强激光驱动之伽玛光源及关键技术与伽玛核物理研讨会，中国科学院高能物理研究所， 2016年6月23-25日.

Nuclear Physics studies with brilliant γ beams at ELI-NP

Luo Wen (罗文)

[1]**南华大学 核科学与技术学院**

[2]Extreme Light Infrastructure - Nuclear Physics, Bucharest, Romania

申明如下：这个报告所涉及的内容是整个ELI-NP合作组的积累贡献，我仅仅是根据报告内容讲解的需要，按我自己的理解将ELI-NP合作组的工作或提及的想法做了一个不完整的罗列。

Outline

1. ELI-NP facility
   - current status
   - overview of physics program at ELI-NP

2. Nuclear Physics studies with brilliant γ beams at ELI-NP
   - Nuclear resonance fluorescence (NRF) studies
   - Gamma above neutron threshold studies
   - Photodisintegration reactions for nuclear astrophysics studies
   - Photo-fission studies

EUROPEAN UNION

GOVERNMENT OF ROMANIA

Structural Instruments 2007-2013

Sectoral Operational Programme "Increase of Economic Competitiveness"

"Investments for Your Future!"

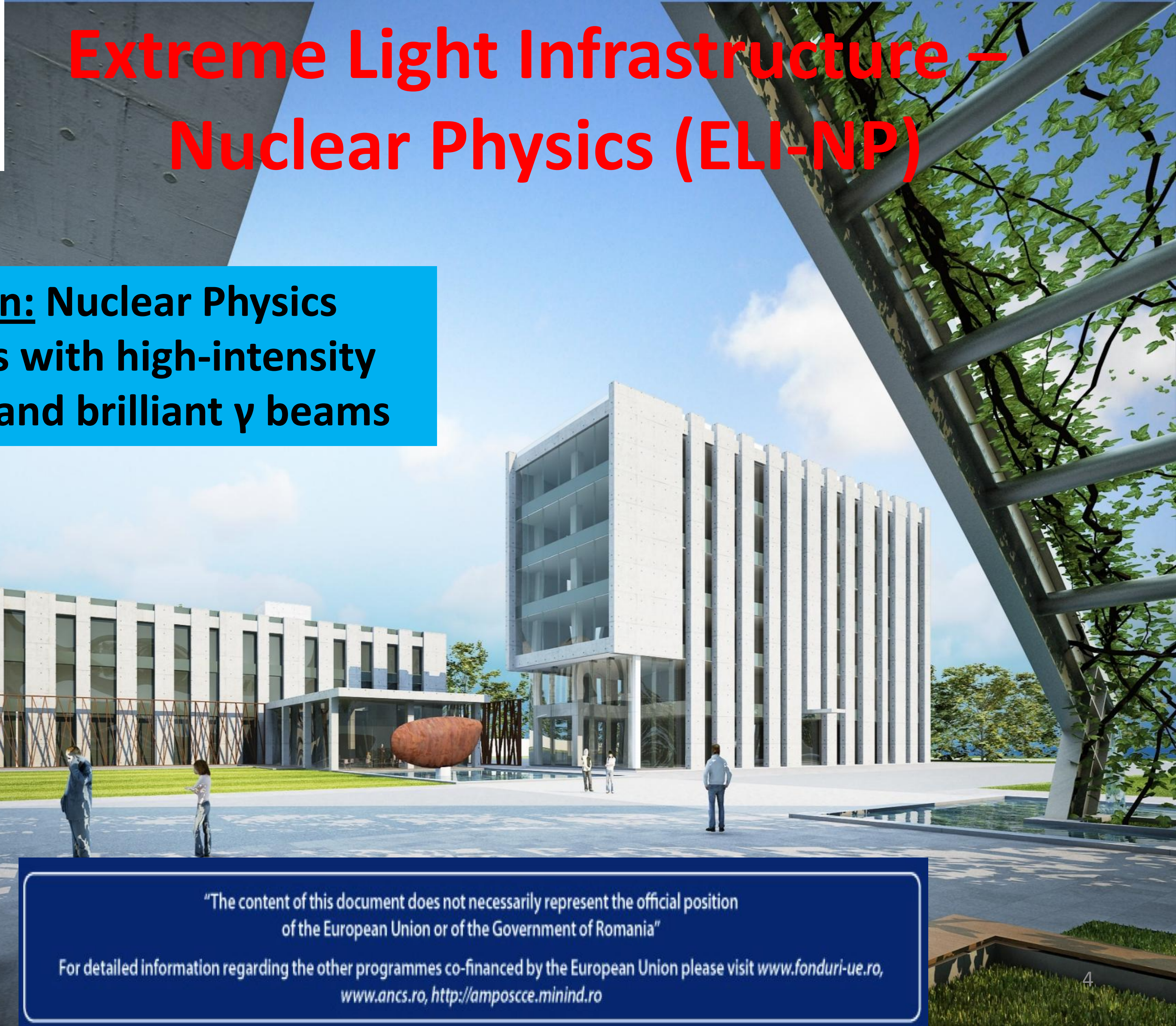
Extreme Light Infrastructure - Nuclear Physics (ELI-NP) - Phase I

www.eli-np.ro

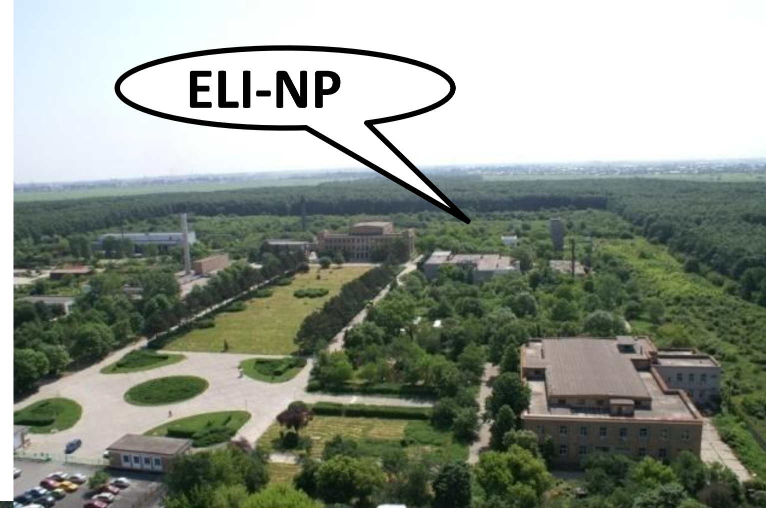
Project co-financed by the European Regional Development Fund

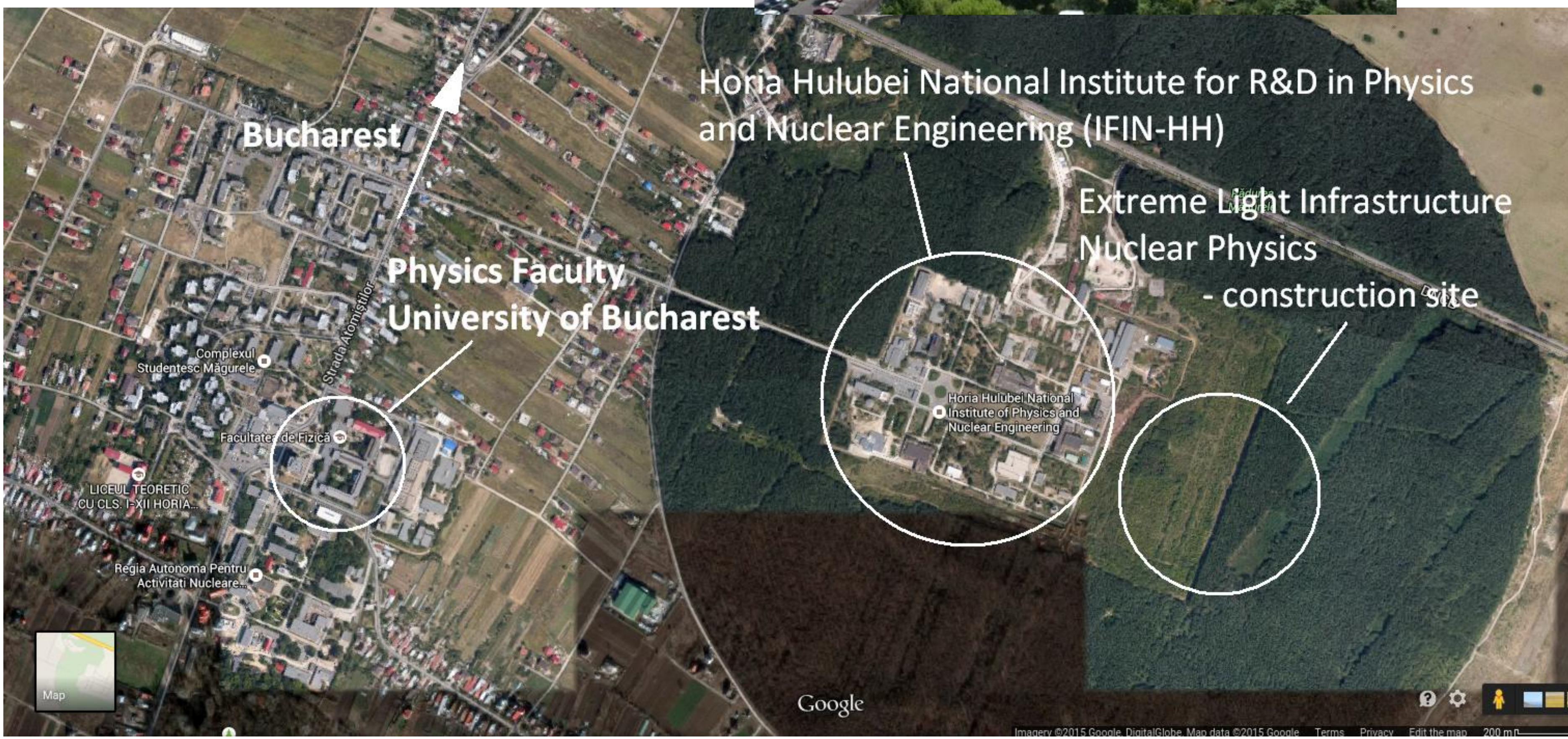
Extreme Light Infrastructure – Nuclear Physics (ELI-NP)

<u>Mission:</u> Nuclear Physics studies with high-intensity lasers and brilliant γ beams



NUCLEAR
Tandem accelerators
Cyclotrons
γ – Irradiator
Advanced Detectors
Biophysics
Environmental Physics
Radioisotopes





The construction will be finished in 2016.
The facility will deliver the first gamma ray beam in 2018.

ELI-NP – Laser and Gamma Beam systems

Laser beam system:

