment at AIST (Tsukuba)

Laser-Compton backscattered γ-ray : $E\gamma$ = 2~32MeV, $\Phi\gamma$ = 10^4 /sec



Key Points to obtain real events with large S/N:

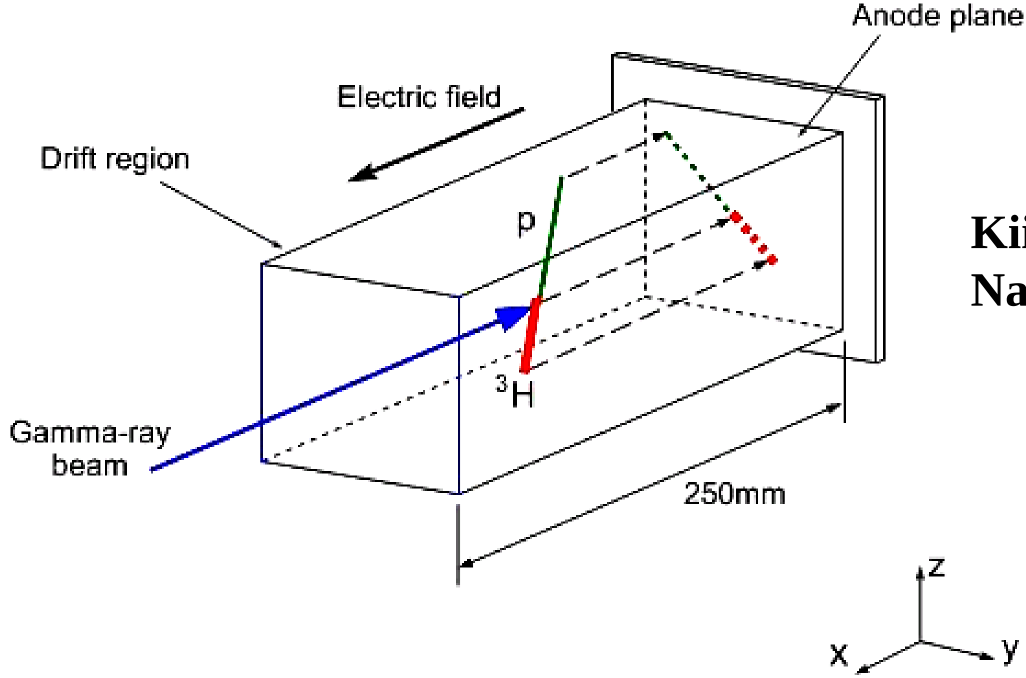
1) Real events: produced (i) along LCS-beam path with 2 mm ϕ

(ii) when pulsed LCS-beam enters TPC

Time Projection Chamber

Target gas :

He + CH_4 (CD_4)



Kii, Shima, Baba, Nagai, NIM (2005)

Key Points :

1) **Track shape, dE/dx, reaction point ⇒ event identification, $d\sigma/d\Omega$, asymmetry (Note: we detect a charged fragment)**

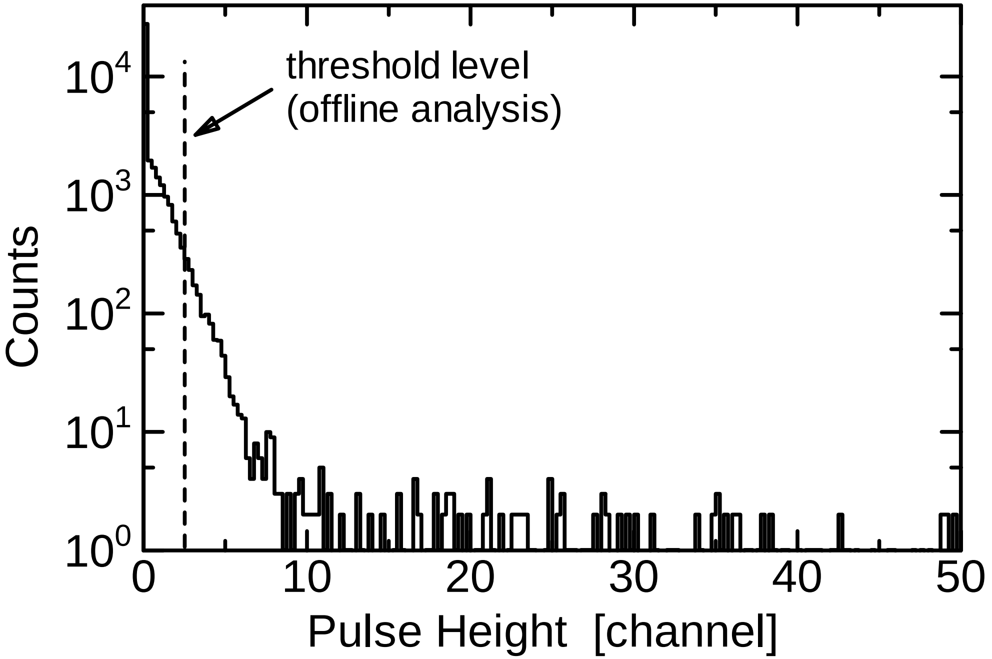
2) **Solid angle: ~ 4π, Detection efficiency : ~100%**

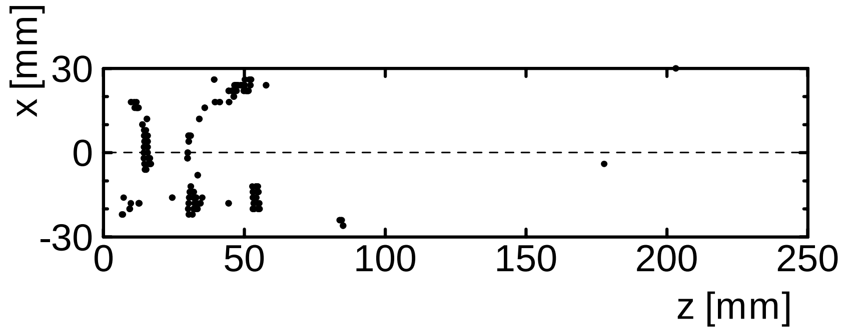
3) **E(ion) decreases, energy deposited in the TPC by ion increases, differs from other detectors, powerful for (γ,N) near threshold.**

How to Identify Events

Background (electron, natural) and True Events (^{4}He, ^{12}C)

1) Electron: small pulse height





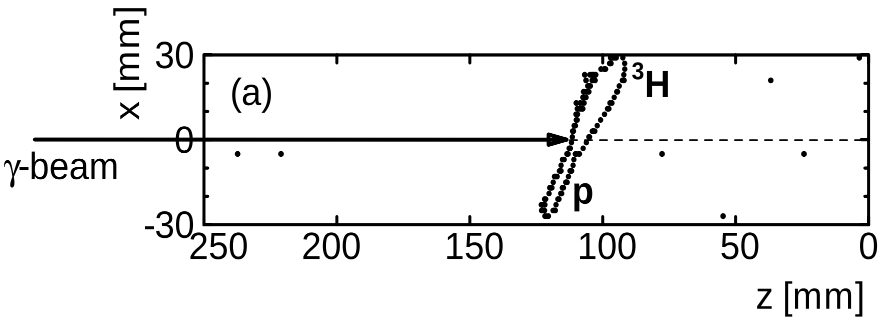
Track of scattered electron

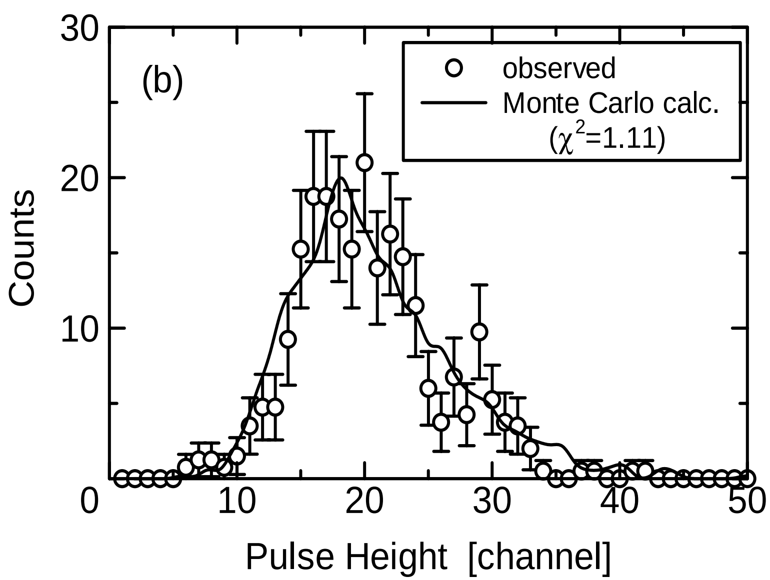
2) True Events of ^{4}He and ^{12}C:

path length, tack width, pulse height, reaction kinematics

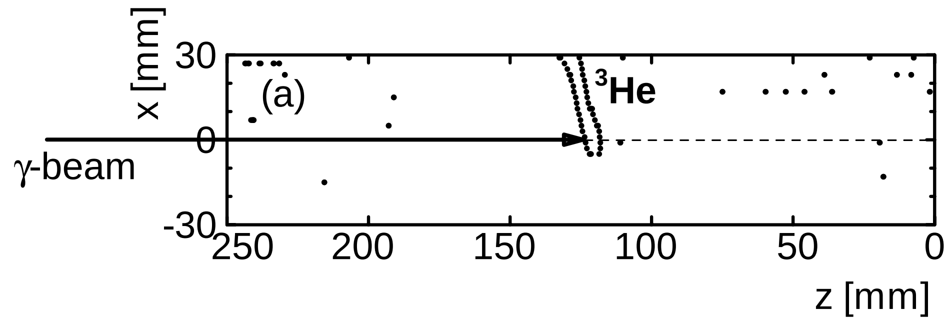
Track Shape & Pulse Height for ^4He

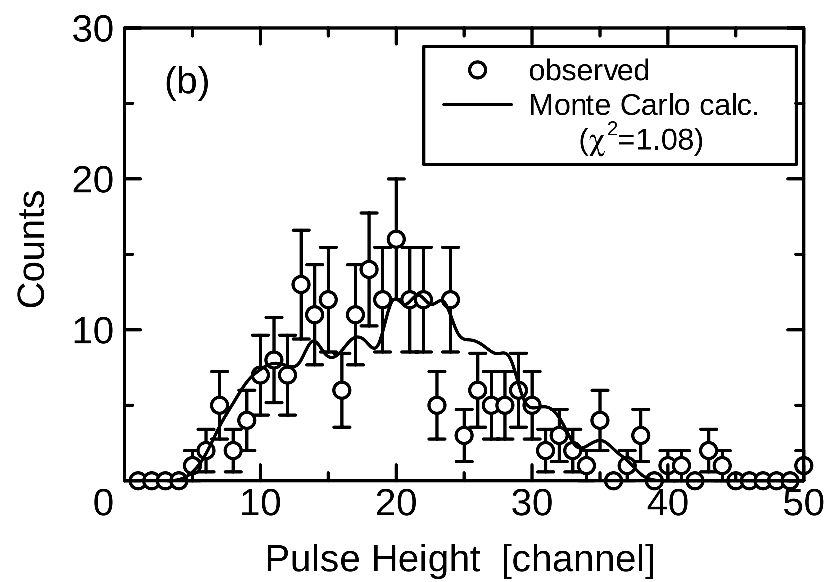
$^4He(\gamma,p)$





$^4He(\gamma,n)$





D(γ,p)n : Critical Test of the System

♦ Why we used it to test the system

1) Use He+CD_4 instead of He+CH_4

2) Energy deposit by proton in the TPC

< energy deposit by ^{3}He

$\sigma(\gamma,p: \text{mb})$ =

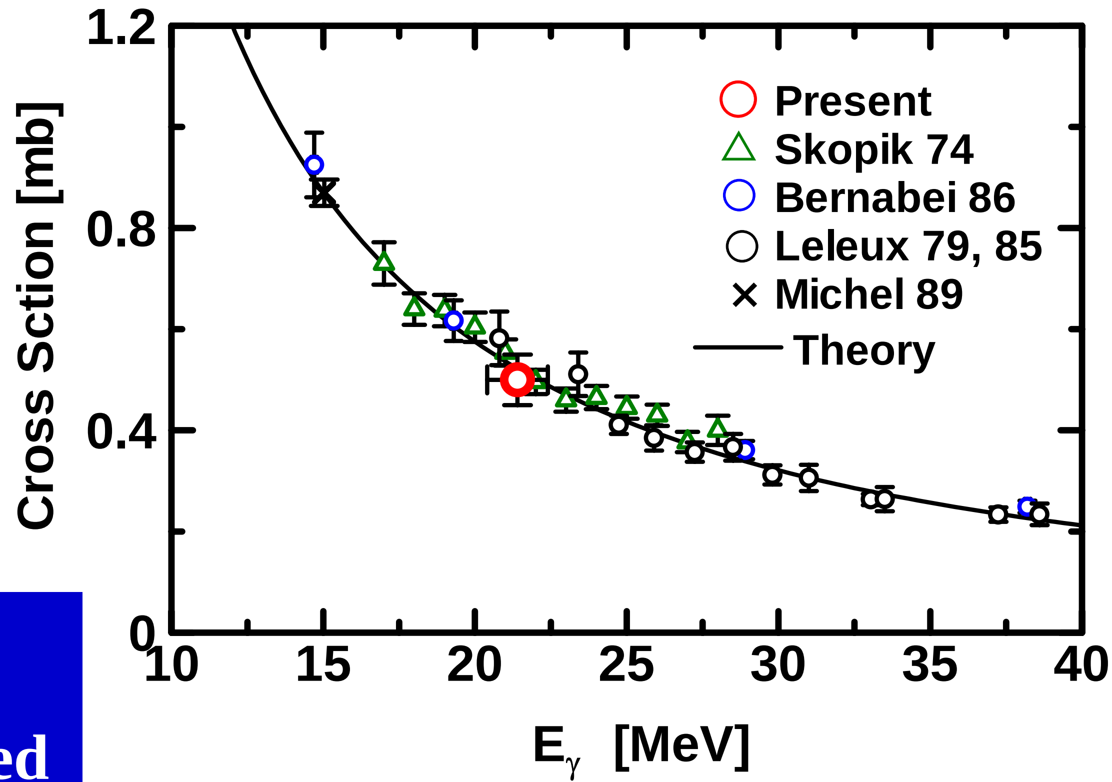
0.56 ± 0.04 ± 0.03

⇔ 0.55 mb (theo.)

