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Structural Instruments
2007-2013

Sectoral Operational Programme
„Increase of Economic Competitiveness”
“Investments for Your Future”

Extreme Light Infrastructure – Nuclear Physics (ELI-NP) - Phase II
Project co-financed by the European Regional Development Fund

Photoneutron reactions studies at ELI-NP using a direct neutron multiplicity sorting method

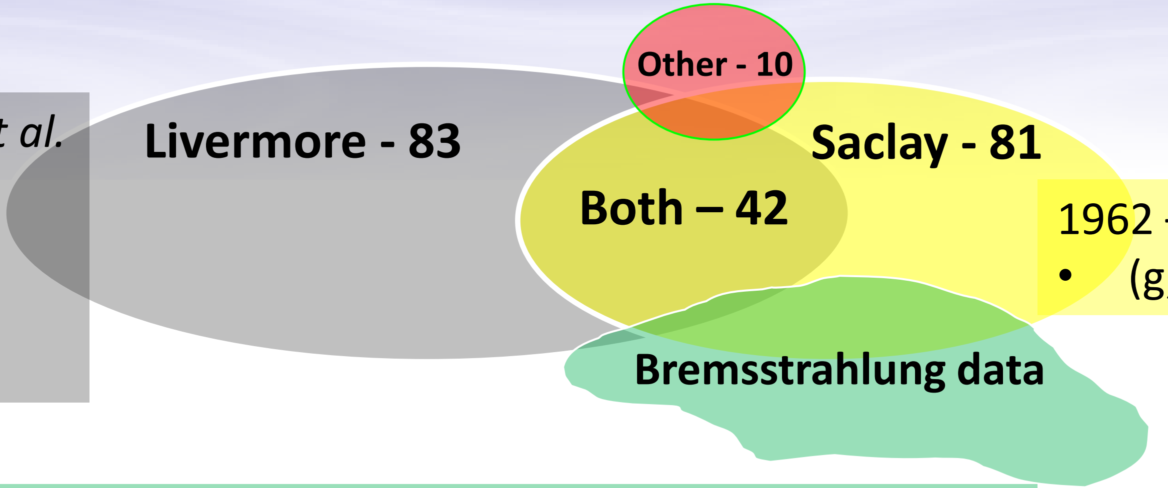
Dan Filipescu

6th Workshop on Nuclear Level Density and Gamma Strength
Oslo, May 8 - 12, 2017

eli Nuclear Physics

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

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)

Courtesy of V. Varlamov

- **measured both at Livermore and Saclay**
- **recently remeasured using 55 MeV maximum energy Bremsstrahlung photon beam at Moscow, by Prof. Varlamov's group.**
- **One of the candidates for investigating the discrepancies between Livermore and Saclay data of (g,xn) cross sections.**

New photoneutron cross section measurements on ^{209}Bi

205	206	207	208	209
(g,4n)	(g,3n)	(g,2n)	(g,1n)	
Sn=29.4 MeV	Sn=22.45 MeV	Sn=14.35MeV	Sn=7.46 MeV	STABLE
15.31 days	6.243 days	31.55 years	3.68E5 years	

Bi

7.7 – 42.5 MeV maximum energy LCS γ-ray beams
(g,1n) – (g,4n) reactions
^{209}Bi monoisotopic target placed in beam
Neutrons recorded with 4π neutron detection system

- ^{3}He counters embedded in moderator
- Flat efficiency neutron detector

DNM sorting method (presentation of H. Ustunomiya)
Photon flux – 100 % efficiency NaI detector

- "pile-up method"
- ~ 10^5 photons/s

Incident photon spectra

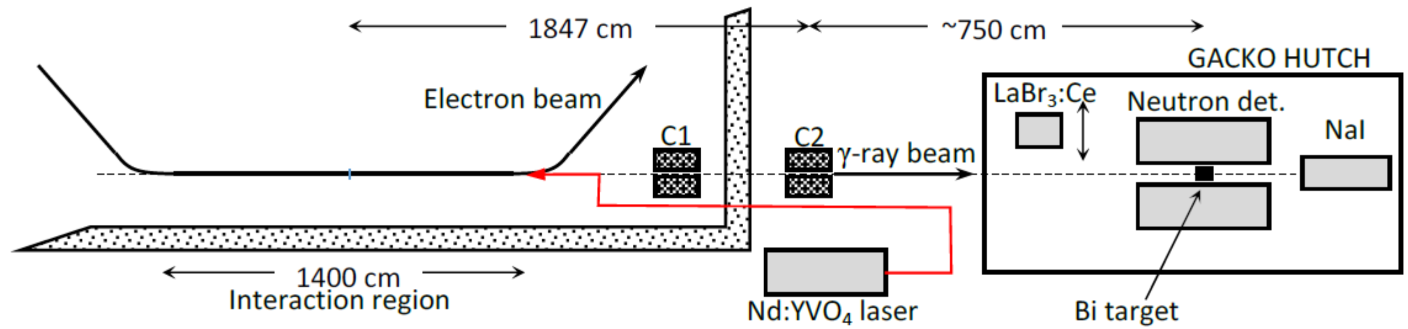
- $LaBr_3$:Ce detector placed in beam
- ~ 2% energy resolution FWHM

25 MHz DAQ
Recorded neutron coincidence events:

- Single events
- Double coincidences
- Triple coincidences
- Quadruple coincidences

480 us time range

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 Sn - good knowledge of incident γ-ray beam spectra

 # target nuclei

- good knowledge of chemical and isotopical composition
- mass measurement
- transverse surface measurement (4, 7 and 10 mm thick targets were used)

Gamma beam production

Incident energy < S_{2n}

LCS gamma-ray beams with maximum energies between 7.7 and ~42.2 MeV were produced with a high power Nd:YVO_4 laser INAZUMA (Spectra-Physics) at the NewSUBARU facility.

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.

Low energy region, below the double neutron emission threshold (S_{2n}= 14.35 MeV)

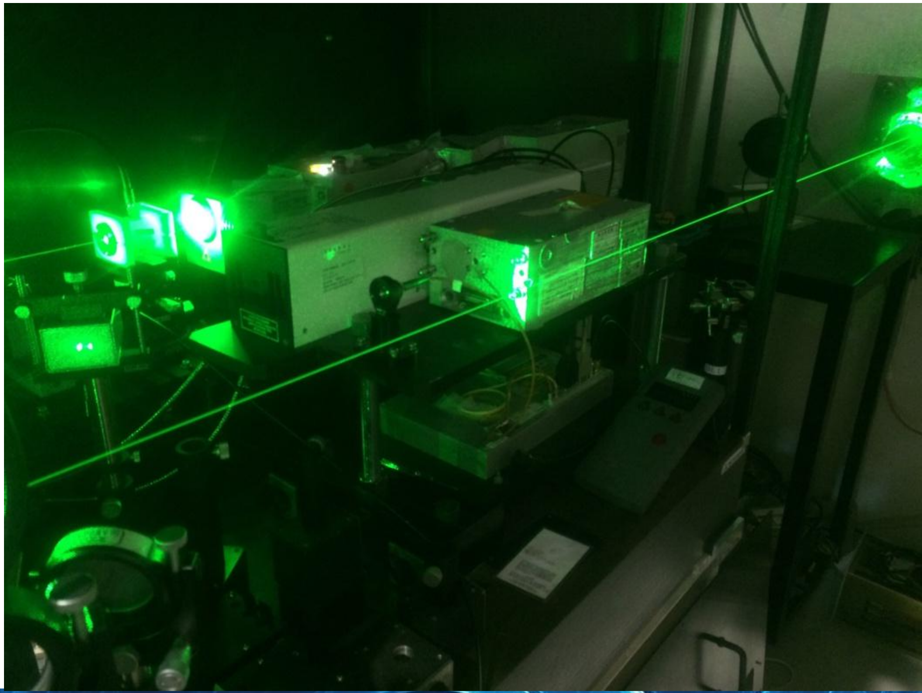
Laser operated in the first harmonic

(λ = 1064 nm; Power = 40 W)

Pulsed, 10 Hz macroscopic time structure,

of 80 ms beam-on and 20 ms beam-off.

The electron beam energy was varied in deceleration mode between 902 and 660 MeV.



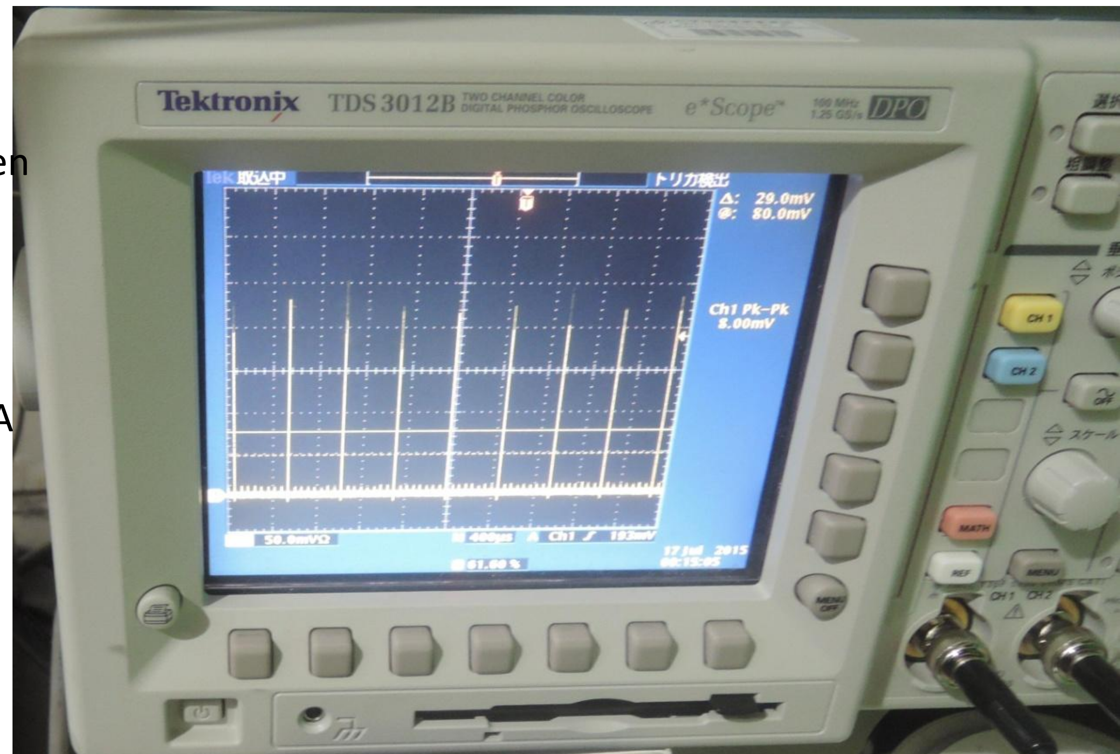
Gamma beam production

S_{2n} < Incident energy < S_{5n}

High energy region, between 14.3 and 42.2 MeV gamma-ray beam maximum energy
Laser was operated in the second harmonic
(λ = 532 nm; power = 14 W)
Electron beam energy was varied:
in deceleration mode from 982 to 640 MeV
in acceleration mode from 982 to 1108 MeV.

- Neutron coincidence measurements above the S_{2n} required a time interval between consecutive γ-ray bunches comparable to the moderation time of neutrons inside the polyethylene block.

