The European Commission's science and knowledge service

Joint Research Centre

European Commission

Nuclear Data

Arjan Plompen

Ecole Joliot Curie, 26 and 27 September 2019, Ile d'Oleron, France

European
Commission

Contents

- Introduction to nuclear research at the European Commission
- Introduction to nuclear data (1st hour)
- Measurements and experiments (2nd hour)
- Modeling and evaluation (3rd hour)

Introduction to nuclear data

- Fields of use.
- How are they used?
- Where do I find nuclear data?

Measurements and experiments

- Reaction data (emphasis)
  - Transmission
  - Capture
  - Fission
  - Scattering
- Structure and decay data
  - Half life
  - Emission probabilities
- Uncertainty in measurements
  - Measurement model
  - Guide to the expression of uncertainty

Modeling and evaluation

- Nuclear reaction modeling
  - Hauser-Feshbach-Moldauer
  - R-matrix
- The JEFF-3.3 evaluation

Nuclear research
European Commission, JRC Geel

The Treaty of Rome

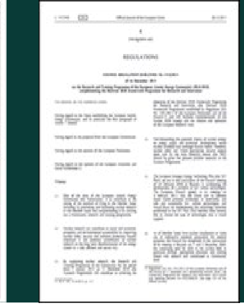
- Treaty establishing The European Atomic Energy Community (EURATOM)

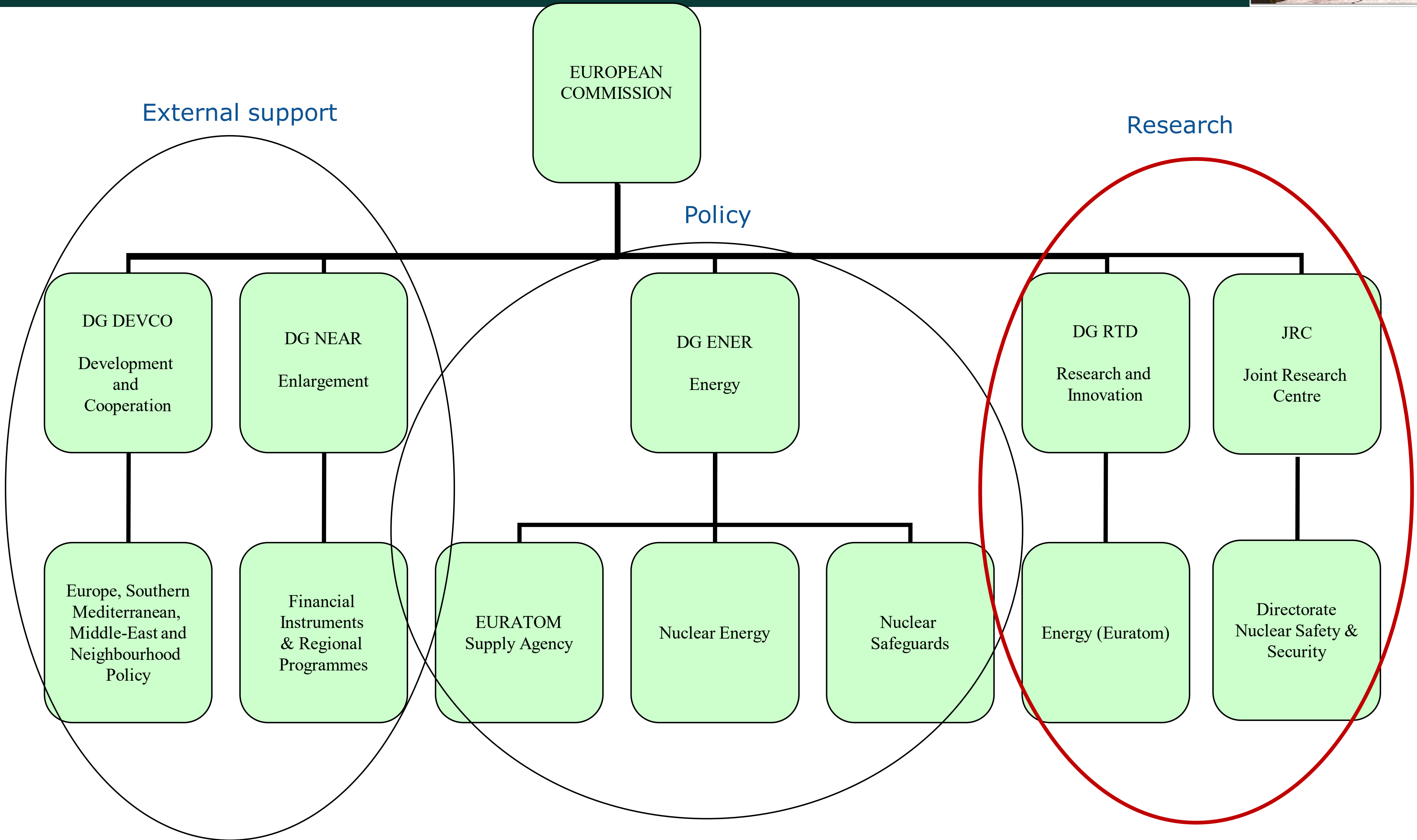
  25 March 1957

- Consolidated version
  26 October 2012,

  Official Journal of the European Union C 327/01

EURATOM structure





EUROPEAN COMMISSION

External support

- DG DEVCO – Development and Cooperation
  - Europe, Southern Mediterranean, Middle-East and Neighbourhood Policy
- DG NEAR – Enlargement
  - Financial Instruments & Regional Programmes

Policy

- DG ENER – Energy
  - EURATOM Supply Agency
  - Nuclear Energy
  - Nuclear Safeguards

