THE HENRYK NIEWODNICZAŃSKI
INSTITUTE OF NUCLEAR PHYSICS
POLISH ACADEMY OF SCIENCES

Nuclear Physics

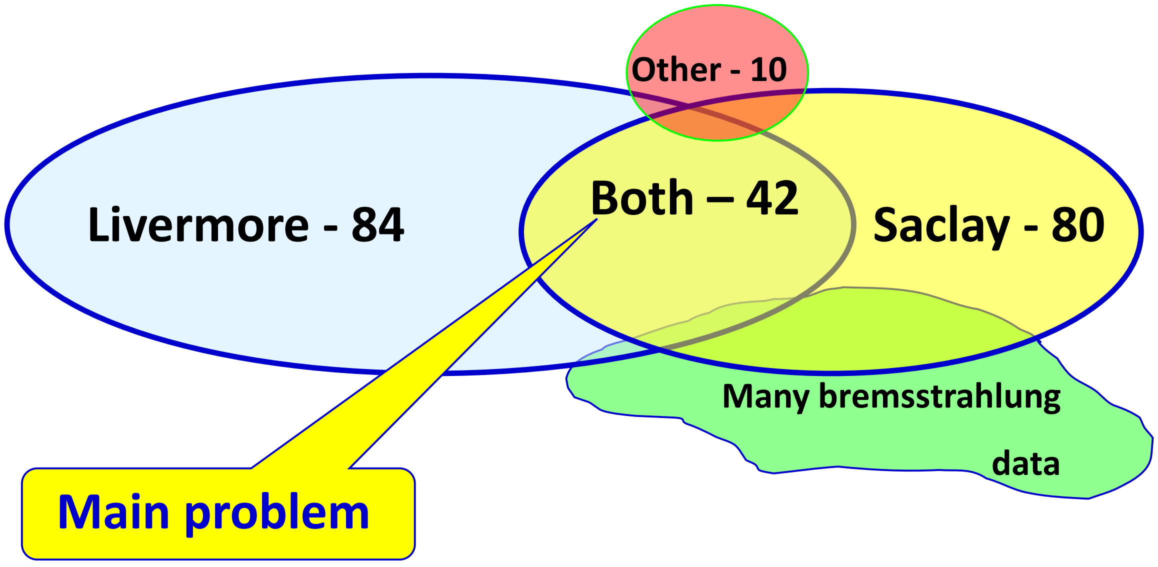
Determination of Photoneutron Cross Sections for ^{165}Ho Using Direct Neutron-Multiplicity Sorting

Mateusz Krzysiek

21st Colloque GANIL 2019 Strasbourg, September 9th-13th 2019

Systematics of the photonuclear C.S. measurements

- Most of the photoneutron cross section measurements were performed in period 1962 – 1986 using quasi-monochromatic annihilation photons using positron in flight annihilation at two major facilities:
  - Saclay (France)
  - 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>

Figure taken from V. Varlamov

Coordinated Research Project on Photonuclear Data and Photon Strength Functions

Approved in July 2015; Code F41032; Duration 2016-2020

Importance of photonuclear data

- radiation shielding and radiation transport analyses
- calculation of absorbed does in the human body during radiotherapy
- activation analyses, safeguards and inspection technologies
- nuclear waste transmutation
- fission and fusion reactor technologies
- astrophysical nucleosynthesis

Main objective of new CRP

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

Specific Research Objectives

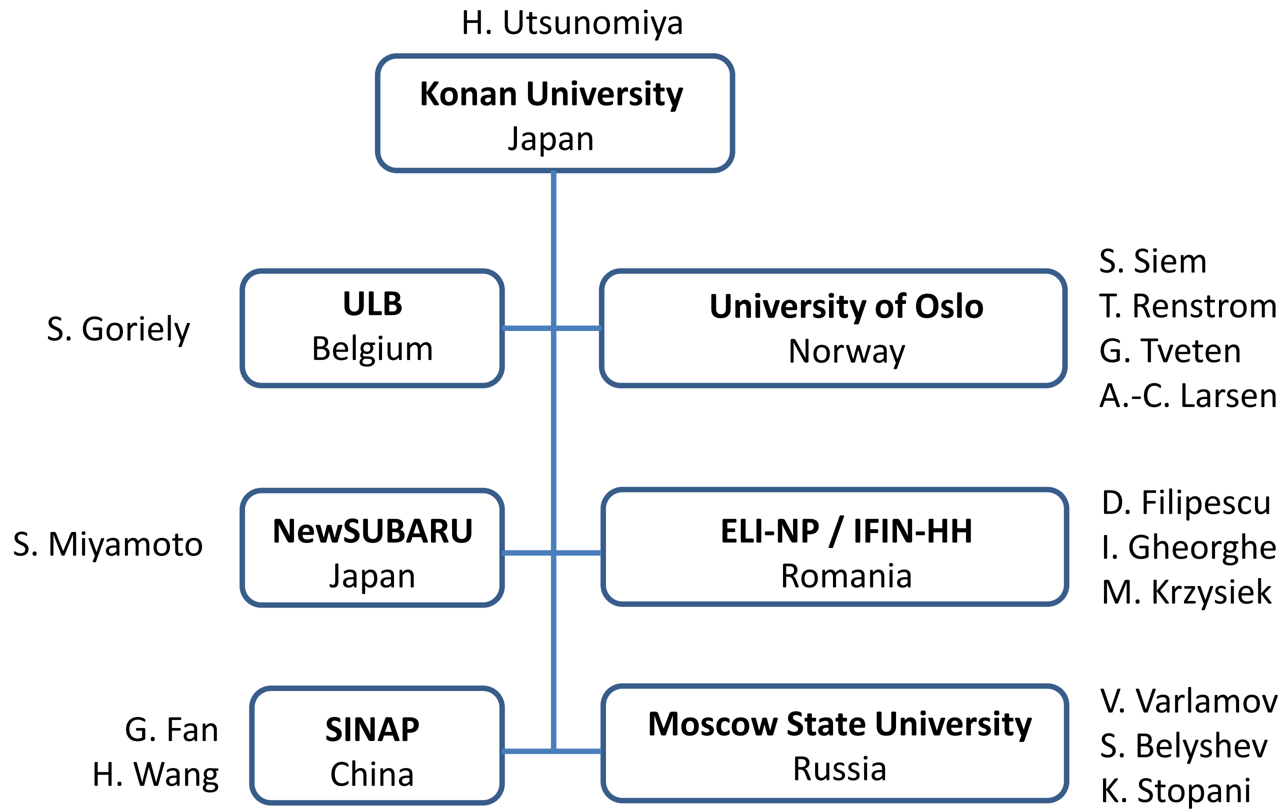
- Measure photonuclear cross-section data where needed
- Update existing evaluations and evaluate new photonuclear data
- Measure photon strength functions where needed
- Compile, assess and evaluate existing photon strength function data
- Develop and use theoretical tools to make recommendations and extrapolations to mass regions where no data exist
- Propose new measurements where needed

PHOENIX Collaboration

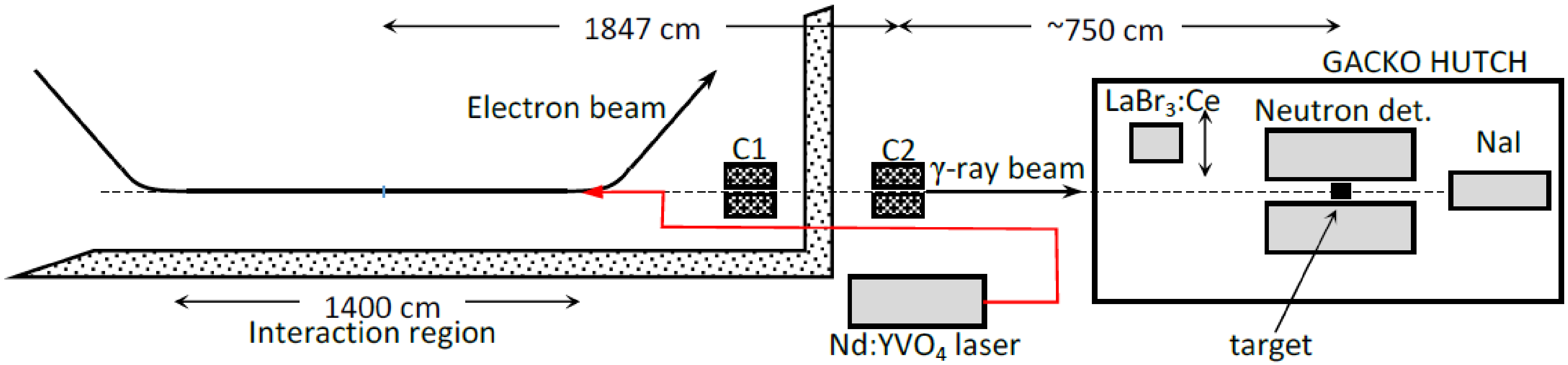
(Photo-excitation and neutron emission cross (x) sections)

Data taking

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



Experimental setup and method



$$\sigma(E_\gamma) = \frac{\#\ \text{interactions}}{\#\ \text{incident photons}\ \#\ \text{target nuclei}}$$

E_γ

- energy calibration of electron beam – Maximum γ-ray beam energy
- average energy of incident γ-ray beam - good knowledge of incident γ-ray beam spectra

 # interactions

- reaction neutrons recorded with a flat efficiency 4pi neutron detector
- detection efficiency calibration and simulation
- RingRatio method of obtaining the reaction neutron average energy

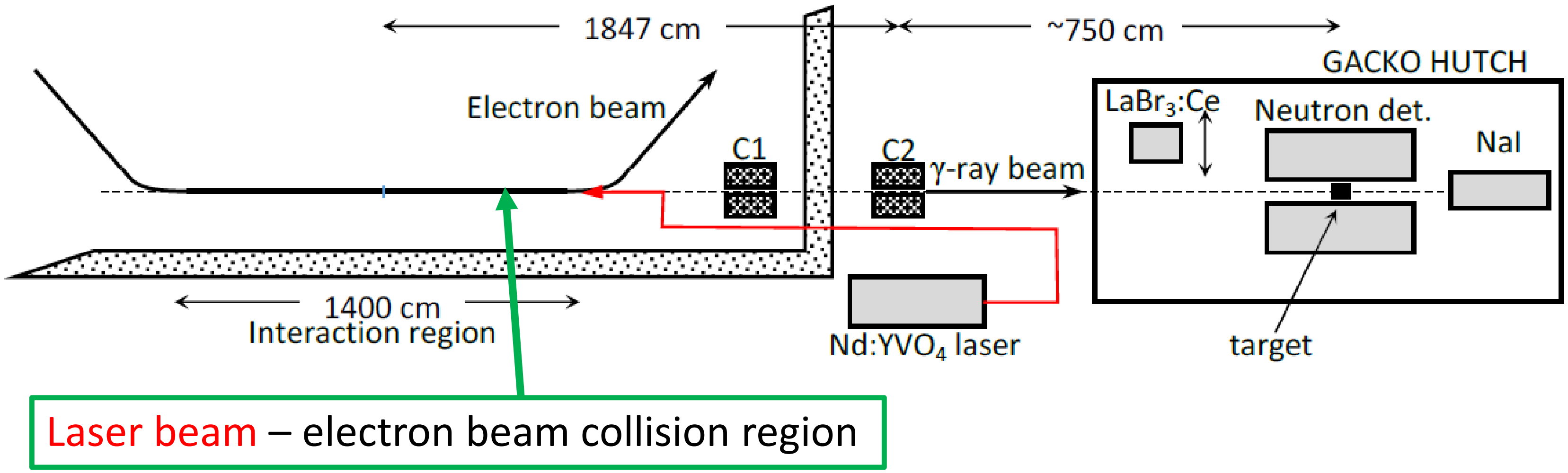
 # incident photons

- Flux monitor - large volume 8” x 12” NaI(Tl) detector
- For high-energy and pulsed γ-ray beams – Pile-up method
- # photons above S_n - good knowledge of incident γ-ray beam spectra

 # target nuclei

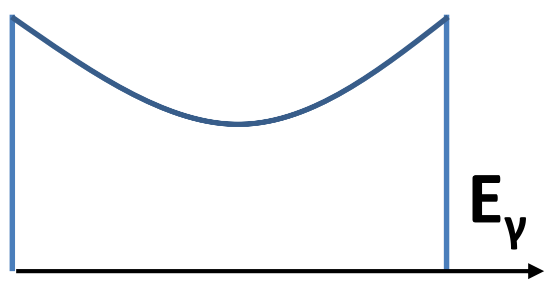
- good knowledge of chemical and isotopical composition
- mass measurement
- transverse surface measurement (4, and 8.14 mm thick targets were used)

γ-ray beam production

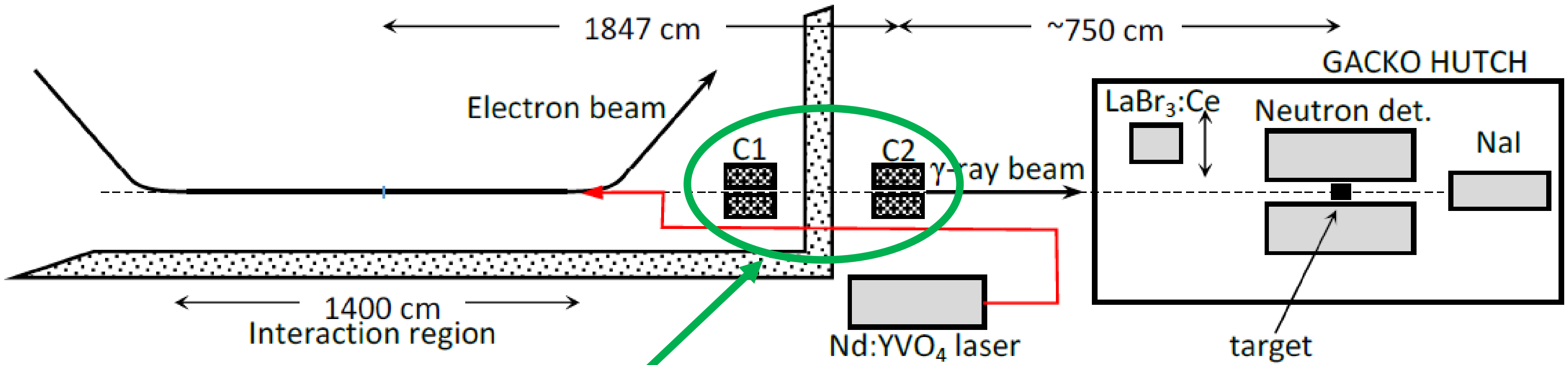


Continuous *Compton* photon spectrum is produced

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

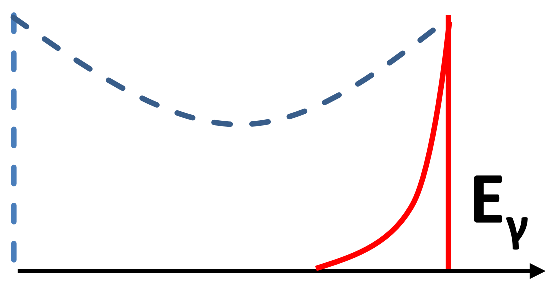


γ-ray beam collimation



Backscattered photons (maximum energy section of the Compton spectrum) selected using collimators.

Quasi-monochromatic photon beam is produced

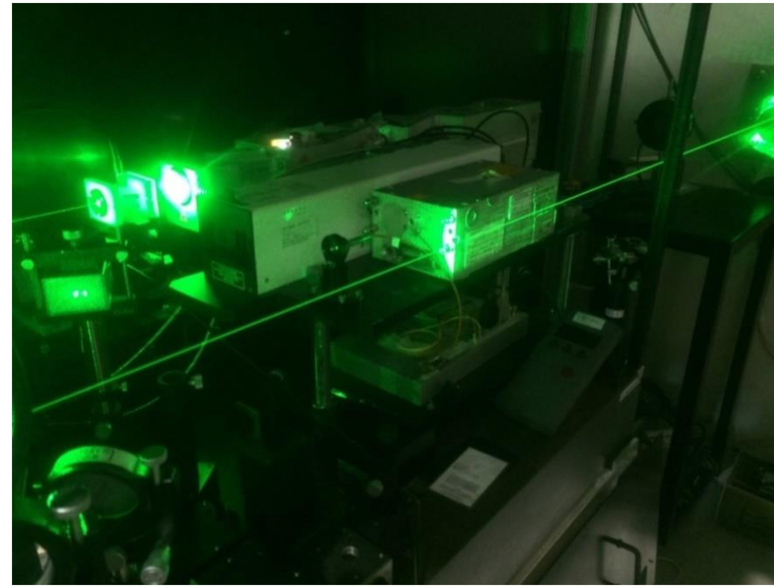


$E_\gamma < S_{2n}$ /max. 38 MeV/

Nd:YVO_4 (Inazuma) laser Ist harmonic
(λ = 1064 nm; power = 40 W)

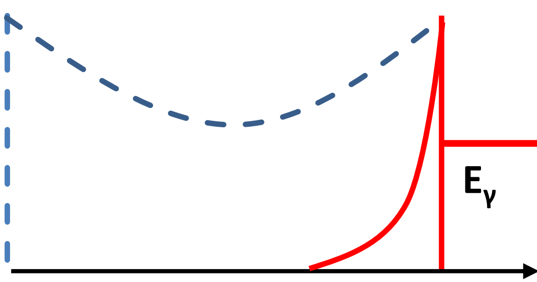
$E_\gamma > S_{2n}$ /max. 74 MeV/

Nd:YVO_4 (Talon) laser IInd harmonic
(λ = 532 nm; power = 20 W)



Electron beam energy between 0.5 and 1.5 GeV

How do we know the absolute energy of the γ-ray beams?

