International Workshop on Neutrino Nuclear Responses for Double Beta Decays and Astro-Neutrino Interactions (NNR16) , September 29-30, 2016, RCNP, Osaka University

Photonuclear Reactions and Astronuclear Physics

Hiroaki Utsunomiya (Konan University)

Contents

1. 9Be(γ,n)8Be
2. (γ,n) vs (n,γ) reactions
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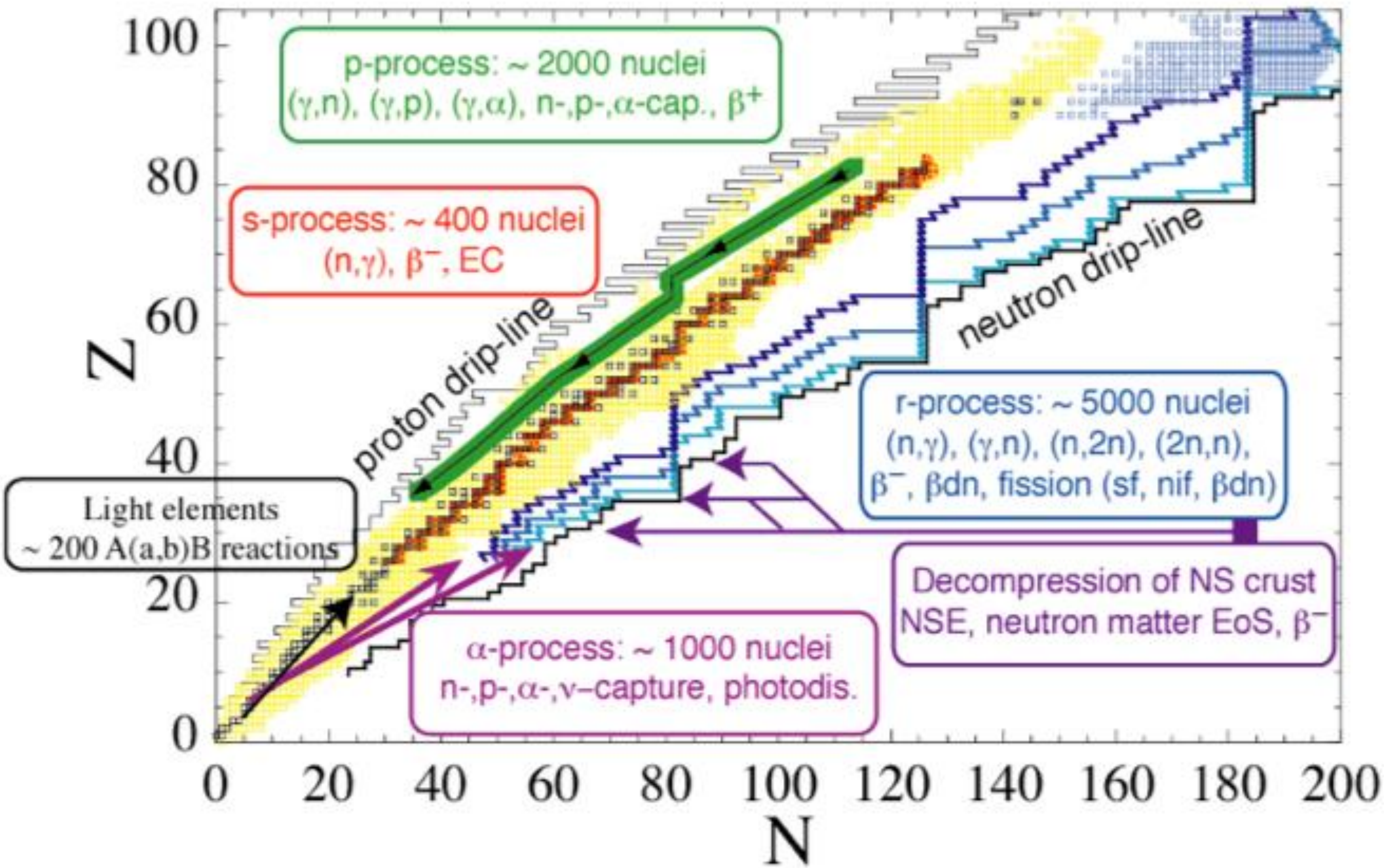
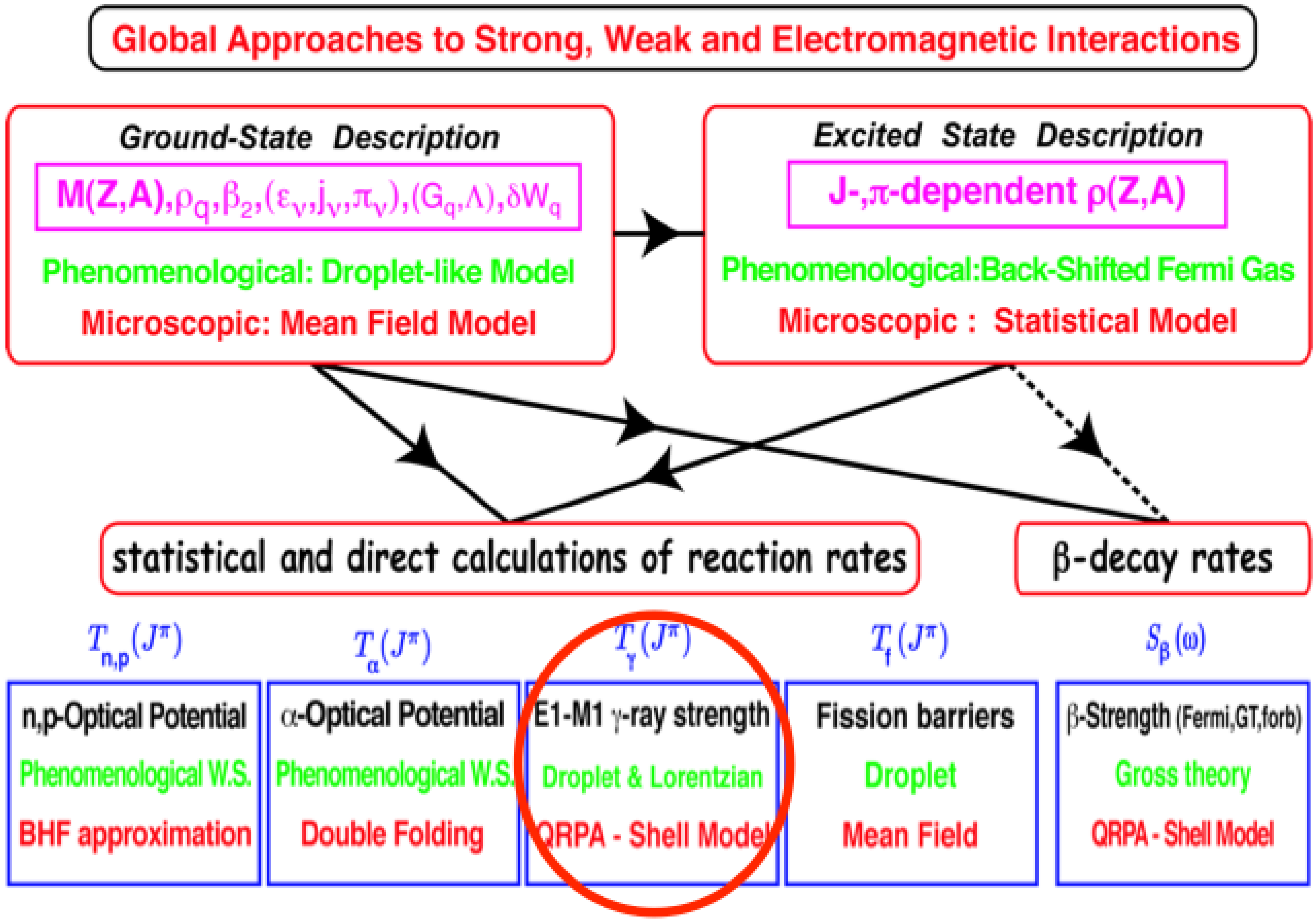
The nuclear physics needs for nucleosynthesis processes



S. Goriely PL002



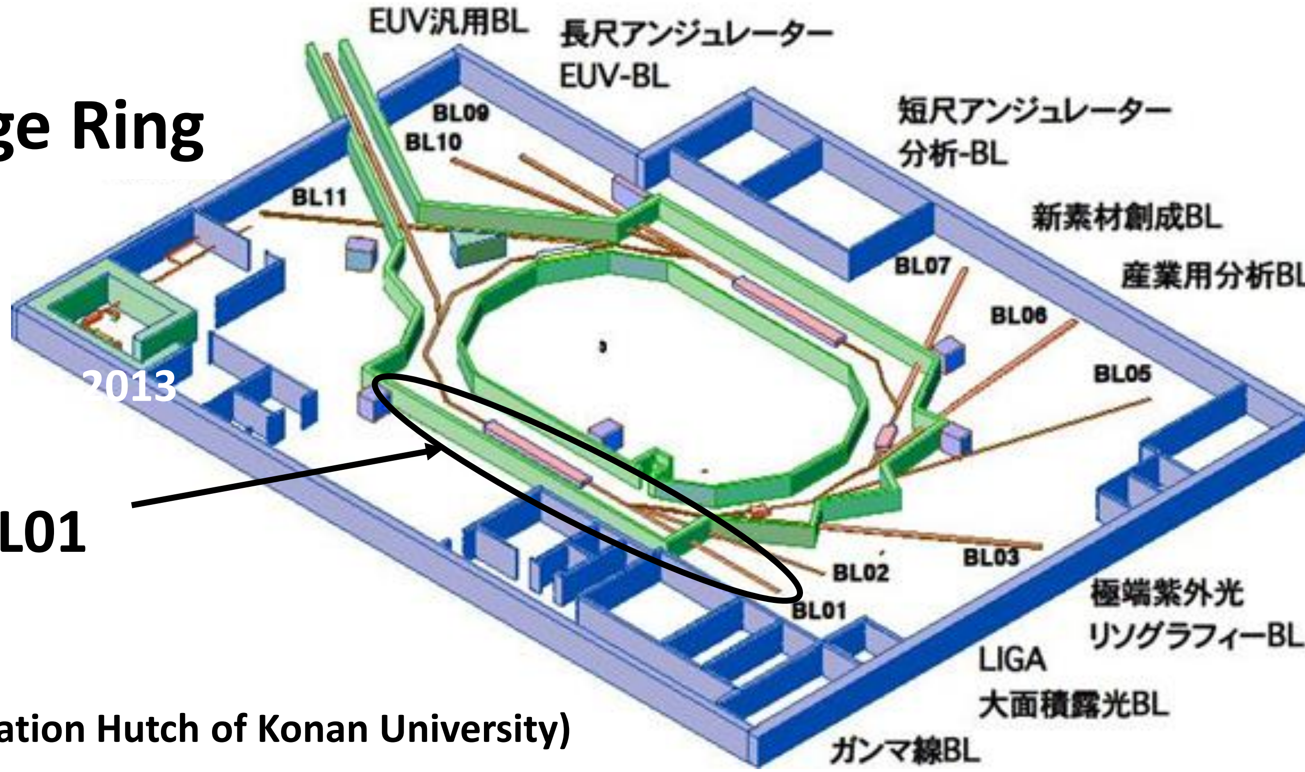
Need for a Universal Global and Microscopic description

