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Cross section measurements with applications to nuclear energy

Arjan Plompen, Peter Schillebeeckx, Stefan Kopecky
Jan Heyse, Markus Nyman, Haroula Rouki,
Alexandru Negret, Catalin Borcea, Adina Olacel,
Philippe Dessagne, Maelle Kerveno

EC-JRC-IRMM, SN3S Unit

European Commission, Joint Research Centre,

Institute for Reference Materials and Measurements

Standards for Nuclear Safety, Safeguards and Security

www.jrc.ec.europa.eu

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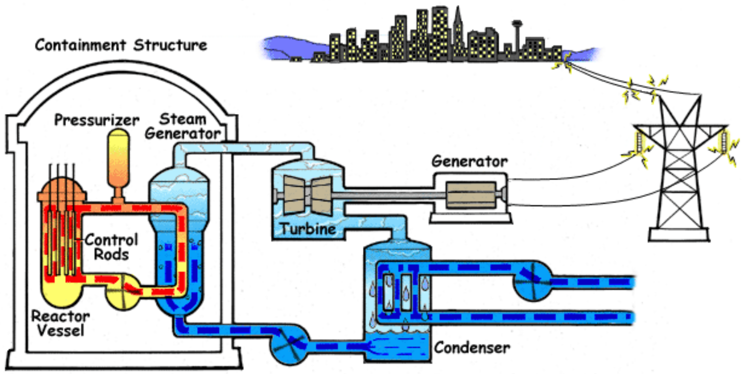
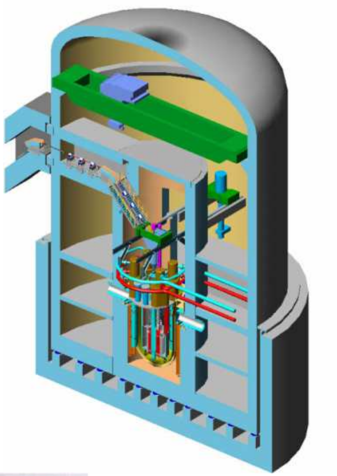
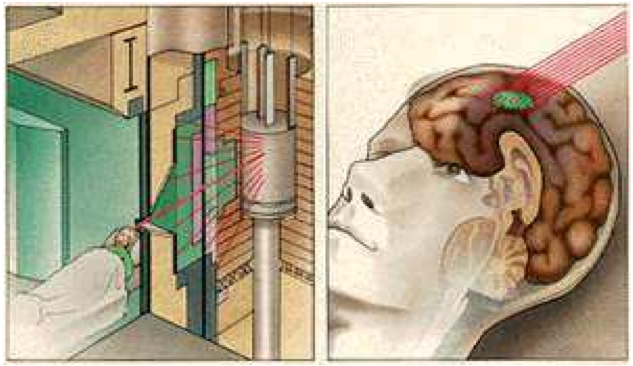
Role of nuclear data

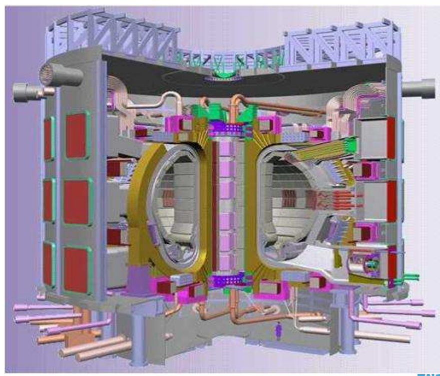
Applications: fission and fusion, radiation protection, nuclear medicine, (nuclear) security, object and materials analysis

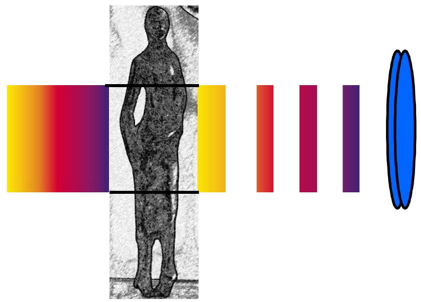
Science: reactions and structure of nuclei, astrophysics, basic physics











Role of nuclear data

How well can we calculate neutron fields, reaction rates, nuclide inventories, radioactivity, dose rates, decay heat, …?
What is the penalty for inaccuracy?

Safety margins for reactivity, power distribution, reactivity coefficients, burnup/time to refuel, enrichment, shielding, spent fuel storage, …
Limits what we may learn from expensive integral experiments.

Boltzmann: Neutron transport

$$\frac{1}{v}\frac{\partial f}{\partial t} + \mathbf{\Omega}\cdot\nabla f + \Sigma_T f = S + \int dE'd\Omega' f(E',\Omega')\Sigma_s(E'\to E,\Omega'\to\Omega)$$

$$S = S_{PF} + S_{dn} + S_{\alpha n} + S_{\text{ext}}$$

$$S_{PF} = \sum_i N_i \int dE' f(E')\overline{\nu}_i(E')\sigma_{F,i}(E') f_{P,i}(E',E)$$

$$\Sigma_s(E\to E',\Omega\to\Omega') = \sum_i N_i \frac{d^2\sigma_{s,i}}{dE'd\Omega'}(E,E',\mathbf{\Omega}\cdot\mathbf{\Omega}')$$

$$\Sigma_T = \sum_i N_i \sigma_{T,i}$$

Bateman: Nuclide evolution

$$\frac{dN_i}{dt} = -\lambda_i N_i - r_i N_i + \sum_{i\neq i}\left\{\lambda_{j\to i} + r_{j\to i}\right\} N_j$$

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CHANDA

CIEMAT, ANSALDO, CCFE, CEA, CERN, CNRS, CSIC, ENEA, GANIL, GSI, HZDR, IFIN-HH, INFN, IST-ID, JRC, JSI, JYU, KFKI, NNL, NPI, NPL, NRG, NTUA, PSI, PTB, SCK, TUW, UB, UFrank, UMainz, UMan, UPC, UPM, USC, UU, UOslo

Challenges in nuclear data for the safety of European nuclear facilities

Coordinator: Enrique Gonzalez
Infrastructure coord. & development

5.4 M€ EC contribution, ≈10M€ total
36 partners, 2013-2017

New neutron beams, new experimental equipment, new evaluation methods, Myrrha safety case, access to validation experiments, transnational access

Transnational access

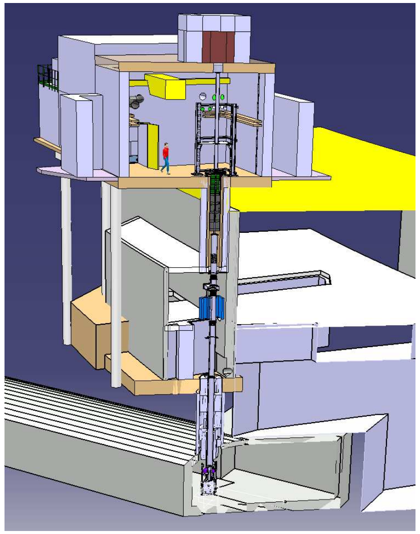
Coordinated A. Junghans

European Commission

Follow-up of succesful programs: EUFRAT, ERINDA (NUDAME, EFNUDAT)
Accelerator-based neutron sources for nuclear applications

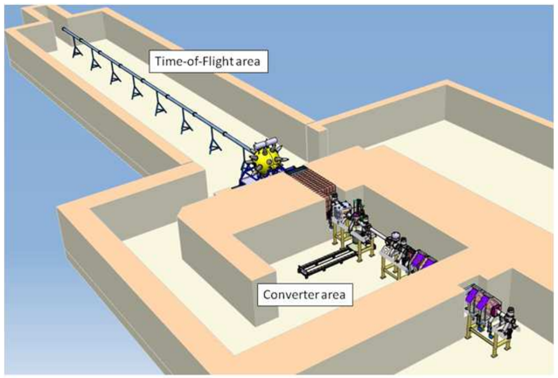
GELINA, IRMM

nELBE, HZDR



CERN, n_TOF, EAR2

GANIL, SPIRAL2, NFS



Support to experiments
Support to scientific visitors

Challenges
HPRL, SG26, NUDATRA

www.nea.fr/html/dbdata/hprl/

European Commission

NEA

Quantatively: Very tight target uncertainties will remain in the picture
- Fission cross sections (2% for MA, nu-bar, neutron-spectrum)
- Fissile nuclides capture cross sections (5% or better)
- Scattering cross sections (2-5%) and angular distributions (^{238}U, ^{56}Fe, ^{23}Na)

Several issues not tackled for a long time are being picked up
- Prompt fission gammas
- Neutron spectra and angular distributions
- Capture of the main fissile nuclides
- (In)elastic scattering of U-238

Technical developments are required for tackling these challenges
- Emphasis on high quality, accurate experiments
- Experiments to improve nuclear models
- New detectors and data-acquistion
- New analysis methods
- New neutron sources

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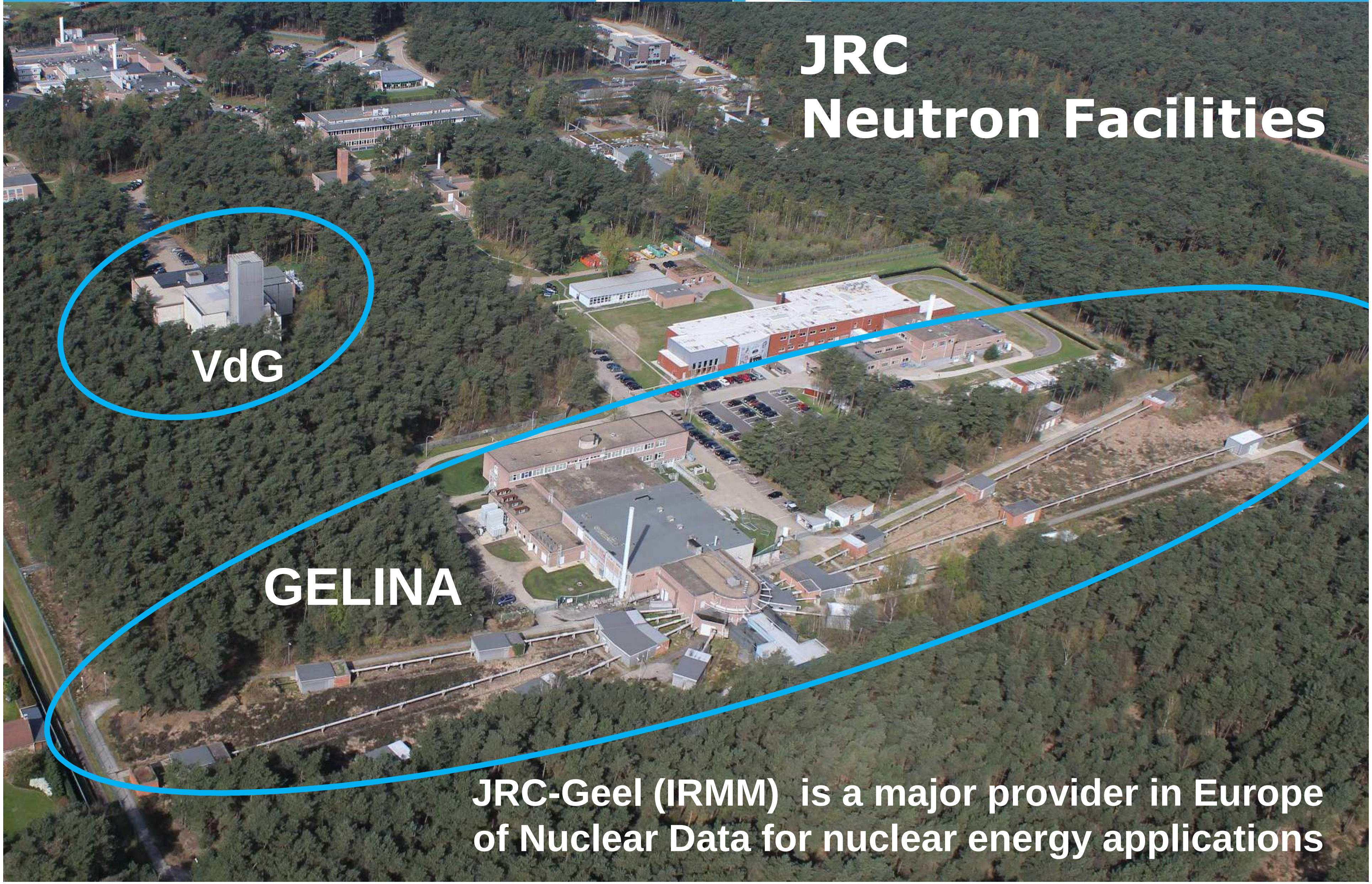
Neutron Facilities



JRC-Geel (IRMM) is a major provider in Europe of Nuclear Data for nuclear energy applications

European Commission

- **Pulsed white neutron source**
  - 10 meV < E_n < 20 MeV
  - 800 Hz
  - 1 ns fwhm
  - 2.5 10^{13} n/s
- **Neutron energy : time-of-flight (TOF)**
- **Multi-user facility: 10 flight paths**
  - 10 m - 400 m

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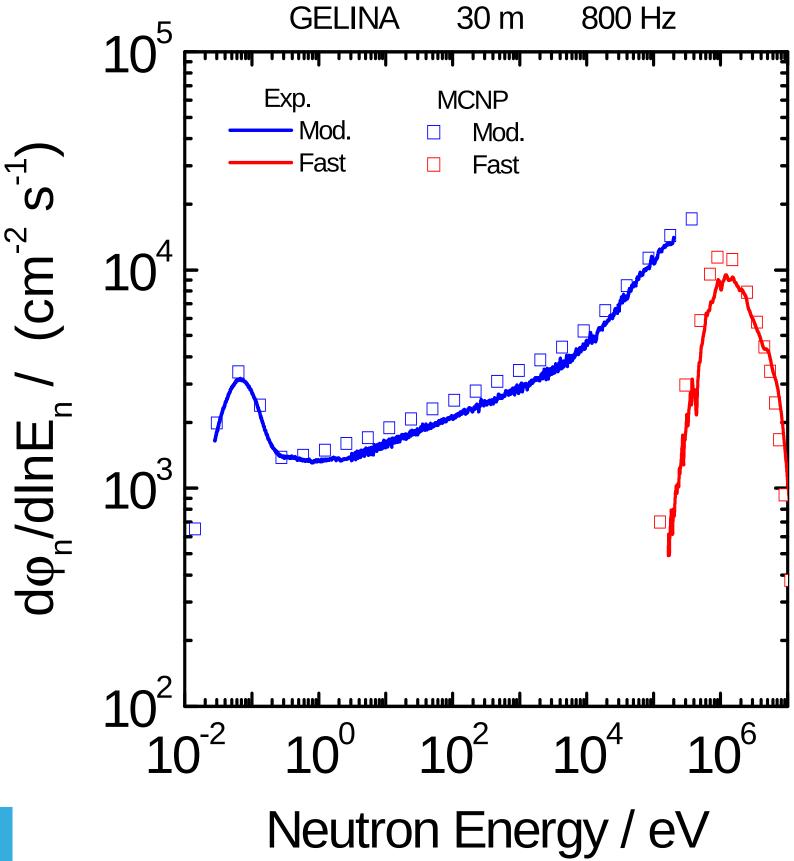
Neutron Production



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Germanium Array for Inelastic Neutron Scattering

GAINS @ FP3/200m

12 HPGe 80 mm ø x 80 mm L
1 keV resolution at 1 MeV (neutrons)
Cross sections 3-5 %

GAINS

Angle integration: $\lambda \leq 3$
Efficiency: calib+MC
Time-response
  12bit 440 MSPS dig.
Flux: U-235(n,f)