- 2 HPLS up to 10 PW – 6 output lines

  2 x 0.1 PW

  2 x 1 PW

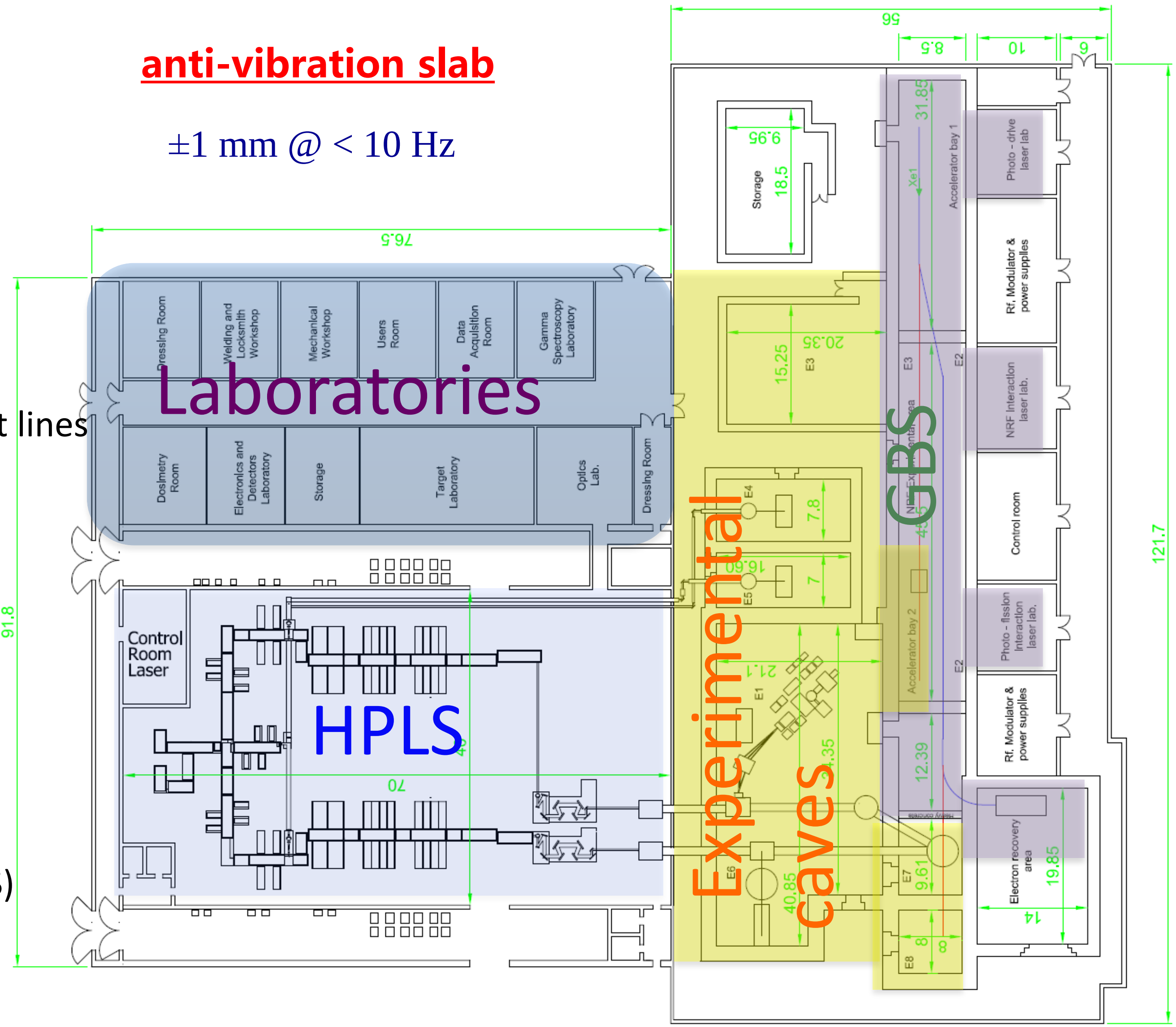
  2 x 10 PW

Gamma beam system

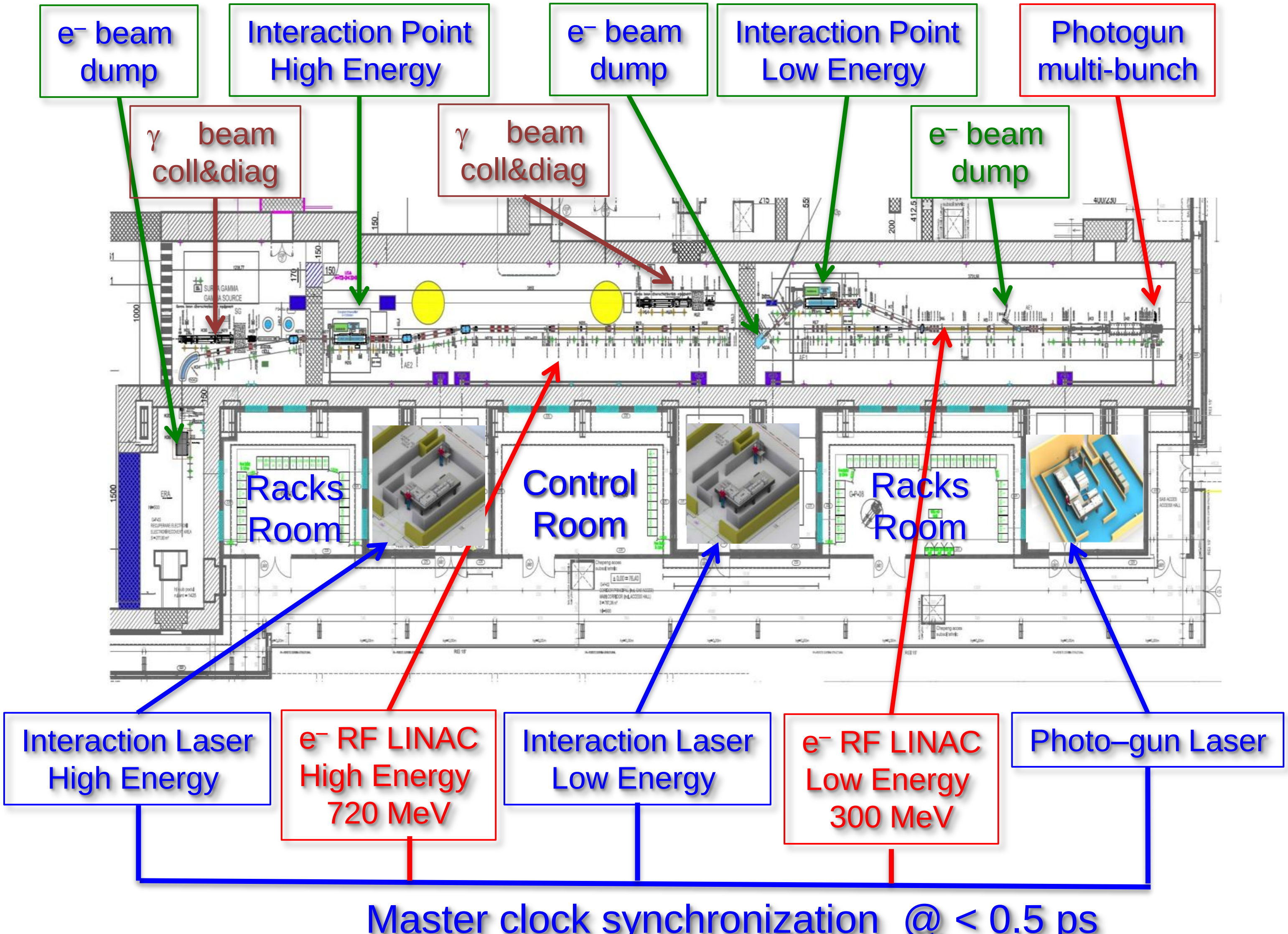
- High intensity
- High energy resolution

Experiments with:

- High power laser beams (HPLS)
- **Gamma ray beams (GBS)**
- Laser + gamma ray beams



Gamma Beam System – Layout

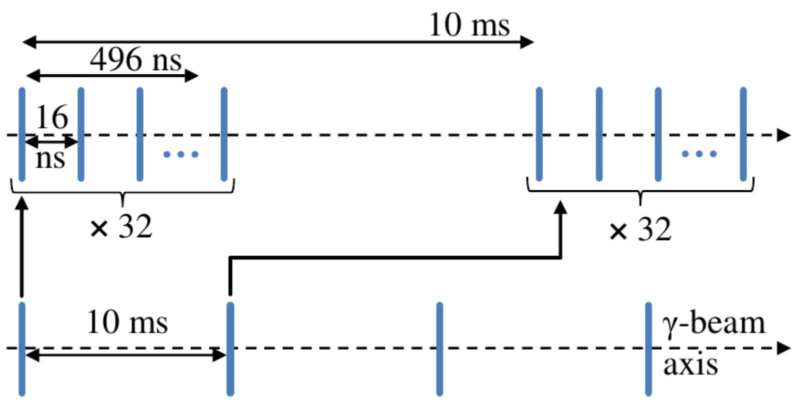


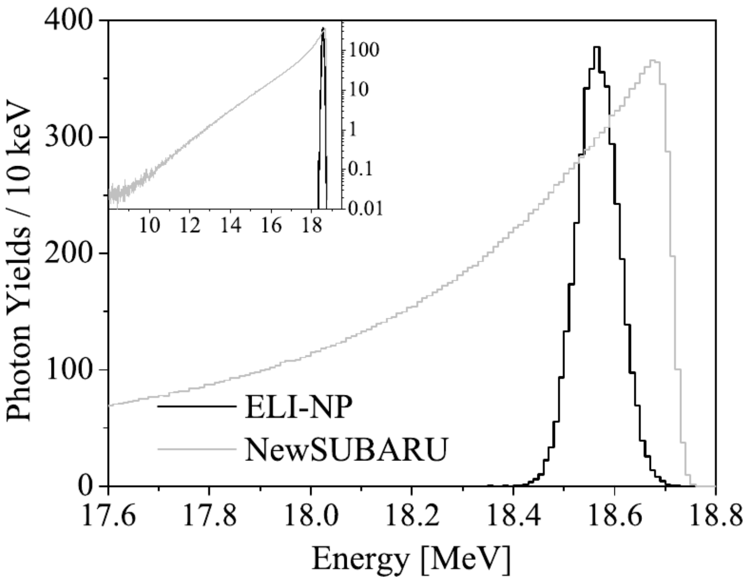
High-Energy Stage: γ rays up to 19.5 MeV

Low-Energy Stage: γ rays up to 3.5 MeV

ELI-NP γ-ray beam

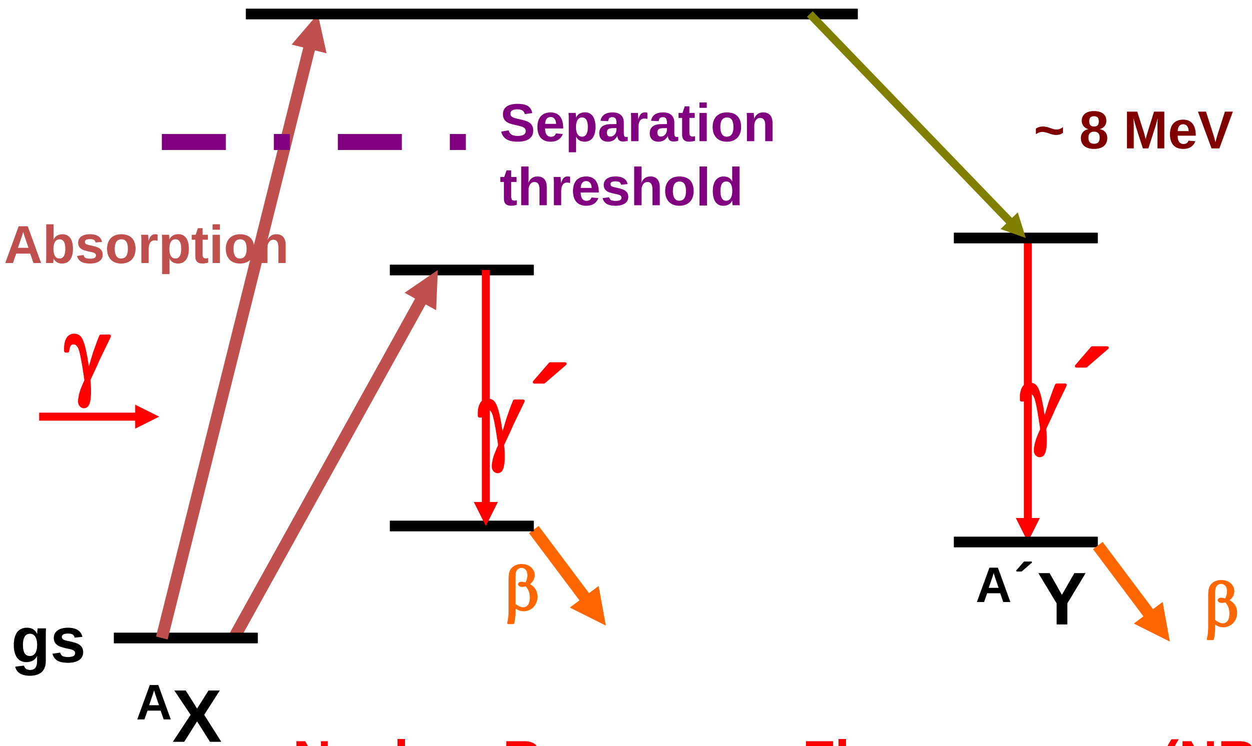
	E_γ [MeV]	ΔE_γ [%]	I_γ^{bw} [ph/sec]
ELI-NP	0.2 - 19.5	$<$ 0.5 (rms)	$8.3 \cdot 10^8$
NewSUBARU	0 - 76	$>$ 1.2 (FWHM)	$\sim 10^5$
HIγS	0 - 100	0.8 - 10 (FWHM)	$\sim 10^7$





	Emittance [nm rad]	σ_{ele} [μm]	E_{ele} [MeV]	ΔE_{ele} [%]	λ_{laser} [nm]	θ_p [deg]	Collimator aperture	E_γ [MeV]	ΔE_γ^{FWHM}
ELI-NP	0.41	30	720	0.1	515	7.5	0.5 mm	18.55	0.5 % 9.3 keV
NewSUBARU	x: 40 y: 4	x: 300 y: 180	1056.56	0.04	1064	0.	C1: 3 mm C2: 1 mm	$E_\gamma^{max} = 18.68$ $E_\gamma^{avg} = 17.79$	2.2 % 41.1 keV

Photonuclear Reactions



Nuclear Resonance Fluorescence (NRF)
Photoactivation
Photodesintegration (-activation)
Photofission