S. Goriely PL002

NewSUBARU Facility

NewSUBARU facility

Electron Storage Ring

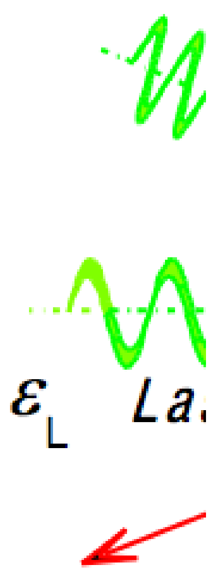


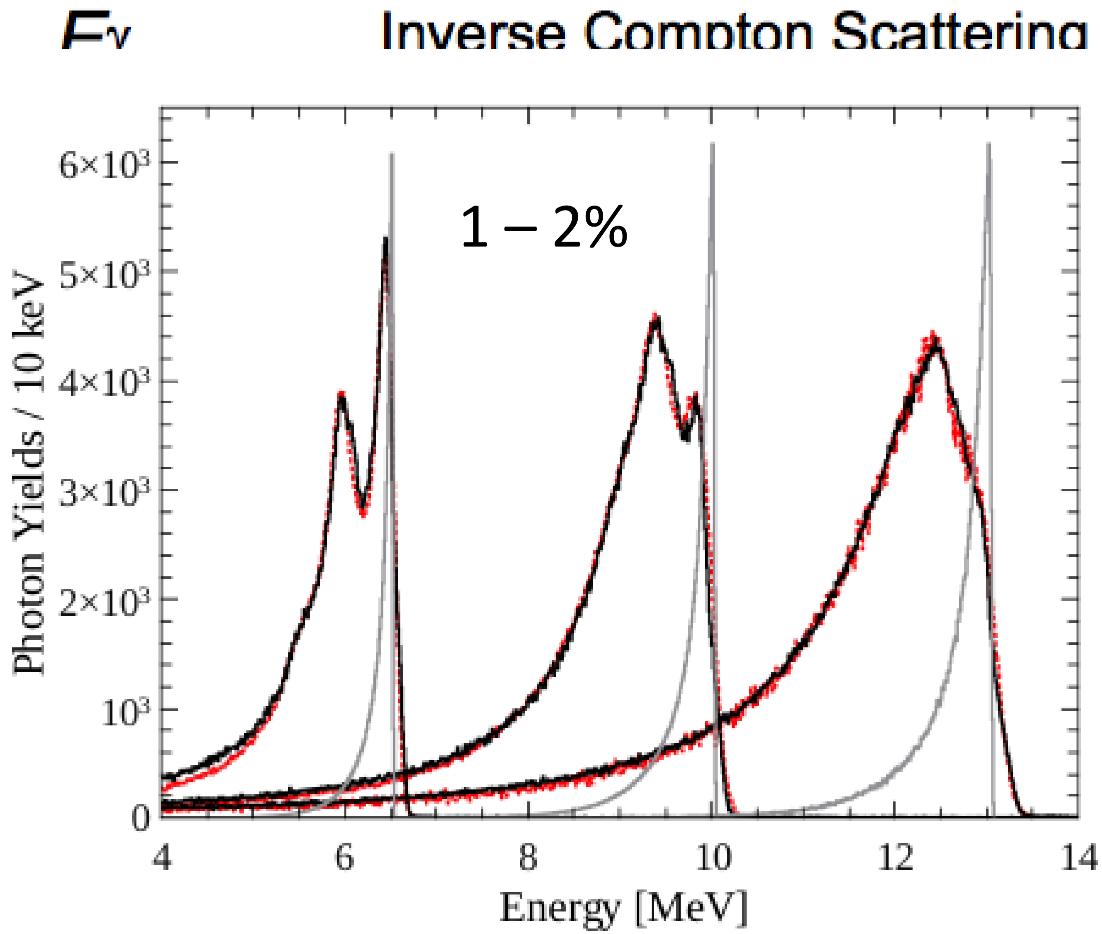
γ-ray beam line BL01

GACKO (Gamma Collaboration Hutch of Konan University)

(Moonlight)

Laser Compton scattering γ-ray beam





e

ation

nillion

factor)

GeV

$$E_\gamma = \frac{\quad}{1 + (}$$

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

$E_\gamma \sim 16$ MeV

Revisiting photodisintegration of ^{9}Be

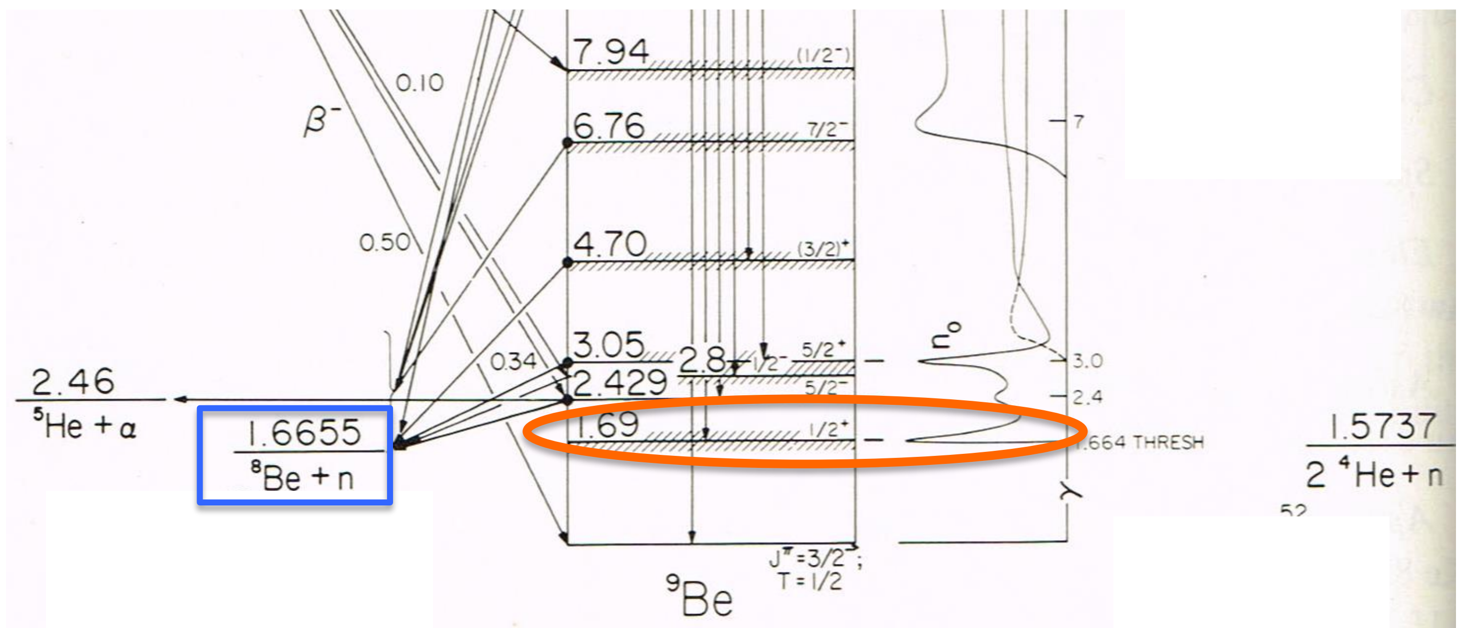
$\alpha\alpha \rightleftarrows {}^8\mathrm{Be}(n,\gamma){}^9\mathrm{Be}$ vs ${}^9\mathrm{Be}(\gamma,n){}^8\mathrm{Be}$

Reciprocity Theorem

H. Utsunomiya et al., PRC 63 (2001)
C.W. Arnold et al., PRC 85 (2012)

Significance of **the ½$^+$ state** just above S_n=1.665 MeV

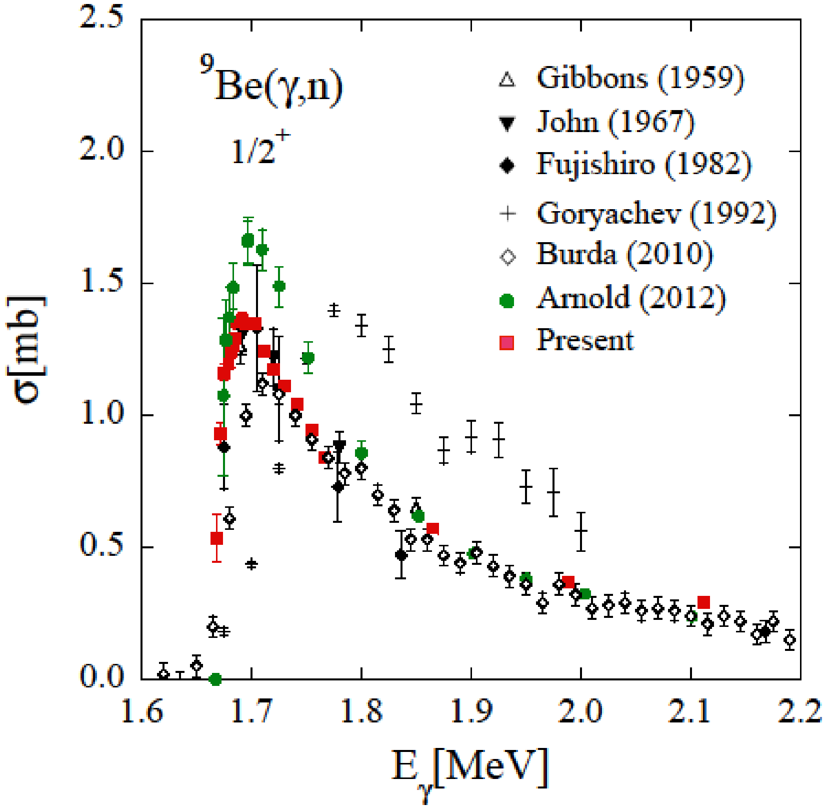
1. Explosive nucleosynthesis
   Type-II supernovae, neutron star mergers
2. Stau-catalyzed big bang nucleosynthesis



