EUROPEAN UNION

Structural Instruments 2014-2020

Project co-financed by the European Regional Development Fund through the Competitiveness Operational Programme
“Investing in Sustainable Development”

Extreme Light Infrastructure-Nuclear Physics
(ELI-NP) - Phase II

Photoneutron measurements for IAEA CRP on updating the current photonuclear data library

I. Gheorghe, H. Utsunomiya, T. Ari-izumi, D. Takenaka, S. Belyshev, K. Stopani,
V. Varlamov, D. Filipescu, M. Krzysiek, G.M. Tveten, T. Renstrøm, D. Symochko,
H. Wang, G. Fan, S. Miyamoto

Coordinated Research Project on Photonuclear Data and Photon Strength Functions

Approved in July 2015; Code F41032; Duration 2016 – 2020.

Photon nuclear data describing interactions of photons with atomic nuclei are of importance for a variety of applications including (i) radiation shielding and radiation transport analyses, (ii) calculation of absorbed does in the human body during radiotherapy, (iii) activation analyses, safeguards and inspection technologies, (iv) nuclear waste transmutation, (v) fission and fusion reactor technologies, and (vi) astrophysical nucleosynthesis.

Also, photon strength functions are important for the theoretical modelling of nuclear reactions, consequently they are relevant sources of information for other databases such as the IAEA Reference Input Parameter Library (RIPL), and evaluated data files such as Evaluated Gamma Activation File (EGAF), Evaluated Nuclear Structure Data File (ENSDF), and transport files in ENDF-6 format which are also supported by the IAEA.

The 1996 – 1999 IAEA CRP "Compilation and Evaluation of Photonuclear Data for Applications" produced three major results:
(i) the IAEA Photonuclear Data Library; (ii) a Handbook on Photonuclear Data for Applications, Cross-sections and spectra. Final report of a co-ordinated research project 1996 - 1999. IAEA-TECDOC-1178, 2000; (iii) additions of compiled experimental photonuclear cross sections in the EXFOR database.

Although this database has been extremely useful to a broad user community, it has become evident that it needs to be revised especially since (i) **some of the data are unreliable and discrepant**, (ii) for 37 isotopes there exist data that have not been evaluated, (iii) improved evaluation techniques are available, (iv) many new data have been published in recent years.

New CRP on Photonuclear Data and Photon Strength Functions

The main goals of the CRP are to

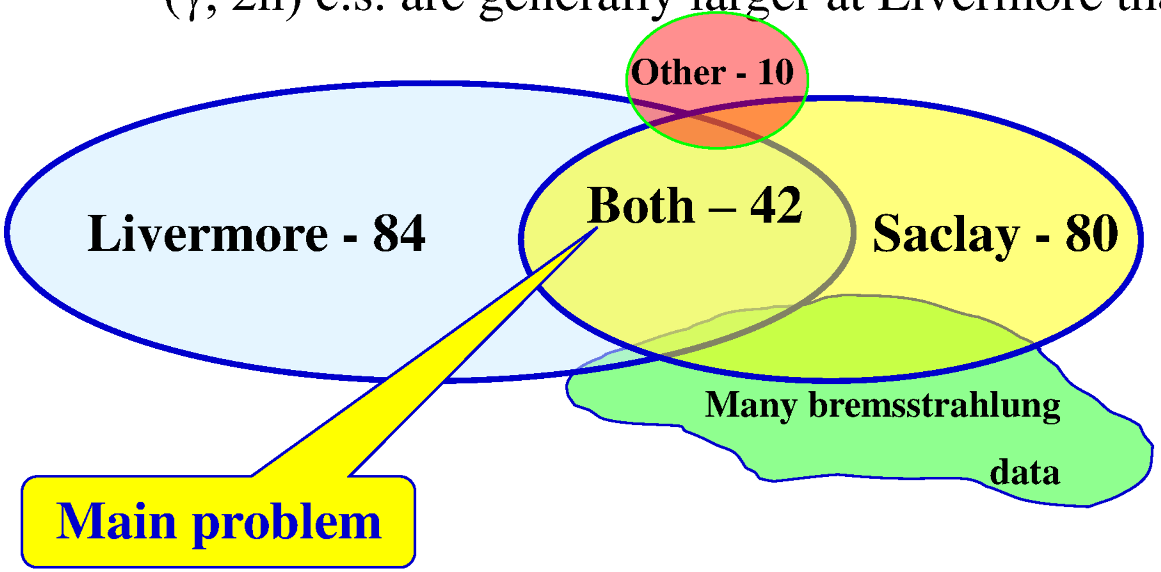
- update the Photonuclear Data Library (1999)
- generate a Reference Database for Photon Strength Functions.

Specific Research Objectives

- **Measure photonuclear cross-section data where needed**
- Update existing evaluations and evaluate new photonuclear data (including total photoabsorption cross sections, partial photonuclear cross sections and photoneutron spectra)
- Measure photon stength functions where needed
- Compile, assess and evaluate existing photon ptrength function data
- Develop and use theoretical tools to make recommendations and extrapolations to mass regions where no data exist
- Propose new measurements where needed.

Systematics of the photonuclear C.S. measurements

- Most of the photoneutron cross section measurements were performed in period 1962 – 1986 using quasi-monochromatic annihilation – QMA photons using positron in flight annihilation at two major facilities:
  - Saclay (France) Photonuclear Data Library – IAEA 2000
  - Lawrence Livermore National Laboratory (USA)
- Large discrepancies in (γ,xn) c.s. measured at the two facilities:
  - (γ, 1n) c.s. are generally noticeably larger at Saclay than at Livermore
  - (γ, 2n) c.s. are generally larger at Livermore than at Saclay.



No systematic way to resolve the discrepancies: <u>New and reliable measurements are required!</u>

PHOENIX* Collaboration

Updated photonuclear data library – (γ, xn) cross sections

Reference database of photon strength functions– (γ, n) cross sections

Data taking - DONE

2015	**^{209}Bi** ^{9}Be
2016	^{197}Au *^{169}Tm* ^{89}Y
2017	^{181}Ta *^{165}Ho* ^{59}Co
2018	*^{159}Tb* ^{139}La ^{103}Rh

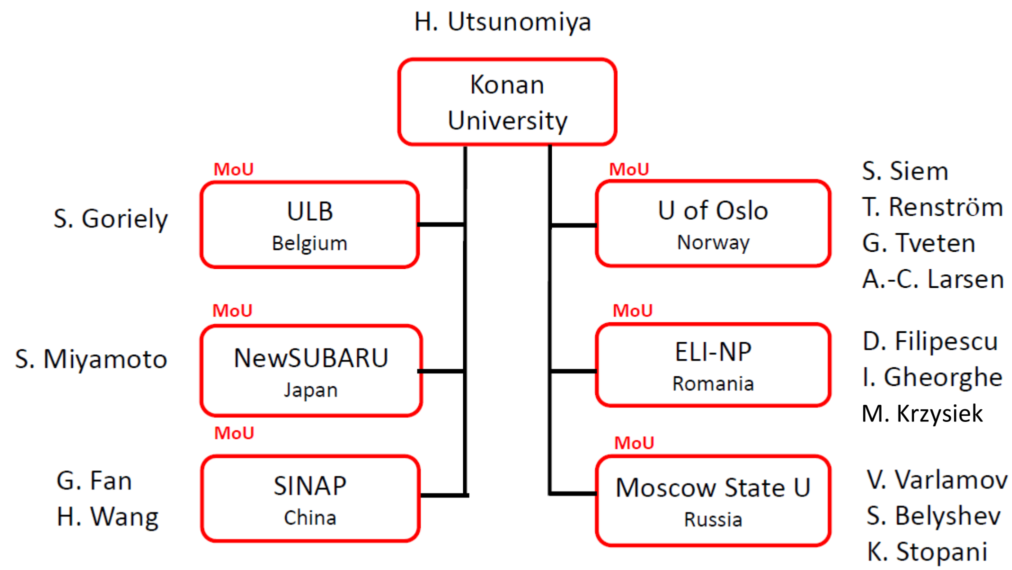
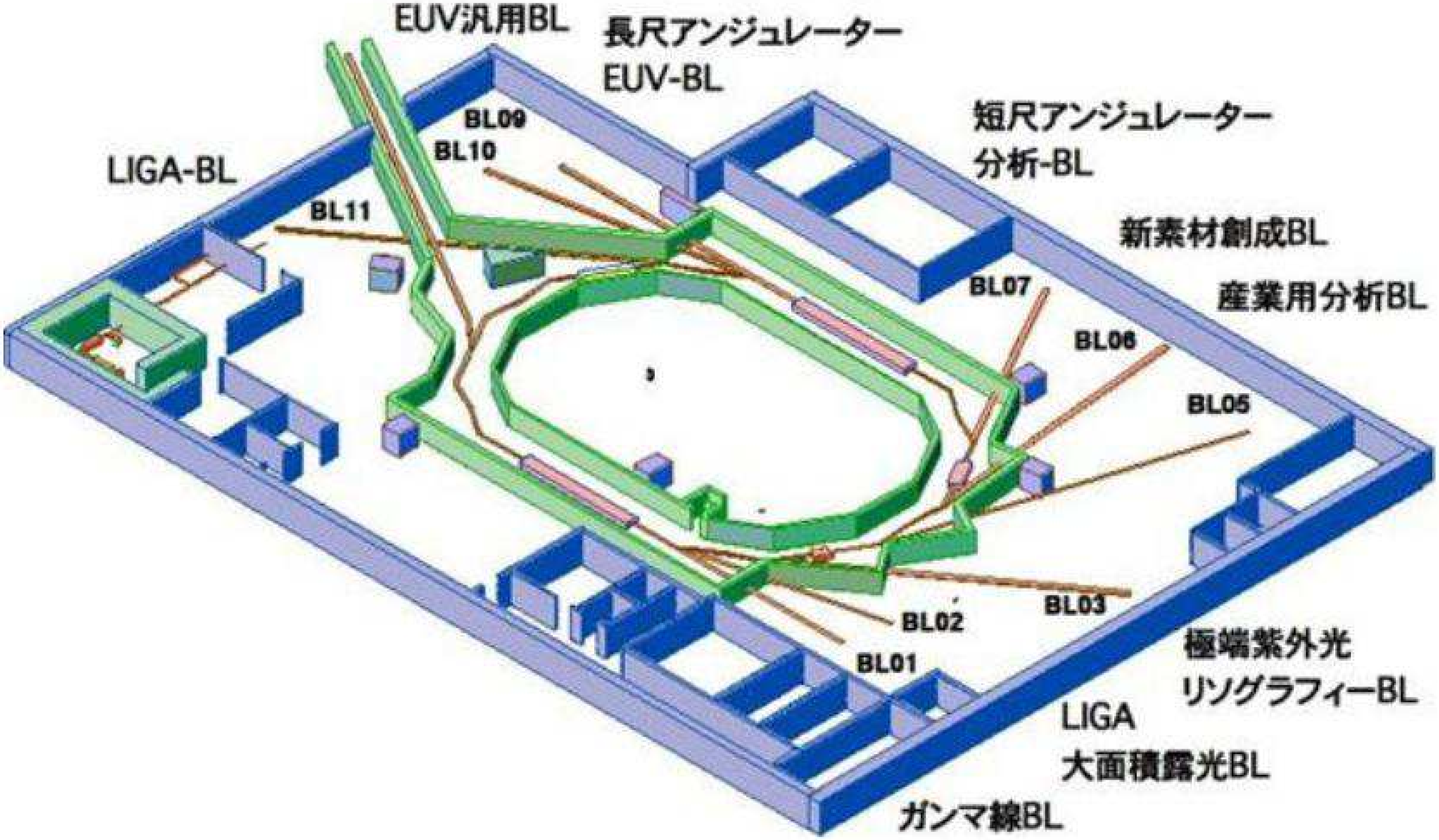