Nuclear physics studies with brilliant γ beams

- Nuclear resonance fluorescence (NRF) studies
  Rom. Rep. Phys. *68, S483–S538, 2016*
- Gamma above neutron threshold studies (ELI-GANT) **Rom. Rep. Phys.** *68, S539–S619, 2016*
- Photodisintegration reactions for nuclear astrophysics studies **Rom. Rep. Phys.** *68, S699–S734, 2016*
- Photo-fission studies
  Rom. Rep. Phys. *68, S621–S698, 2016*

http://www.rrp.infim.ro/inpress.html

Nuclear physics studies with brilliant γ beams

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Nuclear Photonics

Electromagnetic dipole response of nuclei

Nuclear structure

- Modes of excitation below the GDR

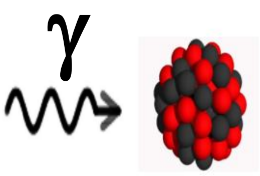
Impact on nucleosynthesis

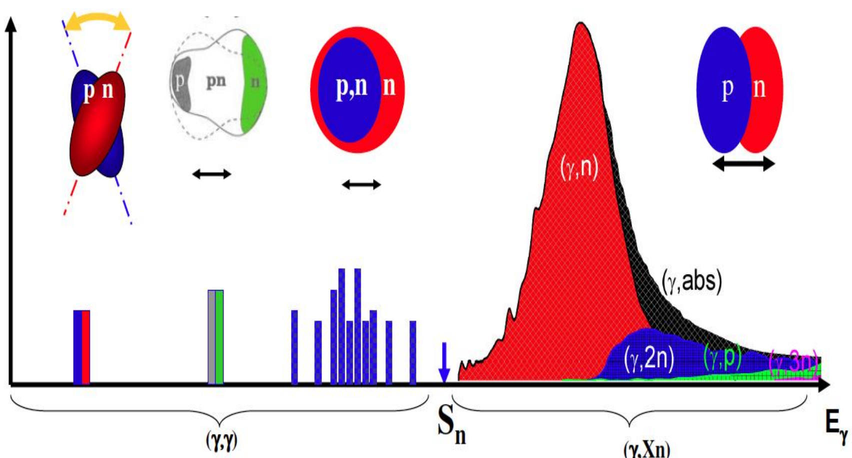
- Gamow window for photo–induced reactions in explosive stellar events

Understanding exotic nuclei

- E1 strength will be shifted to lower energies in neutron rich system

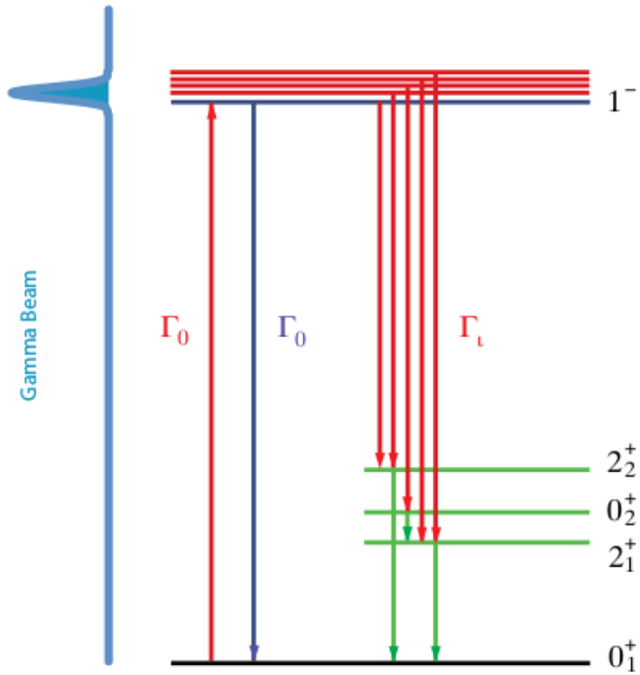
NRE

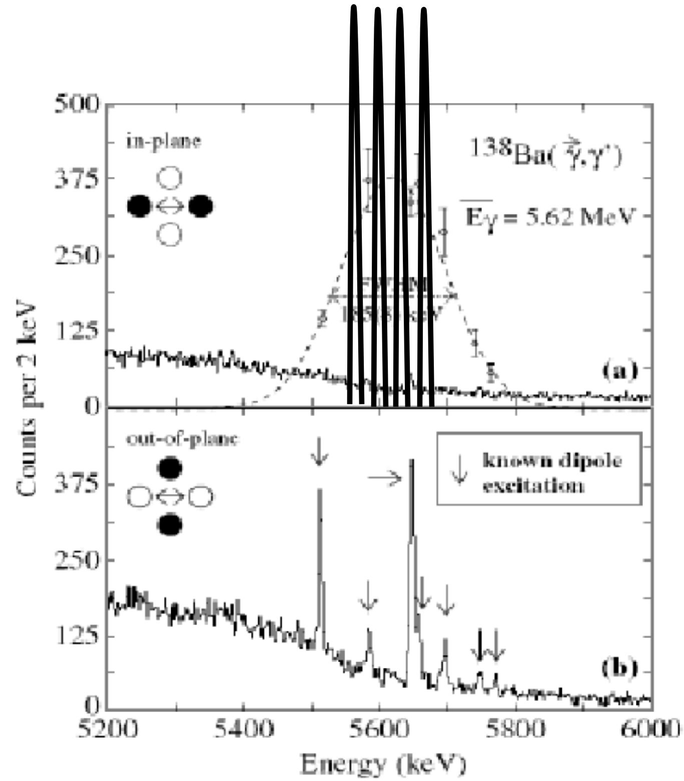




E1 strength distribution

NRF experiments





Primary observables of NRF processes are the energies, intensities, polarizations, and angular intensity distributions of the fluorescent -radiation.

HIγS @ Duke U.

- bandwidth – few%
- spectral density – 10^2 ph/s/eV

ELI-NP

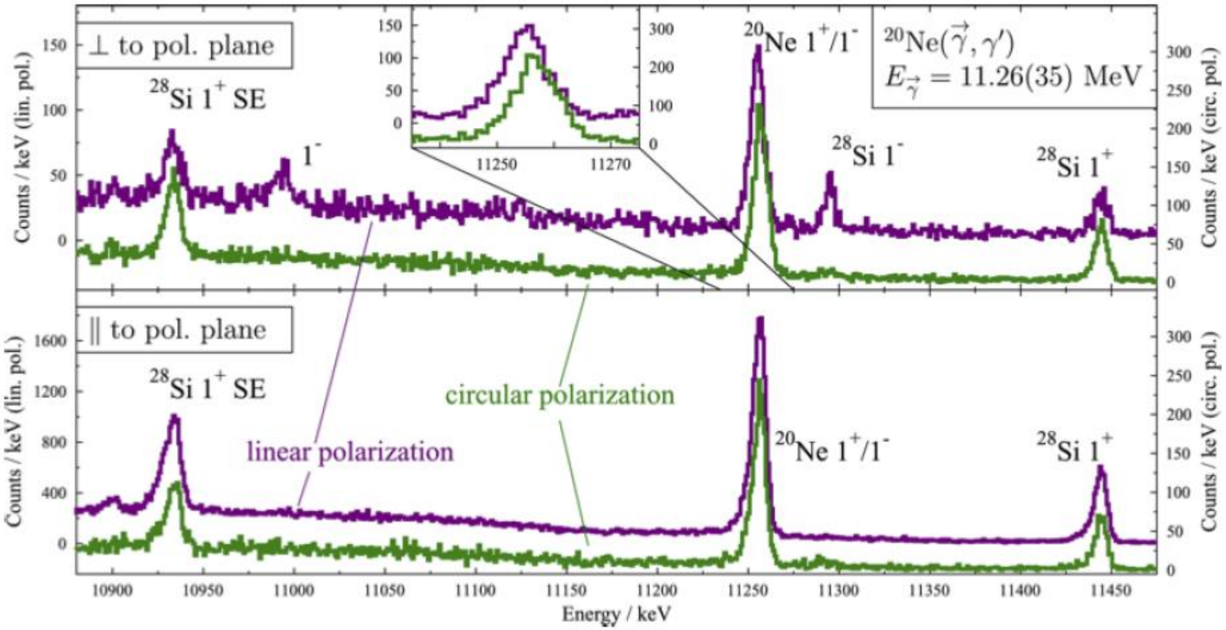
- bandwidth – 0.3%
- spectral density – 10^4 ph/s/eV

NRF physics cases

--- An access to the equation of state and to neutron rich matter: investigation of the Pygmy Dipole Resonance

--- Parity violation in nuclear excitation: The case of ^{20}Ne

Parity doublet in ^{20}Ne



J. Beller, N. Pietralla et al., Physics Letters B 741, 128 (2014).

NRF physics cases

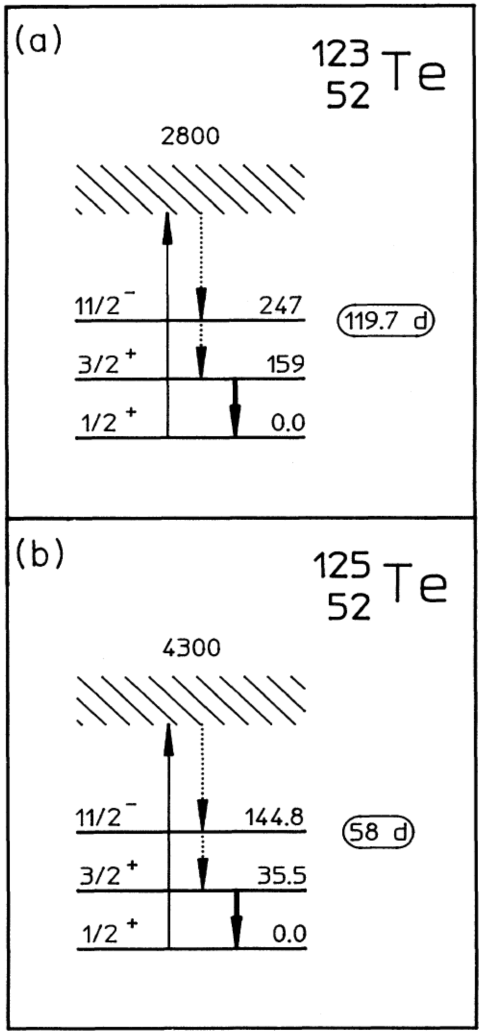
--- Constraints on neutrino-less double-beta ($0\nu\beta\beta$)- decay matrix elements: A novel decay channel of the scissors mode of ^{150}Sm.

--- Proton-neutron symmetry breaking in nuclei: Rotational 2^+ states of the nuclear scissors mode.

--- Electric and magnetic dipole moments in atomic nuclei: The low-energy dipole response of heavy radioactive nuclei.

--- The origin of matter: studies of the photo-response of weakly-abundant nuclei near the N=82 shell closure.

Search suitable doorway states in (γ, γ') reactions



For some spin isomers, certain doorway states are already known.

G. D. Dracoulis et al. Phys. Rev. C 81, 011301(R) (2010)

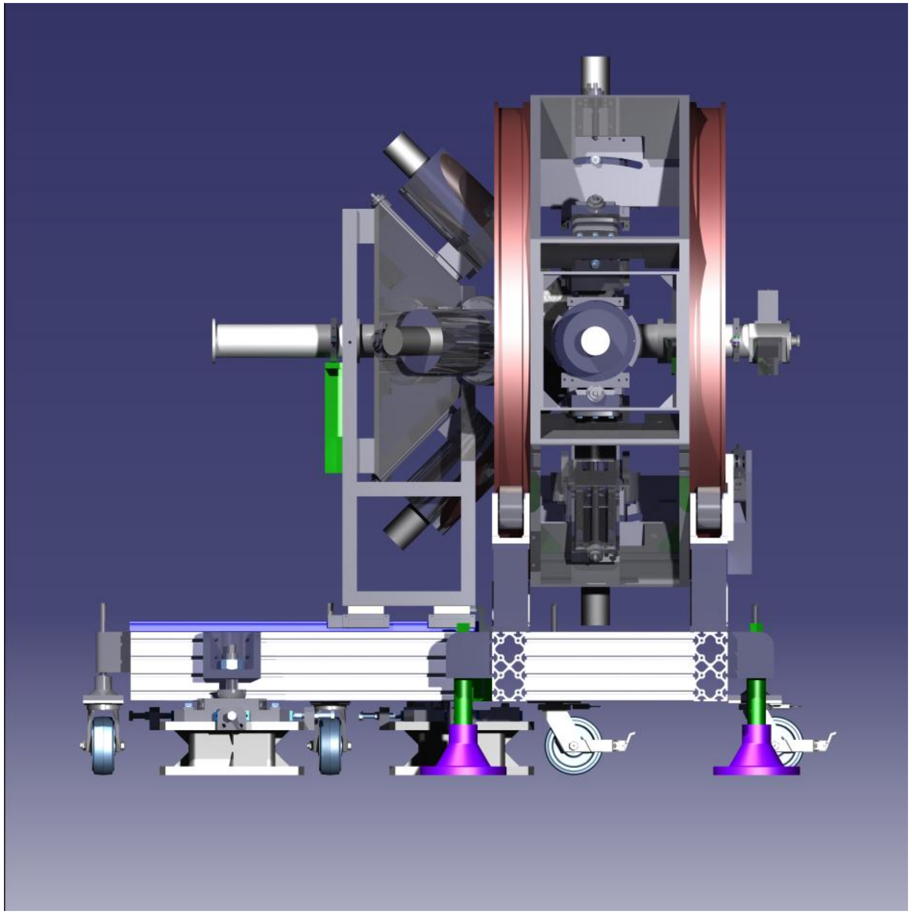
Possible doorway states for resonant photo-excitation of isomers need still to be found.