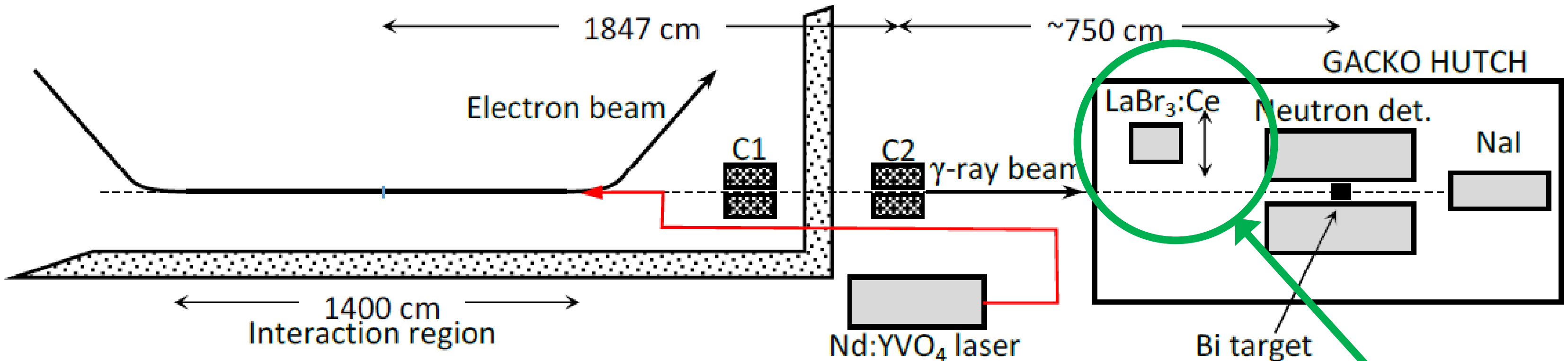


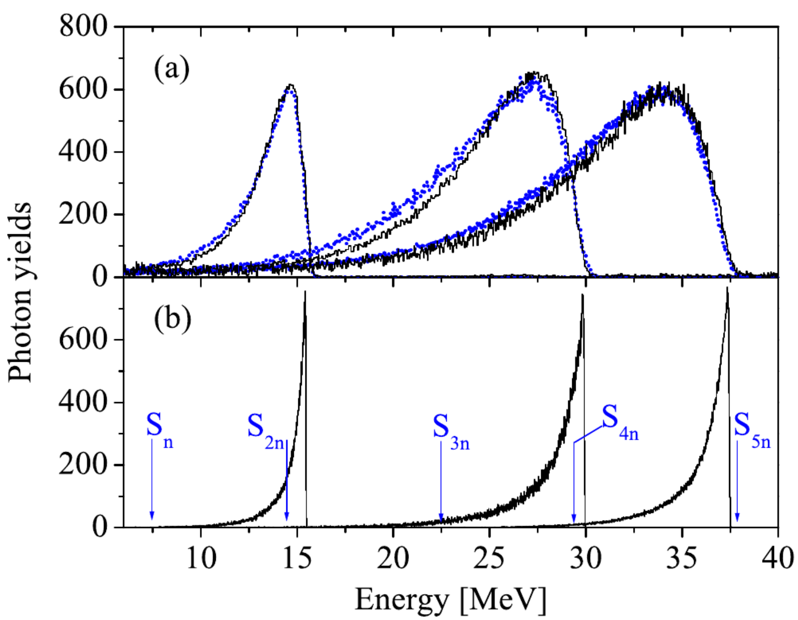
$$E_\gamma^{max} \approx \frac{4\gamma^2 E_p}{1 + 4\gamma^2 E_p / E_e}$$

Laser photon energy – given by atomic transitions in the active medium of the laser
Electron beam energy – calibrated (10^{-5} uncertainty) using low energy γ-ray beams generated with a large wavelength (10.6 μm) CO_2 laser

H. Utsunomiya *et al.*, IEEE TRANSACTION ON NUCLEAR SCIENCE (61),3, 2014

Incident γ-beam spectra

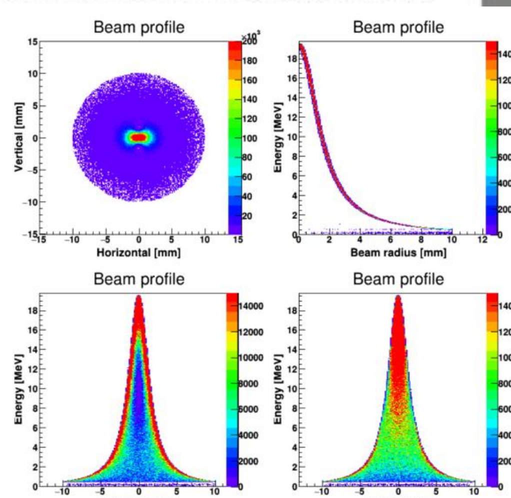


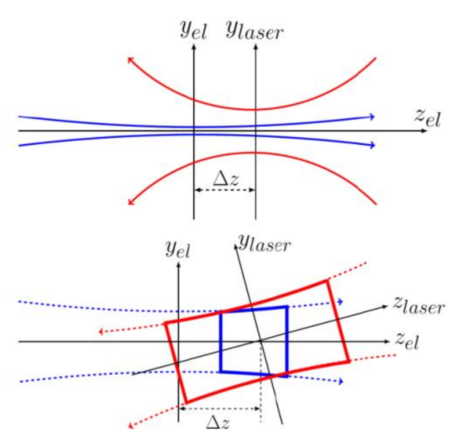


Beam profile monitor:
3.5" x 4.0" $LaBr_3(Ce)$

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).

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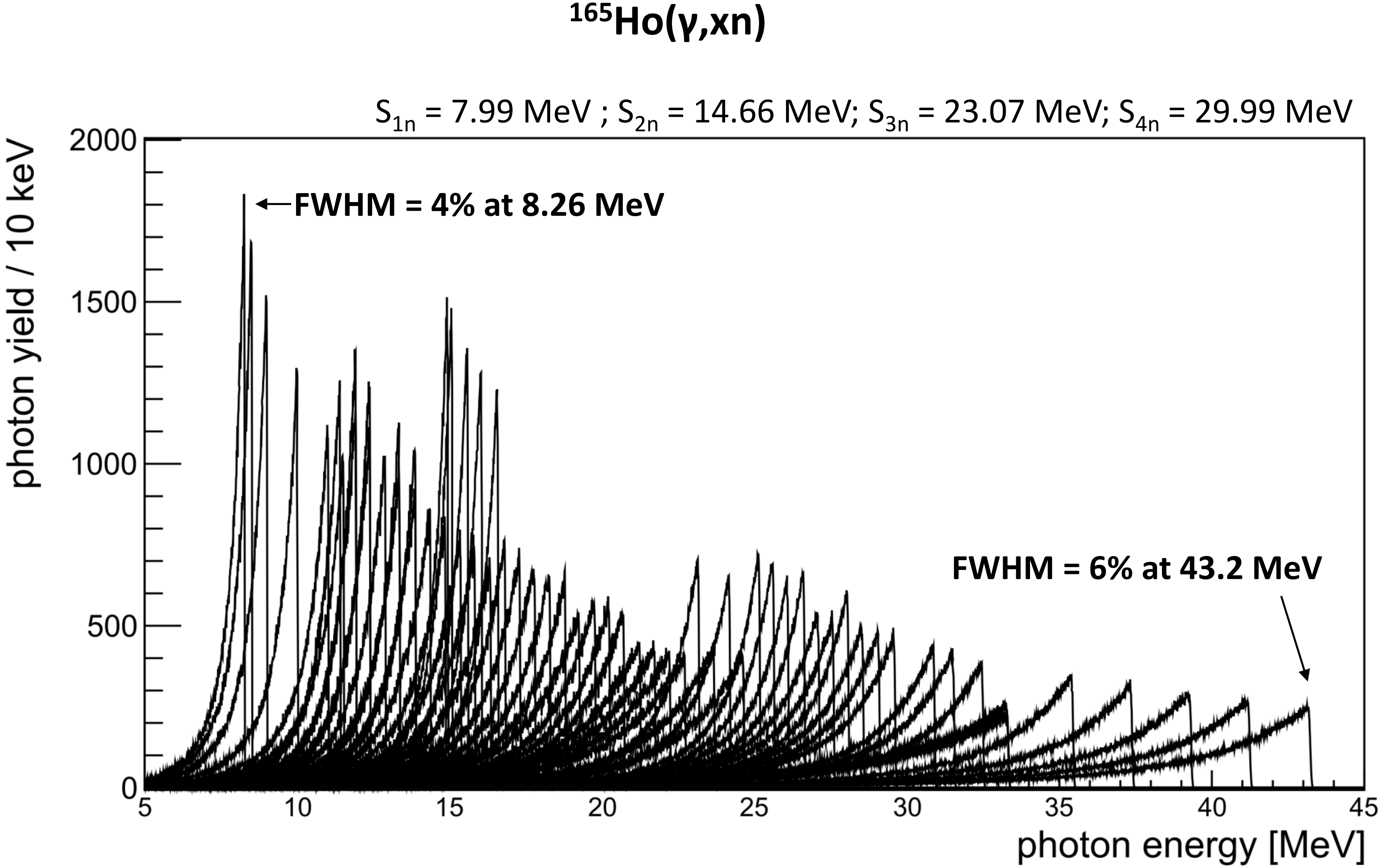
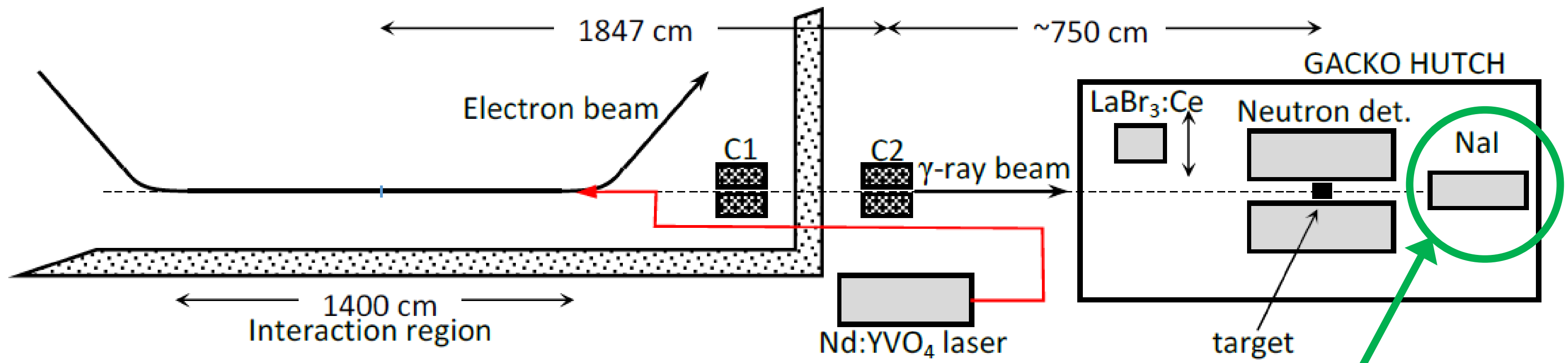
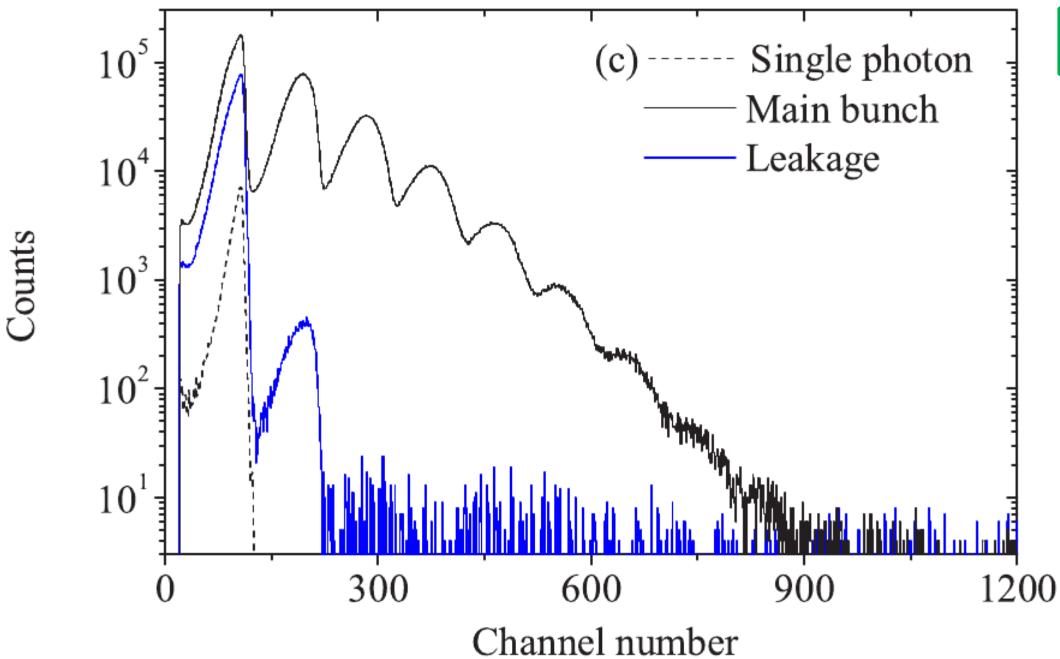


Number of incident photons on target





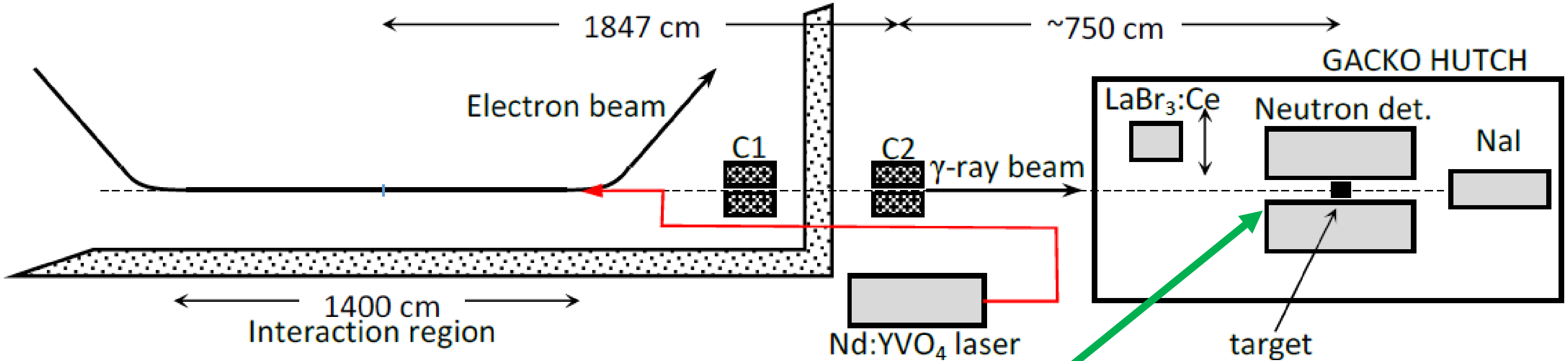
Pile-up and single photon spectra, 24 MeV.
The main LCS γ-ray spectrum displays a Poisson distributed pile-up structure with an average of 1.9 photons/bunch

8" × 12" NaI(Tl) detector;