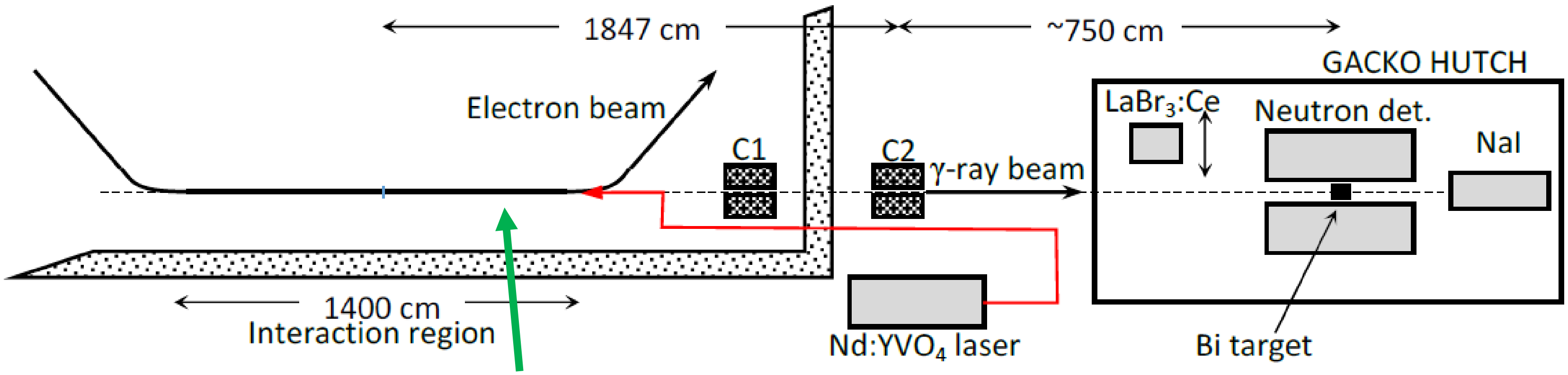
*Photo-excitation and neutron emission cross (x) sections


LEPS, LEPS2
GeV γ
SPring8 8 GeV e- storage ring
SACLA
8 GeV e- linac
8 GeV e- synchroton
1 GeV e- Linac
NewSUBARU
MeV γ

Experimental facility NewSUBARU – GACKO



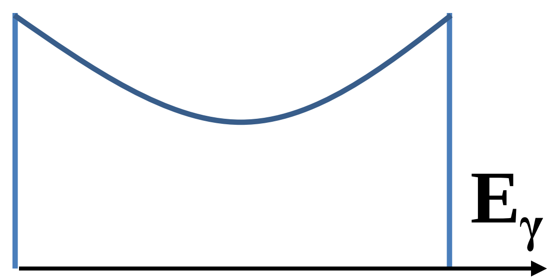
γ-ray beam production



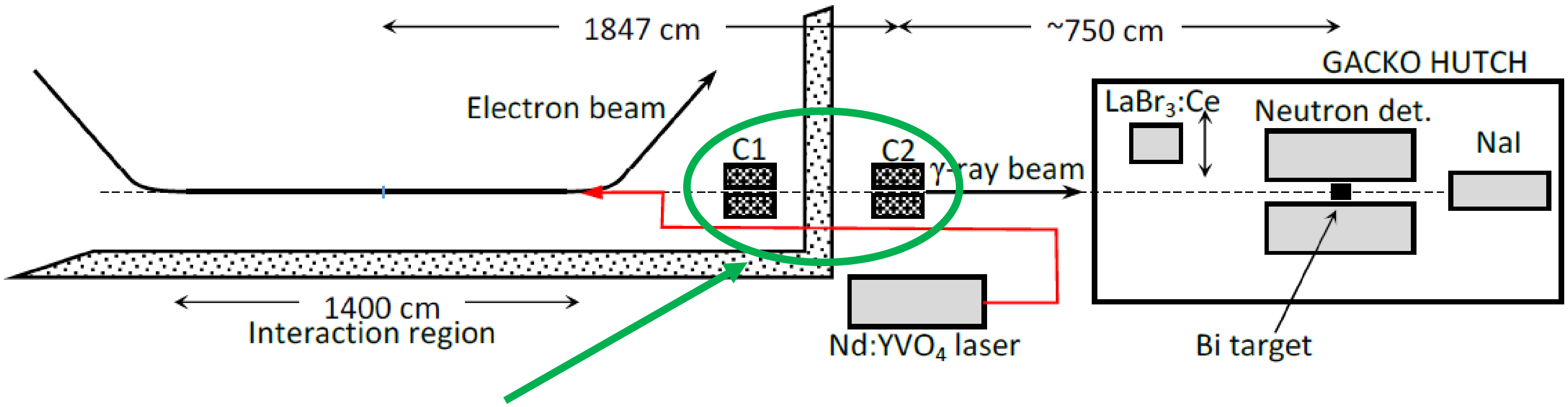
Laser beam – electron beam collision region

Continuous *Compton* photon spectrum is produced

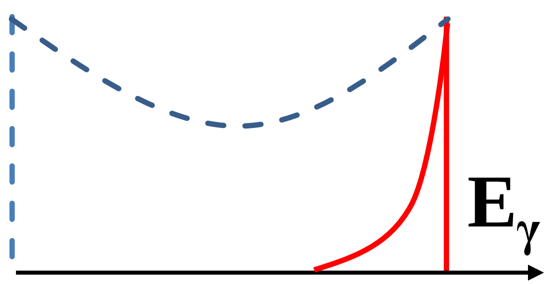
- **Head – on collisions (180º collisions)**
- **Laser and electron beam are unsynchronized**



γ-ray beam collimation

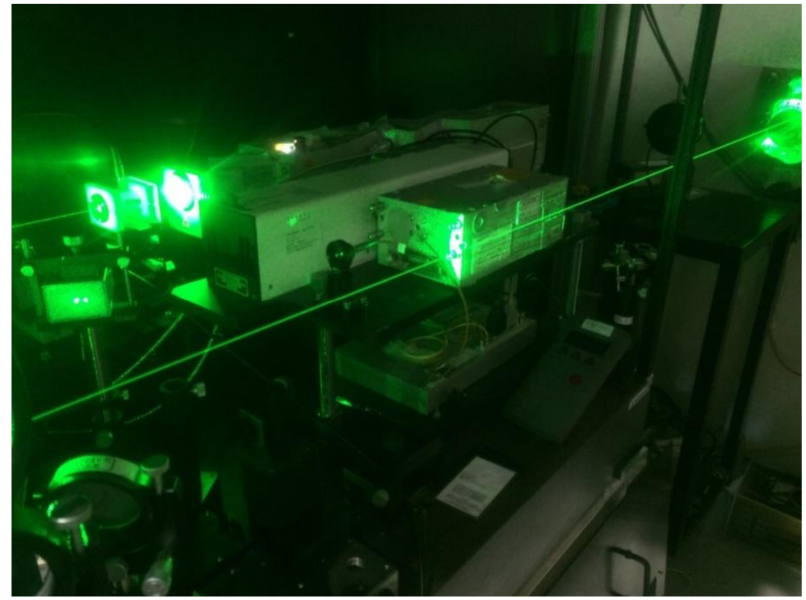


Backscattered photons (maximum energy section of the Compton spectrum) selected using collimators
Quasi-monochromatic photon beam is produced