Highly sensitive method:

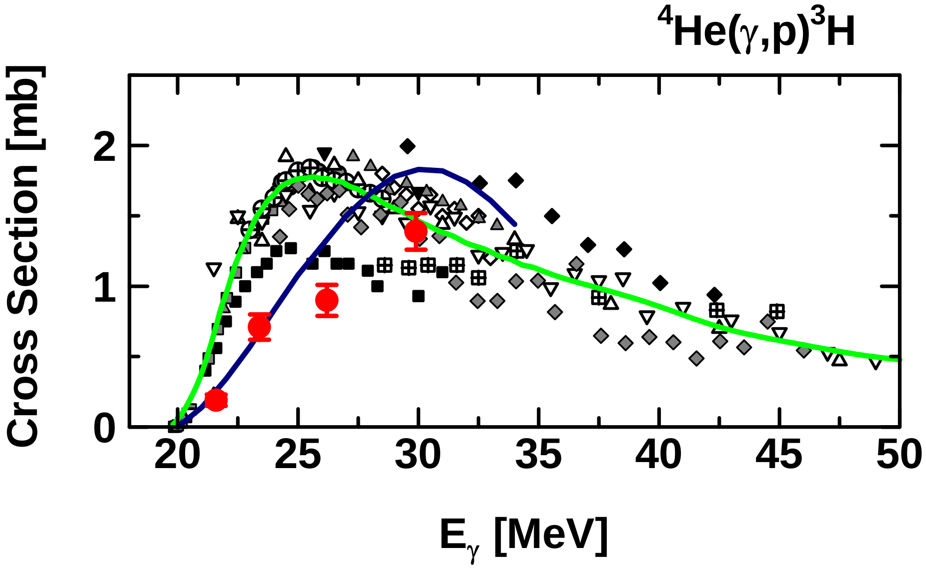
Experimentally demonstrated

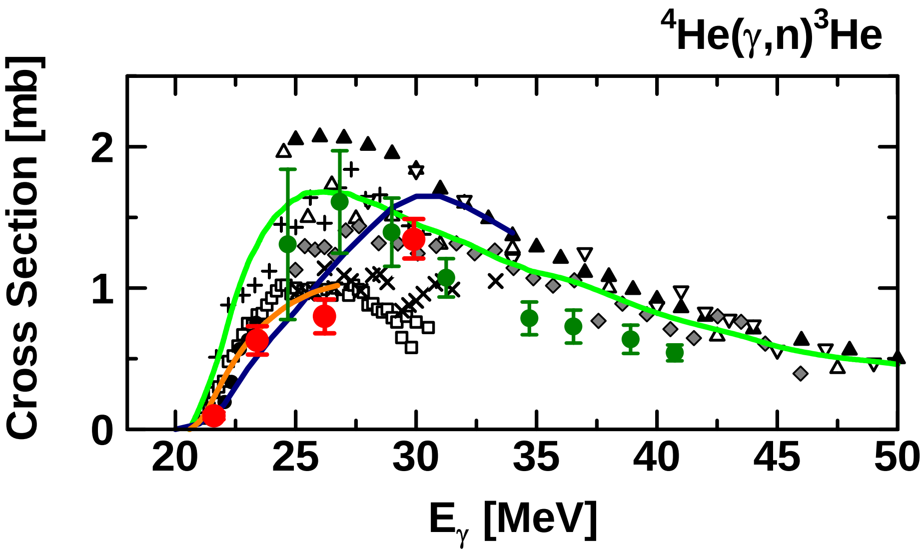
He+CD_4 mixture in TPC



σ(γ,p) & σ(γ,n) for ^{4}He

Shima et al. PR C72(2005)





Efros et al., Lorentz Integ. Trans.

Sandhas et al., Faddeev-AGS formalism

Londergan & Shakin, Shell model with tensor

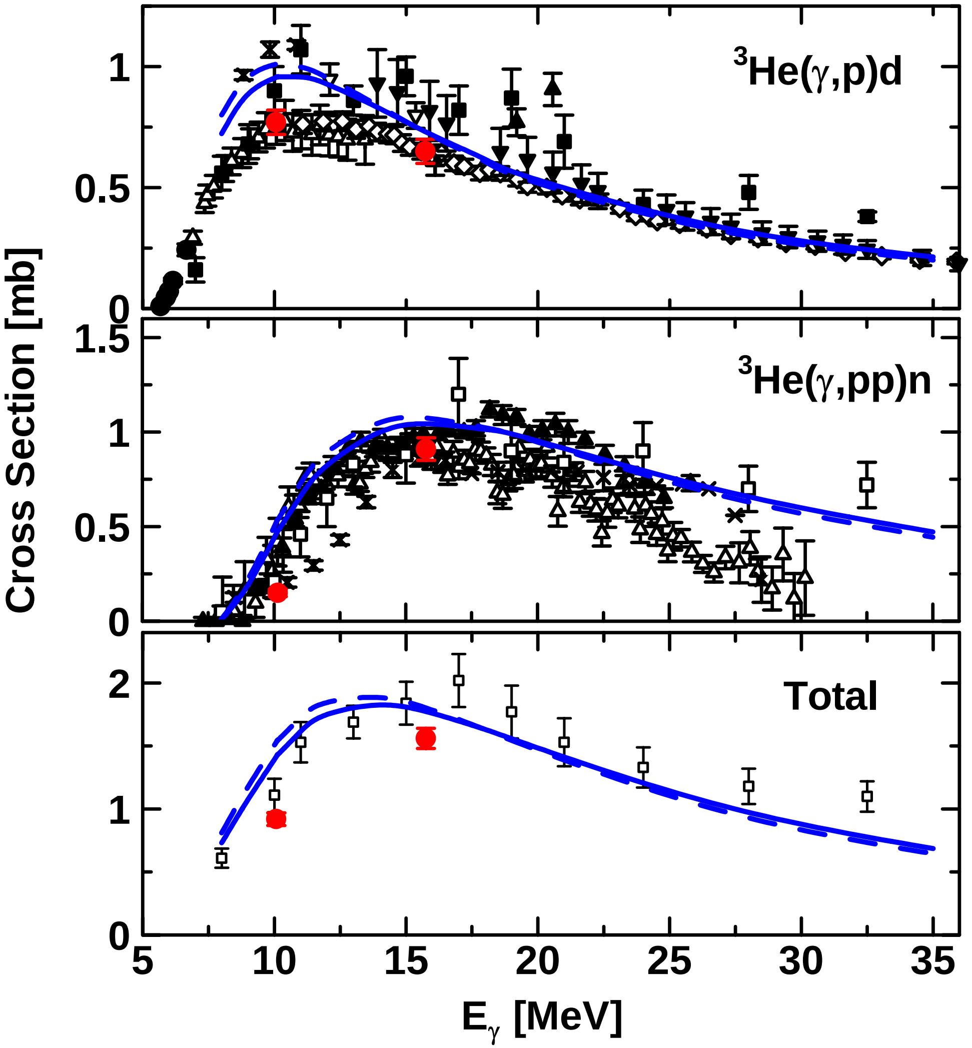
1) σ(γ,p) & σ(γ,p) monotonically increase with energy up to 30 MeV

2) σ(γ,p) differ from old data & recent theoretical cal.

3) σ(γ,n) agree with Berman's data & Sandhas's cal. up to 26 MeV.

4) Tensor force play a role? Open question!

Result for ^{3}He



Naito et al. Phys. Rev. C73 (2006)

Present

Faddeev (AV18)

Faddeev (AV18+Urbana-IX)

(Krakow, Bochum, Julich, Kyusyu)

1) **At 16 MeV, present data agree with old data, & with cal. values.**
2) **At 10.2 MeV, measured σ(*γ,p*) is ~20% & σ(*γ,pp*) is ~ factor 3 smaller than the calculated values.**

$^{12}C(\alpha,\gamma)^{16}O$ reaction study at $E_{c.m.}$=300 keV

Aim:

$^{12}C(\alpha,\gamma)^{16}O$ reaction rate affect on

- C/O ratio after He burning
- Abundance distribution of the elements between C and Fe
- Iron core mass before supernova explosion

↓

The reaction rate of the $^{12}C(\alpha,\gamma)^{16}O$ reaction should be known **in a precision of better than 10 %**

↓

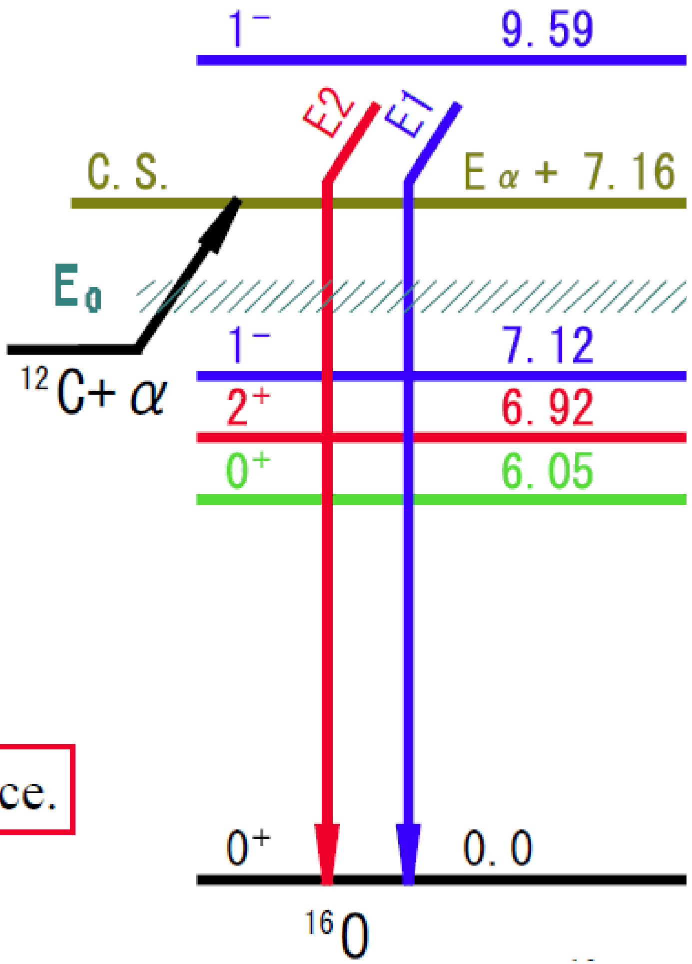
Many experimental efforts performed over 30 years !!

Key points: $^{12}C(\alpha,\gamma)^{16}O$ cross section at $E_{c.m.} \leq 1.5$ MeV