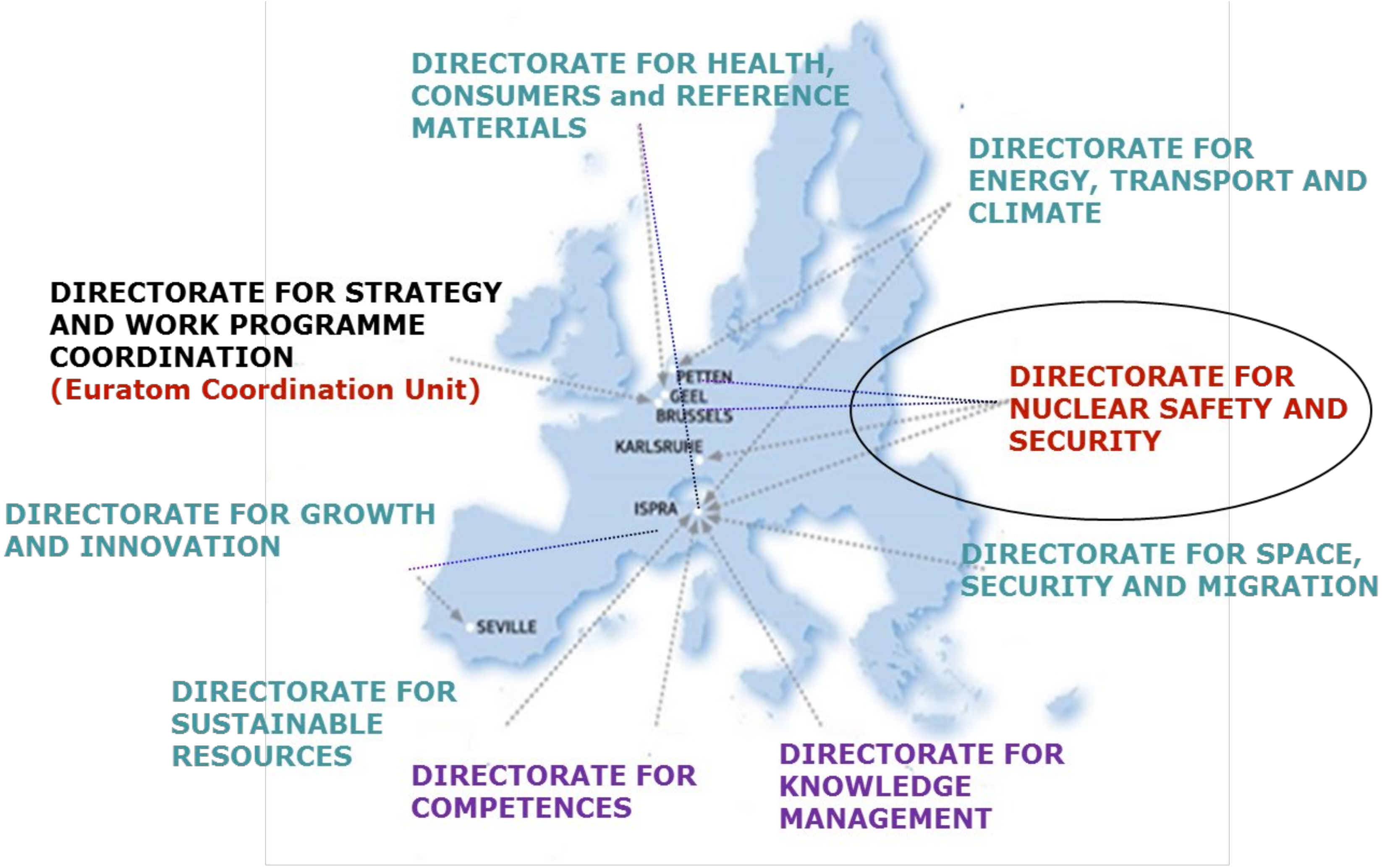
Research

- DG RTD – Research and Innovation
  - Energy (Euratom)
- JRC – Joint Research Centre
  - Directorate Nuclear Safety & Security

European Commission

Joint Research Centre

The European Commission's in-house scientific service



DIRECTORATE FOR HEALTH, CONSUMERS and REFERENCE MATERIALS

DIRECTORATE FOR ENERGY, TRANSPORT AND CLIMATE

DIRECTORATE FOR STRATEGY AND WORK PROGRAMME COORDINATION
(Euratom Coordination Unit)

DIRECTORATE FOR NUCLEAR SAFETY AND SECURITY

DIRECTORATE FOR GROWTH AND INNOVATION

DIRECTORATE FOR SPACE, SECURITY AND MIGRATION

DIRECTORATE FOR SUSTAINABLE RESOURCES

DIRECTORATE FOR COMPETENCES

DIRECTORATE FOR KNOWLEDGE MANAGEMENT

DIRECTORATE FOR RESOURCES

Directorate G – Nuclear Safety and Security

Vision

The JRC EURATOM Research, Development and Training programme will enhance the interface between science, policy and society while keeping the highest standards of its scientific output.

Societal challenges

- *Protecting Society*
- *Fostering Sustainability and Decarbonisation*
- *Promoting Reversibility: back to the green field*
- *Strengthening Global Partnership*
- *Broadening Knowledge and Competence*

Safety of Current and Innovative Systems

- Long-term Operation and Operational Safety
  Fuels and Materials for Gen II and III reactors
  Reactor Design Extension Conditions Modelling and Assessment
- Safety of Advanced Nuclear Systems and Innovative Fuel Cycles
  System Analysis of Emerging Technologies
- Knowledge for nuclear Safety and Policy Support

Security, Safeguards and non-proliferation

- Innovative and Remote Safeguards
  Enhanced Nuclear Materials Measurements
- Methods, Data and knowledge management for Nuclear Non-Proliferation, Safeguard and Security
  Strategic Trade Control
- Nuclear Forensics and Detection of Illicit Trafficking of Nuclear and (other) Radioactive Materials
  CBRNEsec

Decommissioning, Environmental Remediation and Waste management

- Decommissioning and remediation of Damaged Reactors: their cores and sites
  Innovative Techniques/Technologies and standardisation of Practice
- Safety of spent and damaged fuel
  Waste from innovative fuel
- Managing Decommissioning and Waste Management Knowledge

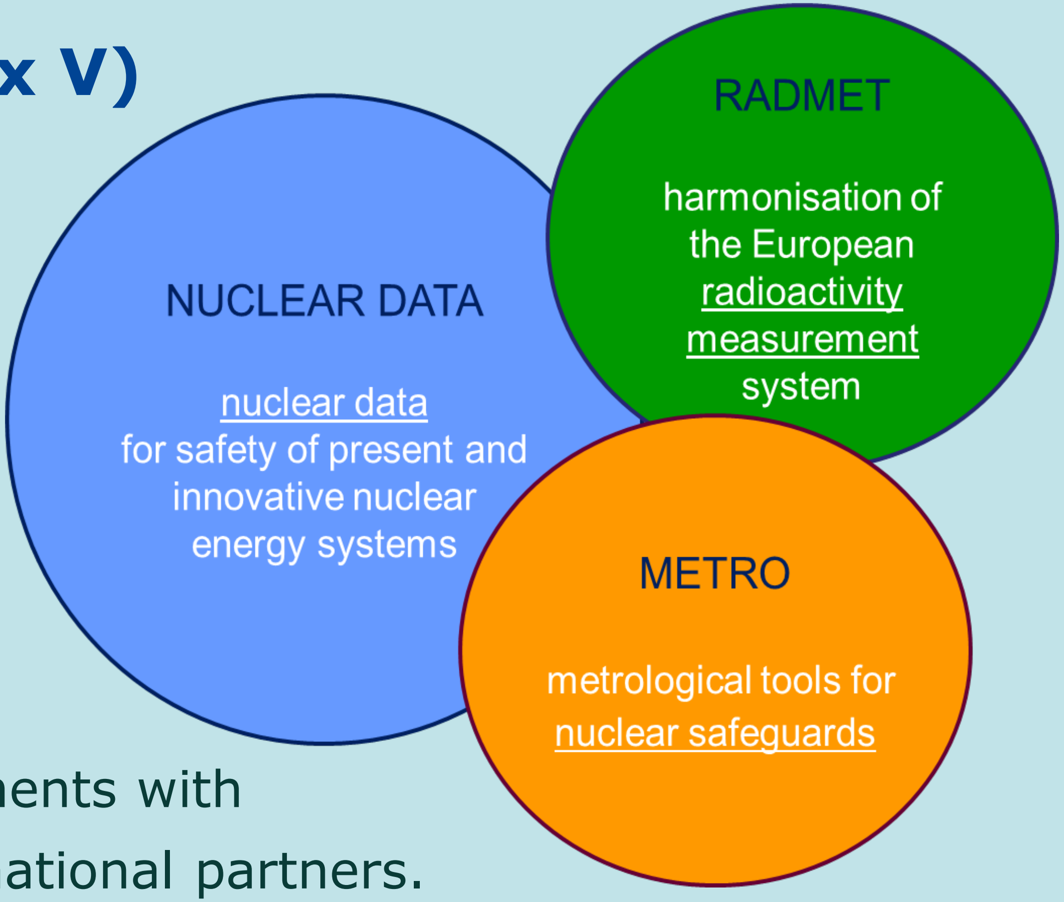
Nuclear Science Applications

- Basic properties of radionuclides and associated applications
- Accelerator based nuclear data measurements and associated applications

Unit G.2
Standards for nuclear safety, security and safeguards

EURATOM Treaty (Art.8 and Annex V)

JRC "shall include a
central bureau for nuclear measurements
specialising in
- nuclear measurements for isotope analysis
- and absolute measurements of radiation
- and neutron absorption".