L.C. Mihailescu et al. NIMA531(2004)375; method
L.C. Mihailescu et al. NIMA578(2007)298; digitizers
D. Deleanu et al. NIMA624(2010)130; γ-detection efficiency
A. Plompen et al. KPS59(2011)1581; FF-detection efficiency
^{52}Cr: L.C. Mihailescu et al. NPA786(2007)1
^{209}Bi: L.C. Mihailescu et al. NPA799(2008)1
^{208}Pb: L.C. Mihailescu et al. NPA811(2008)1
^{23}Na: C. Rouki et al. NIMA672(2012)82;
^{235}U: M. Kerveno et al. PRC87(2013)024609 Graphème set FP16/30m
$0\nu2\beta$ bgs: A. Negret et al. PRC88(2013)027601
^{28}Si: A. Negret et al. PRC88(2013)034604
^{76}Ge: C. Rouki et al. PRC88(2013)0546130
^{24}Mg: A. Olacel et al. PRC…(2014)… in print
^{56}Fe: A. Negret et al. PRC…(2014)… in print
^{12}C, ^{58}Ni, ^{206}Pb, ^{207}Pb, ^{232}Th, ^{238}U; Conf. Proc.
Ongoing: ^{7}Li, ^{48}Ti, ^{57}Fe, ^{63}Cu, ^{65}Cu, Mo, Zr

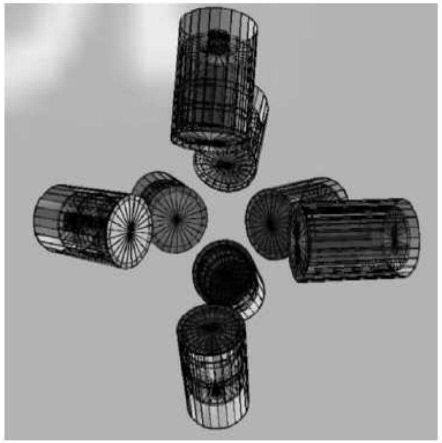
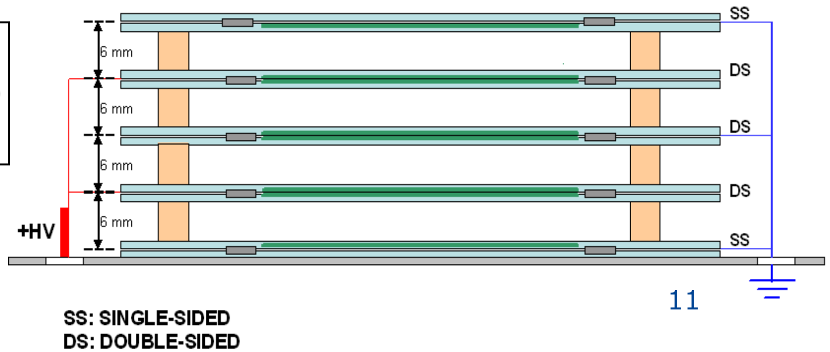
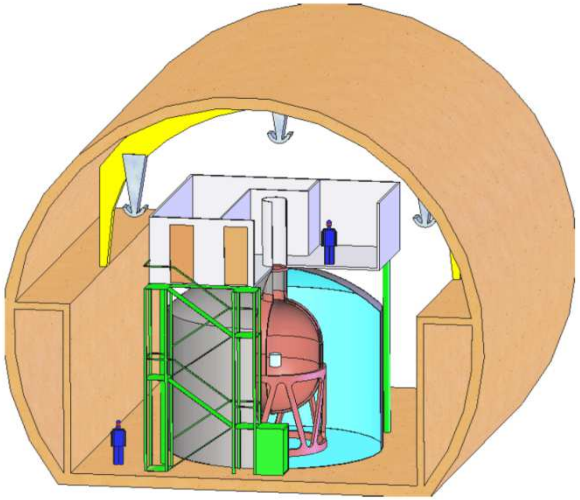


Fig. 1. GAINS. Drawing of the simulated geometry.

$$\sigma = 2\pi \int_{-1}^{1} \frac{d\sigma}{d\Omega}(x)dx = 2\pi \sum_{i=1}^{2} w_i \frac{d\sigma}{d\Omega}(x_i)$$





$^{76}Ge(n,n'g)^{76}Ge$

C. Rouki et al. PRC88(2013)0546130;
w. K. Zuber, A. Domula TUD

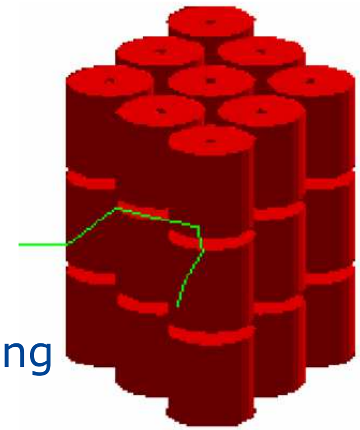
Motivation: background in $0\nu\beta\beta$-experiments

- Is a neutrino its own antiparticle?
- What is the neutrino mass?

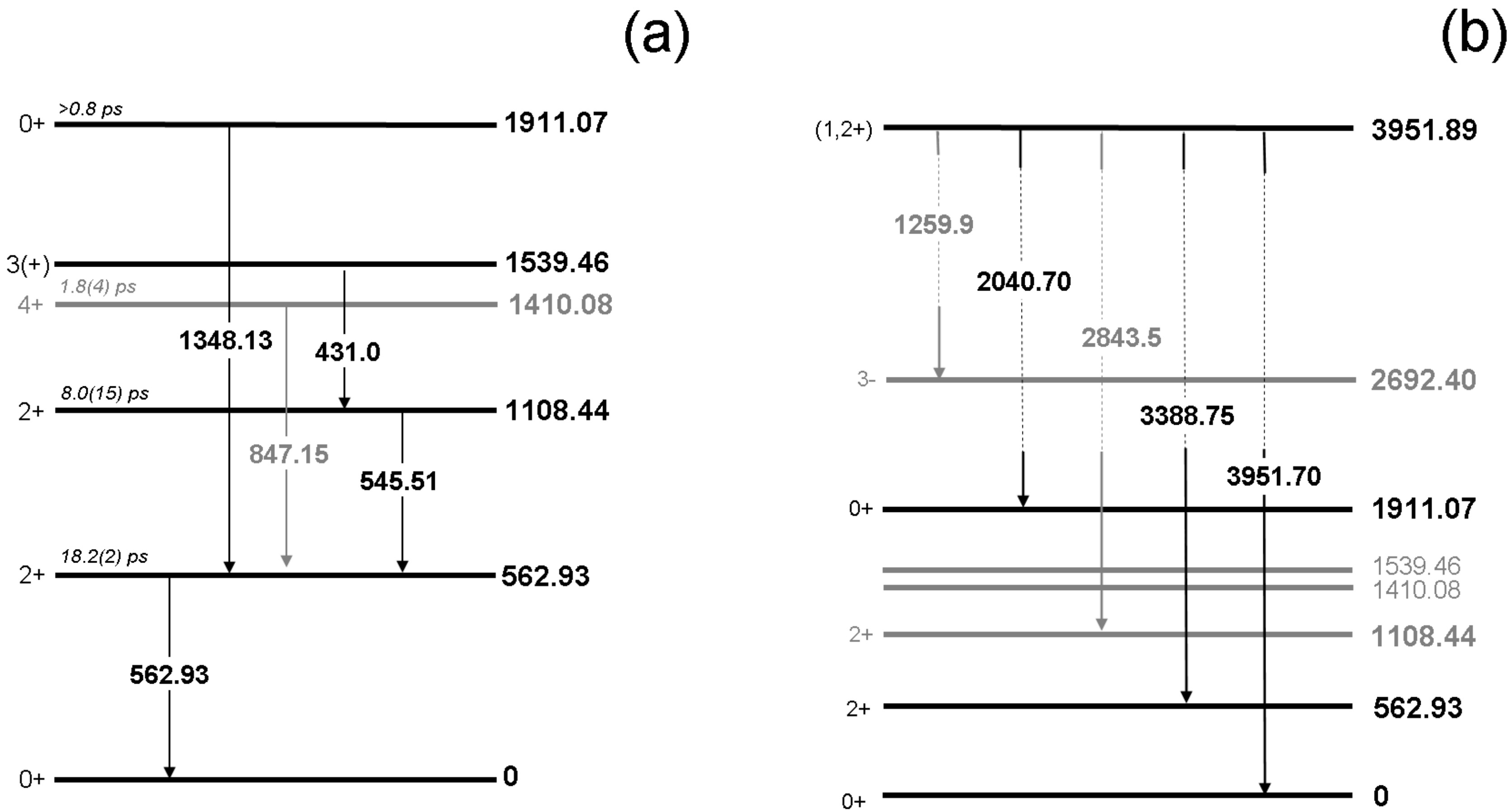
GERDA experiment

- ^{76}Ge, $Q_{\beta\beta}$ = 2039 keV, $T_{1/2} > 2\ 10^{25}$ y
- ^{76}Ge high purity detectors, 9 coaxial 8 x 8cm ø
- Gran Sasso, 3600 mwe
- Background goal 10^{-3} keV^{-1} kg^{-1} y^{-1}
- Components few times 10^{-4} keV^{-1} kg^{-1} y^{-1}

- Two concerns for neutrons
  - Direct production of 2040 keV transition
  - Indirect background due to Eg + Erecoil in inelastic scattering



Relevant portions level scheme ^{76}Ge



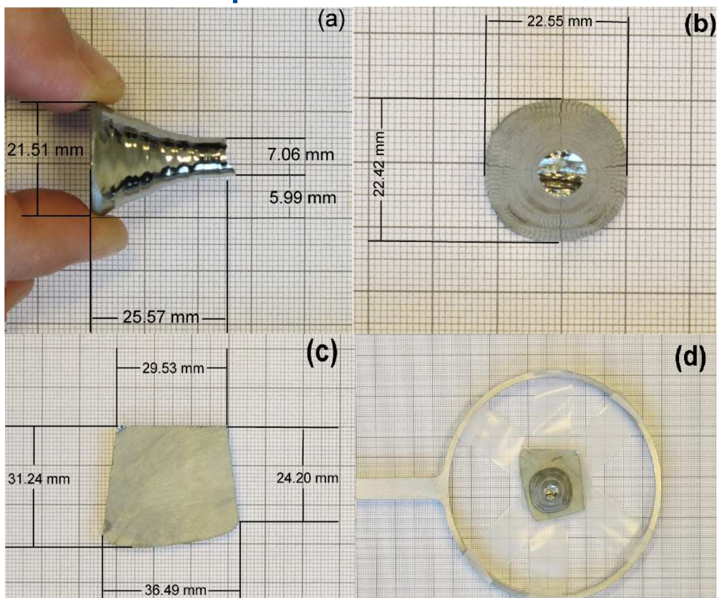
C. Rouki et al. PRC88(2013)0546130

Experiment
$^{76}Ge(n,n'g)^{76}Ge$

32 g, 87% enriched in ^{76}Ge
main systematic uncertainty 10%

Cross section of 2039 keV,
L69→L5 **< 3 mb**
Unshielded: 0.43 event/kg/y
(100x above limit)

Shielded: not an issue (3m H2O!)
Future experiments?

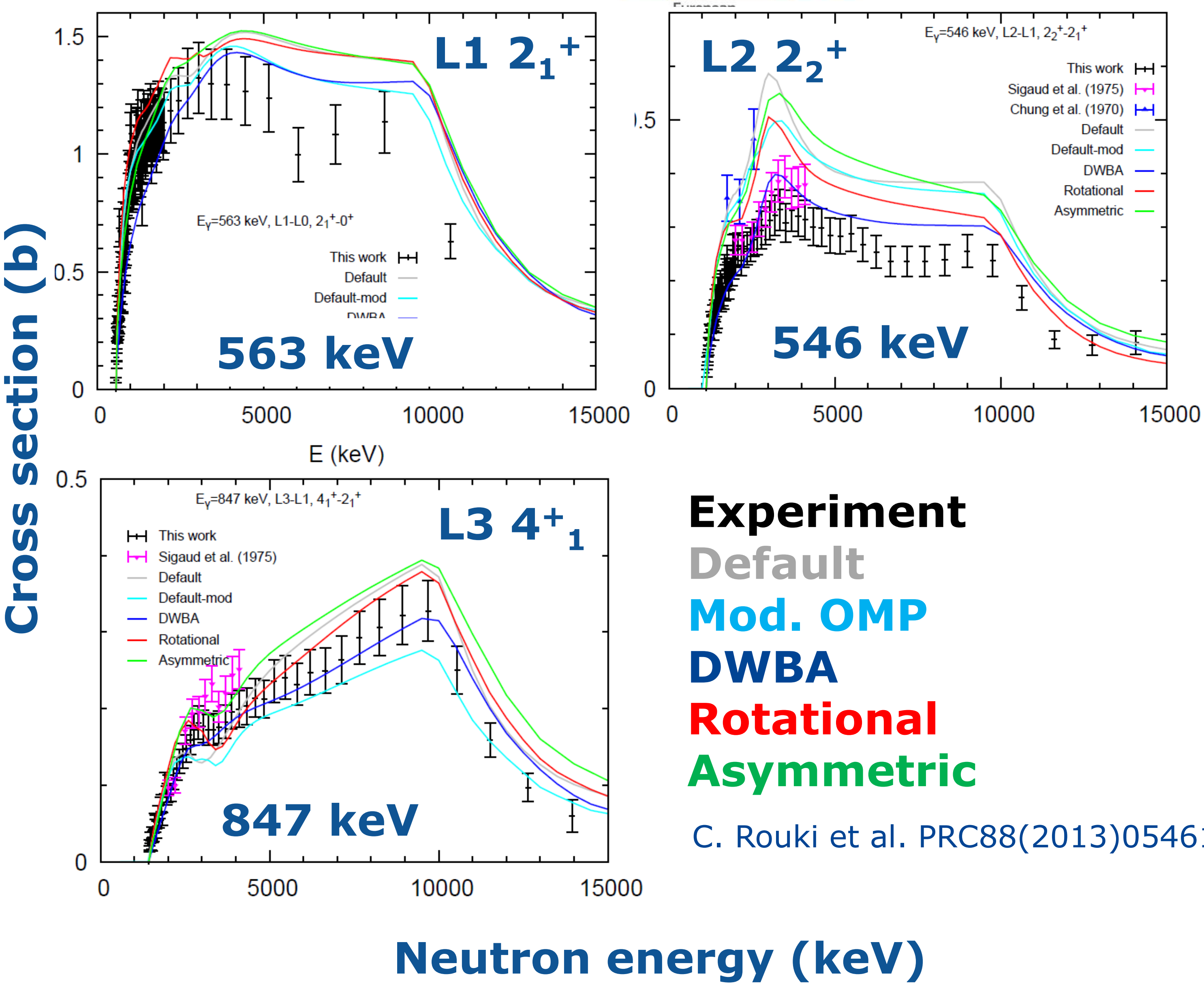


C. Rouki et al. PRC88(2013)0546130

Experimental results
- Five gammas, five levels, INL

TALYS model calculations
- Default phenom.
  - KD omp
  - GC LD
  - Kopecky-Uhl γ-strength
- Modified OMP
- Effect of deformation
  DWBA, Rotational, Asymmetric
  (Toh et al. PRC 2013).
- Microscopic
  - JLM omp, LDA, HF dens.
  - enhanced combinatorial LD
  - HFB γ-strength
  - Here similar to default (not shown)