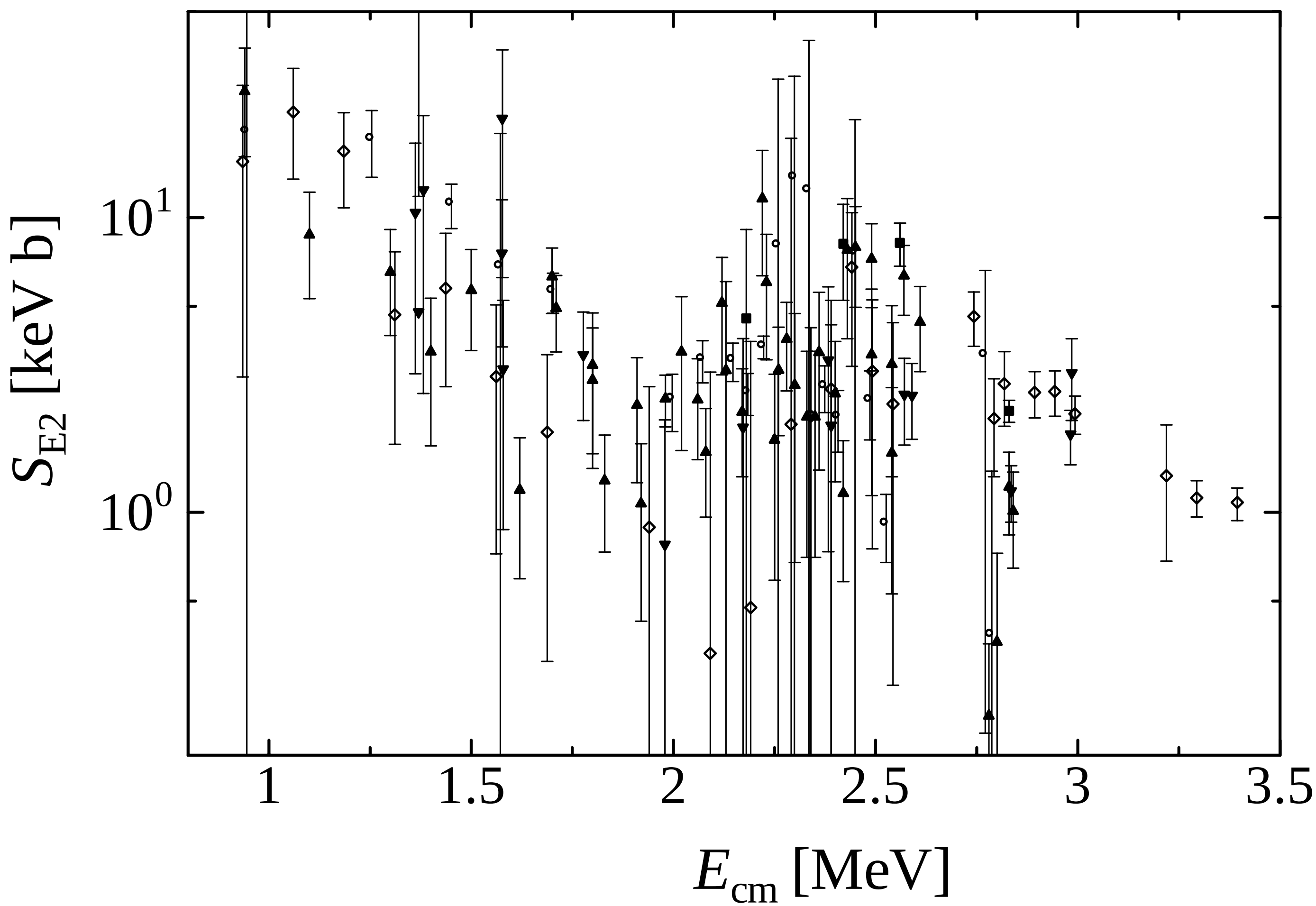
* Cross section < 1 nbarn

- **Electric dipole (E1)**
  $J^{\pi} = 1^{-}$ resonances at –0.045
  2.418 MeV
- **Electric quadrupole E2**
  $J^{\pi} = 2^{+}$ resonance at –0.245 MeV
  Direct Capture Process
- **Cascade (C.S. ⇒ 6.05, 6.92, 7.12)**
  Should be included but their contribution is not so large

These have different energy dependence.



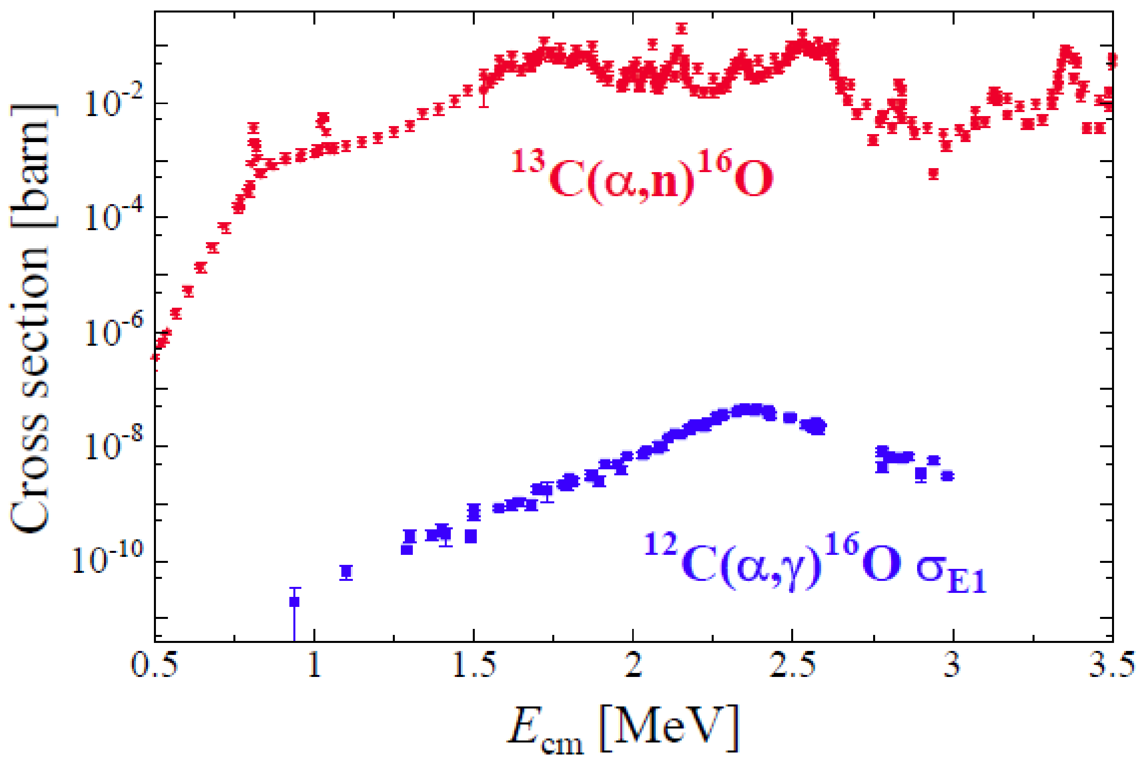
Astrophysical S_{E2} factor



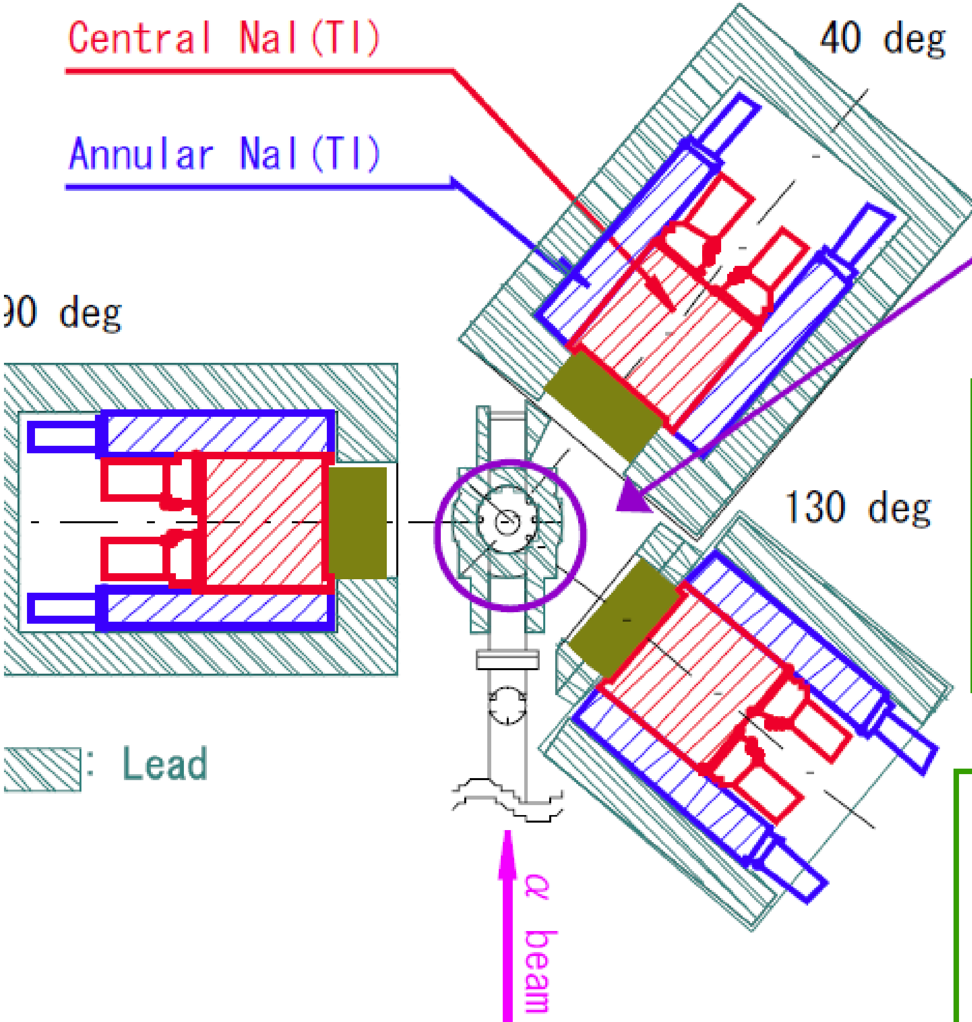
3. Experimental Method and Procedure

Problems on $^{12}C(\alpha,\gamma)^{16}O$ measurement

- Low cross section (**~ 1 nb at E_{cm} ~ 1.5 MeV**)
- Large neutron background due to $^{13}C(\alpha,n)^{16}O$ reaction
  (**$\sigma(\alpha,n) \sim \sigma(\alpha,\gamma) \times 10^7$、$E_n \sim 4$ MeV**)
- Systematic error in the determination of the target thickness



Experimental setup



High efficiency anti-Compton NaI(Tl) spectrometer
⇒ **high statistics**

Enriched ^{12}C target
⇒ reduce neutron yield from $^{13}C(\alpha,n)^{16}O$ reaction

Monitor system for target thickness
⇒ reduce systematic error on target thickness determination

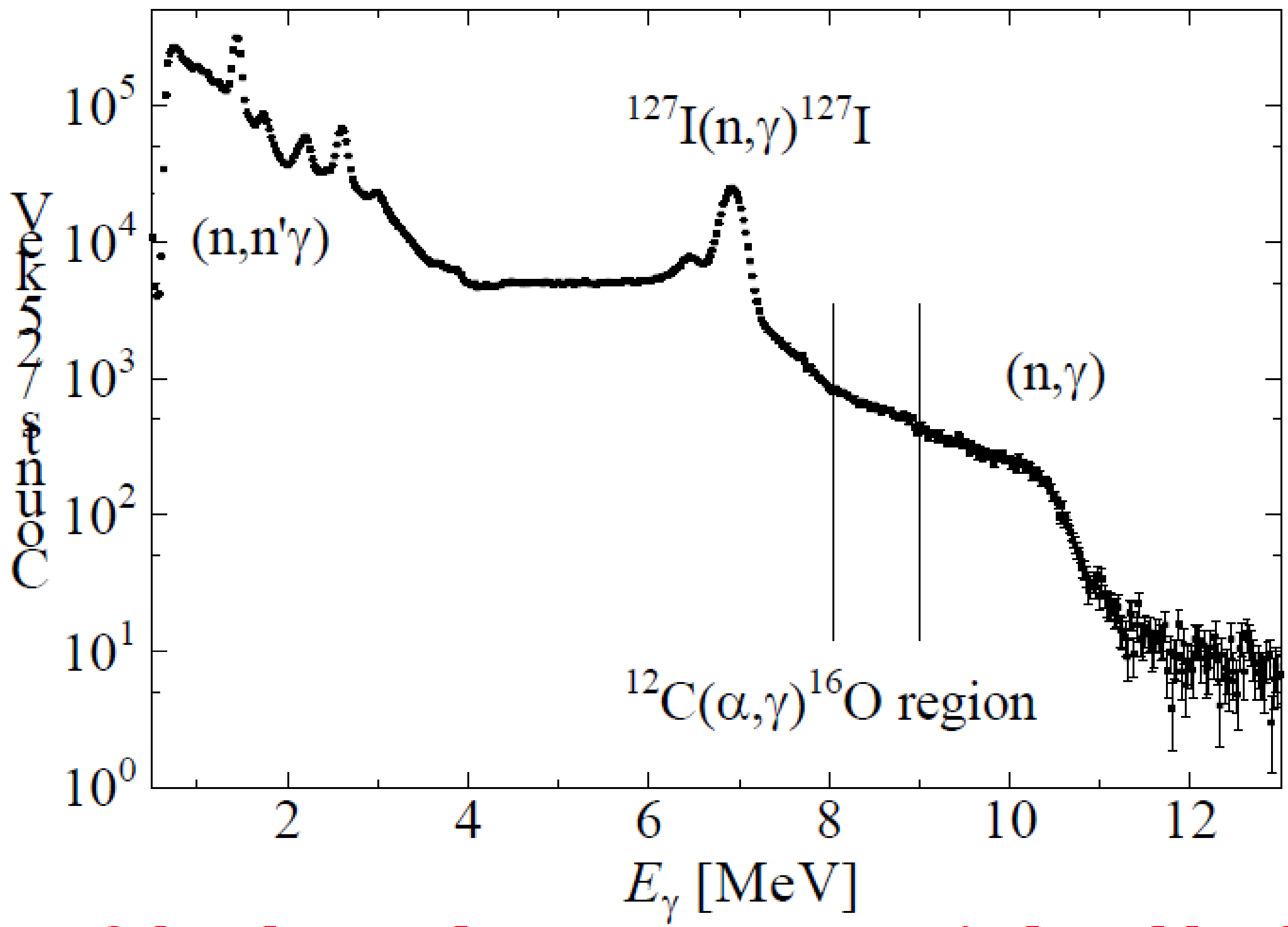
Powerful shield against **neutrons** and **external γ-rays**
⇒ reduce background due to neutron