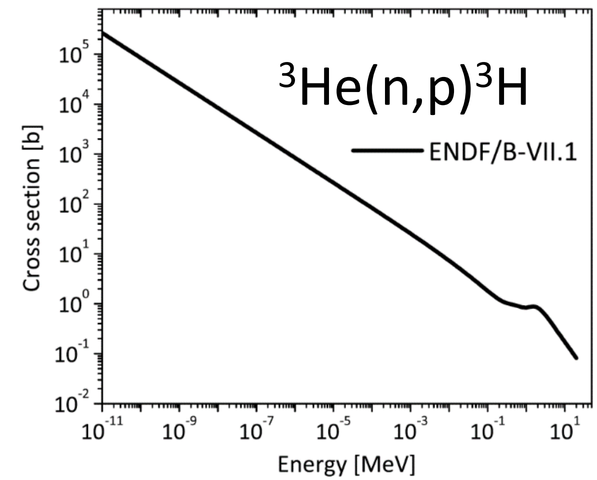
- Pile-up spectra was acquired in beam at full laser power;
- Before and after each measurement single photon spectra was measured at low laser power;
- Total number of photons was obtained as weighting average of the pile-up spectra using single photon spectra as weighting function;
- Beam intensity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

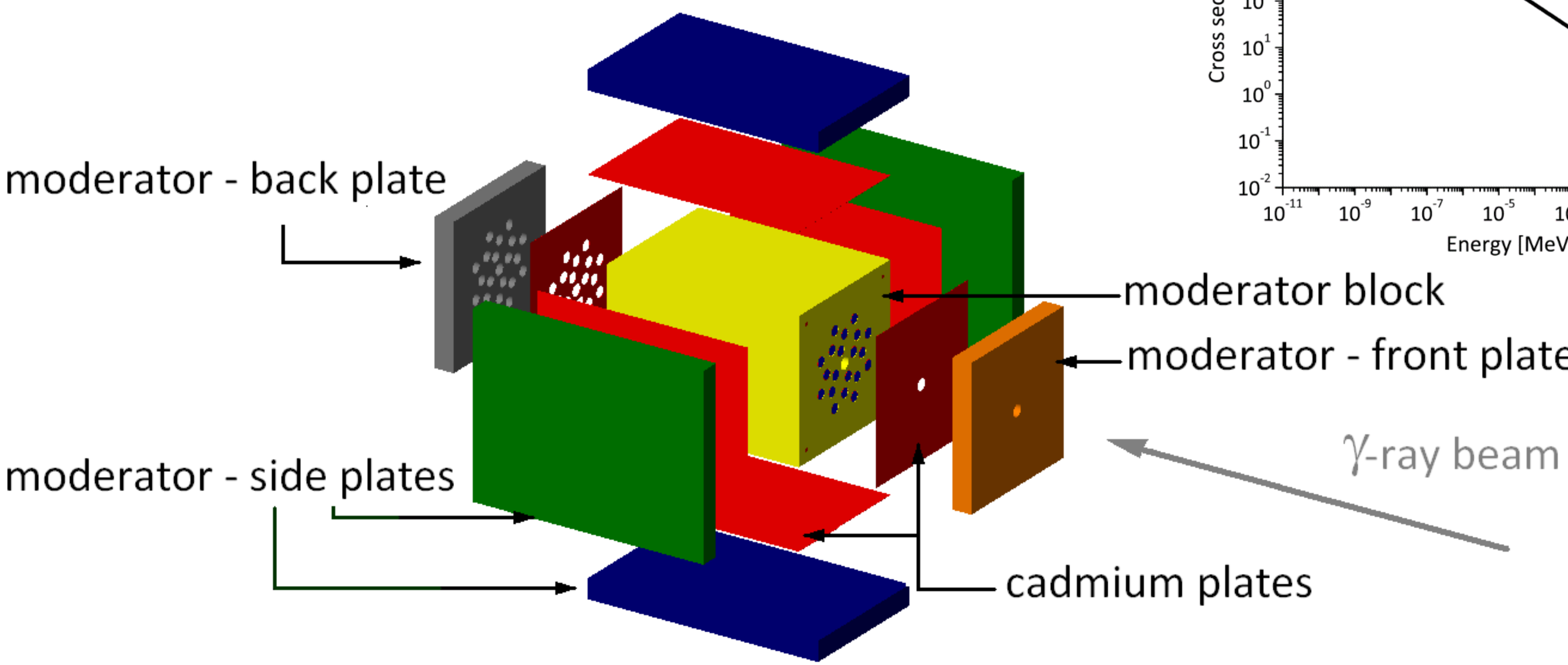
$$N_{\gamma,\mathrm{det}} = \frac{\langle i \rangle_{\mathrm{pileup}}}{\langle i \rangle_{\mathrm{single}}} \left(\sum n_i \right)_{\mathrm{pileup}}$$

Target irradiation and neutron detection



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





Direct neutron multiplicity sorting

Let us consider (γ, xn) reactions with x = 1, 2, 3.

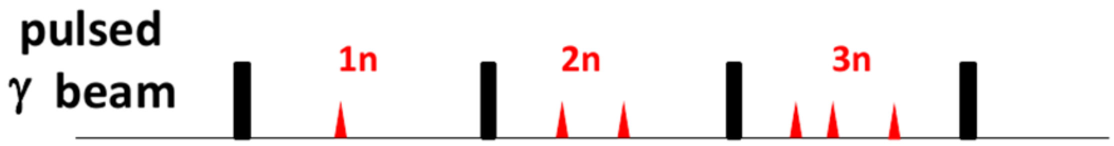
If we can measure the number of the (γ, xn) reactions N_x, we can determine the cross sections σ (γ, xn):

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

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

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

We don't measure the number of reactions but number of coincident neutrons N_s, N_d, N_t



Time between consecutive γ-ray bunches ≈ neutron moderation time

- 1 ms laser pulsing - comparable to the moderation time of neutrons inside the polyethylene block
- 20 ms Beam ON / 80 ms Beam OFF data for background subtraction

1 γ-ray bunch generates no more than 1 reaction → low reaction rates required

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<u>Single neutron events</u>

$$N_s = \boxed{N_1} \cdot \varepsilon(E_1) + \boxed{N_2} \cdot C_1^2 \cdot \varepsilon(E_2) \cdot \big(1 - \varepsilon(E_2)\big) + \boxed{N_3} \cdot C_1^3 \cdot \varepsilon(E_3) \cdot (1 - \varepsilon(E_3))^2$$

<u>Double neutron events</u>

$$N_d = \boxed{N_2} \cdot \varepsilon(E_2)^2 + \boxed{N_3} \cdot C_2^3 \cdot \varepsilon(E_3)^2 \cdot (1 - \varepsilon(E_3))$$

$\varepsilon(E)$:detection efficiency

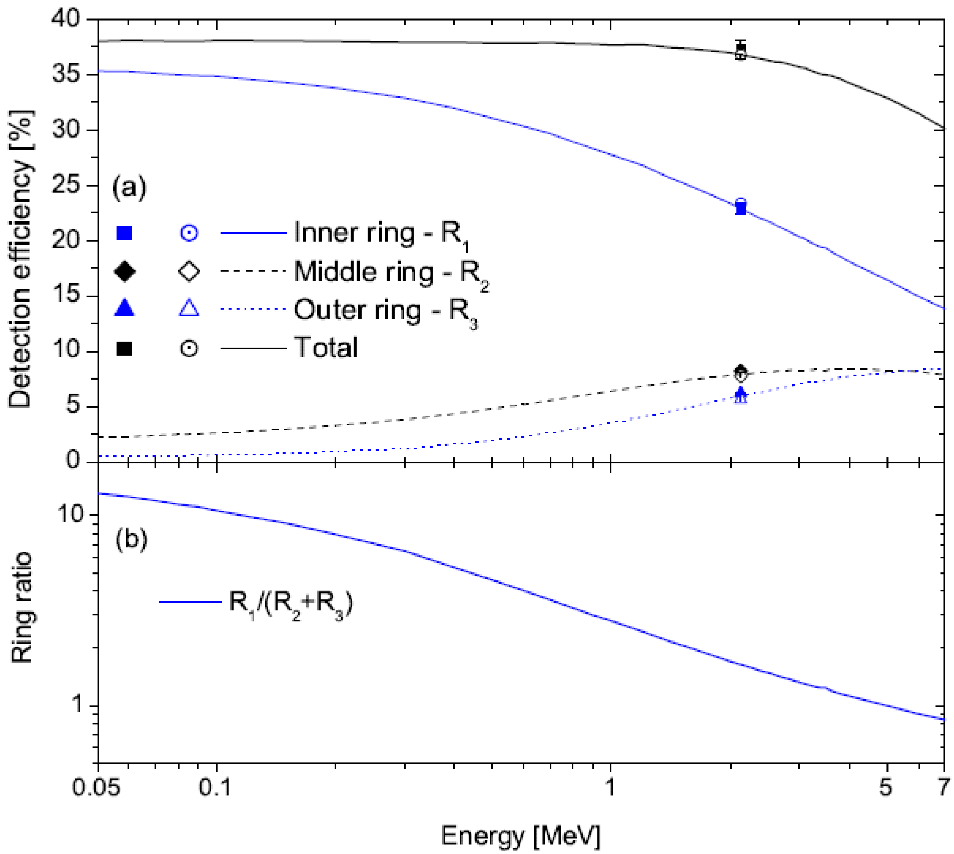
<u>Triple neutron events</u>

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

Solve the system of equations ⇒ N_1, N_2, N_3

Problem: can not estimate $\varepsilon(E_1)$, $\varepsilon(E_2)$, $\varepsilon(E_3)$

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:

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

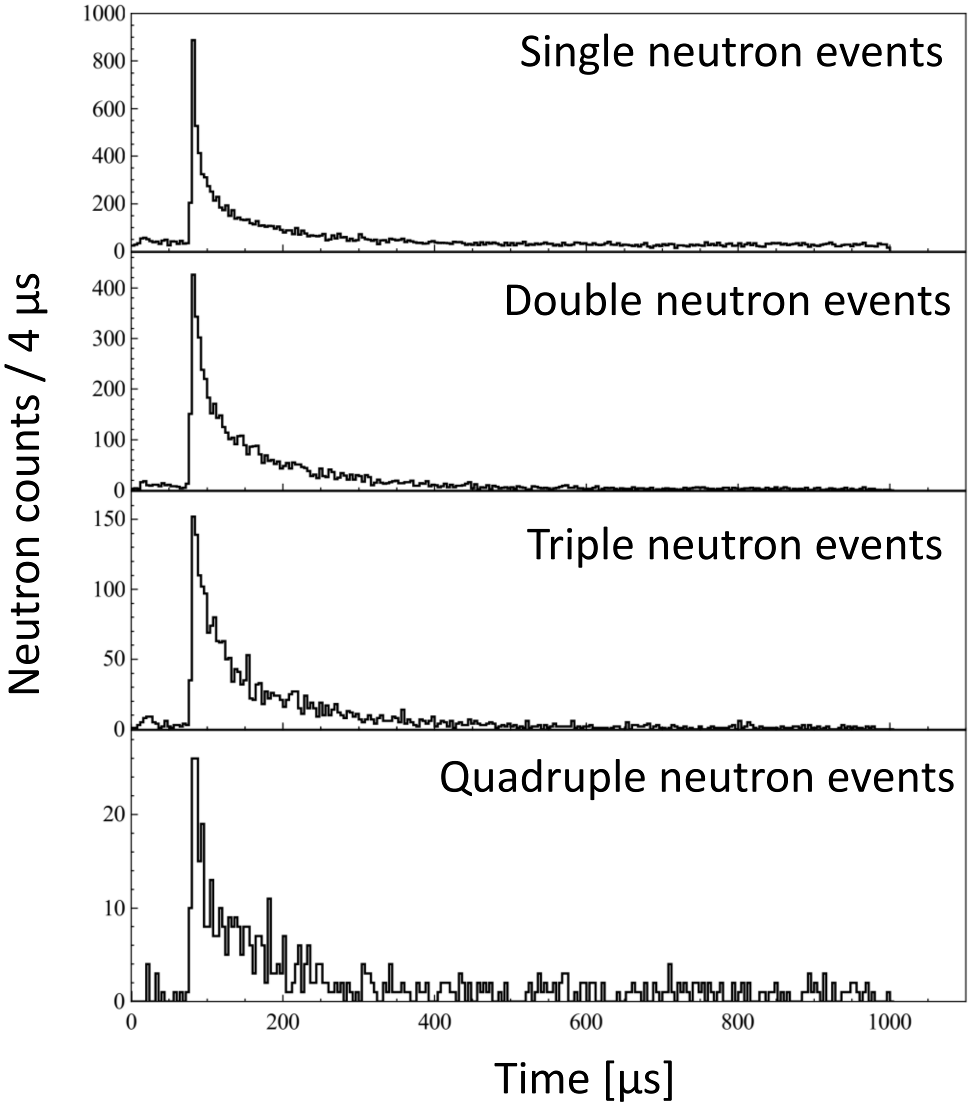
Only one neutron detected:

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

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

Number of 1, 2, 3 and 4 neutron coincidence events

Neutron moderation time curves for coincidences of 1-4 neutrons.



^{165}Ho(γ,xn) reactions

for E_{γ}^{max} = 43.2 MeV

Measured cross sections in *monochromatic* approximation

1) $$N_j = \sum_{i=j}^{m} {}_iC_j \cdot R_i \cdot \varepsilon^j (1-\varepsilon)^{i-j}$$

Measured cross sections in *monochromatic* approximation

1) $N_j = \sum_{i=j}^{m} {}_iC_j \cdot \boxed{R_i} \cdot \varepsilon^j (1-\varepsilon)^{i-j}$ Solve the system of equations $\Rightarrow$ $\mathbf{R_x}$

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Solve the system of equations $\Rightarrow R_x$

2) $$\sigma_{\gamma xn}^{\text{mono}} = \frac{R_x}{N_t N_\gamma \xi f_x}$$

R_x = # (γ,xn) induced reactions
N_t = # target nuclei / unit surface
N_γ = #incident γ-rays on the target
ξ = thick target correction factor
f_x = fraction of photons above S_{xn}

Measured cross sections in *monochromatic* approximation

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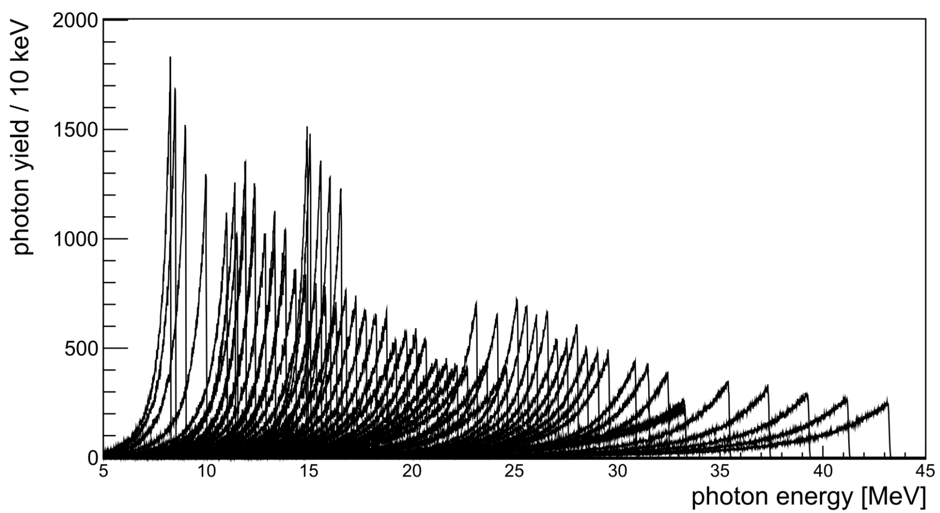
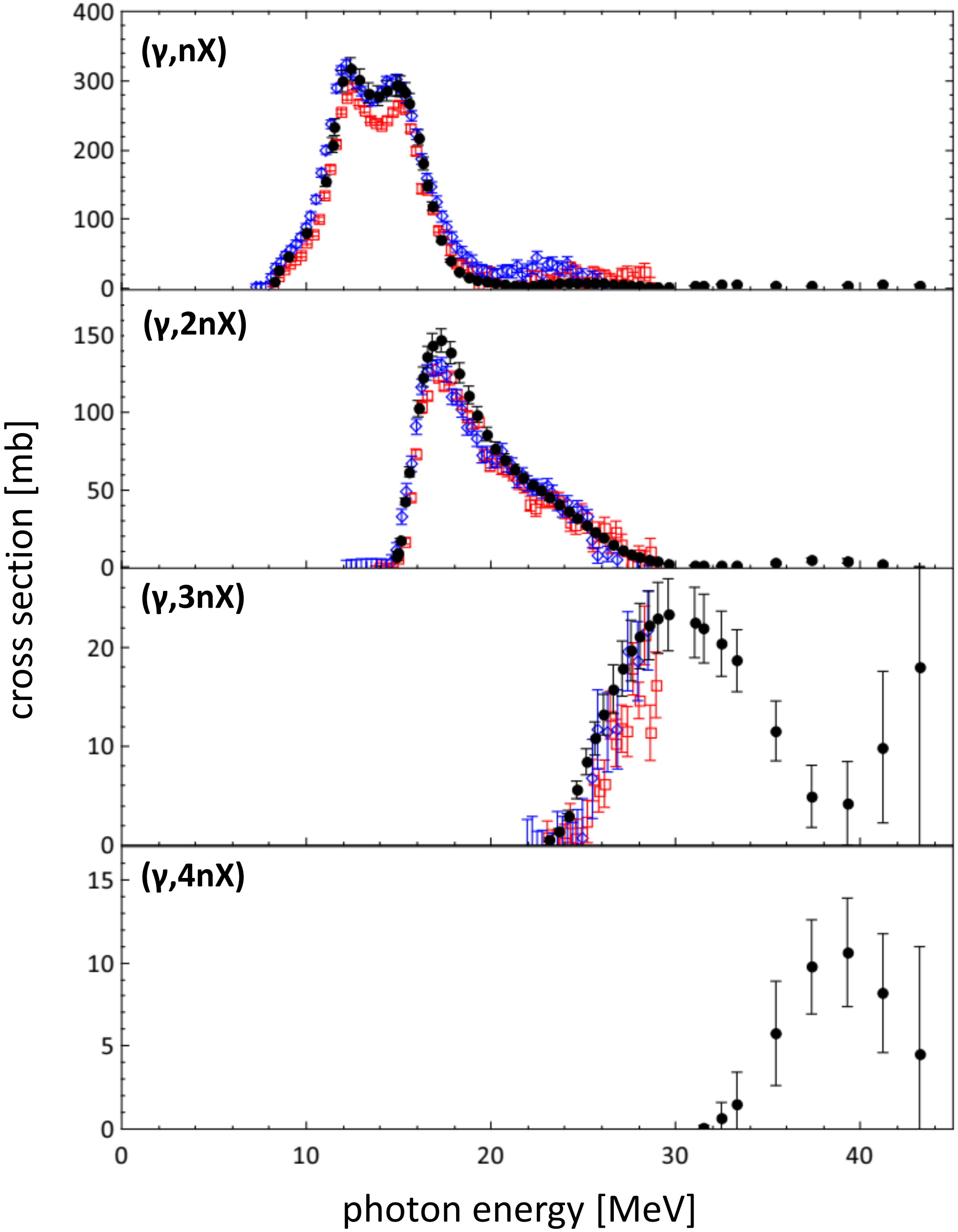
Deconvolution for incident photon spectra

(γ,xn) cross sections to be unfolded using an iterative method of reproducing the monochromatic cross sections by folding a trial cross section with the incident γ spectrum.