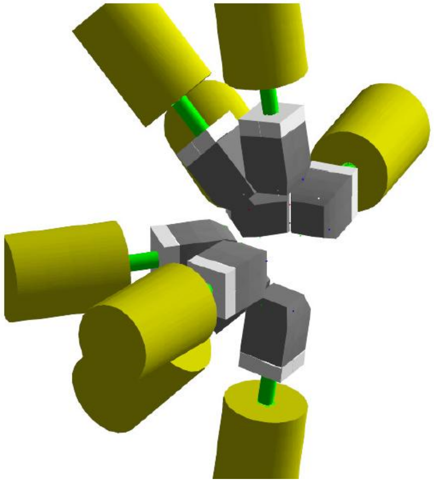
For the example ^{195}Pt(γ,γ')^{195m}Pt, it is likely they exist and the lowest doorway state could be found between 1.1 and 2.5 MeV.

A search for doorway states by activation experiments could be initiated at ELI-NP.

J.J. Carroll et al. Phys. Rev. C 43 (1991) 1238.

γ-ray spectroscopy

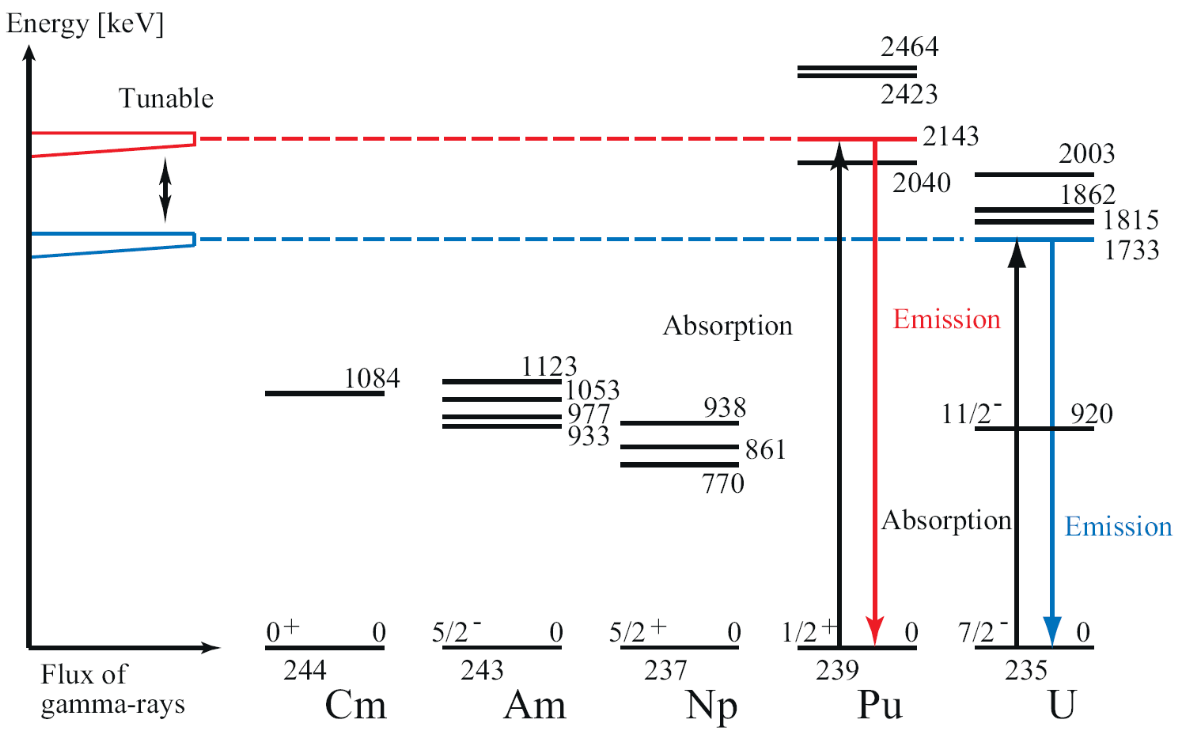




- 8 segmented clover HPGe detectors @ 90° and 135°, $\varepsilon_{total} \cong 6\%$
- Anti-Compton shields (back-catchers)

- In addition, 4 $LaBr_3$ detectors @ 90^o, mounted at 45^o with respect to the CLOVER detectors in the standard configuration, but not shown here.

Potential NRF applications



---- Detection of radioactive isotopes

---- Nondestructive assay of plutonium and minor actinide in spent fuel

---- Detecting clandestine material

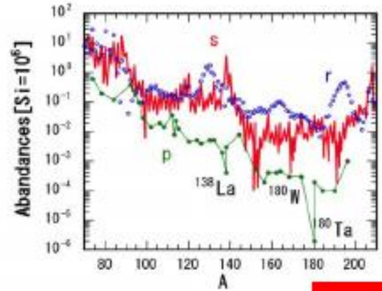
---- Nuclear waste imaging and assay

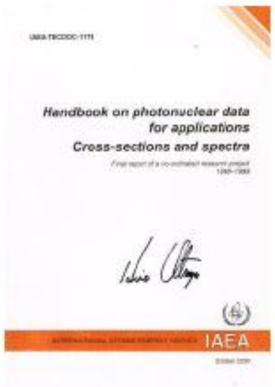
NIMA 621 (2010) 695-700; Applied Physics Express 2 (2009) 036502

Nuclear physics studies with brilliant γ beams

- Nuclear resonance fluorescence (NRF) studies
- Gamma above neutron threshold studies (ELI-GANT)
- Photodisintegration reactions for nuclear astrophysics studies
- Photo-fission studies

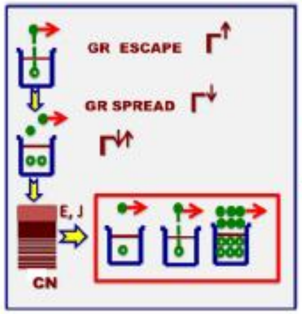
ELI-GANT – Physics program

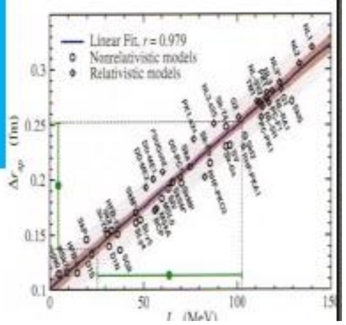




Four Physics Cases

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



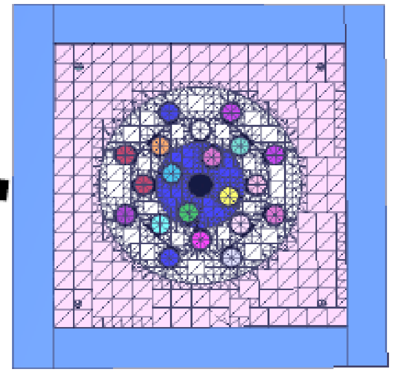


ELI-GANT – Physics program

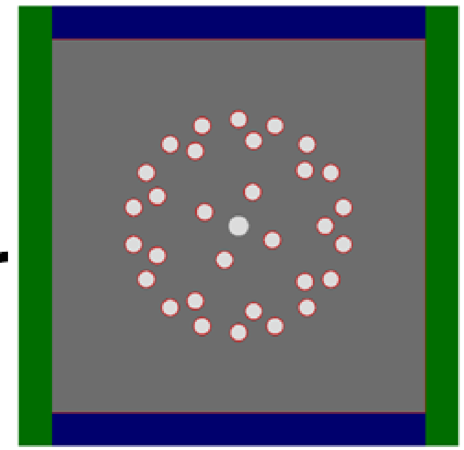
Physics cases

- P-process
- New Compilation
- GDR
- PDR and MDR

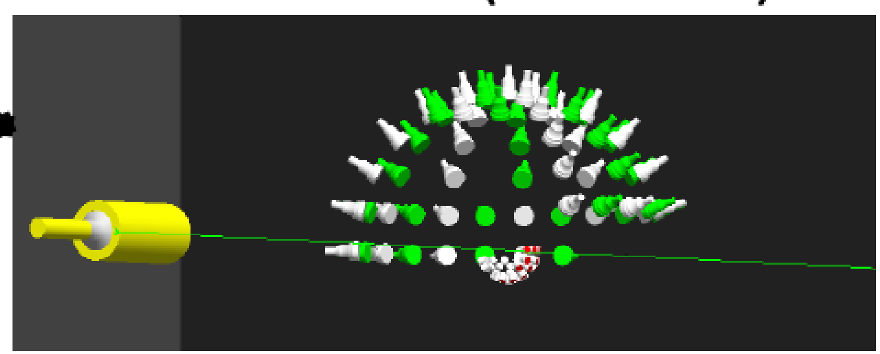
High-efficiency 4π neutron detector (ELIGANT-TNH)



Flat-efficiency 4π neutron detector (ELIGANT-TNF)



Array of $LaBr_3$:Ce, Liquid, and Li glass scintillation detectors (ELIGANT-GN)



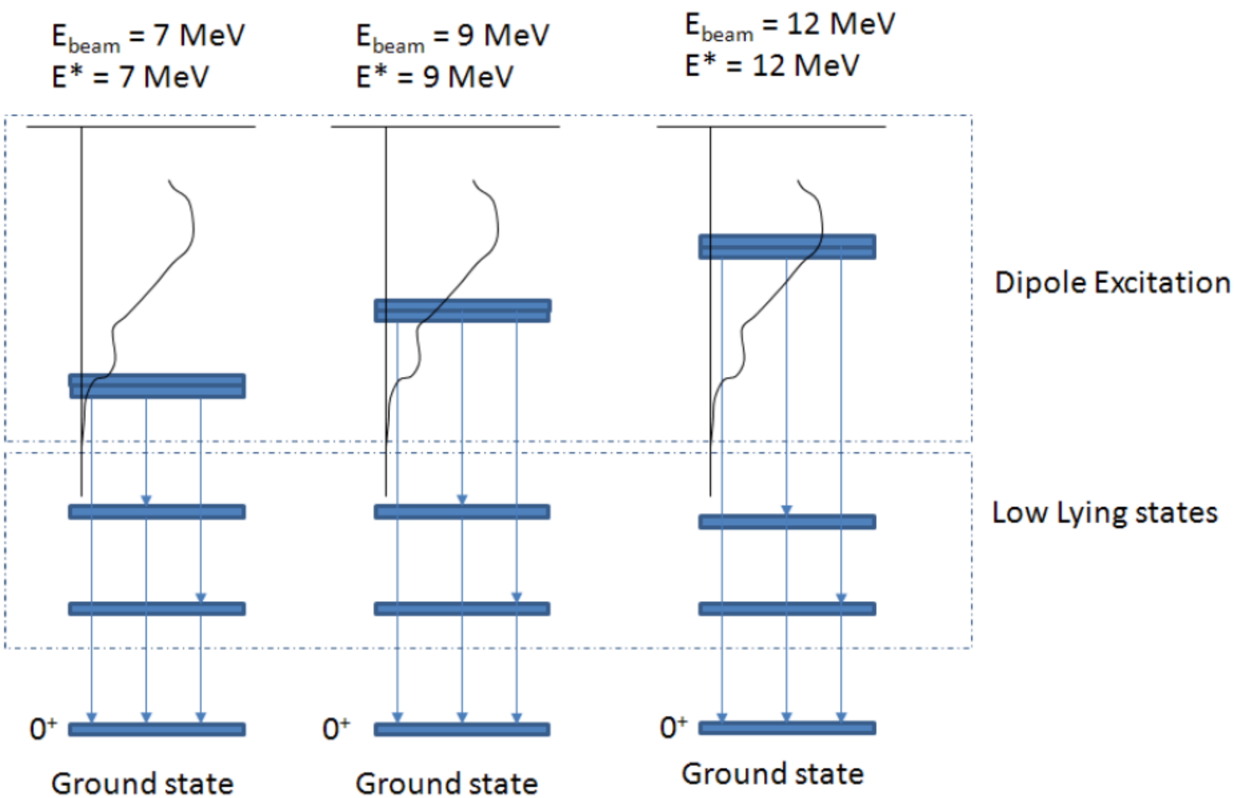
Physics cases addressed by the ELI-GANT group

List of physics cases addressed by the ELIGANT group. Given in the parenthesis is the section in which the corresponding subject of Physics Cases and Technical Proposal is presented.