Gamma emission cross sections



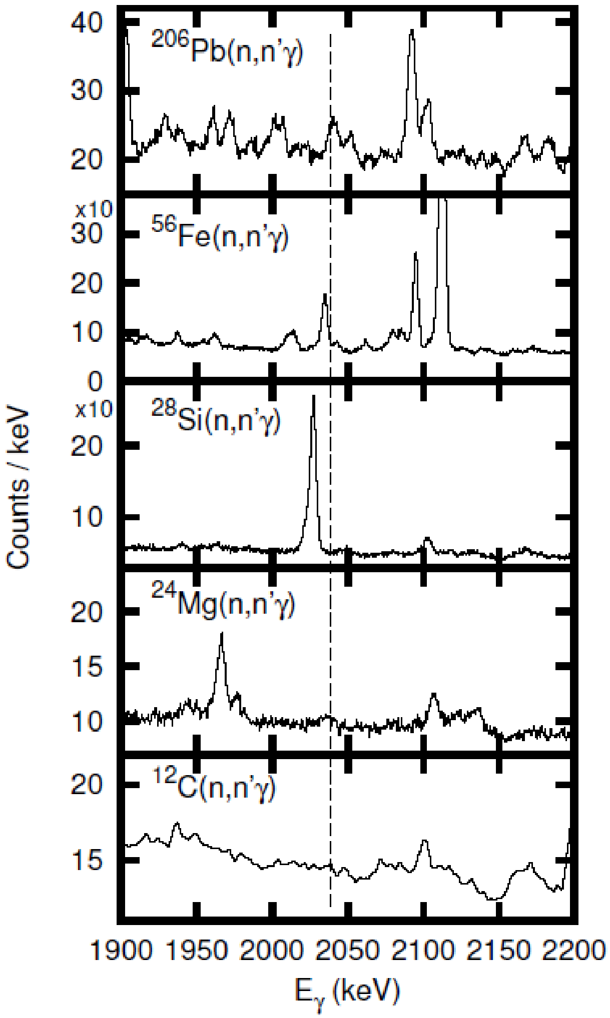
C. Rouki et al. PRC88(2013)0546130

Background
0ν2β experiments

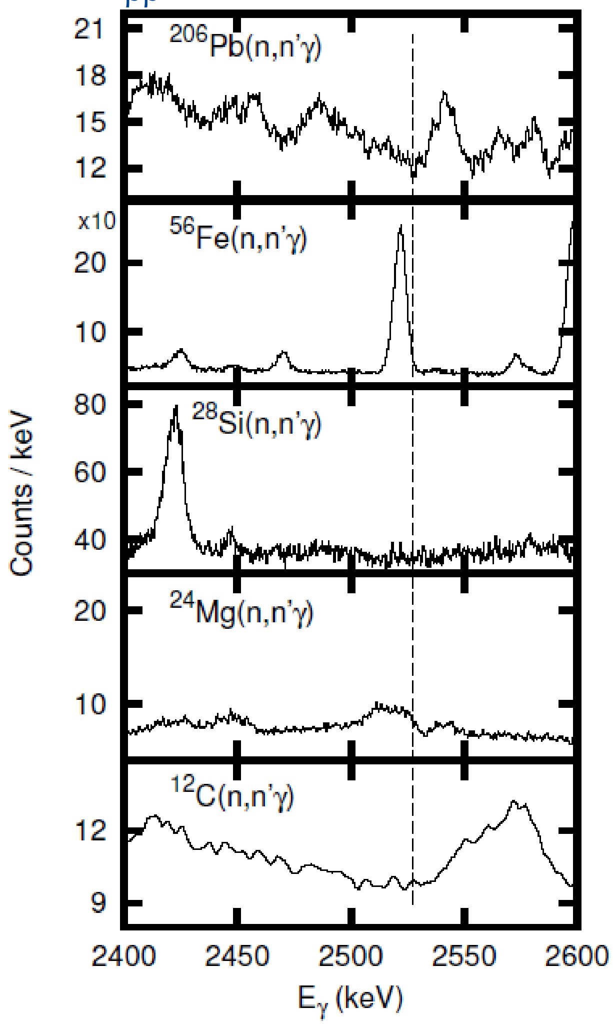
^{206}Pb, ^{56}Fe, ^{28}Si, ^{24}Mg, ^{12}C — Shielding or construction materials

A. Negret, C. Borcea, and A. J. M. Plompen, Phys. Rev. C 88 (2013) 027601

$Q_{\beta\beta}(^{76}Ge)$ 2039 keV



$Q_{\beta\beta}(^{130}Te)$ 2528 keV

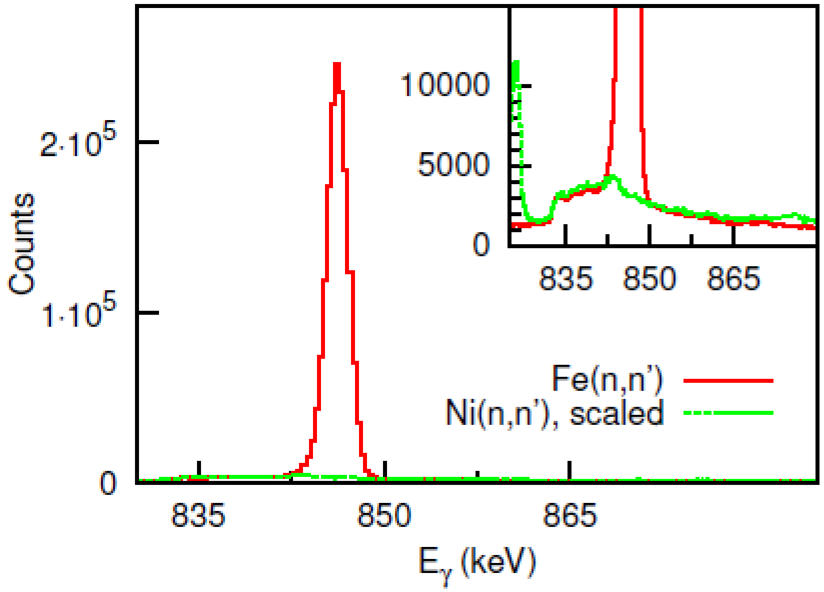


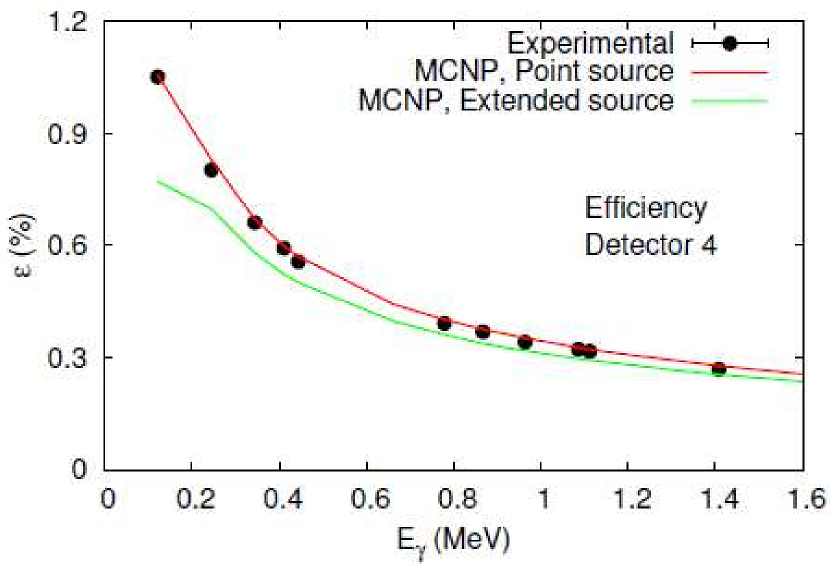
^{56}Fe(n,n'γ)

A. Negret, PRC in print

Attention on accuracy
and systematic effects
20 g's 56Fe(n,n'); 6 g's 56Fe(n,2n)
Resolution (but see table)

E_n range (MeV)	E_n^{avg} (MeV)	E*(^{57}Fe) (MeV)	J^π in ^{57}Fe (TALYS)	Level density (BSFG) (1/MeV)	Level density (Exp.) (1/MeV)
0.9 - 1.4	1.15	8.78	1/2 - 5/2	158	134
1.4 - 1.9	1.65	9.27	1/2 - 5/2	205	94
1.9 - 2.4	2.15	9.76	1/2 - 5/2	265	60
2.4 - 2.9	2.65	10.25	1/2 - 5/2	343	52
2.9 - 3.4	3.15	10.74	1/2 - 5/2	441	46
3.4 - 3.9	3.65	11.23	1/2 - 7/2	858	28



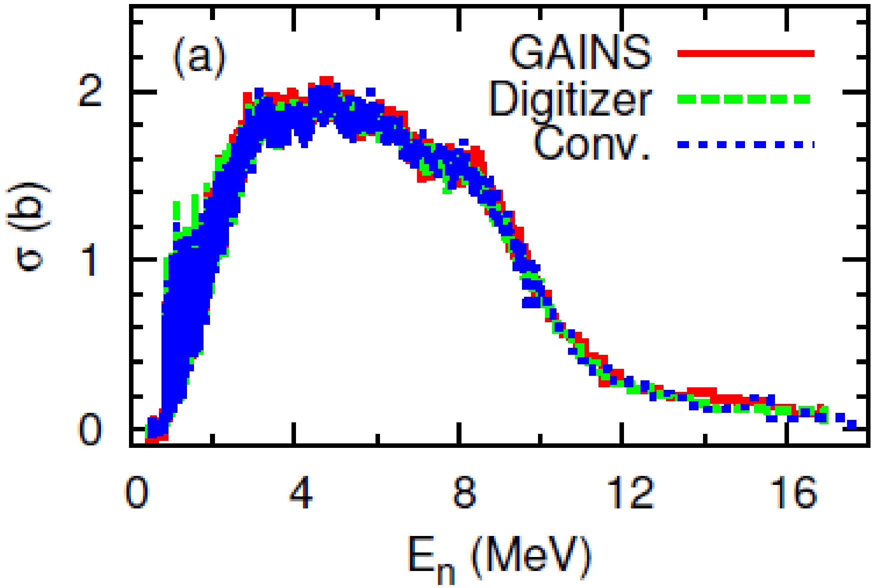


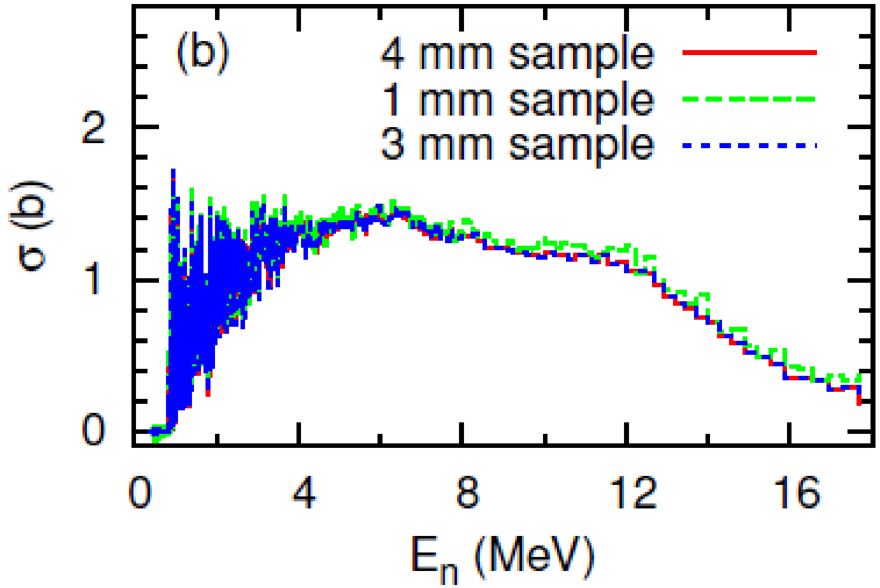
$^{56}Fe(n,n'\gamma)$

A. Negret, PRC in print

^{206}Pb
Different DAQ
Different setups
Earlier: different samples

^{56}Fe
Different sample thicknesses

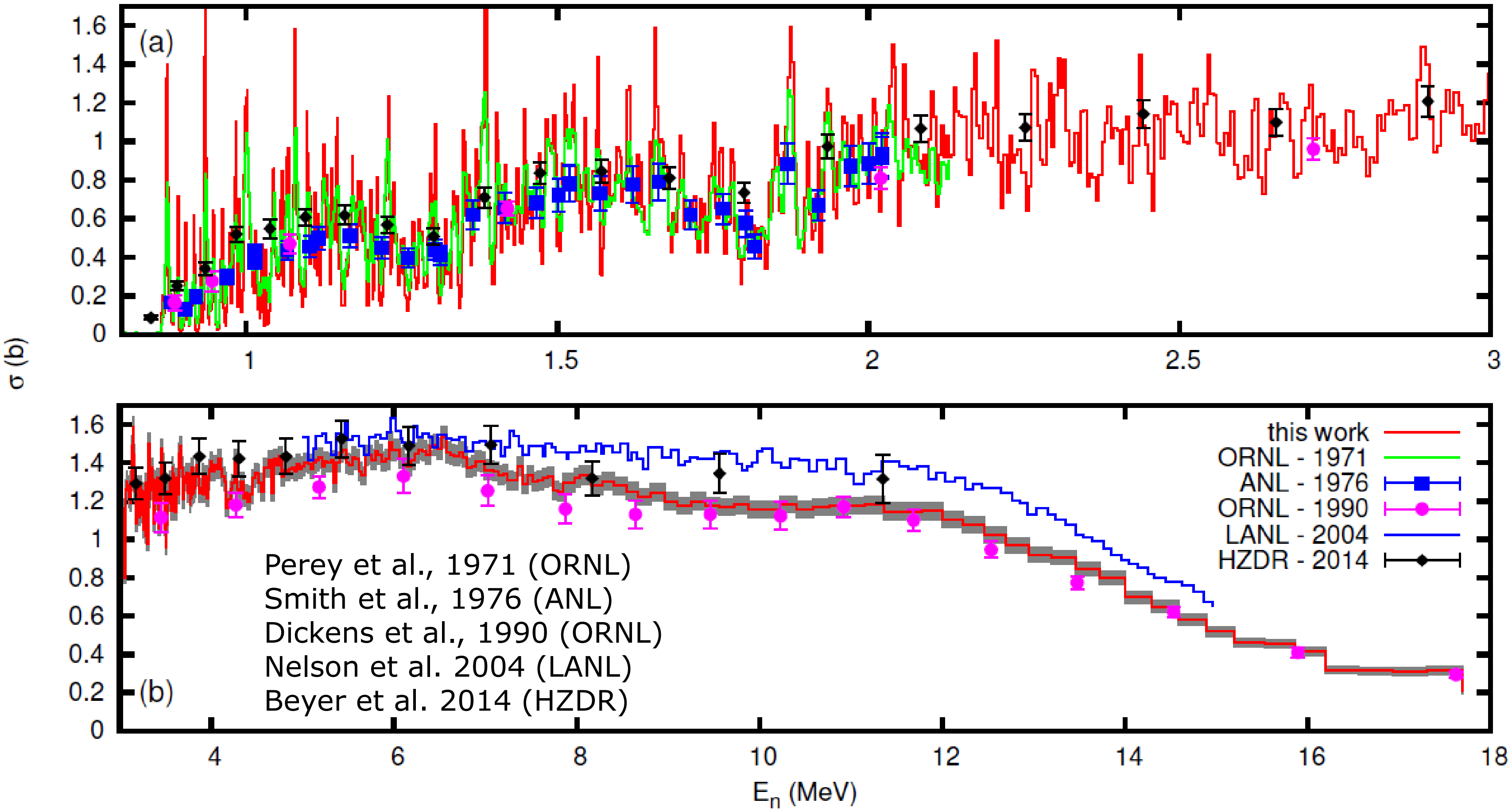




$^{56}Fe(n,n'\gamma)$

A. Negret, PRC in print

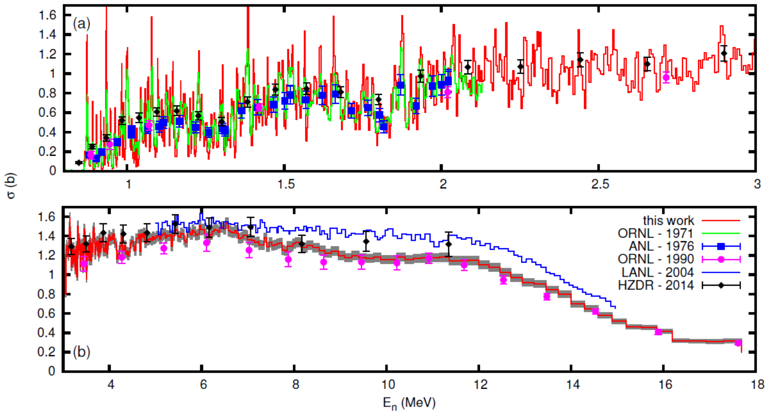
847 keV gamma-ray (L1-g.s.)