- The 60 μs interval provided by the INAZUMA laser was extended to 480 μs by modulating the laser beam intensity.
- Additional optical system comprised of a Pockels cell and a polarizer was used to block 7 out of 8 consecutive laser pulses.

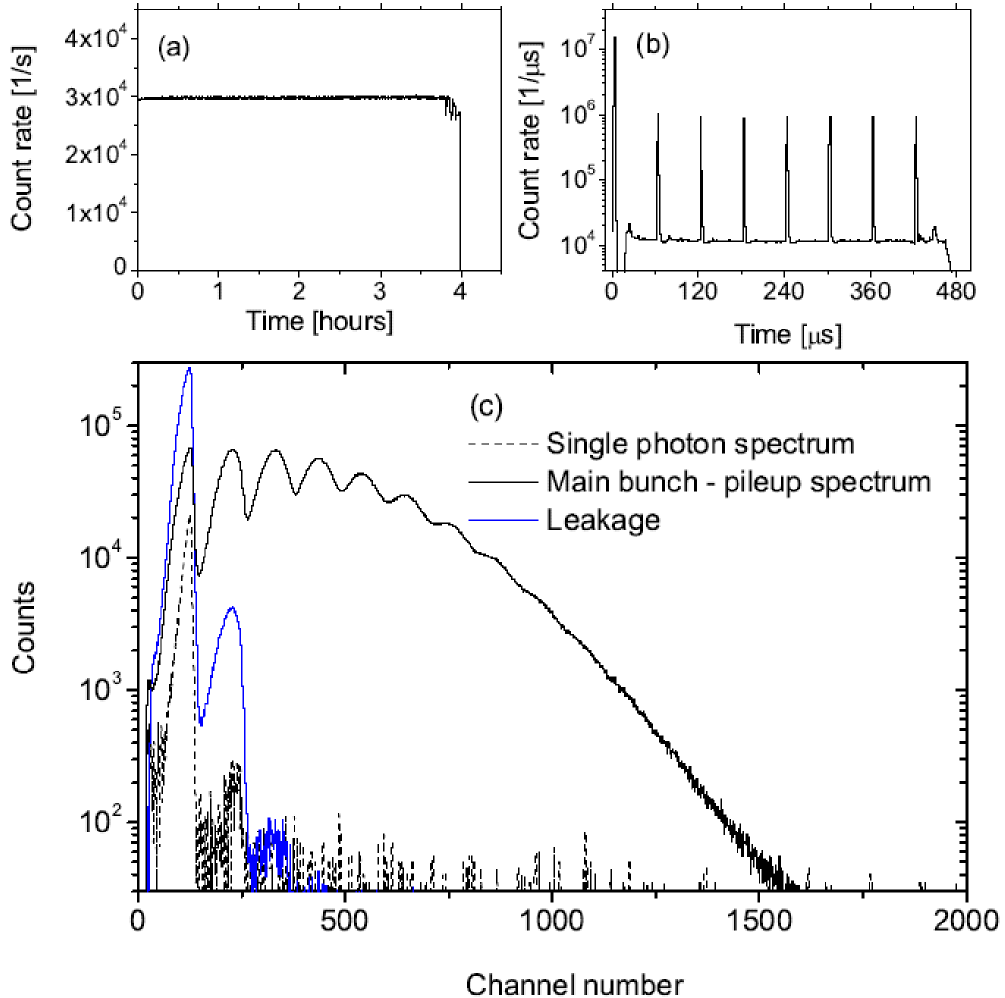


LCS photon counting

- 8" x 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
- The main bunch energy component was isolated using gates in the time-to-previous-clock spectra.

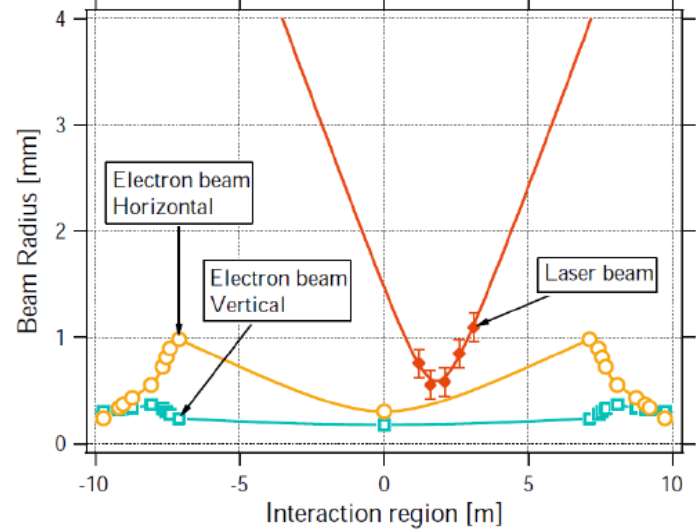
$$N_{\gamma,\text{det}} = \frac{\langle i \rangle_{\text{pileup}}}{\langle i \rangle_{\text{single}}} \left(\sum n_i \right)_{\text{pileup}}$$

Throughout the measurements, the number of leakage γ-rays was below 10% of the total number of LCS photons



Typical experimental pile-up and single photon spectra. The main LCS γ-ray spectrum displays a Poisson distributed pile-up structure with an average of 3.83 photons/bunch, while the partially blocked leakage component has 1.01 photons/bunch.

Incident photon spectrum

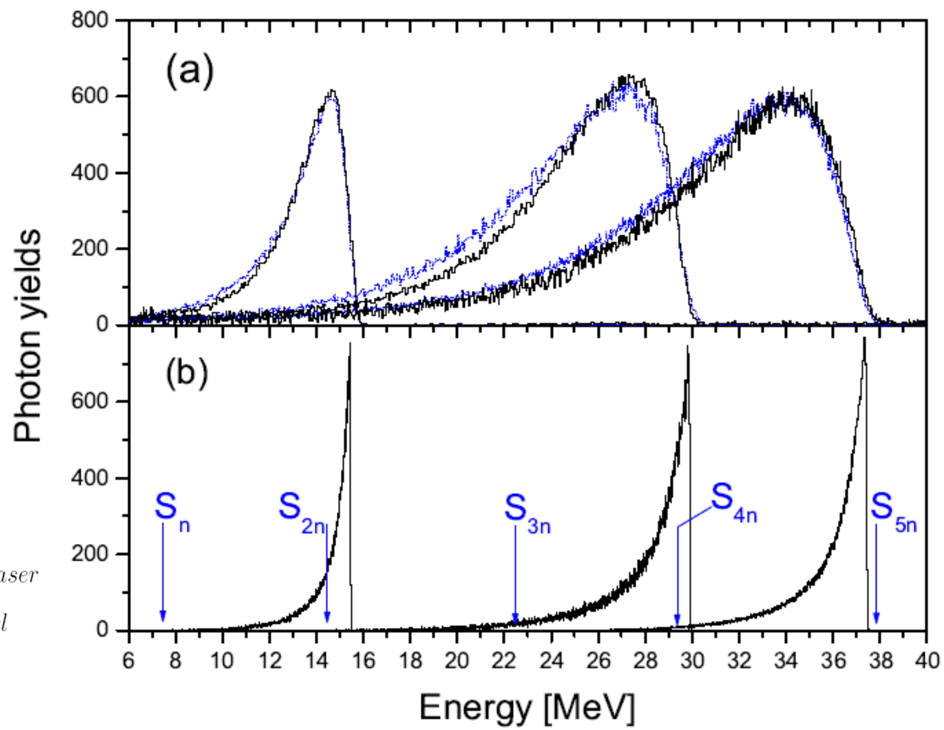


LaBr$_3$:Ce detector placed in beam

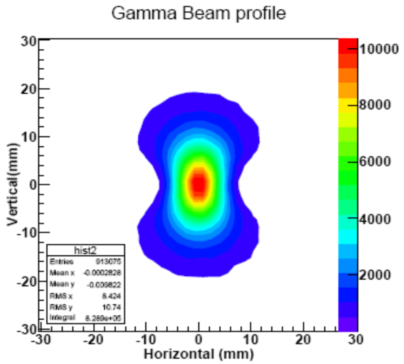
- The Compton backscattering of laser photons on relativistic electrons and the electromagnetic interactions of the gamma-ray beams inside the LaBr$_3$:Ce detector were simulated using the GEANT4 Monte Carlo code.
- The energy spectra of the LCS gamma-ray beams incident on the targets were obtained by reproducing the LaBr$_3$:Ce detector response.

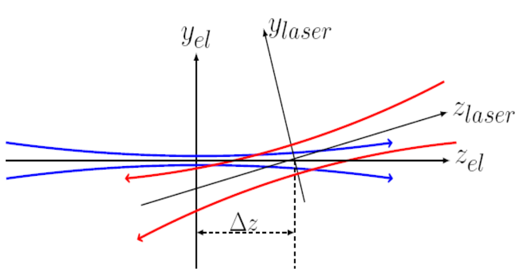
Figure: Energy spreads of 2.4 %, 1.6 % and 2. % FWHM for the gamma-ray beams of 15.4, 29.9 and 37.4 MeV maximum energy, respectively.

- Reliable simulations of incident LCS gamma-ray beam incident spectra are necessary for obtaining the average photon energy and the fractions of useful photons with energies above given reaction thresholds and for the deconvolution of the raw cross sections.

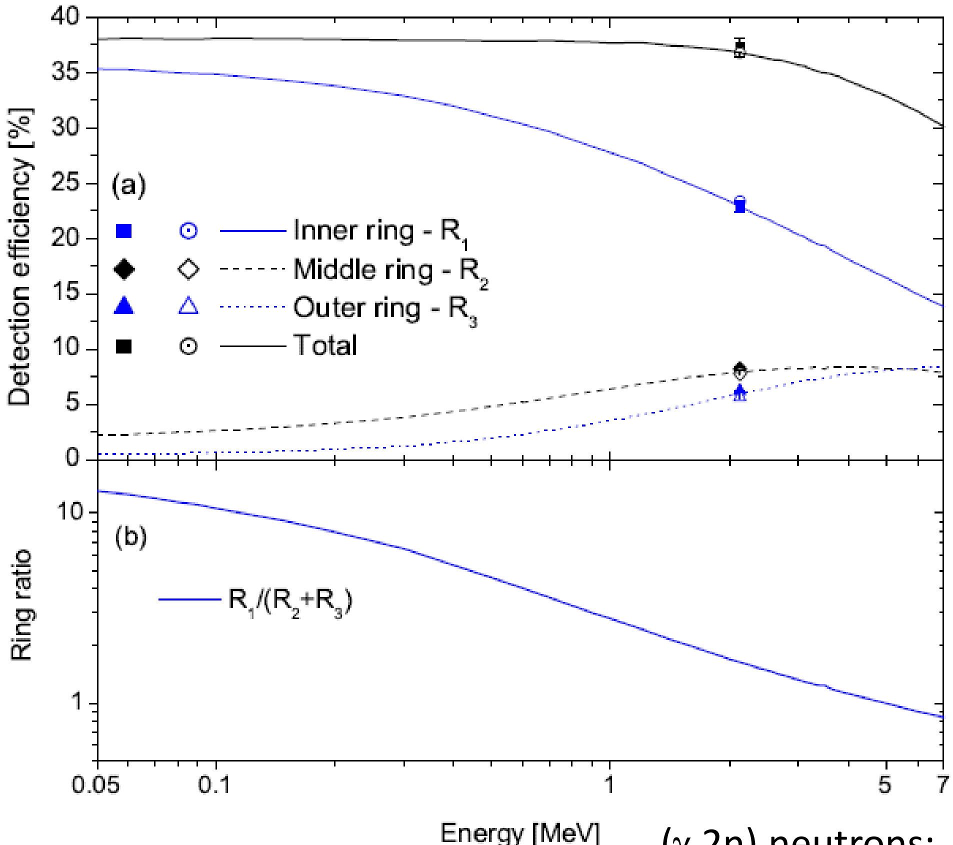


Gamma ray beams had energy resolution values between 1.6 ~ 7 %.