Partial photoneutron cross sections - unfolded



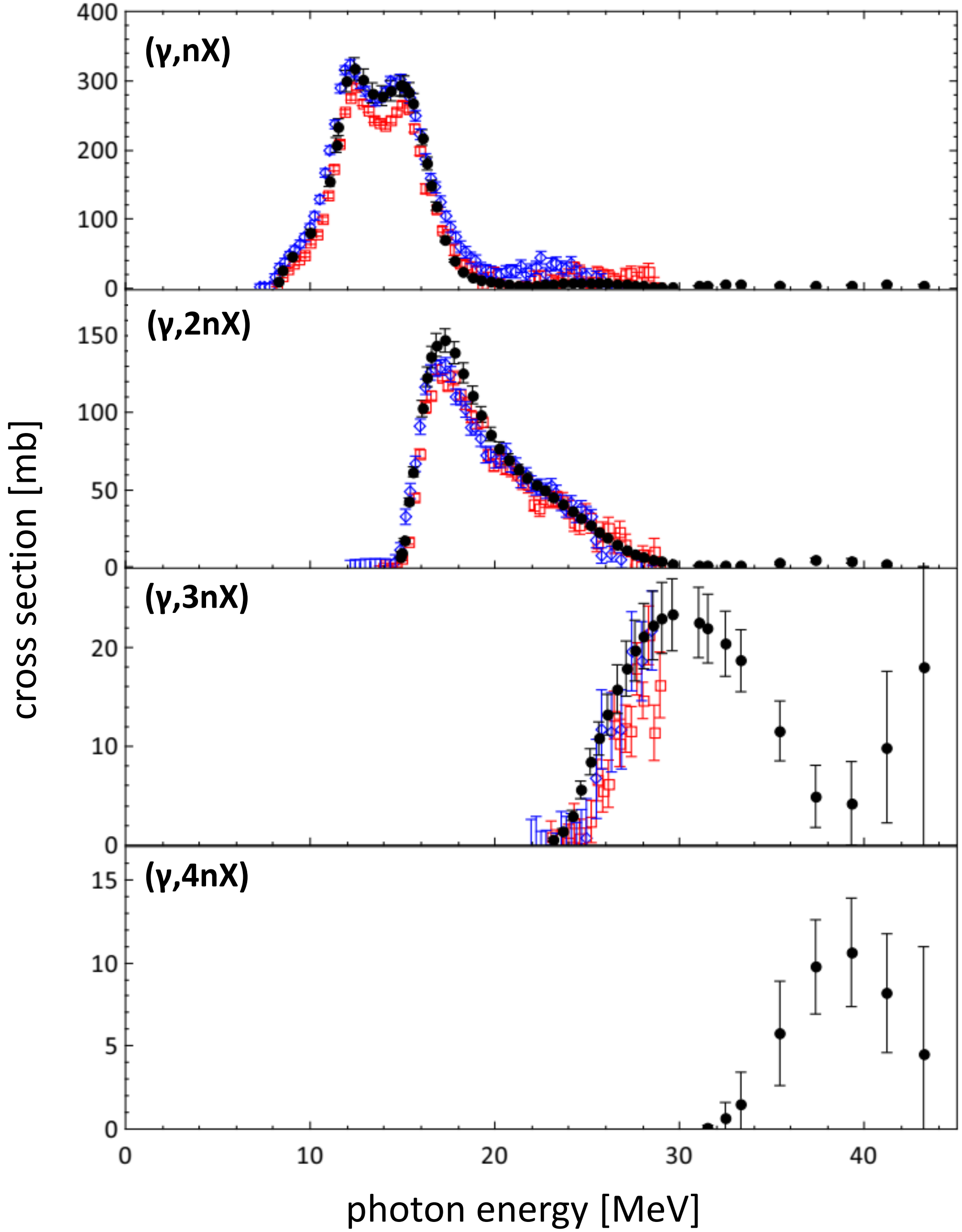
γ + ^{165}Ho

Saclay **Bergere** *et al.*, (1968)

Livermore **Berman** *et al.*, (1969)

Present results - preliminary

Partial photoneutron cross sections - unfolded



γ + ^{165}Ho

Saclay **Bergere** *et al.*, (1968)

Livermore **Berman** *et al.*, (1969)

Present results - preliminary

Preliminary conclusions

- (γ,n) similar to Bergere et al.
- (γ,2n) higher than both
- (γ,3n) similar to Bergere et al.
- (γ,4n) measured for the first time

Preparing ELI-NP Gamma above Neutron Threshold experiments

IFIN 9 MV Tandem proposal,
together with the Oslo, Milano, Kobe, Moscow, Darmstadt and Krakow collaborators.

Preparatory Gamma Above Neutron Threshold experiments

Present study: Test and calibration of the ELIGANT-TN flat efficiency neutron detection system

T. Renstrøm,[1] D. Filipescu,[2] I. Gheorghe,[2] T. Glodariu,[2] M. Krzysiek,[2,3] M. Boromiza,[4] A. Negret,[4] A. Olacel,[4] C. Petrone,[4] F.L. Bello Garrote,[1] H. Berg,[1] F. Furmyr,[1] D. Gjestvang,[1] G. Henriksen,[1,5] V.W. Ingeberg,[1] A.-C. Larsen,[1] V. Modamio,[1] L.G. Pedersen,[1] S. Rose,[1] S. Siem,[1] G. Tveten,[1] F. Zeiser,[1] S. Belyshev,[6] A. Kuznetsov,[7] K. Stopani,[7] P. van Beek,[8] H. Scheit,[8] D. Symochko,[8] M. Ciemala,[3] M. Kmiecik,[3] A. Maj,[3] F. Camera,[9,10] G. Gosta,[9] O. Wieland,[9] T. Ari-izumi,[11] and H. Utsunomiya[11]

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Preparatory Gamma Above Neutron Threshold experiments

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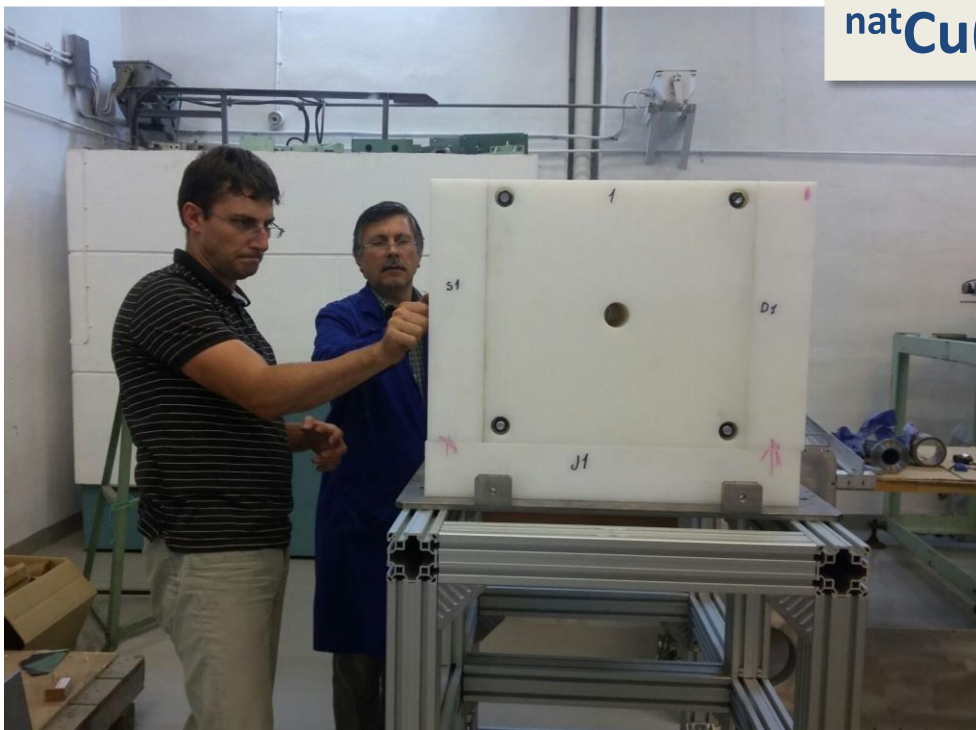
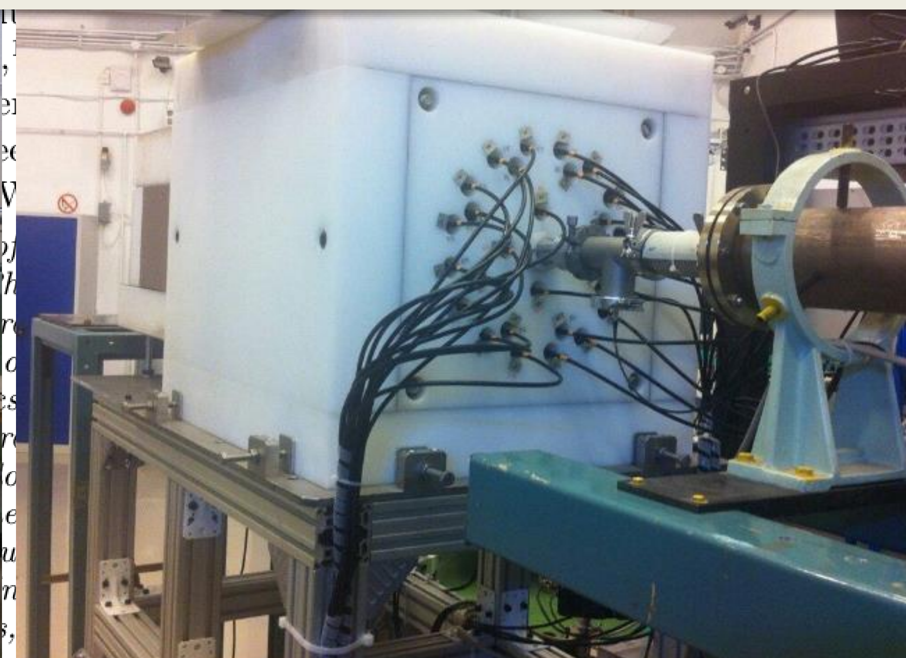
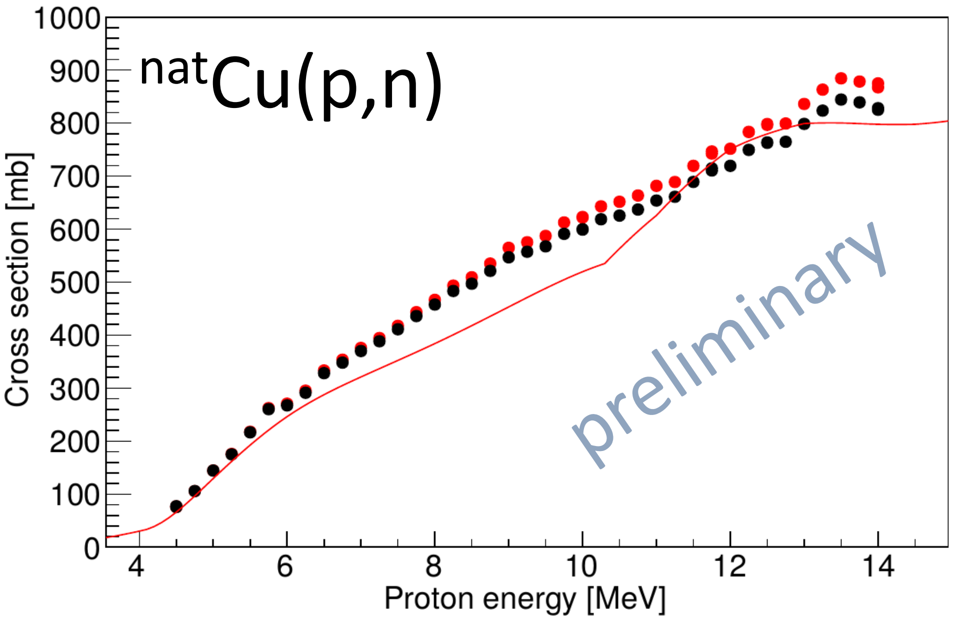
$^{nat}Cu(p, n)$ and $^{nat}Al(p, n)$ cross sections





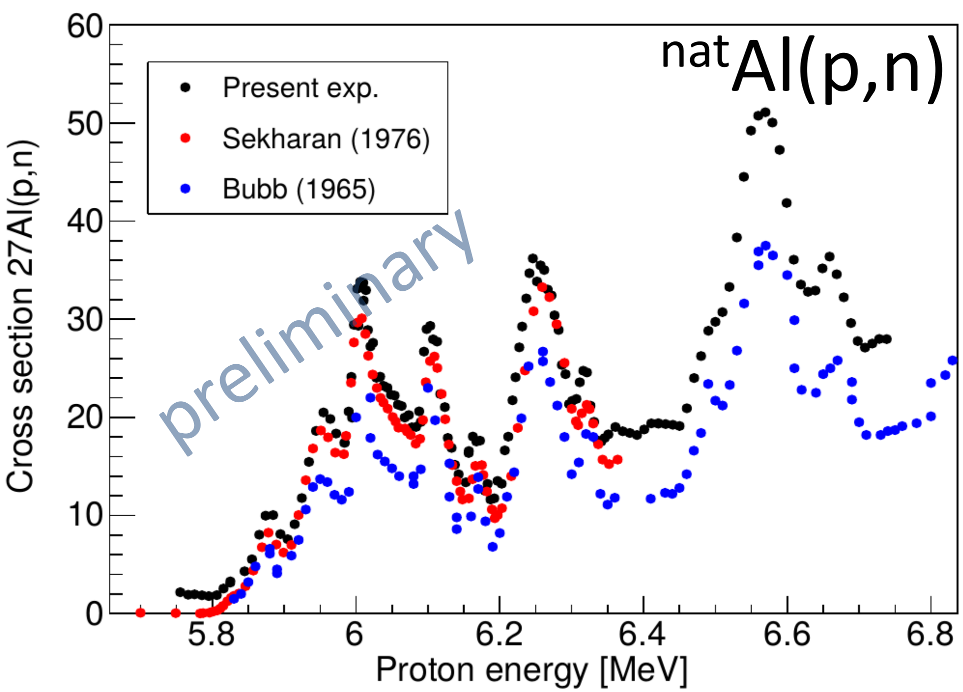
[11]Department of Physics, Konan University, Okamoto 8-9-1, Higashinada, Kobe 658-8501, Japan