Pulsed α beam ⇒ reduce background due to neutron

(1) γ-ray spectrum

All event observed by NaI(Tl) spectrometer

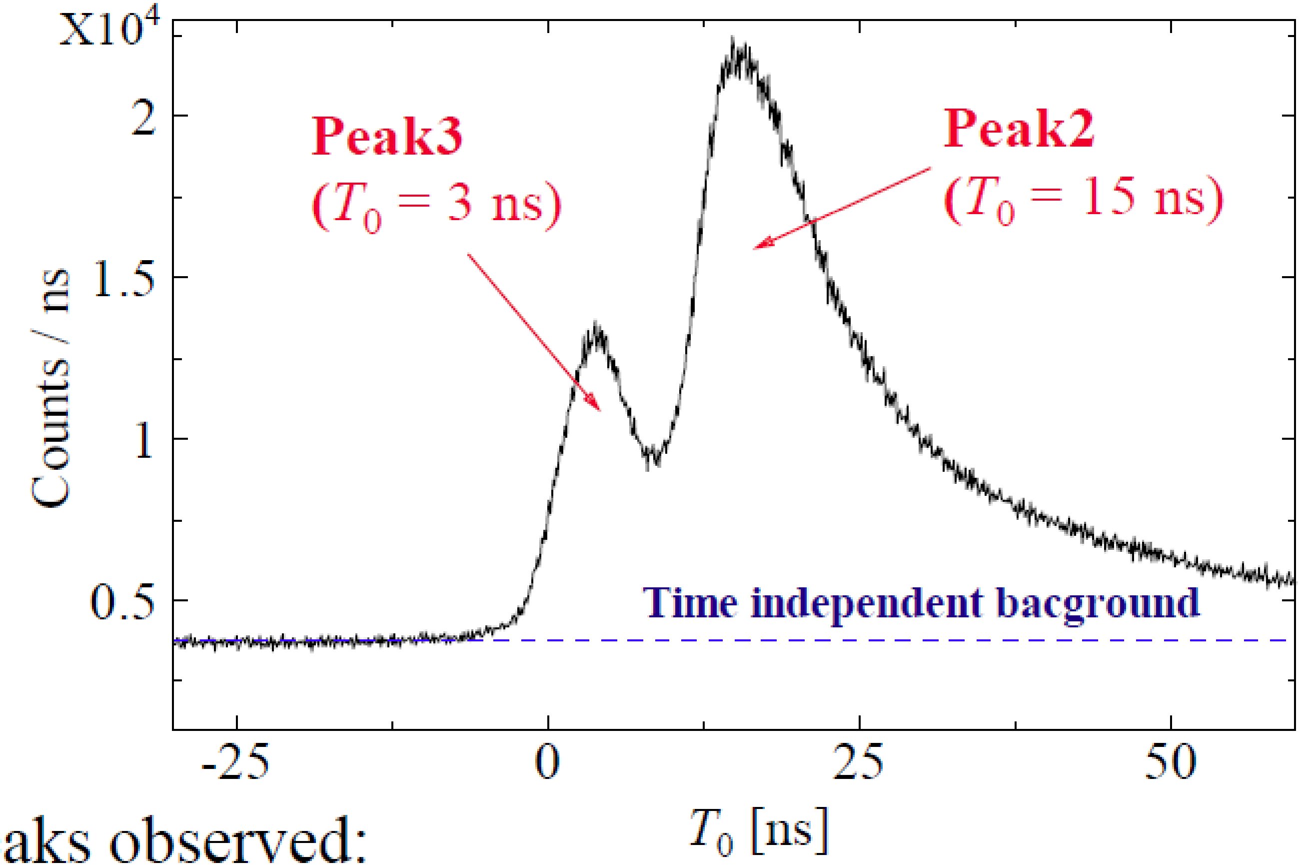
($\theta = 90^\circ$, $E_\alpha = 2.270$ MeV)



Most of the observed event → neutron induced background

(1-2) Background due to neutrons

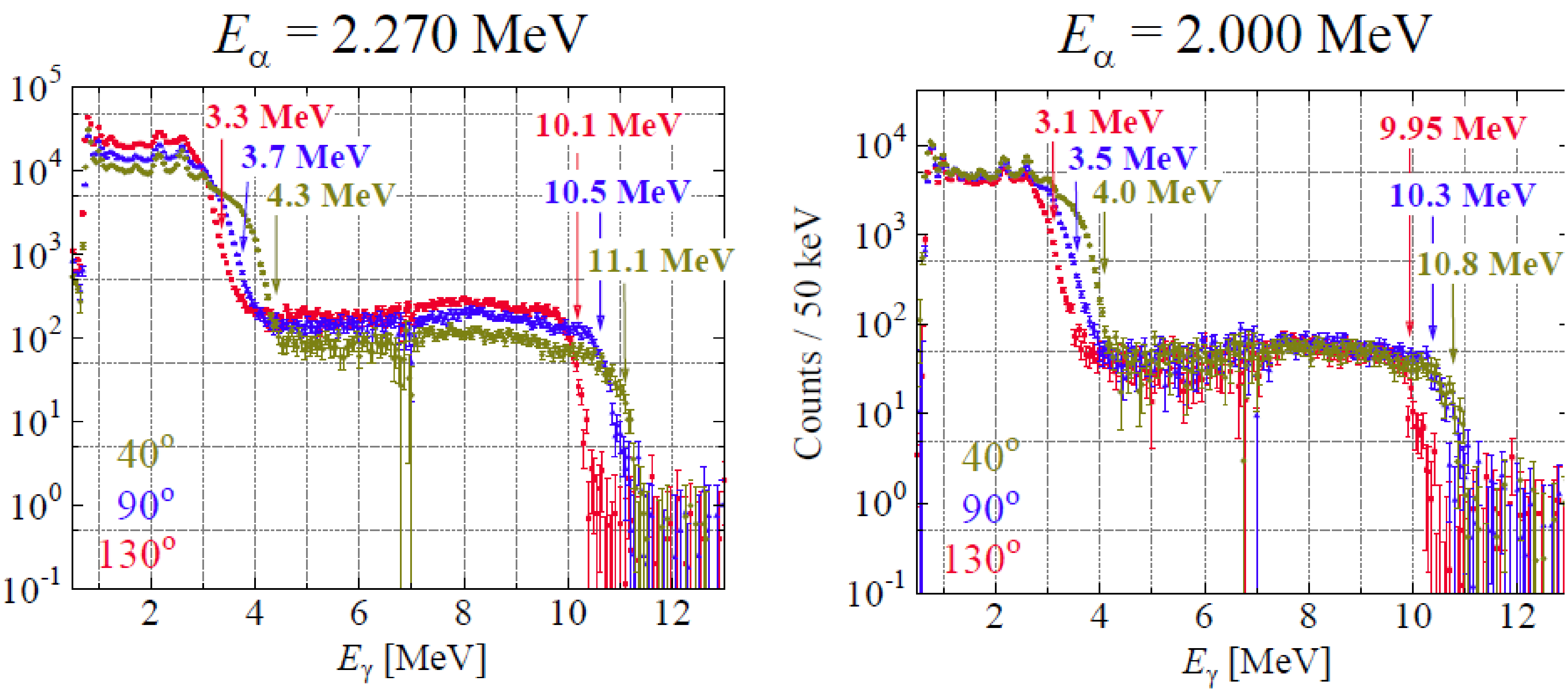
TOF spectrum obtained by NaI(Tl) spectrometer



Two peaks observed:

- Peak2 (T_0 ~ 15 ns ⇒ L ~ 45 cm ⇒ **NaI(Tl) spectrometer**)
- Peak3 (T_0 ~ 3 ns ⇒ L ~ 9 cm ⇒ **Target chamber or Pb shield**)

γ-rays contained in peak2

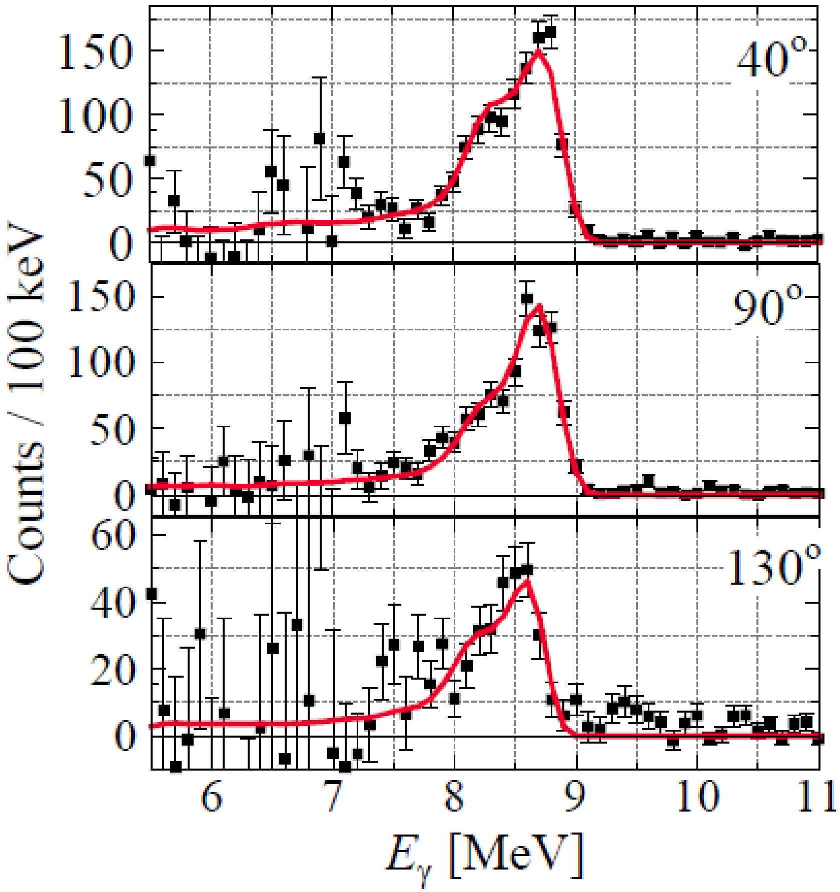


- γ-rays up to 4 MeV ⇒ ^{127}I(n,n'γ)^{127}I reaction
- γ-rays up to ~ 11 MeV ⇒ ^{127}I(n,n'γ)^{128}I reaction

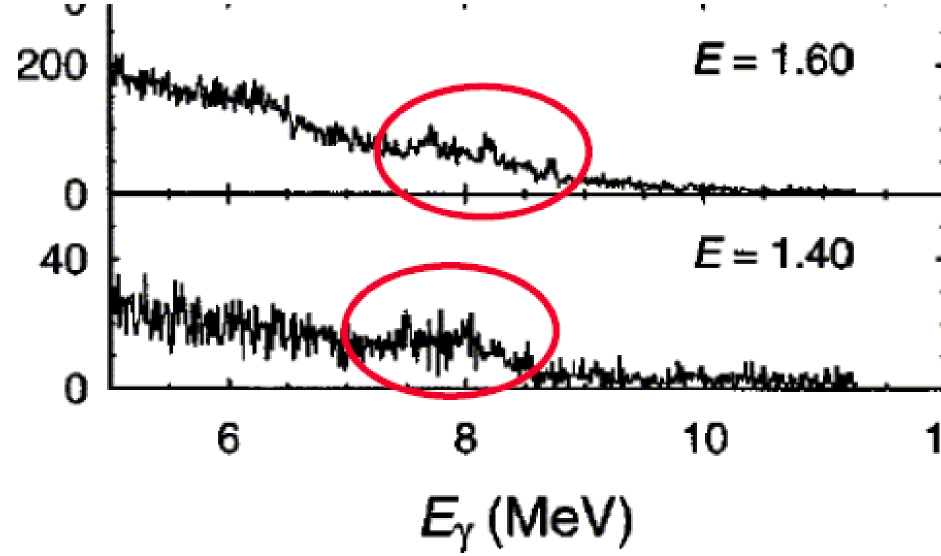
Maximum energies of continuum γ-rays are consistent with calibrated neutron energy from the ^{13}C(α,n)^{16}O reaction

$^{12}C(\alpha,\gamma)^{16}O$ γ-ray spectrum

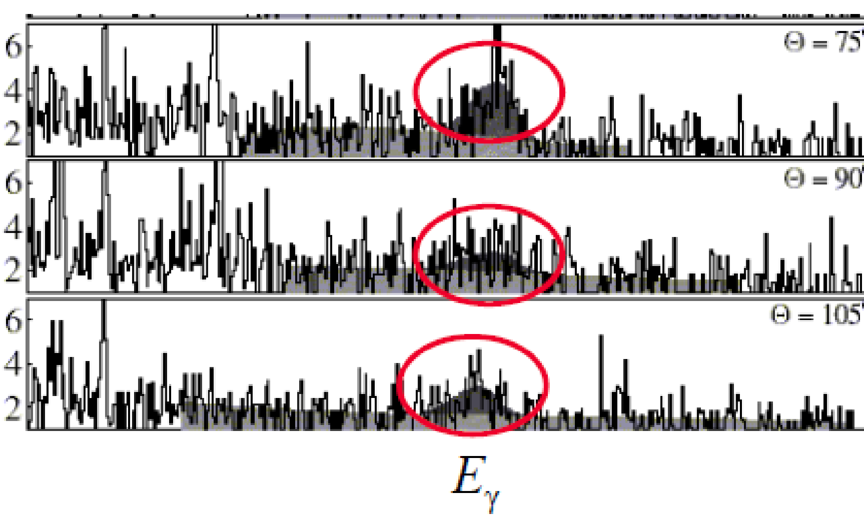
Present results (E_{cm} ~ 1.6 MeV)



Ouellet et al. 1996



Kunz et atl. 2001 (E_{cm} = 1.25 MeV)

