# レーザーコンプトン散乱ガンマ線が拓く原子核・宇宙核物理
# Laser Compton-scattered gamma rays for nuclear physics and astrophysics

日本物理学会　2020年秋季大会　熊本大学

9月17日　SJ会場　13:30 – 17:15

実験核物理領域、理論核物理領域、宇宙線・宇宙物理領域

シンポジウム　軽中重核の電弱励起・崩壊と宇宙物理

## Outline

1. IAEA Photonuclear Data Project
2. Laser Compton-scattering $\gamma$-ray Beam
3. Direct Neutron-multiplicity Sorting Method
4. New Photonuclear Data
5. New Facilities
6. Future Prospect

# PHOENIX Collaboration for IAEA-CRP

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I. Gheorghe, D.M. Filipescu (IFIN-HH)
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H. Wang, G. Fan (SINAP)
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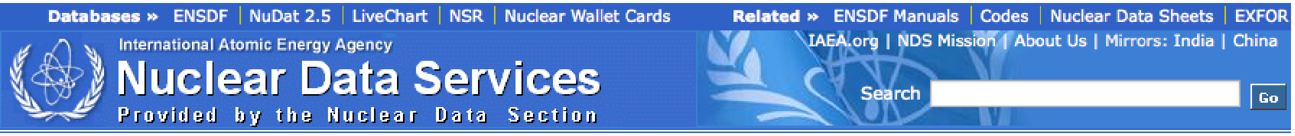
M. Krzysiek (Krakow)
Y.-W. Lui (Texas A&M)
S. Miyamoto (U. Hyogo)




# IAEA Photonuclear Data Project

IAEA-CRP(Coordinated Research Project), Code F41032, 2016-2020

## Reference database for photon strength functions

S. Goriely, P. Dimitriou, M. Wiedeking, T. Belgya, R. Firestone, J. Kopecky, M. Krtička, V. Plujko, R. Schwengner, S. Siem, H. Utsunomiya, S. Hilaire, S. Péru, Y. S. Cho, D. M. Filipescu, N. Iwamoto, T. Kawano, V. Varlamov & R. Xu

*The European Physical Journal A* volume 55, Article number: 172 (2019)

https://www-nds.iaea.org/photonuclear/

## IAEA Photonuclear Data Library 2019

T. Kawano, Y.S. Cho, P. Dimitriou, D. Filipescu, N. Iwamoto, V. Plujko, X. Tao, H. Utsunomiya, V. Varlamov, R. Xu, R. Capote, I. Gheorghe, O. Gorbachenko, Y.L. Jin, T. Renstrøm, M. Sin, K. Stopani, Y. Tian, G.M. Tveten, J.M. Wang, T. Belgya, R. Firestone, S. Goriely, J. Kopecky, M. Krtička, R. Schwengner, S. Siem, M. Wiedeking

Nuclear Data Sheets Volume 163, January 2020, Pages 109-162

https://www-nds.iaea.org/photonuclear/

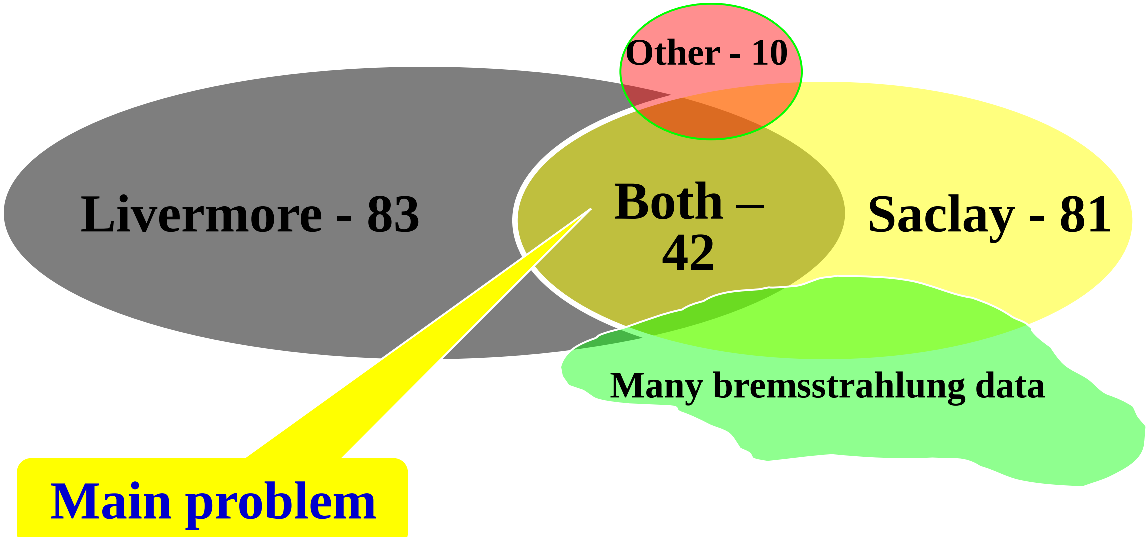
# Partial GDR Cross Section Measurements

The ultimate goal is to resolve the long-standing discrepancy between the Livermore and Saclay data of (γ,xn) cross sections.

The majority of experimental data for partial photonuclear reaction cross sections were obtained at Livermore (USA) and Saclay (France)

**Atlas of Photoneutron cross sections obtained with monoenergetic photons (S.S.Dietrich, B.L.Berman. Atom. Data and Nucl. Data Tables, 38 (1988) 199)**

Berman's library - EXFOR entries L0001 – L0059 (~ 174 data sets)

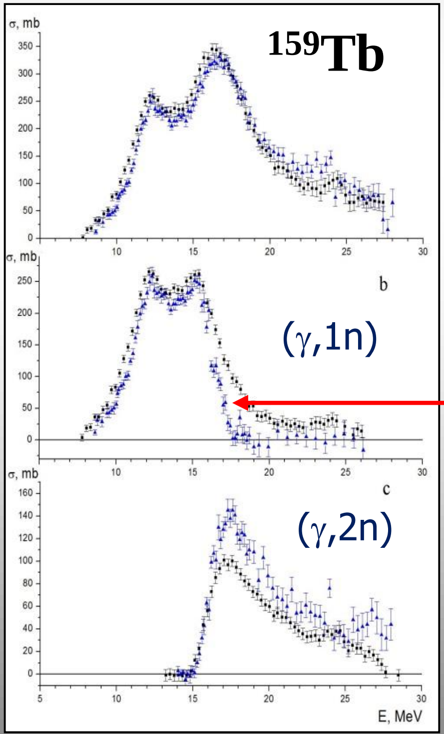



Courtesy of Varlamov

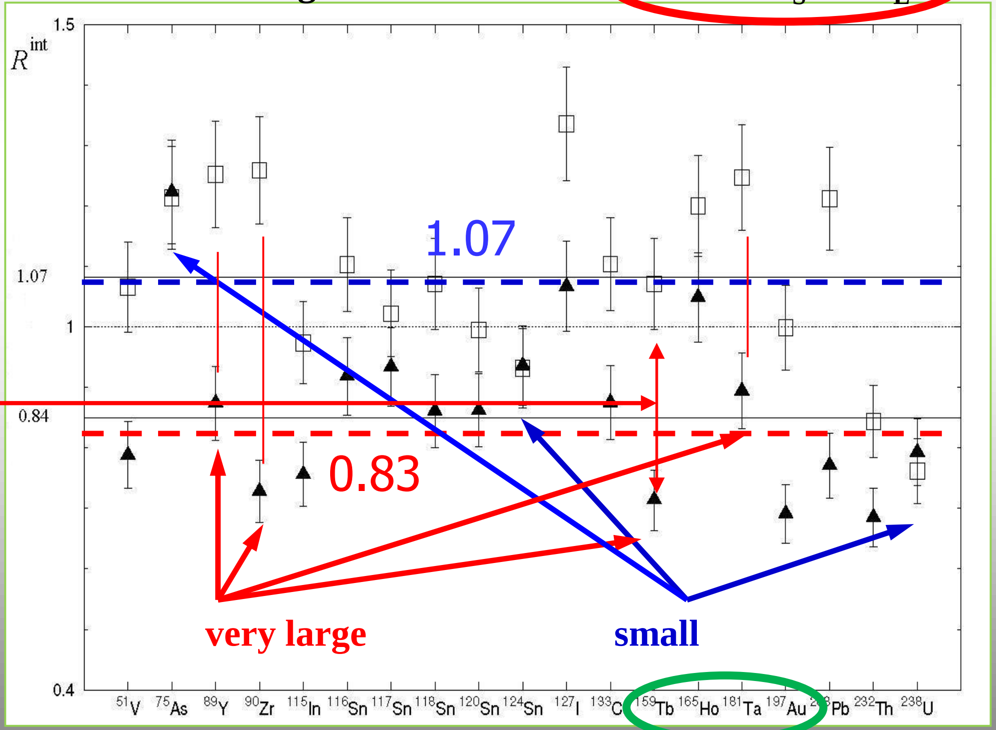
Courtesy of Varlamov

**Main problem for 19 nuclei investigated in both Labs:**
**(γ, 1n) cross sections are larger at Saclay but those for (γ, 2n) - at Livermore.**

**V.V.Varlamov, N.N.Peskov, D.S.Rudenko, M.E.Stepanov. Consistent Evaluation of Photoneutron Reaction Cross Sections Using Data Obtained in Experiments with Quasimonoenergetic Annihilation Photon Beams at Livermore (USA) and Saclay (France). INDC(CCP)-440, IAEA NDS, Vienna, Austria, 2004, p. 37.**