Red curve: IAEA recommendation

Red dots: Present results considering constant 37% efficiency

Black dots: Present results considering ring ratio deduced efficiency



Black dots: Present results considering constant 37% efficiency

EUROPEAN UNION

Structural Instruments 2014-2020

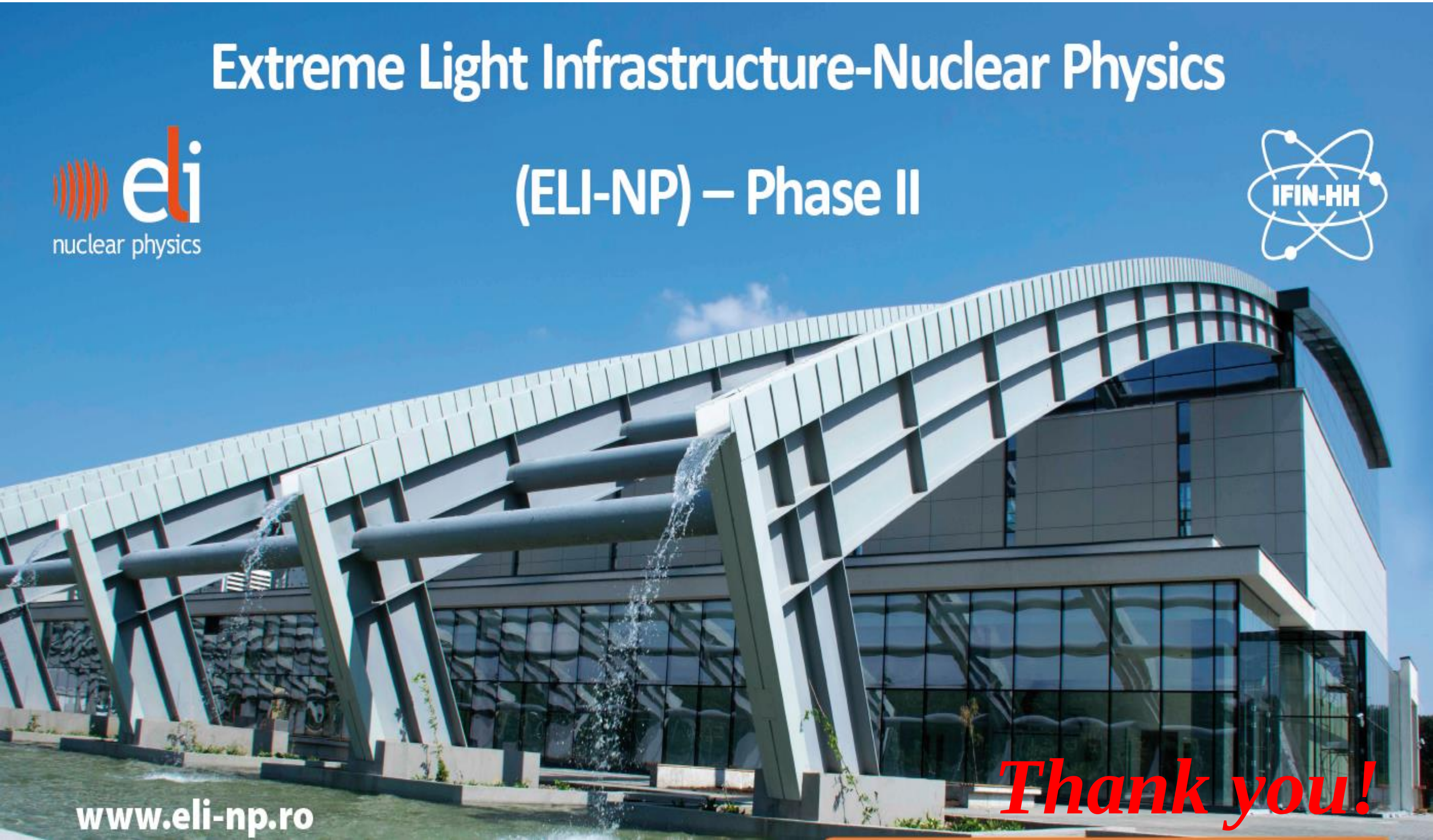
Project co-financed by the European Regional Development Fund through the Competitiveness Operational Programme
“Investing in Sustainable Development”

Extreme Light Infrastructure-Nuclear Physics

eli nuclear physics

(ELI-NP) – Phase II

IFIN-HH



Collaboration

M. Krzysiek[1,2], I. Gheorghe[2,3], H. Utsunomiya[4], D. M. Filipescu[2,4], S. Belyshev[5], K. Stopani[6], T. Renstrøm[7], G. M. Tveten[7], H. Wang[8], G. Fan[8], Y-W. Lui[9], T. Ari-izumi[4], S. Miyamoto[10], H. Scheit[11], D. Symochko[11], E. Açiksöz[2], M. Boromiza[4], F. Camera[12], C. Costache[4], I. Dinescu[4], G. Gosta[12], A. Ionescu[4], A. Maj[1] , A. Negret[4], C. Nita[4], A. Olacel[4], C. Petrone[4], A. Serban[4], C. Sotty[4], L. Stan[4], R. Suvaila[4], S. Toma[4], A. Turturica[4], S. Ujeniuc[4], O.Wieland[12], F.B. Zeiser[7]

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[12] INFN section of Milano, Italy

Thank you!

Direct neutron multiplicity sorting method

Validation against full Monte Carlo simulations of the experiment

- Implement the detection geometry and physics processes into the Geant4 code
- ***<u>Simulate realistic (g,xn) photoneutron emissions</u>***

Neutron source simulated using a Monte Carlo reaction modelling code (provided by T. Kawano)

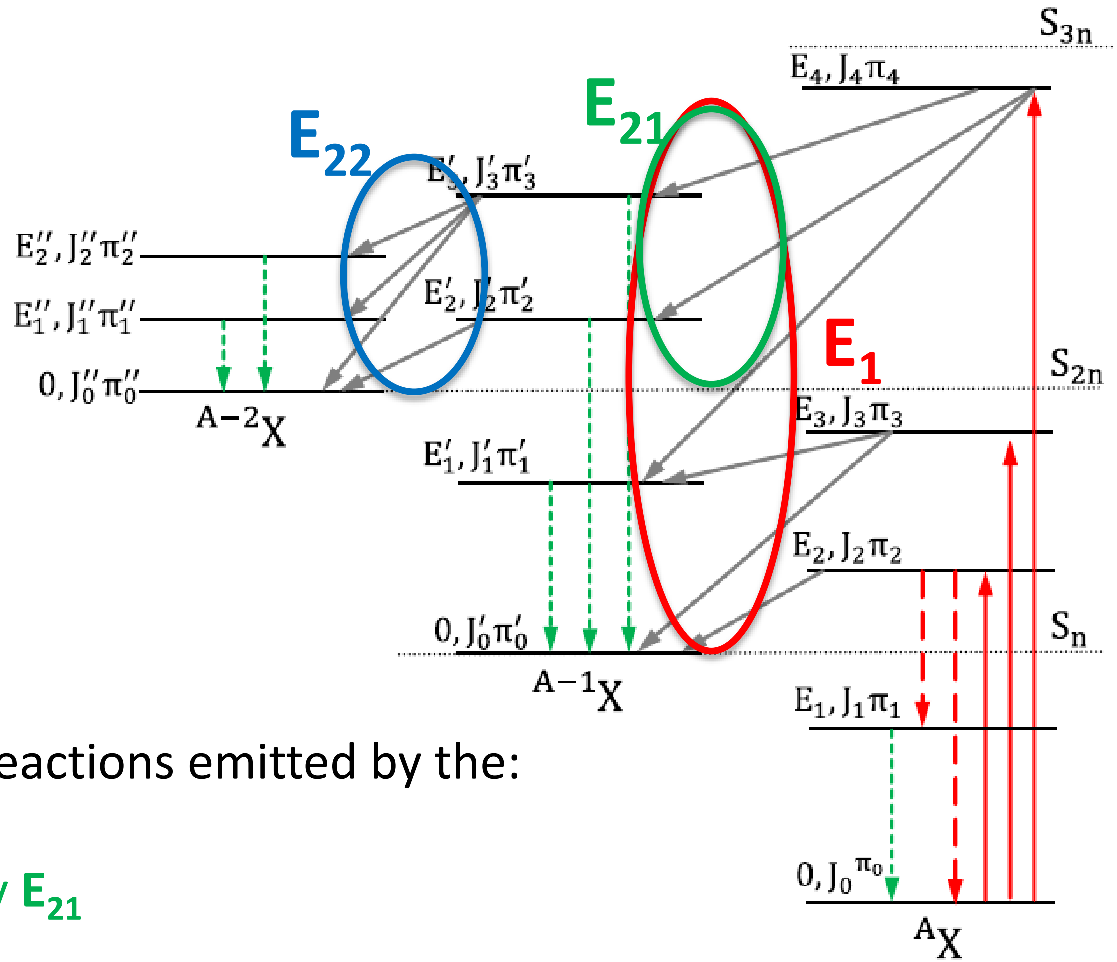
- ^{209}Bi(g,xn) neutron emission spectra
- The code provides specific decay paths for each event:
  - Particle type and energy for each CN, event
- Isotropic emission was considered

Validation procedure

1. Emit the reactions from the center of the detector
2. Transport the reaction particles through the detector
3. Analyse the simulated ^3He counter energy deposition spectra using the DNM sorting technique.
4. Compare the DNM results with the input ones, namely the Kawano ones.

Why use the Kawano MC SM calculation?

Energy spectrum of each successive emitted neutron for each reaction channel is needed.
Example for measurements above S_{2n} and below S_{3n}



Neutrons from (g,1n) reactions
Average energy $\mathbf{E_1}$
Energy range: 0 to E_g-S_n

Neutrons from (g,2n) reactions emitted by the:

- ^{A}X nucleus
  - Average energy $\mathbf{E_{21}}$
- ^{A-1}X nucleus
- Average energy $\mathbf{E_{22}}$

Energy range: ~(0 to E_g–S_{2n})

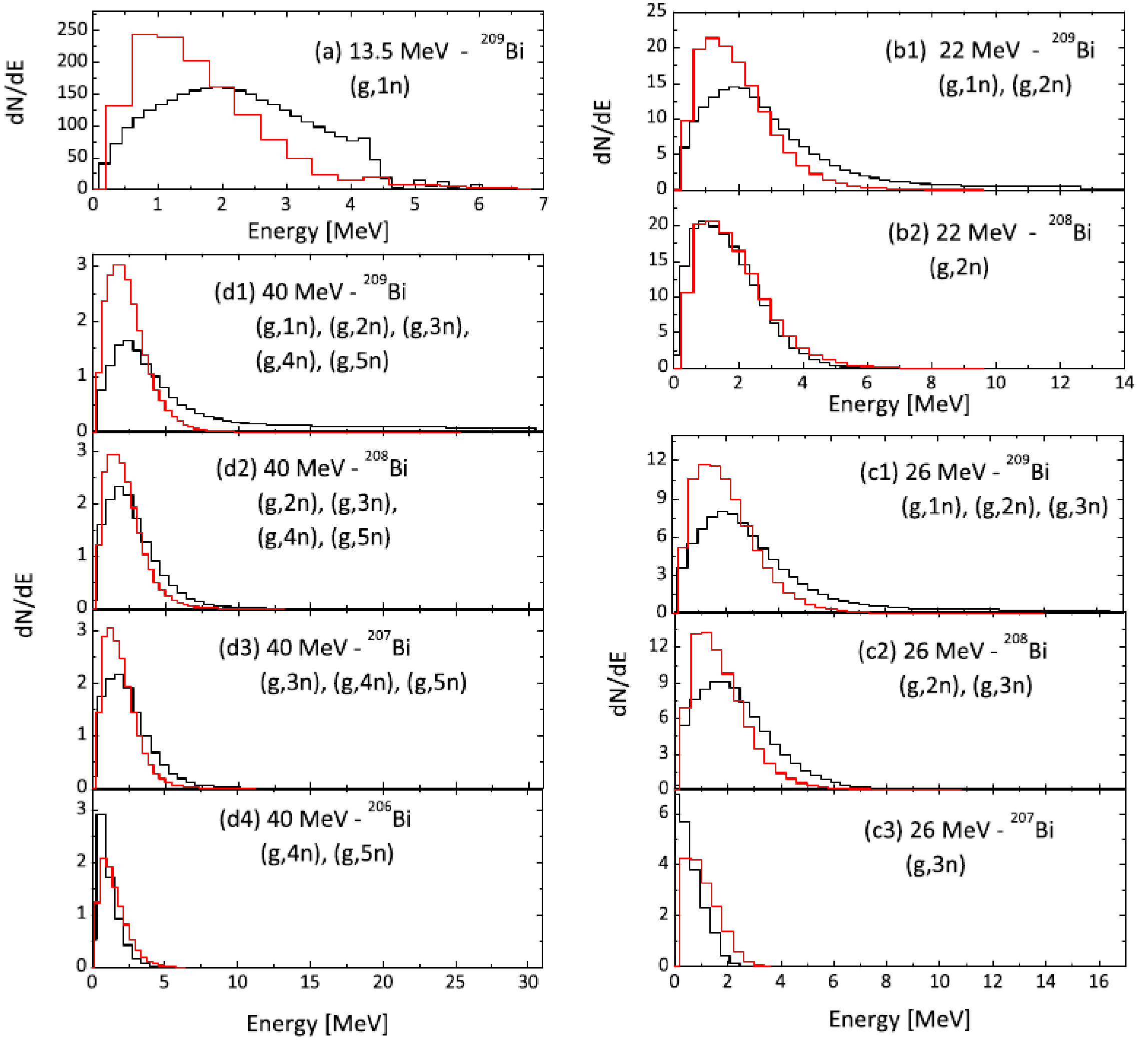
Total neutron emission spectrum from each compound nucleus.

Comparison with EMPIRE.

13.5, 22, 26, 40 MeV
incident energies

S_{5n} = 37.97 MeV

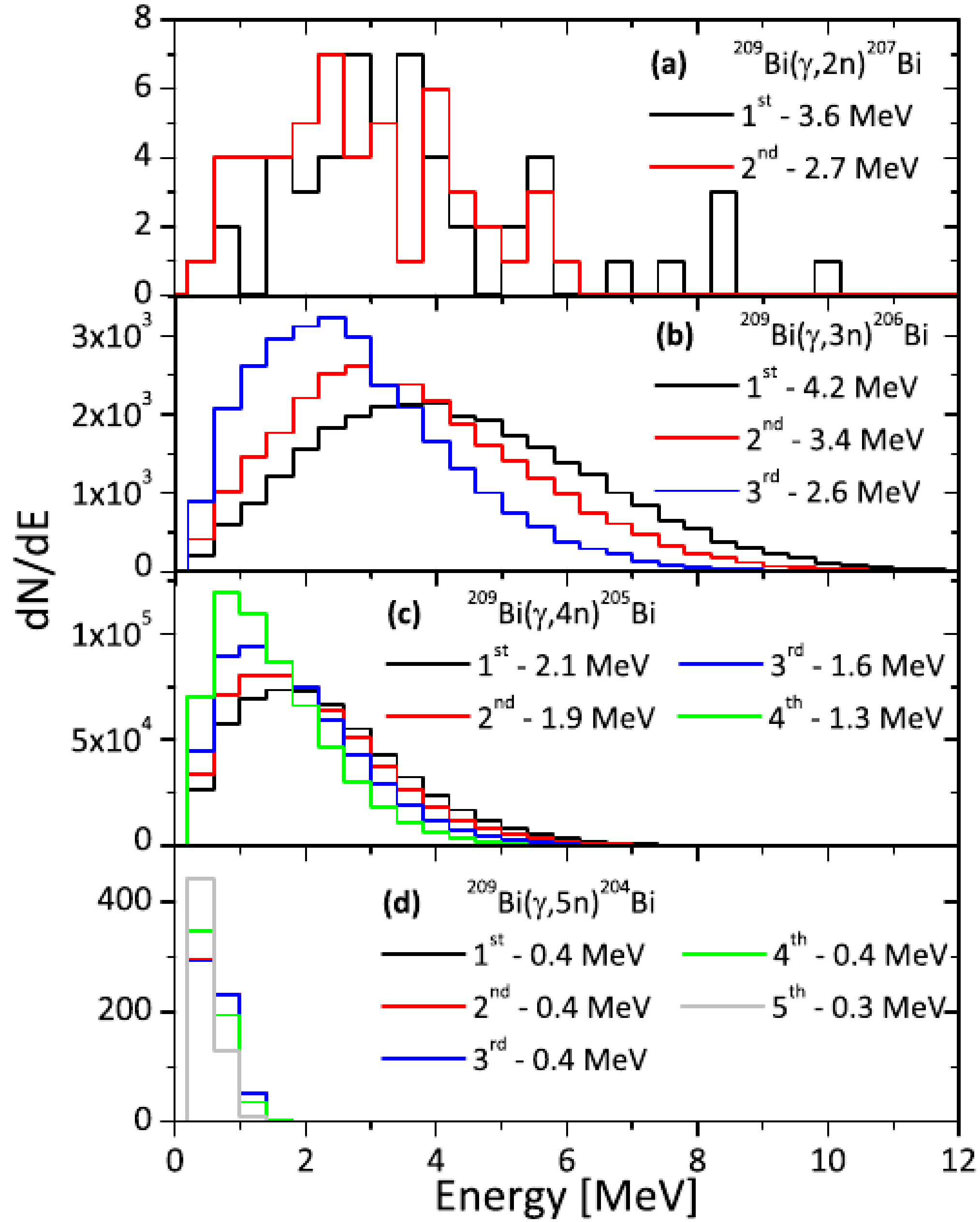
Monte Carlo reaction modelling code.