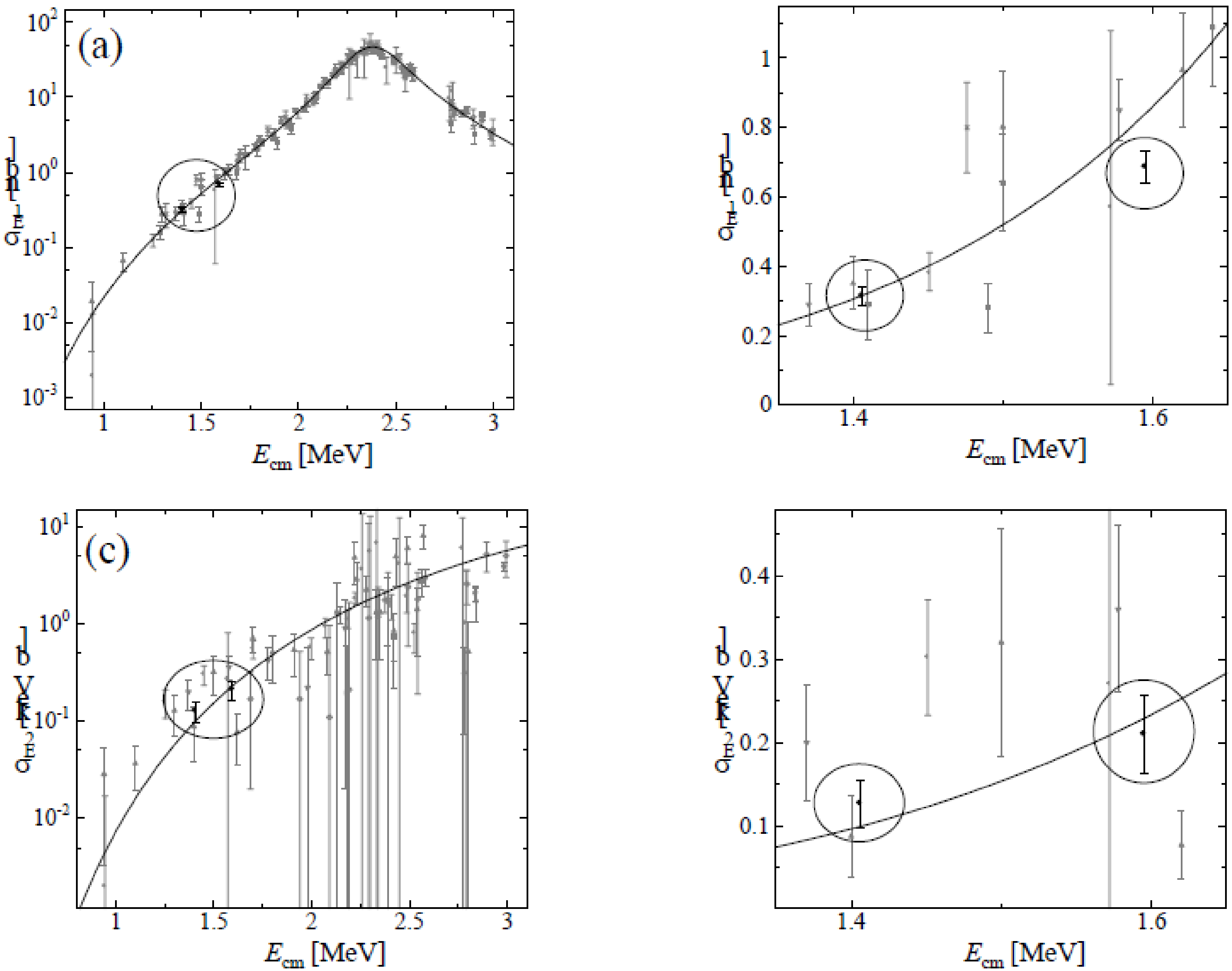


Observed γ-ray peak with a large S/N and high statistics

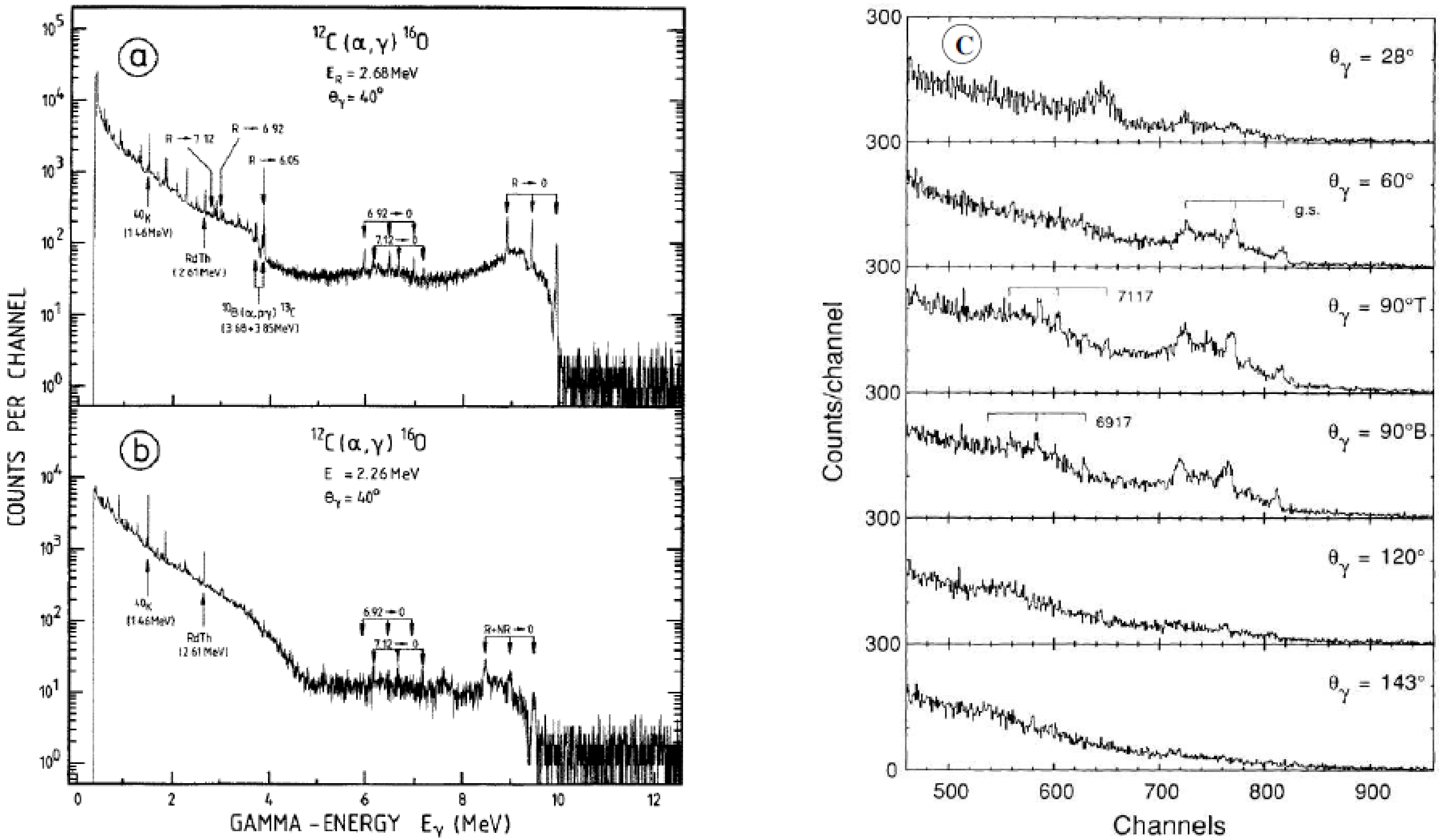
Results (total cross sections)

σ_{E1}

σ_{E2}

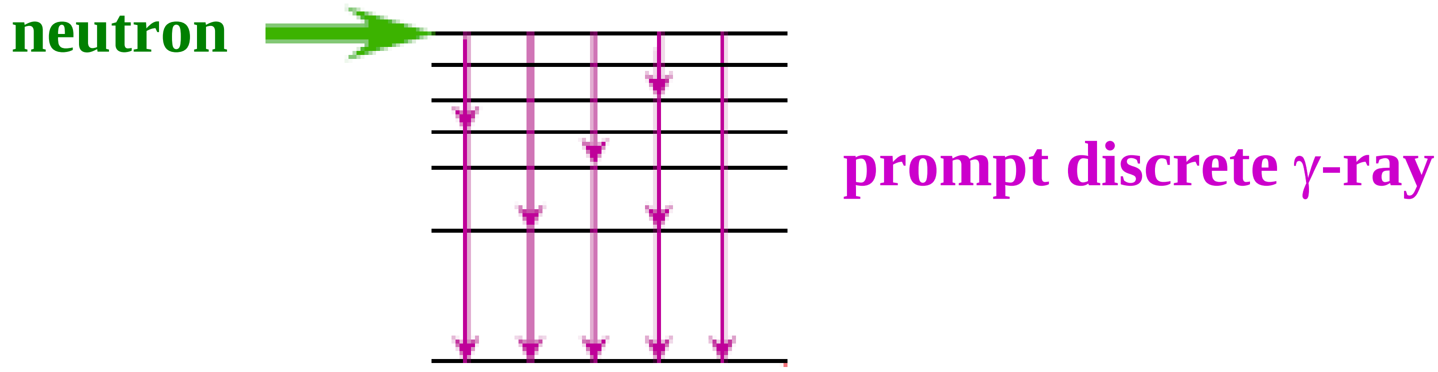


Precision of the present result ≫ Previous results



a
$^{12}C(\alpha,\gamma)^{16}O$
E_R = 2.68 MeV
θ_γ = 40°
R → 7.12
R → 6.92
R → 6.05
^{40}K (1.46 MeV)
RdTh (2.61 MeV)
$^{10}B(\alpha,p\gamma)^{13}C$ (3.68 + 3.85 MeV)
6.92 → 0
7.12 → 0
R → 0
b
$^{12}C(\alpha,\gamma)^{16}O$
E = 2.26 MeV
θ_γ = 40°
^{40}K (1.46 MeV)
RdTh (2.61 MeV)
6.92 → 0
7.12 → 0
R+NR → 0
COUNTS PER CHANNEL
GAMMA - ENERGY E_γ (MeV)
c
θ_γ = 28°
θ_γ = 60°
g.s.
θ_γ = 90°T
7117
θ_γ = 90°B
6917
θ_γ = 120°
θ_γ = 143°
Counts/channel
Channels

keV Neutrons Radiative Capture Reaction



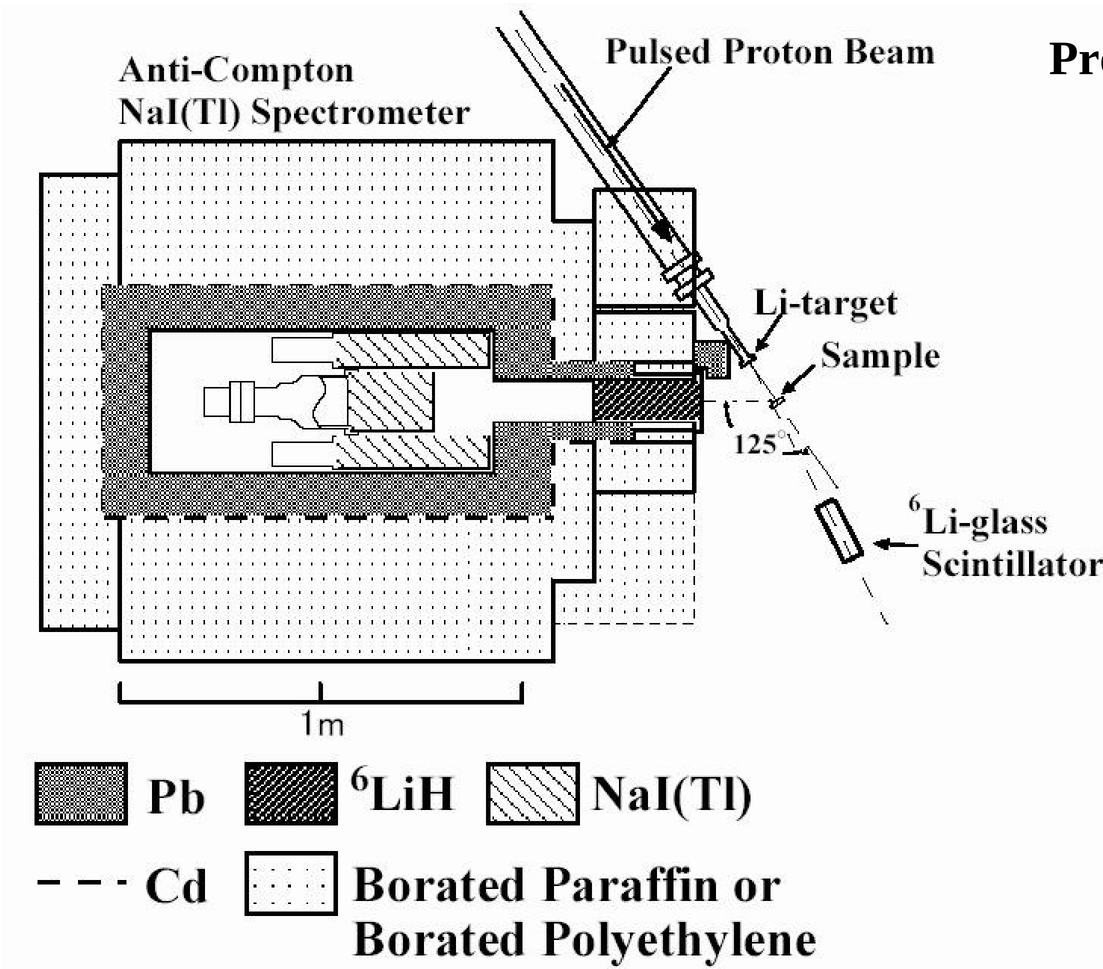
Comparison of (n,γ) to (γ,N) studies

(γ,N)	(n,γ)
ground & continuum	ground + continuum
	+ excited bound states

Essential point:

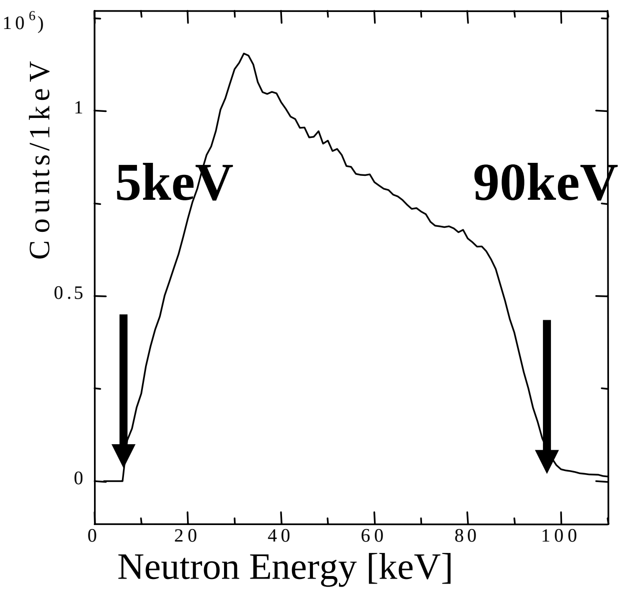
Detect discrete γ-rays from the (n,γ) to low-lying states

Experimental Setup



Proton beam: 3.2 MV Pelletron at Tokyo Inst. Tech.