Physics cases	*Day 1* experiments	Instrumentation
p-process nucleosynthesis	$^{180}Ta(\gamma,n)^{179}Ta$ $^{138}La(\gamma,n)^{137}La$	ELIGANT-TNH
Nuclear structure of GDR	$^{208}Pb(\gamma,\gamma_0)^{208}Pb$: ground-state gamma decay of GDR in ^{208}Pb:	ELIGANT-GN
New compilation	$^{159}Tb(\gamma,xn)$ (x=1–2)	ELIGANT-TNF
Nuclear structure of PDR and MDR		ELIGANT-GN

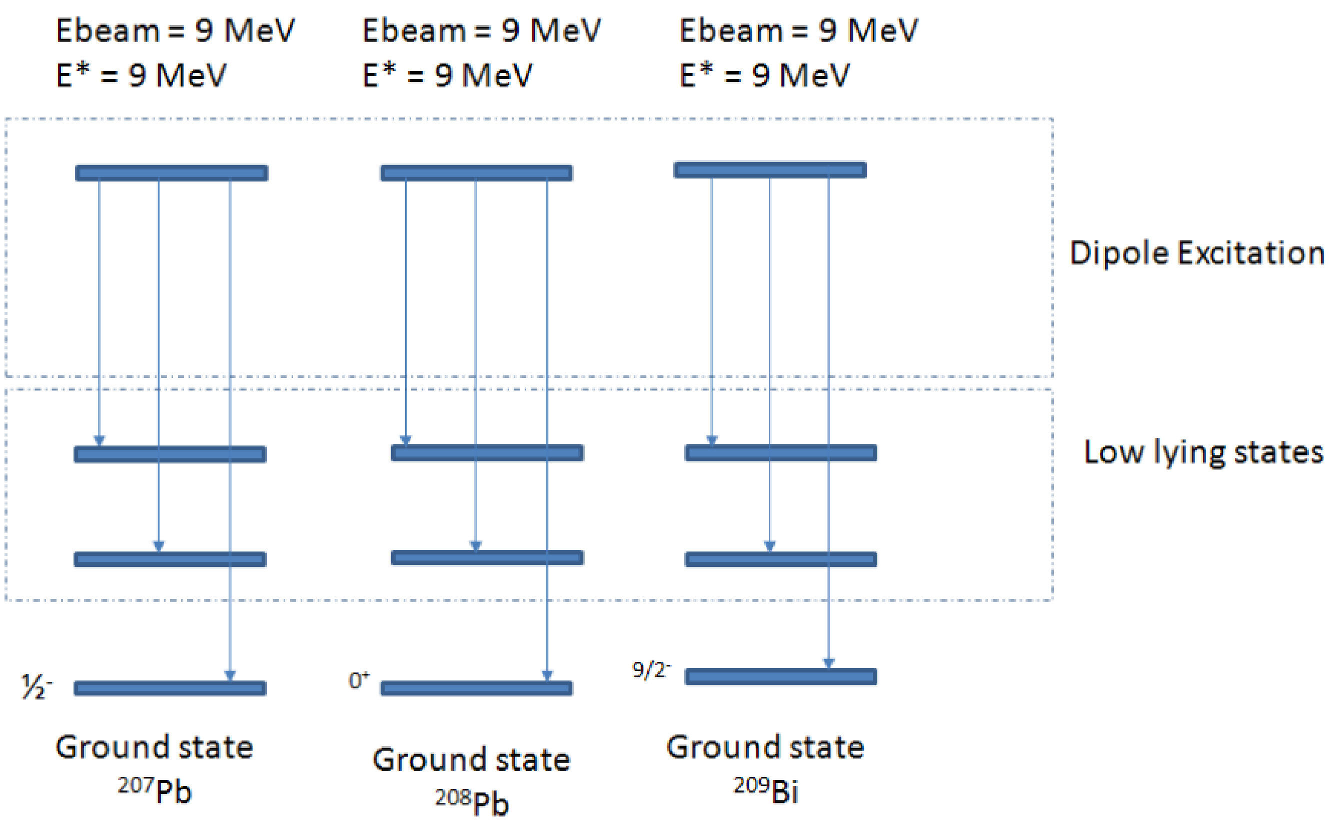
The $^{180}Ta(\gamma,n)^{179}Ta$ cross section cannot be estimated from experimental data using the reciprocity theorem, the radiative neutron capture cross section on the unstable ^{179}Ta being unmeasured.

Gamma decay of GDR in ^{208}Pb



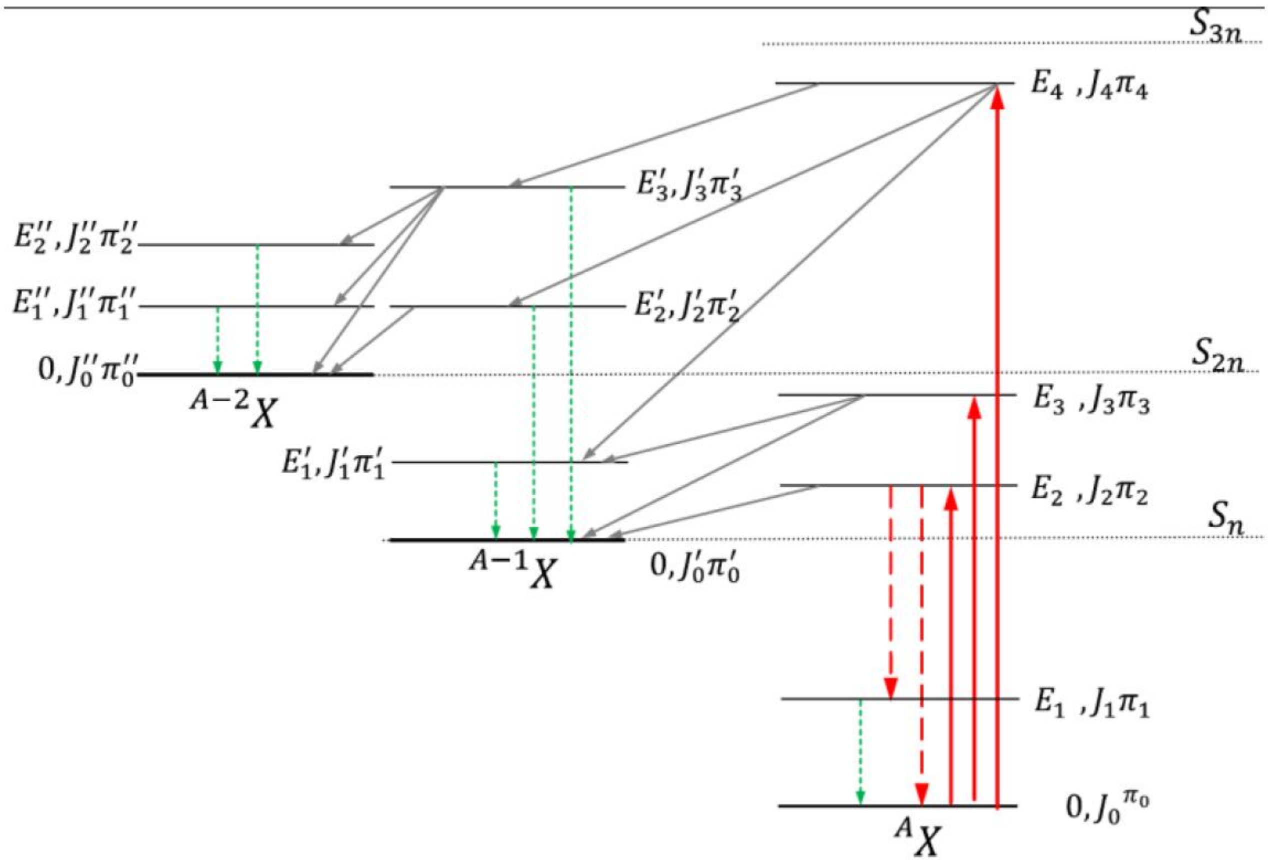
It shows in a schematic way the proposed experiment, namely the measurement of the branching ratio of the gamma decay in ^{208}Pb to the ground state in an energy interval between 7 to 12 MeV. For the excitation energy of about 12.5 MeV a branching ratio of about 1% is obtained for GDR by calculation.

Gamma decay of the PDR



Scheme of the ground state decay for ^{208}Pb, ^{207}Pb and ^{209}Bi. The comparison of the branching ratio in the three nuclei can provide a solution of the highly disputed question on the collective character of the PDR.

Neutron decay of GDR

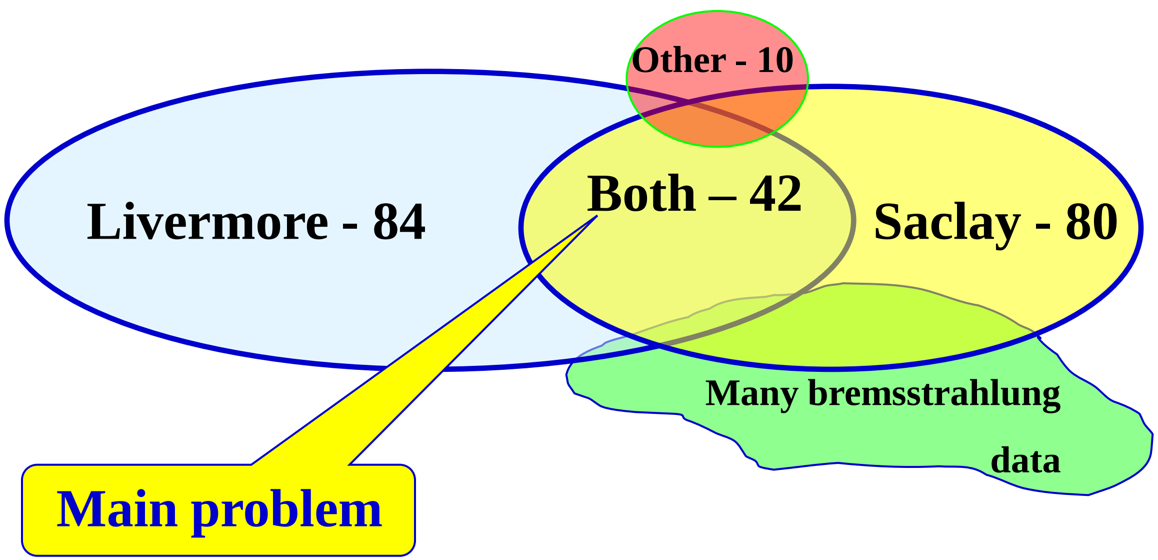


It depicts complex branchings of the neutron decay of GDR in a nucleus.

New compilation of total and partial Photoneutron cross sections for GDR!

Purpose of study on neutron decay of GDR

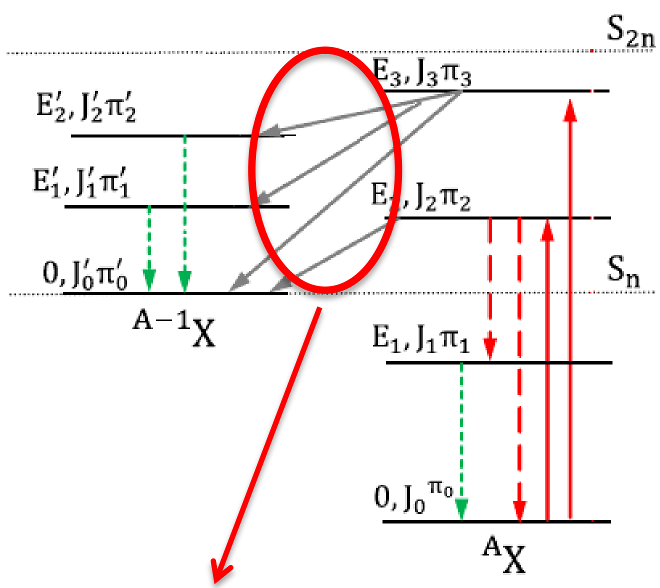
- Most of the photoneutron cross section measurements were performed using quasi-monochromatic annihilation – QMA photons using positron in flight annihilation at two major facilities:
  - Saclay (France)
  - Lawrence Livermore National Laboratory (USA)
- Large discrepancies in (γ,xn) c.s. measured at 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.