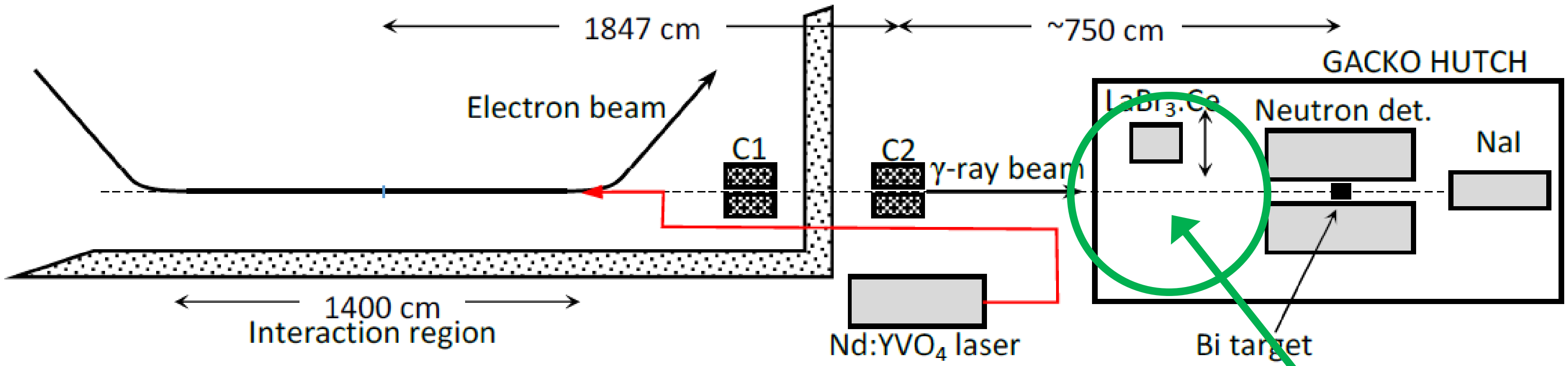


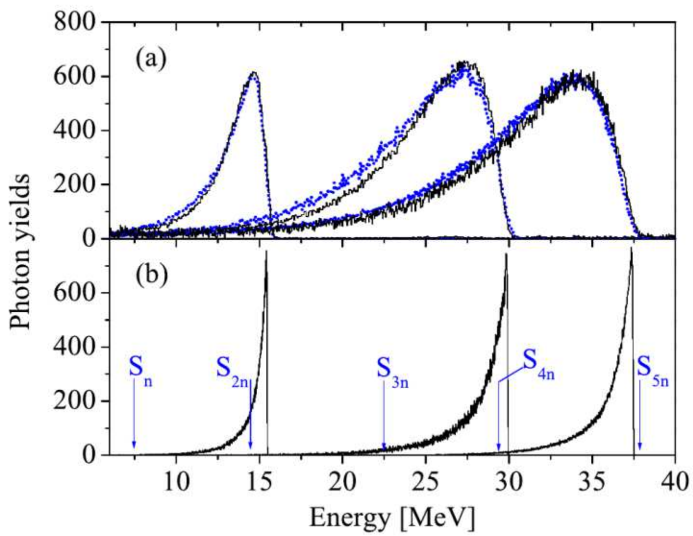
$E_\gamma < S_{2n}$ max. 17 MeV
$Nd{:}YVO_4$ (Inazuma) Laser Ist harmonic
(λ = 1064 nm; Power = 40 W)

$E_\gamma > S_{2n}$ max. 74 MeV
$Nd{:}YVO_4$ (Talon) Laser IInd harmonic
(λ = 532 nm; Power = 20 W)



Electron beam energy between 0.5 and 1.5 GeV.





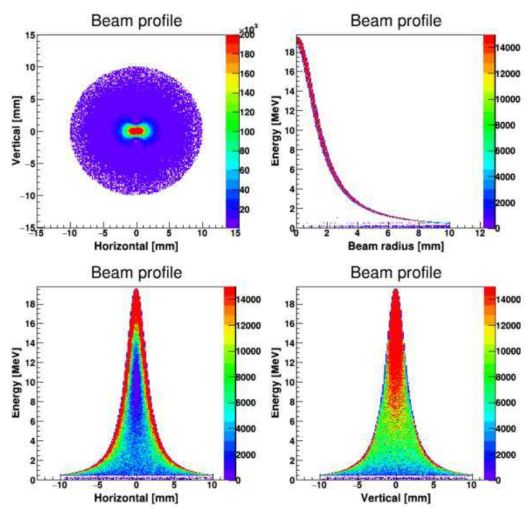
Beam profile monitor:

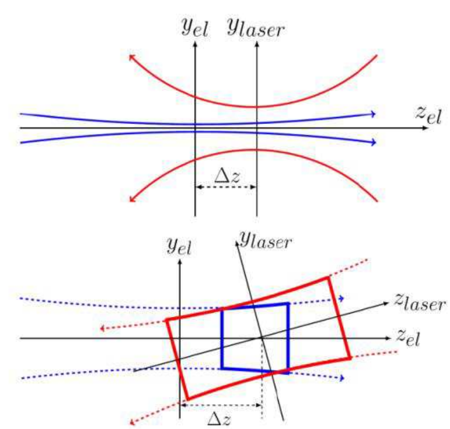
3.5" x 4.0" $LaBr_3(Ce)$

Energy spread

1.6 - 7 %

GEANT4 simulations



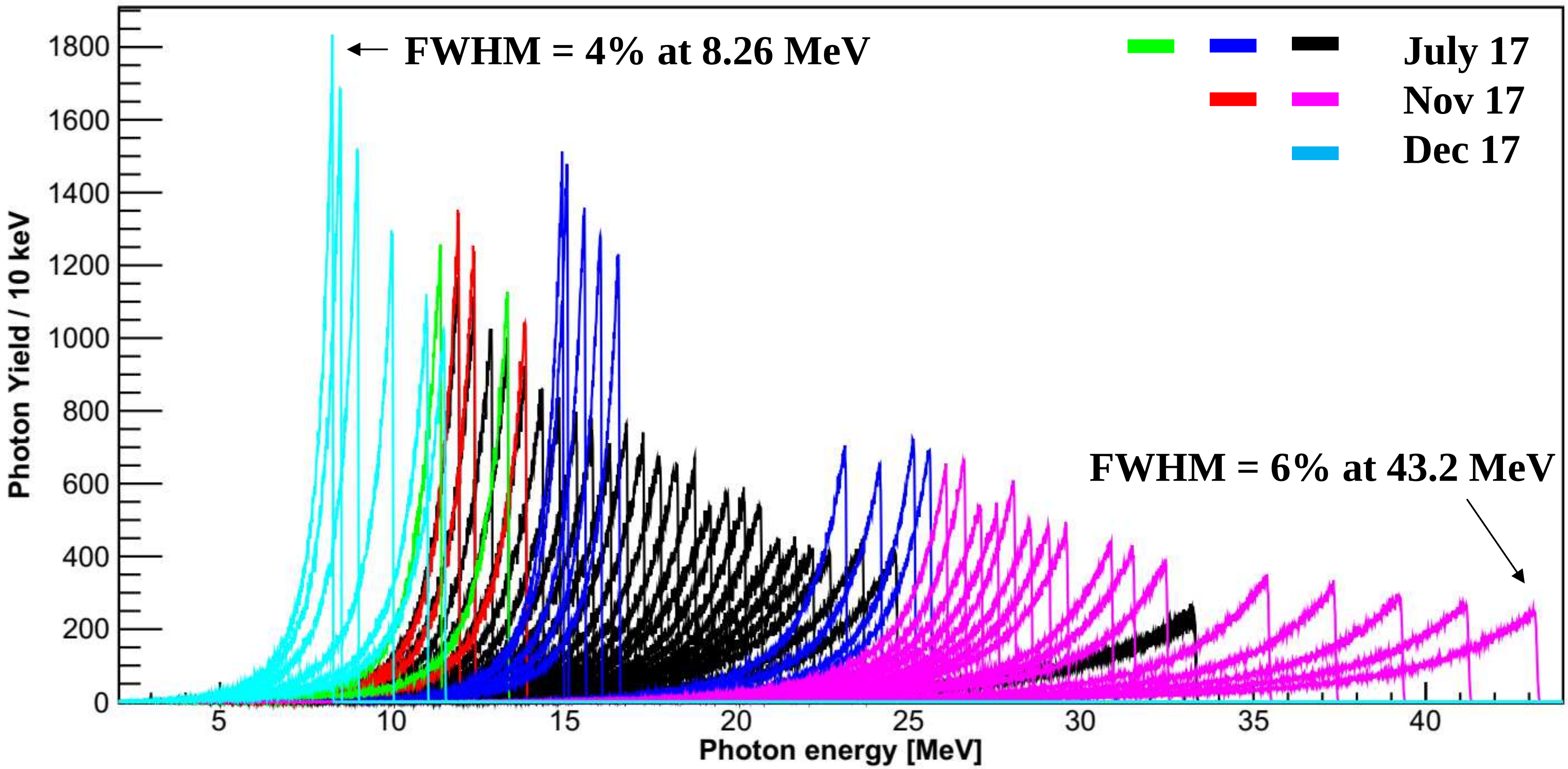


D. M. Filipescu, *et al.*,
Phys. Rev. C 90, 064616, (2014).
H.-T. Nyhus, *et al.*,
Phys. Rev. C 91, 015808, (2015).

Incident gamma beam spectra

$^{165}Ho(\gamma,xn)$

S_{1n} = 7.99 MeV ; S_{2n} = 14.66 MeV; S_{3n} = 23.07 MeV; S_{4n} = 29.99 MeV



Number of incident photons on the target

- 8” 12” NaI(Tl) detector;

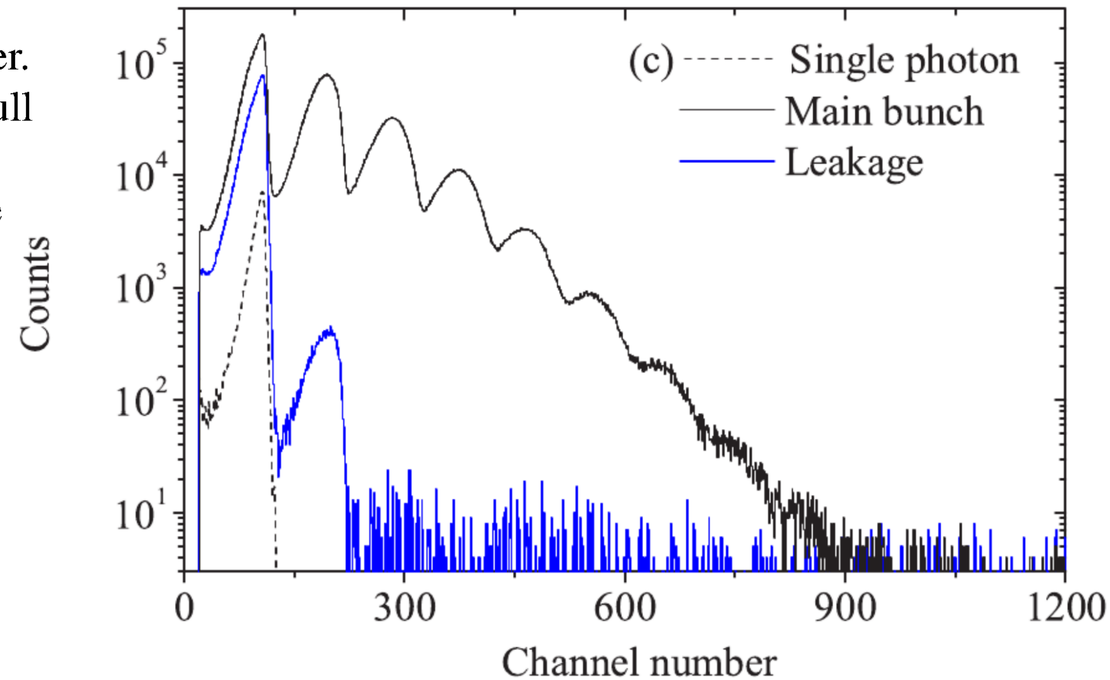
Bunch pulse width:

Electron – 20 ps Laser ~ 60 ns

→ Time structure of the γ-beam given by laser.