RADMET

harmonisation of the European radioactivity measurement system

NUCLEAR DATA

nuclear data for safety of present and innovative nuclear energy systems

METRO

metrological tools for nuclear safeguards

A solid basis for contemporary engagements with the institutions, member states & international partners.

CBNM (1960)

European Commission

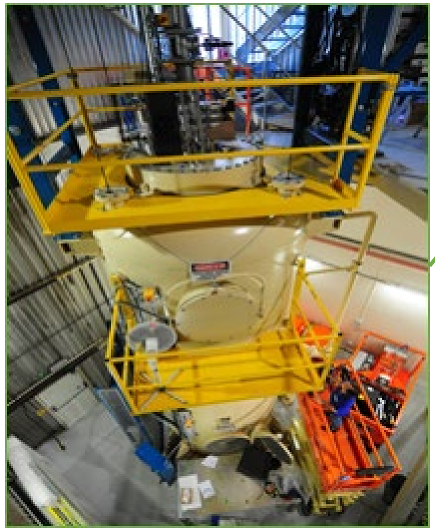
What do we work for?

- Nuclear science and technology applications to interests of a modern society
  - Main concerns: Nuclear safety and security & Climate change
  - Examples of spin offs: Medical applications & Cultural heritage
- A bright, safe, secure and healthy Europe – citizen well-being
- Working for and with Member States, Directorates General, partners – co-design
- An open, accountable, innovative & modern JRC
  - JRC Open Access to Research Infrastructure
  - Education and Training
  - Standardization
  - Exploratory Research

Nuclear facilities of JRC-Geel

GELINA

MONNET



NUCLEAR DATA

nuclear data
for safety of present and
innovative nuclear
energy systems

RADMET

harmonisation of
the European
radioactivity
measurement
system

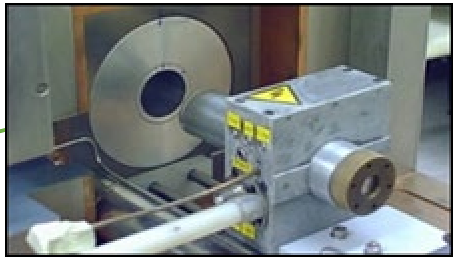
METRO

metrological tools for
nuclear safeguards

TARGET

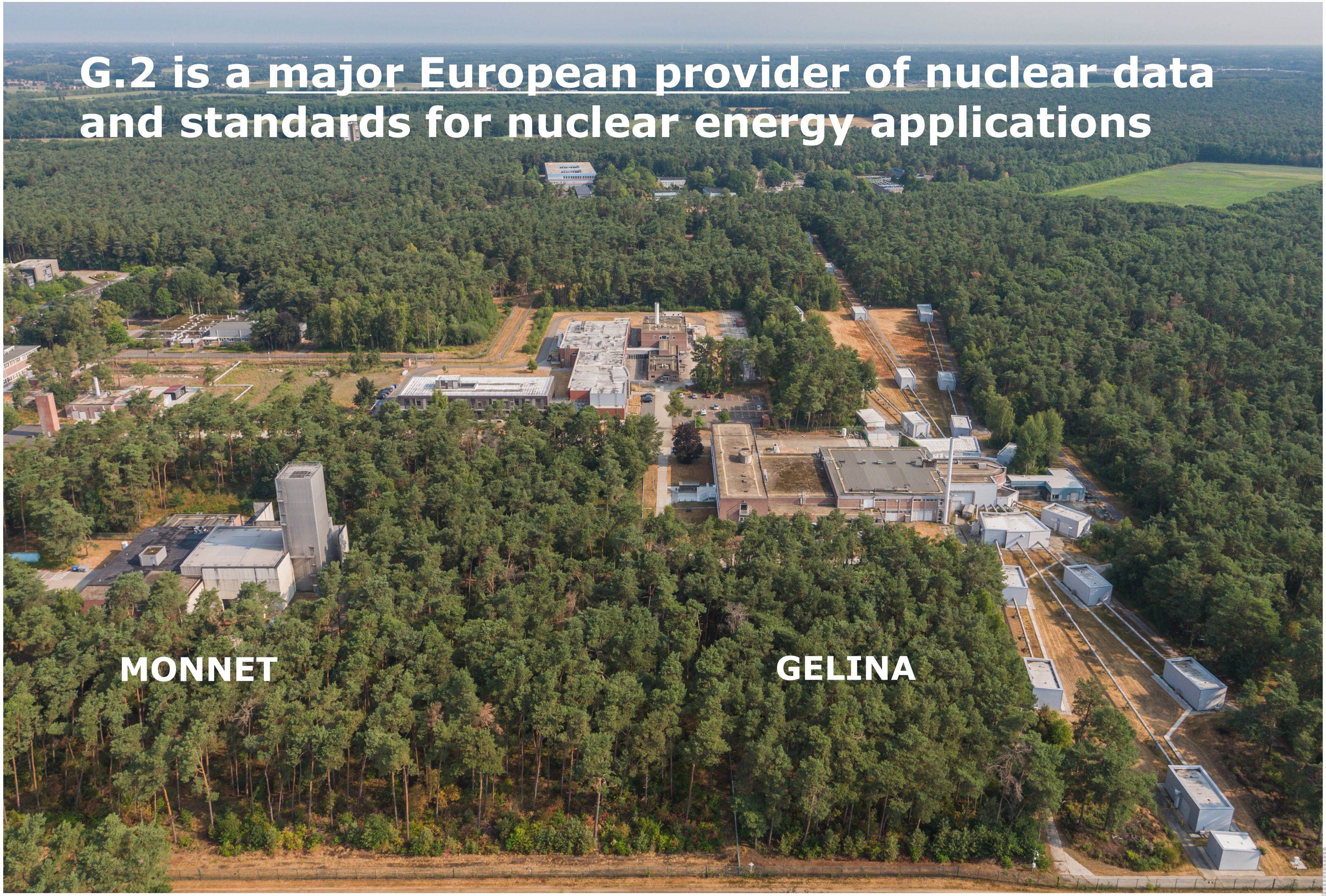
METRO

RADMET



HADES

G.2 is a major European provider of nuclear data and standards for nuclear energy applications