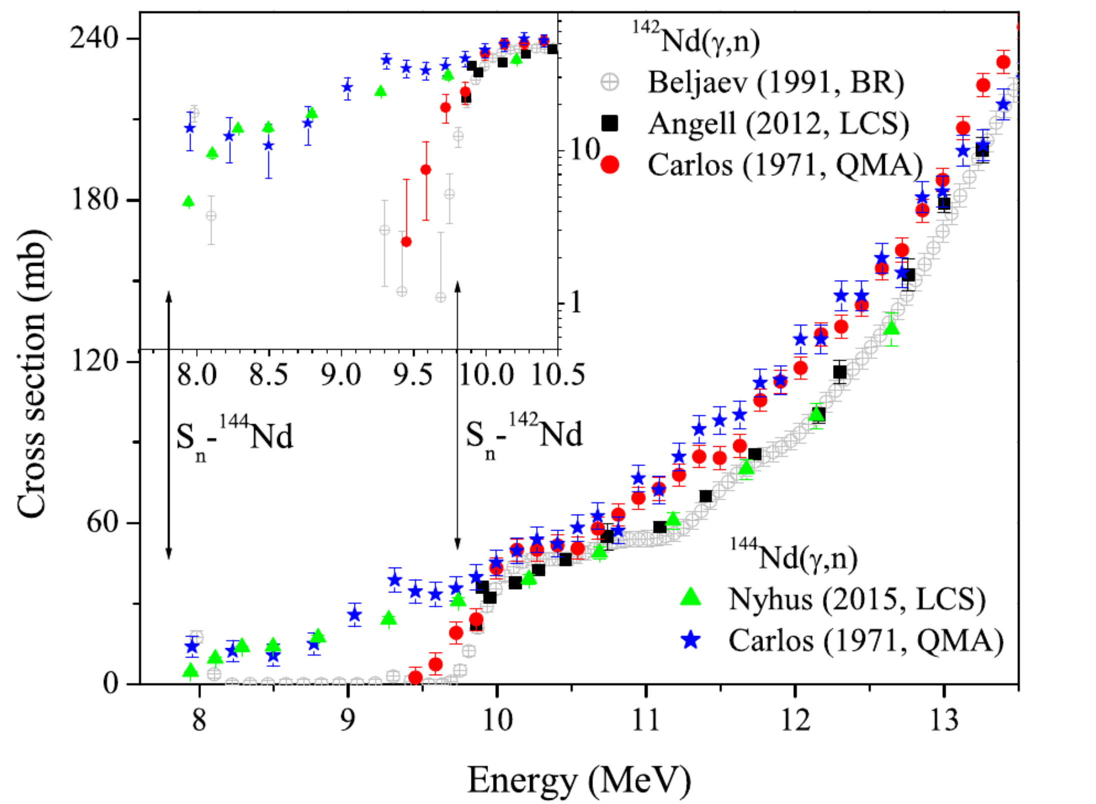
No systematic way to resolve the discrepancies: <u>New and reliable measurements are required!</u>

For (γ,1n) cross sections – measurements using LCS γ-ray beam and the high efficiency neutron detector developed at GACKO offer the required precision and reliability

$E_\gamma < S_{2n} \Rightarrow (\gamma,1n)$



Average energy E_{avg} determined using the ring ratio method



For (γ,2n), (γ,3n), … cross sections

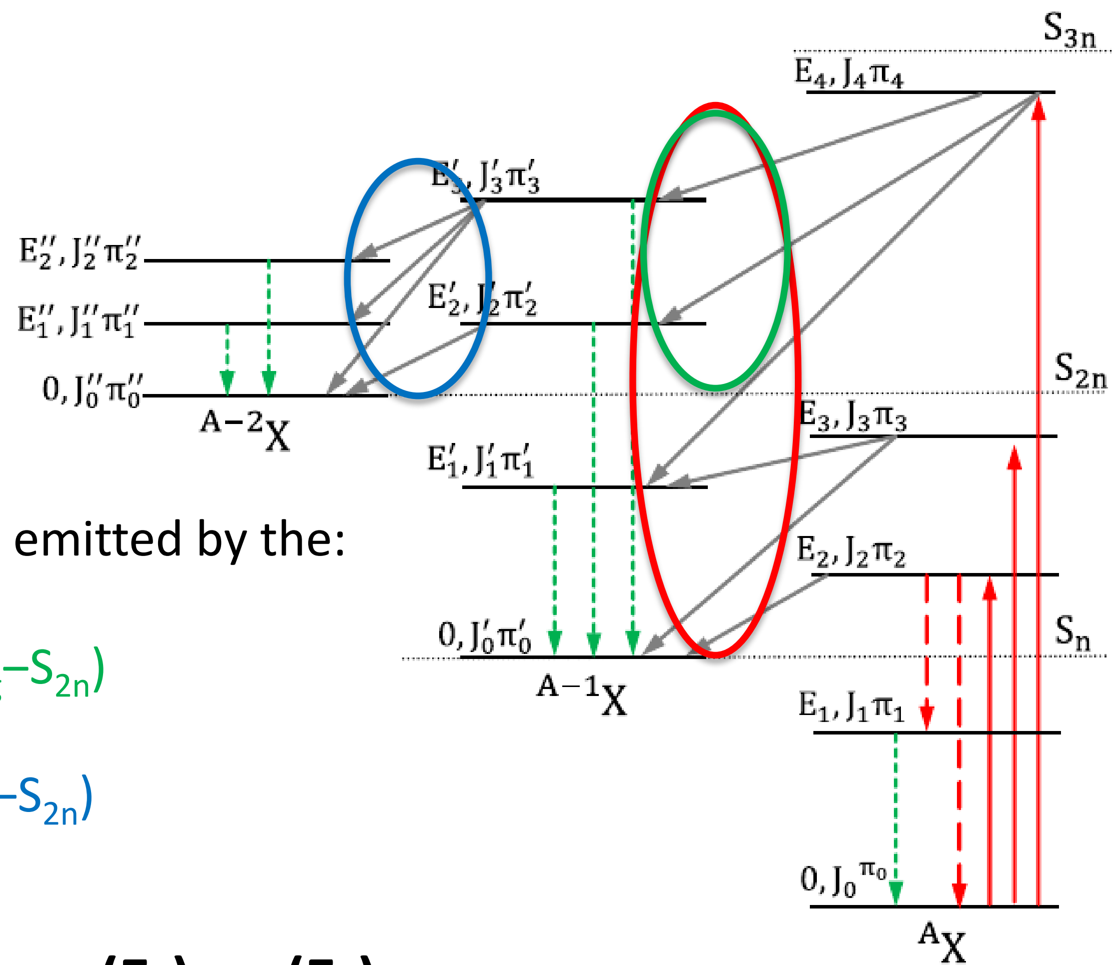
Example:

$$E_\gamma < S_{3n} \Rightarrow (\gamma,1n) + (\gamma,2n)$$

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
  - Energy range: ~(0 to E_g–S_{2n})
- $^{A-1}$X nucleus
  - Energy range: ~(0 to E_g–S_{2n})

Average energy $\mathbf{E_2}$

$$E_1 \neq E_2 \Rightarrow \varepsilon(E_1) \neq \varepsilon(E_2)$$

Let us assume $E_\gamma < S_{4n} \Rightarrow (\gamma,1n), (\gamma,2n), (\gamma,3n)$ induced reactions

N_1, N_2, N_3 = number of (g,1n), (g,2n), (g,3n) induced reactions

E_1, E_2, E_3 = average energy of (g,1n), (g,2n), (g,3n) neutrons

N_s, N_d, N_t = number of single, double and triple neutron events

Adjust experimental conditions to have maximum one reaction per γ-ray beam pulse

Single neutron events:

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

Double neutron events:

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

Triple neutron events:

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

N_s, N_d, N_t - we measure directly

N_1, N_2, N_3 - we must determine to obtain the cross sections

E_1, E_2, E_3 - ? Can not be determined using the ring ratio method. **PROBLEM!**

A neutron multiplicity sorting technique with
a flat efficiency neutron detector is required!

Considering a flat efficiency neutron detector and $E_\gamma < S_{4n}$ we have:

Single neutron events:

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

Double neutron events:

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

Triple neutron events:

$$N_t = N_3 \cdot \varepsilon^3$$

N_s, N_d, N_t - we measure directly

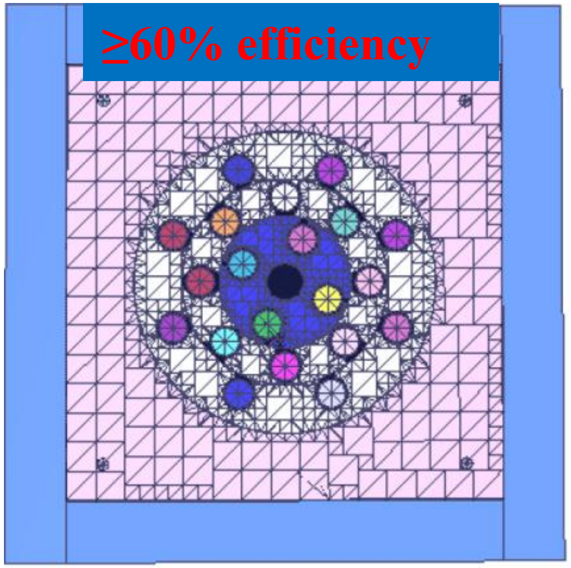
ε - known by direct measurement and by simulation

N_1, N_2, N_3 - we determine to obtain the

(γ,1n), (γ,2n), (γ,3n) cross sections

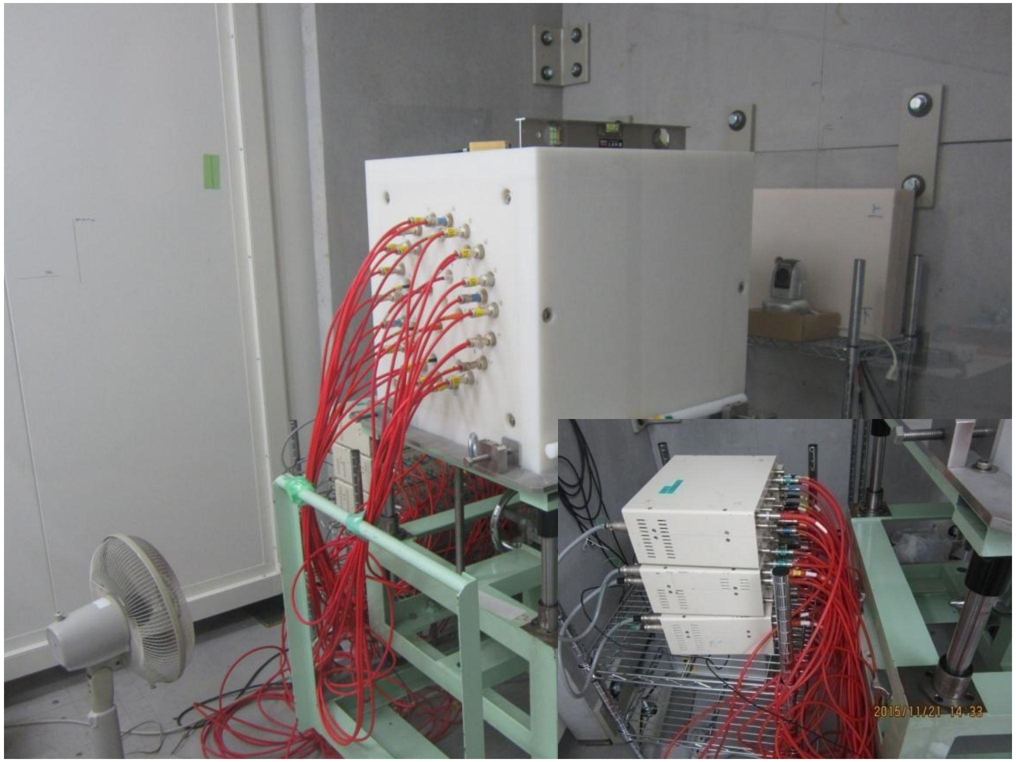
High efficiency neutron detector array

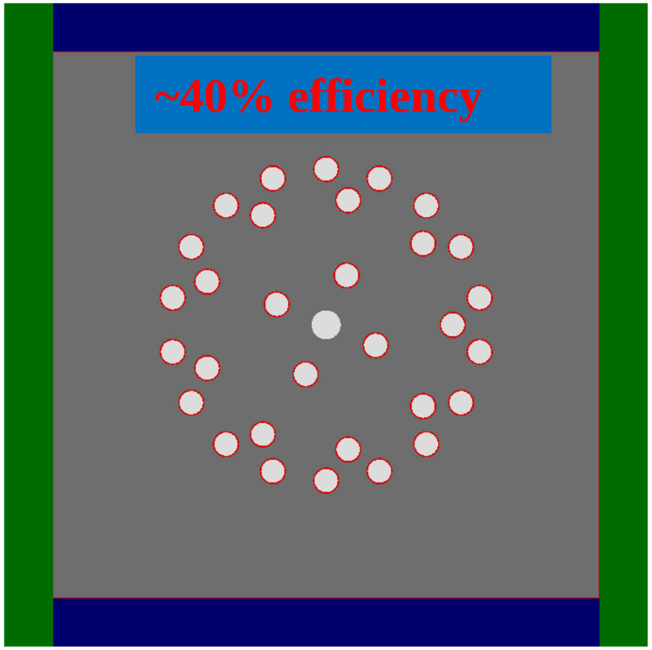
Neutron detector array installed at the gamma beam line GACKO.