- Pile-up spectra was acquired in beam at full laser power;
- Before and after each measurement single photon spectra was measured at low laser power;
- Total number of photons was obtained as weighting average of the pile-up spectra using single photon spectra as weighting function;
- Beam intensity up to ~ 10^5 γ-rays per second

$$N_{\gamma,\mathrm{det}} = \frac{\langle i \rangle_{\mathrm{pileup}}}{\langle i \rangle_{\mathrm{single}}} \left(\sum n_i \right)_{\mathrm{pileup}}$$

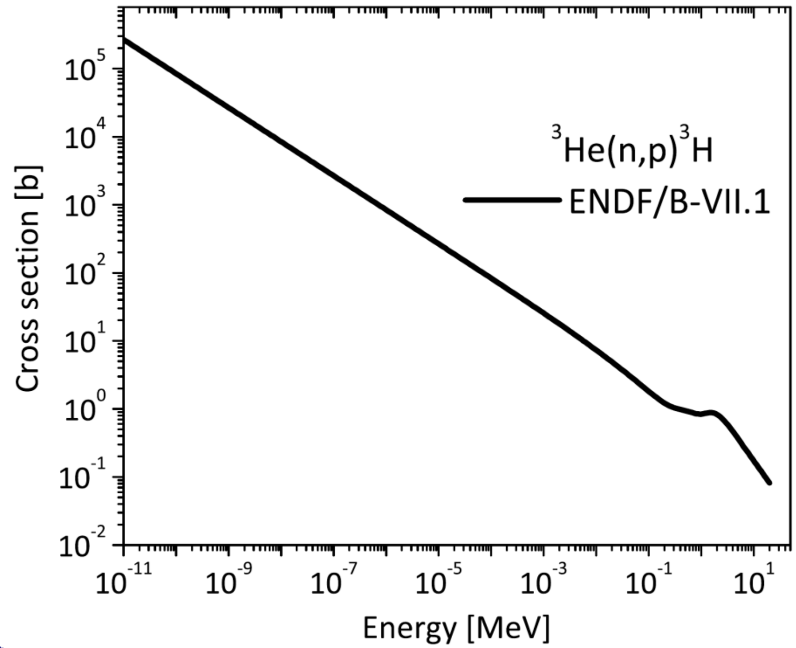


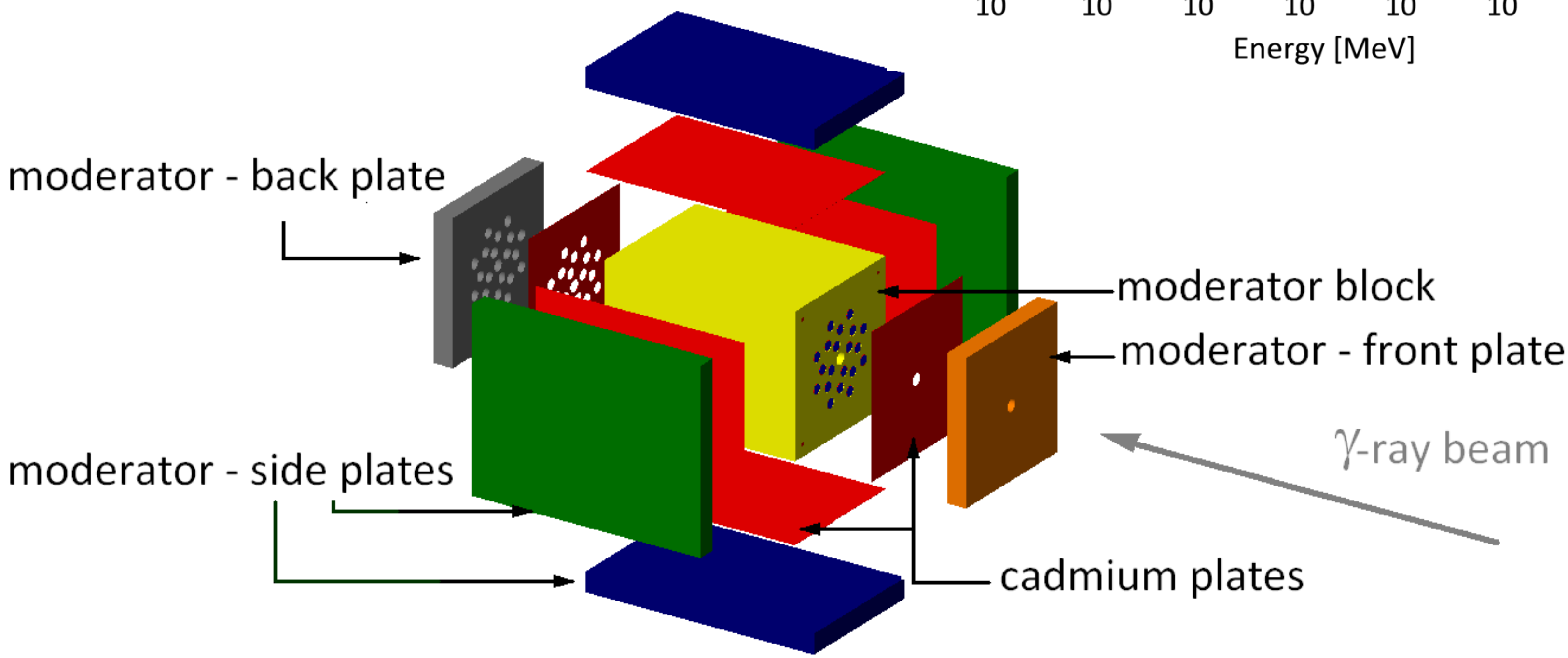
Pile-up and single photon spectra, 24 MeV.
The main LCS γ-ray spectrum displays a Poisson distributed pile-up structure with an average of 1.9 photons/bunch.

Neutron detection

^{3}He proportional counters embedded in polyethylene block.

$$^{3}He(n,p)^{3}H$$





Direct neutron-multiplicity sorting

Let us consider (γ,xn) reactions with x = 1 - 3

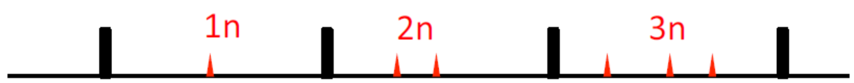
If we can measure the number of (γ,xn) reactions N_x with x = 1 – 3, we can determine the cross sections $\sigma(\gamma,xn)$.

$$N_1 = N_\gamma N_T \sigma(\gamma,1n)$$

$$N_2 = N_\gamma N_T \sigma(\gamma,2n)$$

$$N_3 = N_\gamma N_T \sigma(\gamma,3n)$$

γ pulsed beam at 1kHz



However, what we can measure is the number of neutrons observed *N_y (y=s,d,t)*.

Single neutron events

$$N_s = \boxed{N_1} \cdot \varepsilon(E_1) + \boxed{N_2} \cdot {}_2C_1 \cdot \varepsilon(E_2) \cdot (1-\varepsilon(E_2)) + \boxed{N_3} \cdot {}_3C_1 \cdot \varepsilon(E_3) \cdot (1-\varepsilon(E_3))^2$$

Double neutron events

$$N_d = \boxed{N_2} \cdot \varepsilon(E_2)^2 + \boxed{N_3} \cdot {}_3C_2 \cdot \varepsilon(E_3)^2 \cdot (1-\varepsilon(E_3))$$

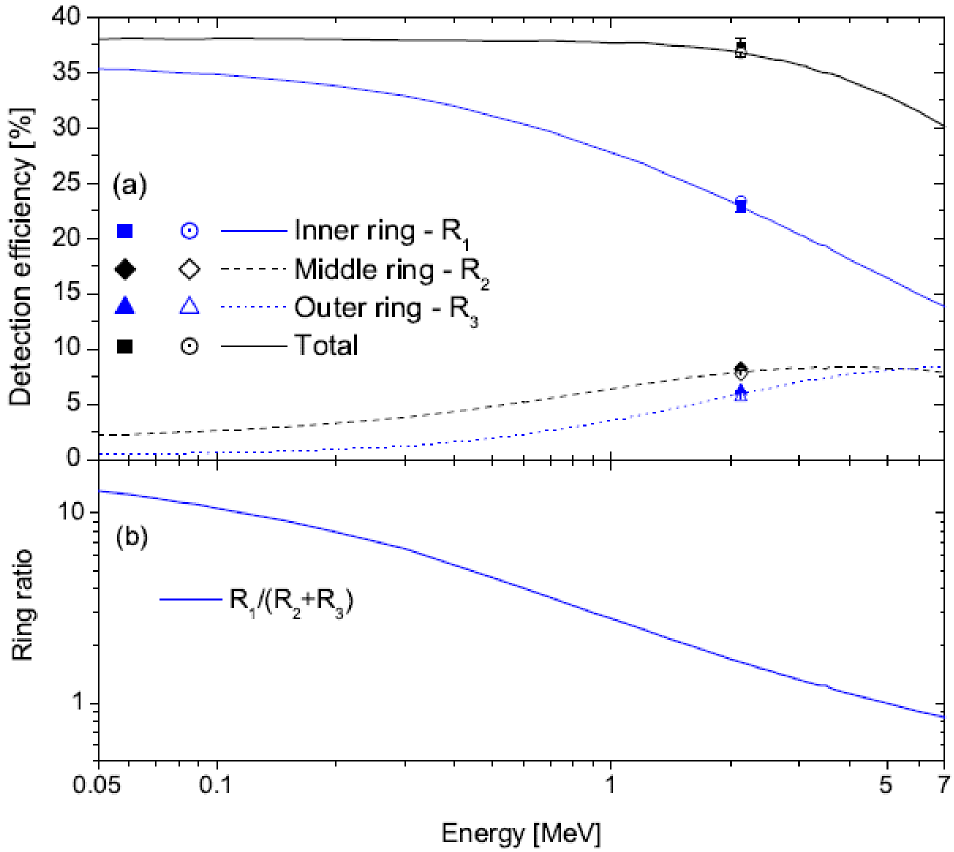
Triple neutron events

$$N_t = \boxed{N_3} \varepsilon(E_3)^3$$

ε(E) : detection efficiency

Problem! Ring Ratios $\not\longrightarrow$ E1, E2, E3

Solution? Flat efficiency neutron detector!