For and with

Member States,

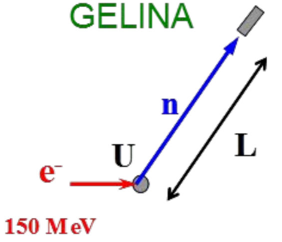
OECD-NEA
IAEA

International
partners

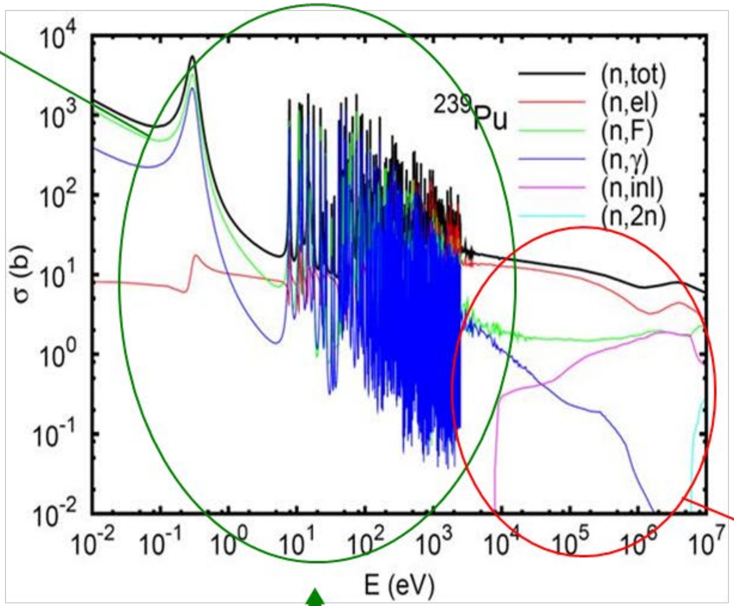
GELINA and MONNET accelerator laboratories

Time-of-flight measurements

GELINA



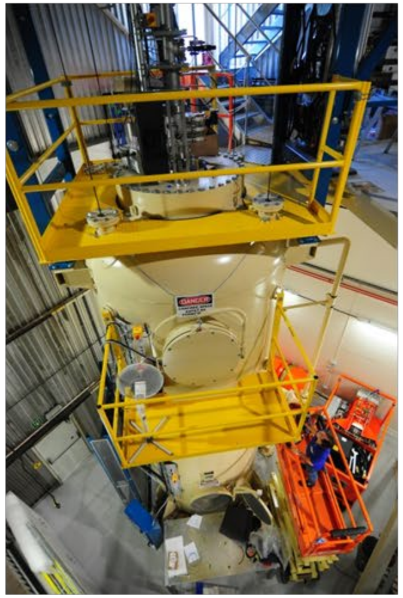
$$E = \frac{1}{2}mv^2 \propto \left(\frac{L}{T}\right)^2$$

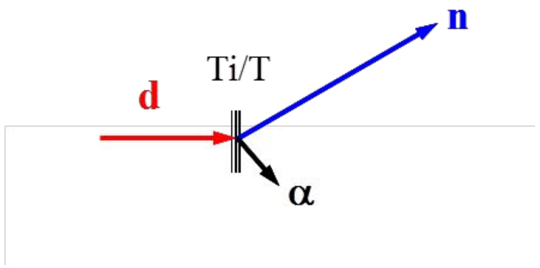


energy resolution

Mono-energetic neutron beams

MONNET





Nuclear science applications

- Nuclear data research
- Non-destructive analysis
- Neutron and photon transport
- Detector characterisation
- Dosimetry
- Material science
- Medical applications
- Basic physics (fission, astrophysics, …)

- Cross-cutting disciplines

Challenge: Climate Change - carbon free energy

Nuclear energy can be an important component in the mix

2016	CO2	CO2-free	Nuclear	Bio+waste
world	81%	19%	5%	10%
EU 28	72%	**28%**	14%	10%
Belgium	71%	29%	20%	7%
France	47%	**53%**	42%	7%
Germany	79%	21%	7%	10%
Sweden	29%	**71%**	33%	25%

Countries with a high percentage CO_2-free energy use (nuclear) electricity for heating.

Still a lot to do for CO_2-free transport.

Data International Energy Agency, Total primary energy supply

Challenges for nuclear energy

- Cost of construction
- Perception of risk & public opinion

  Legacy of major accidents, Fukushima and Chernobyl, and the shadow they project over the future.
- Communication in a difficult era

European Commission

Challenge: Climate Change - carbon free energy

Nuclear energy can be an important component in the mix

CO_2 reduction
- 2020-target -20%
- 2030-target -40%

Public IEA data

region	1990 Mt CO2	2016 Mt CO2	2016/1990	reduction	2017 population	2017 Mt/Mh
world	**20518**	**32316**	**1.6**	**-58%**	**7.7E+09**	**4.2**
EU28	**4027**	**3192**	**0.79**	**21%**	**5.1E+08**	**6.2**
Sweden	52	38	0.73	27%	1.0E+07	3.8
France	346	293	0.85	15%	6.7E+07	4.4
Switzerland	41	38	0.93	7%	8.5E+06	4.5
United Kingdom	549	371	0.68	32%	6.6E+07	5.6
Belgium	106	92	0.87	13%	1.1E+07	8.1
Germany	940	731	0.78	22%	8.3E+07	8.9
Netherlands	148	157	1.1	-6%	1.7E+07	9.2
United States	4803	4833	1.0	-1%	3.3E+08	14.8
China	2122	9102	4.3	-329%	1.4E+09	6.6

Introduction to nuclear data

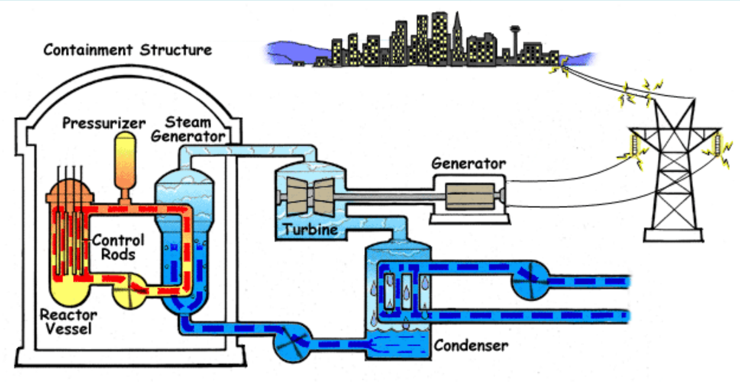
- Fields of use.
- How are they used?
- Where do I find nuclear data?

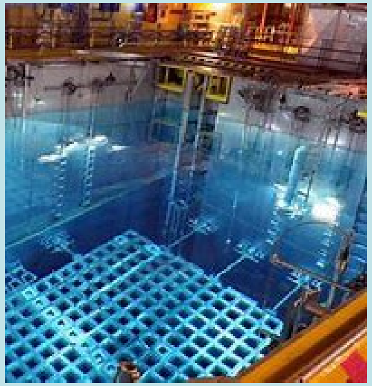
Nuclear data and applications

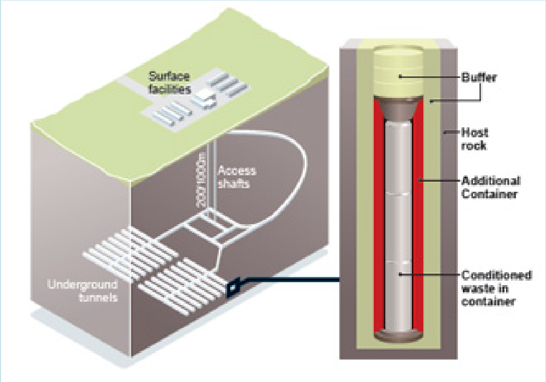
JEFF project: Towards a general-purpose library

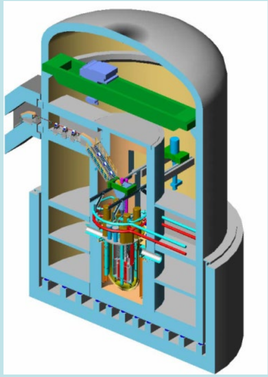
Applications: fission and fusion, radiation protection, nuclear medicine, (nuclear) security, object and materials analysis