Neutron detection system



Flat efficiency:

<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:

ε^2 = 16%

Only one neutron detected:

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

<u>(γ,3n) neutrons:</u>

3 neutrons detected:

ε^3 = 6.4%

2 neutron detected:

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

Only one neutron detected:

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

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)

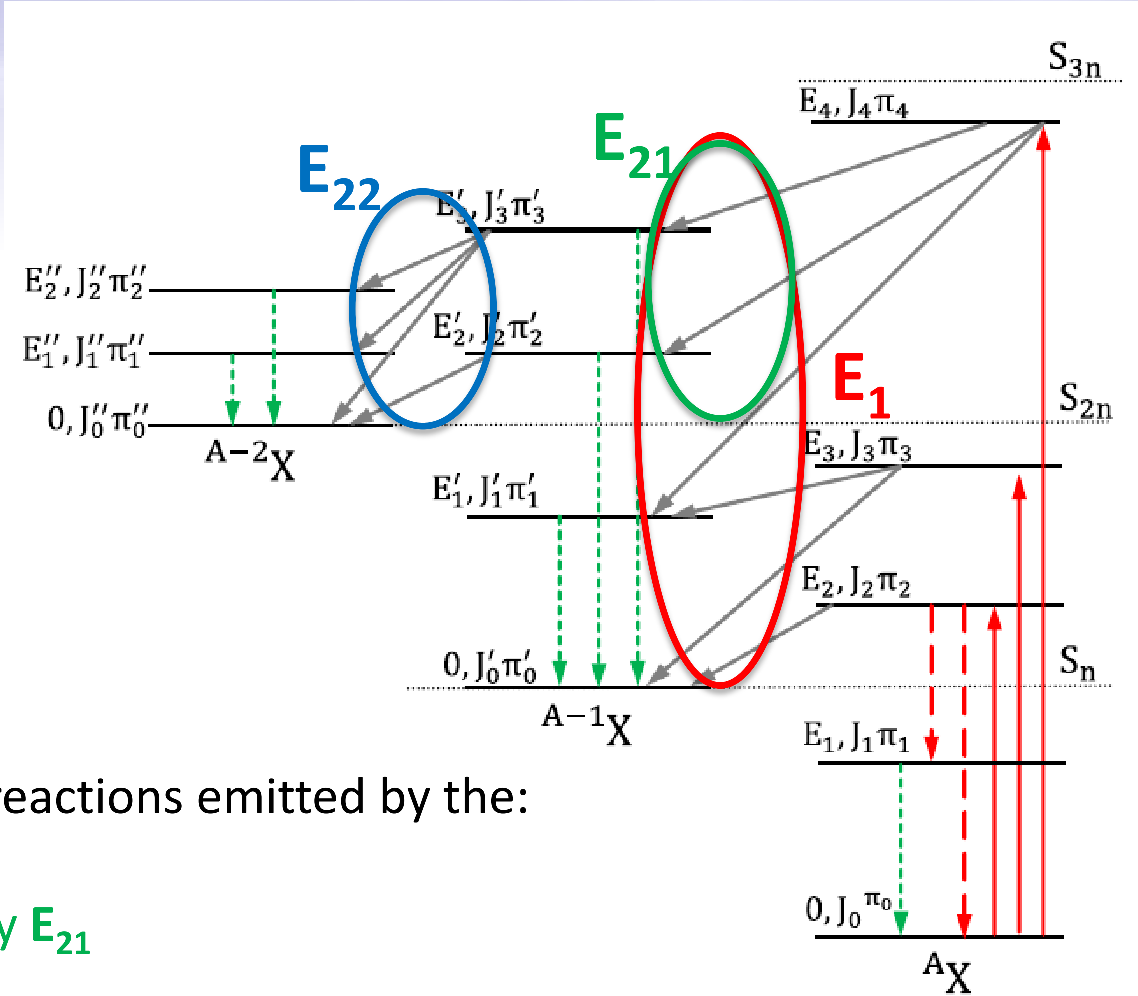
- ^{209}Bi(g,xn) neutron emission spectra
- The code provides specific decay paths for each event:
  - Particle type and energy for each CN, event
- Isotropic emission was considered

Validation procedure

1. Emit the reactions from the center of the detector
2. Transport the reaction particles through the detector
3. Analyse the simulated ^{3}He 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})

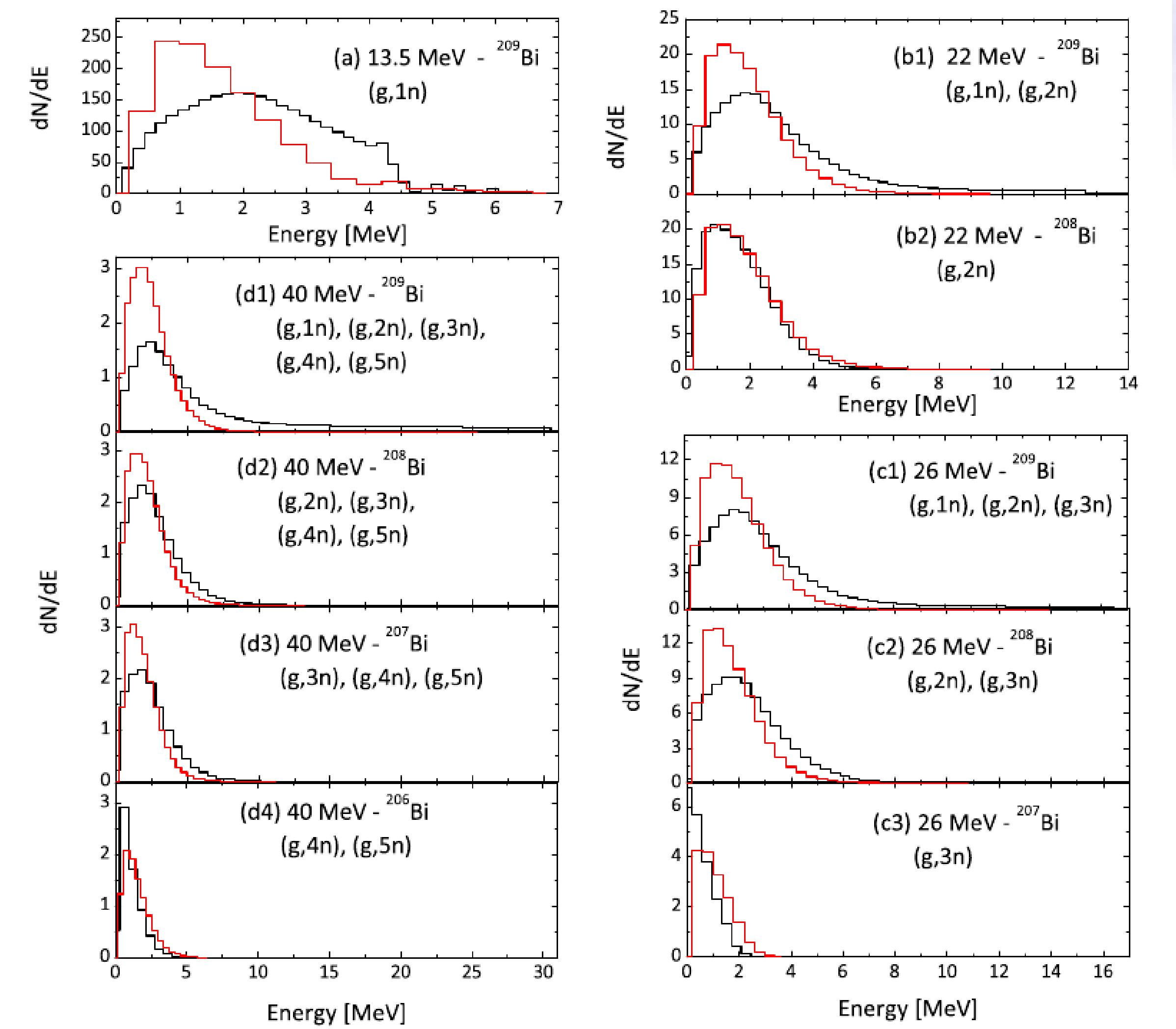
Total neutron emission spectrum from each compound nucleus.

Comparison with EMPIRE.

13.5, 22, 26, 40 MeV
incident energies

S_{5n} = 37.97 MeV

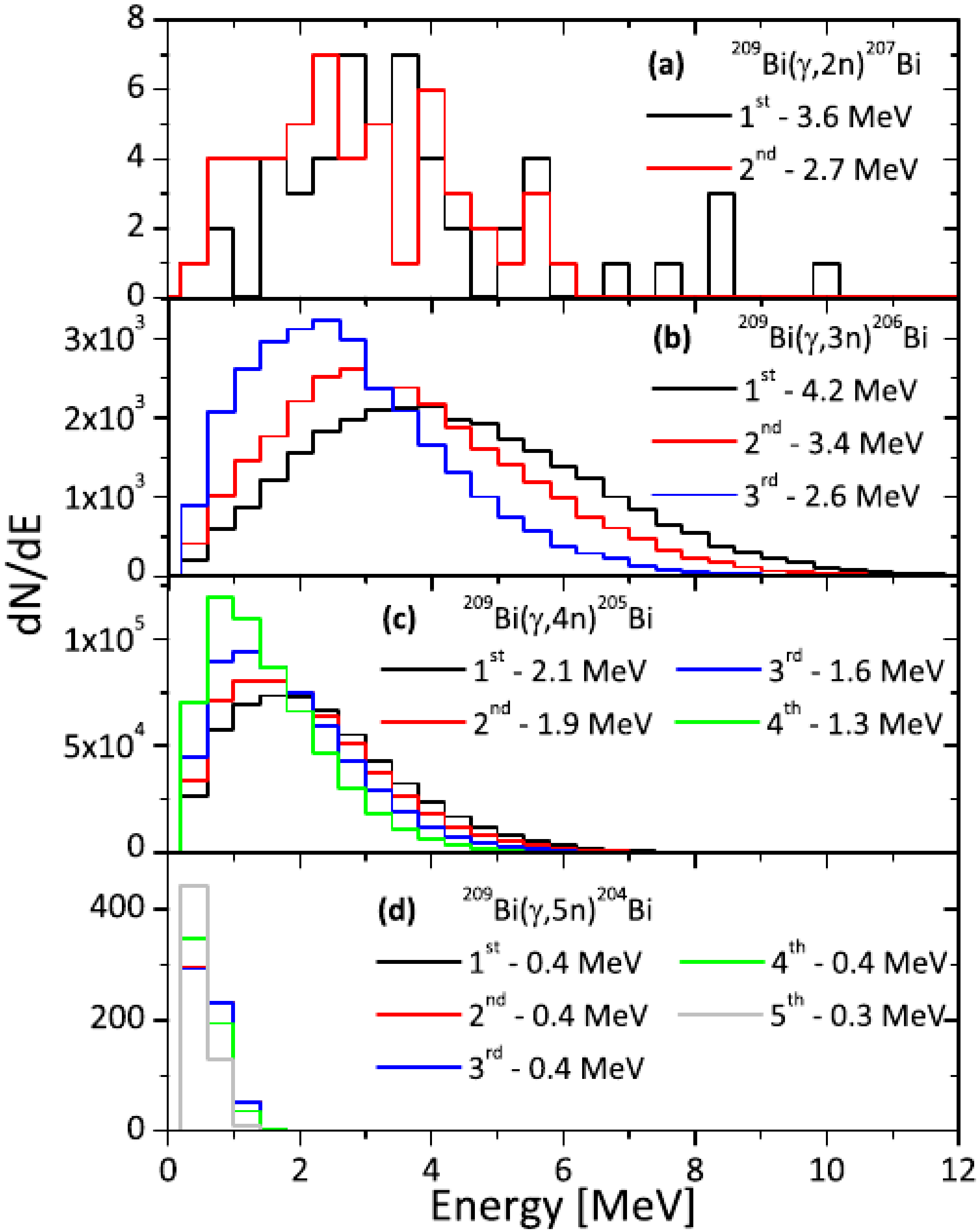
Monte Carlo reaction modelling code.