Configuration	^{3}He counters	Distance
Inner ring	4	3.8 cm
Middle ring	8	7.0 cm
Outer ring	8	10.0 cm
Total	20	

Flat efficiency neutron detector array





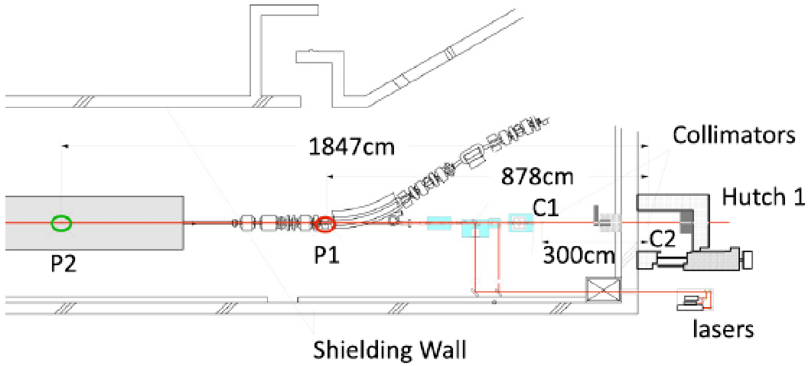
Configuration	^{3}He counters	Distance
Inner ring	4	5.5 cm
Middle ring	9	13 cm
Outer ring	18	16 cm
Total	31	

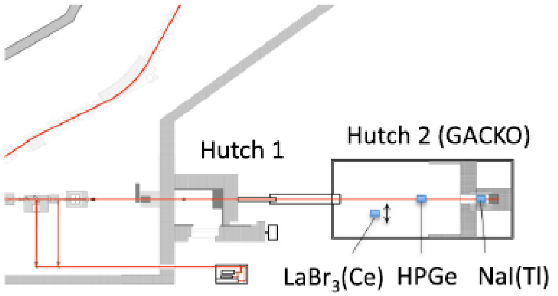
Moderator size: 46 cm

Preparatory experiment - Photoneutron measurements of Sm and Nd isotopes at NewSUBARU

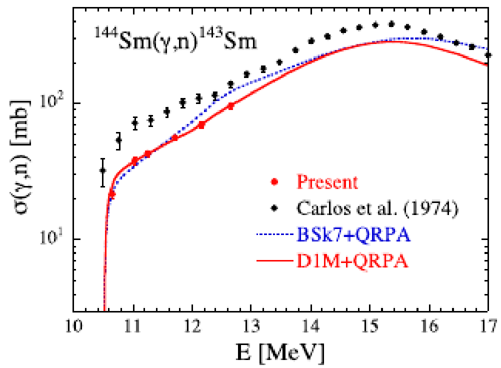
Participated to the measurements

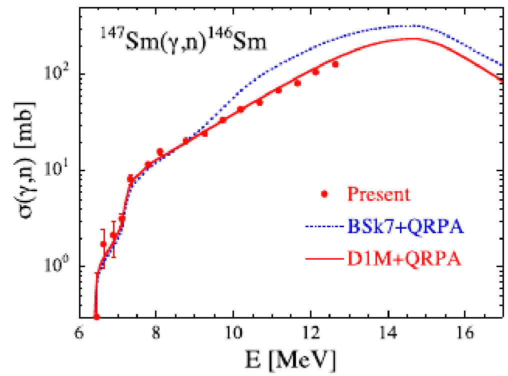
- Electron energies between 573 and 850 MeV
- Q-switch Nd : YVO_4 laser INAZUMA
- 5.87 – 13 MeV γ-ray beams
- High efficiency 4π neutron detector
- LaBr3 detector for energy monitor
- 80% NaI-Tl detector flux monitor
- enriched samples of ^{144}Sm, ^{147}Sm, ^{148}Sm, ^{149}Sm, ^{150}Sm, ^{152}Sm, and ^{154}Sm in oxide form (Sm_2O_3)

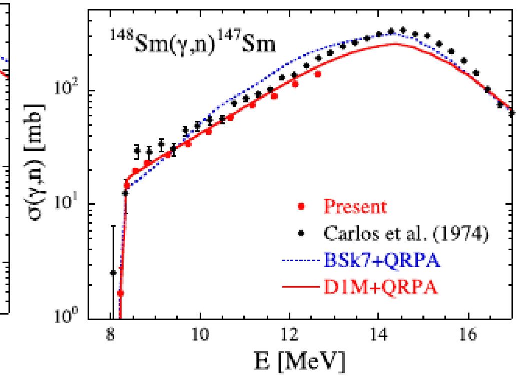


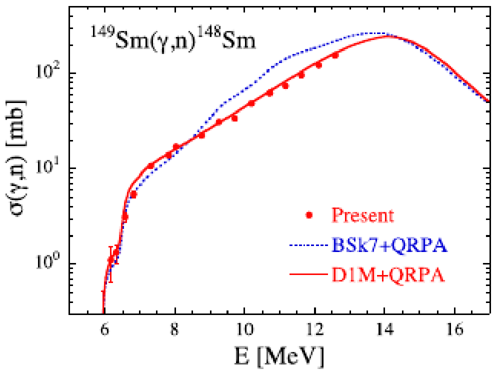


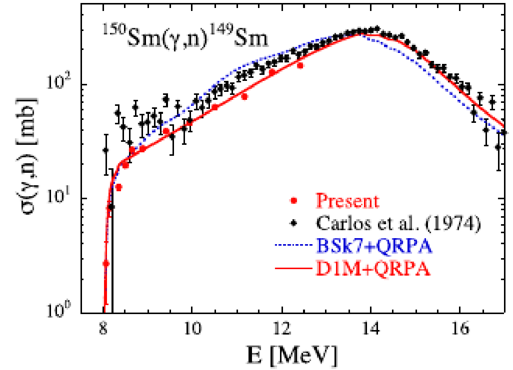
Preparatory experiment - Photoneutron measurements of Sm and Nd isotopes at NewSUBARU

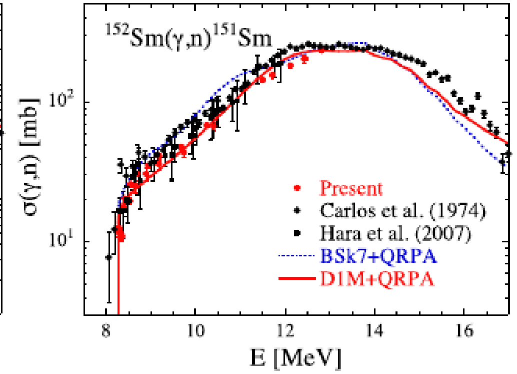


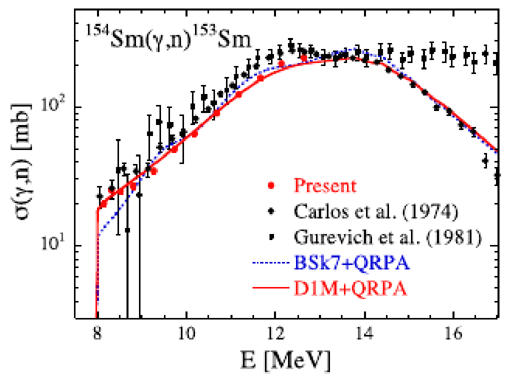








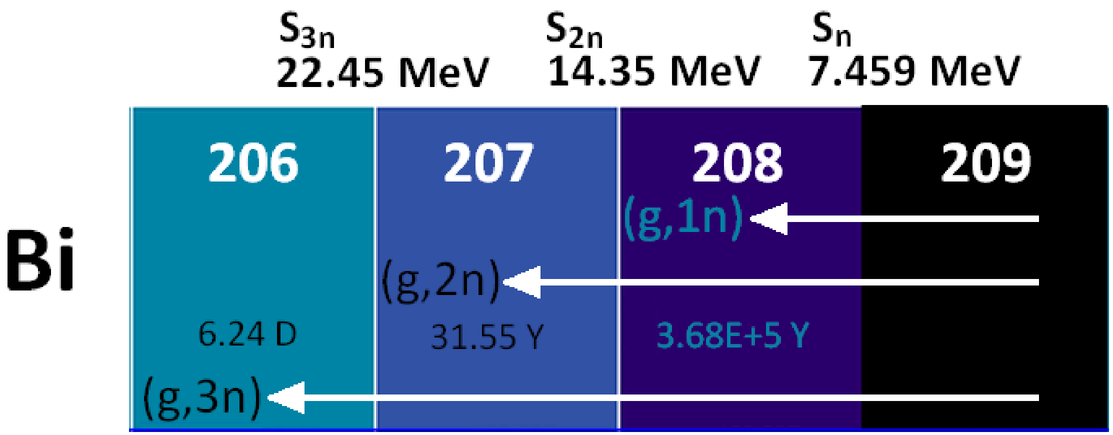




Microscopic calculations performed by S. Goriely

D. M. Filipescu et al., Phys. Rev. C **90, 064616 (2014)**

^{209}Bi(g,xn) cross sections measurements has been performed in Japan July 2015



(g,1n) measurements:

7.5 to 14.35 MeV γ-ray beams

Nd:YVO_4 laser INAZUMA – 1st harmonic

Electron energies - 600 to 900 MeV

High efficiency 4π neutron detector

(g,2n), (g,3n) measurements:

14.5 to 28 MeV γ-ray beams

Nd:YVO_4 laser INAZUMA – 2nd harmonic

Electron energies - 640 to 900 MeV

Flat efficiency 4π neutron detector

$LaBr_3$ detector for energy monitor
100% NaI-Tl detector flux monitor
Monoisotopic thick ^{209}Bi target

Efficiency calibration of the flat-efficiency detector at NIMJ (National Institute of Metrology of Japan) in Tsukuba.

Last November, (γ,n) cross section measurement for γ-ray strength functions of ^{89}Y, ^{203}Tl and ^{205}Tl nuclei has been performed at NewSUBARU facility

S. Siem A.-C. Larsen et al. University of Oslo, Norway

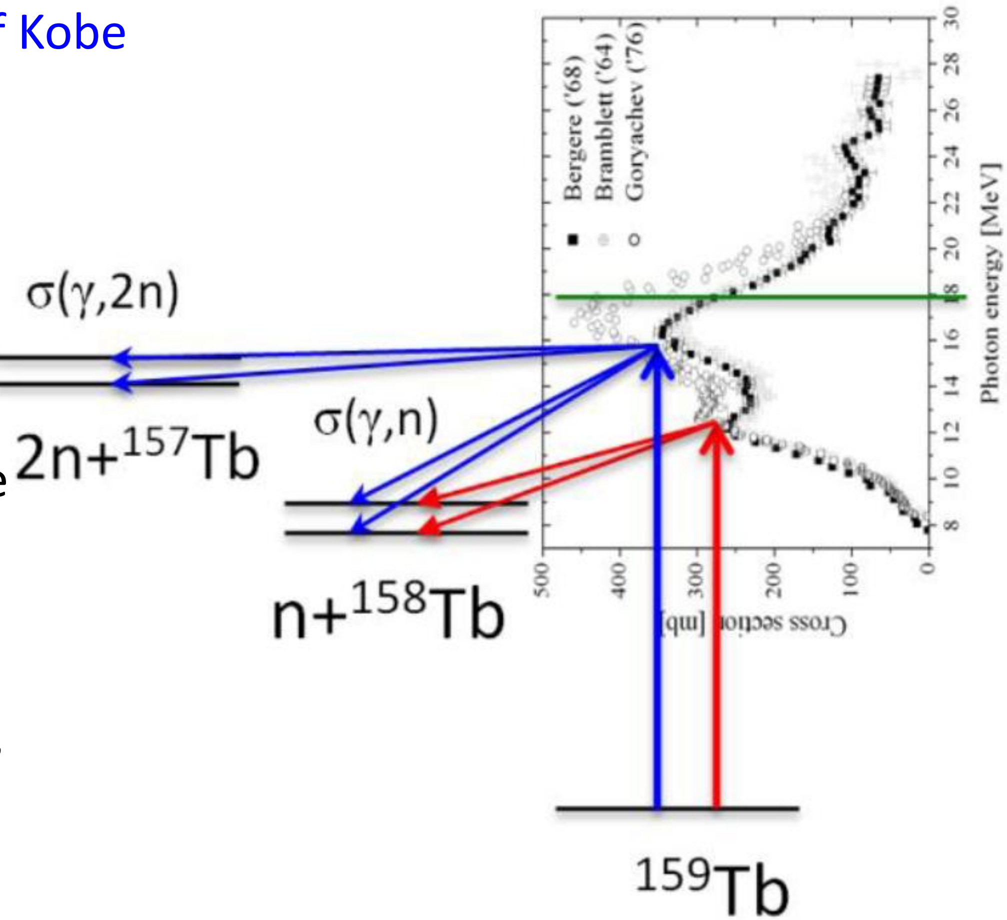
And (γ,xn) measurement for giant dipole resonance of ^{9}Be have been performed.

H. Utsunomiya, Konan University of Kobe

A new Coordinated Research Project (CRP) of the International Atomic Energy Agency (IAEA) “Updating the Photonuclear Data Library and Generating a Reference Database for Photon Strength Functions”

PI: H. Utsunomiya

该项目拟实验研究9种核素的（γ, xn）反应截面，15种核素的（γ, n）反应截面。



Proposals for future measurements using The ELI-NP monoenergetic γ–quanta source with energies up to ~ 19 MeV.

The new measurements for isotopes for which we found out the most prominent disagreements between experimental and evaluated reaction cross sections are of great interest on the first stage.

1-st priority: ^{159}Tb (B2n = 14.9 MeV), ^{181}Ta (B2n = 14.2 MeV), ^{208}Pb (B2n = 14.1 MeV).