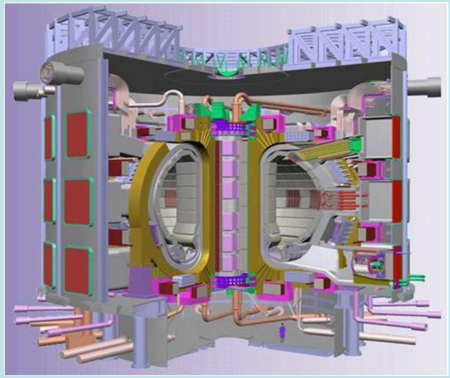
Science: reactions and structure of nuclei, astrophysics, basic physics

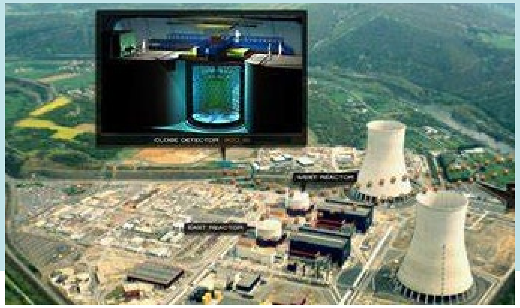


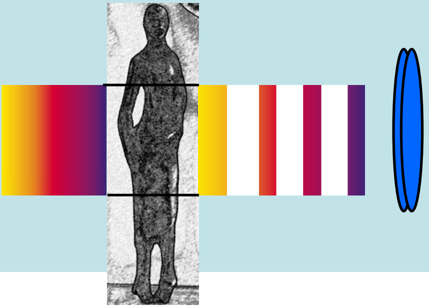


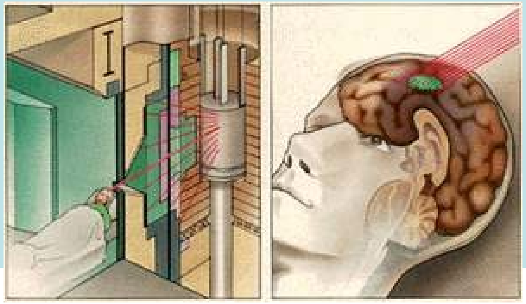












Nuclear data and modeling

Boltzmann and Bateman equations: Neutron transport and reactions and inventory evolution.

Others: photon transport, heating, charged particle induced reactions at accelerators, radioactivity, nuclear structure and decay

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

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

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

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

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

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

- **Source terms**

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

- **Safety margins**

Reactivity, power distribution, reactivity coefficients, burnup/time to refuel, enrichment, shielding, spent fuel storage, …

- **Planning and interpretation**

Limits to learning from expensive integral experiments (cost reduction in development)

Nuclear data in modeling

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

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

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

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

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

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

- **Cross sections**
  - Total cross section
  - Scattering & reaction cross sections
  - Fission, capture, (n,xn), (n,xp), (n,xa), …
  - (double) differential cross sections

  - Neutron-induced (reactors, fuel cycle)
  - Photon induced (reactors & accelerators)
  - Charged-particle induced (accelerators)
- **Parameters characterizing reactions**
  - Yields: neutron, photons, fission fragments, ...
  - Resonance parameters: energy, widths, …

Nuclear data in modeling

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

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

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

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

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

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

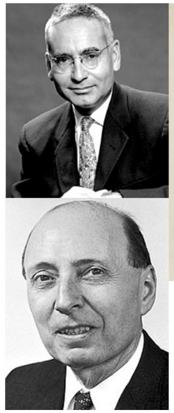
- **Structure and Decay data**
  - Level structure of a nucleus
  - Half life of the levels (including ground state)
  - Type of decay for each level
  - Branching ratios
  - Emission probabilities
  - Emission spectra
  - Conversion factors

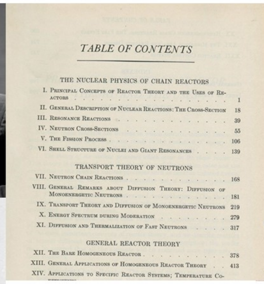
Modeling for cost reduction

- Reliable predictions with credible uncertainty margins.
- We are a far cry from that in the nuclear field
- Lots of expert judgement and ad-hoc methods and codes.
- Lots of tests needed for innovative ideas.
- Knowledge management through data libraries, codes and procedures can make major steps forward with modern software technology

The physical theory of neutron chain reactors

Alvin M. Weinberg and Eugene P. Wigner,
University of Chicago Press (1958)





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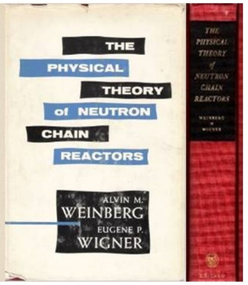
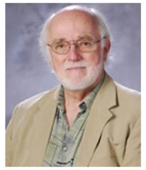
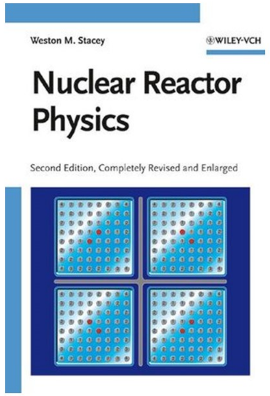


Nuclear Reactor Physics

Weston M. Stacey, Wiley-VCH, 2nd ed. (2007)