PHYSICAL REVIEW C 92, 064323 (2015)

Photodisintegration of ^{9}Be through the $1/2^+$ state and cluster dipole resonance

H. Utsunomiya,[1,2] S. Katayama,[1] I. Gheorghe,[3,4] S. Imai,[1] H. Yamaguchi,[2] D. Kahl,[2] Y. Sakaguchi,[2]
T. Shima,[5] K. Takahisa,[5] and S. Miyamoto[6]

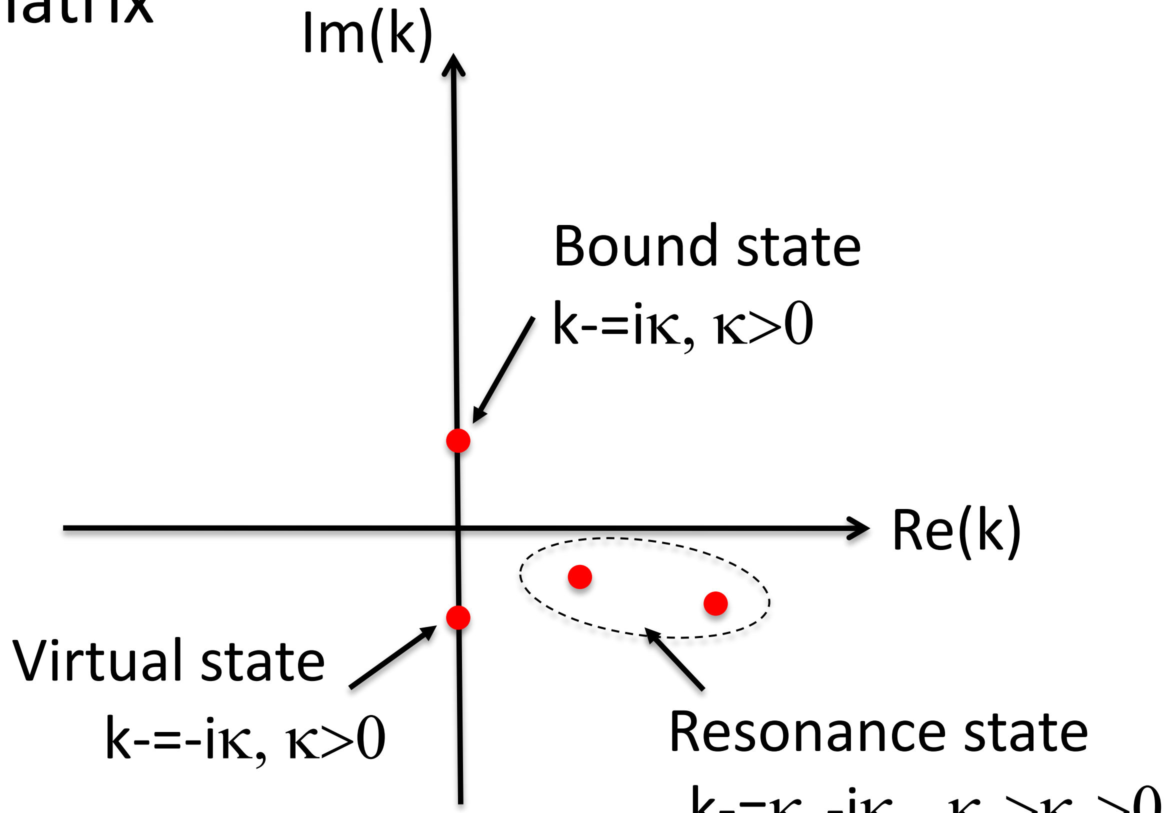


Comparisons

½+ state	Present	Arnold (2012)	Utsunomiya (2001) Sumiyoshi (2002)
Peak cross section [mb]	1.35	1.65	1.3
E_R [MeV]	1.728±0.001	1.731±0.002	1.748 ±0.01 1.735 ±0.003
B(E1) ↓ [e^2fm^2]	0.111±0.004	0.136 ±0.002	0.107±0.007 0.104±0.002
Γ_γ (eV)	0.595±0.002	0.738±0.002	0.598±0.004 0.568±0.001
Γ_n (keV)	214±7	213±6	283±42 225±12

S-matrix for n-^{8}Be scattering

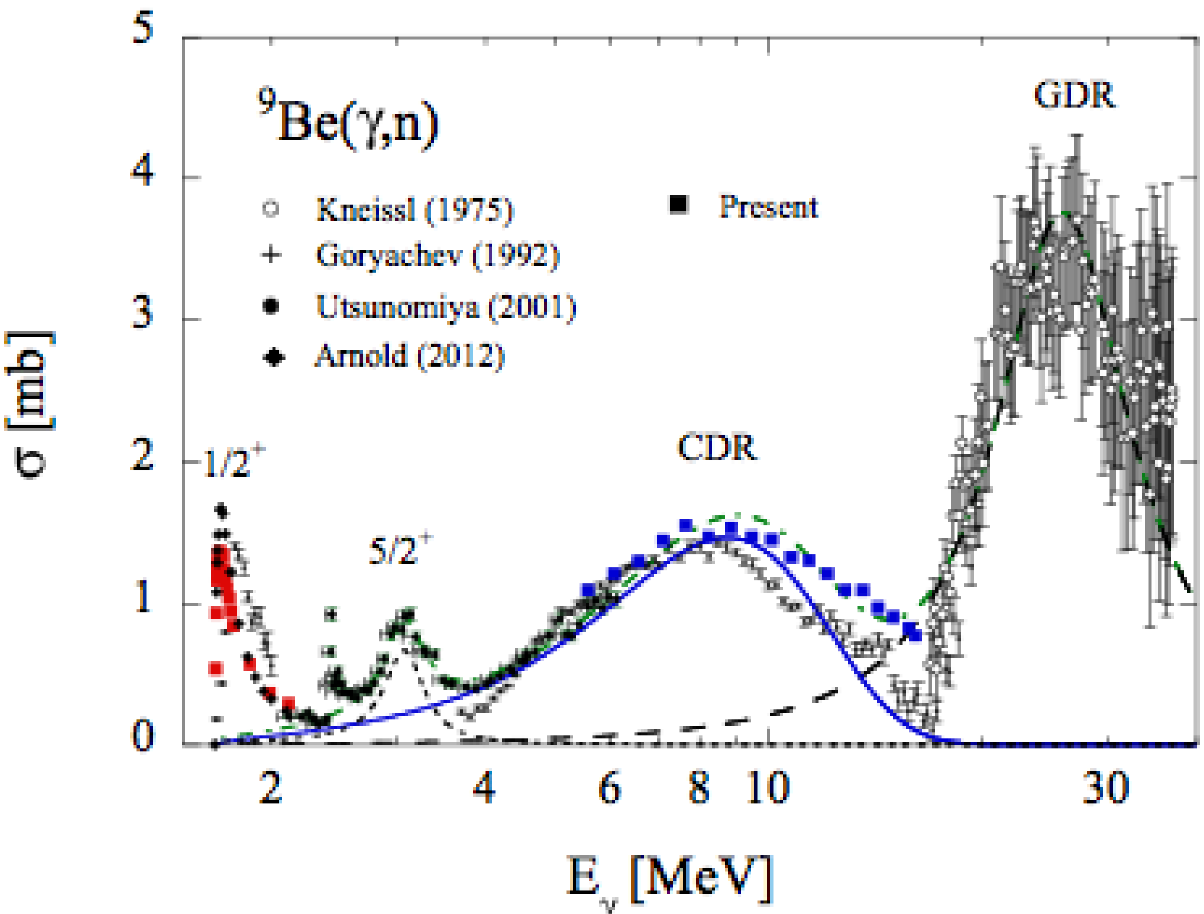
Poles of S-matrix



CDR Data

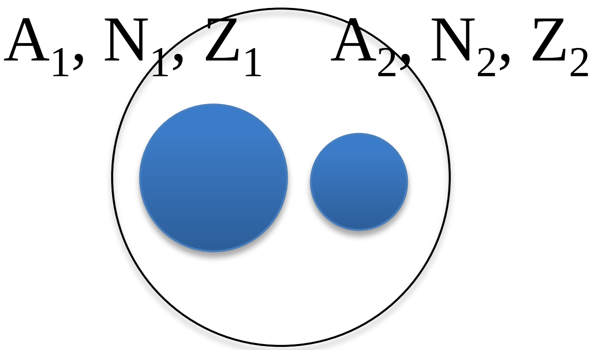
$$\int \sigma_{CDR}(E)dE = 11.3 MeV \cdot mb$$

GDR: Lorentzian function
CDR: Gaussian function
$5/2^+$ state: Breit-Wigner

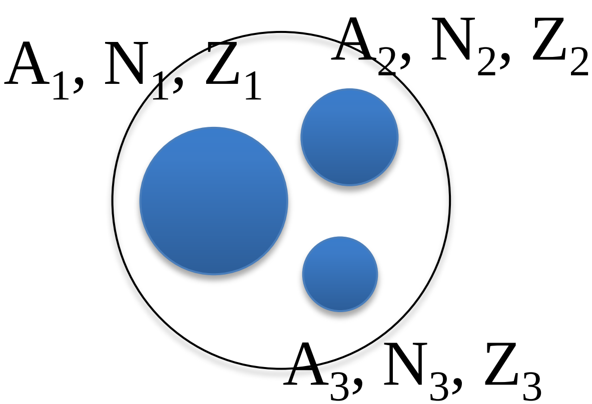


Cluster dipole sum rule

Y. Alhassid, M. Gai, G.F. Bertsch, Phys. Rev. Lett. 49, 1482 (1982)
H. Sagawa, M. Homma, Phys. Lett. B 251, 17 (1990)
R. De Diego, E. Garrido, A.S. Jensen, D.V. Fedorov, Phys. Rev. C 77, 024001 (2008)



A, N, Z



TRK

$$\int \sigma_{E1}(E)dE = 60\left(\frac{NZ}{A} - \sum_{i=1} \frac{N_iZ_i}{A_i}\right) MeV \bullet mb$$