Neutron
^{7}Li(*p*,*n*)
En=10-90keV

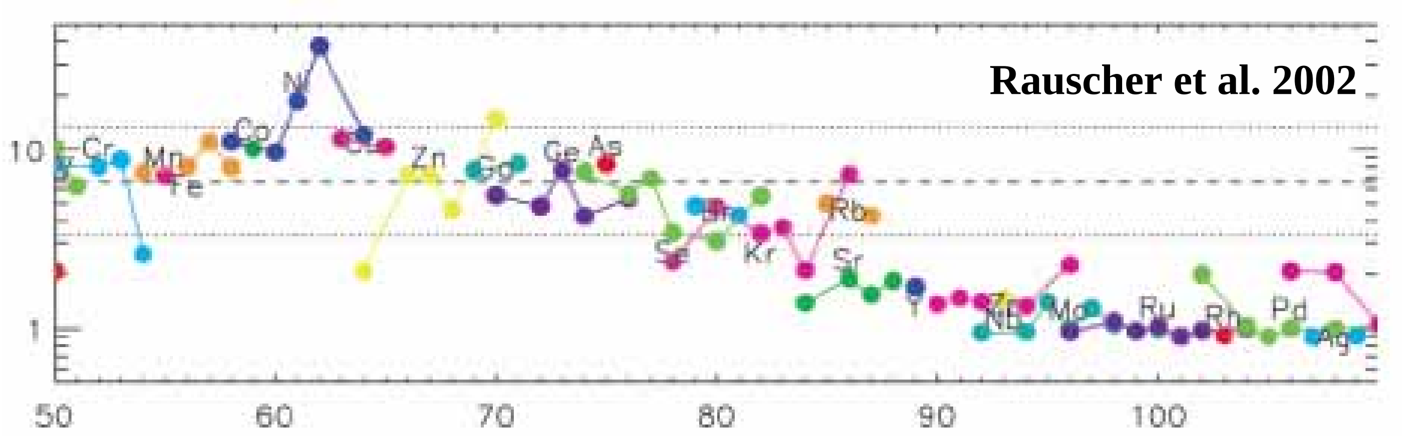


^{197}Au: Normalization of the cross section well known within 3% uncertainty

Weak Component: bottle-neck reaction $^{62}Ni(n,\gamma)^{63}Ni$

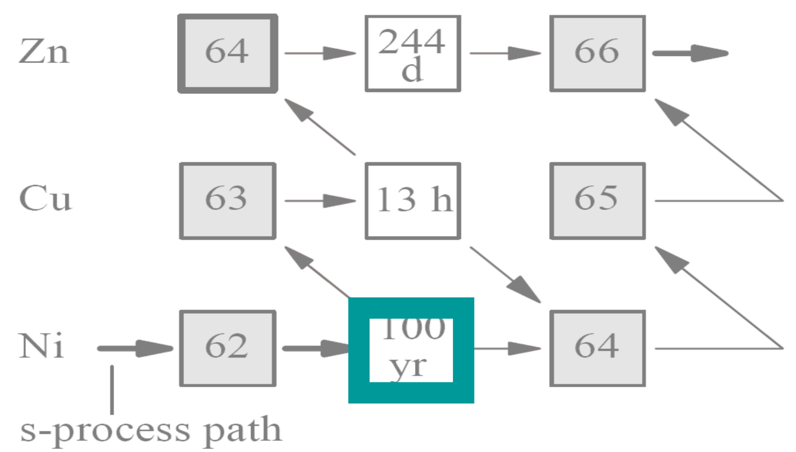
From onset of central H-burning through explosion as Type II SN
Population I stars of 15 ~ 25 M⊙

Overproduction factor



Mass number A

- Overproduction of ^{62}Ni compared to the solar abundance
- $\sigma(n,\gamma{:}^{62}Ni)$ affects overall calculated abundance for weak s-process elements



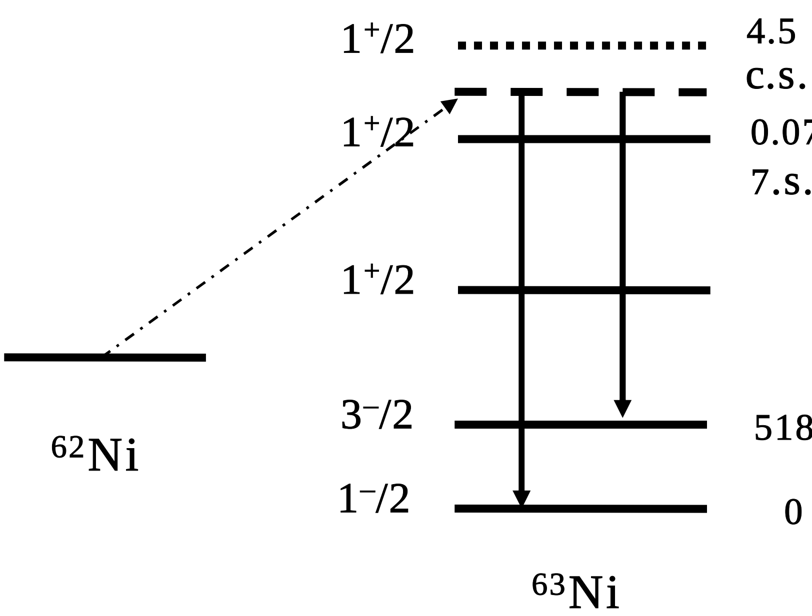
♦ **Previous data on $\sigma(n,\gamma{:}^{62}Ni)$ at a stellar temperature**

- **well known at thermal energy**
- **MACS (Maxwellian averaged capture cross section) at 30 keV**

26(5) mb Beer (74), 35.5(4) mb Bao (87), 12.5(4) mb Bao (00)

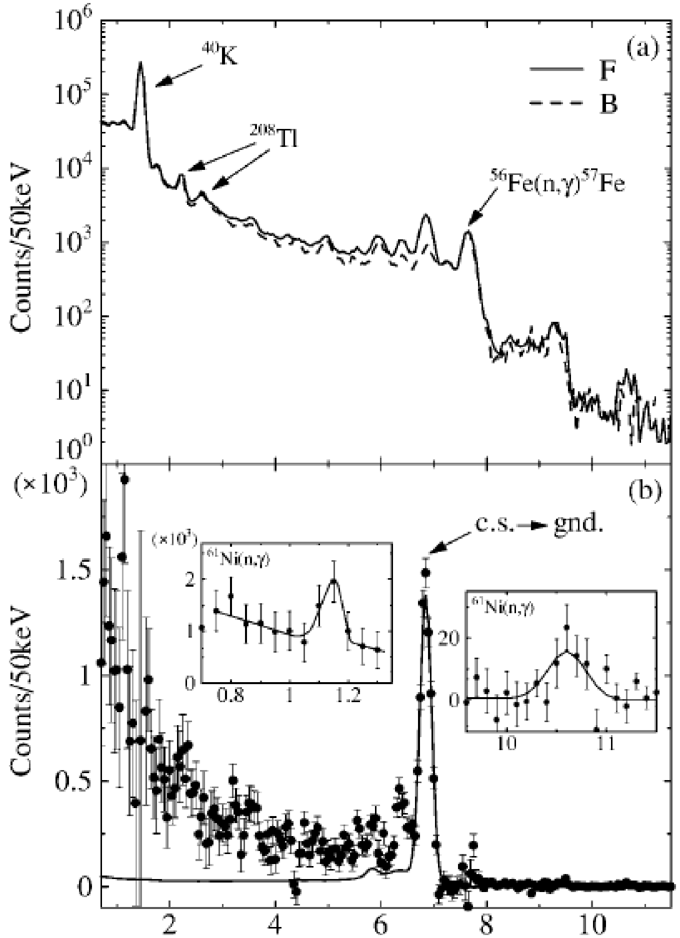
Problems in obtaining $\sigma(n,\gamma{:}^{62}Ni)$ at keV

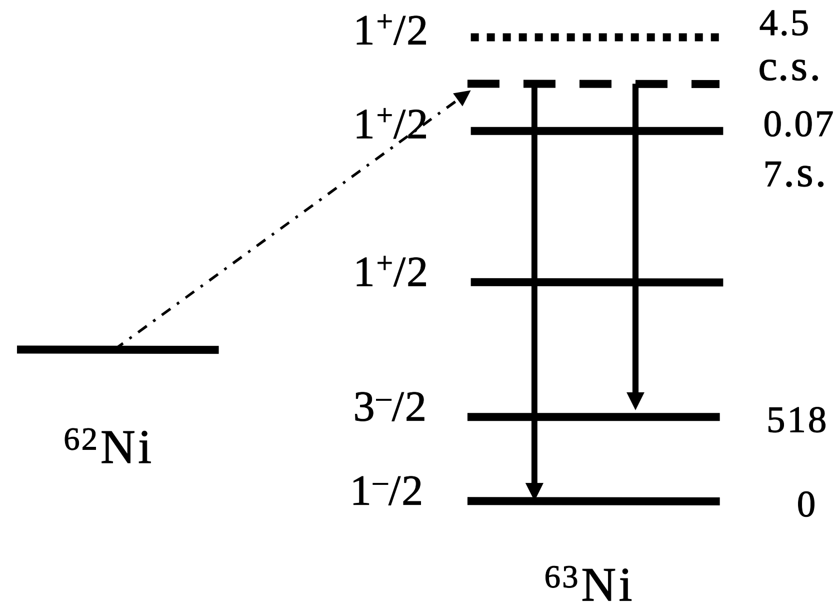
- **assume s-wave capture & apply a 1/v law ?**
- **contribution of the sub-threshold resonance at -0.077 keV and the near threshold resonance at 4.5 keV ?**



♦ γ-ray spectrum for $^{62}Ni(n,\gamma)^{63}Ni$

Tomyo et al. ApJ.(2005) Lett.





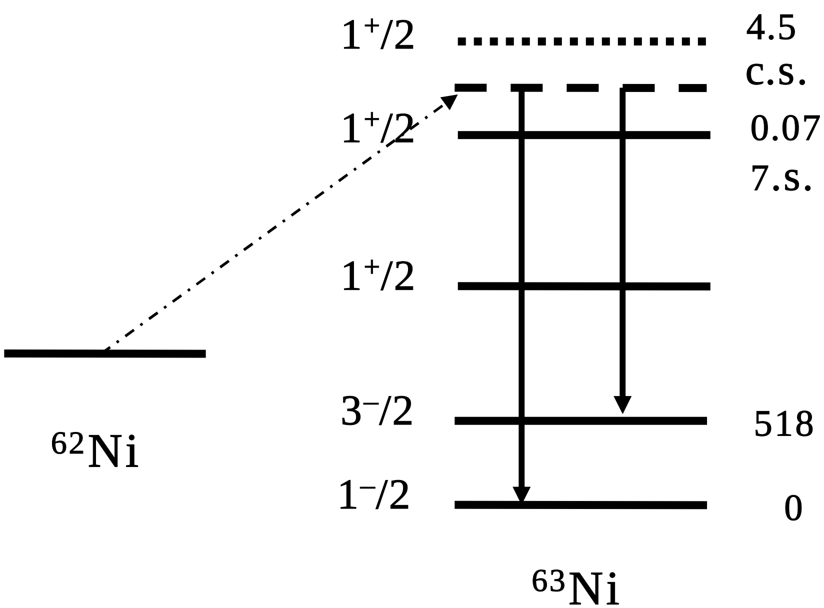
♦ **Characteristic point of the γ-ray spectrum:**