Flat efficiency: 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:

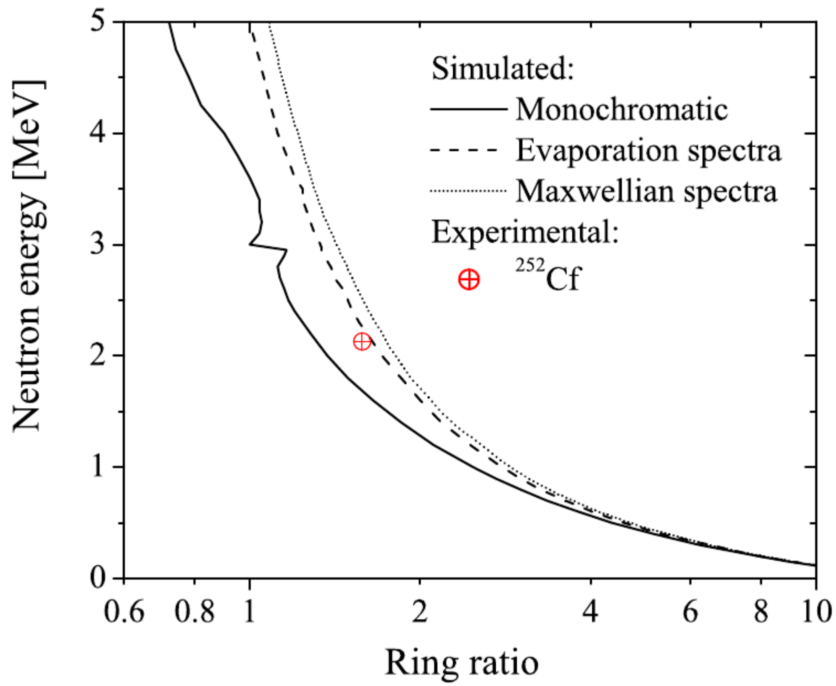
$\varepsilon(1-\varepsilon)^2 = 14.4\%$

Hiroaki Utsunomiya, *et al.*, NIM A **871** (2017) 135–141

Ring ratio method
Information on average energy of the emitted neutrons.

Total detection efficiency – flat.

The detection efficiency of each ***individual ring*** changes significantly with energy.
Different amount of moderator is found between the target and each ring: the inner ring and the outer rings display different detection efficiency trends.



$$R_R^{th}(E) = \frac{\varepsilon_{R_1}(E)}{\varepsilon_{R_2}(E) + \varepsilon_{R_3}(E)}$$

$$R_R^{exp}(E) = \frac{N_{R_1}(E)}{N_{R_2}(E) + N_{R_3}(E)}$$

Experimental:

$$\langle E \rangle_{mono} = 1.7 \text{ MeV}$$

$$\langle E \rangle_{evap} = 2.25 \text{ MeV}$$

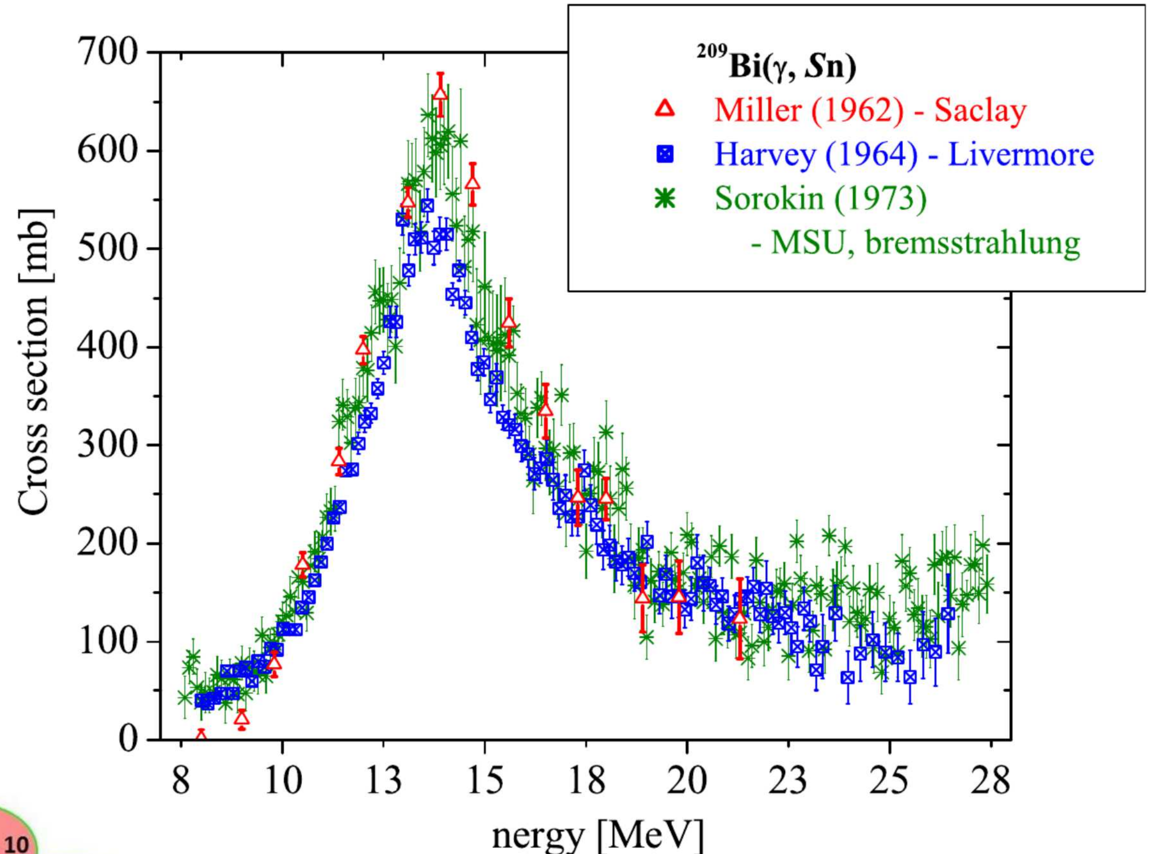
$$\langle E \rangle_{Maxw} = 2.5 \text{ MeV}$$

Literature: 2.13 MeV

Average neutron energy: 20 % uncertainty

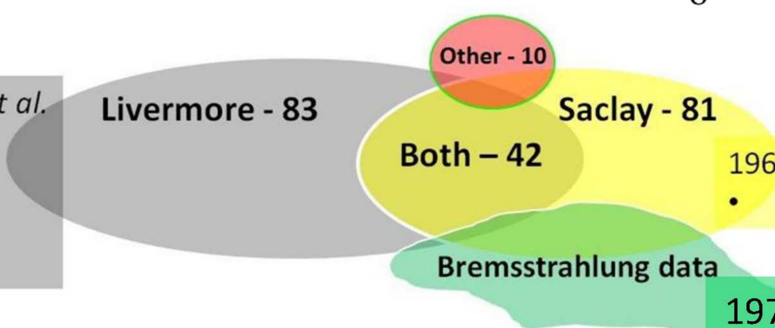
^{209}Bi(γ,xn)

First experiment



One of the candidates for investigating the discrepancies between Livermore and Saclay data of (γ,xn) cross sections.

1964 – Harvey *et al.*
- (g, n)
- (g, 2n)
- (g, tot)
- (g,S_n)



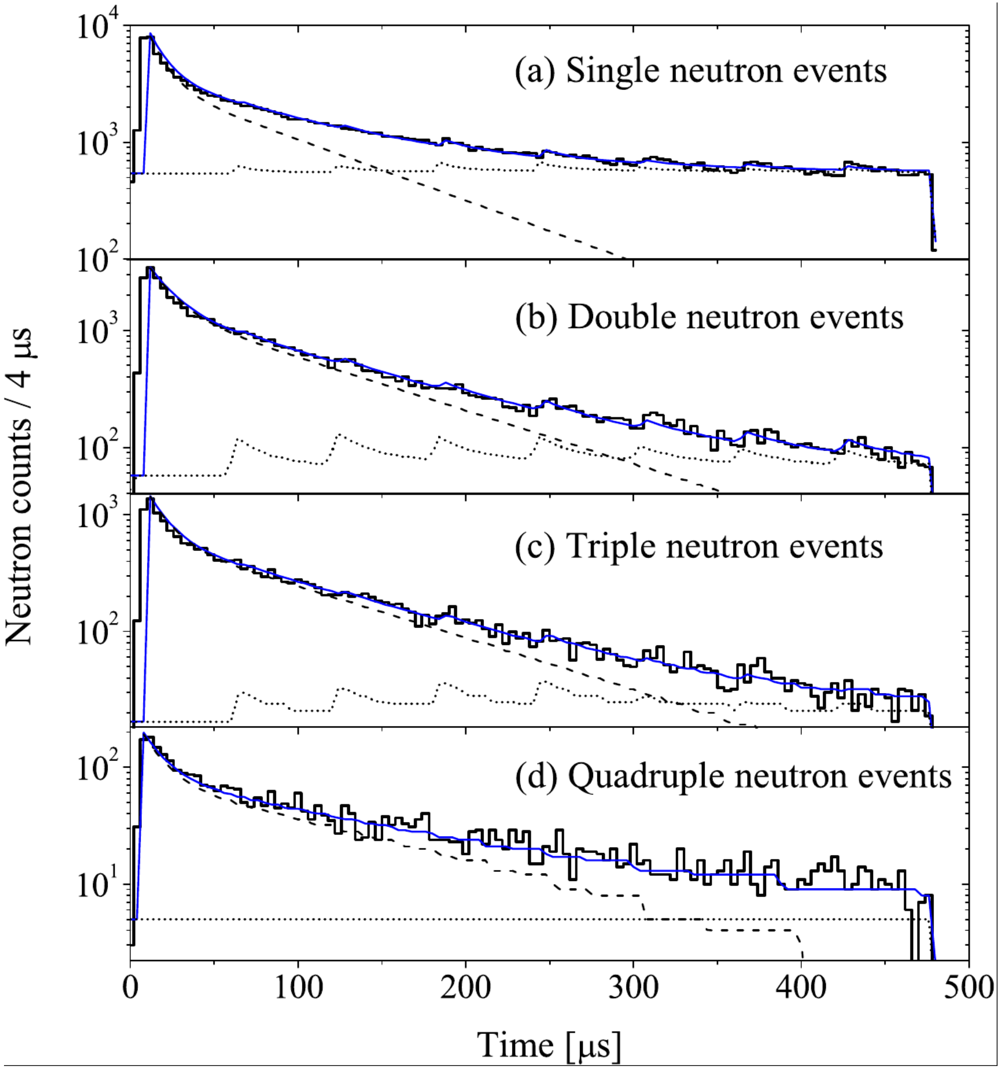
1962 – Miller *et al.*
- (g,S_n)

2015 – Belyshev *et al. (Moscow MSU)*
Relative yields for:
- (g, n) , (g, 2n) , (g, 3n) , (g, 4n) , (g, 5n) , (g, 6n)

1973 – Sorokin *et al. (Moscow MSU)*
Photoneutron yields
35 MeV betatron
Varied the electron beam energy by 100 keV between 7 and 28 MeV.
Penfold-Leiss unfolding method.