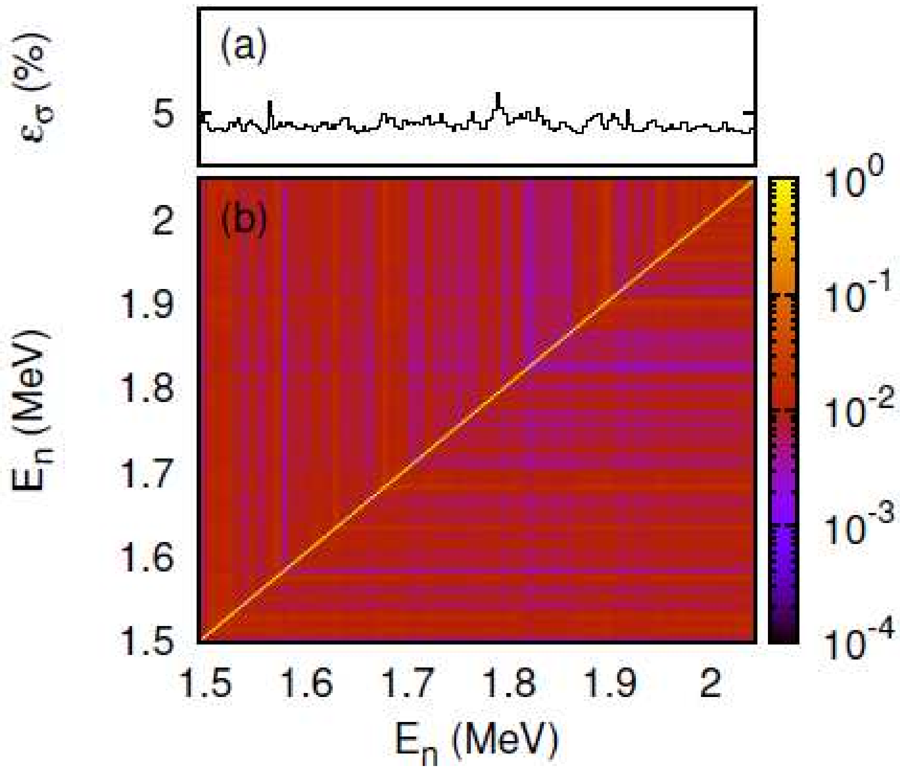


$^{56}Fe(n,n'\gamma)$

A. Negret, PRC in print

847 keV gamma-ray (L1-g.s.)
Uncertainties
- γ-efficiency
  - Source 0.7%
  - Simulations 2%
- FF-efficiency 1.5%
- All-in 5-6% (statistics)





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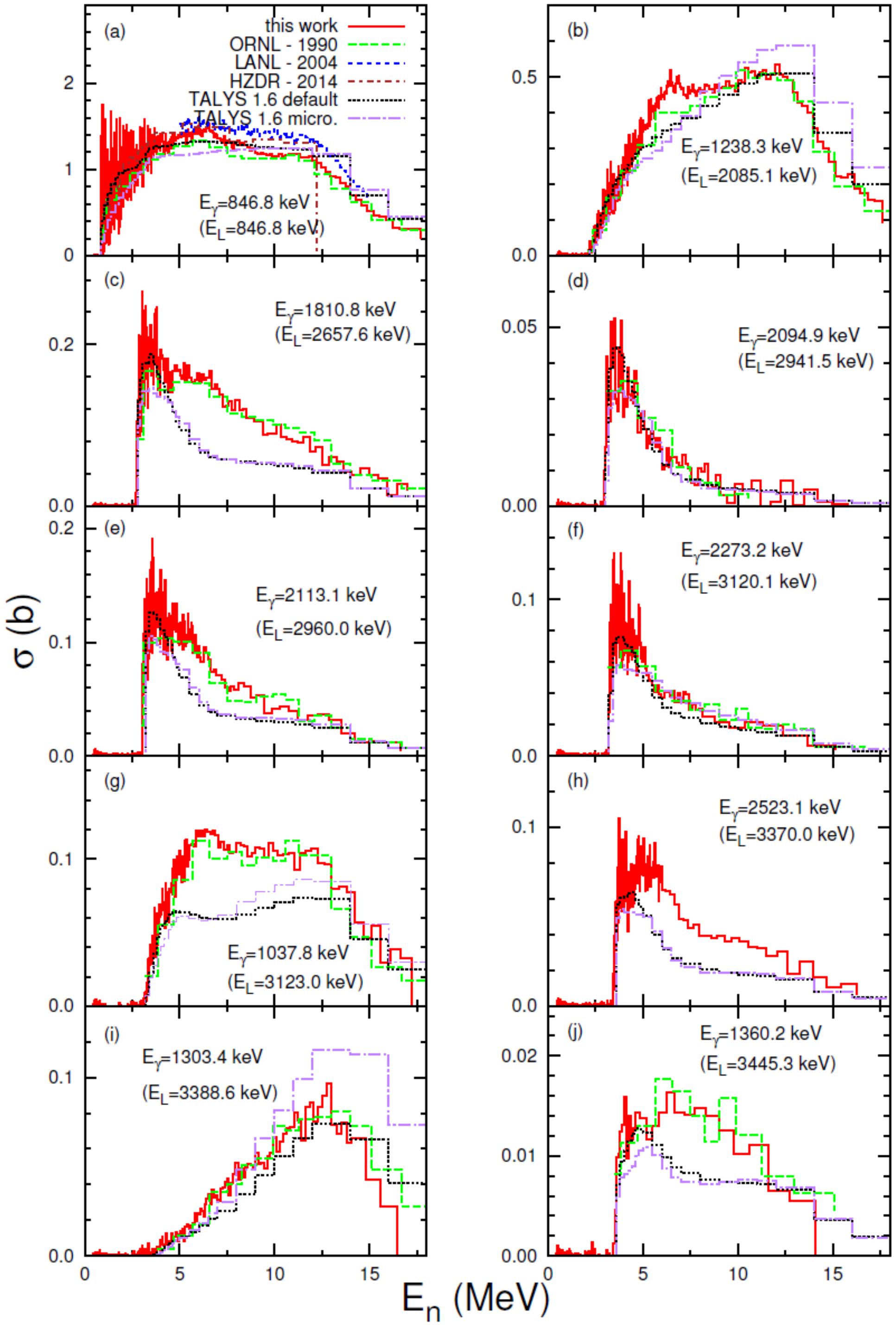
$^{56}Fe(n,n'\gamma)$

A. Negret, PRC in print

TALYS versus gamma-production
Default calculation
Microscopic calculation

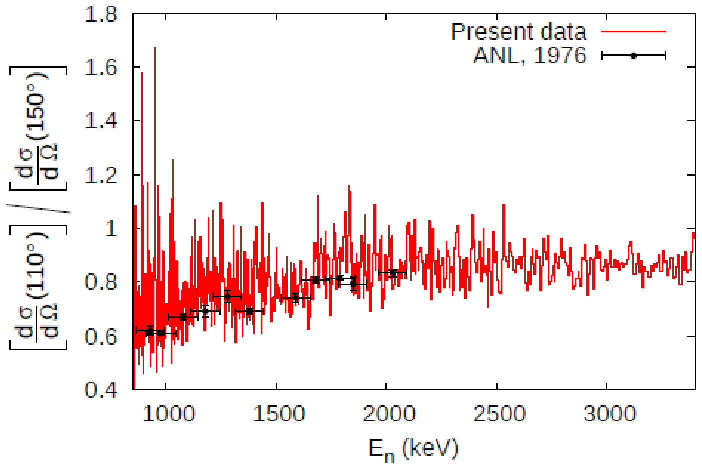
Agreement comparable
Mixed level of agreement
Do we really understand

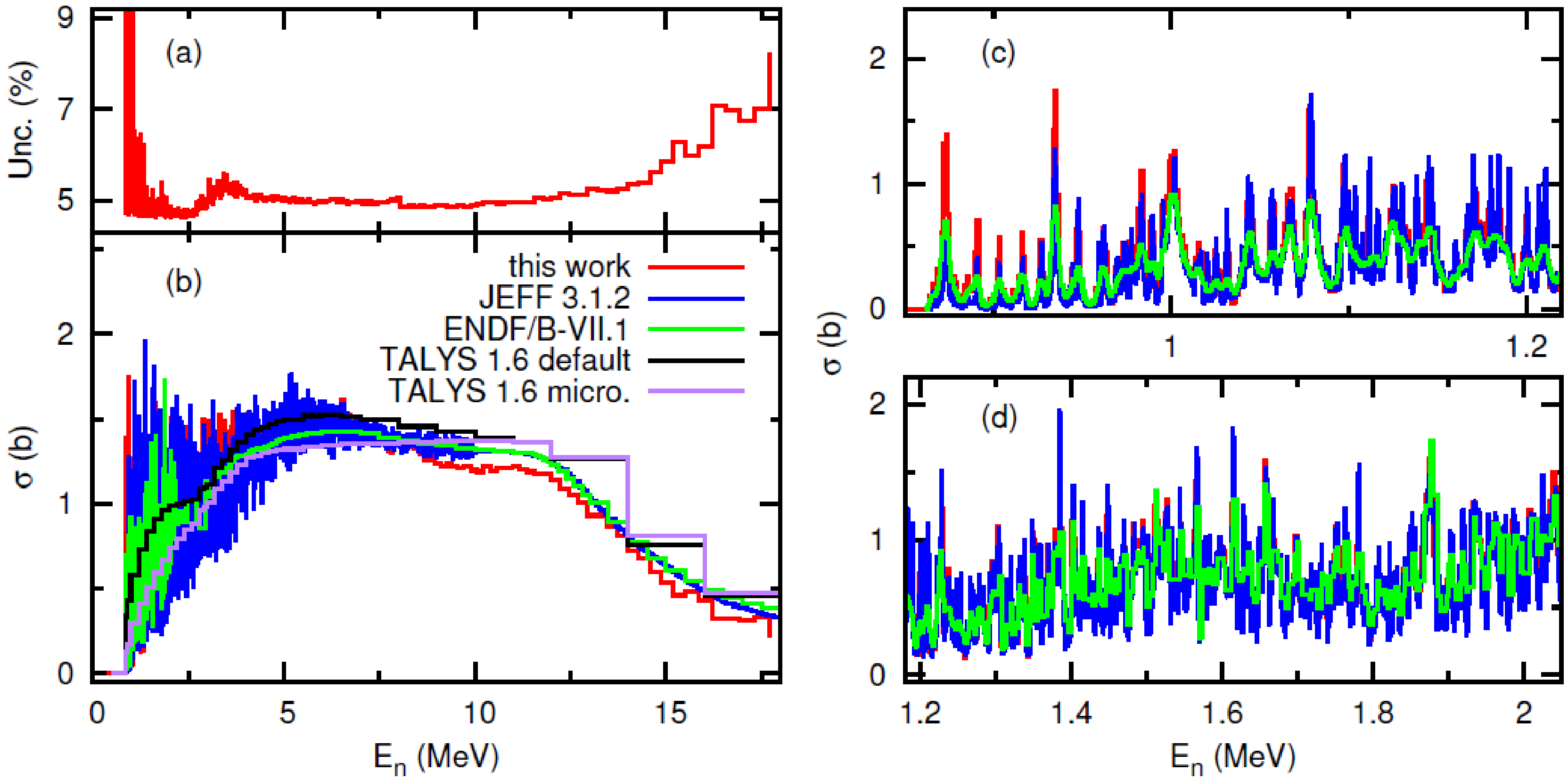
- gamma-decay
- transition discrete-continuum?



$^{56}Fe(n,n'\gamma)$

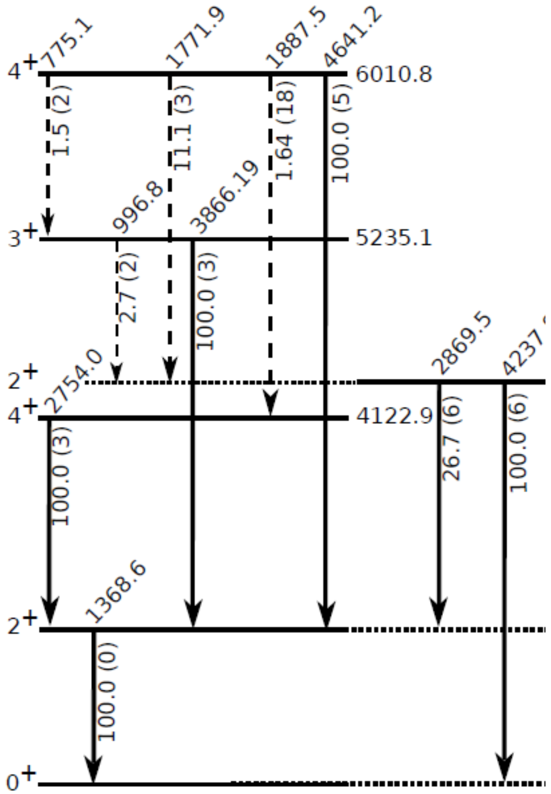
A. Negret, PRC in print



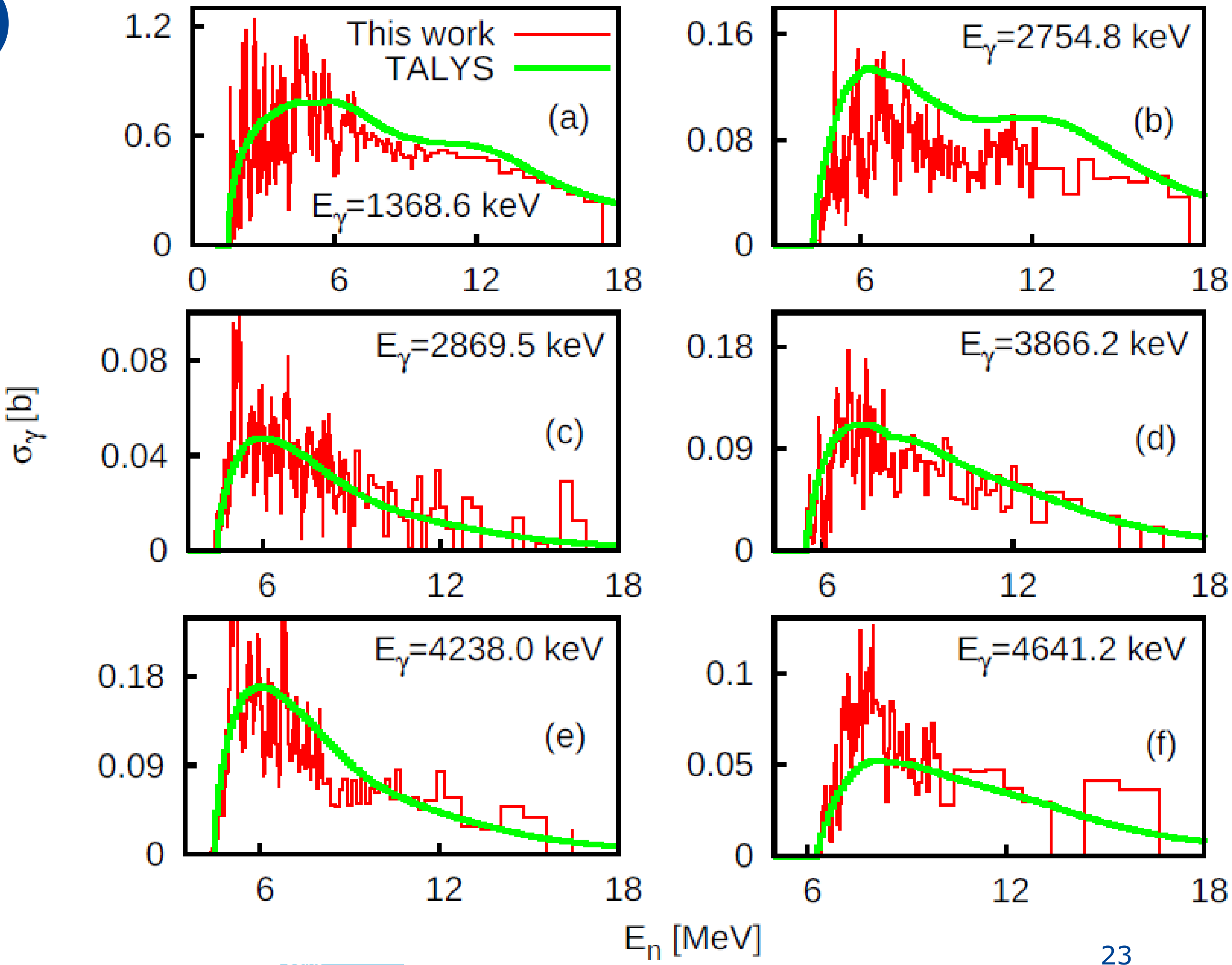


^{24}Mg(n,n'g)