TRK 133.3 MeV mb

$$^{9}\mathrm{Be} = {}^{8}\mathrm{Be} + \mathrm{n} \quad \rightarrow \quad 60 \times \frac{2}{9} = 13.3\, MeV \cdot mb$$

$$^{9}\mathrm{Be} = \alpha + \alpha + \mathrm{n} \quad \rightarrow \quad 60 \times \frac{2}{9} = 13.3\, MeV \cdot mb$$

Comparisons

Experimental result ^{9}Be

$$\int \sigma_{CDR}(E)dE = 11.3\,MeV \cdot mb$$

TRK 133.3 MeV mb

Cluster dipole sum rule

^{8}Be+n 13.3 MeV mb

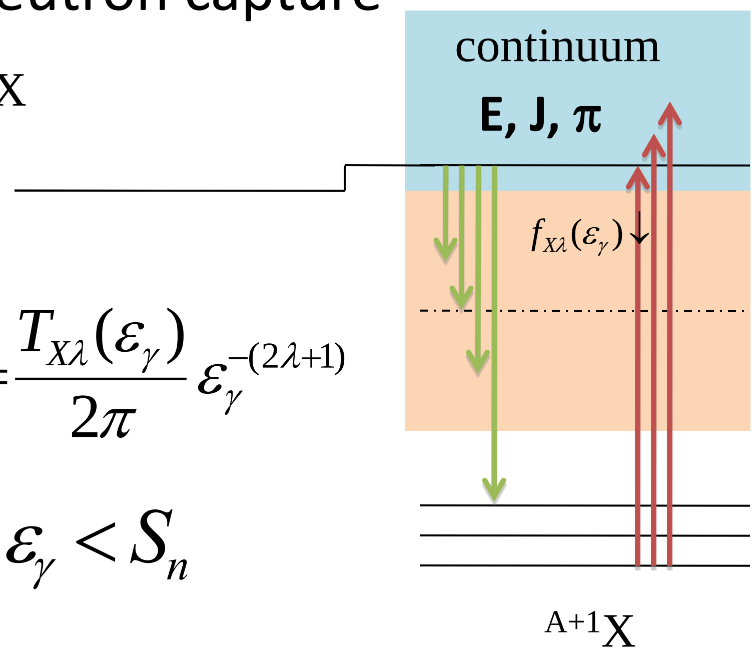
$\alpha + \alpha + n$ 13.3 MeV mb

(n,γ) and (γ,n) reactions are interconnected through the γ-ray strength function in the statistical model calculation.

Radiative neutron capture

$^{A}X(n,\gamma)^{A+1}X$

n+^{A}X



$$f_{X\lambda}(\varepsilon_\gamma)\downarrow = \frac{T_{X\lambda}(\varepsilon_\gamma)}{2\pi}\varepsilon_\gamma^{-(2\lambda+1)}$$

$$\varepsilon_\gamma < S_n$$

Photoneutron emission

$^{A+1}X(\gamma,n)^{A}X$

$$f_{X\lambda}(\varepsilon_\gamma)\uparrow = \frac{\varepsilon_\gamma^{-2\lambda+1}}{(\pi\hbar c)^2}\frac{\langle\sigma_{X\lambda}^{abs}(\varepsilon_\gamma)\rangle}{2\lambda+1}$$

$$\varepsilon_\gamma > S_n$$

Brink Hypothesis $\quad f_{X\lambda}(\varepsilon_\gamma)\downarrow \approx f_{X\lambda}(\varepsilon_\gamma)\uparrow$

A unified understanding of (γ,n) and (n,γ) cross sections

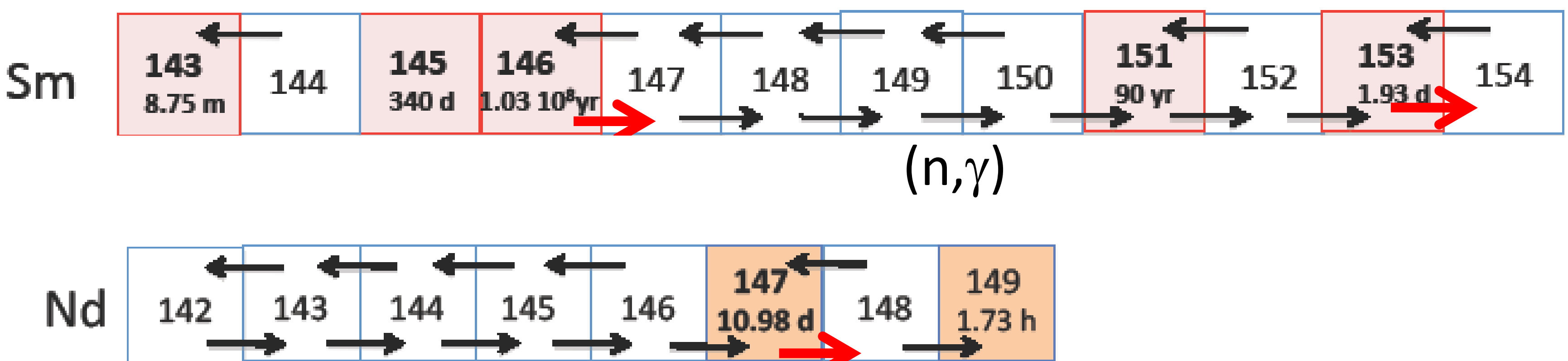
γ-ray strength function method

H. Utsunomiya et al., PRC 82, 064610 (2009).

Radiative neutron capture cross section are sensitive to the E1 strength function below the neutron threshold

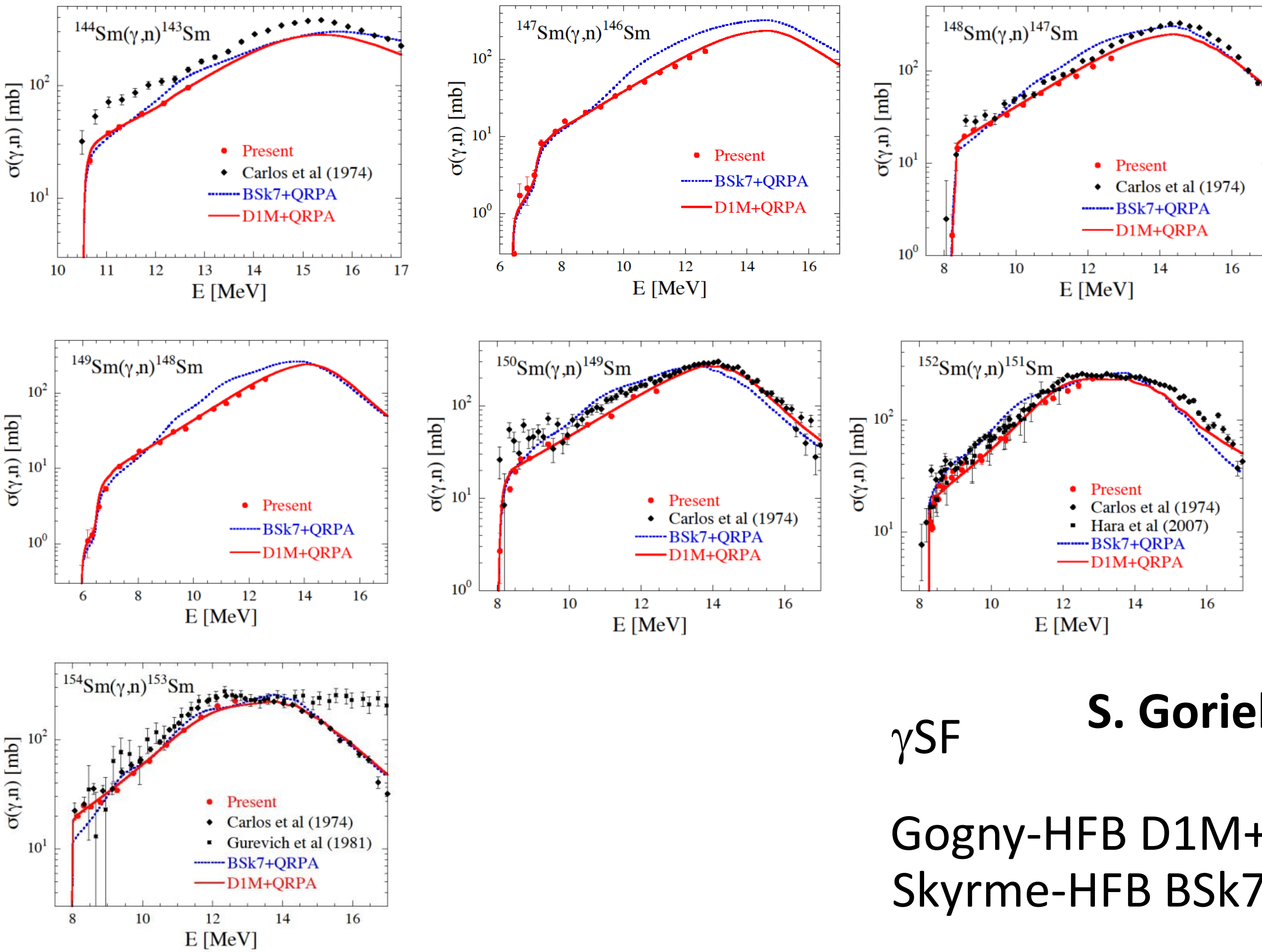
Filipescu et al.,
PHYSICAL REVIEW C **90**, 064616 (2014)

(γ,n)



H.-T. Nyhus
PHYSICAL REVIEW C **91**, 015808 (2015)