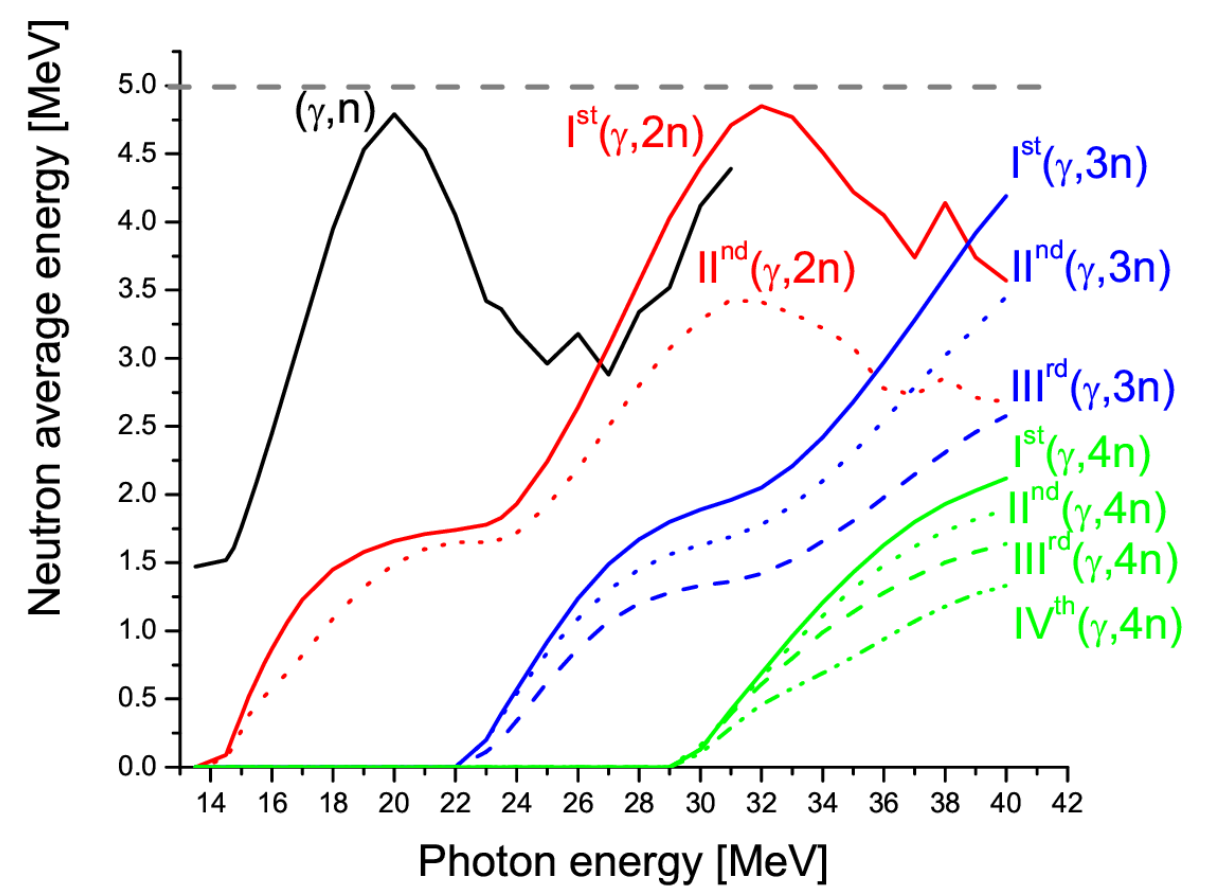
Information provided by Monte Carlo statistical model code.

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

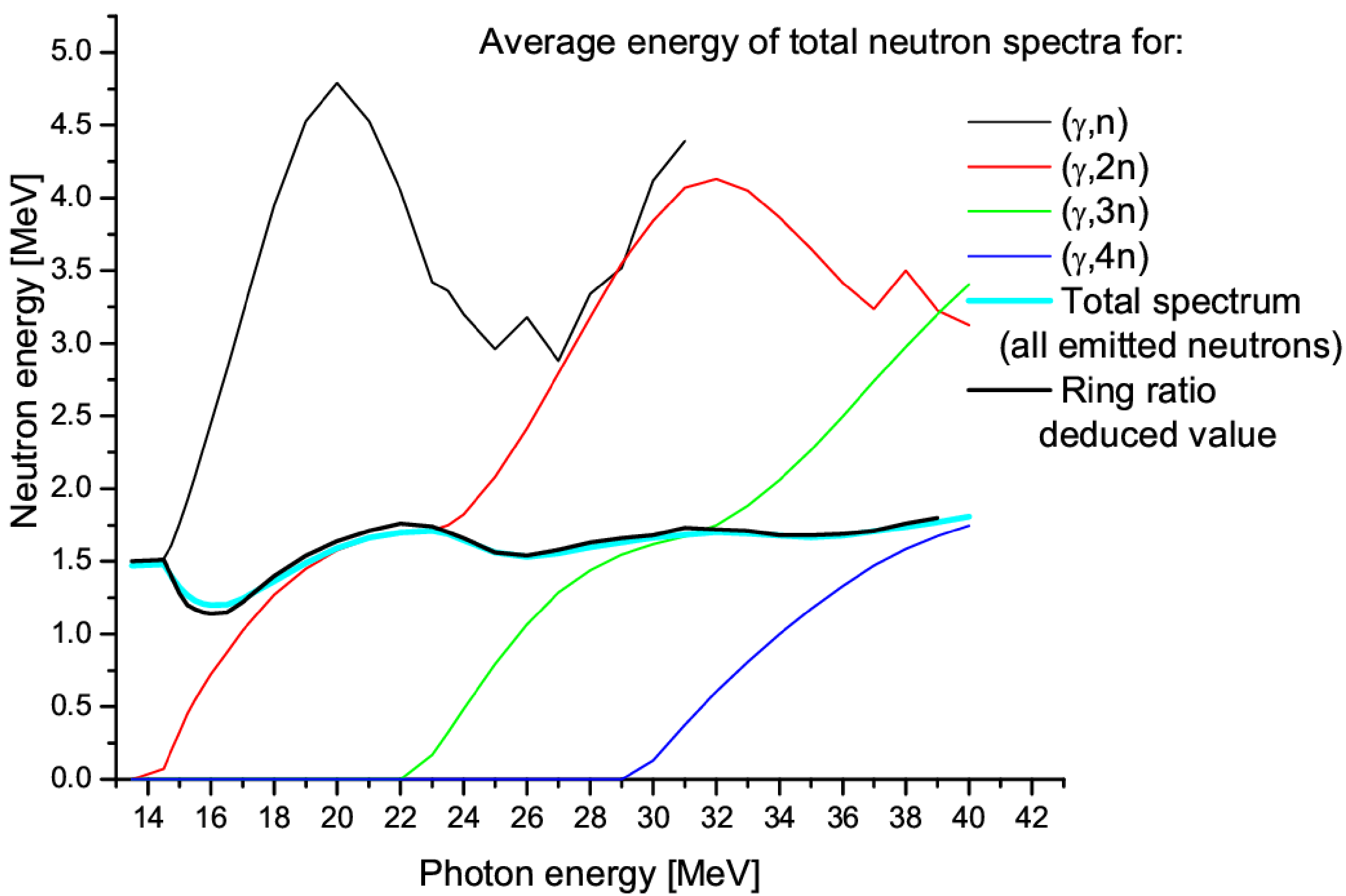
40 MeV incident energy
S_{5n} = 37.97 MeV
Monte Carlo reaction modelling code.



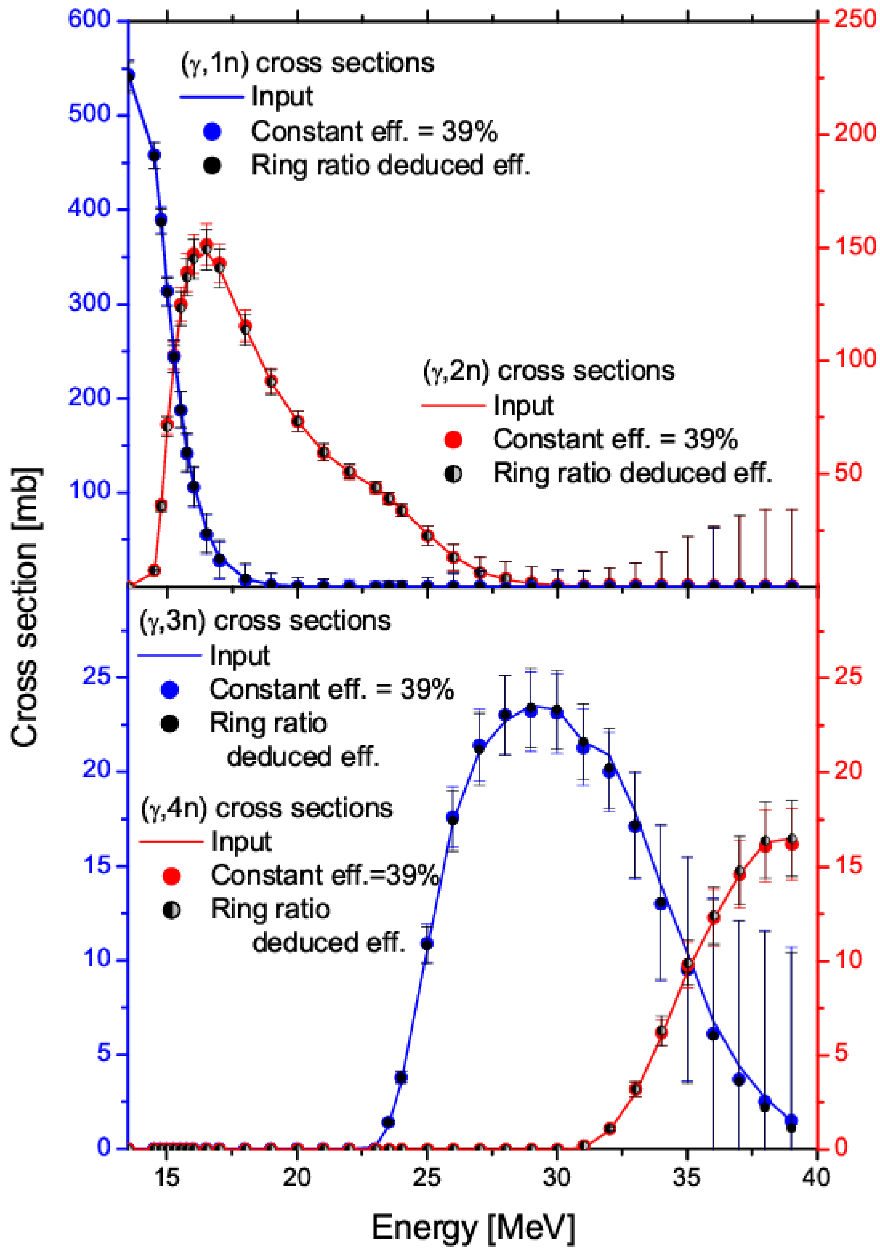
(1) Is the FED flat efficiency energy interval enough for the ^{209}Bi(g,xn) measurements?