A. Olacel et al., PRC, in print

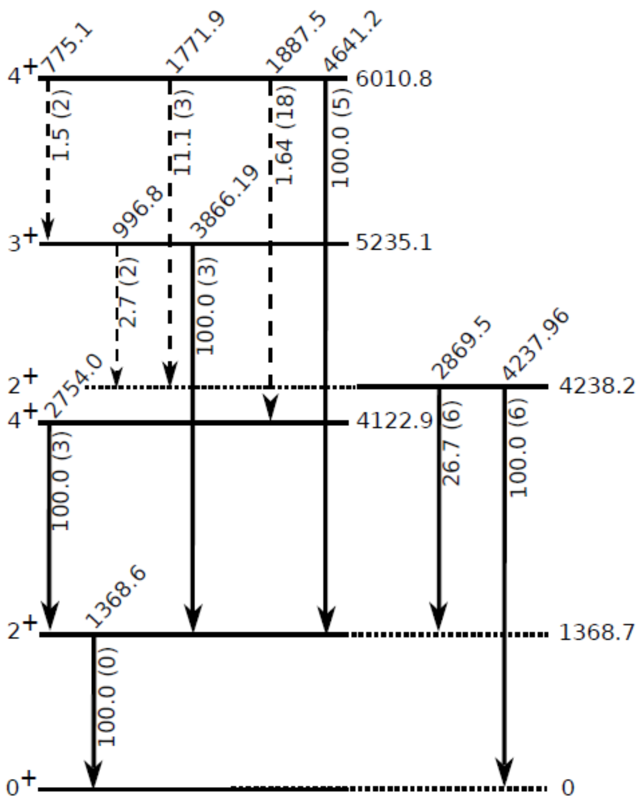


Gamma production

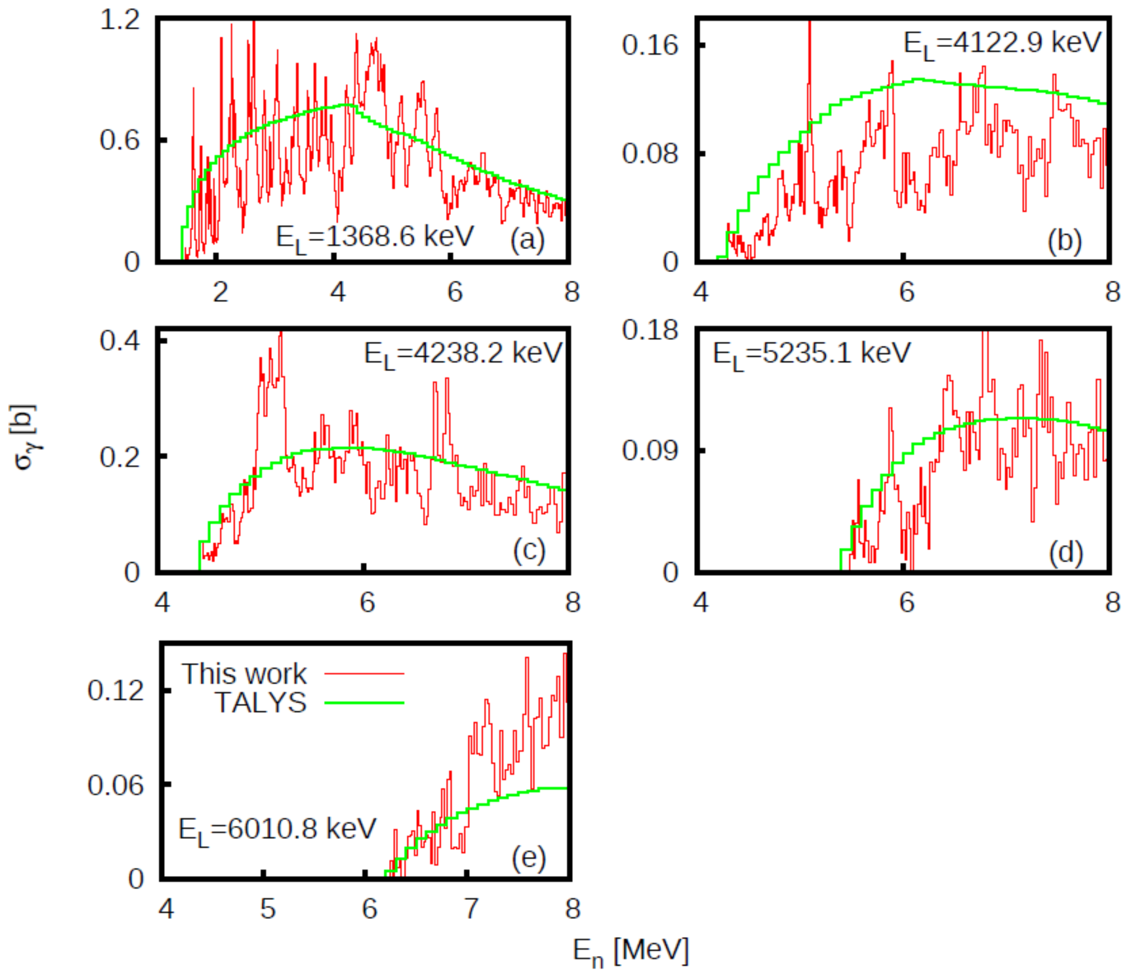


$^{24}Mg(n,n'g)$

A. Olacel et al., PRC, in print



Level cross sections



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^{24}Mg(n,n'g)

A. Olacel et al., PRC, in print

Level (keV)	Formula	Range (keV)
1368.7	$\sigma^{\gamma}_{1369}(E_n) - \sigma^{\gamma}_{2755}(E_n) - \sigma^{\gamma}_{2870}(E_n) - \sigma^{\gamma}_{3866}(E_n)$-$\sigma^{\gamma}_{4641}(E_n)$	1426.2 - 6703.0
4122.9	$\sigma^{\gamma}_{2755}(E_n) - 0.0164\sigma^{\gamma}_{4641}(E_n)$	4296.2 - 7936.7
4238.2	$1.267\sigma^{\gamma}_{4238}(E_n) - 0.027\sigma^{\gamma}_{3866}(E_n) - 0.11\sigma^{\gamma}_{4641}(E_n)$	4416.6 - 6703.0
5235.1	$1.027\sigma^{\gamma}_{3866}(E_n) - 0.015\sigma^{\gamma}_{4641}(E_n)$	5455.3 - 7936.8
6010.8	$1.142\sigma^{\gamma}_{4641}(E_n)$	6263.0 - 8140.7

TABLE IV. Theoretical level densities vs experimental level densities

E_n range (MeV)	Average E_n (MeV)	E*(^{25}Mg) (MeV)	J(^{25}Mg) (TALYS)	Theor. level density (MeV^{-1}) (BSFG)	Exp. level density(MeV^{-1})
1.73 - 2.78	2.26	9.5	1/2 - 5/2	19	18
2.78 - 3.82	3.30	10.5	1/2 - 7/2	36	18
3.82 - 4.87	4.34	11.5	1/2 - 7/2	53	10
4.87 - 5.91	5.39	12.5	1/2 - 7/2	79	13
5.91 - 6.95	6.43	13.5	1/2 - 9/2	132	11
6.95 - 7.99	7.47	14.5	1/2 - 9/2	191	10
7.99 - 9.03	8.51	15.5	1/2 - 9/2	275	8

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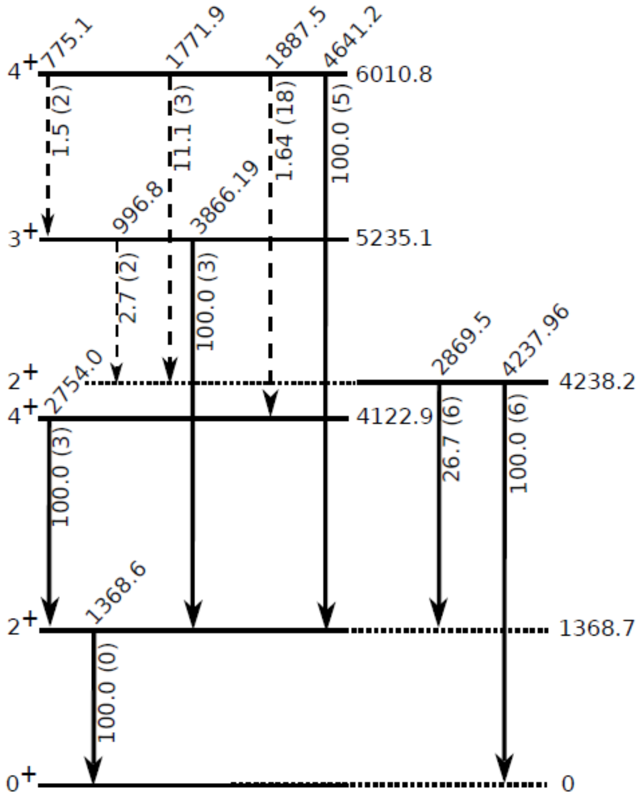
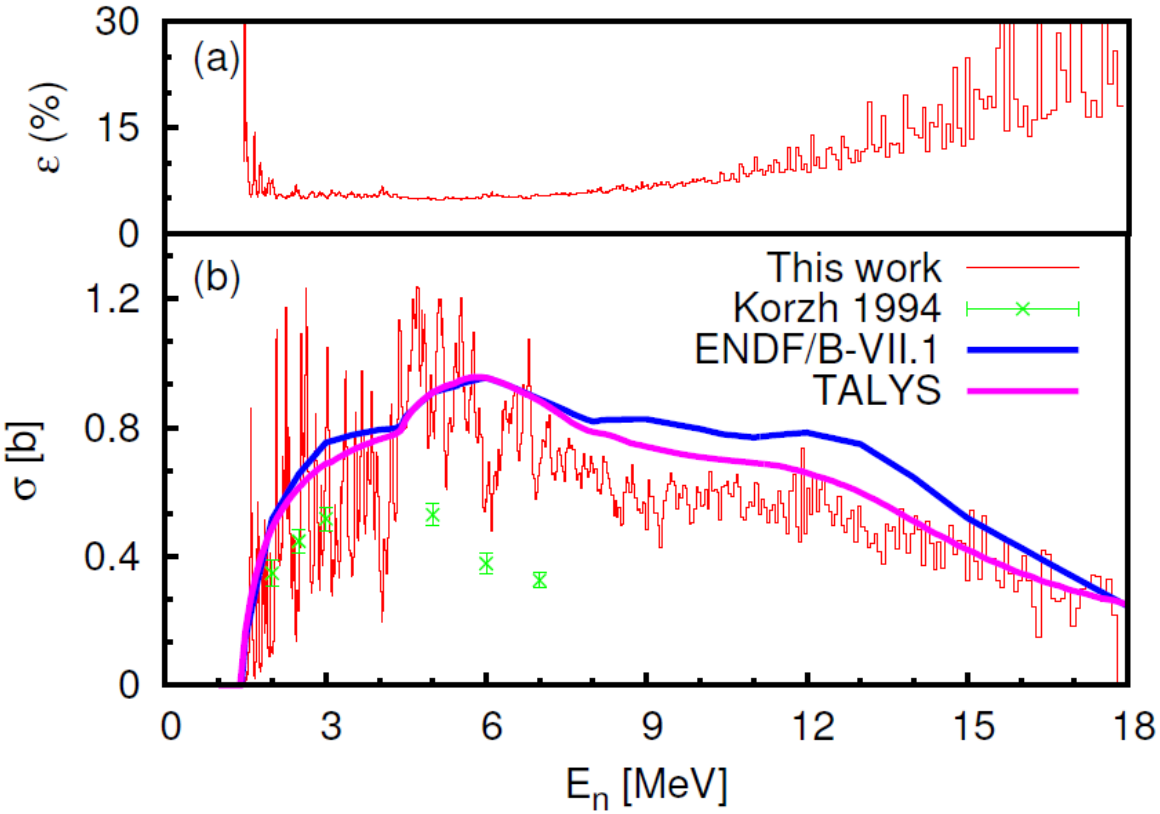
^{24}Mg(n,n'g)



Total inelastic cross section



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$^{7}Li(n,n'g)$
A possible γ-standard?