**Ratios of integrated cross sections $R^{int} = \sigma^{int}_S / \sigma^{int}_L$**




**Squares - □ - ratios for (γ, 1n) reactions – are larger than 1.0:**

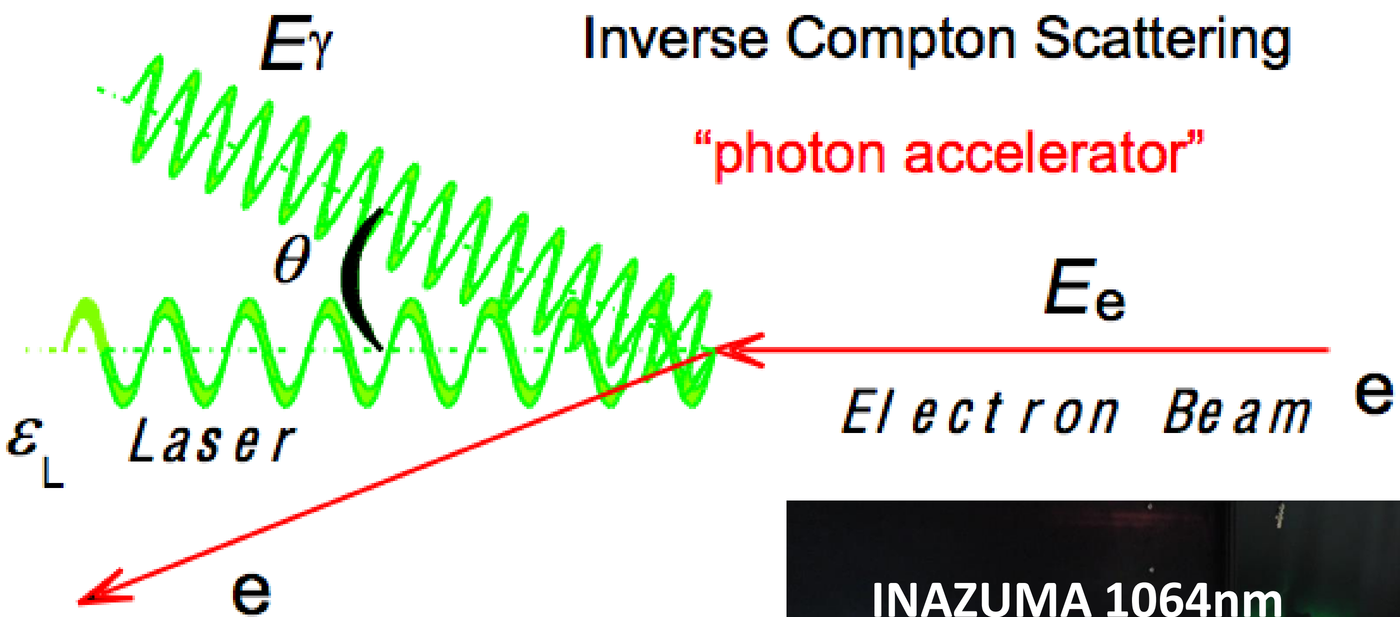
**<R> ~ 1.07.**

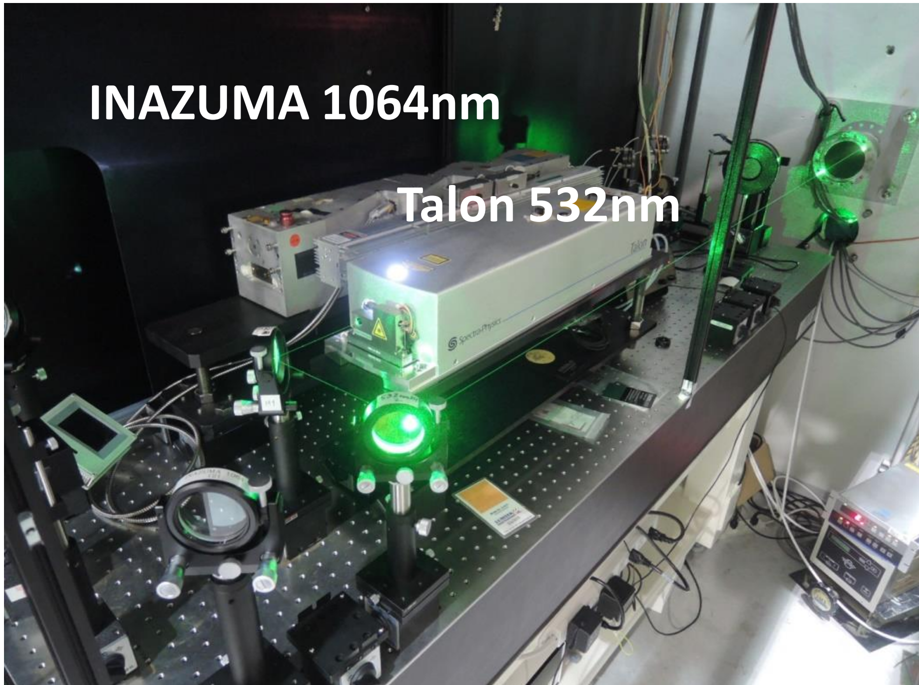
**Triangles - ▲ - ratios for (γ, 2n) reactions – are smaller than 1.0:**

**<R> ~ 0.83.**


SPring8
SACLA
1 GeV e- Linac
NewSUBARU
MeV γ

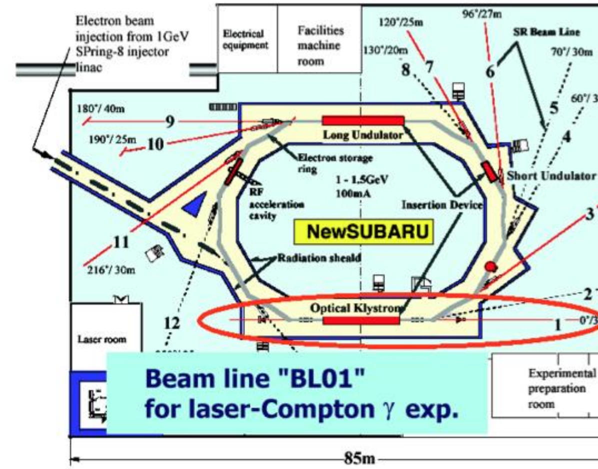
# Laser Compton scattering

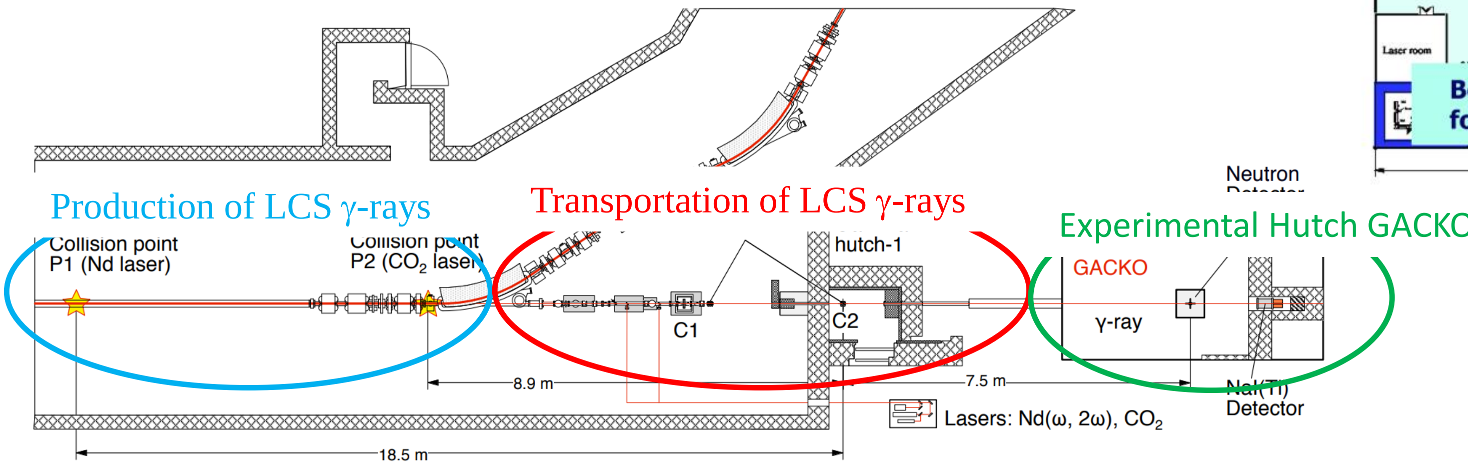


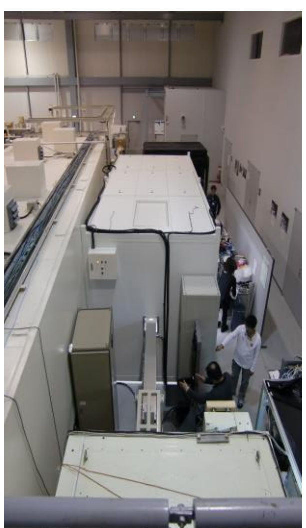

$E_e = 0.5 – 1.5$ GeV
$E_\gamma = 1 – 76$ MeV

# NewSUBARU γ-ray beamline




GACKO
(Gamma collaboration hutch of Konan University)