(γ,n) cross sections for Sm isotopes

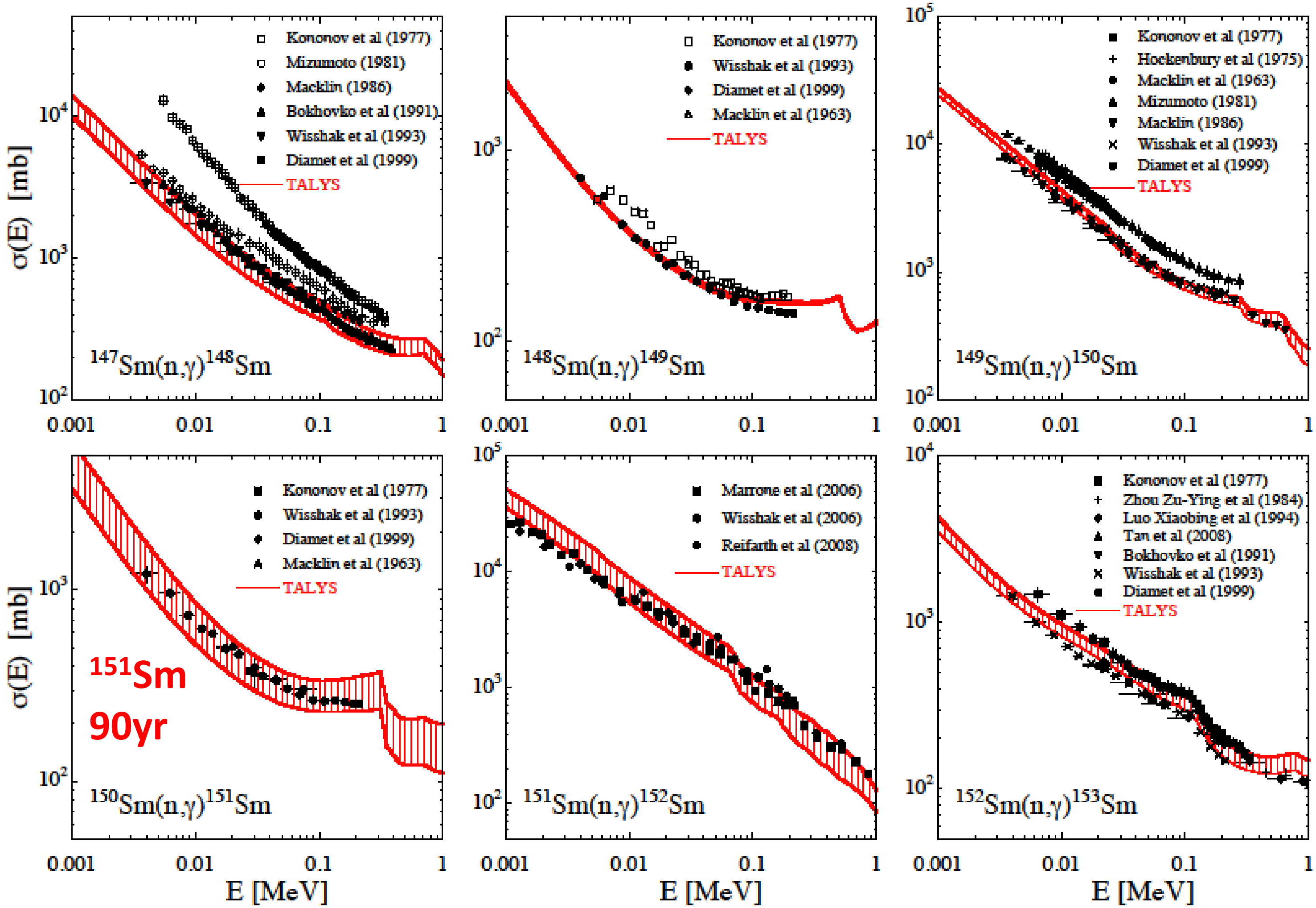


S. Goriely

γSF

Gogny-HFB D1M+QRPA
Skyrme-HFB BSk7+QRPA

(n,γ) cross sections for Sm isotopes



γSF S. Goriely Gogny-HFB D1M+QRPA

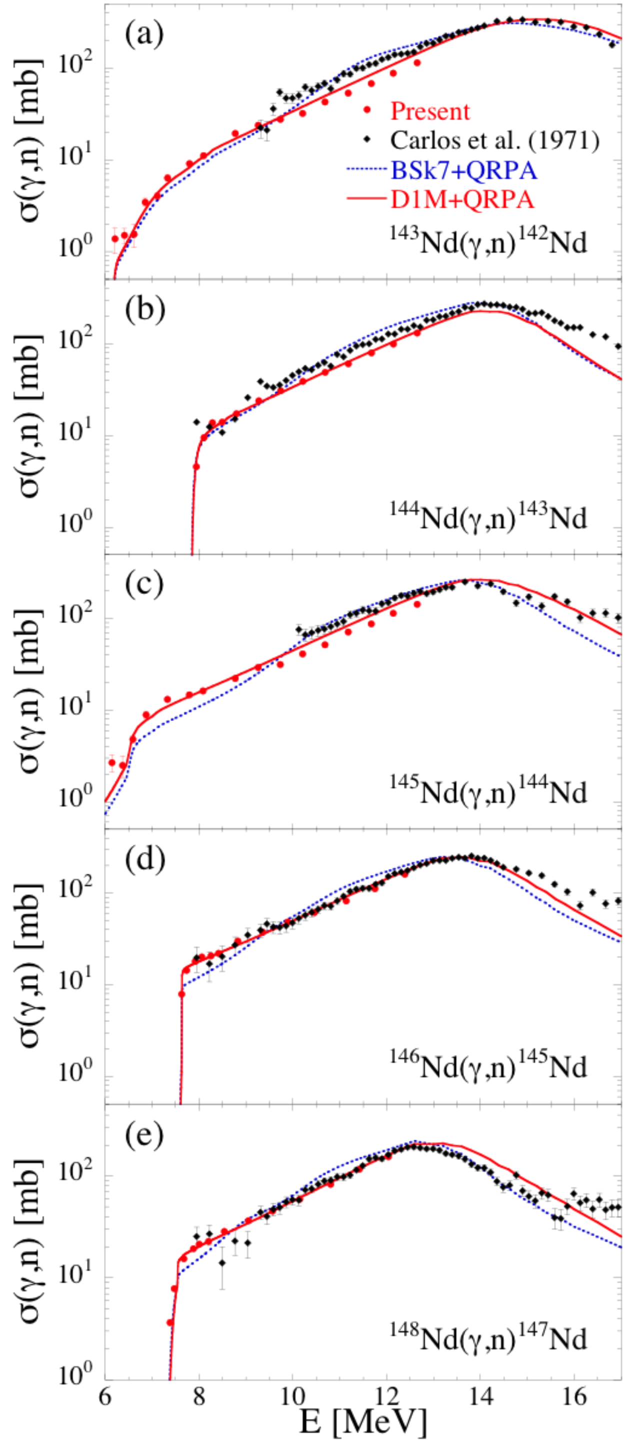
(γ,n) cross sections for Nd isotopes

S. Goriely

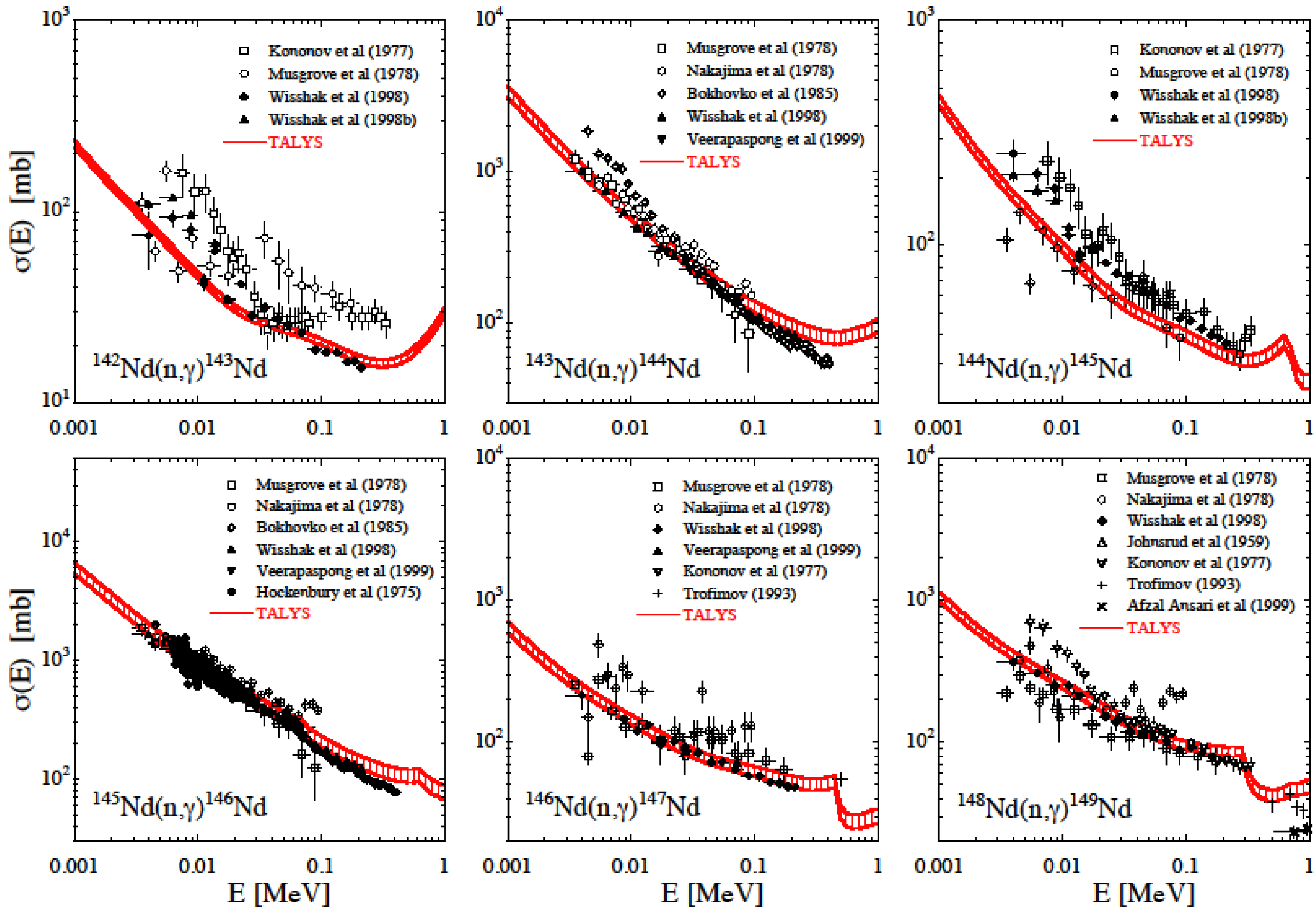
γSF

Gogny-HFB D1M+QRPA

Skyrme-HFB BSk7+QRPA



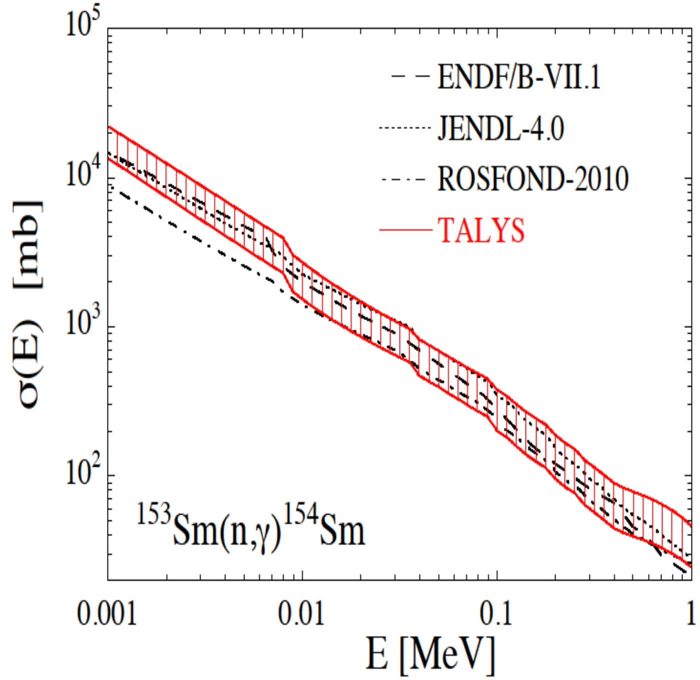
(n,γ) cross sections for Nd isotopes



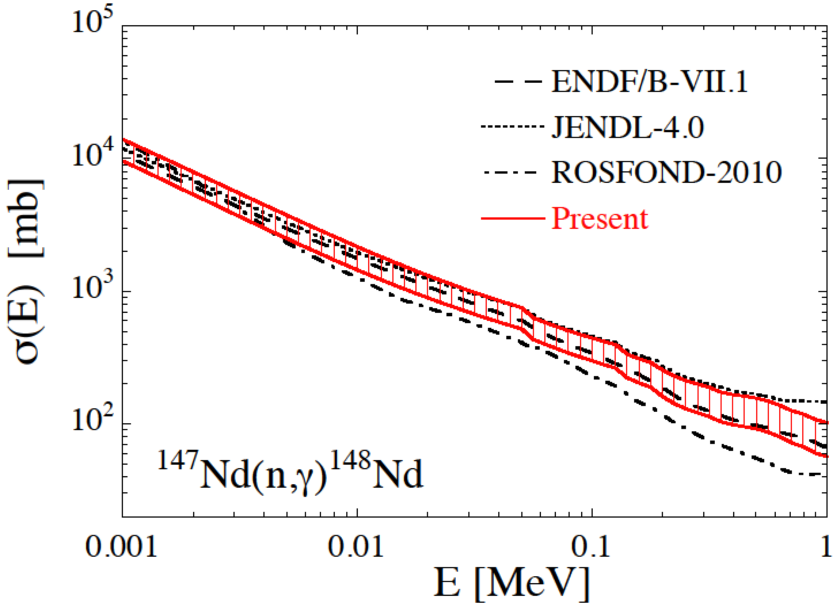
γSF S. Goriely Gogny-HFB D1M+QRPA

(n,γ) cross sections for unstable nuclei

^{153}Sm
1.93d



^{147}Nd
10.98d



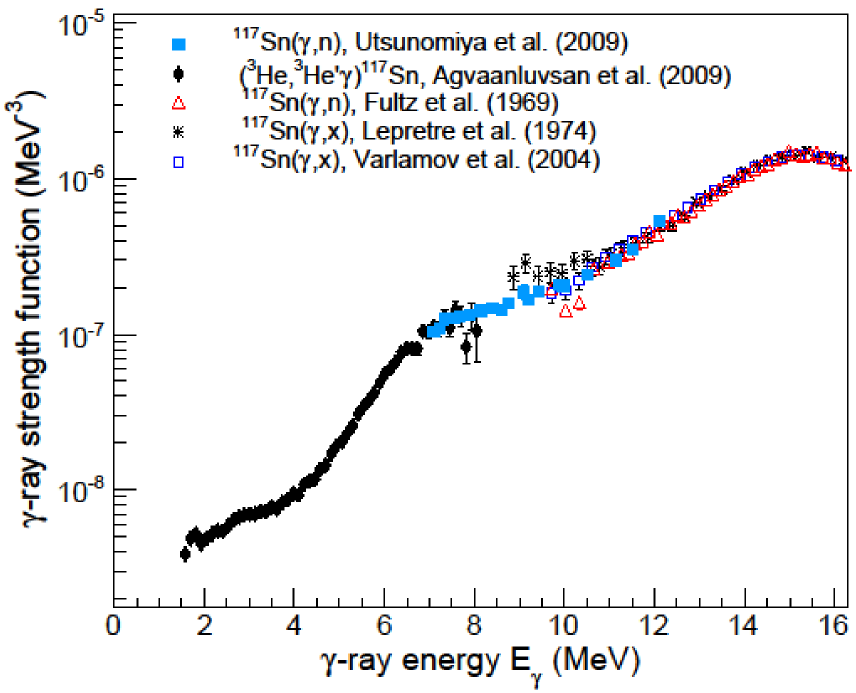
Schwengner I394
Siem R396

Experimental γSF

Data of (γ,n), (γ,γ’) and particle-gamma coin. (Oslo Method)

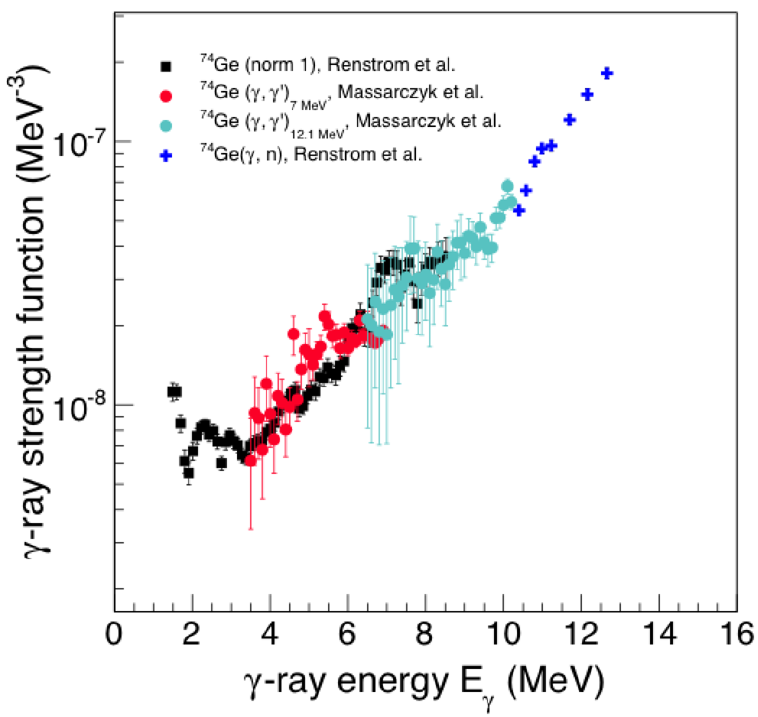
^{117}Sn

U. Agvaanluvsan *et al.*, PRL 102 (2009)



^{74}Ge

T. Renström et al., PRC 93 (2016)



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Coordinated Research Project on Photonuclear Data and Photon Strength Functions

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

1st Research Coordination Meeting of the CRP on Updating the Photonuclear Data Library and generating a Reference Database for Photon Strength Functions, 4-8 April 2016, IAEA, Vienna