^{209}Bi data analysis
Number of 1, 2, 3 and 4 neutron coincidence events

Neutron moderation time curves for coincidences of 1-4 neutrons.
^{209}Bi(γ,xn) reactions, for E_{γ}^{max}=42.2 MeV



Each decay was fitted with:

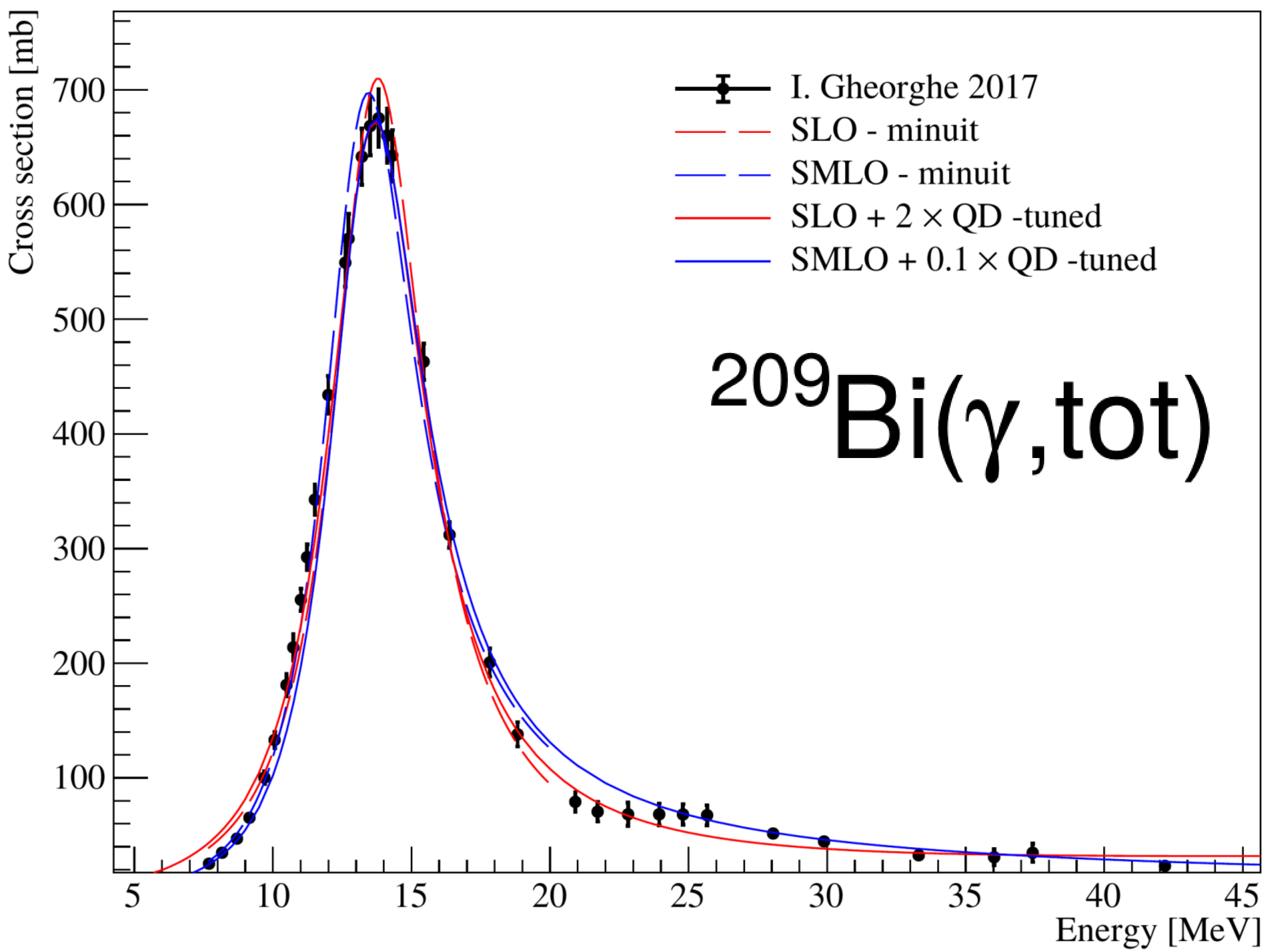
$$h_x(t) = A_{1x} \cdot \exp\left(\frac{xT - t}{\tau_{1x}}\right) + + A_{2x} \cdot \exp\left(\frac{xT - t}{\tau_{2x}}\right)$$

The total spectrum was fitted with:

$$h(t) = B + \sum_{x=0}^{x=7} h_x(t)$$

Reaction neutrons = total – fitted background

$$N_j = \frac{1}{j} \cdot [N_j^{\text{tot}} - \int B dt - \sum_{x=1}^{x=7} \int h_x(t) dt]$$