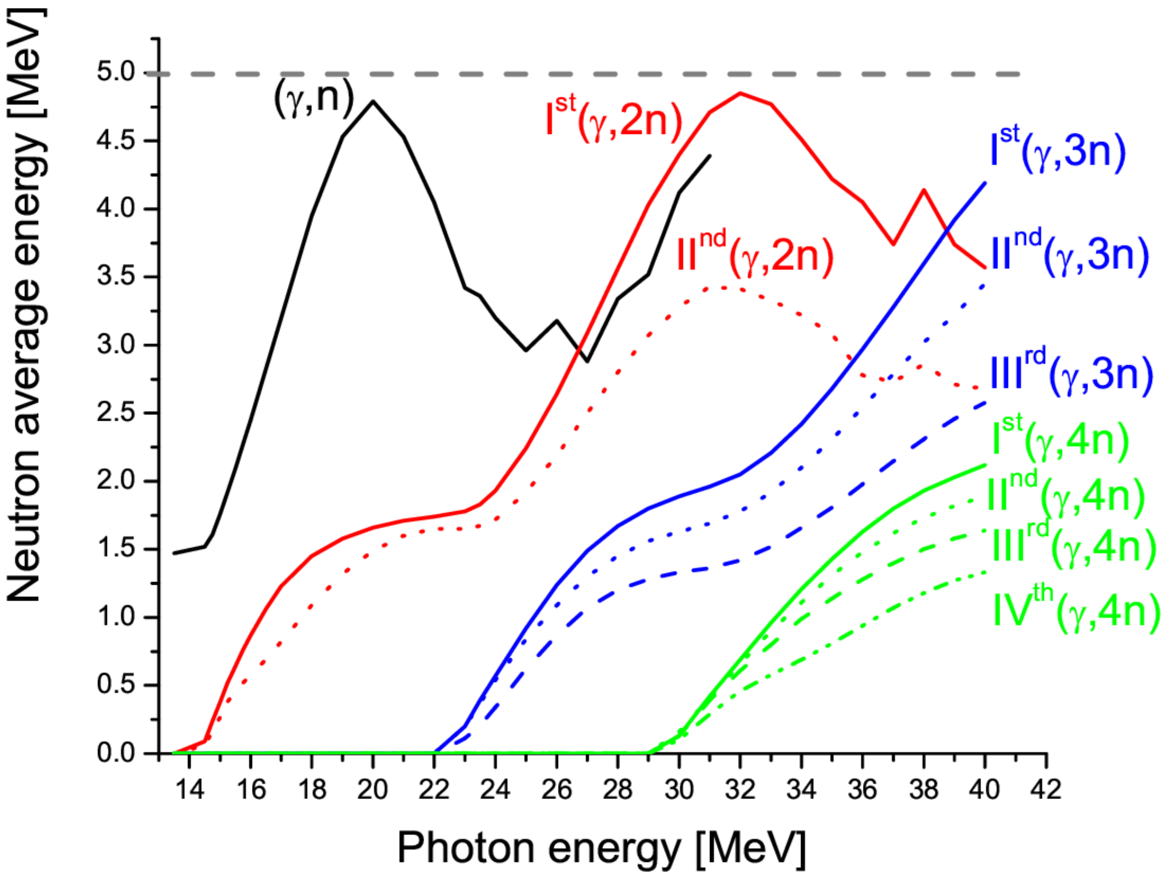
Information provided by Monte Carlo statistical model code.

Energy spectra of each successively emitted neutron for each reaction channel.

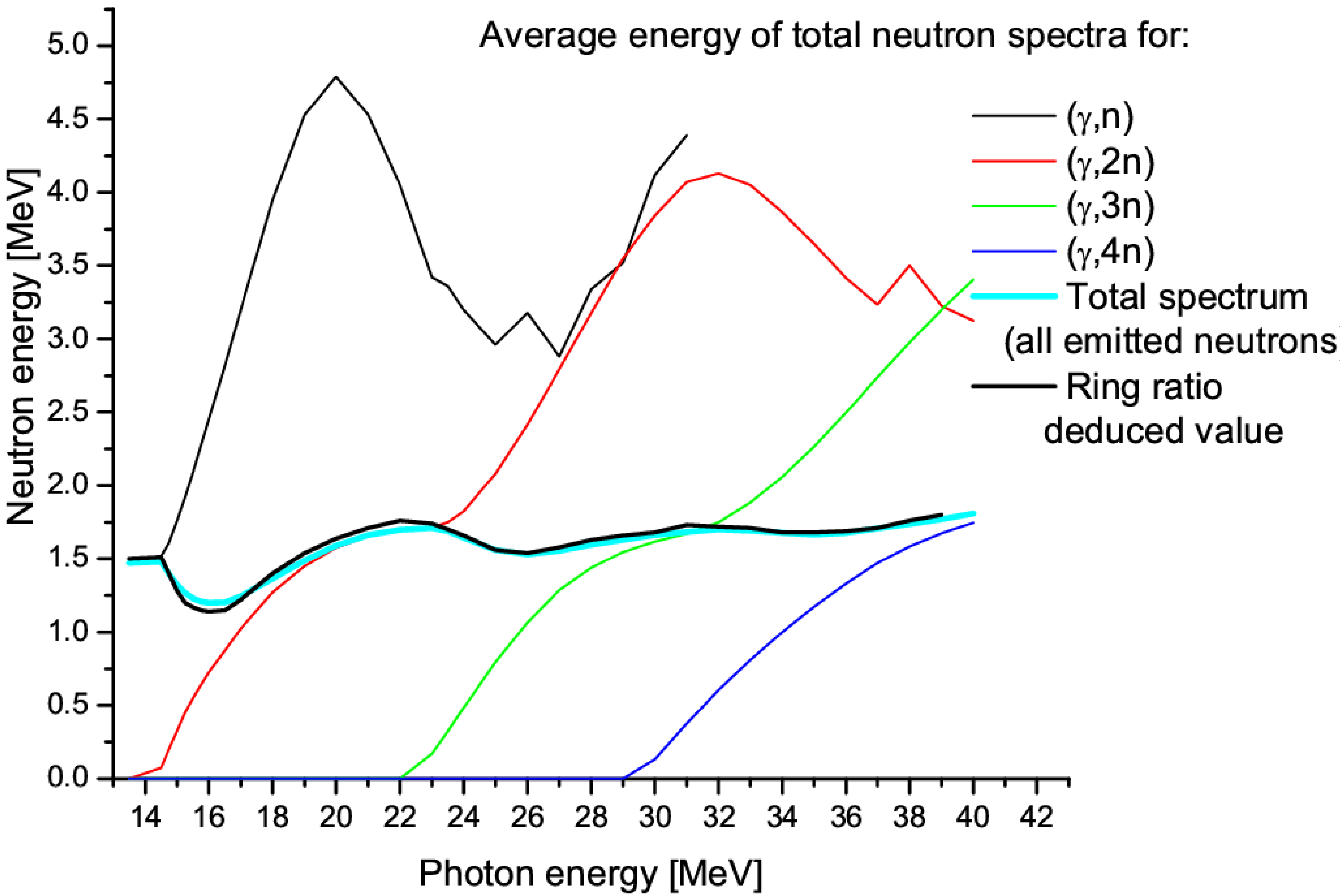
40 MeV incident energy
S_{5n} = 37.97 MeV
Monte Carlo reaction modelling code.



(1) Is the FED flat efficiency energy interval enough for the ^{209}Bi(g,xn) measurements?



Average energy of total neutron spectra

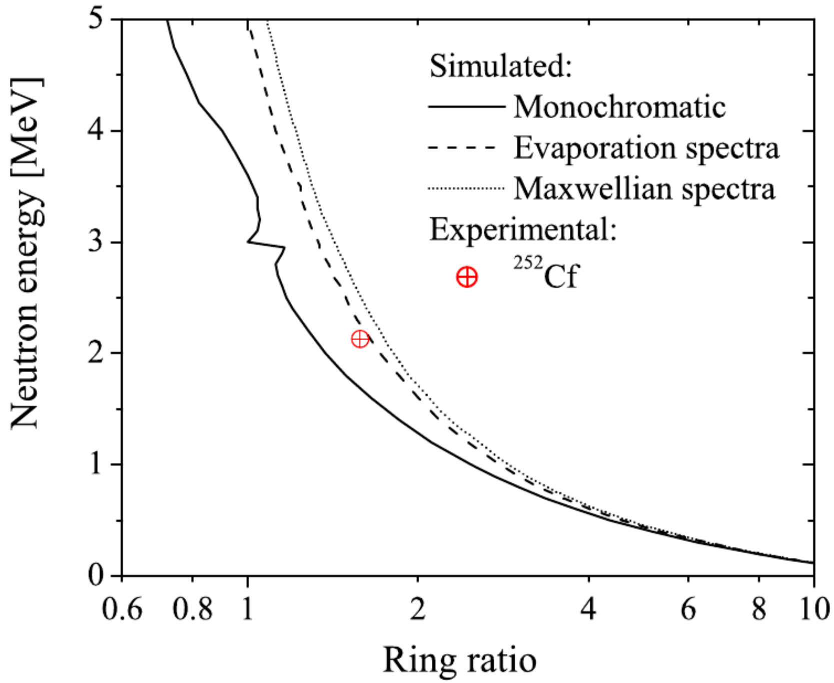


Ring ratio method

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:

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

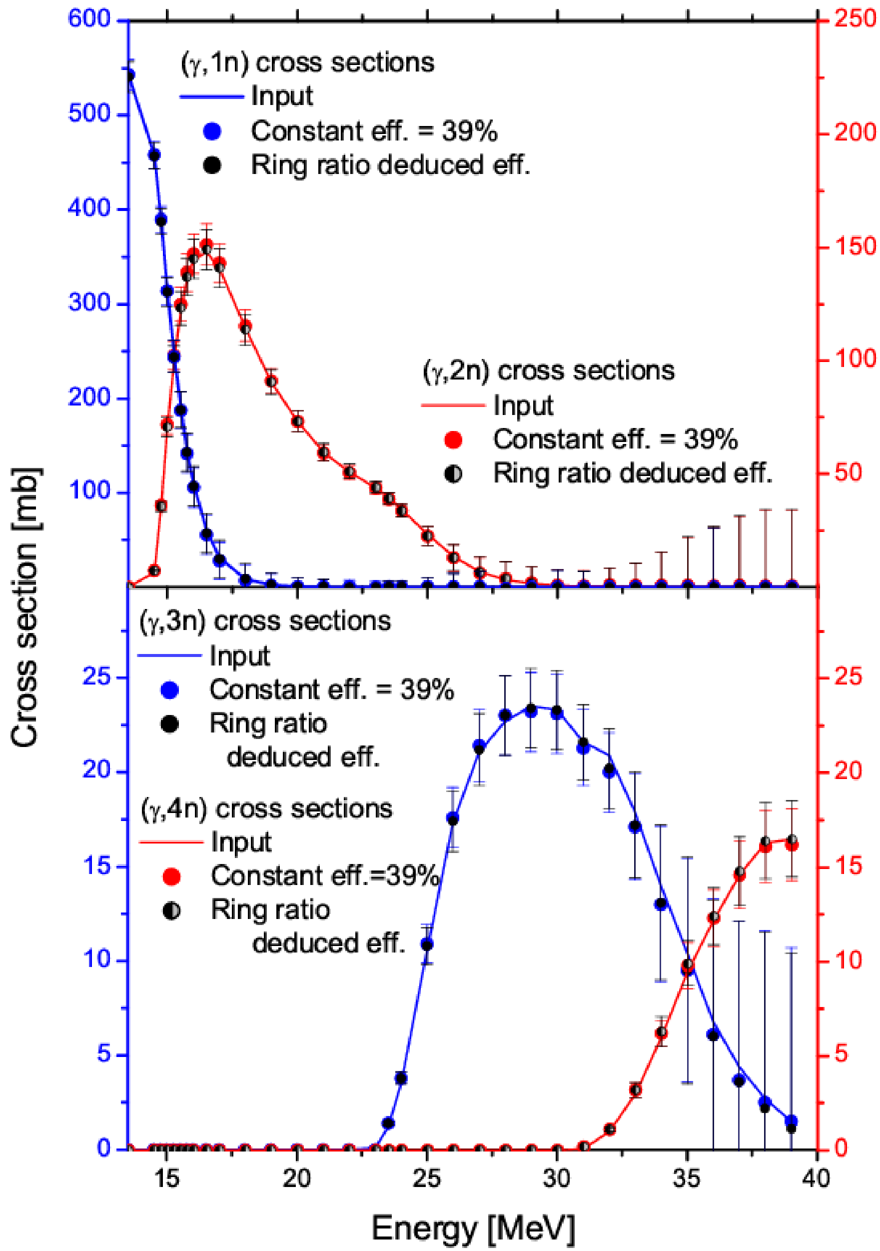
$$\langle E \rangle_{evap} = 2.25 \text{ MeV}$$

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

Literature: 2.13 MeV

Average neutron energy: 20 % uncertainty

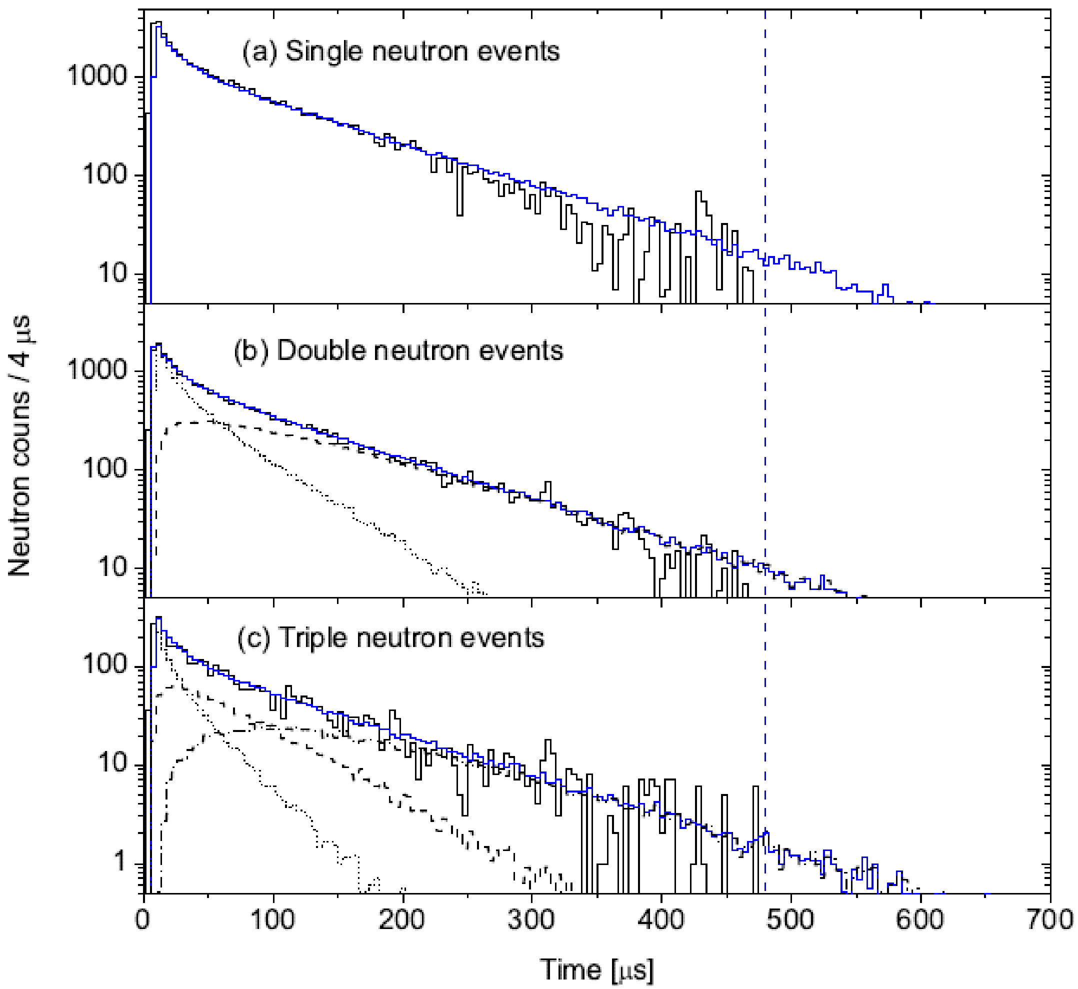
(2) Do we reproduce the input cross sections by applying the Direct Neutron Multiplicity Sorting method?