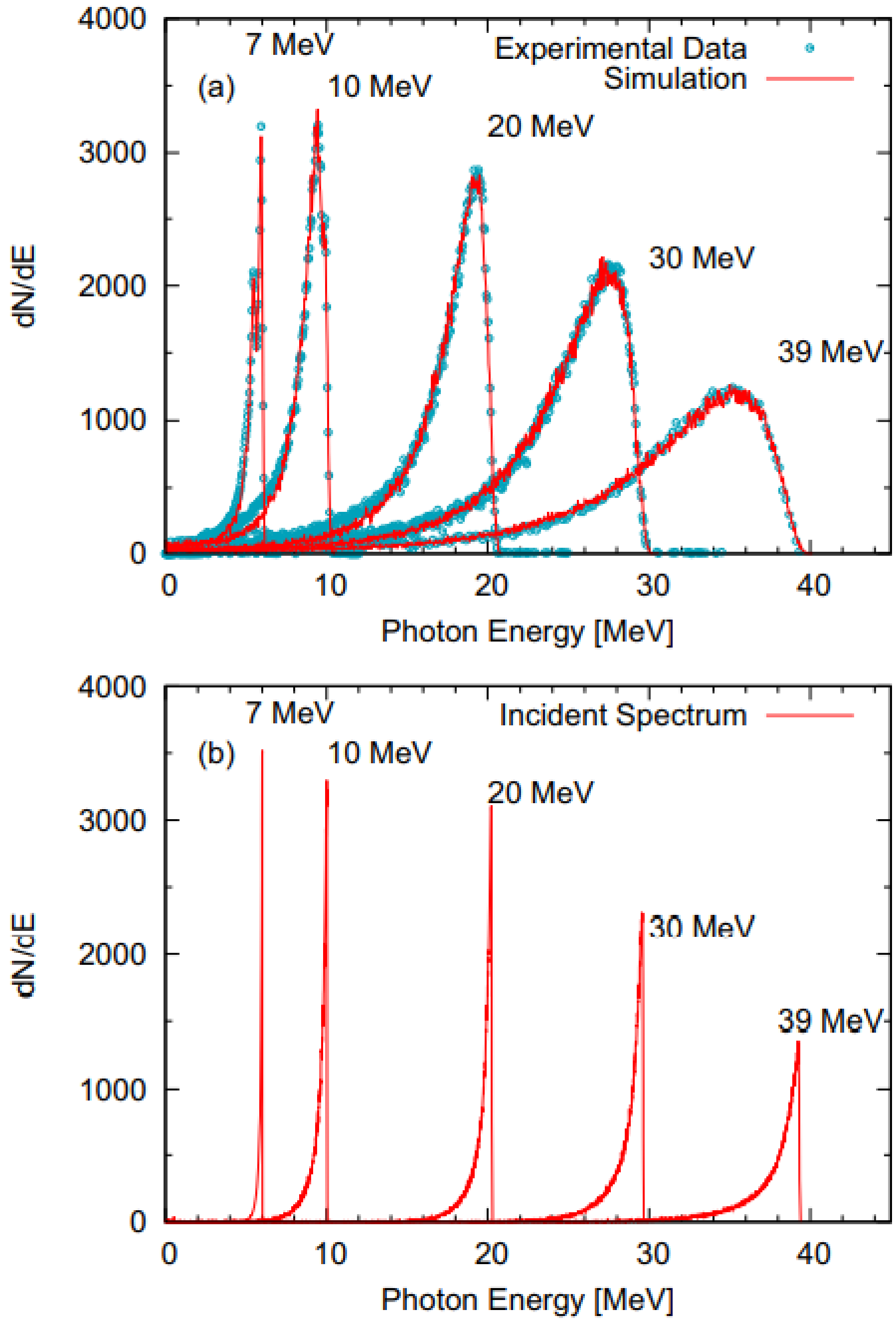



$N_\gamma \sim 10^5$ cps
C1:3mm$^\phi$
C2:2mm$^\phi$

# Energy Spread

Energy Profile Monitor
3.5” x 4.0” LaBr3(Ce)

ΔE/E ~ 1 - 3%



# Energy calibration of electron beams

H. Utsunomiya et al., IEEE Transactions on Nuclear Science, 61, 1252 (2014)

$\Delta E/E = (5.5 - 9.4) \times 10^{-5}$

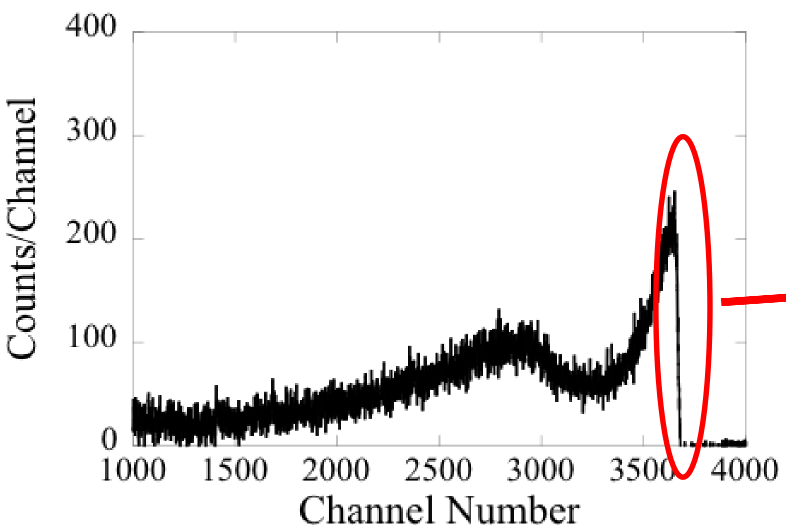
Best fit: $E_e$=860.72 MeV

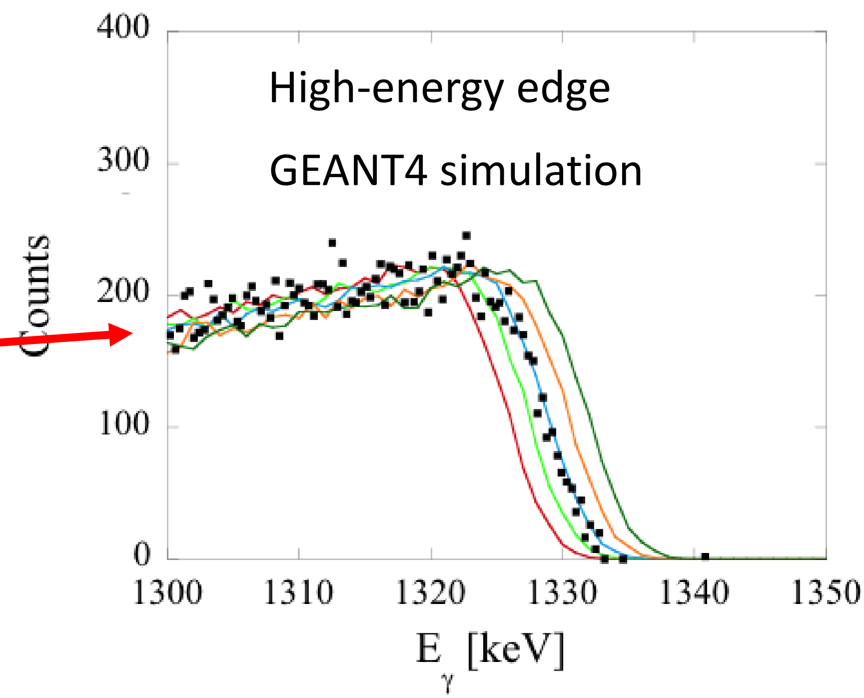
$E_e$ dependence:

$E_e$=860.72 ± 0.50 MeV

$E_e$=860.72 ± 1.00 MeV

Response function of a Ge detector



# Flux Calibration of Pulse $\gamma$-ray Beams

H. Utsunomiya et al., NIM A 896, 103 (2018)

Pile-up method/Poisson-fitting method

H. Toyokawa et al., IEEE Trans. Nucl. Sci. 47 (2000)

T. Kii et al., Proc. 12th Sym. Acc. Sci. and Tech., ICRP (RIKEN) 1999

T. Kondo et al., NIM A 659 (2011)

## Flux Monitor

8.0” x 12.0” NaI(Tl)

100% efficiency

Methodologically

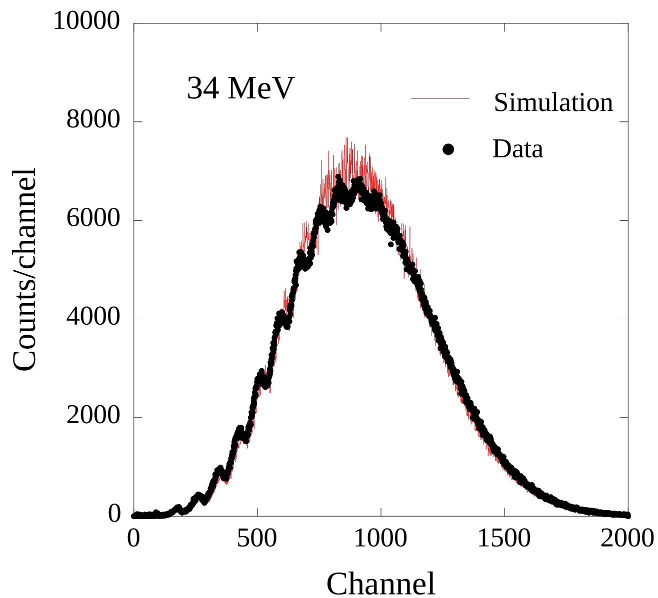
$\Delta N_\gamma / N_\gamma < 0.1\%$

Experimentally

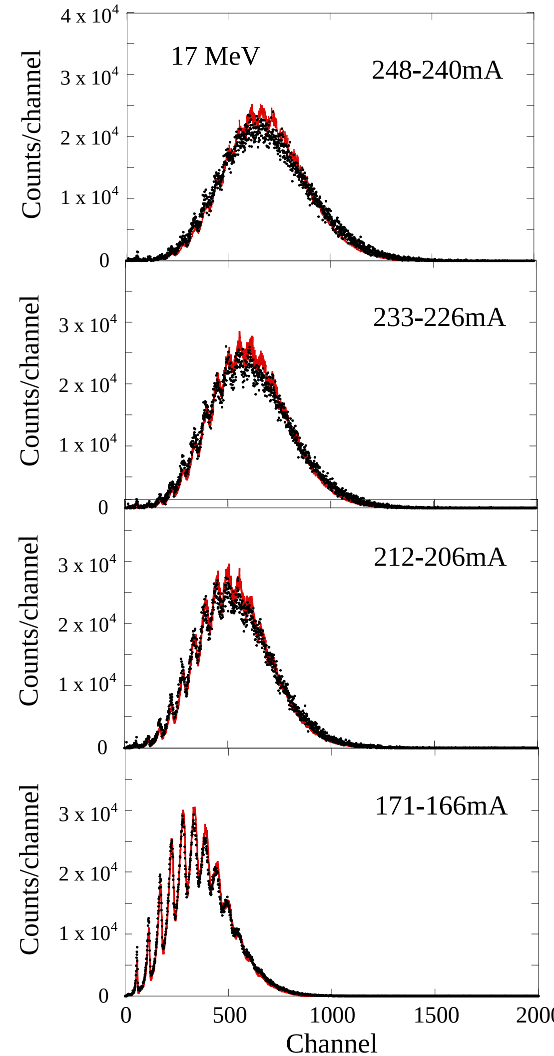
$\Delta N_\gamma / N_\gamma \sim 1\text{–}3\ \%$