Average energy of total neutron spectra



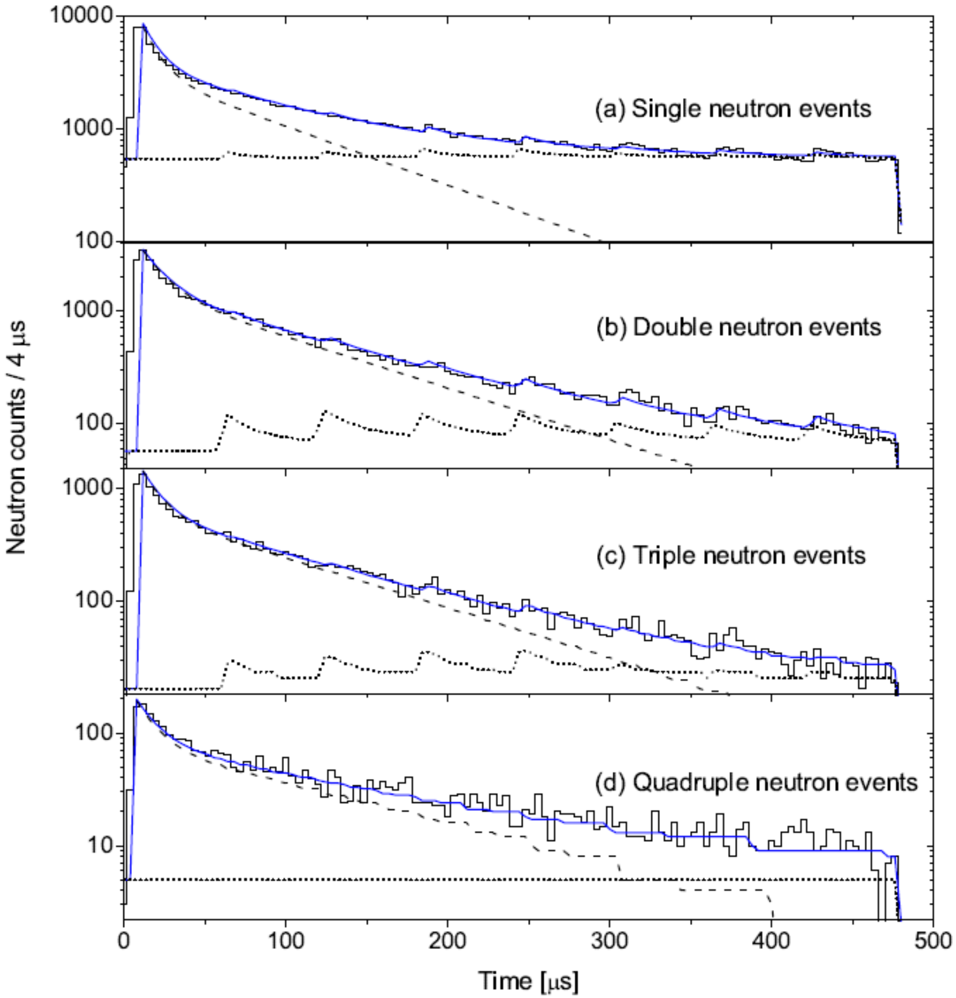
(2) Do we reproduce the input cross sections by applying the Direct Neutron Multiplicity Sorting method?



CONCLUSION:

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

Extraction of Single, Double, Triple, Quadruple events



Each decay was fitted with:

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

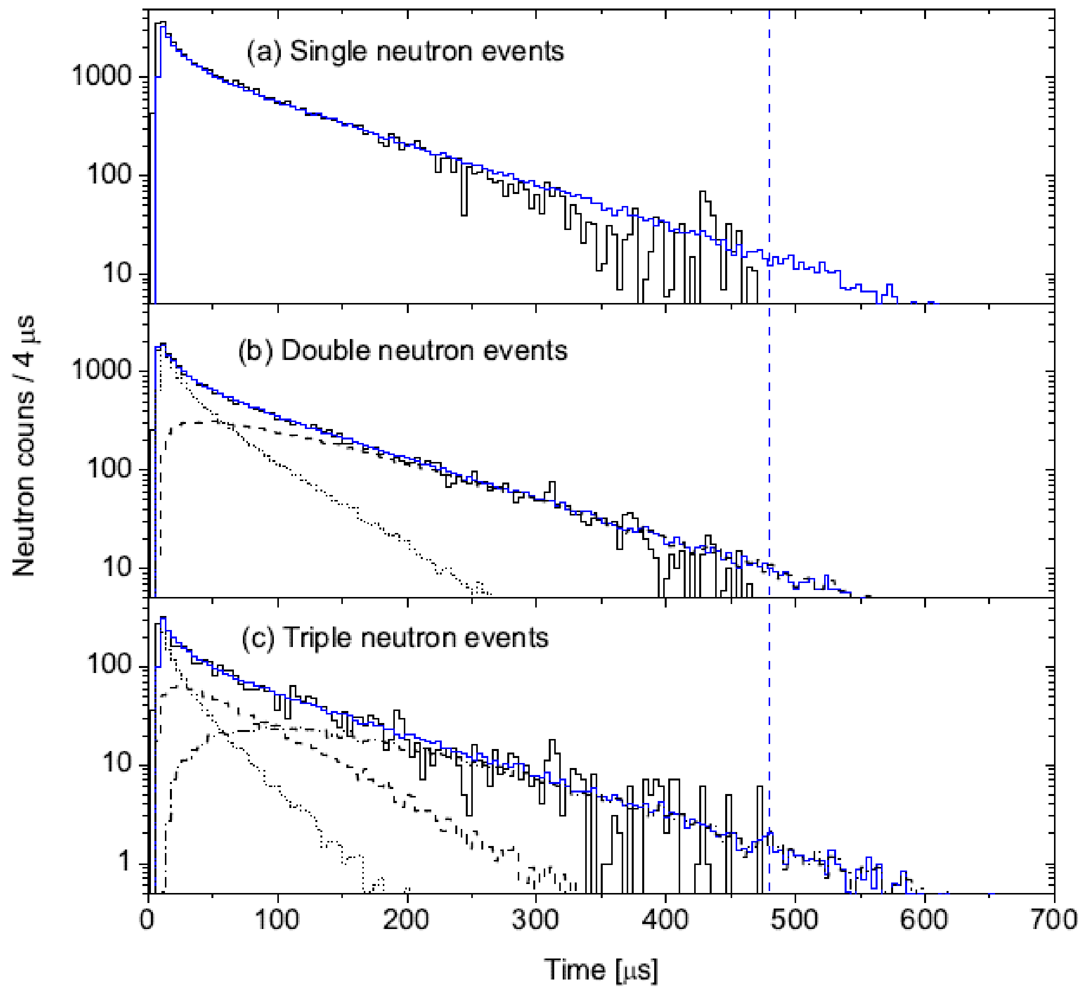
The total spectrum was fitted with:

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

# of Reaction neutrons = spectrum integral – fitted background component

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

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.

Measured cross sections in *monochromatic* approximation

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

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}

Correction (1) for Multiple firing effect

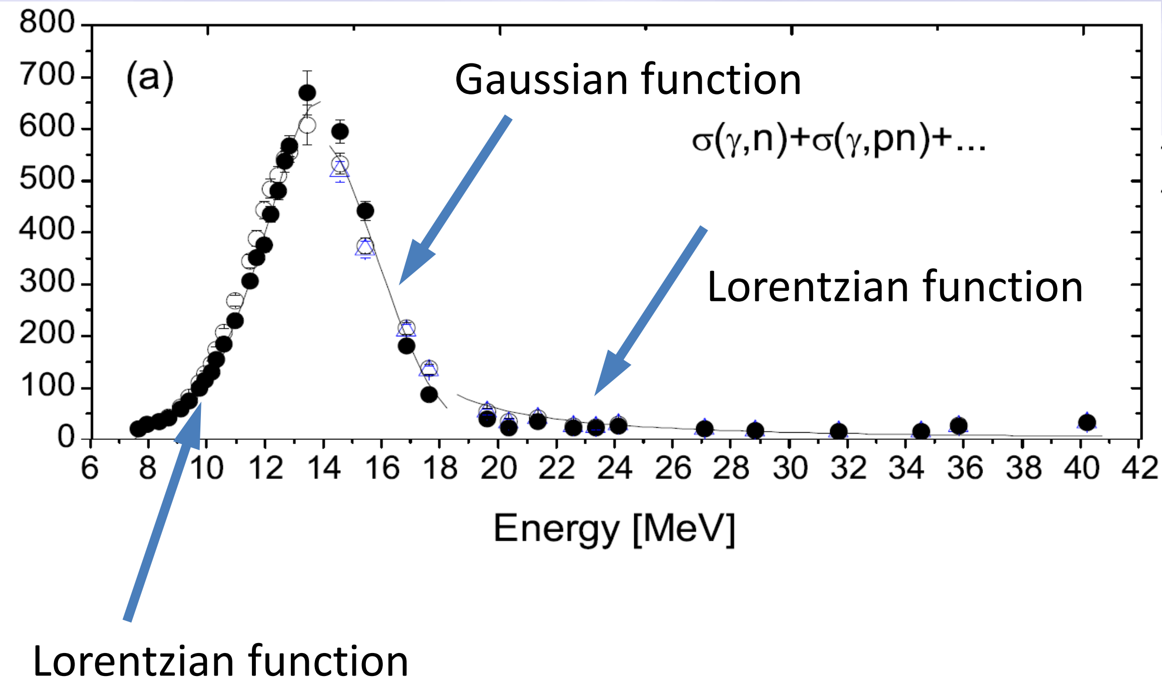
Low reaction rates are required for DNM sorting experiments, to avoid cases when two separate reactions are generated on two nuclei during a given photon pulse.