I. Gheorghe *et al.***,** Phys. Rev. C **96**, 044604 (2017).

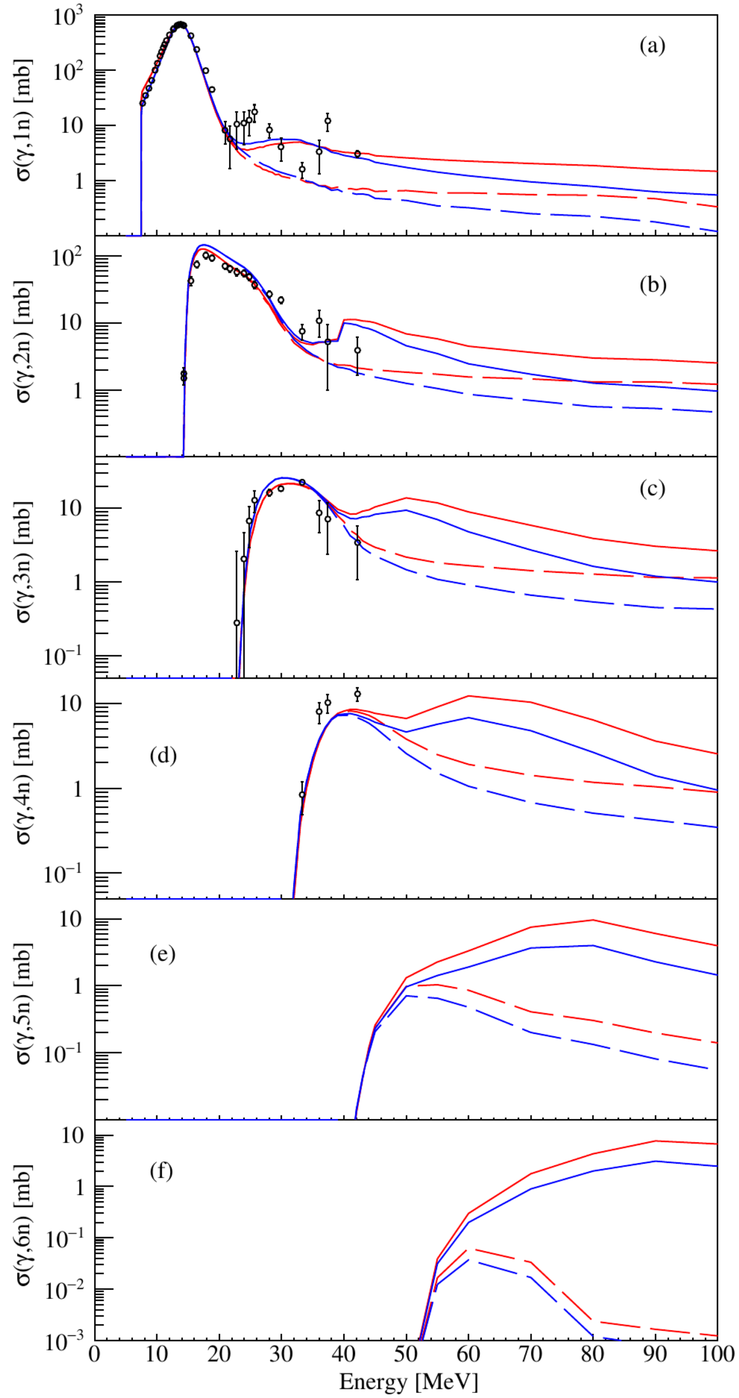
$^{209}Bi(\gamma,xn)$

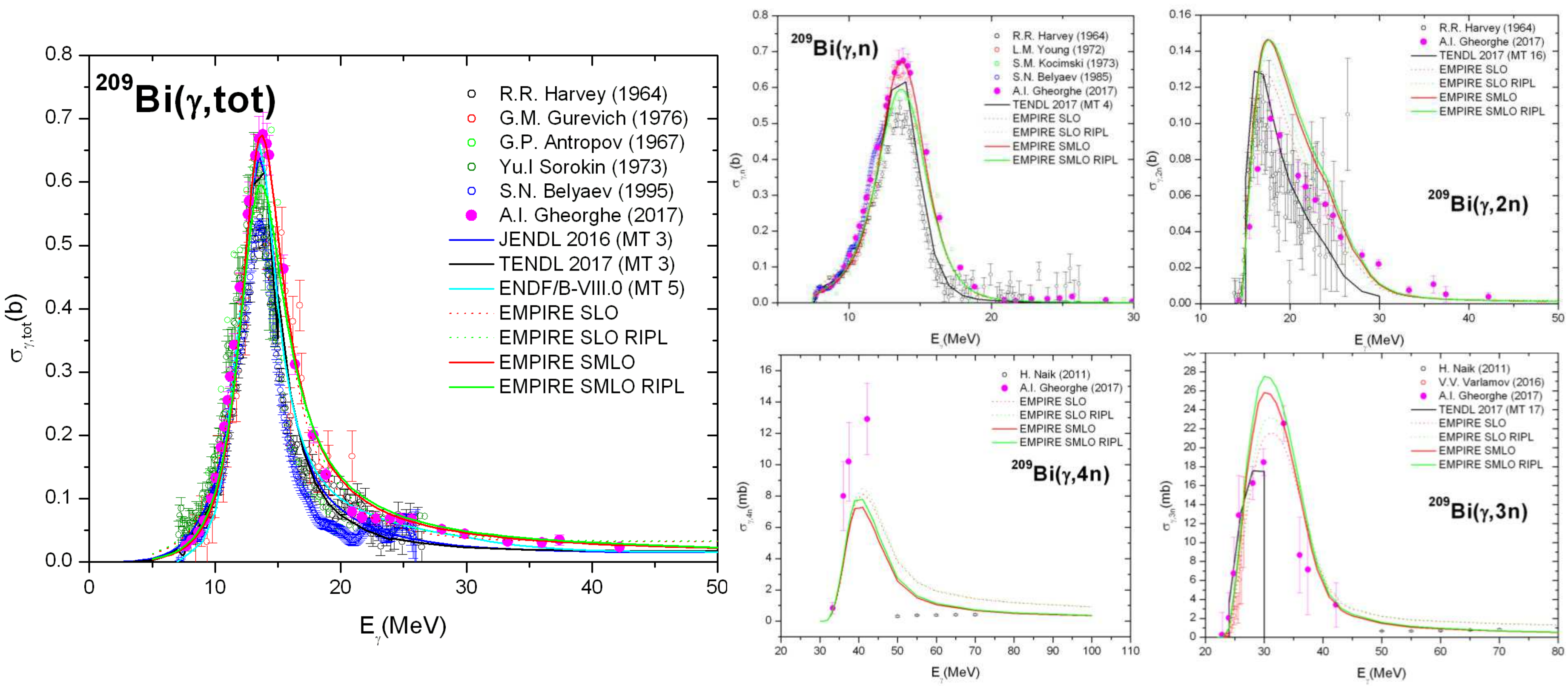
Red curves:
SLO gsf
QD factor = 2.

Blue curves:
SMLO gsf
QD factor = 0.1

Full lines – charged particle emission contribution included (g,xn)+(g,xnp)+(g,xna)+(g,xn2p)+…

Dashed lines – neutron emission ONLY

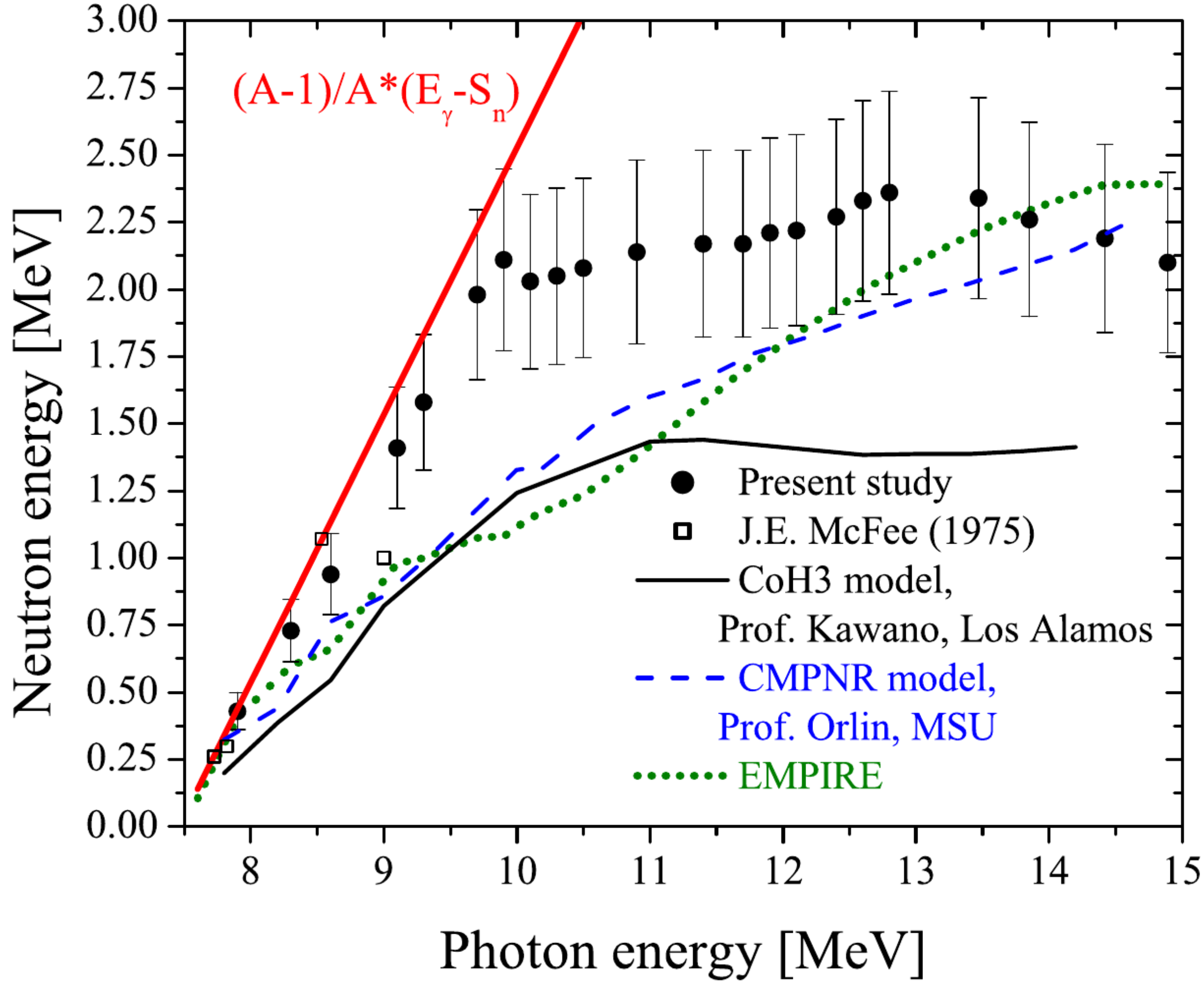


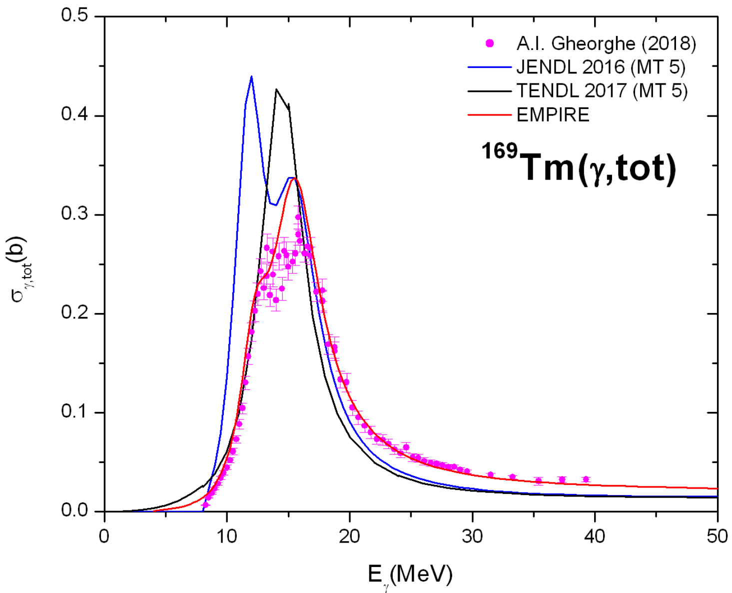


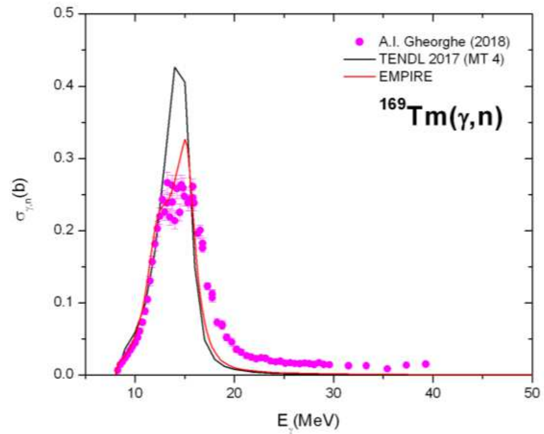
The EMPIRE 3.2.3 Malta code was used for statistical model calculations.

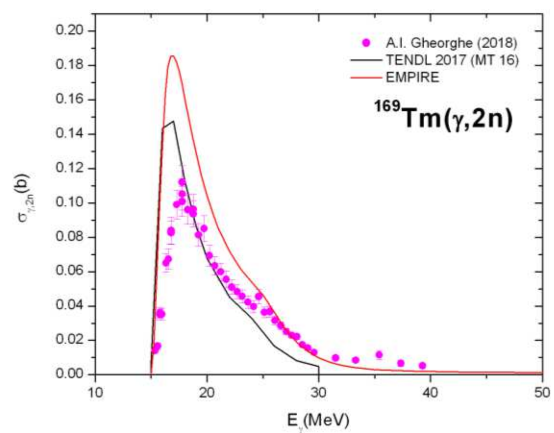
Both the SLO and SMLO parametrizations of the GSF have been tested, with parameters adjusted to reproduce the latest NewSUBARU results. These calculations are compared with the ones obtained using GDR parameters recommended by V.A.Plujko et al, At. Data Nucl. Data Tables, in press, (2018); https://arxiv.org/abs/1804.04445.