## Multi-photon Spectra

Top-up



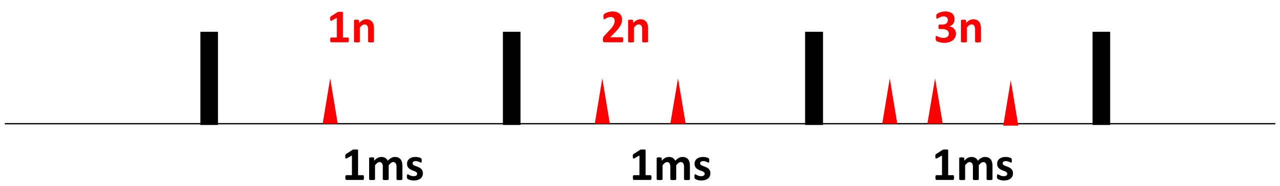

Time variation



# Direct Neutron-multiplicity Sorting Method

H. Utsunomiya *et al.*, NIM A **871**, 135 (2017)

## $\gamma$-ray beam at 1 kHz




Experimental Observable $N_i$: *i*-fold events i=1,2,3,4

Number of Reactions $R_j$: $(\gamma, jn)$ *j=1,2,3,4*

Cross sections $R_j = N_\gamma N_t \boldsymbol{\sigma_j}(\gamma, jn)$

**N=FR** $N_i = \sum_{j=i}^{4} F_{ij} R_j$ $\boldsymbol{F_{ij} = {}_jC_i \varepsilon^i (1-\varepsilon)^{j-i}}$

**N, R: vector**

**F: 4 x 4 matrix**

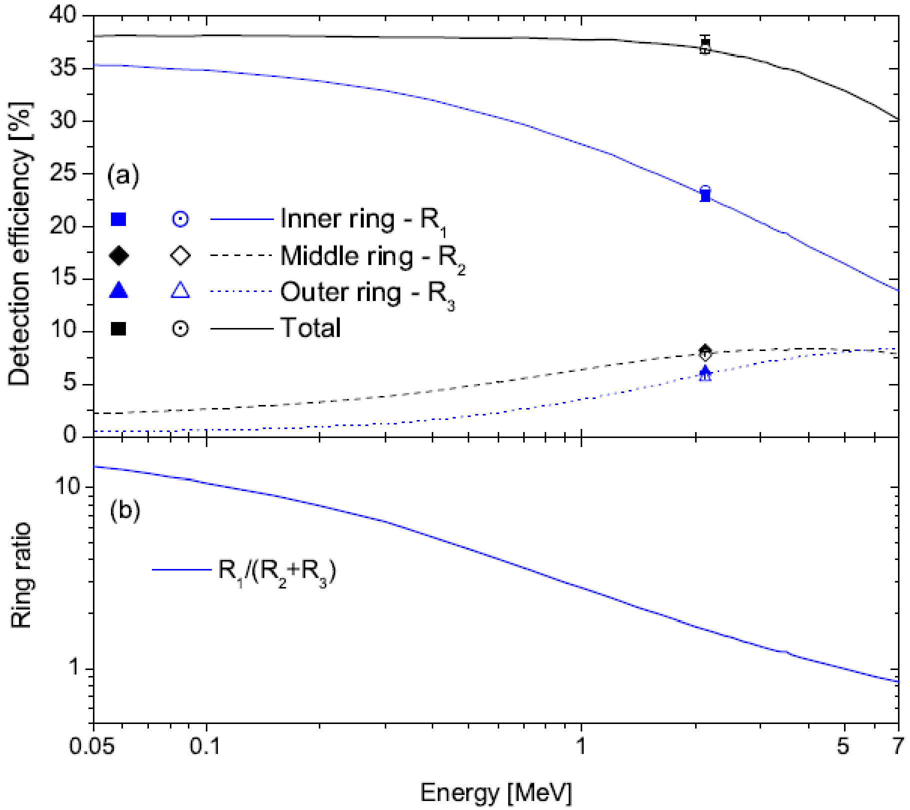
$\varepsilon$ : neutron detection efficiency

$$N_1 = R_1\ {}_1C_1\varepsilon + R_2\ {}_2C_1\varepsilon(1-\varepsilon) + R_3\ {}_3C_1\varepsilon(1-\varepsilon)^2 + R_4\ {}_4C_1\varepsilon(1-\varepsilon)^3$$

**$\mathbf{R=F^{-1}N}$**

# Flat efficiency neutron detector

H. Utsunomiya *et al.*, NIM A **871**, 135 (2017)




| Configuration | $^3$He counters | Distance [cm] |
|---|---|---|
| Ring 1 | 4 | 5.5 |
| Ring 2 | 9 | 13.0 |
| Ring 3 | 18 | 16.0 |
| Total | 31 | |

Flat efficiency: $\boldsymbol{\varepsilon}$=36.5 (1.6) %

<u>(γ,n) neutrons:</u>

38.0 - 35.7 % over 0 - 3 MeV

38.0 - 32.9 % over 0 - 5 MeV

<u>(γ,2n) neutrons:</u>

Both neutrons detected:

$\varepsilon^2 = 16\%$

Only one neutron detected:

$\varepsilon(1-\varepsilon) = 24\%$

<u>(γ,3n) neutrons:</u>

3 neutrons detected:

$\varepsilon^3 = 6.4\%$

2 neutron detected:

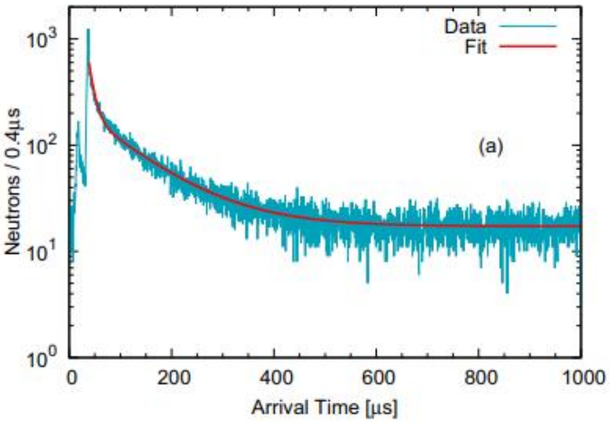
$\varepsilon^2(1-\varepsilon) = 9.6\%$

Only one neutron detected:

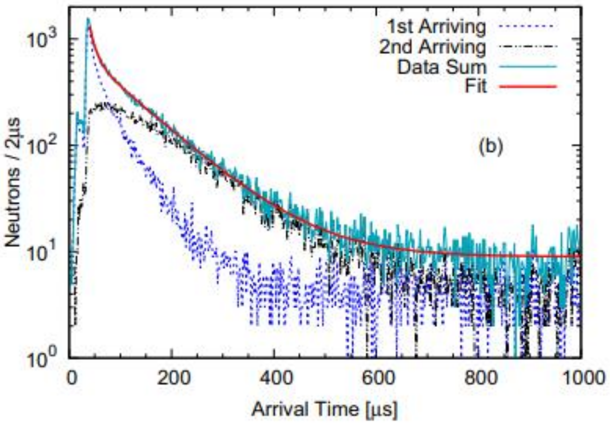
$\varepsilon(1-\varepsilon)^2 = 14.4\%$

# Neutron Time Distribution

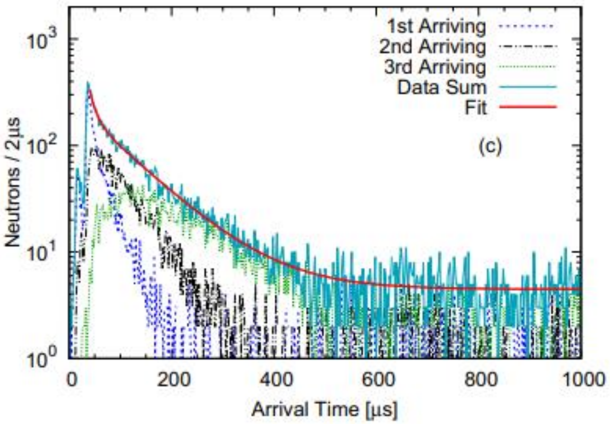
1-fold events




2-fold events




3-fold events



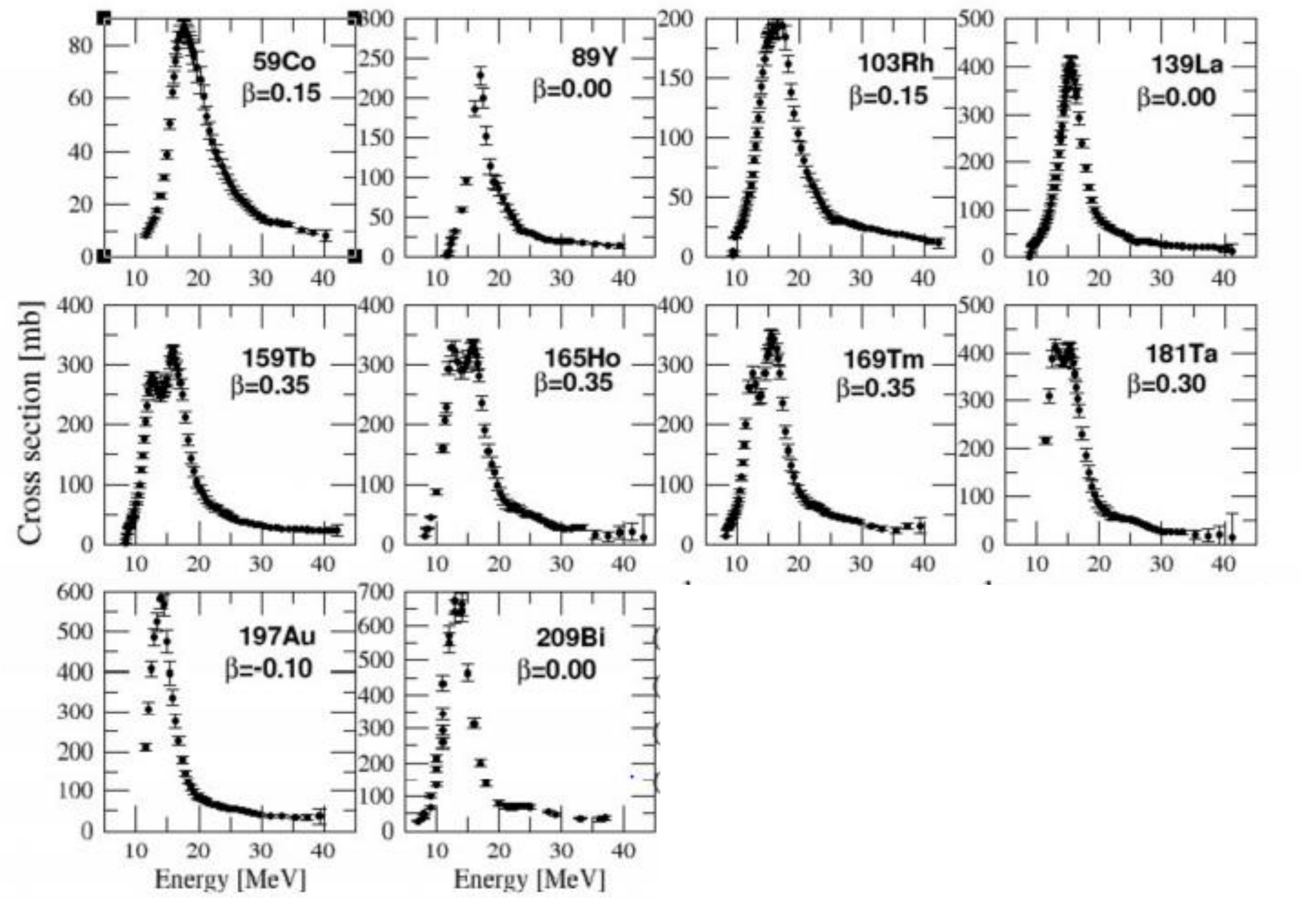
# Total Cross Sections

<u>IAEA-CRP</u>

PHOENIX Collaboration (IFIN-HH/ELI-NP, Moscow, Shanghai, Oslo)