CONCLUSION:

Demonstrated that the neutron multiplicity sorting technique based on a FED is reliable and gives correct and accurate results.

Corrections for limited coincidence time gate



Using the Kawano Monte Carlo neutron source,
we simulated the FED response.

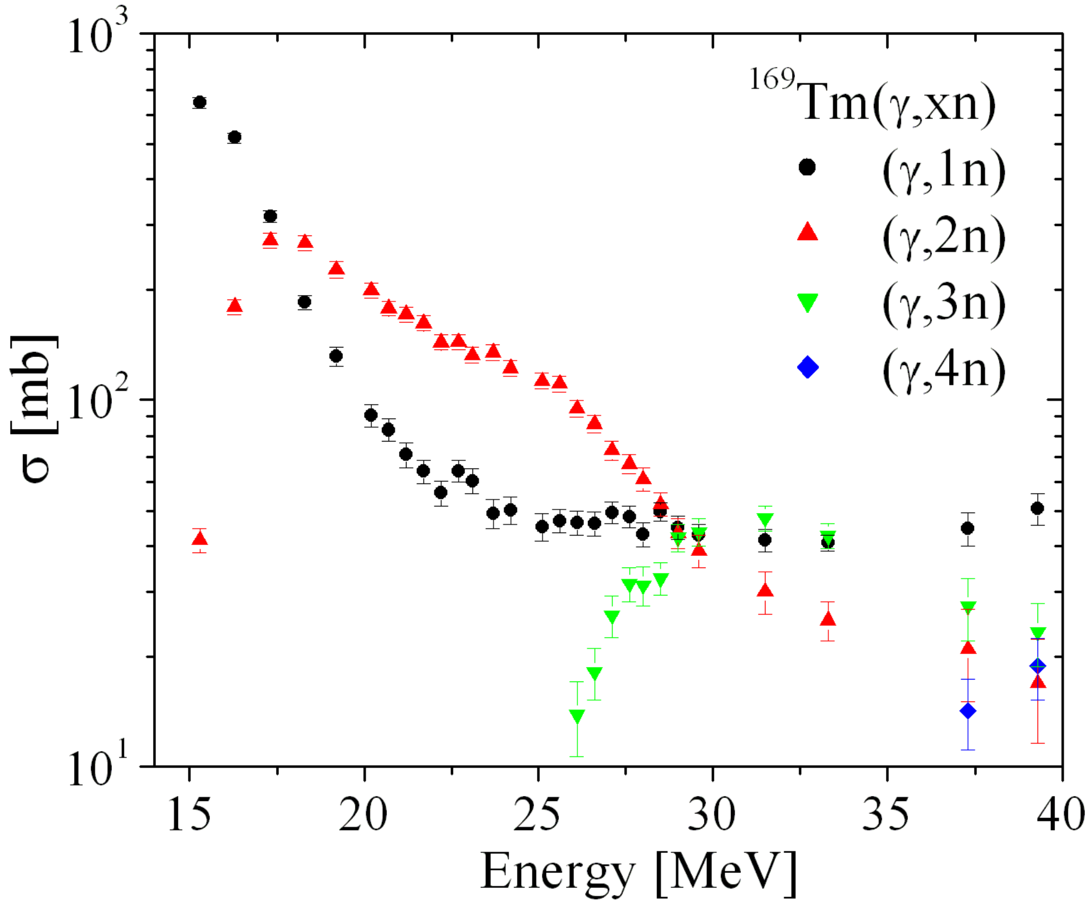
The simulations are reproducing very well the experimental spectra.

Concluded that:

- 2% of double neutron events are registered as 2 single events
- 3% of triple neutron events are registered as 1 double and 1 single
- 4% of quadruple neutron events are registered as 1 triple and 1 single.

The number of events were corrected accordingly.

Preliminary results – ^{169}Tm



a + A → C → b+ B

Entrance channel:

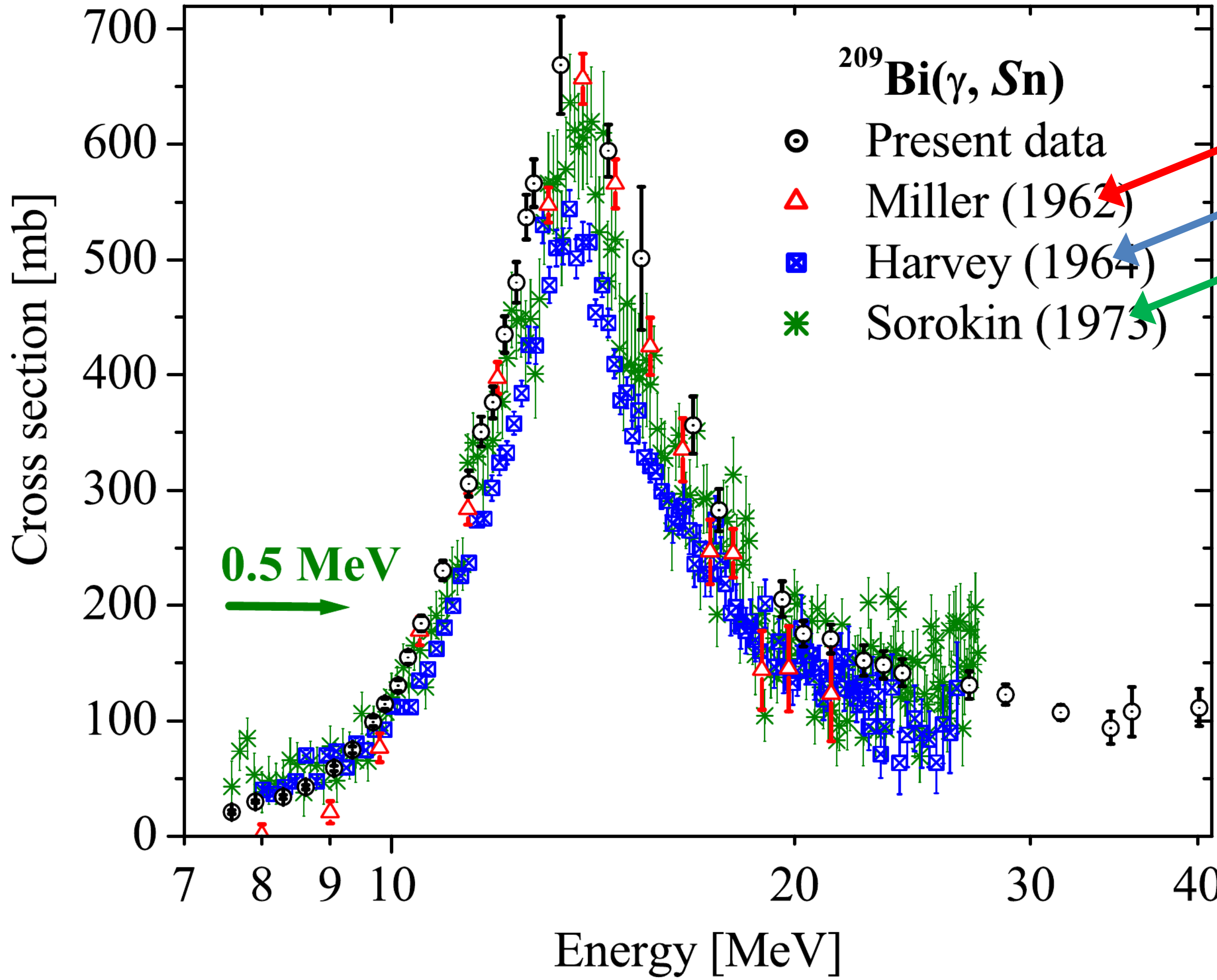
1. For incident Particle: using a direct model (optical model or coupled channels), direct reactions are explicitly calculated and all other reactions are grouped together into the “reaction” cross section.
2. For incident photon: the Photon absorption model provides the total photoabsorption cross section assuming CN and pre-equilibrium mecanism only.

Exit channel:

1. The absorption cross section is shared among all possible individual channels using a fluctuation / statistical / Compound Nucleus model.
2. Using the popular Hauser Feschbach model, the emission probability is computed using the transfer coefficients T and the level density functions.
3. The transfer coefficients
   1. For particle emission are obtained using a direct model
   2. For gamma emission are obtained using dedicated models – gamma strength functions.

$$\sigma_{\alpha',\alpha} = \frac{1}{4\pi}\lambda_\alpha^2 \sum_{J^\Pi} g_\alpha^J \frac{\sum_{lj} T_{\alpha lj}^{J\pi} \sum_{l'j'} T_{\alpha' l' j'}^{J\pi}}{\sum_{l''j''} T_{\alpha'' l'' j''}^{J\pi}}$$

Photoneutron cross sections on ^{209}Bi



Positron in flight annihilation data of:

Saclay

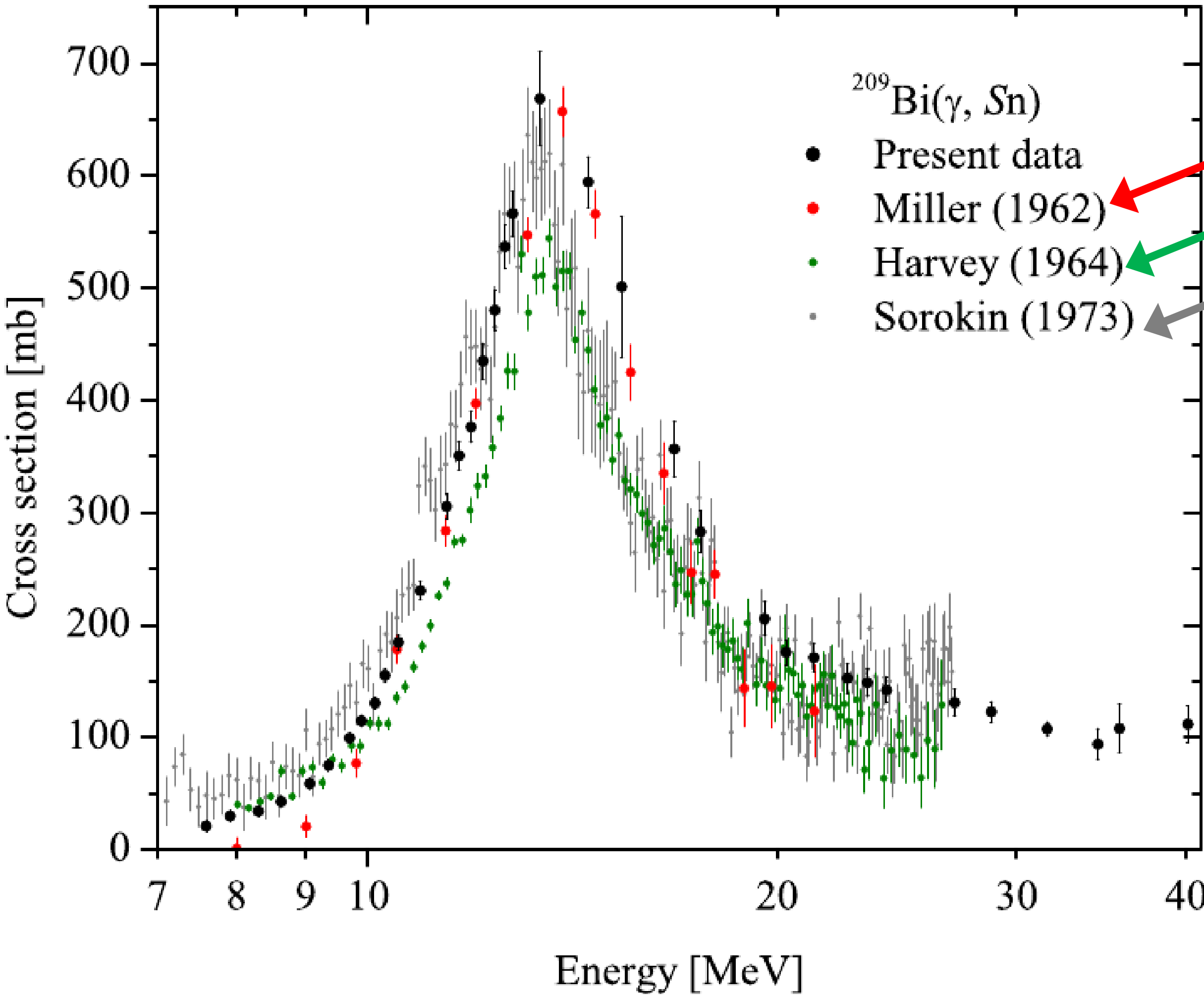
Livermore

Bremsstrahlung data taken at the Moscow Univ.

Present data are in good agreement with the:
Saclay positron in flight annihilation
bremsstrahlung
measurements.

The bremsstrahlung data are shifted by 0.5 MeV in the figure.

Photoneutron cross sections on ^{209}Bi



Positron in flight annihilation data of:

Saclay

Livermore

Bremsstrahlung data taken at the Moscow Univ.

Present data are in good agreement with Saclay positron in flight annihilation measurement.

There is a 0.5 MeV energy shift between present data and the bremsstrahlung ones.

Measured cross sections in *monochromatic* approximation

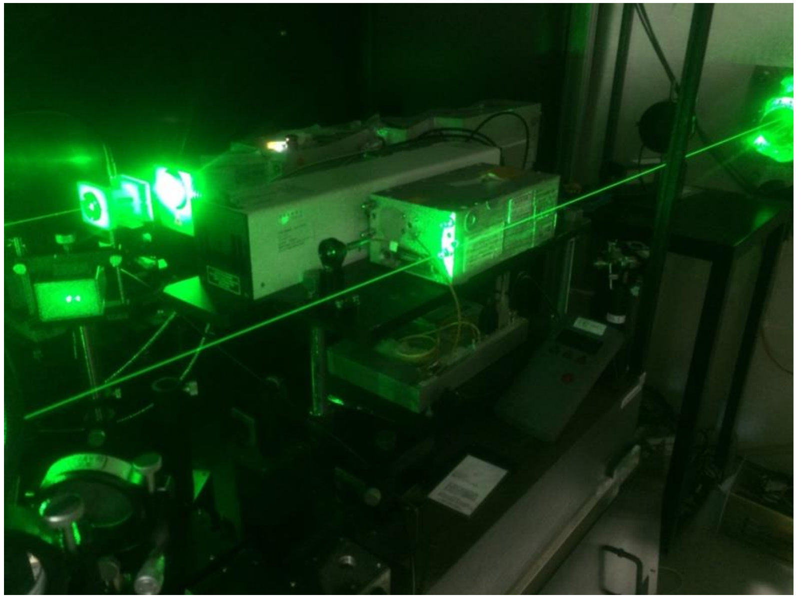
$$N_j = \sum_{i=j}^{m} {}_iC_j \cdot R_i \cdot \varepsilon^j (1-\varepsilon)^{i-j}$$ Solve the system of equations $\Rightarrow R_x$

$$\sigma_{\gamma xn}^{\mathrm{mono}} = \frac{R_x}{N_t N_\gamma \xi f_x}$$

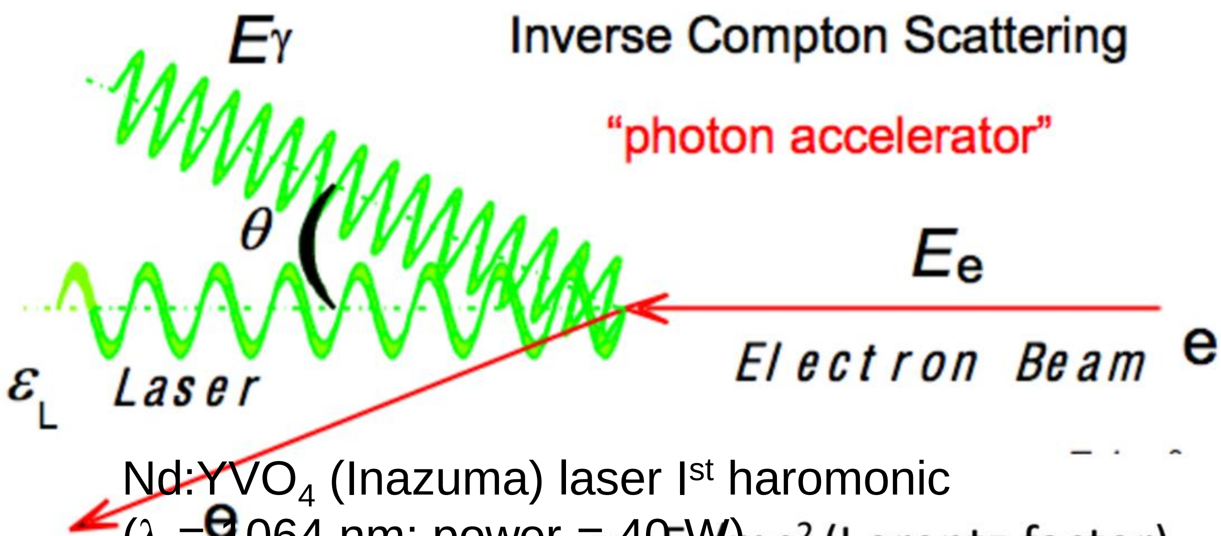
R_x = # (γ,xn) induced reactions
N_t = # target nuclei / unit surface
N_γ = #incident γ-rays on the target
ξ = thick target correction factor
f_x = fraction of photons above S_{xn}

γ-ray beam production

LCS γ-ray beams with maximum energies between 7.7 and ~42.2 MeV were produced with a $Nd:YVO_4$ laser (Spectra-Physics). The laser was operated in Q-switch mode at 16.66 kHz frequency - 60 μs time interval between consecutive laser bunches.
Energy of injected electrons – 982 MeV.