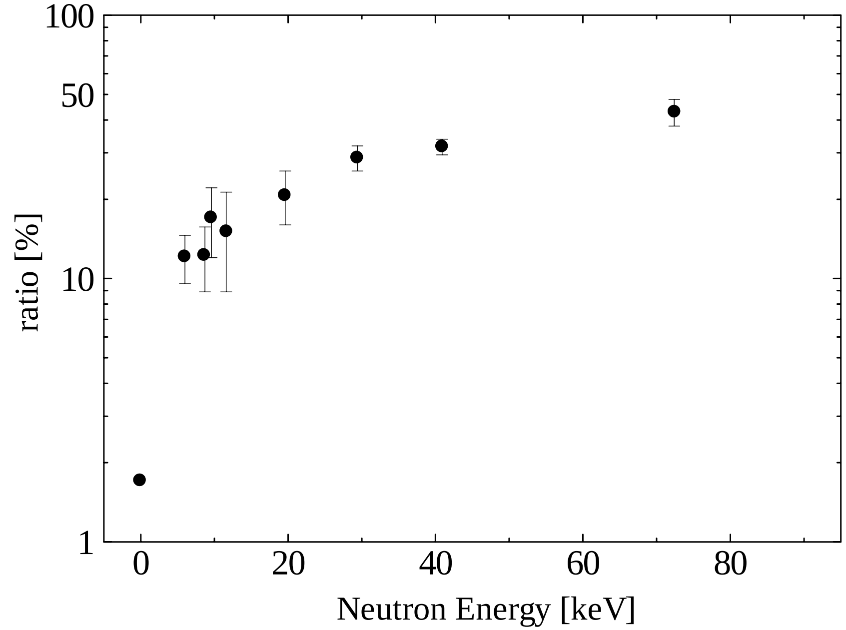
- **Partial cross section for the 6.8 MeV γ-ray from the neutron capture by ^{62}Ni to the ground state: ~ half of the total cross section.**

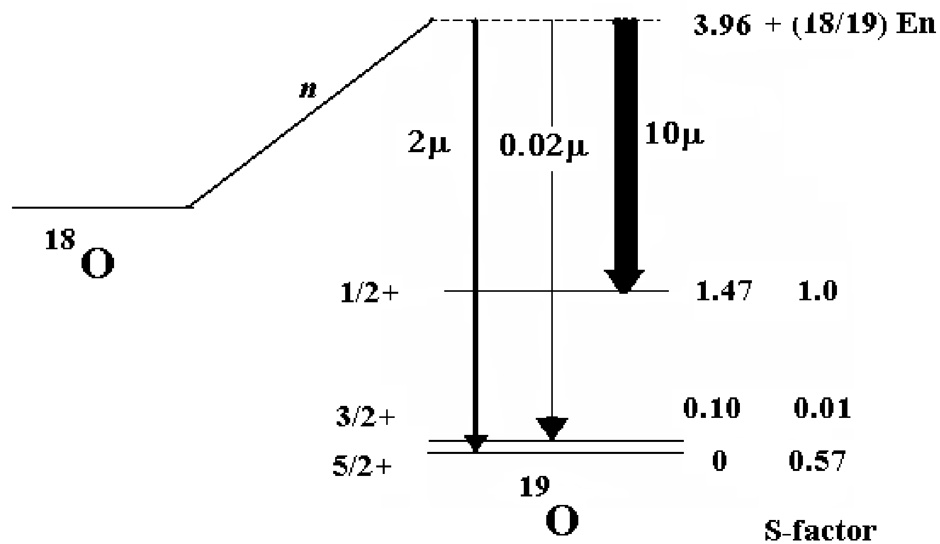
→ reaction proceed a non-resonant s-wave capture

- **Ratio Y_γ(c.s.→3/2-)/Y_γ(c.s.→1/2-) is very small?**

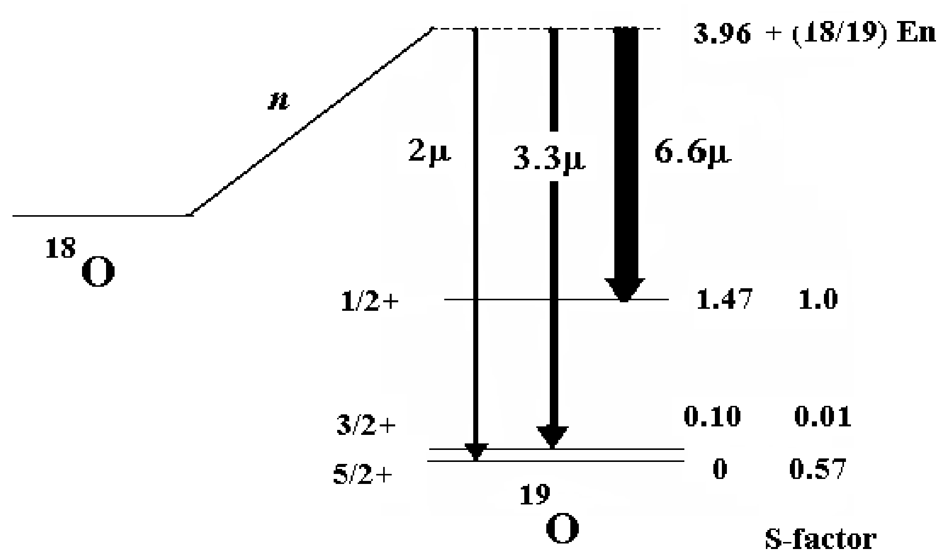
Measured γ-ray branching ratio as a function of *En* : $\dfrac{I\gamma(\text{c.s.} \rightarrow 3/2^-)}{I\gamma(\text{c.s.} \rightarrow 1/2^-)}$







3.96 + (18/19) En
n
2μ
0.02μ
10μ
18O
1/2+
1.47
1.0
3/2+
0.10
0.01
5/2+
0
0.57
19O
S-factor



3.96 + (18/19) En
n
2μ
3.3μ
6.6μ
18O
1/2+
1.47
1.0
3/2+
0.10
0.01
5/2+
0
0.57
19O
S-factor

Summary

1) Method for photonuclear reaction study: developed

→ allow to measure observables with high precision

2) Method for $^{12}C(\alpha,\gamma)^{16}O$ reaction study: developed

→ allow to determine $\sigma(\alpha,\gamma)$ down to $E_{c.m.} \leq 1.0$ MeV

3) Method for (n,γ) reaction study: improve Igashira Gr.

→ allow to measure very small $\sigma(n,\gamma)$ of ~1 μb

4) Method for (n,n') and $(n,n'\gamma)$ reaction study: developed.

→ provide crucial information to calculate $\sigma(n,\gamma)$ for the excited nuclear state in stellar environments

Open New Generation of Nuclear Astrophysics Study

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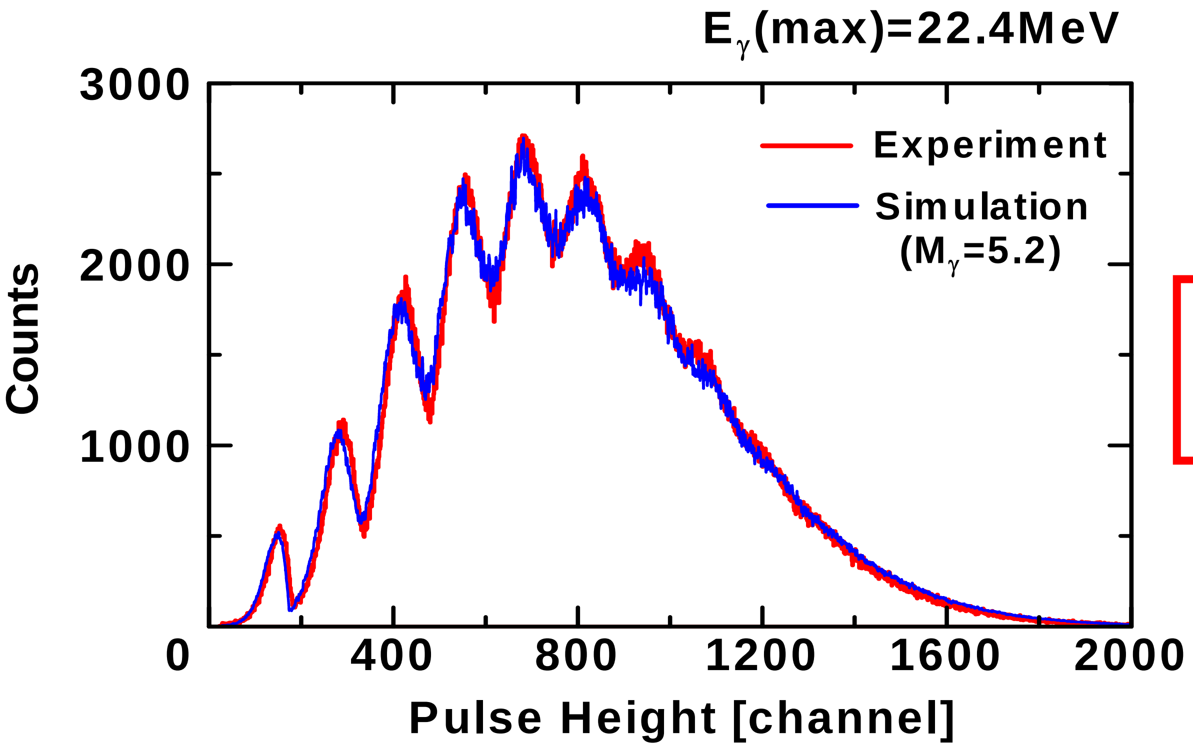
γ-ray Pulse Height & LCS Photon Flux



Average flux ~10^4 /s

⇔ Pulse rate 1~5kHz

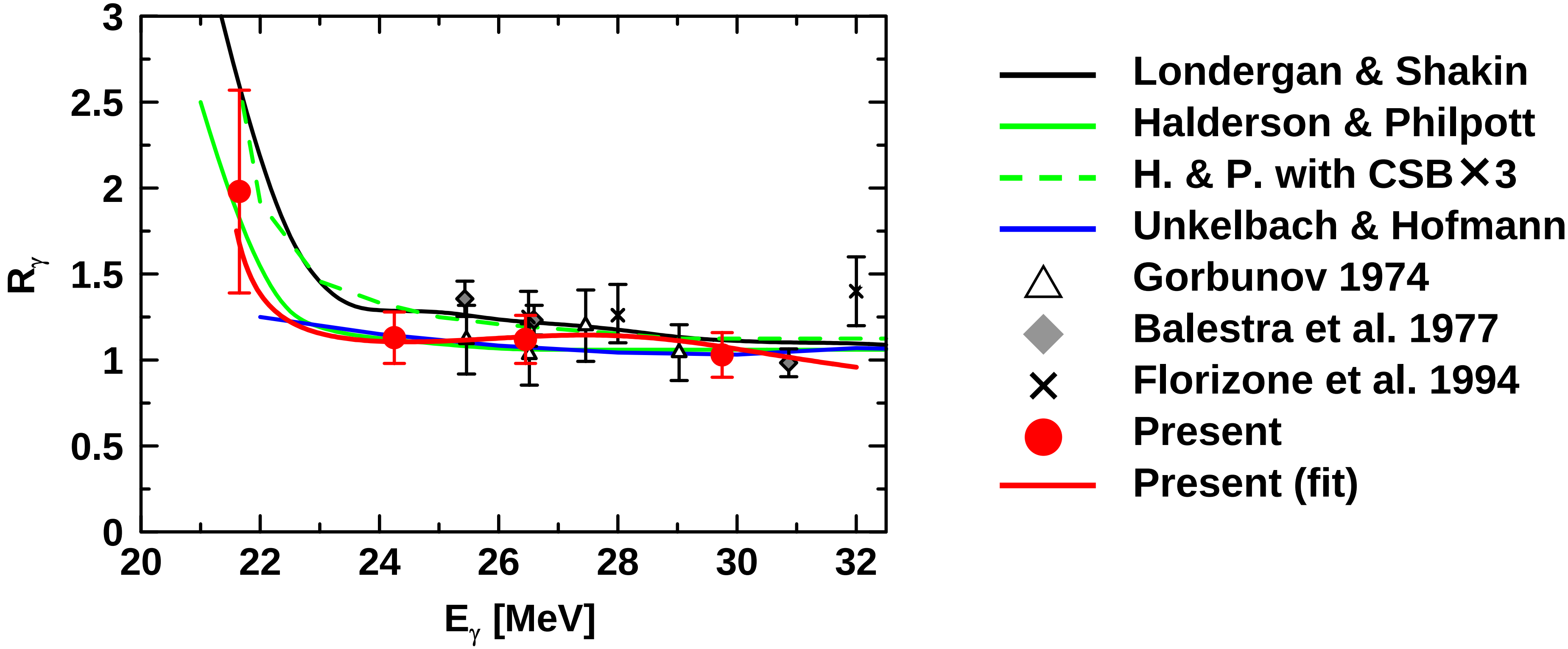
Photon counting by pile-up analysis

LCS Photon Flux $\Phi\gamma$:

$\Phi_\gamma = M_\gamma \times R$. M_γ : photon multiplicity R : laser pulse rate