New Data for 11 nuclei

9Be, 59Co, 89Y, 103Rh, 139La, 159Tb, 165Ho, 169Tm, 181Ta, 197Au, 209Bi

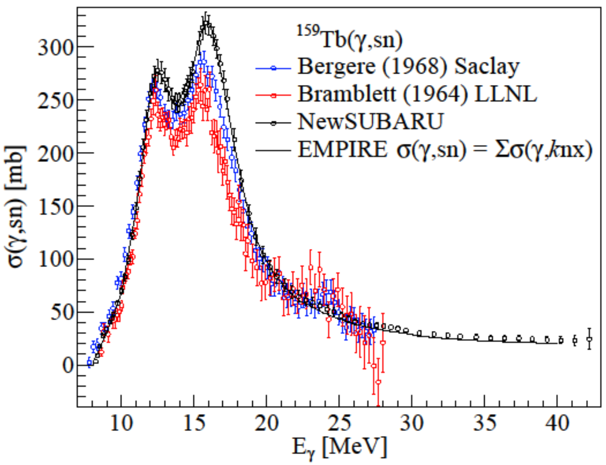


IAEA-CRP F41032

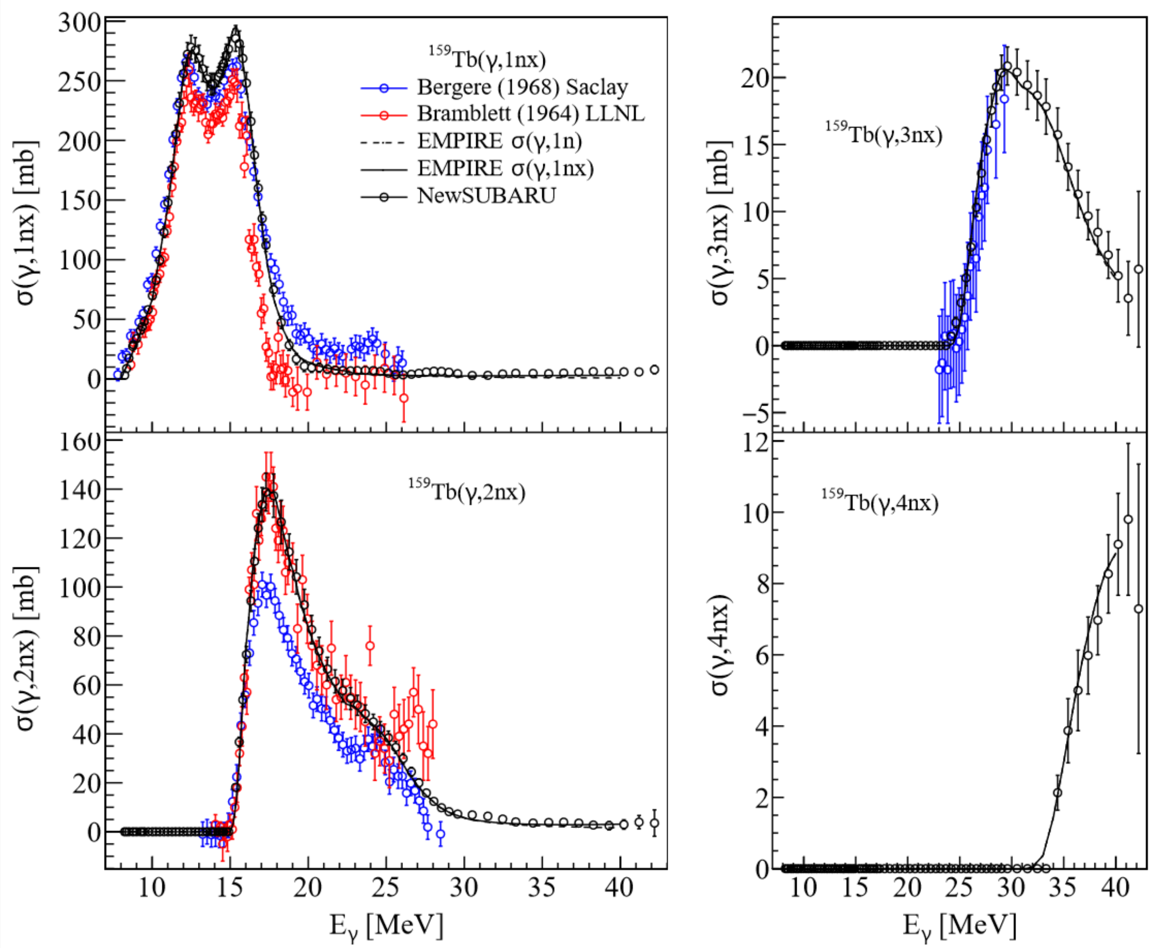
# 159Tb

IAEA-CRP Data
Evaluation: EMPIRE

Total cross sections: $\sum_i \sigma(\gamma, inx)$



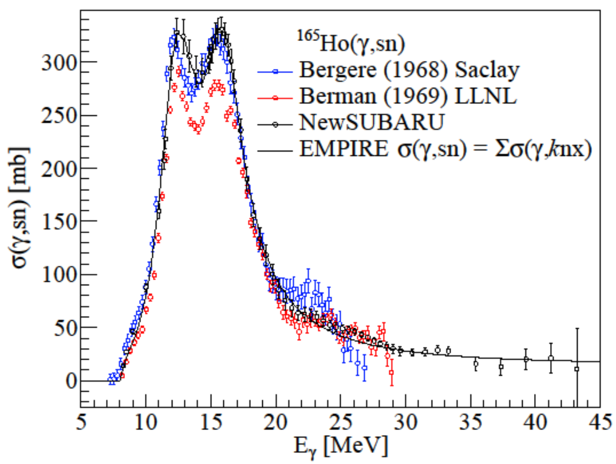

Partial cross sections: $\sigma(\gamma, inx)$



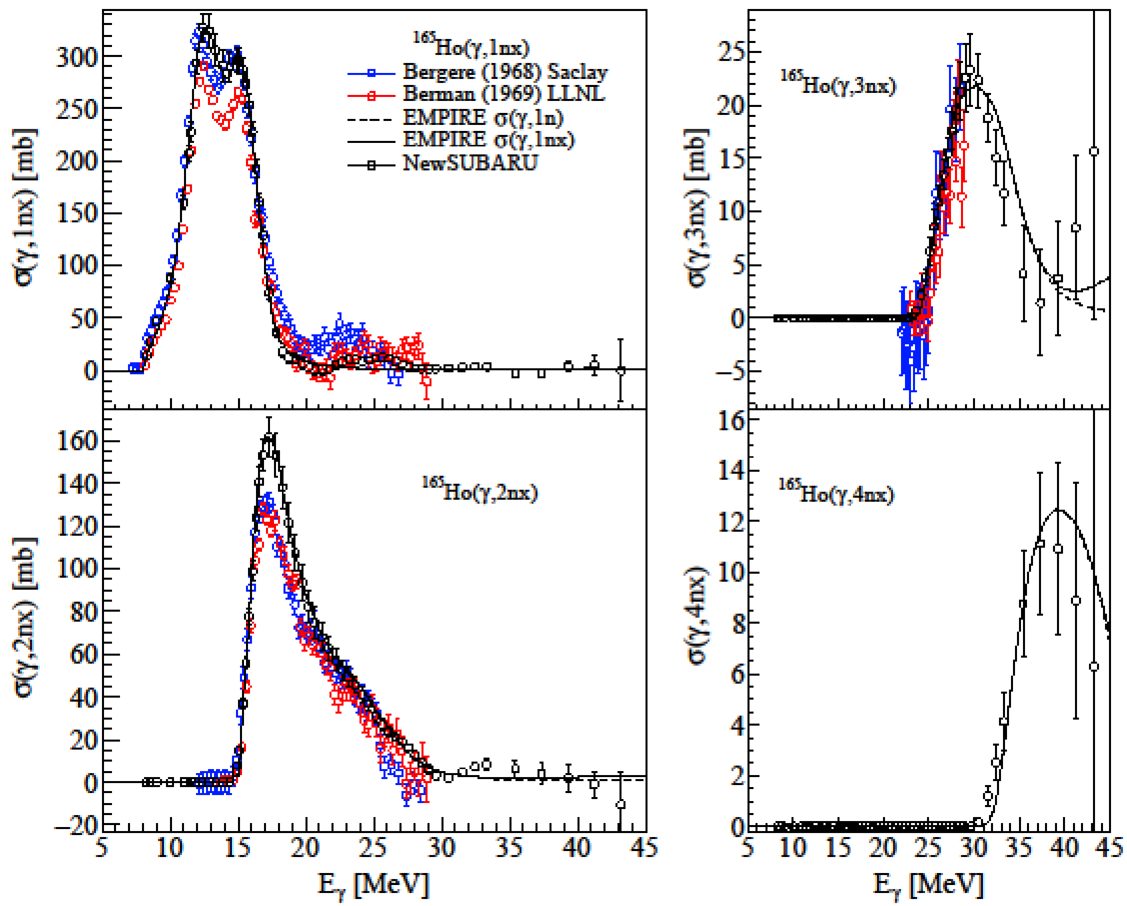
# 165Ho

IAEA-CRP Data
Evaluation: EMPIRE

Total cross sections: $\sum_i \sigma(\gamma, inx)$



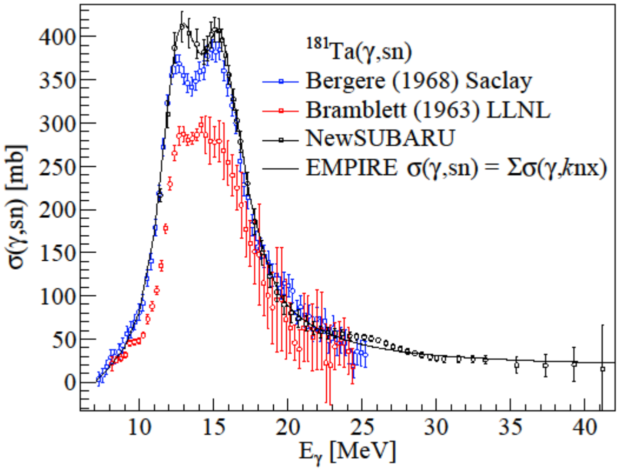

Partial cross sections: $\sigma(\gamma, inx)$