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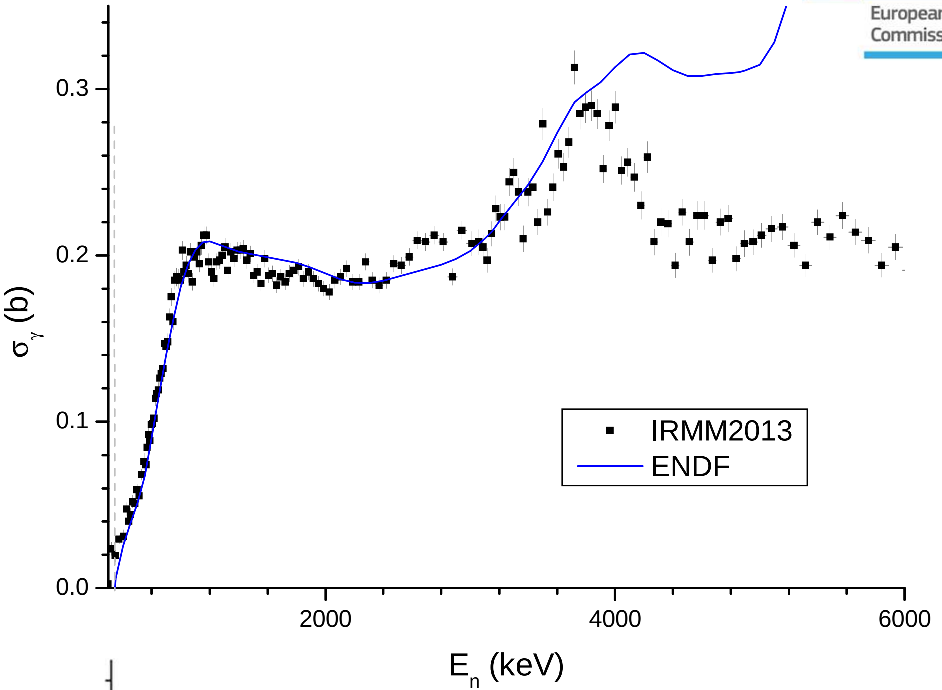

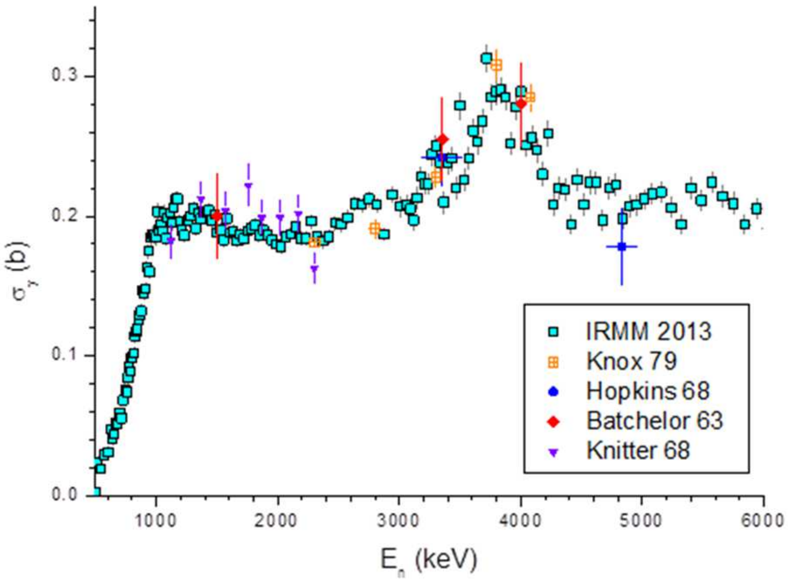

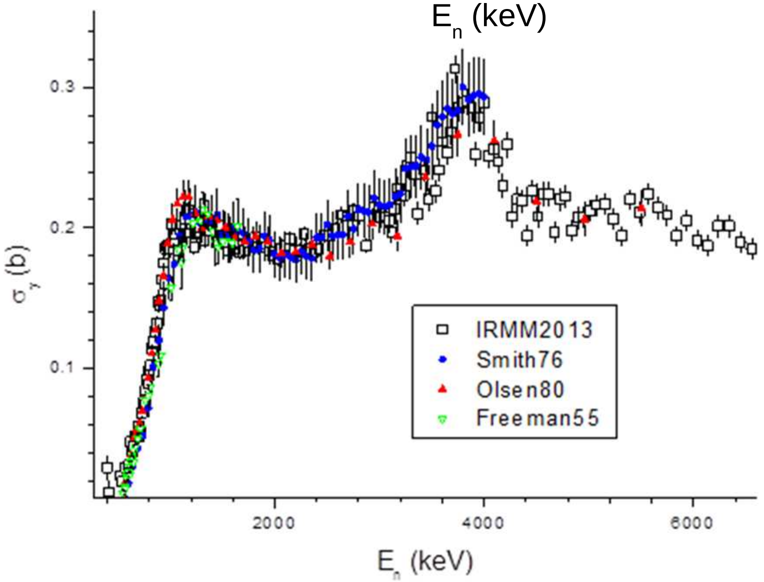

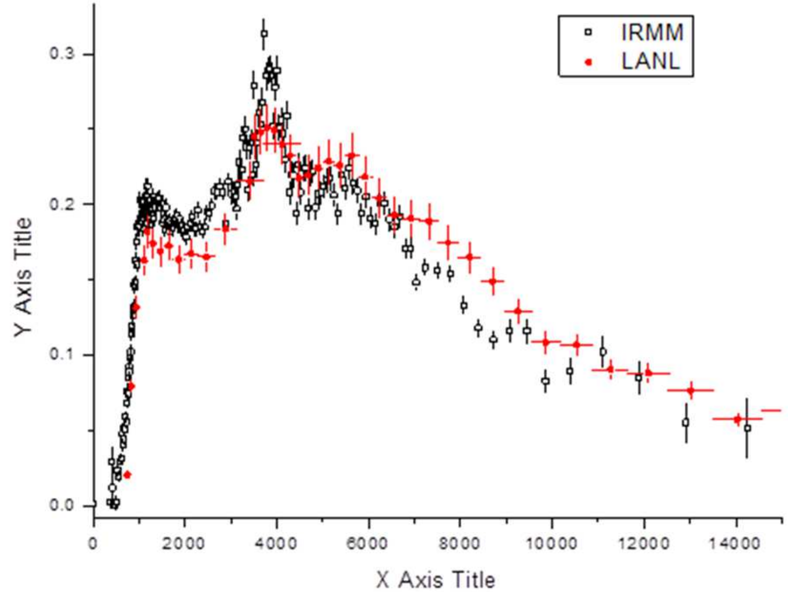

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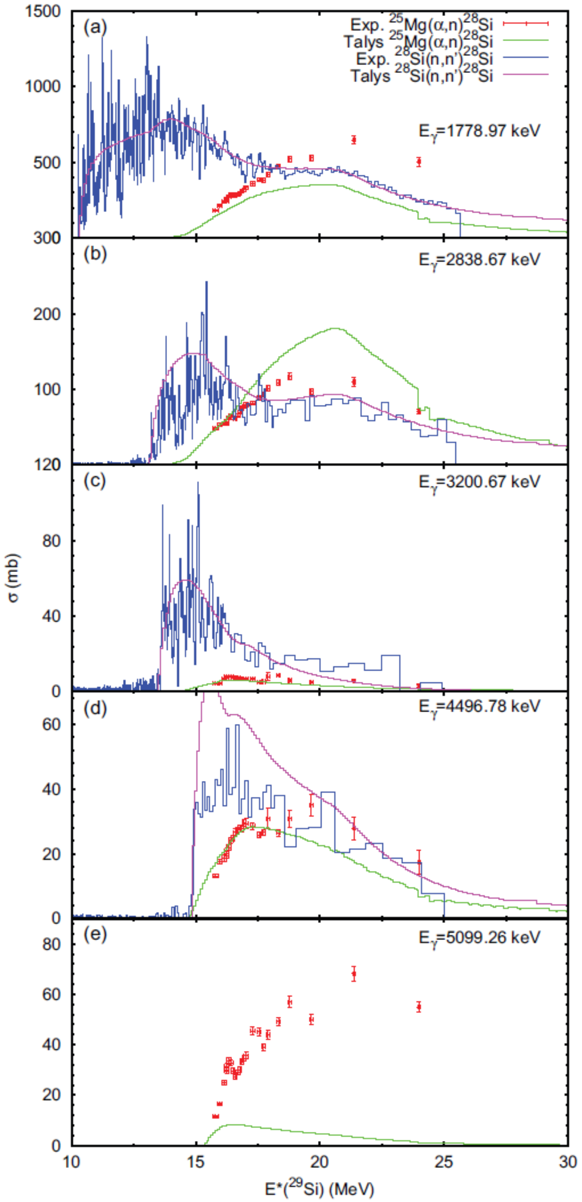
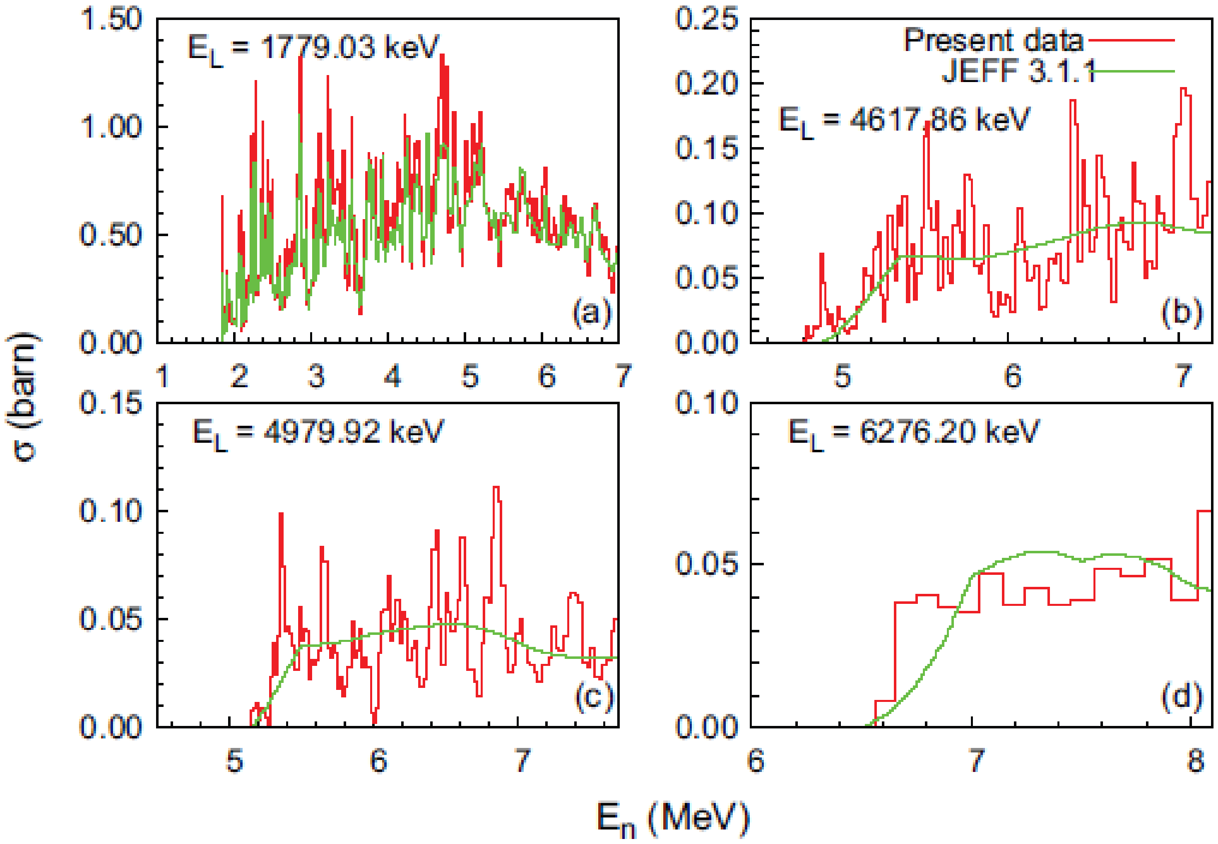
$^{28}Si(n,n'g)$ vs $^{25}Mg(a,ng)$

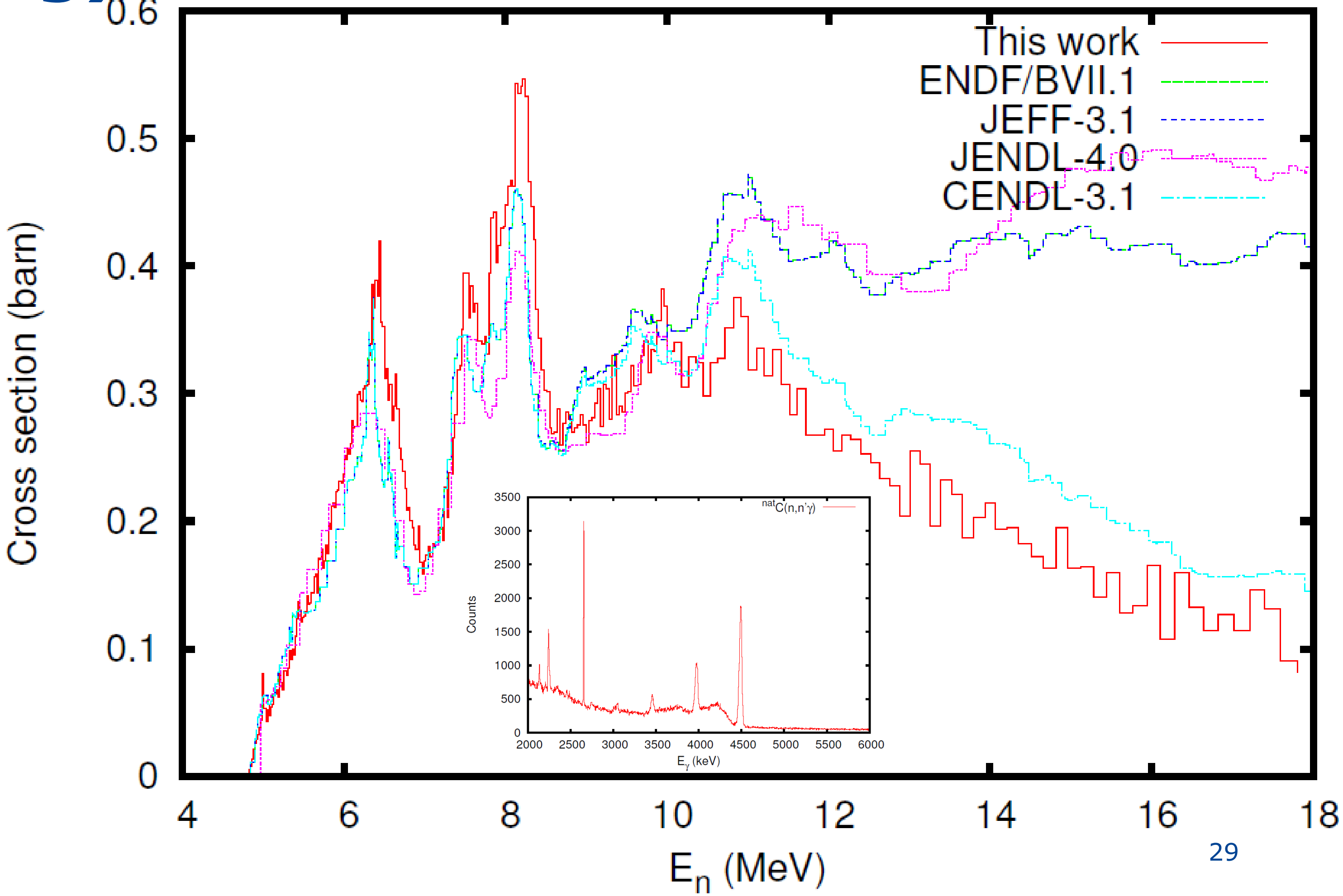




A. Negret et al. Phys. Rev. C 88 (2013) 034604

$^{12}C(n,n'g)$

A. Negret et al. NDS…(2014)…
ND2013, only one gamma-ray 4439 keV)



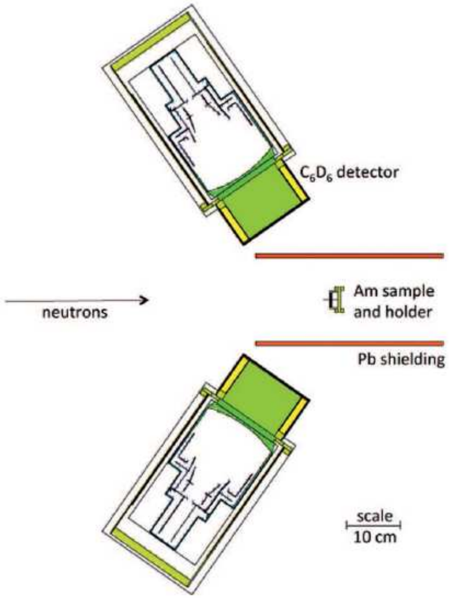
European Commission

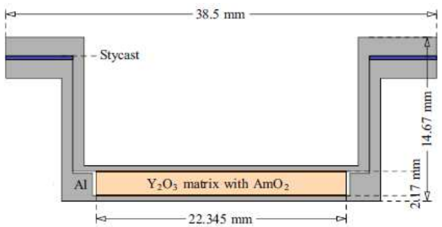
$^{241}Am(n,\gamma)^{242}Am$

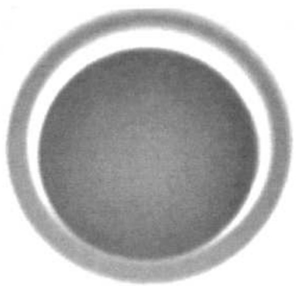
C. Lampoudis et al. EPJ Plus 128(2013)86