The 1st Research Coordination Meeting of the CRP was held from **4-8 April 2016**, at the IAEA, Vienna. The meeting discussed the work plans of the CRP participants, and agreed on additional joint actions and assignments that are needed in order to achieve the goals of the CRP.

IAEA-CRP F41032 4 year-project (2016-2020)

H. Utsunomiya (Konan University, Japan)
V.V. Varlamov (Moscow State University, Russian Federation)
N. Iwamoto (JAEA, Japan)
Y-S. Cho (KAERI, S. Korea)
D. Filipescu (IFIN-HH/ELI-NP, Romania)
R. Xu (CIAE, China)
R. Schwengner (HZDR, Germany)
T. Kawano (LANL, USA)
R. Firestone (University of California, Berkely, USA)
T. Belgya (CER / Hungarian Academy of Sciences, Hungary)
S. Goriely (Université Libre de Bruxelles, Belgium)
V. Plujko (Taras Shevchenko National University, Ukraine)
M. Wiedeking (iThemba LABS, S. Africa)
S. Siem (University of Oslo, Norway)
M. Krticka (Charles University in Prague, Czech Rep.)

https://www-nds.iaea.org/CRP-photonuclear/index_1RCM.html

V. Varlamov
R395

Photonuclear Data Library

IAEA-TECDOC-1178 (2000)

https://www-nds.iaea.org/publications/tecdocs/iaea-tecdoc-1178/

Two major data providers:
Lawrence Livermore National Laboratory (USA)
Centre d'Etudes Nucleaires de Saclay (France)

In general,

$$\sigma_{1n}^{Saclay} > \sigma_{1n}^{LLNL}$$
$$\sigma_{2n}^{Saclay} < \sigma_{2n}^{LLNL}$$

There are long-standing discrepancies between the Livermore and Saclay data of (γ,xn) cross sections, that cannot be resolved in any systematic way.