Charge Symmetry

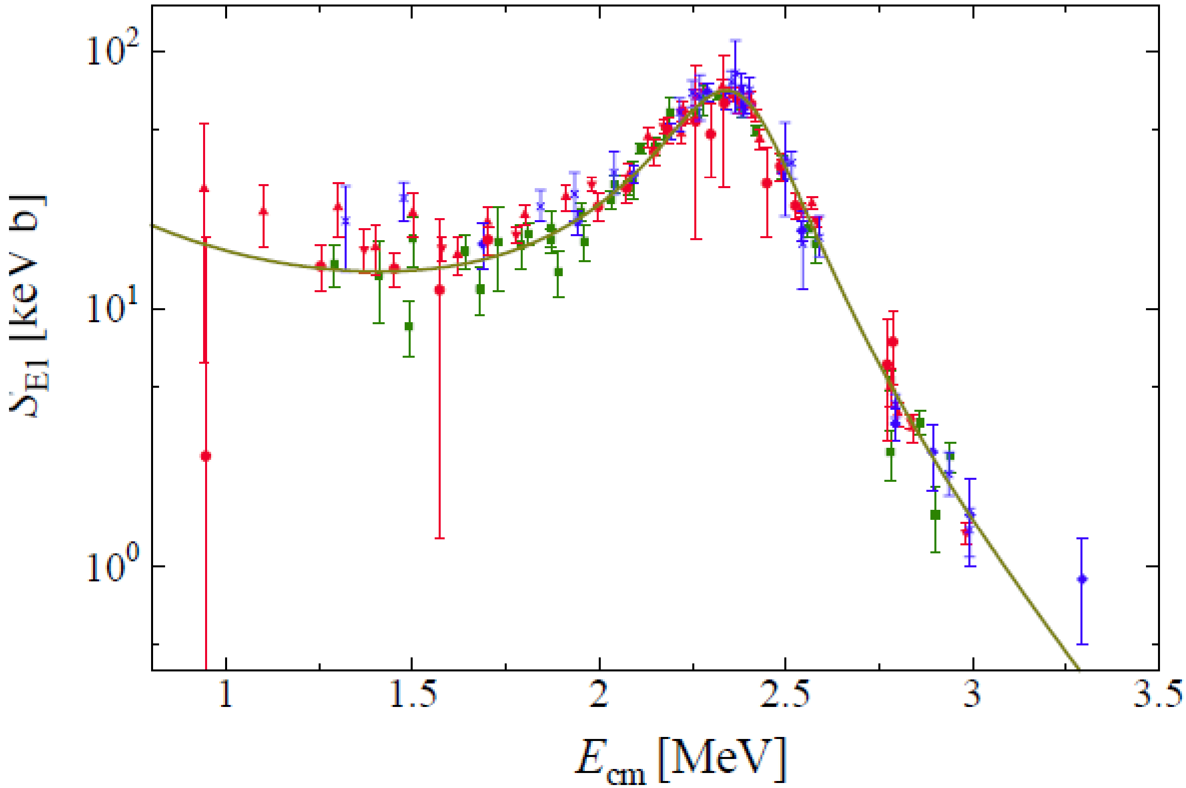
Ratio of two body cross sections, R= σ(γ,p)/σ(γ,n)



- First simultaneous measurement with 4 π geometry
- Consistent with an expected value without CSB.

(1-3) E1 capture cross section

- **γ-ray angular distribution**
- **Observed γ-ray at $\theta_\gamma = 90^\circ$ in far geometry**
- **Observed γ-ray at $\theta_\gamma = 90^\circ$ in closed geometry and correct for E2 contribution**



Astrophysical S-factor

$$\sigma(E) = \frac{S(E)}{E}\exp(-2\pi\eta)$$

Solid line: R-matrix

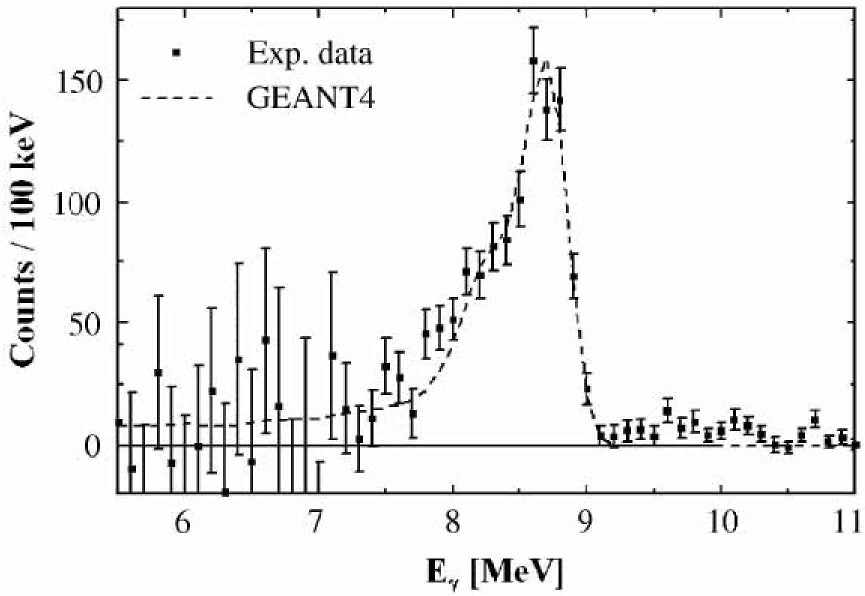


Fig. 13. Net γ-ray energy spectrum of the $^{12}C(\alpha,\gamma)^{16}O$ reaction in the energy range from 5.5 to 11 MeV. Here, the calculated spectrum is shown as a dotted line.

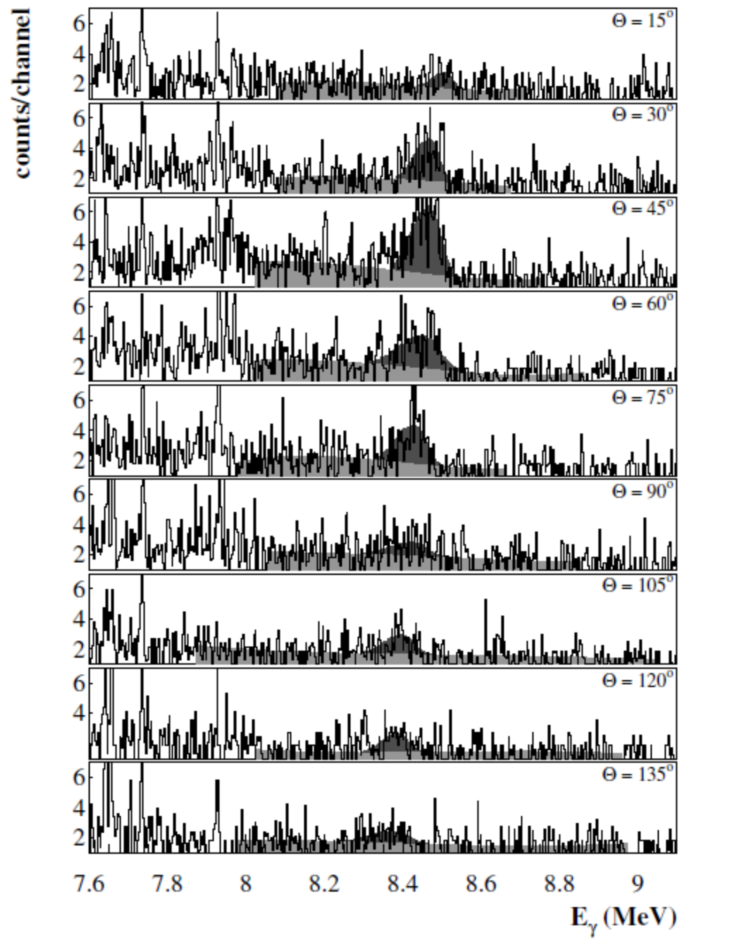


FIG. 2. High energy part of the γ spectra measured at $E_{\rm cm}$ = 1.254 MeV and angular positions between Θ = 15°−135°. The relevant peak (γ_0) is located at about 8.4 MeV and is marked by the dark area. The corresponding background is marked as grey area. The He^+ currents were about 400 μA and the measuring time was altogether 150 h.

Kunz et al., Phys. Rev. Lett. (2001)

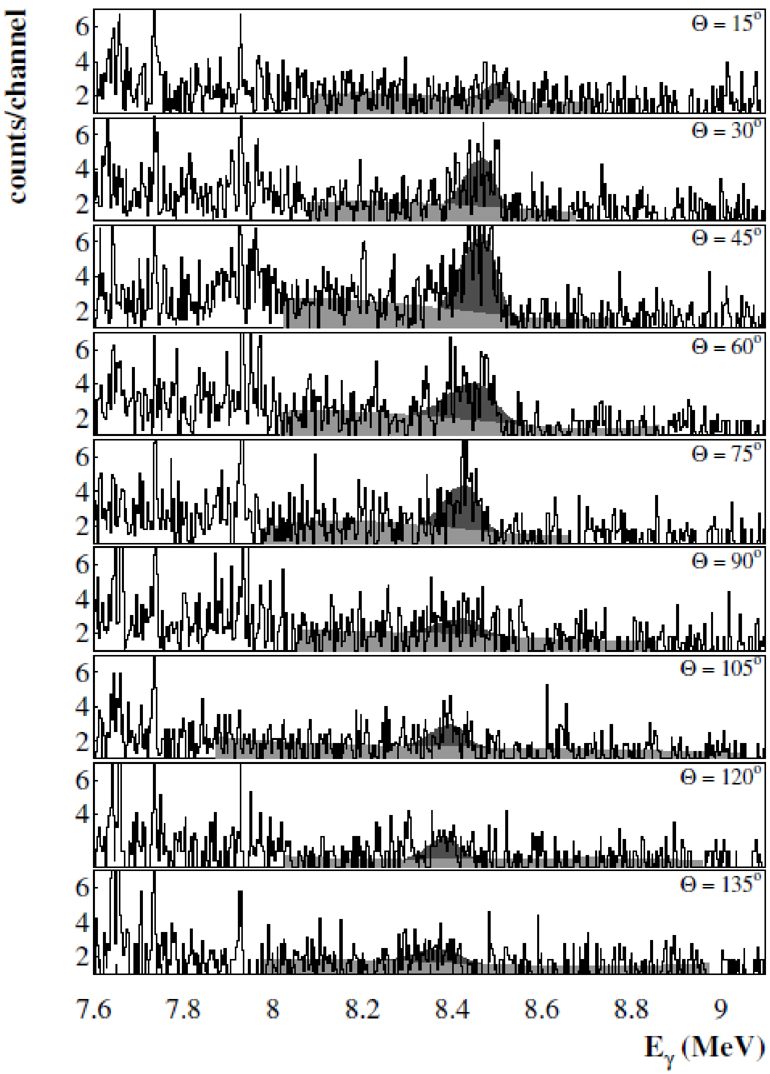


FIG. 2. High energy part of the γ spectra measured at E_{cm} = 1.254 MeV and angular positions between $\Theta = 15°-135°$. The relevant peak (γ_0) is located at about 8.4 MeV and is marked by the dark area. The corresponding background is marked as grey area. The He^+ currents were about 400 μA and the measuring time was altogether 150 h.

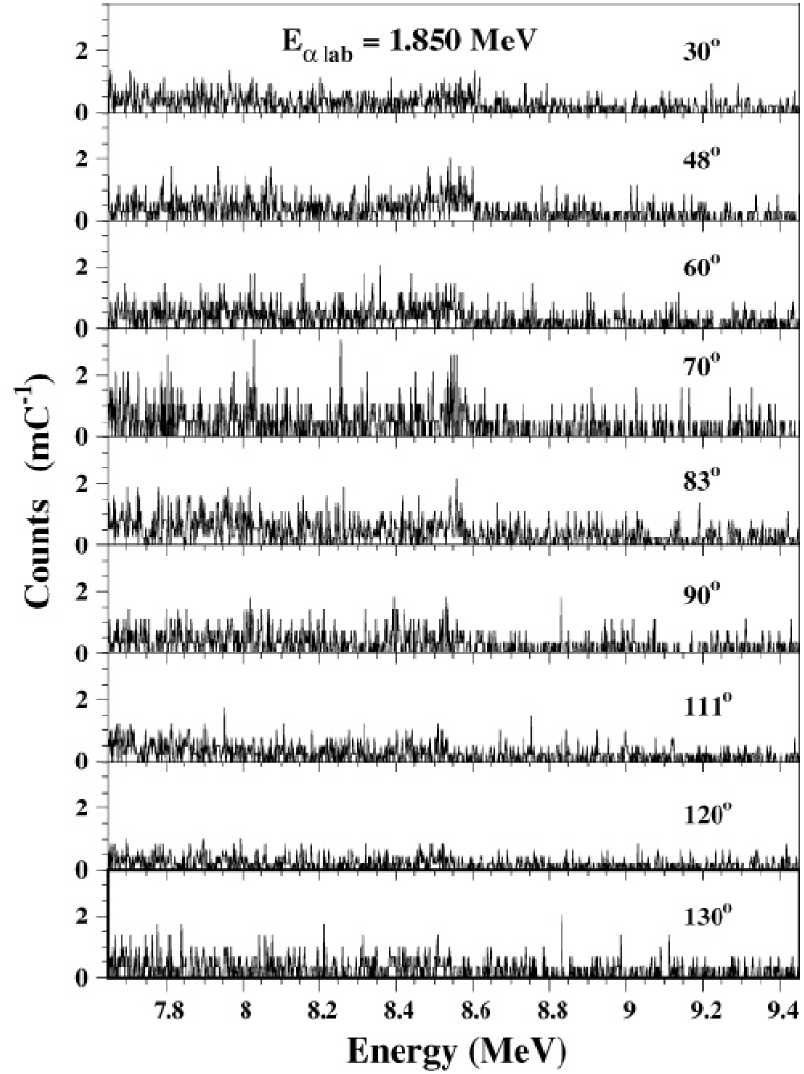


FIG. 6. γ-ray spectra of the $^{12}C(\alpha,\gamma)^{16}O$ reaction for $E_{\alpha,lab}$ = 1.850 MeV ($E_{c.m.\,eff.}$ = 1.305 MeV), the lowest beam energy of this experiment in the angular range $30°-130°$ measured with the nine EUROGAM detectors. Full energy γ peak is around 8.56 MeV.

Assuncao et al. Phys. Rev. C (2006)