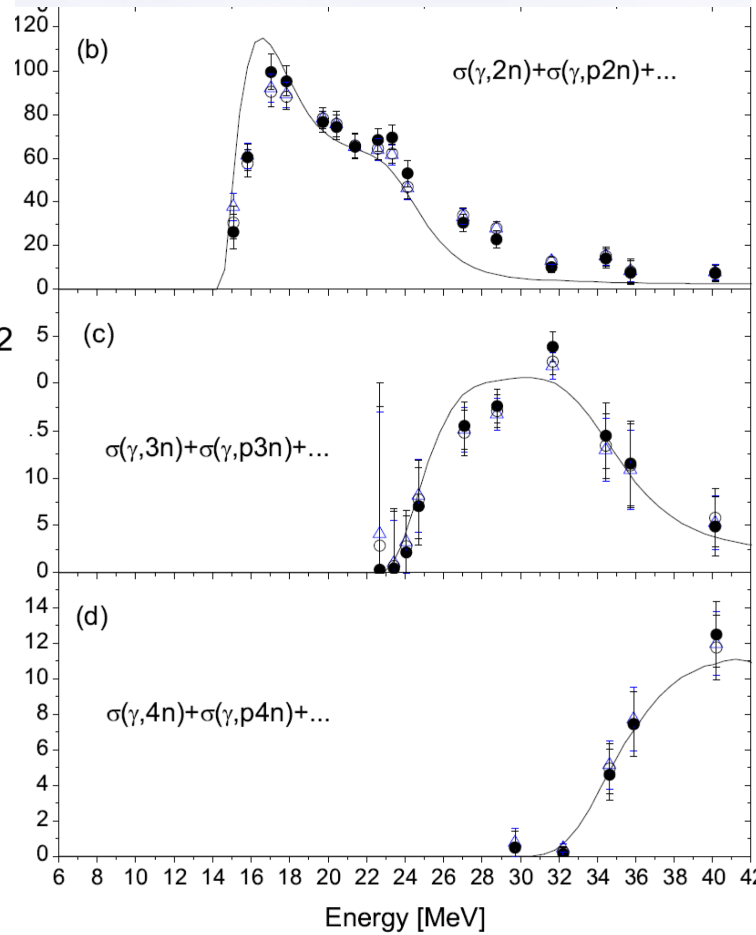
During the experiment, based on reaction cross section estimations, we tuned the incident photon flux and used properly thick targets for each irradiation energy.

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

(g,n) data were deconvoluted using the iterative Taylor expansion method.





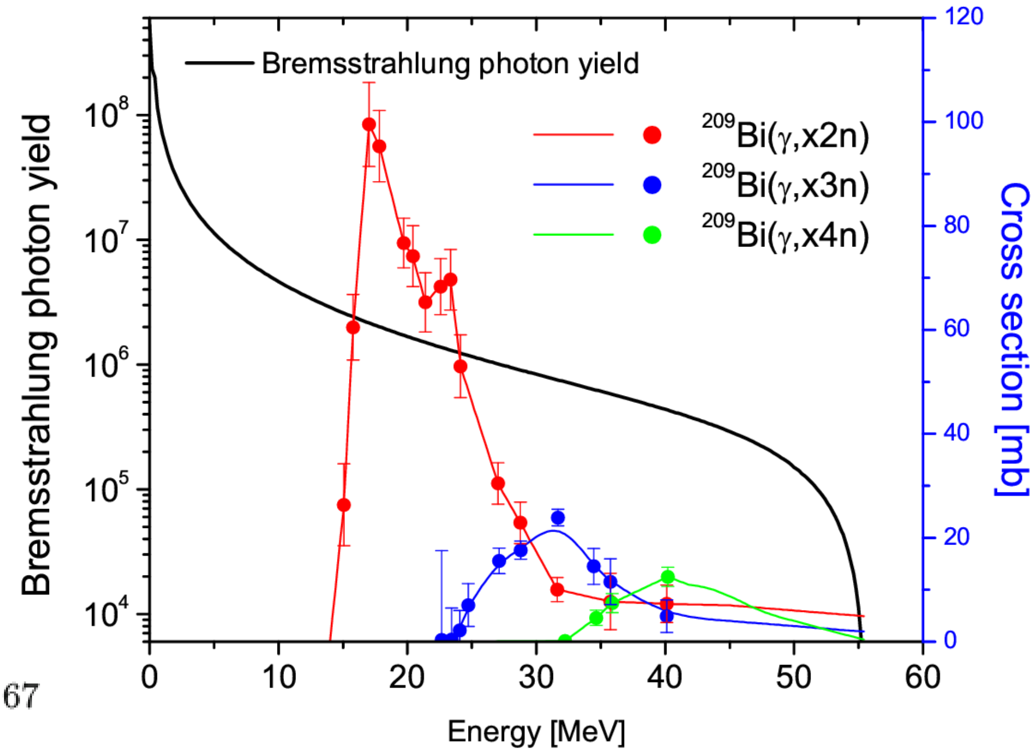
Deconvolution for incident photon spectra (g,2n), (g,3n) and (g,4n) were unfolded using a polynomial fit on several regions .

Comparison with Bremsstrahlung data

NewSUBARU exeperimental cross sections convoluted with MSU bremsstrahlung spectrum to compare resulting yields with the experimental ones measured using the activation technique in 2015.

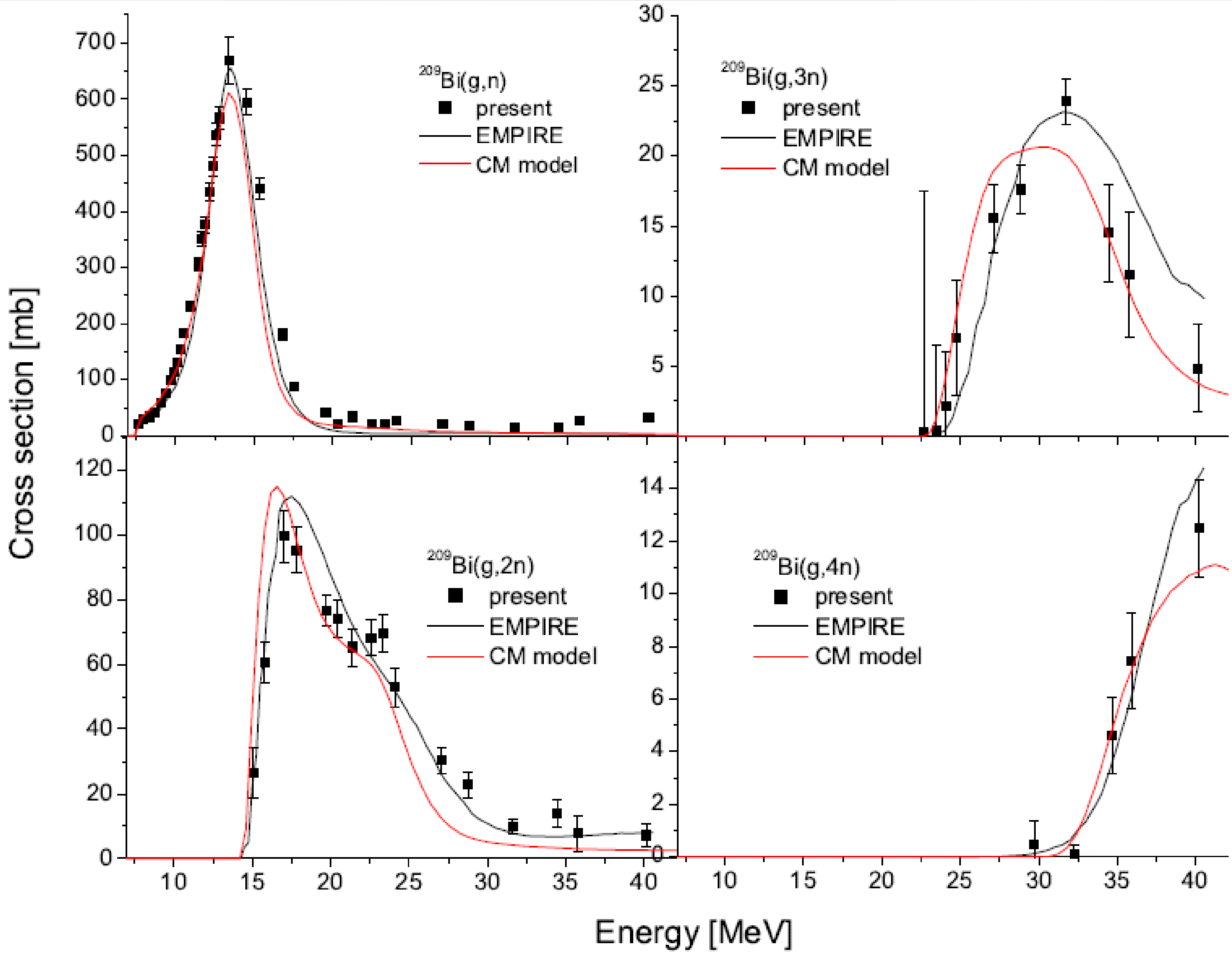
S. Belyshev *et al.*

Eur. Phys. J. A (2015) **51**: 67

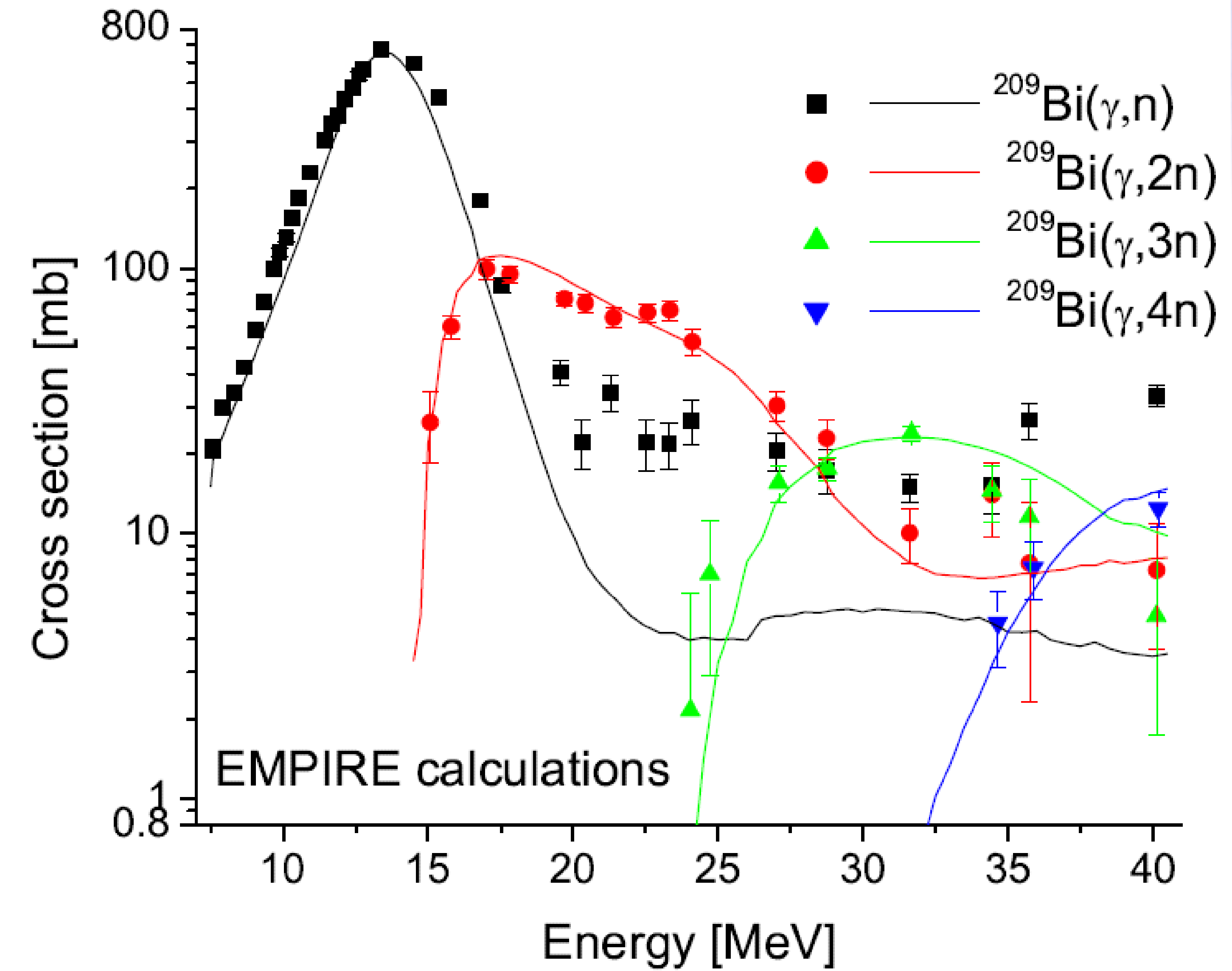


Reaction	Reaction Yield, 10^{10}/C	
	MSU (experimental)	NewSUBARU(convolution)
(g,2n)	2.3(2) x 10^4	3.0(6) x 10^4
(g,3n)	3.1(3) x 10^3	3.6(6) x 10^3
(g,4n)	1.02(8) x 10^3	1.1(2) x 10^3