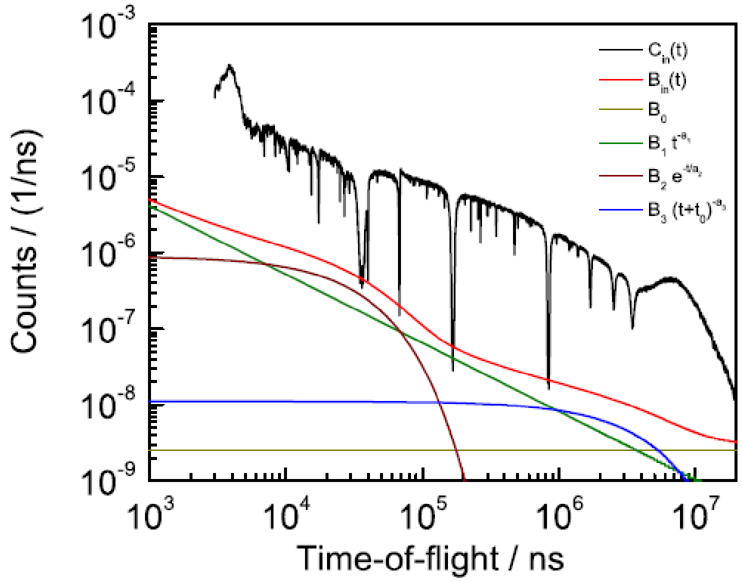
Capture and transmission

324.6(1.2) g 241Am (nano particles AmO_2 in 3g Y_2O_3)
22.345(30) mm diameter
2.068(10) 10^{-4} atoms/b





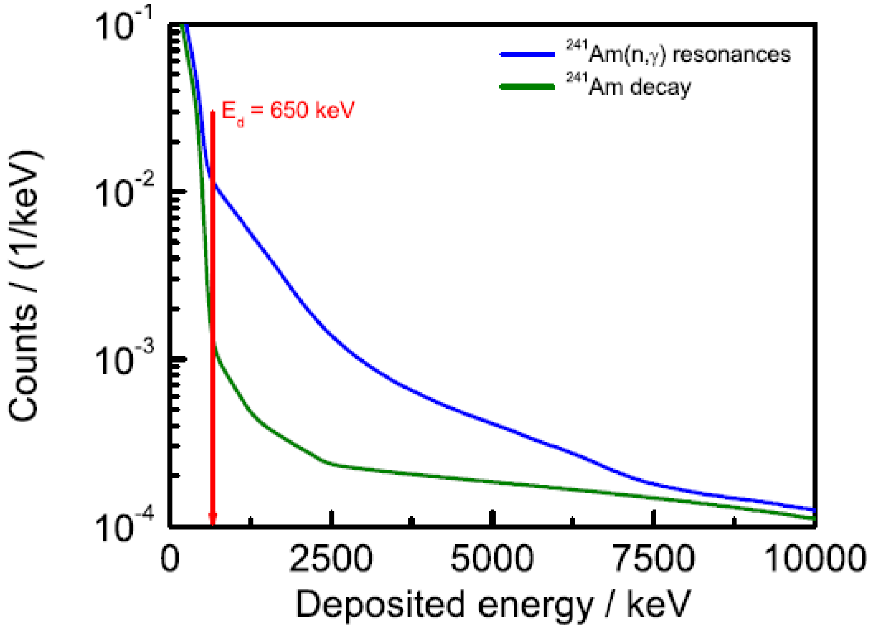


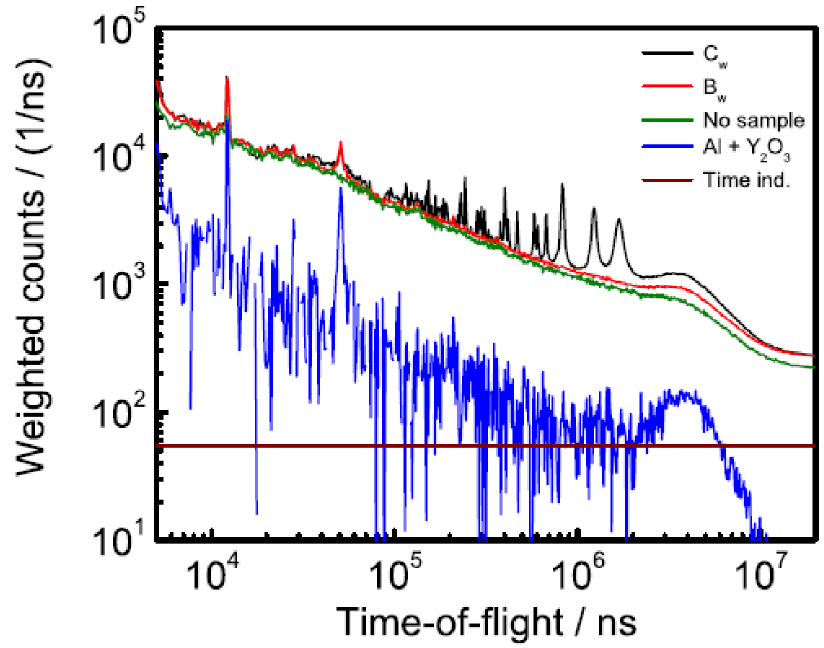


$^{241}Am(n,\gamma)^{242}Am$

C. Lampoudis et al. EPJ Plus 128(2013)86

Capture

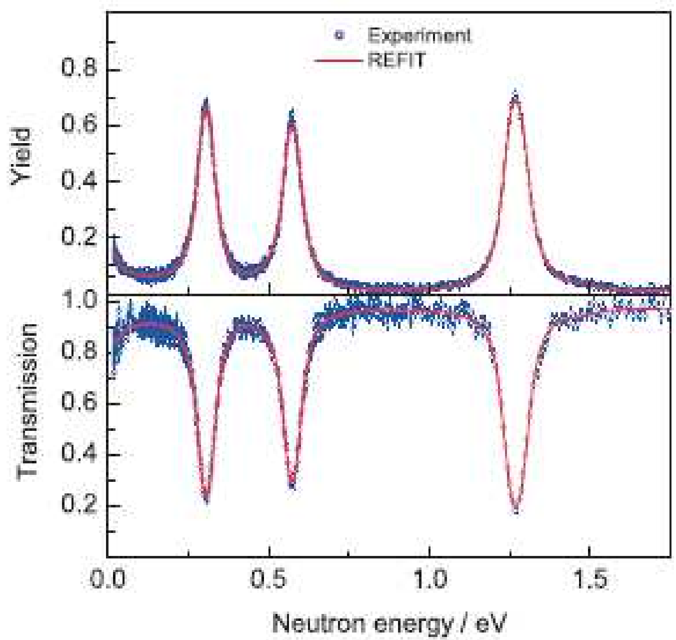


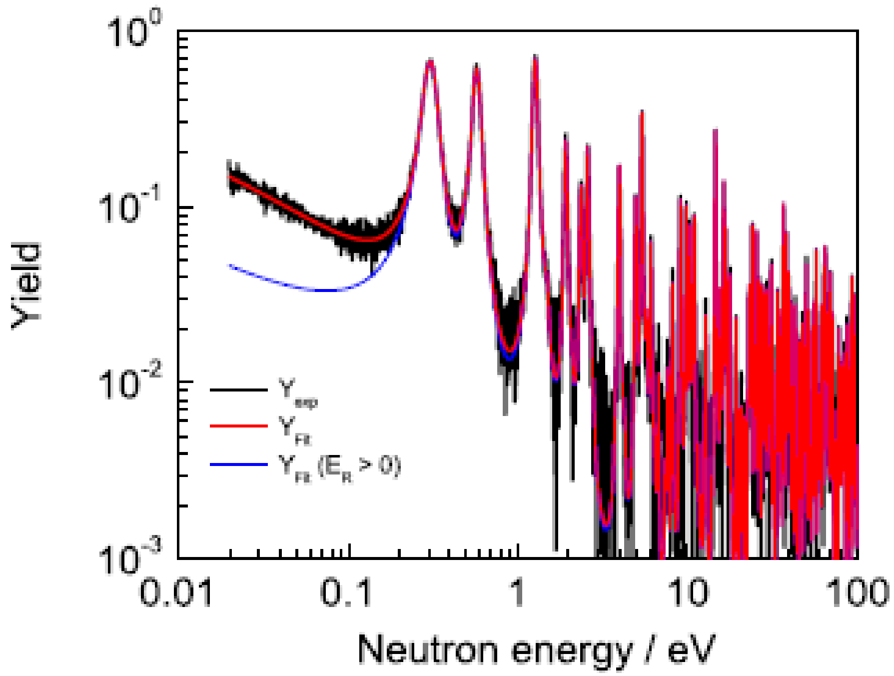


$^{241}Am(n,\gamma)^{242}Am$

C. Lampoudis et al. EPJ Plus 128(2013)86

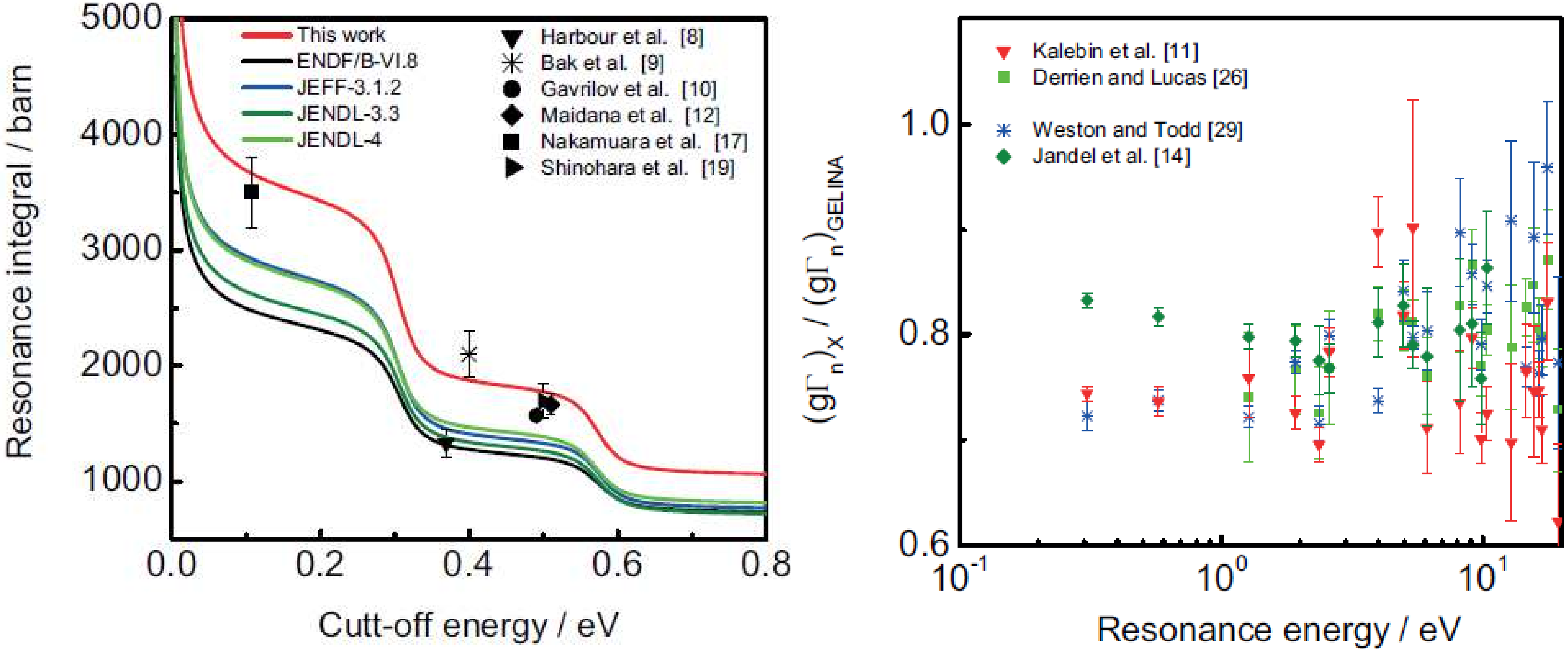
Capture and transmission





$^{241}Am(n,\gamma)^{242}Am$

C. Lampoudis et al. EPJ Plus 128(2013)86



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$^{241}Am(n,\gamma)^{242}Am$

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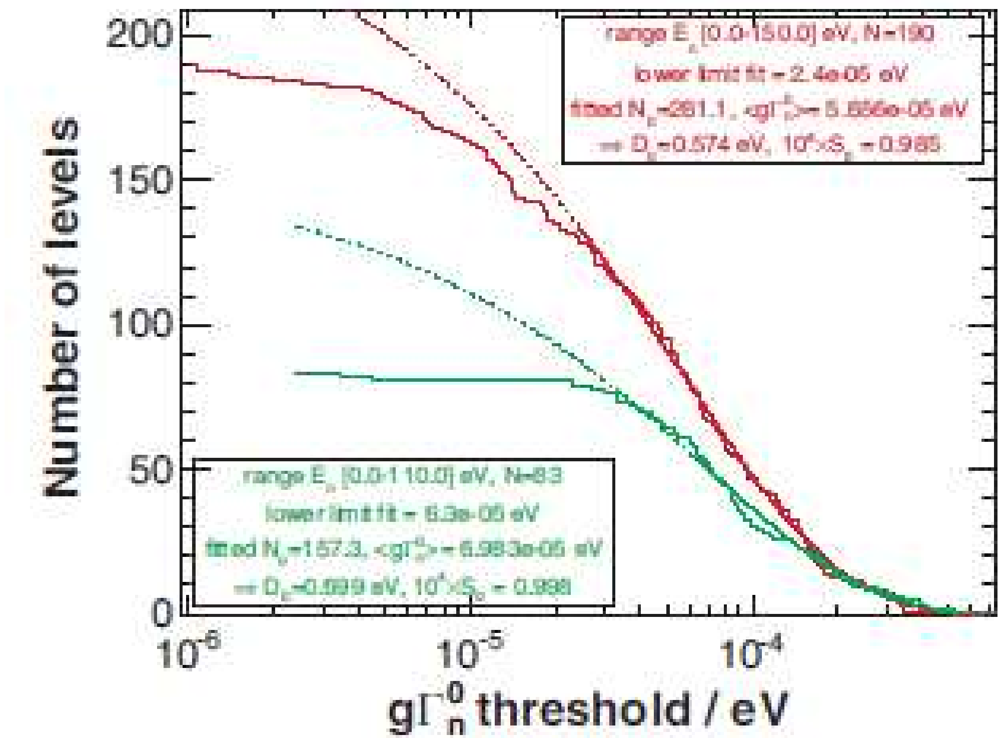
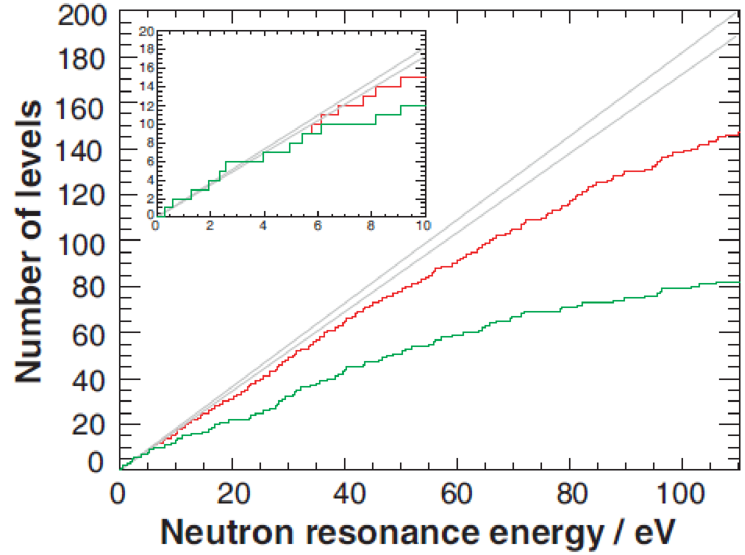
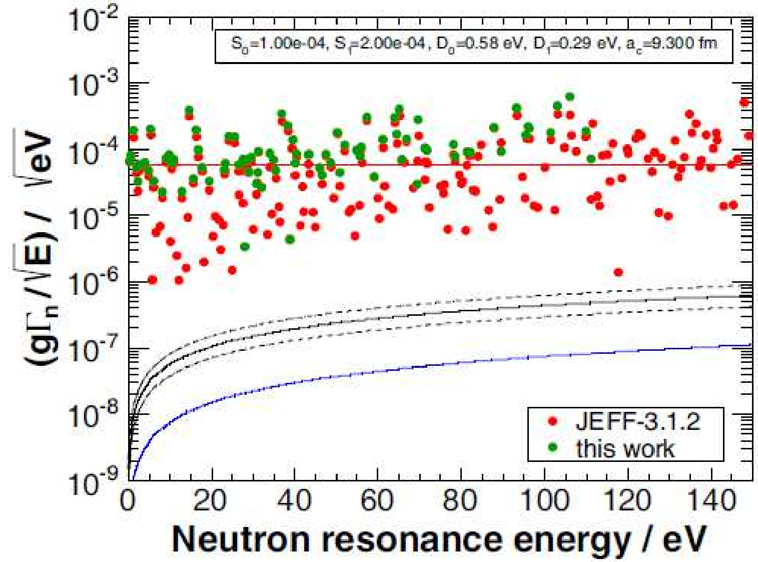