γ-ray beam production



Nd:YVO_4 (Inazuma) laser Ist haromonic
(λ = 1064 nm; power = 40 W)

$\gamma = E_e/mc^2$ (Lorentz factor)

$\sim$ 2×10^3 for E_e=1 GeV

$$E_\gamma = \frac{4\gamma^2\varepsilon_L}{1 + (\gamma\theta)^2 + 4\gamma\varepsilon_L/(mc^2)}$$

$$E_\gamma \approx 4\gamma^2\varepsilon_L$$

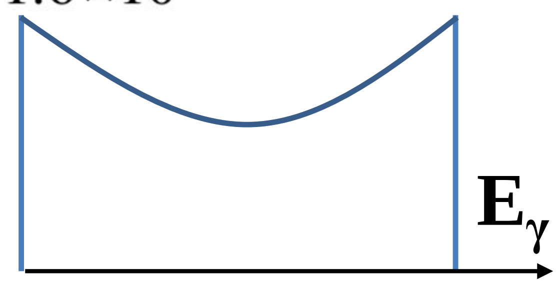
$$\Delta E/E \cong \left\{\left(\frac{2\Delta E_e}{E_e}\right)^2 + \gamma^4(\theta_e^2 + \theta_c^2)^2\right\}^{1/2}$$

Energy amplification

$$E_\gamma / \varepsilon_L \approx 4\gamma^2 \sim 1.6\times10^7$$

$\varepsilon_L \sim$ 1eV

$E_\gamma \sim$ 16 MeV



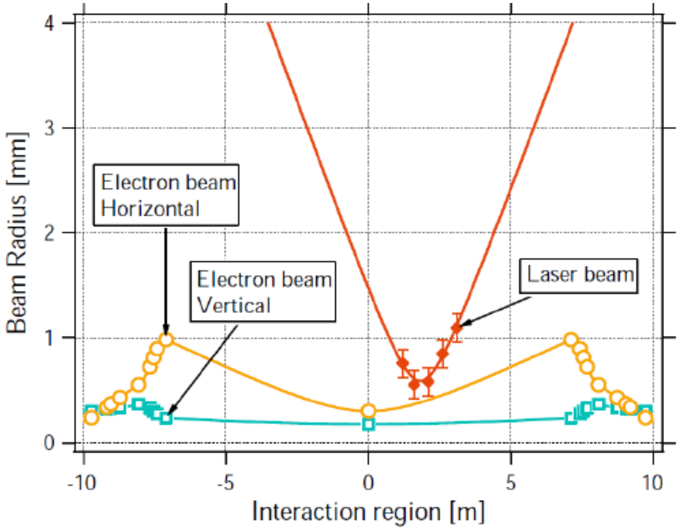
Question 1:

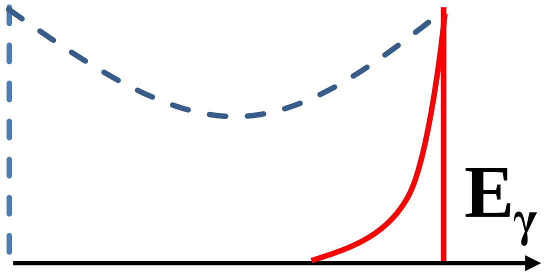
How do we know the energy resolution and energy spectrum of the collimated γ-ray beams?

Depending on the:

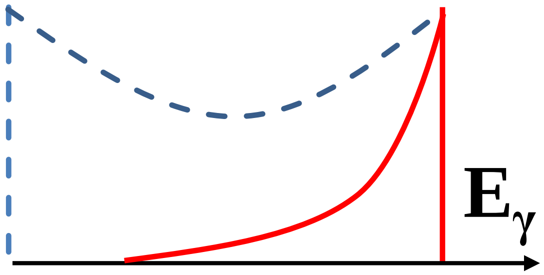
- Collimator aperture
- Electron and laser beam properties

the energy spectrum of the incident γ-ray beam may change significantly:

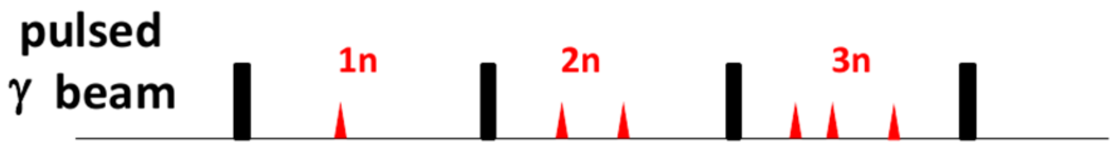




OR



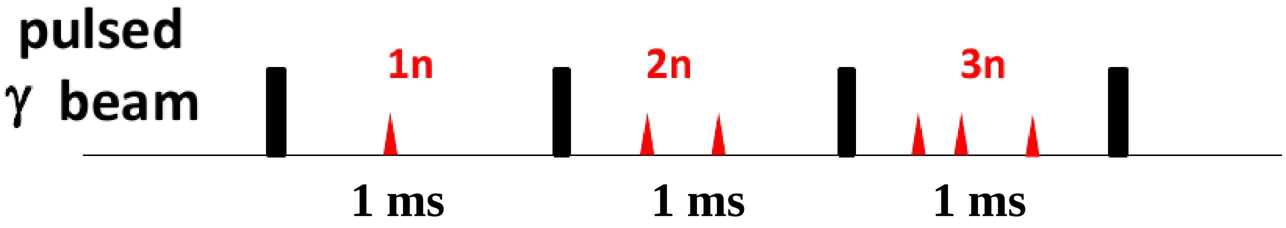
Direct neutron multiplicity sorting



(1) Time between consecutive γ-ray bunches ≈ neutron moderation time

- 1 ms laser pulsing - comparable to the moderation time of neutrons inside the polyethylene block
- 20 ms Beam ON / 80 ms Beam OFF data for background subtraction

(2) 1 γ-ray bunch generates no more than 1 reaction → low reaction rates required



However, what we can measure is NOT the number of reactions BUT the number of neutrons observed.

Single neutron events

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

Double neutron events

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

Triple neutron events

$$N_t = \boxed{N_3} \varepsilon^3$$

ε: detection efficiency

Here, the detection efficiency ε is independent of neutron kinetic energies. We can solve a set of equations to obtain N_1, N_2, and N_3.

Still to do …

Correction (1) for Multiple firing effect

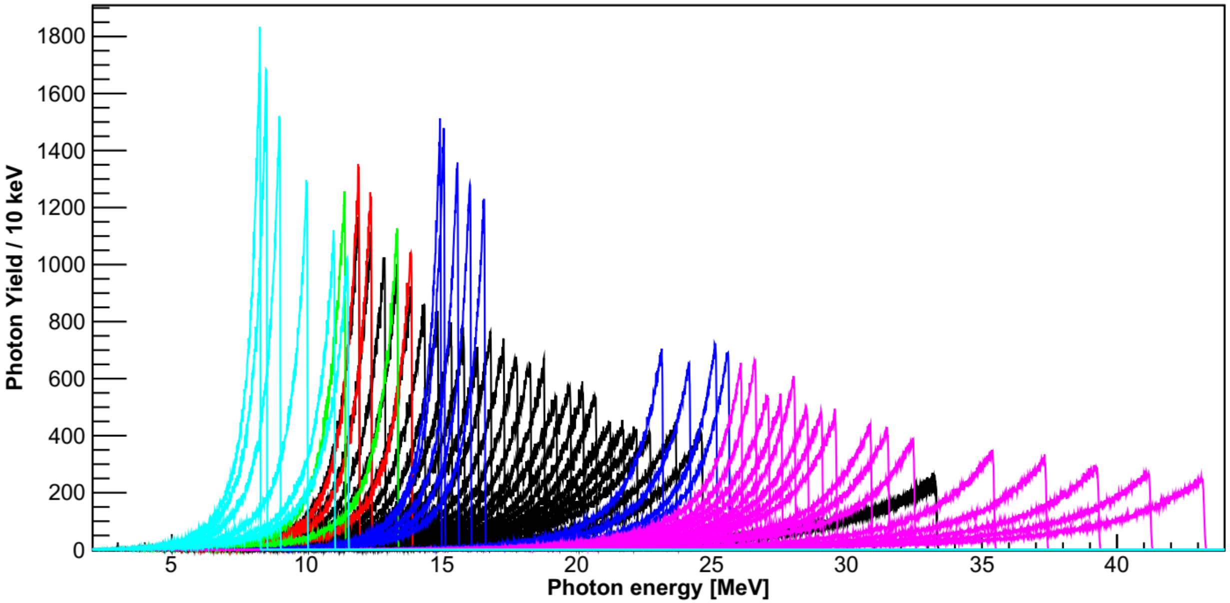
Low reaction rates are required for DNM sorting experiments, to avoid cases when two separate reactions are generated on two nuclei during a given photon pulse.

During the experiment, based on reaction cross section estimations, we tuned the incident photon flux and used properly thick targets for each irradiation energy.

During the data analysis, using the measured values for the monochromatic reaction cross sections, the average number of photons per gamma-ray bunch and target characteristics, we computed for each irradiation point the probabilities of generating multiple firing reactions.

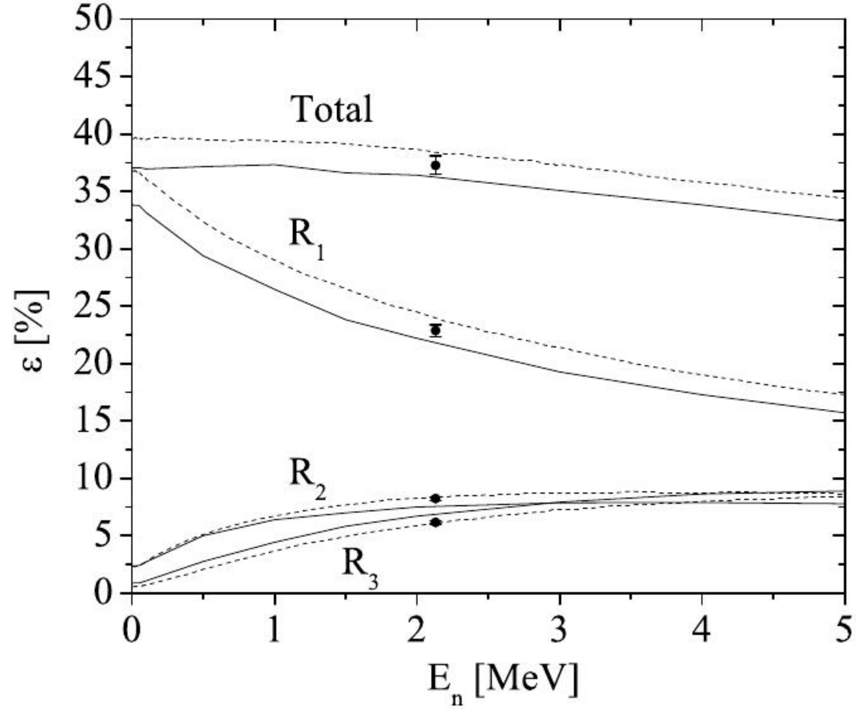
Correction (2) - deconvolution for incident photon spectra

The (γ,2n), (γ,3n) and (γ,4n) cross sections to be unfolded using an iterative method of reproducing the monochromatic cross sections by folding a trial cross section with the incident γ spectrum.



Status of Photoneutron reactions cross section measurements at ELI-NP

- ✓ Get knowhow
- ✓ Electronics
  - ✓ Procurement and testing of:
    - ➢ High Voltage power supply
    - ➢ Preamp + CFD + ADC
    - ➢ Data acquisition system
- ✓ ^{3}He counters
  - ✓ Procurement
  - ✓ Tested with Pu-Be neutron source and background radiation
  - ✓ Optimize working parameters with dedicated electronics
- ✓ Mechanical structure
  - ✓ Designed moderator for flat efficiency
  - ✓ Assemble working stand (Bosh frames + metallic support plate)
  - ✓ Procure high density polyethylene plates
  - ✓ Manufacture moderator
  - ✓ Procure Cadmium plates
  - ✓ Manufacture: Cd plates, beam line, target holder, beam dump
- ✓ Calibrate and test the detection system using charged particle beams
  - ✓ Monitor reactions for efficiency calibration
    - ✓ $^{nat}Cu(p,n)^{63}Zn$ ($T_{1/2}$ = 38.47 minutes)
    - ✓ Cross check using the activation technique
  - ✓ Test ring ratio technique



Many thanks to our CAD designer, Eng. G. Ciocan

Gamma ray beam source

Warm electron RF Linac

- multi–bunch photogun

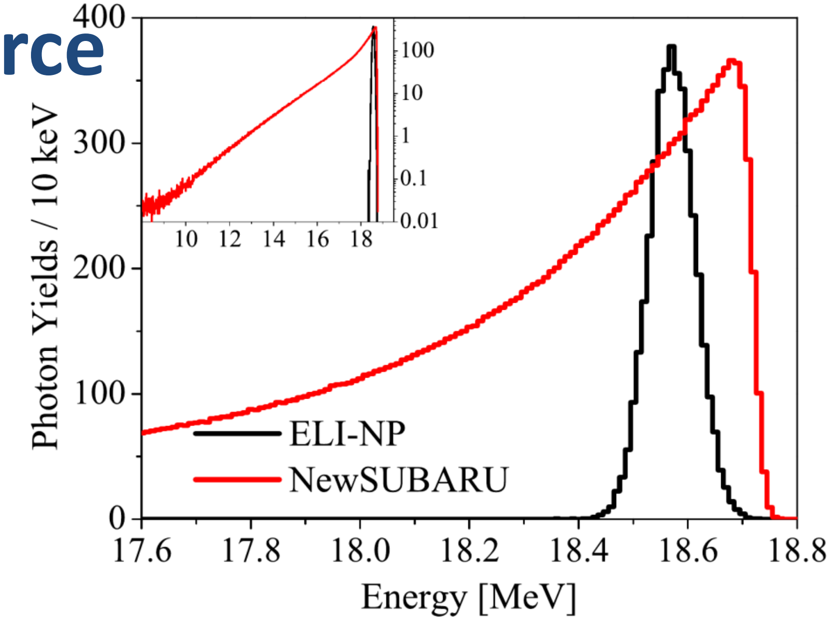
(32 e⁻ microbunches of 250 pC @100 Hz RF)

- two acceleration stages (300 MeV and 720 MeV)

High average power, J–class 100 Hz ps Collision Laser

- state–of–the–art cryo–cooled Yb:YAG (200 mJ, 2.3 eV, 3.5 ps)
- two lasers (one for low–Eg and both for high–Eg)

Energy (MeV)	0.2 – 19.5
Spectral Density (ph/s·eV)	$> 0.5 \cdot 10^4$
Bandwidth rms (%)	≤ 0.5
# photons/s within FWHM bdw.	$\leq 8.3 \cdot 10^8$
Source rms size (mm)	10 – 30
Source rms divergence (mrad)	25 – 200
Linear polarization (%)	> 95



	E_γ [MeV]	ΔE_γ [%]	I_γ^{bw} [ph/sec]
ELI-NP	0.2–19.5	< 0.5 (rms)	$8.3 \cdot 10^8$
NewSUBARU	0–76	> 1.2 (FWHM)	$\sim 10^5$
HIγS	0–100	0.8–10 (FWHM)	$\sim 10^7$