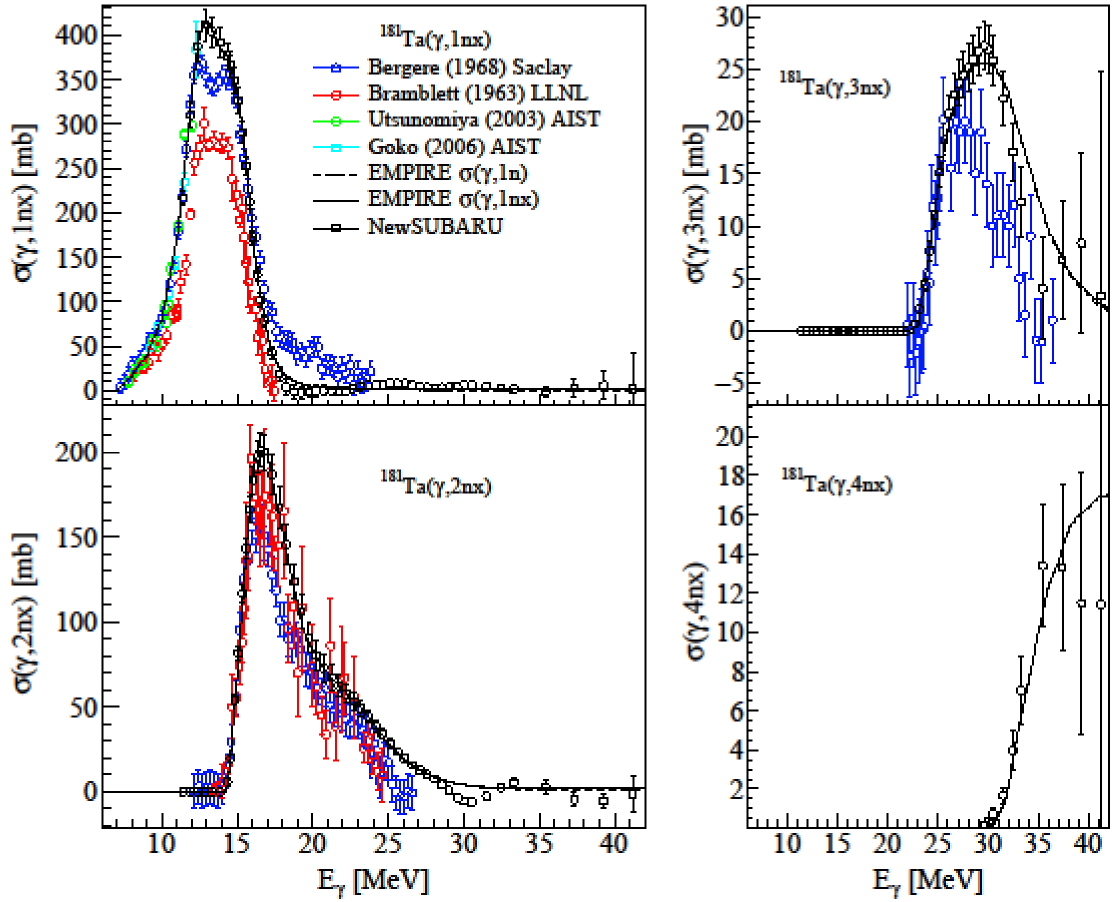
# 181Ta

IAEA-CRP Data
Evaluation: EMPIRE

Total cross sections: $\sum_i \sigma(\gamma, inx)$




Partial cross sections: $\sigma(\gamma, inx)$

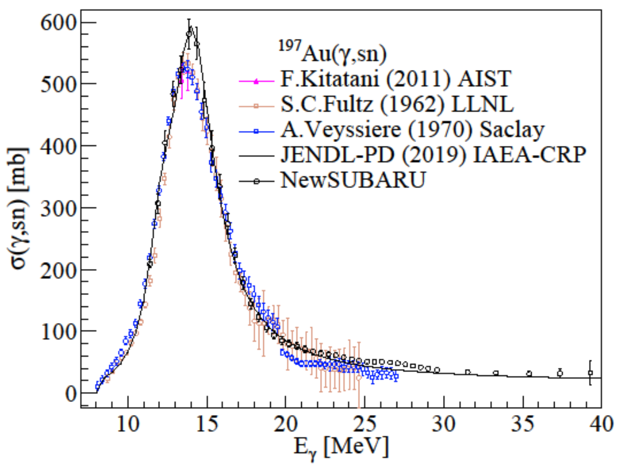


IAEA-CRP F41032

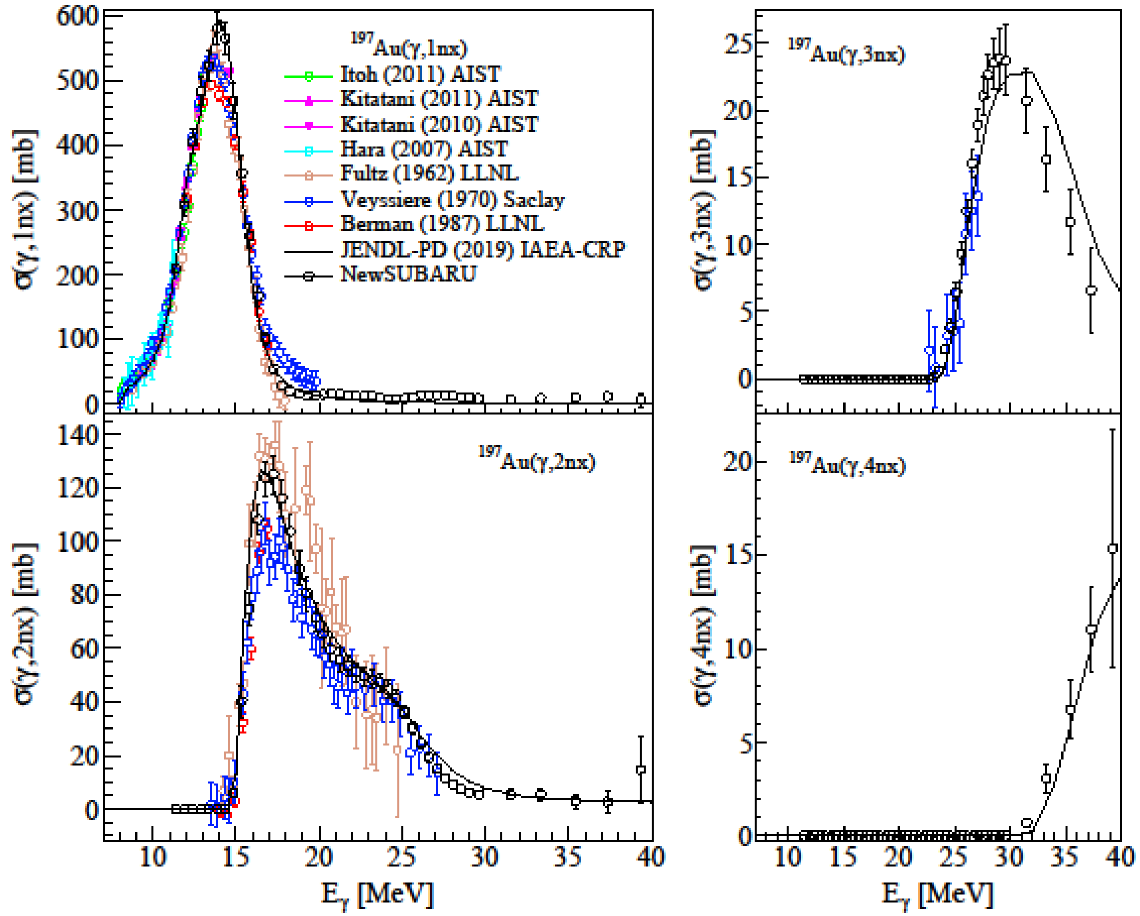
# 197Au

IAEA-CRP Data
Evaluation: JENDL-PD, CCONE

Total cross sections: $\sum_i \sigma(\gamma, inx)$




Partial cross sections: $\sigma(\gamma, inx)$

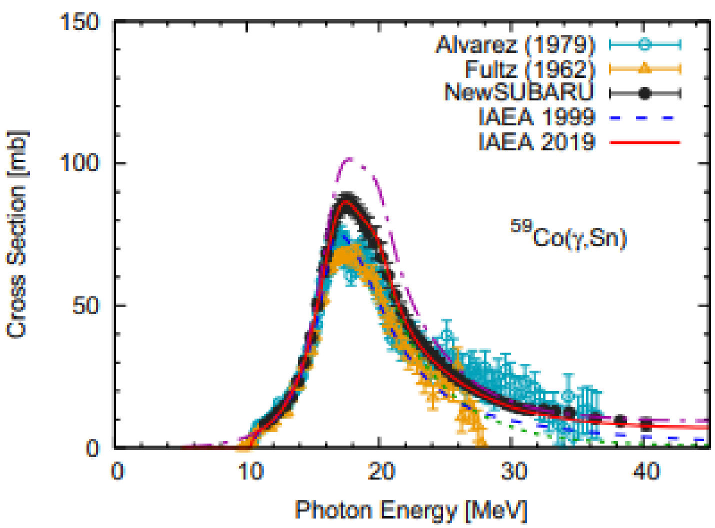


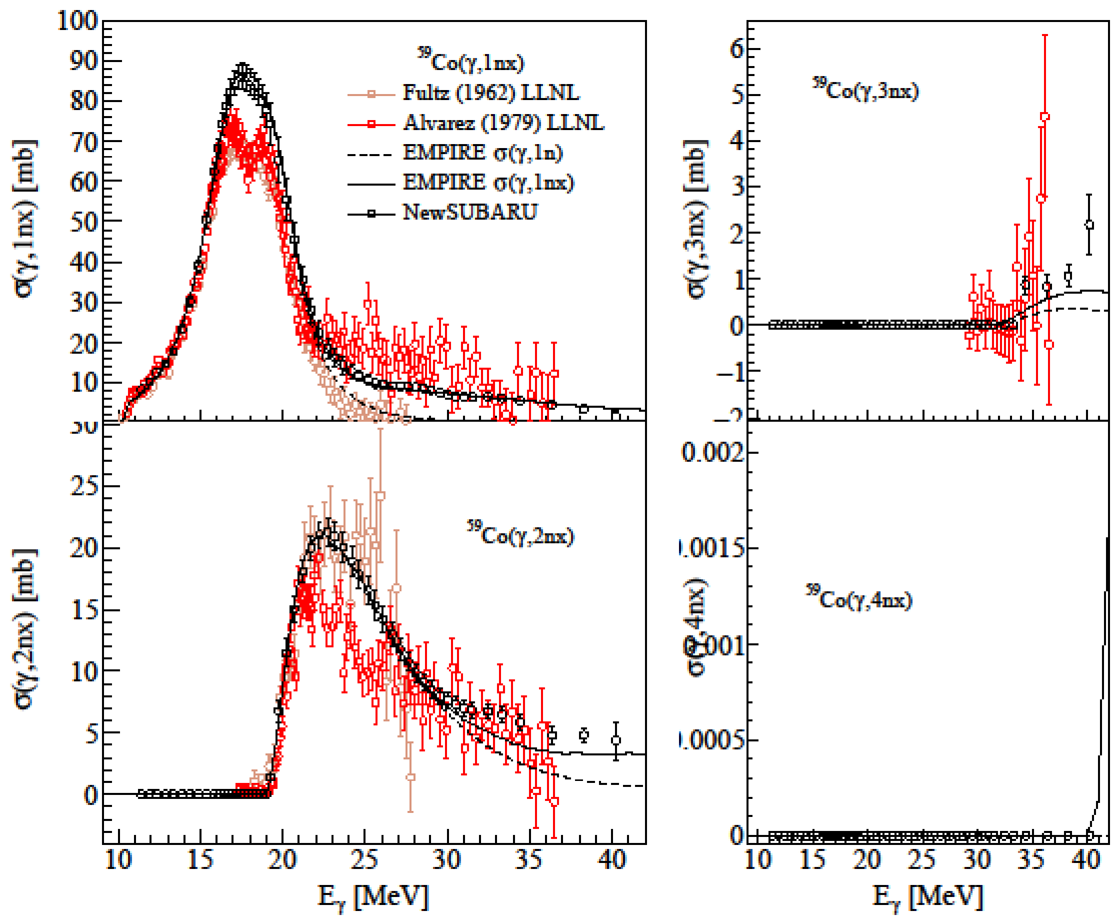
# 59Co

IAEA-CRP Data
Evaluation: EMPIRE

Partial cross sections: $\sigma(\gamma, inx)$

Total cross sections: $\sum_i \sigma(\gamma, inx)$