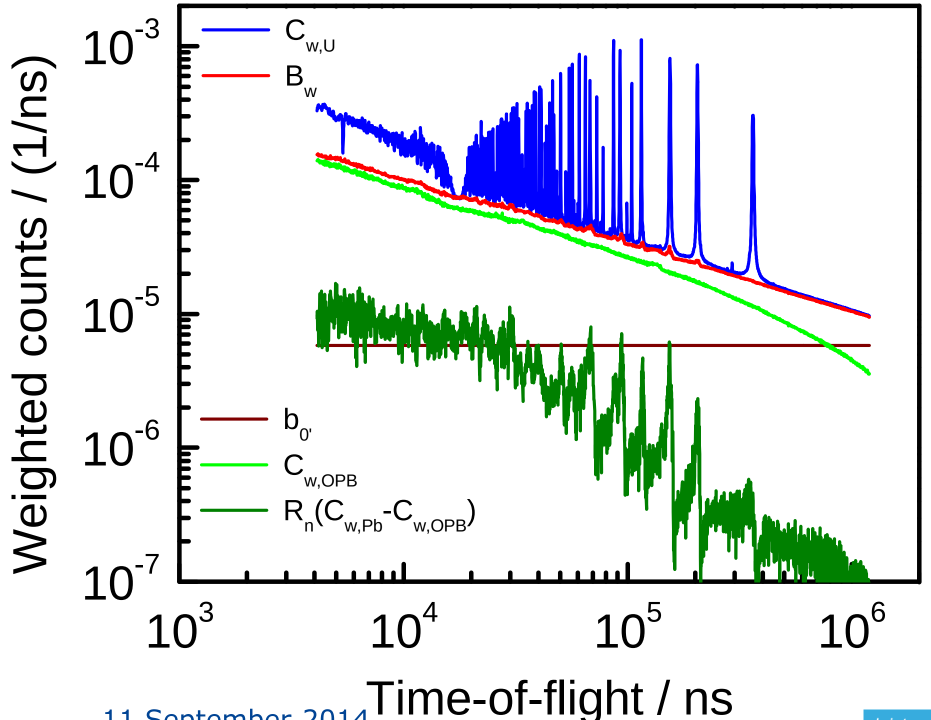


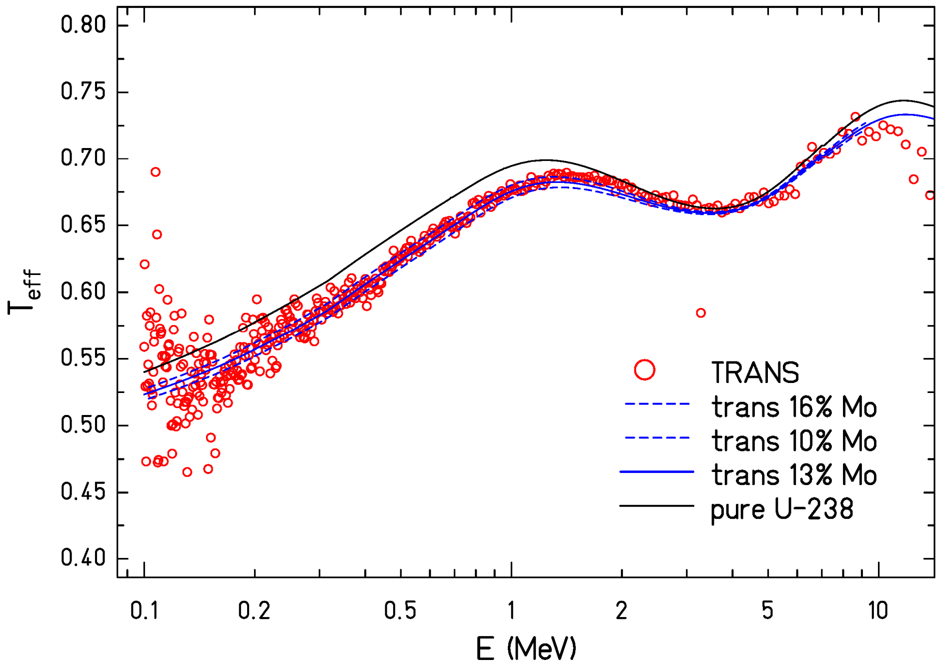


Joint Research Centre

$^{238}U(n,\gamma)$ and (n,tot)

Can we get it down to 2% in the unresolved and fast energy resonance range?
Collaboration with A. Junghans (nELBE) for tranmsission

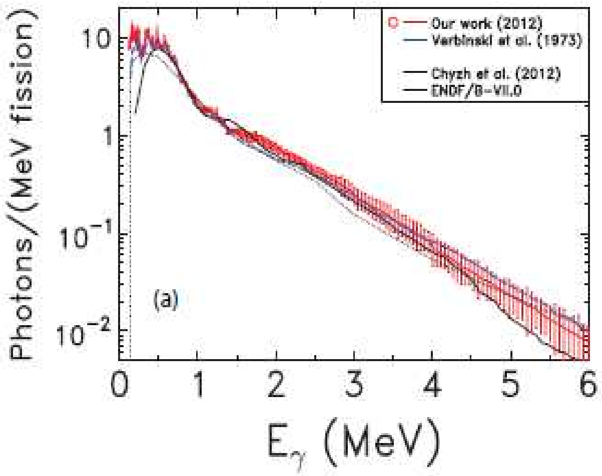


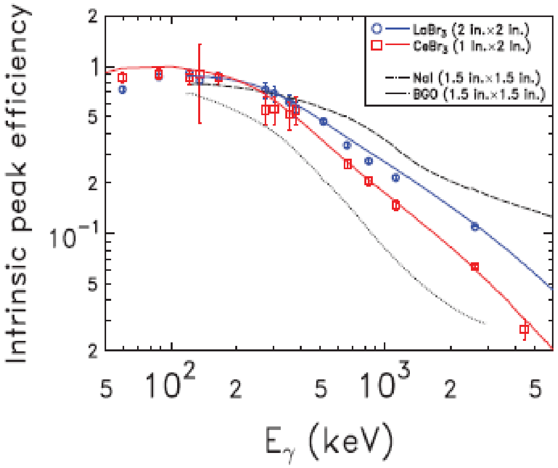


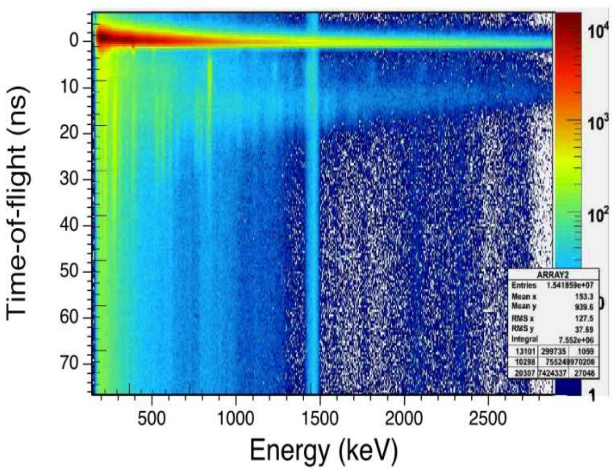
Prompt fission gammas

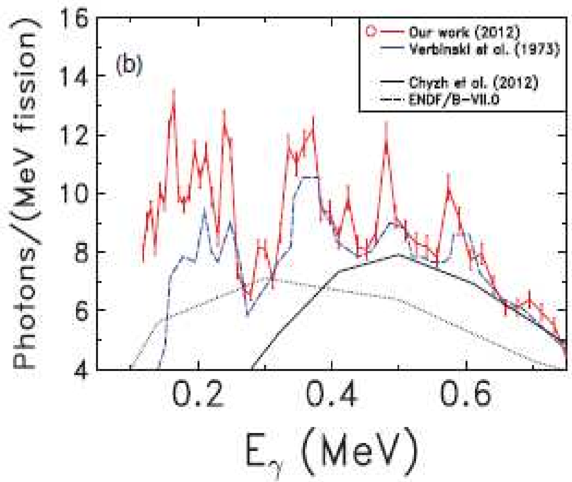
European Commission

New gamma-ray detectors: $LaBr_3$, LaC
Testing and characterisation
First demonstration ^{252}Cf
Ongoing/nearly completed ^{235}U
TOF, FIC vs gamma detector
Neutron-gamma separation





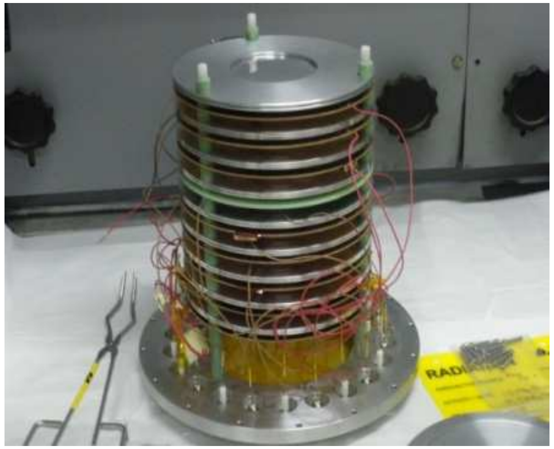


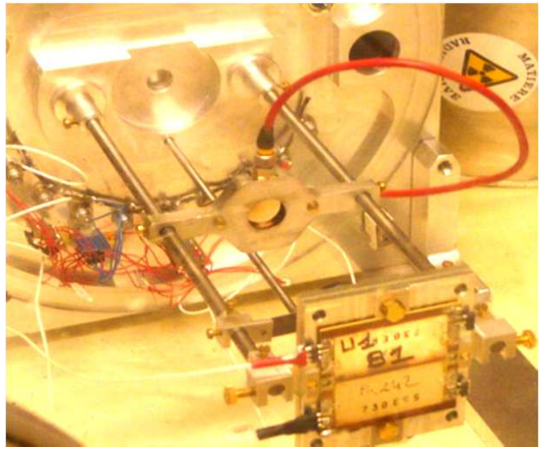


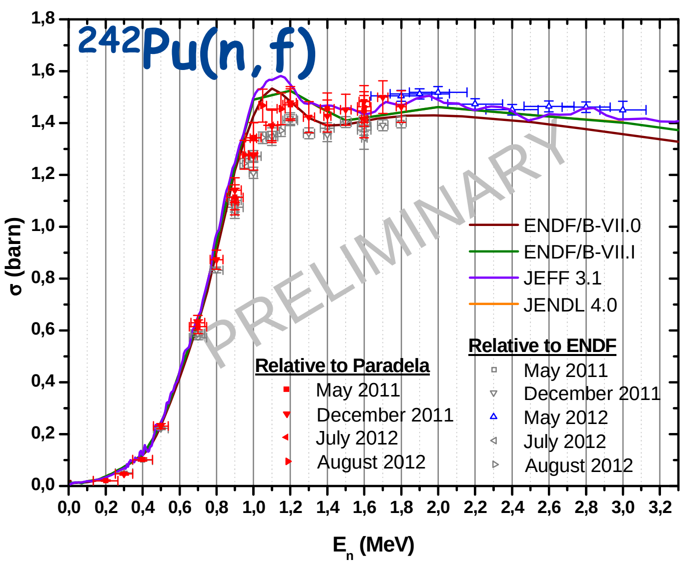
PRC87(2013)024601 Billnert et al.

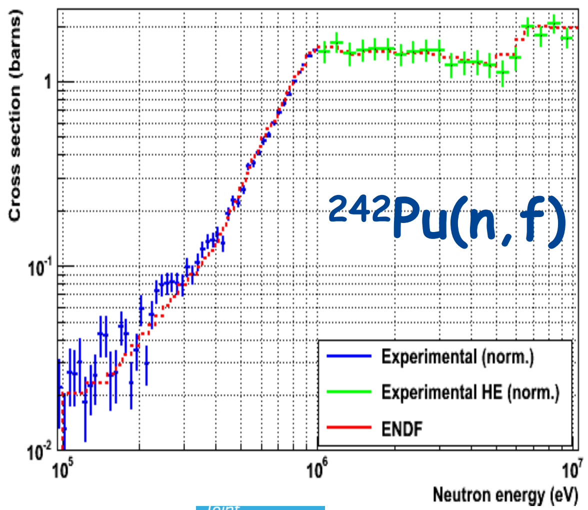
IRMM and EU experiments
^{240,242}Pu(n,f) cross sections

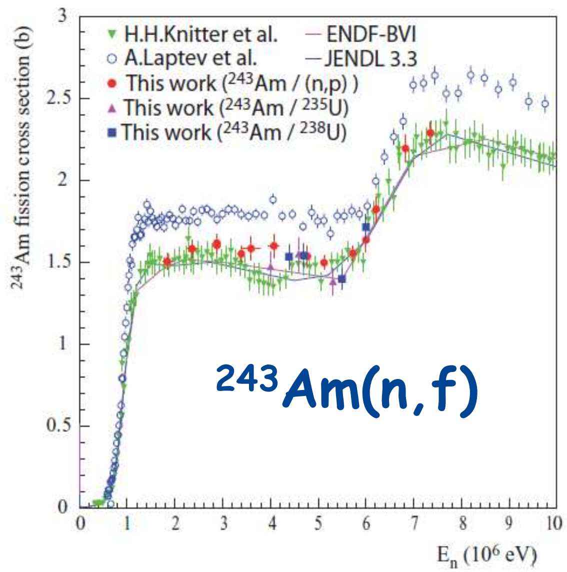
IRMM	CERN	CENBG











European Commission

Summary

Overview was presented of recent results for inelastic scattering obtained at IRMM with collaborators from IFIN-HH, CNRS/IPHC and TUD.

Recent achievements for capture and transmission of ^{241}Am were shown along with ongoing work for the capture and transmission of ^{238}U, involving nELBE.

JRC-Geel/IRMM has an active program of cross section measurements and reaction parameter determinations for nuclear energy applications, embedded in European and international collaborations.

Prioritization is important in view of the available resources: NEA High priority request list for nuclear data.

Brugge – Bruges, West Flanders, Belgium

ND2016

Oud Sint Jan or St Janshospitaal

Organized by IRMM

W. Mondelaers, A. Plompen,

F.-J. Hambsch, P. Schillebeeckx