2-nd priority: ^{94}Zr (B2n = 14.9 MeV), ^{186,188,189,190,192}Os (B2n = 14.9,14.3,13.9,13.7,13.3 MeV).

3-d priority (measurements would be possible for narrow energy range (~ 2 - 3 MeV)) ^{115}In (B2n = 16.3 MeV), ^{116}Sn (B2n = 17.1 MeV).

4-th priority new data will be evaluated further.

Because the correspondent final nuclei (^{157,158}Tb, ^{179}Ta, ^{206,207}Pb, ^{92,93}Zr, ^{184}Os, ^{113}In, ^{114,115}Sn) are not suitable candidates for activation measurements.

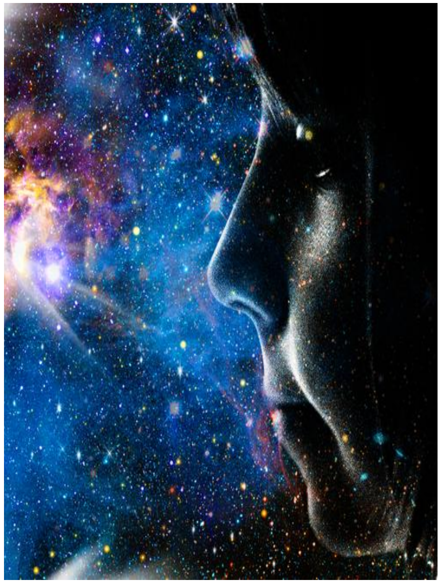
Nuclear physics studies with brilliant γ beams

- Nuclear resonance fluorescence (NRF) studies
- Gamma above neutron threshold studies (ELI-GANT)
- Photodisintegration reactions for nuclear astrophysics studies
- Photo-fission studies

(γ,α) and (γ,p) reactions for nuclear astrophysics

- The $^{16}O(\gamma,\alpha)^{12}C$ reaction
- The $^{24}Mg(\gamma,\alpha)^{20}Ne$ reaction
- The $^{22}Ne(\gamma,\alpha)^{18}O$ reaction
- The $^{19}F(\gamma,p)^{18}O$ reaction
- The $^{21}Ne(\gamma,\alpha)^{17}O$ reaction

Best illustration of the anthropic principle: Observations in the Universe must be compatible with the conscious life that observes them.

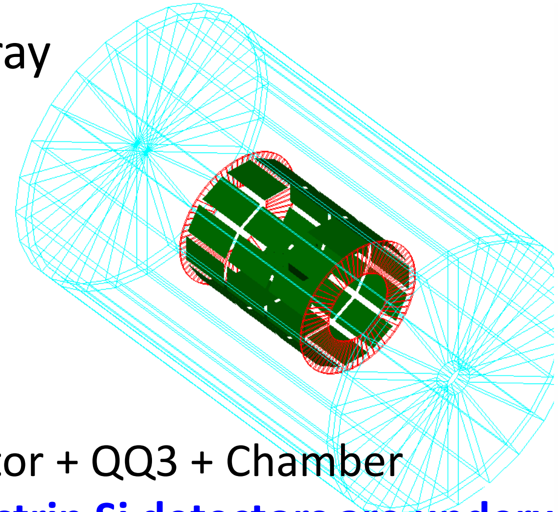


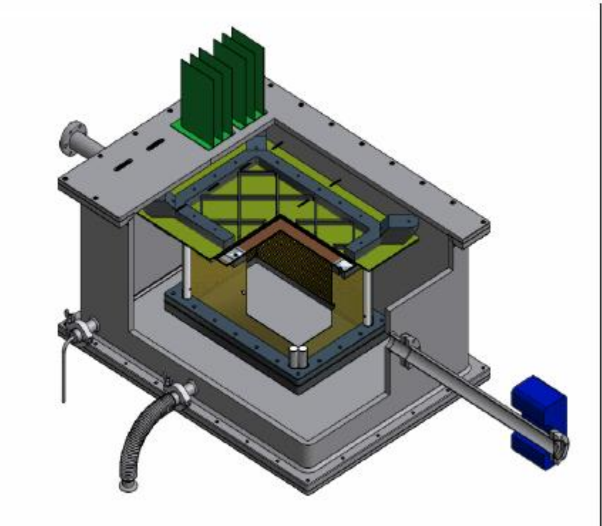
$$\omega_A \frac{\sigma_A(X,\gamma)}{\lambda_\alpha^2} = \omega_B \frac{\sigma_B(\gamma,X)}{\lambda_\beta^2}$$

<u>Instrumentation:</u>

(i) ELISSA: Large-area Si SD array

(ii) ELI-eTPC





SSX3 detector + QQ3 + Chamber

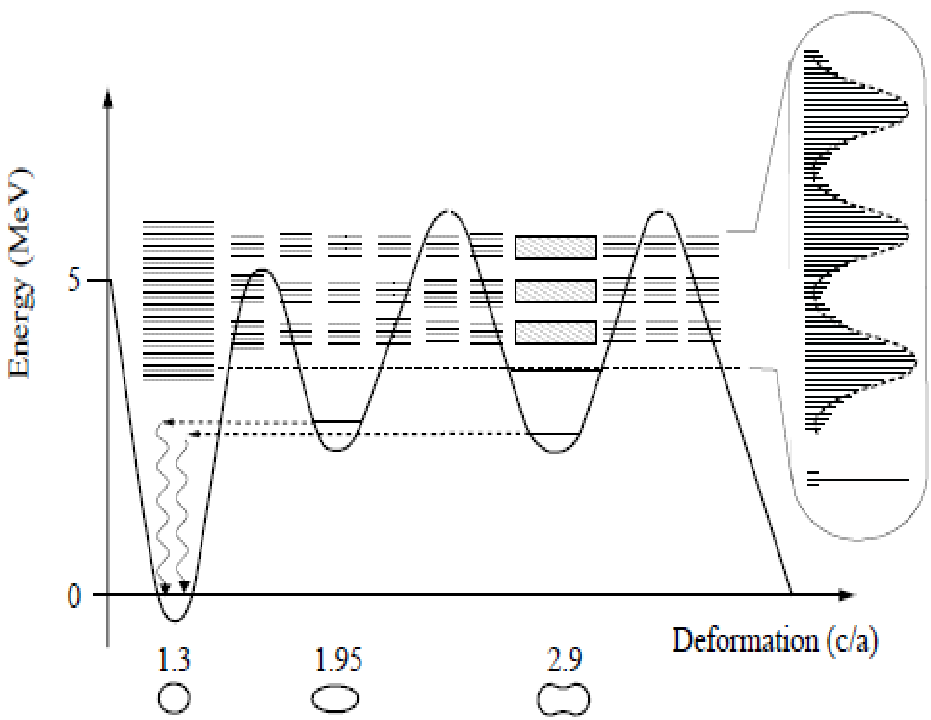
Tests of 40 strip Si detectors are underway

Nuclear physics studies with brilliant γ beams

- Nuclear resonance fluorescence (NRF) studies
- Gamma above neutron threshold studies (ELI-GANT)
- Photodisintegration reactions for nuclear astrophysics studies
- Photo-fission studies

Photo-fission studies

1. Studies in the 2nd and 3rd minimum of the fission barrier: transmission resonances
2. Rare fission modes: ternary fission, Pb radioactivity
3. Structure of neutron-rich nuclei: the A ≈ 100 Sr-Zr and rare-earth neutron-rich deformed regions

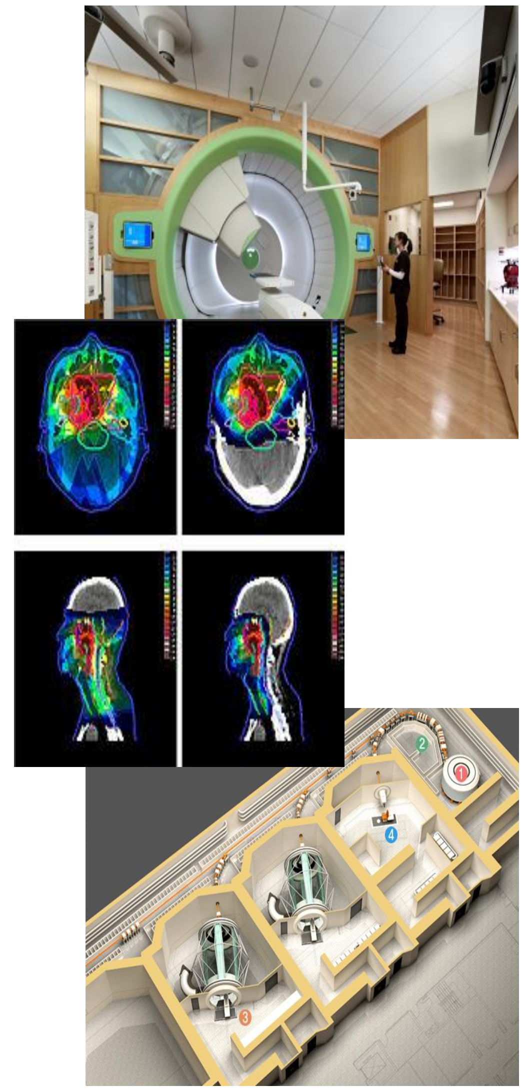


schematical description of the occurrence of transmission resonances

P.G. Thirolf et al., EPJ Web of Conferences 38, 08001 (2012)

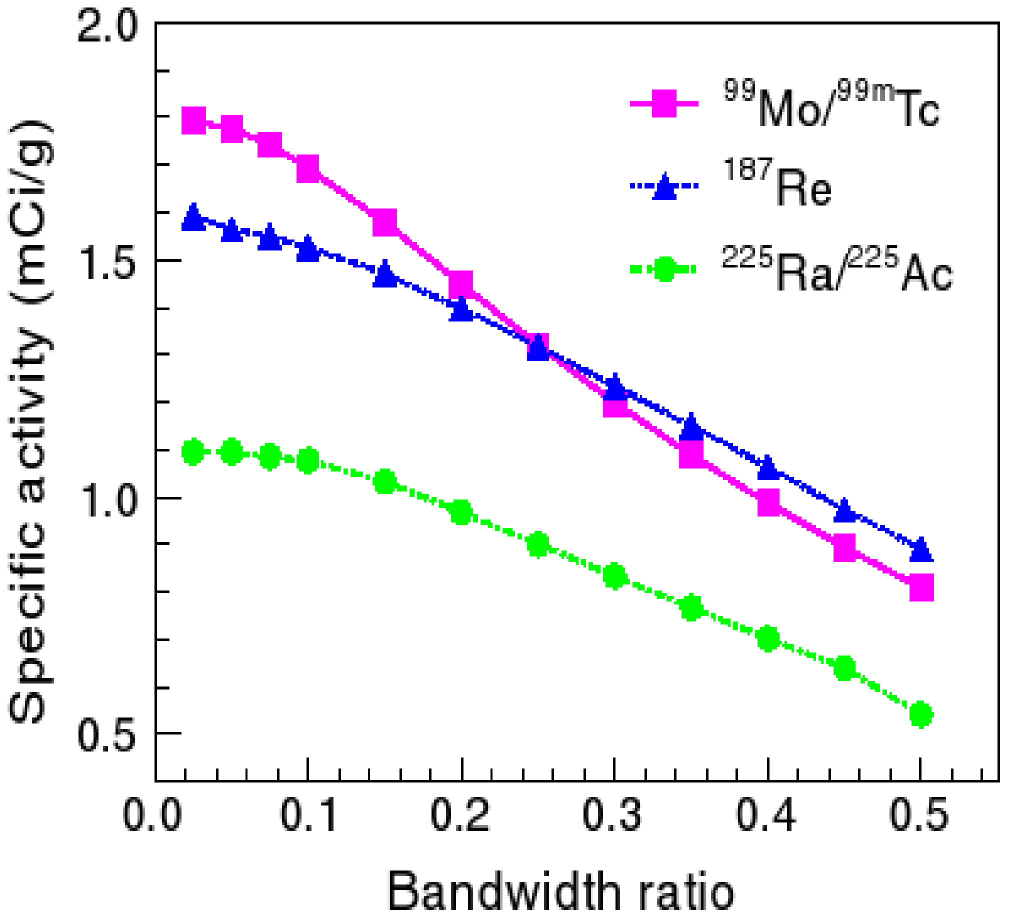
Radioisotopes for medical use

- **New approaches and methods for producing radioisotopes urgently needed**
- **Mo-99 and other medical isotopes used globally for diagnostic medical imaging and radiotherapy**
- **^{195m}Pt**: In chemotherapy of tumors it can be used to exclude ”non responding” patients from unnecessary chemotherapy and optimizing the dose of all chemotherapy



Medical radioisotopes

Rom. Rep. Phys. 68, S847 (2016)



Dana Niculae (IFIN-HH)
Wen Luo
Mariana Bobeica
D.L.B.

Wen Luo et al., Appl. Phys. B 122, 8 (2016)

Thank you for your attention!