# Theoretical analysis of the IAEA Data

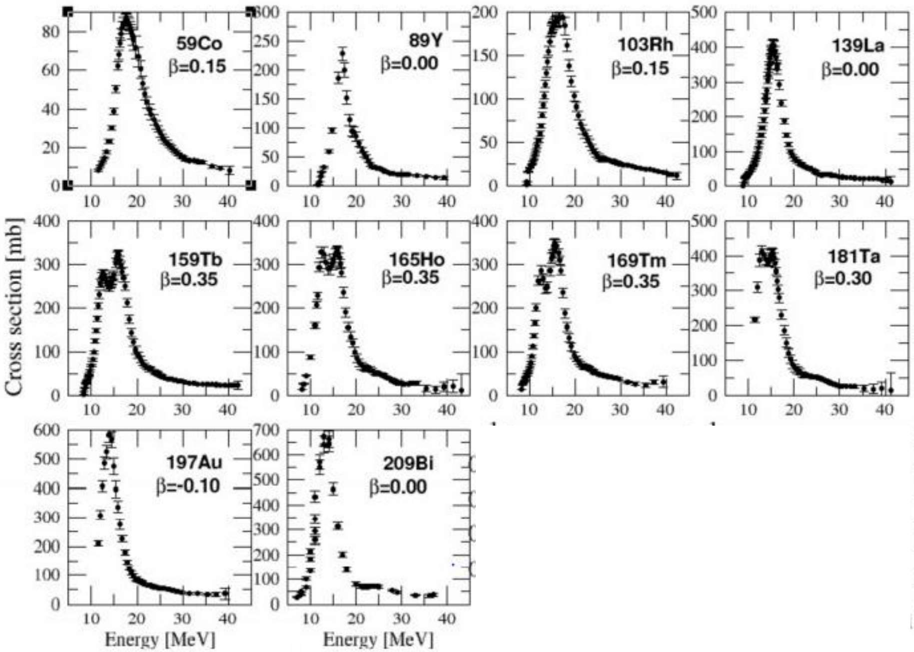
S. Péru, S. Hilaire, CEA/DAM/DIF France

G. Colò, X. Roca-Maza, Milano, INFN

S. Goriely, ULB

*To be submitted in October, 2020*

New IAEA Data for 10 nuclei



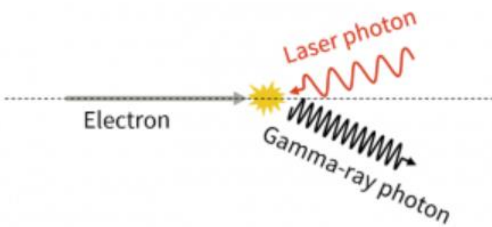

Nuclear Theory
Mean-field plus quasi-particle random phase approximation (QRPA)
Spherical and axially-deformed nuclei
Gogny and Skyrme interactions

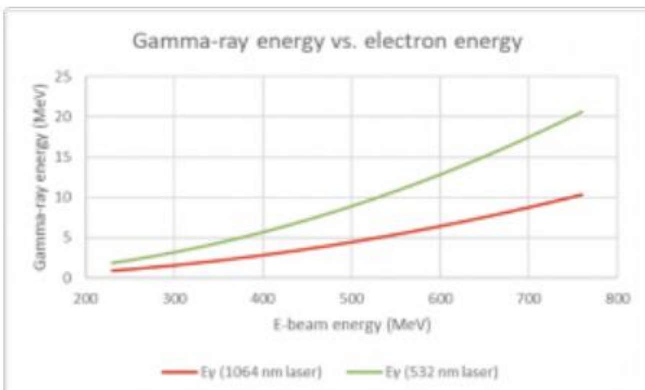
$\Sigma_{TRK}$: Integrated cross sections: EWSR/TRK
$E_c$: Centroid energy
$\alpha_D$: Polalizability J, L, $\Delta r_{np}$