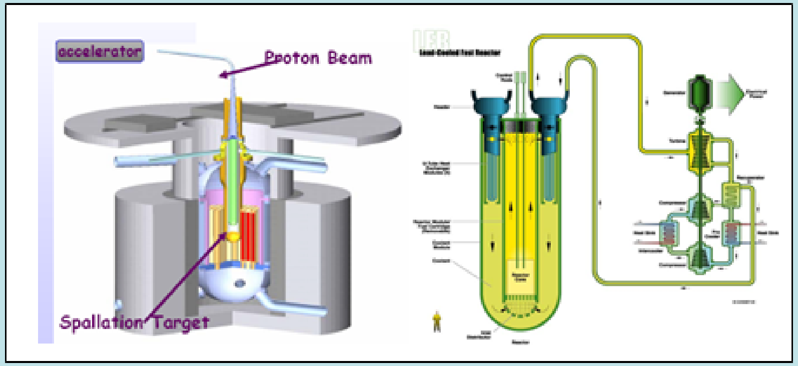


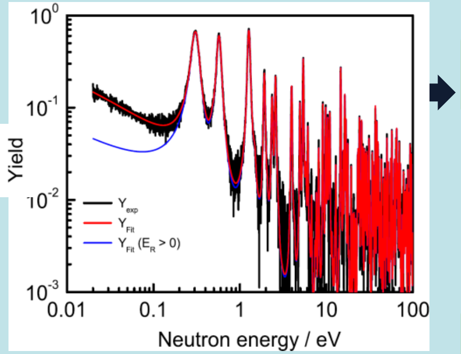


From science to application

Reactive versus proactive: ensure best science for every application

Feedback & new needs





Microscopic data

Theory

Benchmark data

Evaluation, verification & validation

Data Library

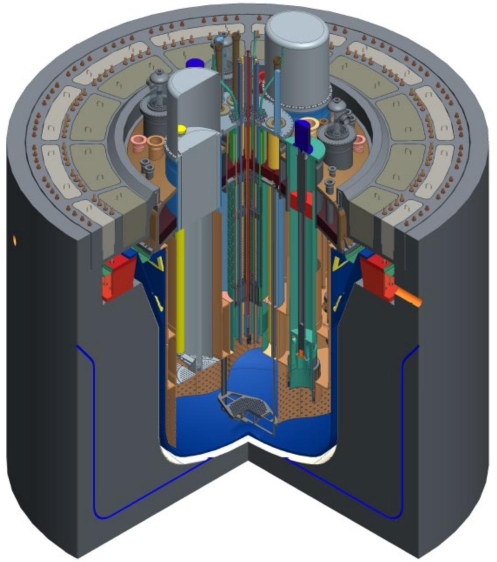
Research & Development

Industry

Regulatory bodies

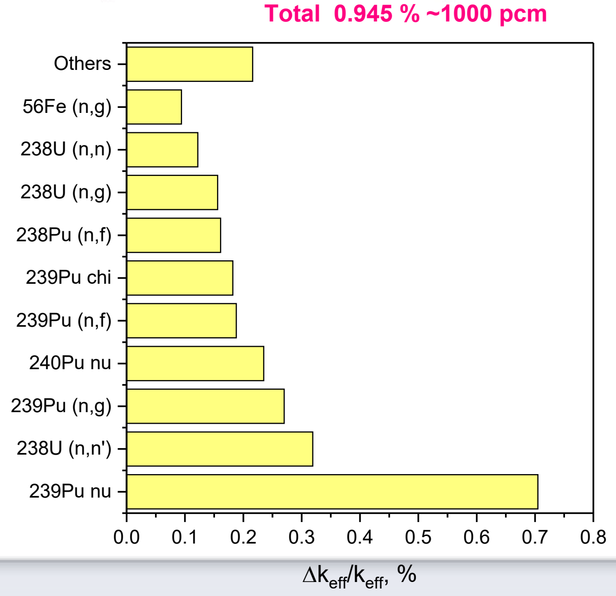
Alexey Stankovskiy

MYRRHA K_{eff} uncertainty and data priorities



Cov. data	$\Delta k_{eff}/k_{eff}$, %
SCALE-6.0m	0.945
COMMARA-2	~0.5
JENDL-4.0	0.553

Target accuracy satisfatory: $\frac{\Delta k_{eff}}{k_{eff}} \sim 300pcm$



Increase of confidence by reducing the uncertainties is needed for

- ^{239}Pu: (n,γ) both in resonance and fast energy region, (n,f) fast, χ and $\bar{\upsilon}$ fast
- ^{238}U: (n,n') fast, (n,γ) resonance and fast, (n,n) resonance and fast
- ^{56}Fe: (n,γ) resonance and fast
- ^{235}U: $\bar{\upsilon}$, (n,f), (n,γ) resonance and fast

Already covered by CIELO project

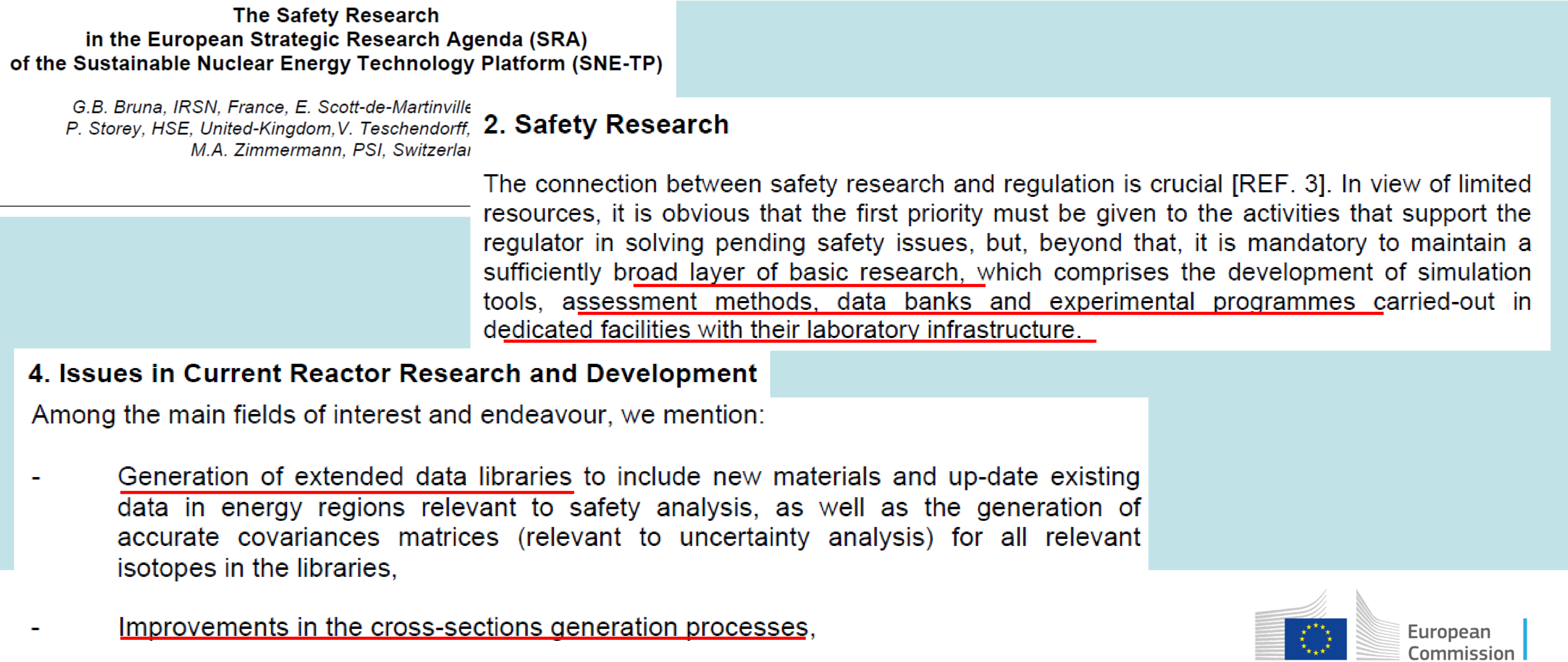
Not contributing essentially to k_{eff} and β_{eff} but impact fluxes, decay heat…

Impact burnup, decay heat

- ^{209}Bi (n,γ) and (n,n') resonance and fast
- ^{208}Pb (n,n) and (n,n') resonance and fast
- ^{241}Pu (n,f) resonance and fast
- ^{242}Pu (n,f) fast
- ^{240}Pu: $\bar{\upsilon}$ fast
- ^{238}Pu: (n,f) both resonance and fast

Focus on

Nuclear data for safety



The Safety Research
in the European Strategic Research Agenda (SRA)
of the Sustainable Nuclear Energy Technology Platform (SNE-TP)

G.B. Bruna, IRSN, France, E. Scott-de-Martinville
P. Storey, HSE, United-Kingdom,V. Teschendorff,
M.A. Zimmermann, PSI, Switzerla

2. Safety Research

The connection between safety research and regulation is crucial [REF. 3]. In view of limited resources, it is obvious that the first priority must be given to the activities that support the regulator in solving pending safety issues, but, beyond that, it is mandatory to maintain a sufficiently broad layer of basic research, which comprises the development of simulation tools, assessment methods, data banks and experimental programmes carried-out in dedicated facilities with their laboratory infrastructure.