PHOENIX* Collaboration for IAEA-CRP F41032

* **Pho**to**e**xcitation and **n**eutron em**i**ssion cross (**x**) sections

Official (IAEA) and Extra Assignments

- **(γ,xn) data with x=1-3 for 11 nuclei for updating the photonuclear data library**

The Konan team: ^{197}Au, ^{181}Ta, ^{139}La, ^{9}Be

The ELI-NP team: ^{209}Bi, ^{169}Tm, ^{165}Ho, ^{159}Tb

The MSU team: ^{103}Rh, ^{89}Y, ^{59}Co

- **(γ,n) data for 18 (+4) nuclei for generating a reference database for photon strength functions**

The Konan team: ^{160}Gd, ^{158}Gd, ^{157}Gd, ^{156}Gd, ^{64}Ni, ^{61}Ni, ^{60}Ni, ^{58}Ni, ^{13}C

The Oslo team: ^{205}Tl, ^{203}Tl, ^{192}Os, ^{185}Re, ^{184}W, ^{183}W, ^{182}W, ^{138}Ba, ^{137}Ba, ^{89}Y, ^{68}Zn, ^{66}Zn, ^{64}Zn

Nuclei underlined

Done

Time Schedule of PHOENIX Collaboration

Nuclei underlined

Done

2015

(γ,xn) (x=1-3): 209Bi, 9Be

γSF (γ,n): 205Tl, 203Tl, 89Y

2016

(γ,xn) (x=1-3): 197Au, 169Tm, 89Y

γSF: 192Os, 185Re, 138Ba, 137Ba, 64Ni, 61Ni, 60Ni, 58Ni, 13C

2017

(γ,xn) (x=1-3): 181Ta, 165Ho, 59Co

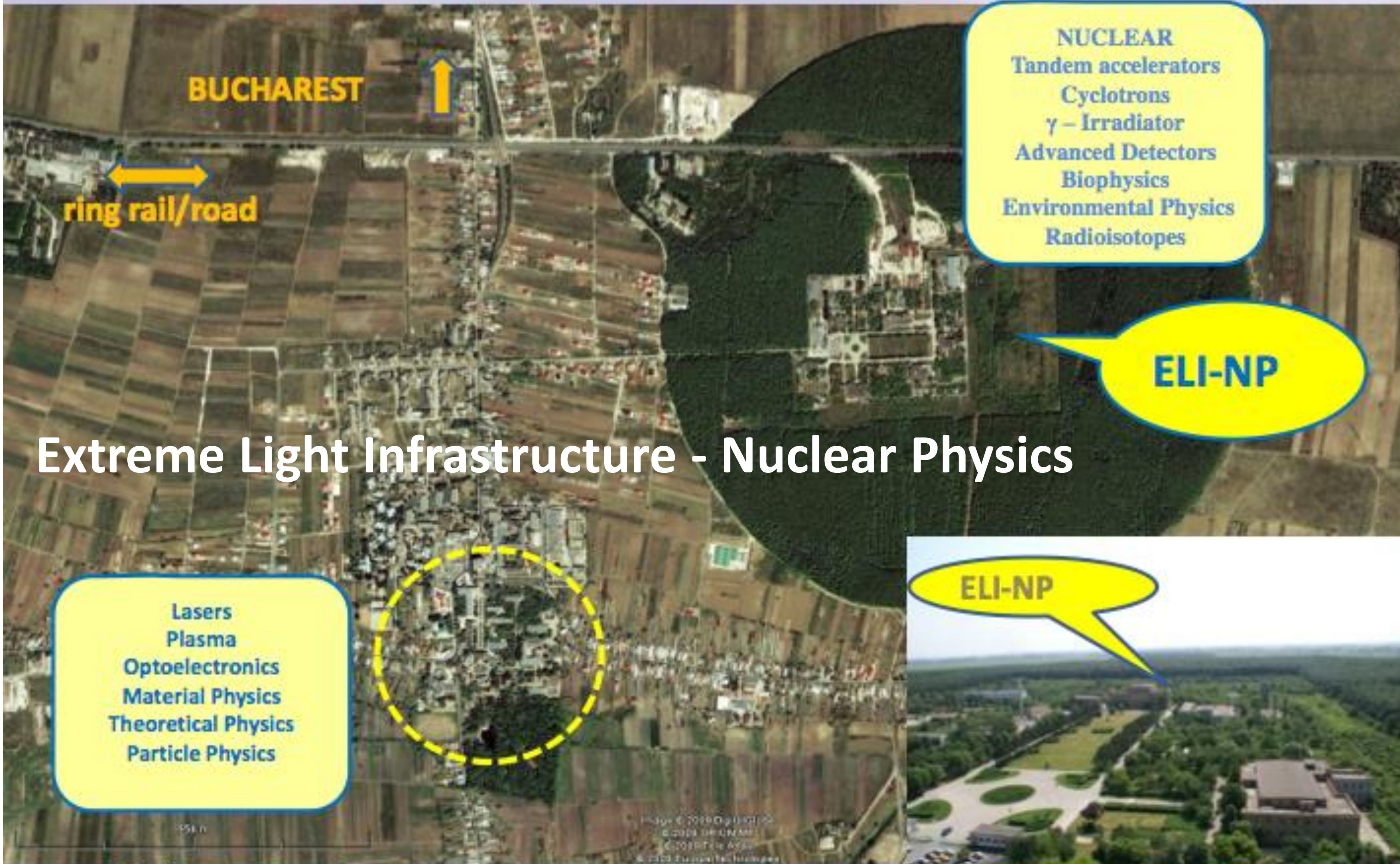
γSF: 184W, 183W, 182W, 68Zn, 66Zn

2018

(γ,xn) (x=1-3): 159Tb, 139La, 103Rh

γSF: 160Gd, 158Gd, 157Gd, 156Gd, 64Zn

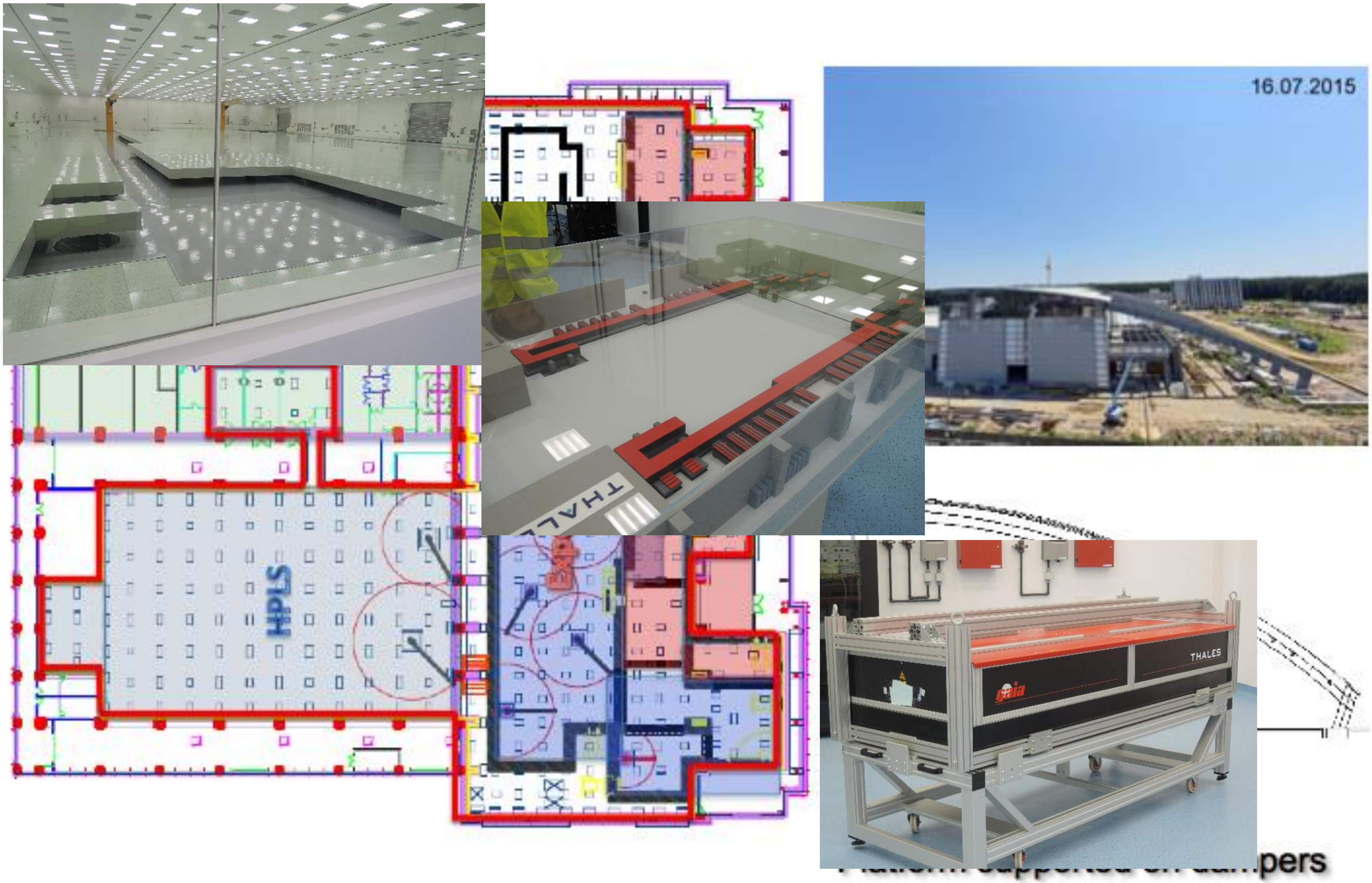
Bucharest-Magurele National Physics Institutes