# ELI-NP

## Extreme Light Infrastructure -Nuclear Physics

October 4, 2019, 3-year contract, €49M
Lyncean Technologies (CA, USA)
IFIN-HH



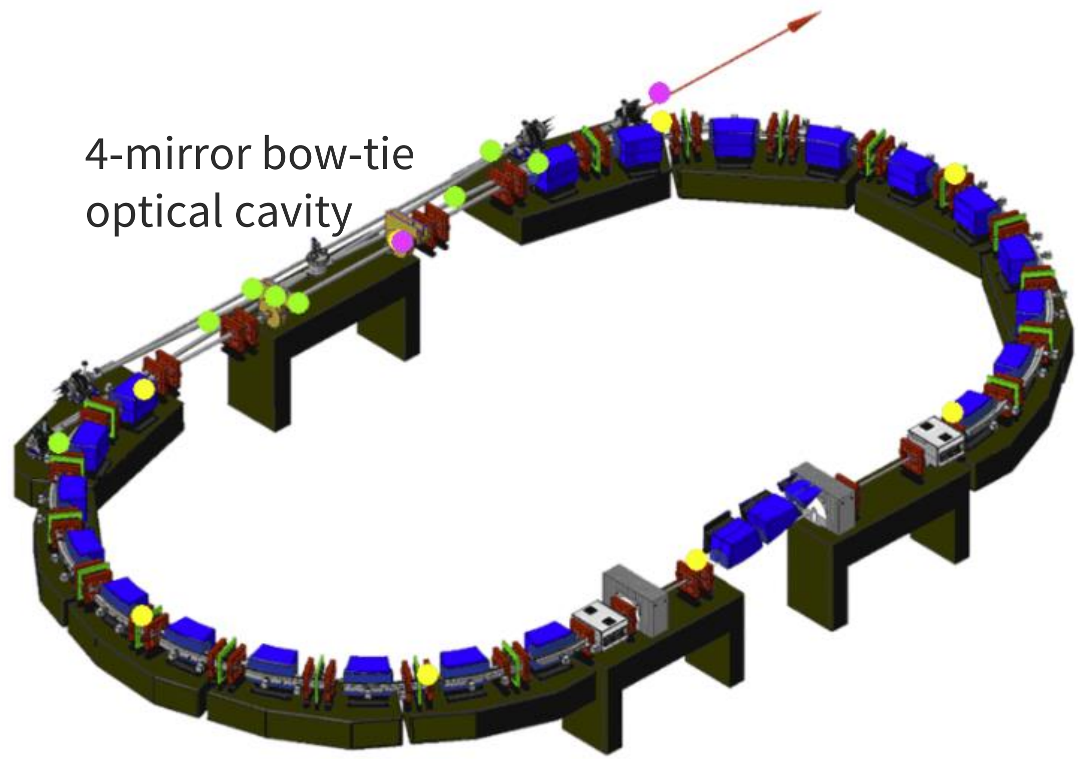

$E_{\gamma}^{max}$=19.5 MeV

$\Delta E/E \sim 0.5\%$

$N_{\gamma}^{max} \sim 10^{9}$ cps

**THE LYNCEAN COMPACT GAMMA-RAY SOURCE (CGS)**

VEGA (Variable Energy Gamma-ray ) System



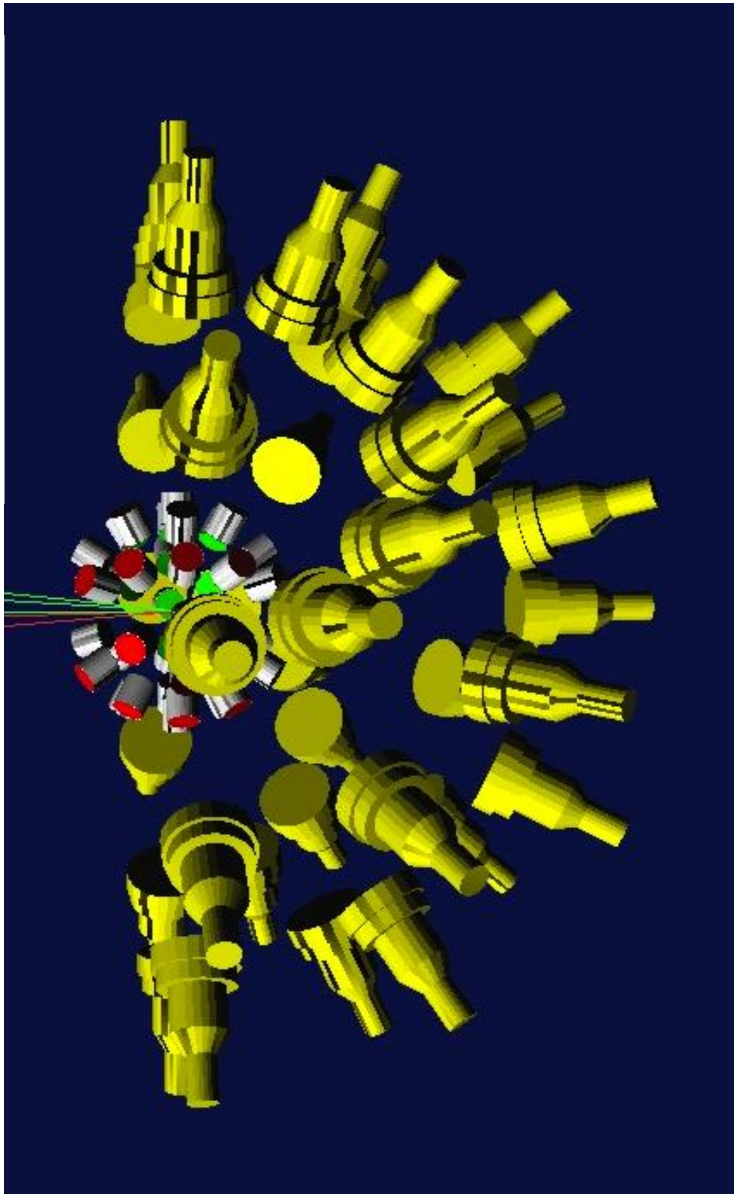
# GANT Group
(Gamma Above Neutron Threshold)

Array of neutron and gamma detectors

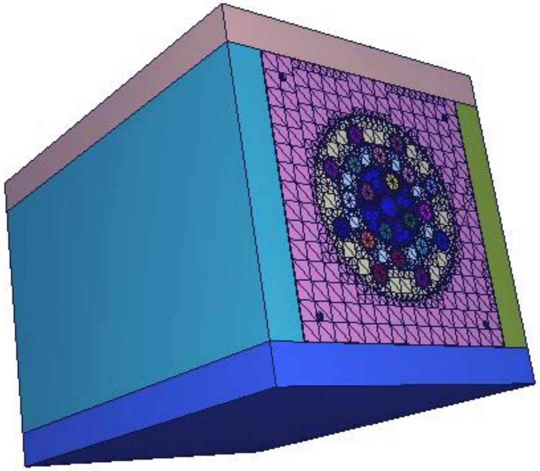
Physics

- GDR
- Pygmy dipole
- M1
- gs $\gamma$ decay

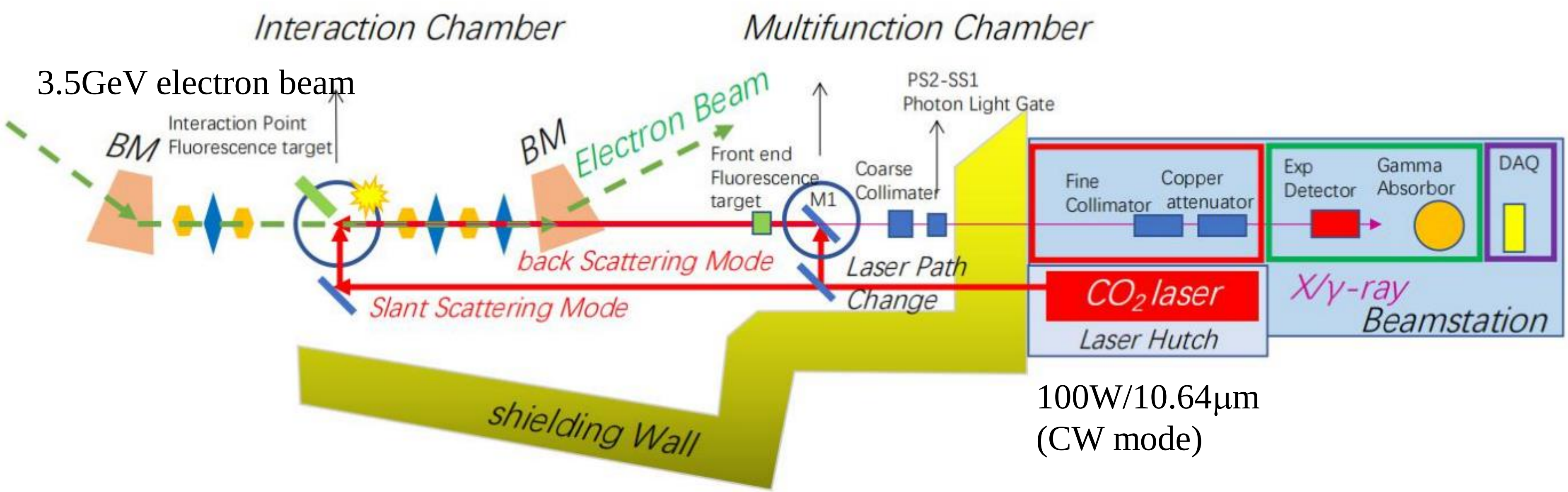
- LaBr3(Ce)
- CeBr3
- liquid scintillator (BC501A)
- Li glass (GS20)

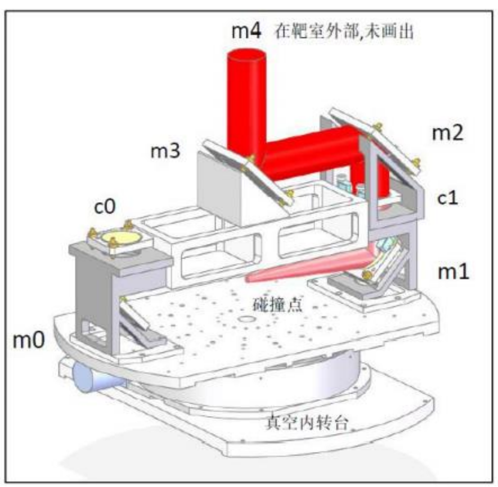


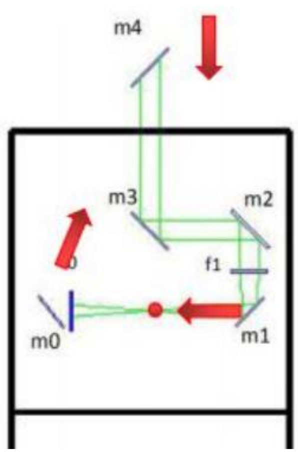
4$\pi$ neutron detector



# SLEGS (Shanghai Laser Electron Gamma Source)
# Shanghai Light Source



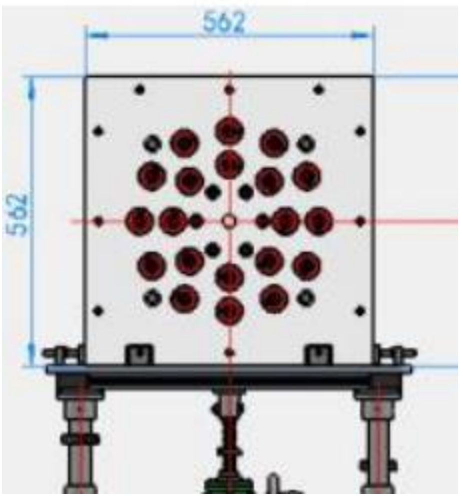



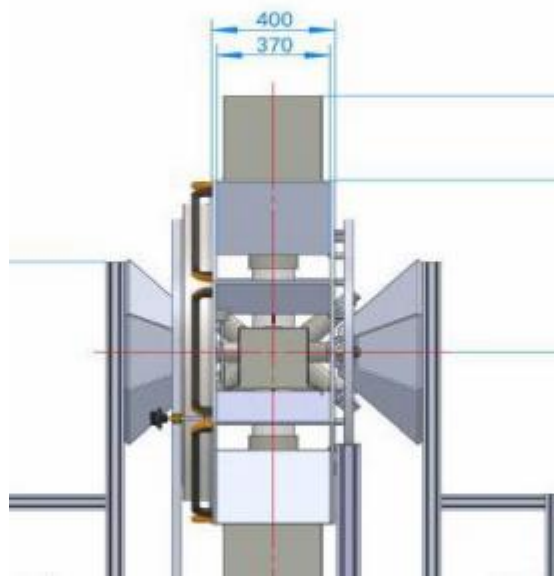

Installation in mid-2020
Open to users in 2022

Table 1, The parameters of SLEGS

| Name | Parameters |
|---|---|
| Energy range | 0.4-20 MeV |
| Resolution | ~5 % (2mm Collimator) |
| Integrated Flux | $10^5$phs/s@20° – $10^7$ phs/s@180° |
| Divergence | <0.5 mrad |




4π neutron detector




NRF detector
2 Clover HPGe, 2 Large HPGe
8 LaBr3(Ce)

# Future Prospect of Photonuclear Reaction Study

## Post IAEA-CRP

1. Nuclei < Fe **PANDRA project** (Tamii)
   Origin of ultra high-energy cosmic rays (Kido, )
   Neutron and charged-particle channels
   Experimental limitation: $E_\gamma^{max} \sim 20$ MeV @ ELI-NP, Shanghai
   $E_\gamma > 20$ MeV Model calculations
   Mean-field (Inakura), Shell model (Utsuno)
   Antisymmetrized molecular dynamics (Kimura)
   6Li, 7Li (RCNP, Kyoto) @ NewSUBARU

2. Nuclei across the chart of nuclei
   Deformed nuclei, Isotope dependence
   208Pb, 112Sn, 116Sn, 120Sn, 124Sn @ NewSUBARU (TU Darmstadt et al.)
   238U, 232Th @ NewSUBARU (Shanghai, IFIN-HH, JAEA, Kyoto)

**Systematics of GDR**

- photoabsorption cross section, $\gamma$-ray strength function
  TRK/EWSR
- Centroid energy
- Polalizability symmetry energy, neutron skin thickness