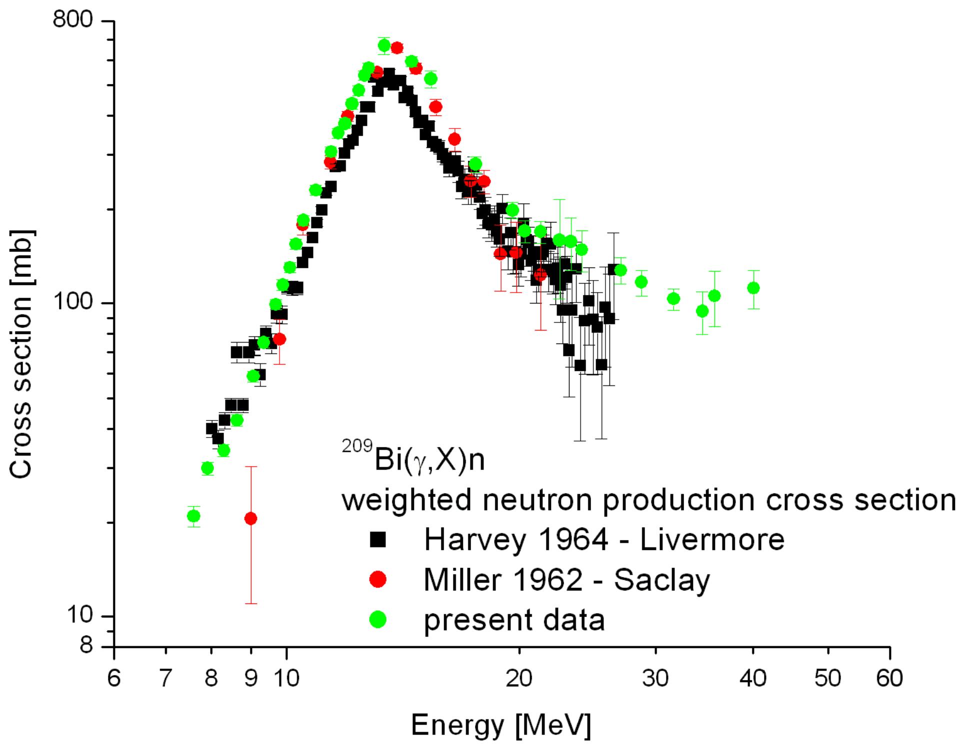
Photoneutron cross sections on ^{209}Bi

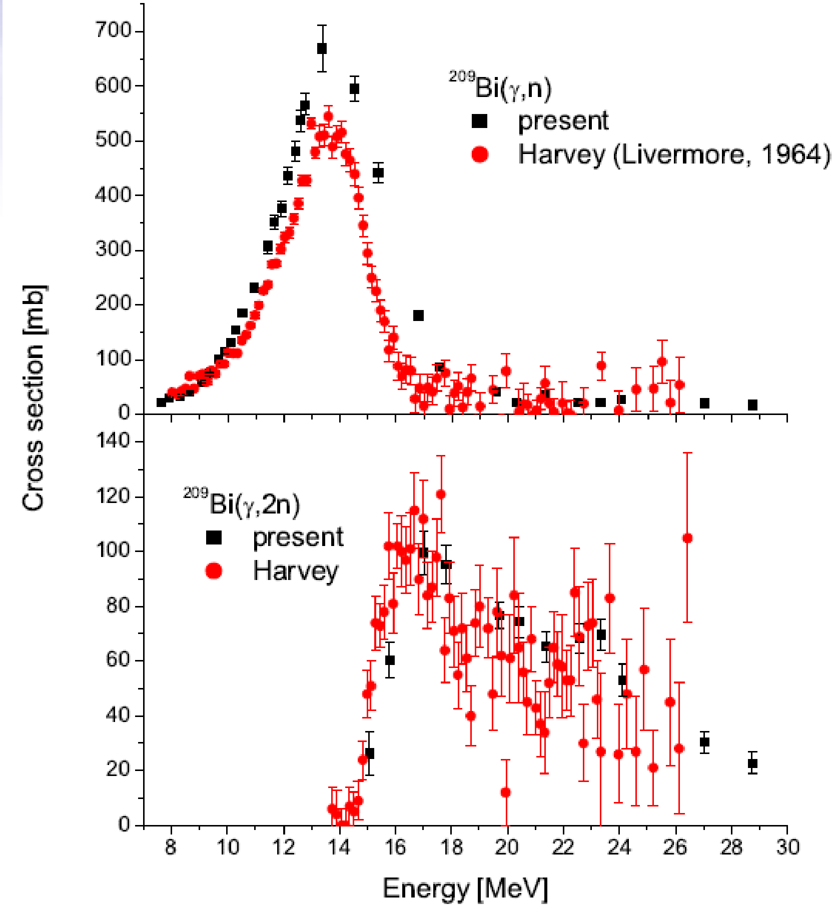


Photoneutron cross sections on ^{209}Bi

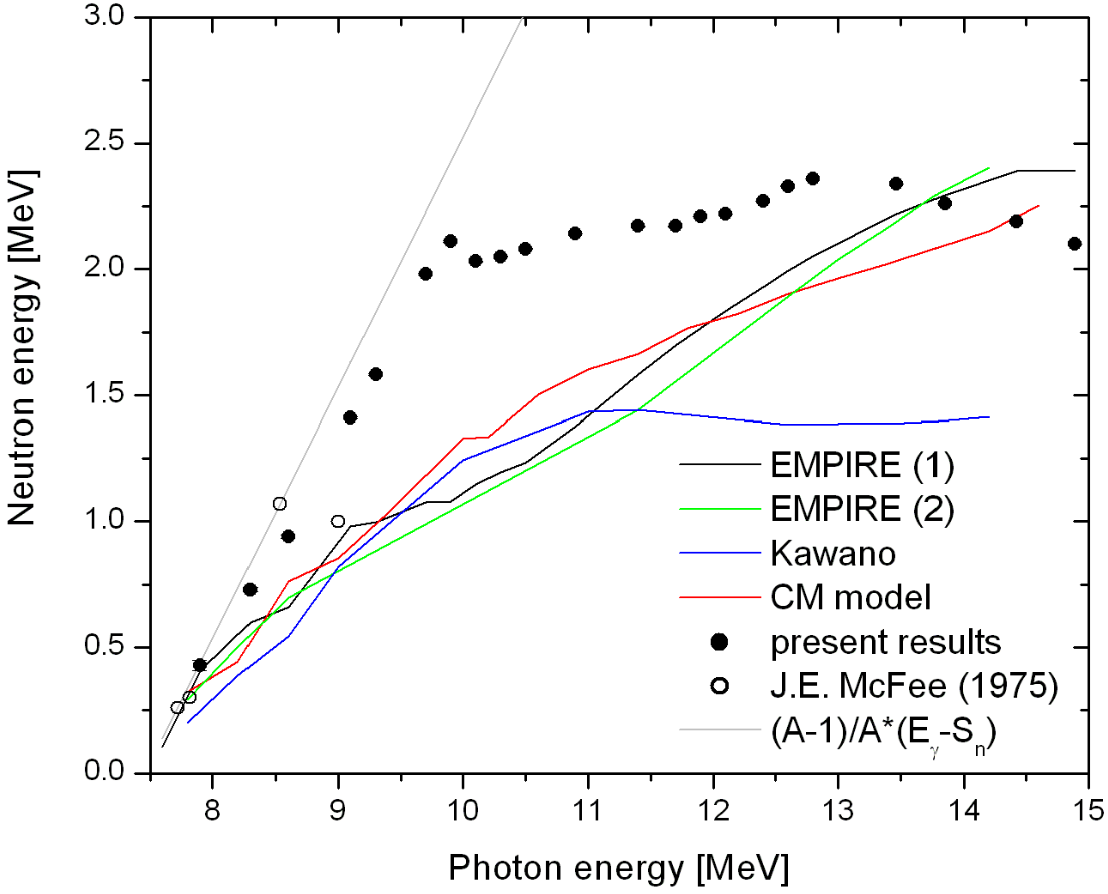


Photoneutron cross sections on ^{209}Bi





Average energy of emitted neutron



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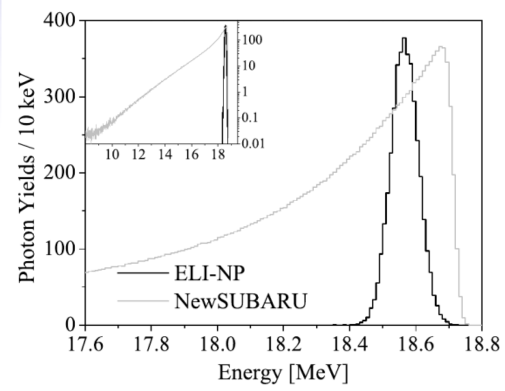
Total and partial photoneutron cross section measurements for the GDR at ELI-NP

Laser photons – relativistic electrons Compton scattering
Yb:YAG ***100 Hz ps Collision Laser*** (200 mJ, 2.3 eV, 3.5 ps)
Low emittance warm electron RF Linac (720MeV, 100 Hz RF)
Very brilliant γ-ray source
- 0.2 to 19.5 MeV
- relative energy resolution 0.5% FWHM
- ~ 10^8 photons/s in FWHM bandwidth



Gamma
Above
Neutron
Threshold

Four Physics Cases

P-process Nucleosynthesis	**New Compilation of (γ,xn) CS**
Nuclear Structure of GDR	**Nuclear Structure of PDR and MDR**

New Direct Neutron Multiplicity (DNM) sorting technique based on a flat efficiency neutron detection system.
Pioneering experiments currently performed at the NewSUBARU gamma beam line facility.