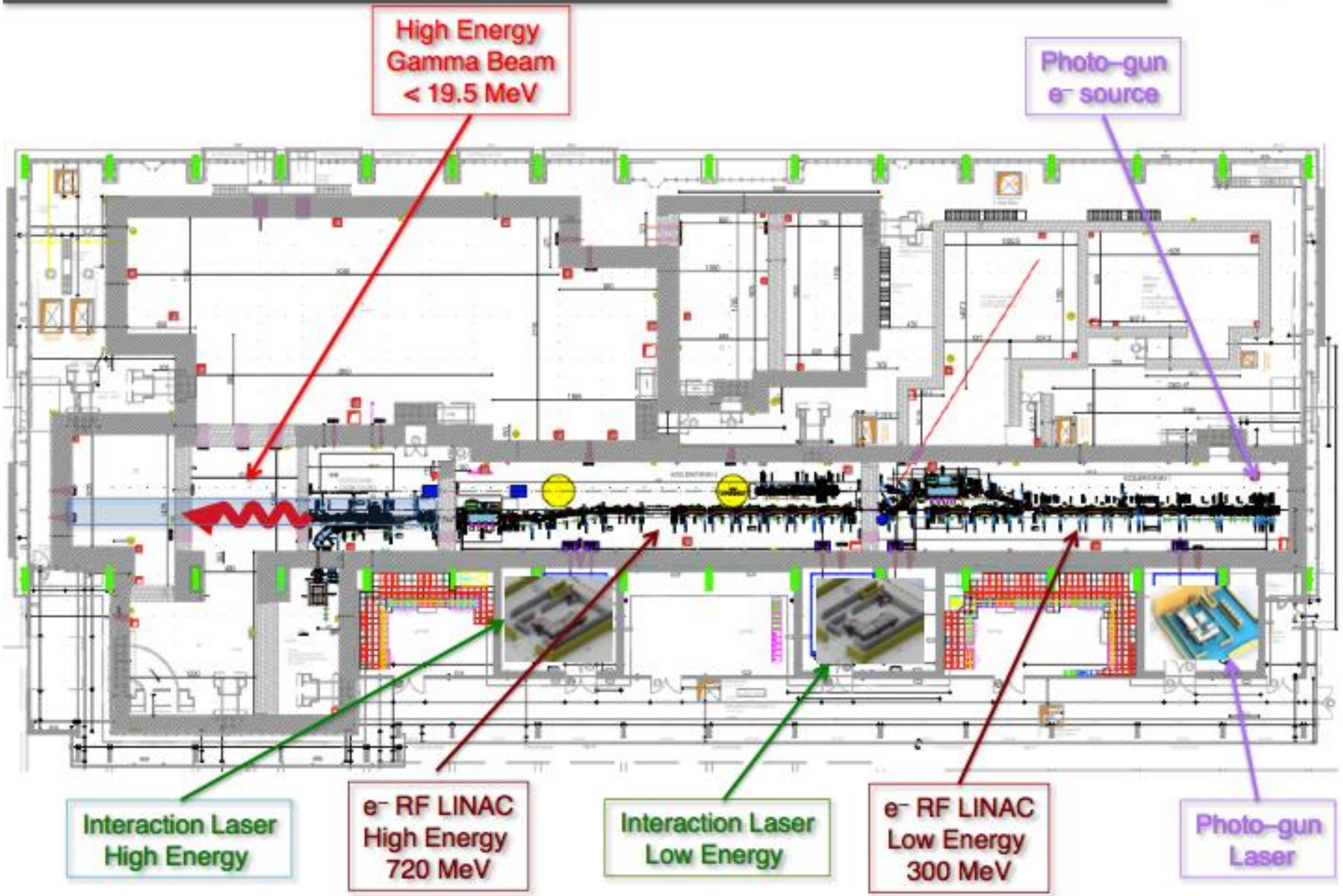
September 2016

ELI–NP – Experimental Building Layout

Nuclear Physics eli

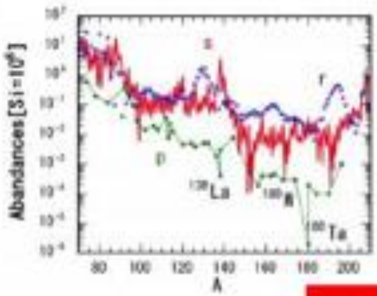


Gamma Beam System Layout



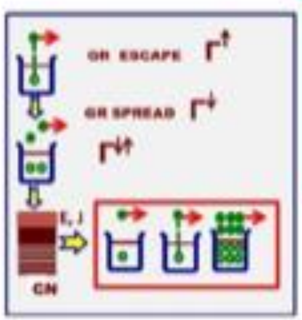
ELI-GANT – Physics program

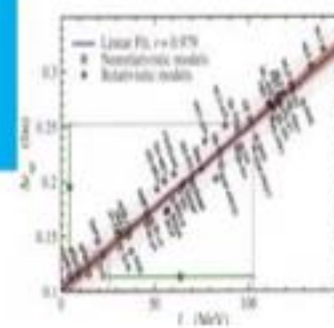
(Gamma Above Neutron Threshold)



Four Physics Cases

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



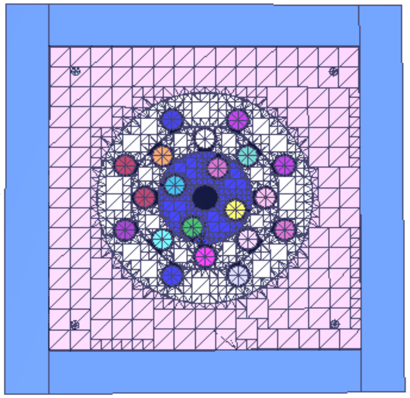


Instrumentation

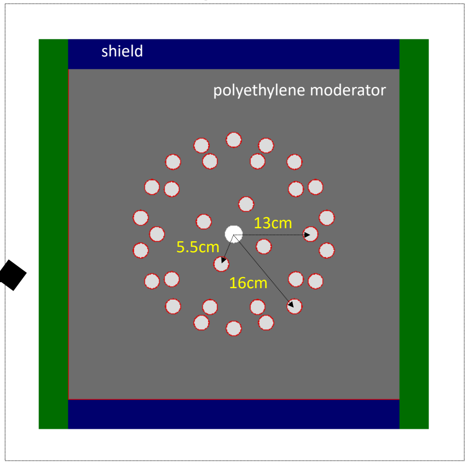
Physics cases

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

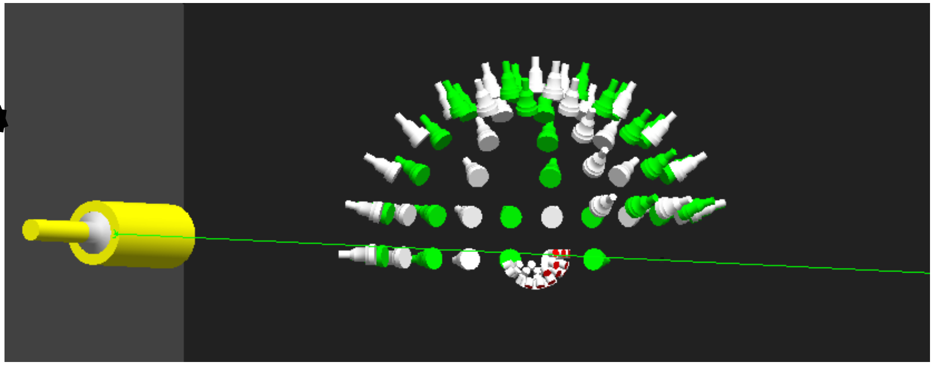
High-efficiency 4π neutron detector (ELIGANT-TNH)



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

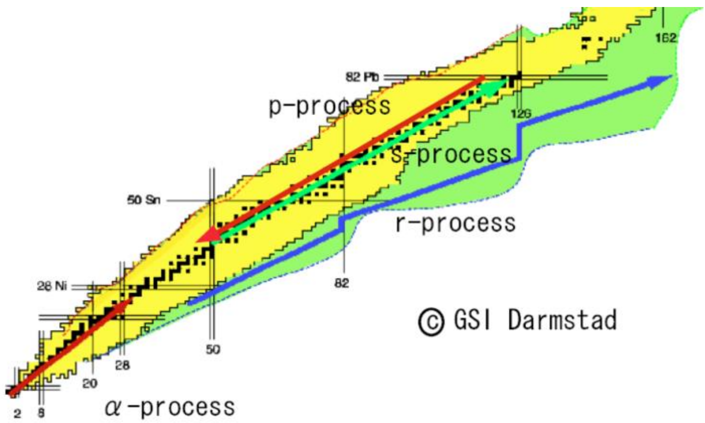


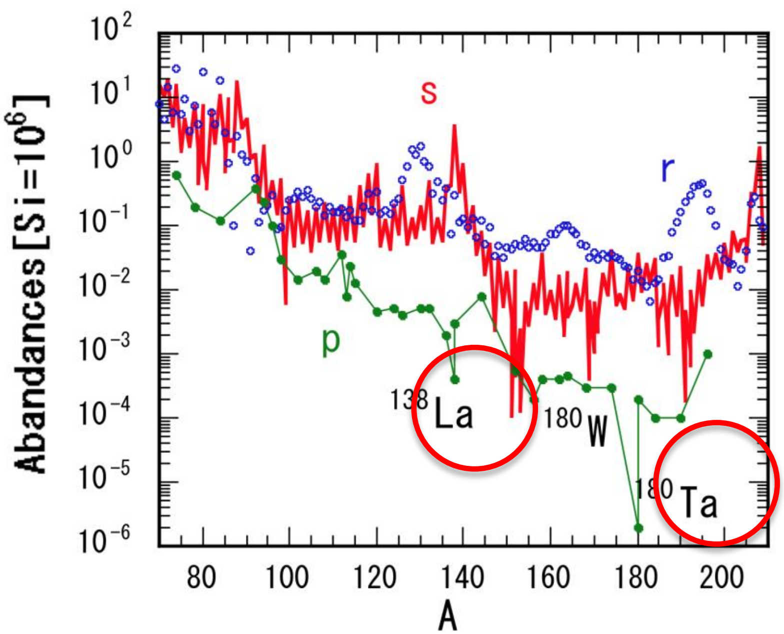
Array of $LaBr_3$:Ce, $CeBr_3$, Liquid, and Li glass scintillation detectors (ELIGANT-GN)



P-process nucleosynthesis

Photonuclear reactions play a major role.





35 neutron-deficient rare isotopes

Day 1 experiments

$^{180}Ta(\gamma,n)^{179}Ta$

$^{138}La(\gamma,n)^{137}La$

1mg targets

Nucleus	Natural abundance (%)	Abundance (10^6 Si) Anders&Grevesse
180Ta	0.012	2.48E-06
190Pt	0.014	0.00017
184Os	0.02	0.000122
156Dy	0.06	0.000221
120Te	0.09	0.0043
124Xe	0.09	0.00571
126Xe	0.09	0.00509
138La	0.09	0.000409
158Dy	0.1	0.000378
132Ba	0.101	0.00453
130Ba	0.106	0.00476
180W	0.12	0.000173
168Yb	0.13	0.000322
162Er	0.14	0.000351
196Hg	0.15	0.00048
174Hf	0.16	0.000249
136Ce	0.185	0.00216
152Gd	0.2	0.00066
138Ce	0.251	0.00284
115Sn	0.34	0.0129
78Kr	0.35	0.153
84Sr	0.56	0.132
114Sn	0.66	0.0252
74Se	0.89	0.55
108Cd	0.89	0.0143
112Sn	0.97	0.0372
102Pd	1.02	0.0142
106Cd	1.25	0.0201
164Er	1.61	0.00404
98Ru	1.87	0.035
144Sm	3.07	0.0008
113In	4.29	0.0079
96Ru	5.54	0.103
94Mo	9.25	0.236
92Mo	14.84	0.378

Summary

1. IAEA-CRP F41032 Nuclear Data project
   - Updating the photonuclear data library
   - Generating a reference database for photon strength functions
2. Applications of the reciprocity theorem in (γ,n) (γ,p) (γ,α) reactions on light nuclei
3. The ELI-NP will open up a new horizon of photonuclear reaction studies for rare isotopes, including the p-process nucleosynthesis.

Collaborators

ULB, Belgium

S. Goriely and his research network

ELI-NP, Romania

D. Filipescu and I. Gheorghe

Lomonosov Moscow State U.

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Kyoto U., Japan

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JAEA, Japan

F. Kitatani

Texas A&M, USA

Y.-W. Lui

Thank you for your attention!