4. Issues in Current Reactor Research and Development

Among the main fields of interest and endeavour, we mention:

- Generation of extended data libraries to include new materials and up-date existing data in energy regions relevant to safety analysis, as well as the generation of accurate covariances matrices (relevant to uncertainty analysis) for all relevant isotopes in the libraries,
- Improvements in the cross-sections generation processes,

Nuclear data for advanced reactors

SRIA 2013

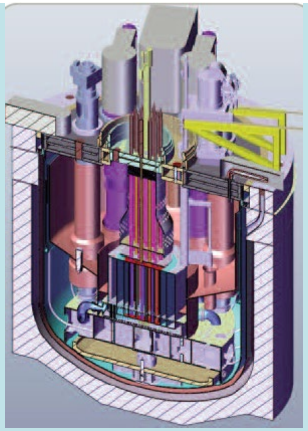
- Sustainable Nuclear Energy Technology Platform
- Innovation in nuclear energy
- ESNII European Sustainable Nuclear Infrastructure Initiative

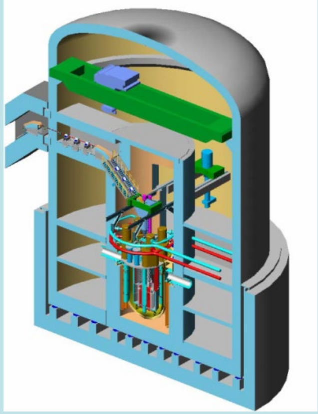
SNETP

Sustainable Nuclear Energy Technology Platform

Strategic Research and Innovation Agenda

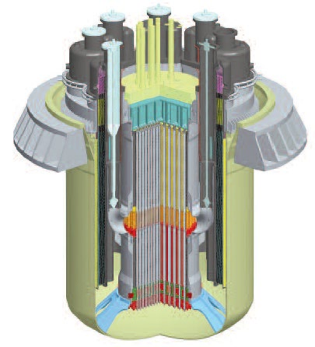
February 2013





ASTRID
ALFRED

MYRRHA
ALLEGRO

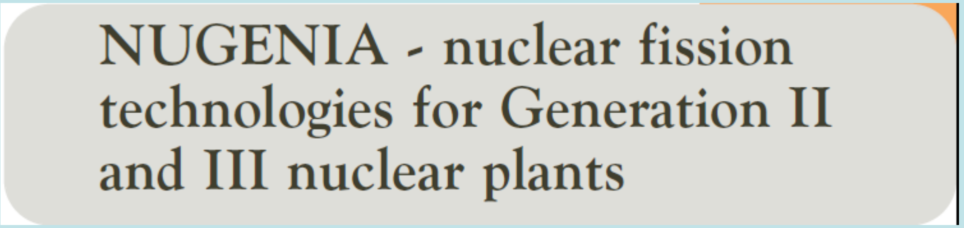


Nuclear data and nuclear power, today

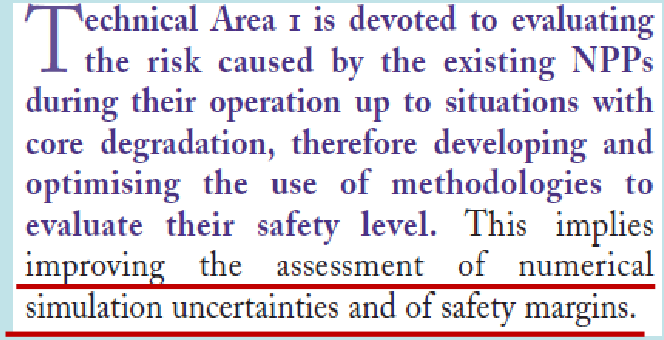
SNETP
SUSTAINABLE NUCLEAR ENERGY TECHNOLOGY PLATFORM

Strategic Research and Innovation Agenda

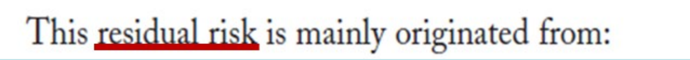
February 2013



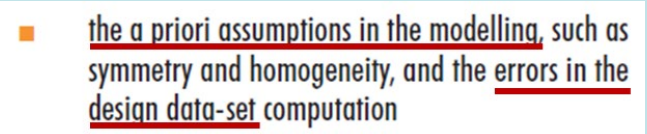
NUGENIA - nuclear fission technologies for Generation II and III nuclear plants



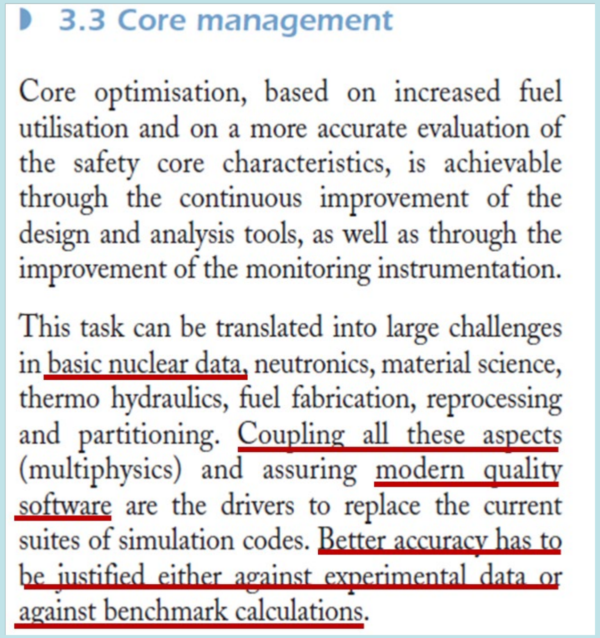
Technical Area 1 is devoted to evaluating the risk caused by the existing NPPs during their operation up to situations with core degradation, therefore developing and optimising the use of methodologies to evaluate their safety level. This implies improving the assessment of numerical simulation uncertainties and of safety margins.



This residual risk is mainly originated from:



- the a priori assumptions in the modelling, such as symmetry and homogeneity, and the errors in the design data-set computation



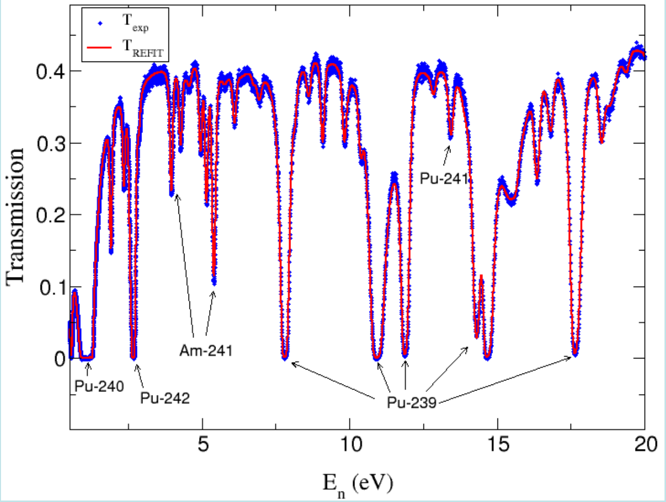
3.3 Core management

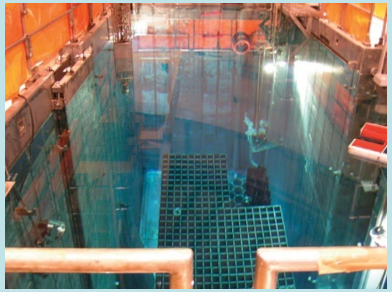
Core optimisation, based on increased fuel utilisation and on a more accurate evaluation of the safety core characteristics, is achievable through the continuous improvement of the design and analysis tools, as well as through the improvement of the monitoring instrumentation.