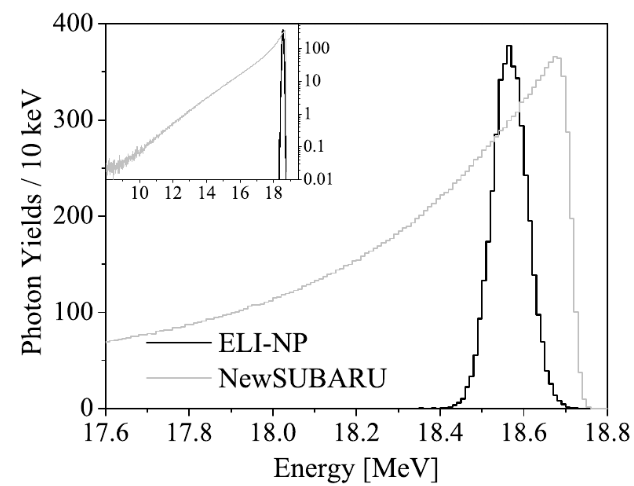
Gamma ray beam source

Warm electron RF Linac

- multi–bunch photogun

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

- two acceleration stages (300 MeV and 720 MeV)

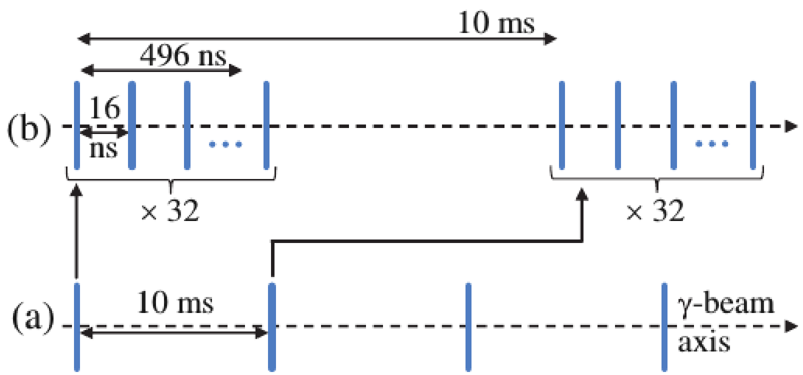


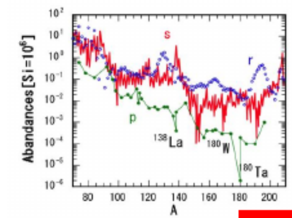
High average power, J–class 100 Hz ps Collision Laser

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

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.	≤ $8.3 \cdot 10^8$
Source rms size (mm)	10 – 30
Source rms divergence (mrad)	25 – 200
Linear polarization (%)	> 95

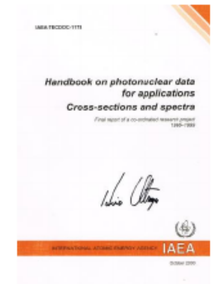
	E_γ [MeV]	ΔE_γ [%]	I_γ^{bw} [ph/sec]
ELI-NP	0.2–19.5	< 0.5 (rms)	$8.3 \cdot 10^8$
NewSUBARU	0–76	> 1.2 (FWHM)	$\sim 10^5$
HIγS	0–100	0.8–10 (FWHM)	$\sim 10^7$

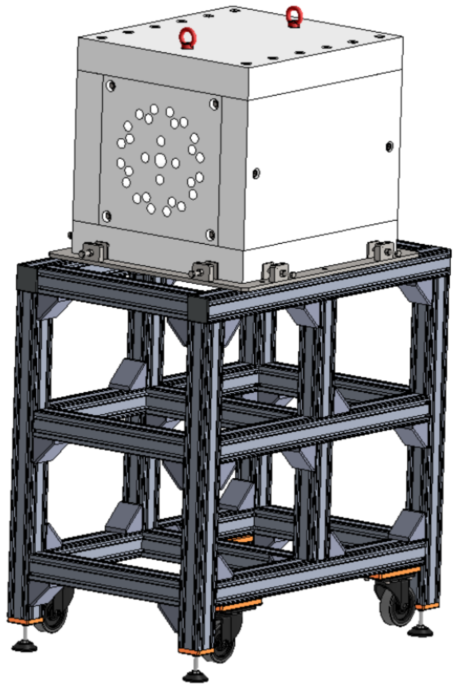




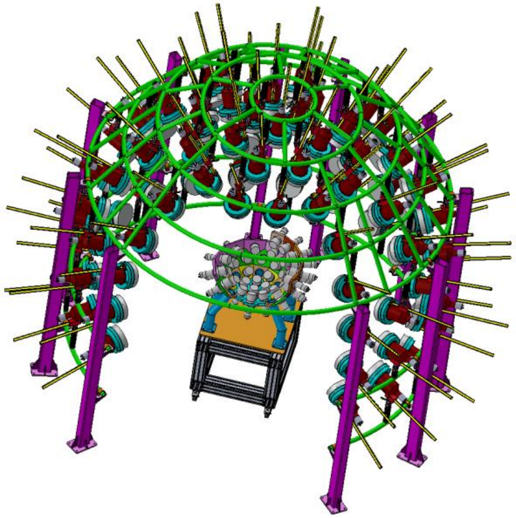
Four Physics Cases

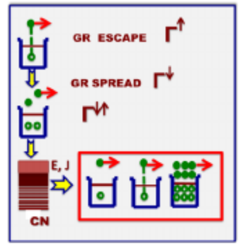
P-process Nucleosynthesis	New Compilation of (γ,xn) CS





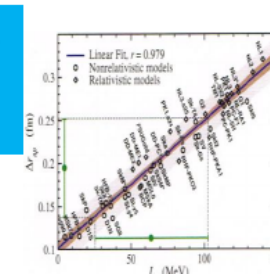
^{3}He neutron counters 30 pcs.





Nuclear Structure of GDR

Nuclear Structure of PDR and MDR



LaBr$_3$:Ce γ det.
15 pcs.

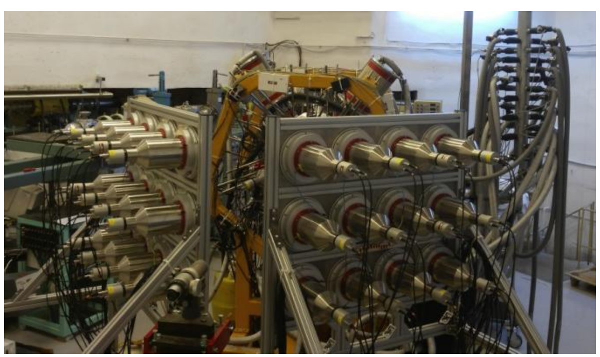
Detector characterization tests and Preparatory experiments at 9 MV and 3 MV IFIN-HH TANDEM accelerators

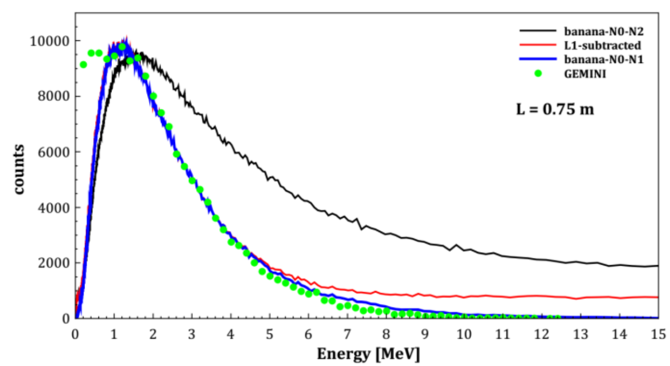
First neutron spectroscopy tests
^{6}Li@22MeV on ^{58}Ni

CeBr$_3$ γ det.
15 pcs.

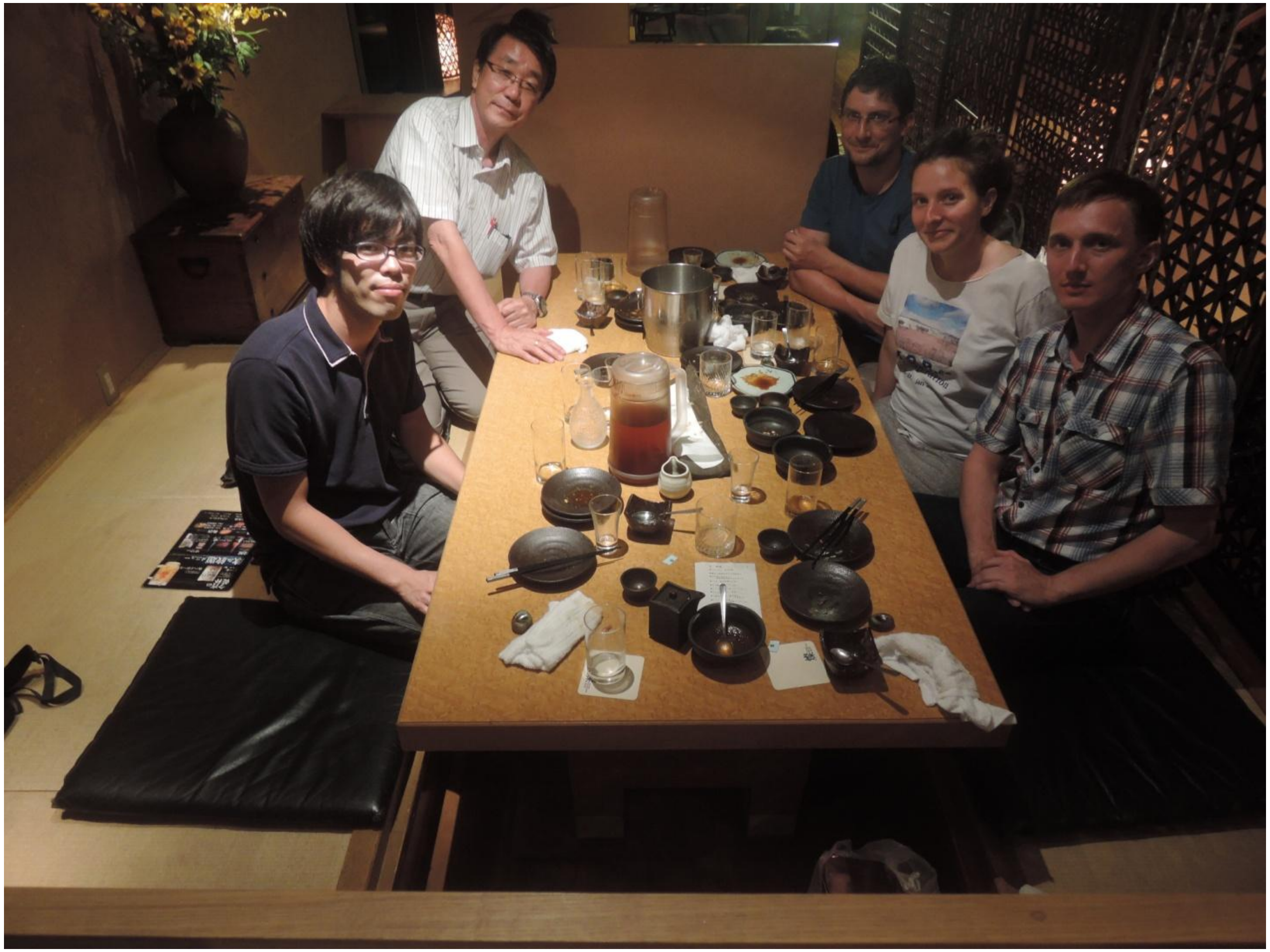
25 pcs. EJ-301 &
25 pcs. ^{6}Li glass

EJ 301 liquid scintillators & RoSPHERE detector array





Experimental team



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