Average energy of emitted neutron

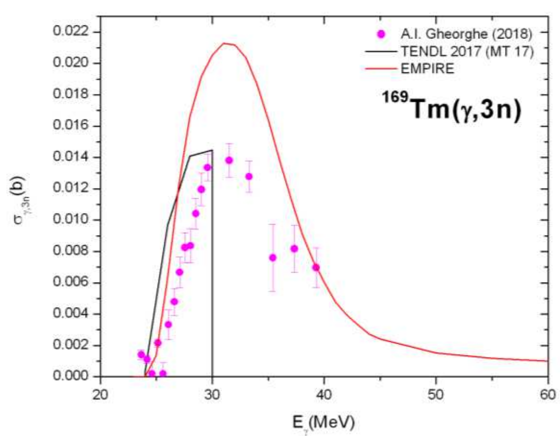


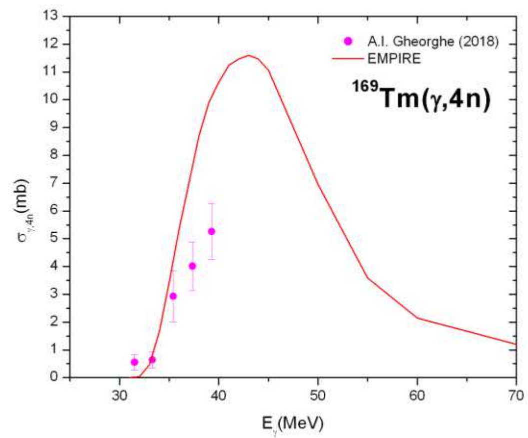




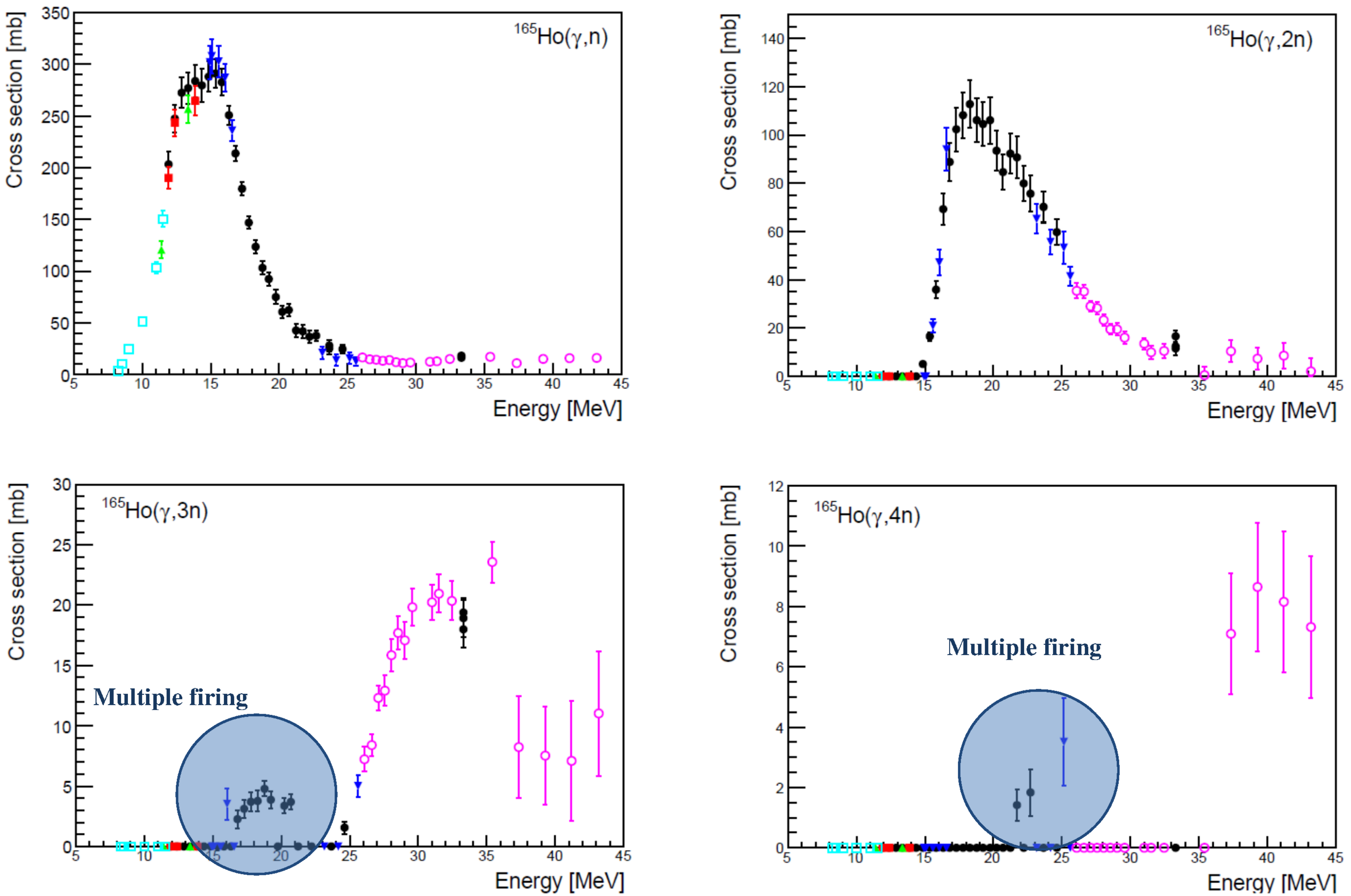


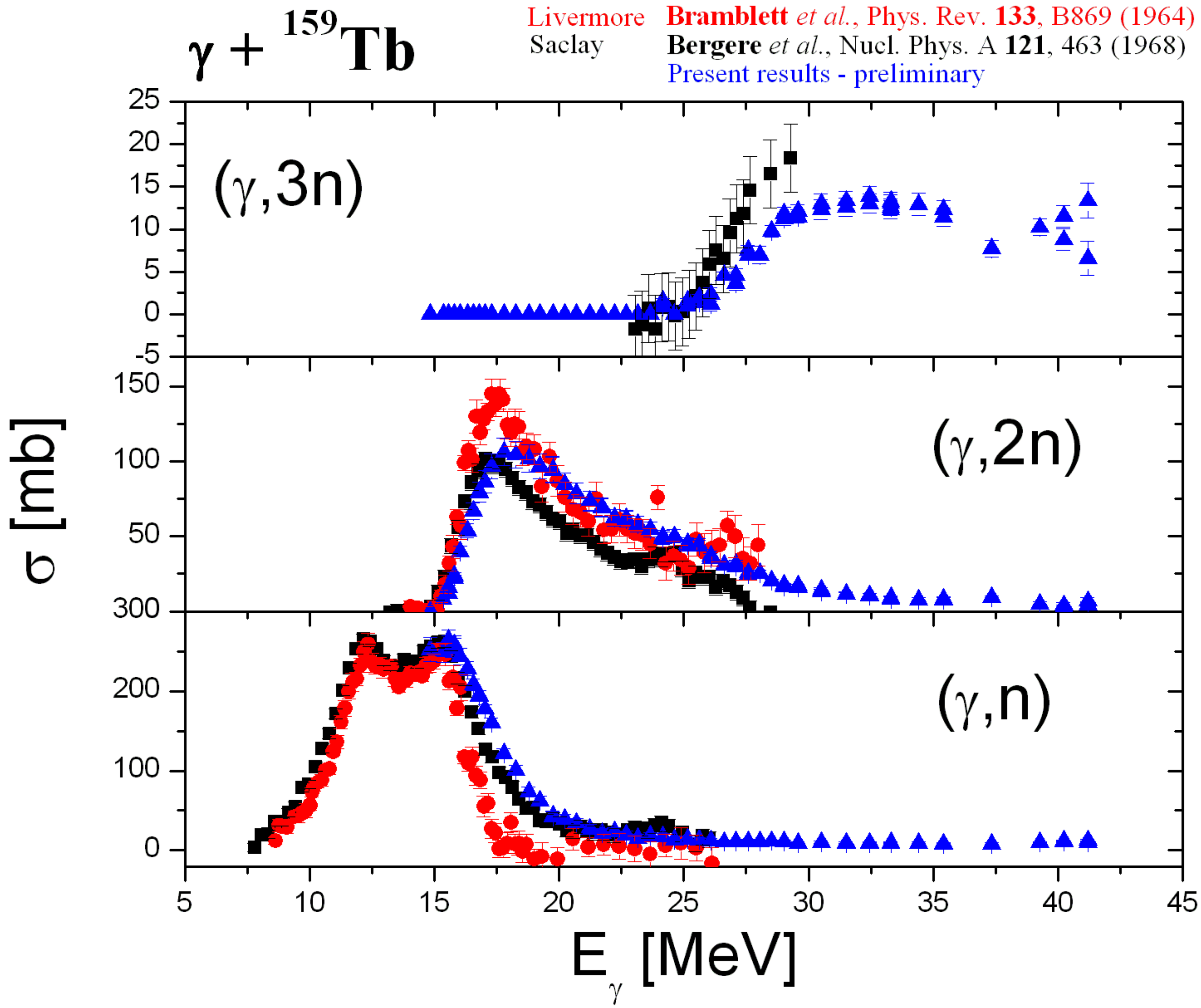
^{169}Tm: GDR parameters retrieved from RIPL-3 - theoretical predictions. The results are compared with the ***preliminary*** NewSUBARU experimetal results.





Preliminary ^{165}Ho(γ,xn) cross sections





γ + ¹⁵⁹Tb
Livermore
Saclay
Bramblett et al., Phys. Rev. 133, B869 (1964)
Bergere et al., Nucl. Phys. A 121, 463 (1968)
Present results - preliminary
(γ,3n)
(γ,2n)
(γ,n)
σ [mb]
E_γ [MeV]

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I. Gheorghe[1], H. Utsunomiya[2], T. Ari-izumi[2], D. Takenaka[2], S. Belyshev[3], K. Stopani[4], V. Varlamov[4], D. Filipescu[1], M. Krzysiek[1,5], G.M. Tveten[6], T. Renstrøm[6], D. Symochko[7], H. Wang[8], G. Fan[8], S. Miyamoto[9]

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