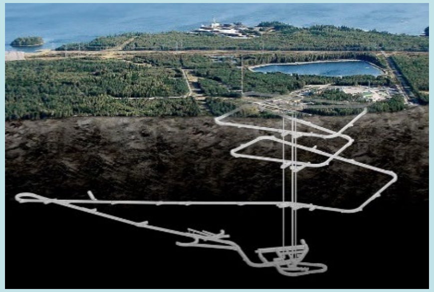
This task can be translated into large challenges in basic nuclear data, neutronics, material science, thermo hydraulics, fuel fabrication, reprocessing and partitioning. Coupling all these aspects (multiphysics) and assuring modern quality software are the drivers to replace the current suites of simulation codes. Better accuracy has to be justified either against experimental data or against benchmark calculations.

Accurate non-destructive analysis

- Safeguards control of spent/accident fuel storage
- Use of neutron time-of-flight capture and transmission methods with accurate resonance parameters
- Method development JRC-JAEA
- Possible extensions under investigation





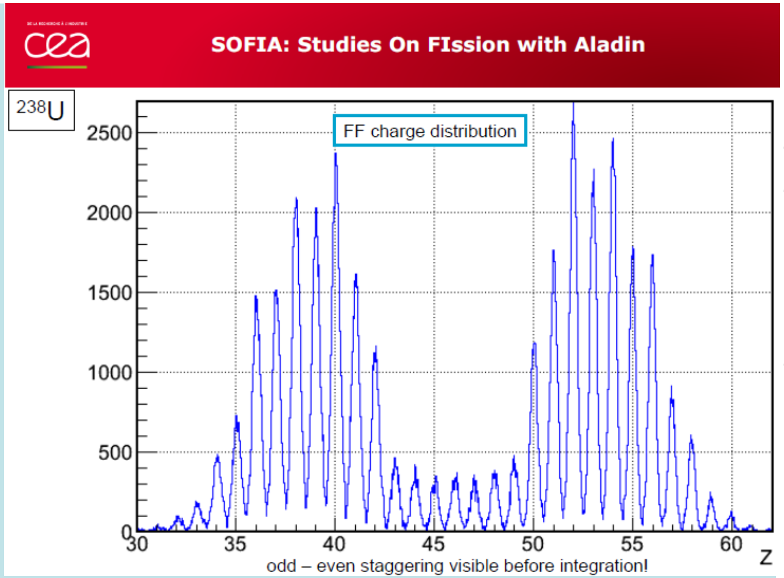


Pu-isotope	Declared %*	NRTA	Ratio
Pu-238	0.95174	0.979±0.018	1.029
Pu-239	62.6025	62.54±0.1	0.999
Pu-240	25.3526	26.25±0.02	1.039
Pu-241	1.5641	1.574±0.008	1.007
Pu-242	4.1489	3.983±0.008	0.960
Am-241	6.2870	6.316±0.008	1.005

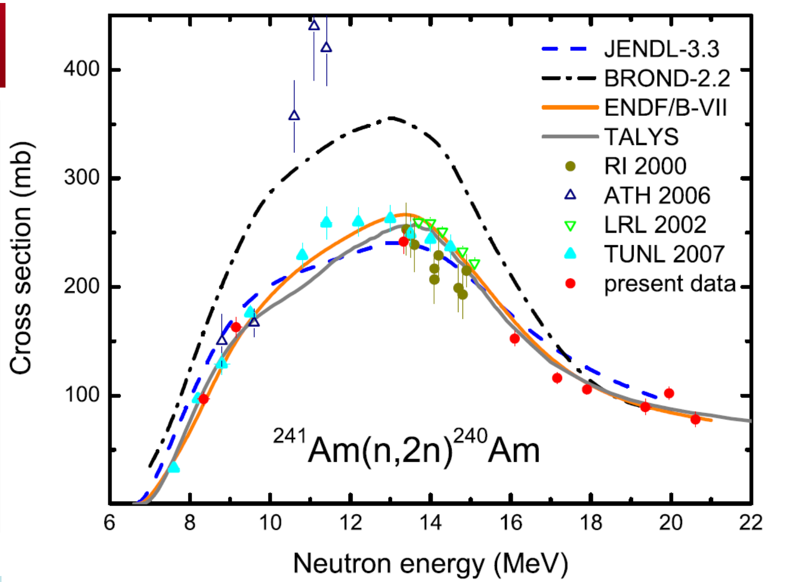
CBRNe

Chemical, biological, radionuclide, nuclear and explosive defence

- Considerable political interest
- Emergency preparedness
- Forensics
- Radioactivity
- Fission products (nuclear data)
- Induced activity (nuclear data)
- Dirty bombs



T. Gorbinet et al. Nuclear Data Week, November 2013, OECD-NEA, Paris



Excellent example how good modeling may predict a cross section before the measurement
TALYS - BRC, ENDF/B-VII - LANL
C. Sage et al. Phys. Rev. C 81 (2010) 064604

Available nuclear data libraries

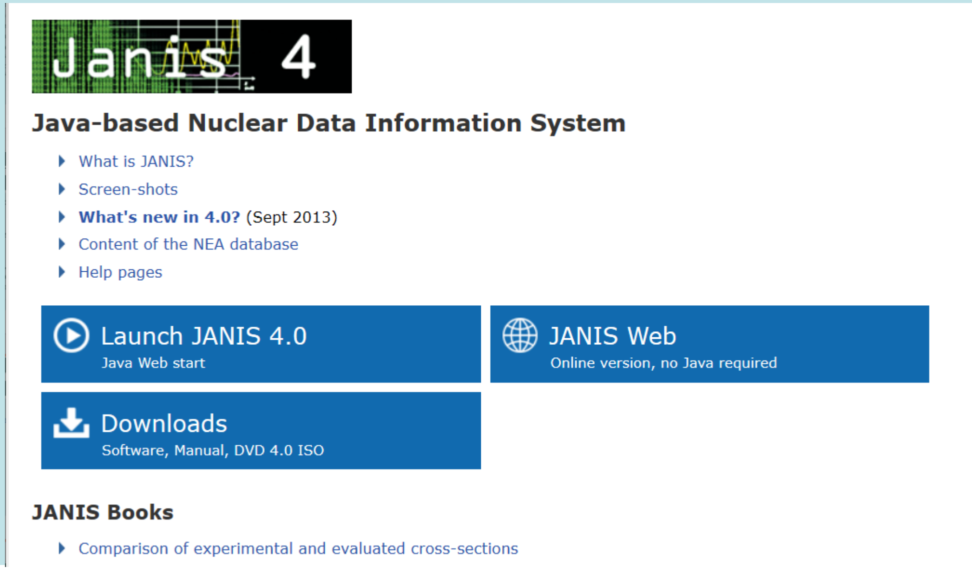
- OECD-Nuclear Energy Agency http://www.oecd-nea.org/dbdata/jeff/ Databank
  - Joint evaluated fission and fusion nuclear data library (JEFF-3.3, Nov. 2017)
  - Nuclear Science/WPEC: CIELO - H, O, Fe, ^{235}U, ^{238}U, ^{239}Pu
- US CSEWG – www.nndc.bnl.gov ENDF/B-VIII.0 (Jan. 2018)
- JAEA Nuclear Data Center wwwndc.jaea.go.jp/jendl, JENDL-4.0, 4.0+
- IAEA www-nds.iaea.org: Special purpose libraries (inden, standards, ripl, irdff, fendl, ibandl…; physics modeling, dosimetry, fusion, ion-beam analysis …)
- TENDL TENDL-2017 (tendl2019 in the making)
- CENDL: China, CENDL-3.2
- Russia: BROND and ROSFOND

Website: NEA

http://www.oecd-nea.org/dbdata/

High Priority Request List

for nuclear data

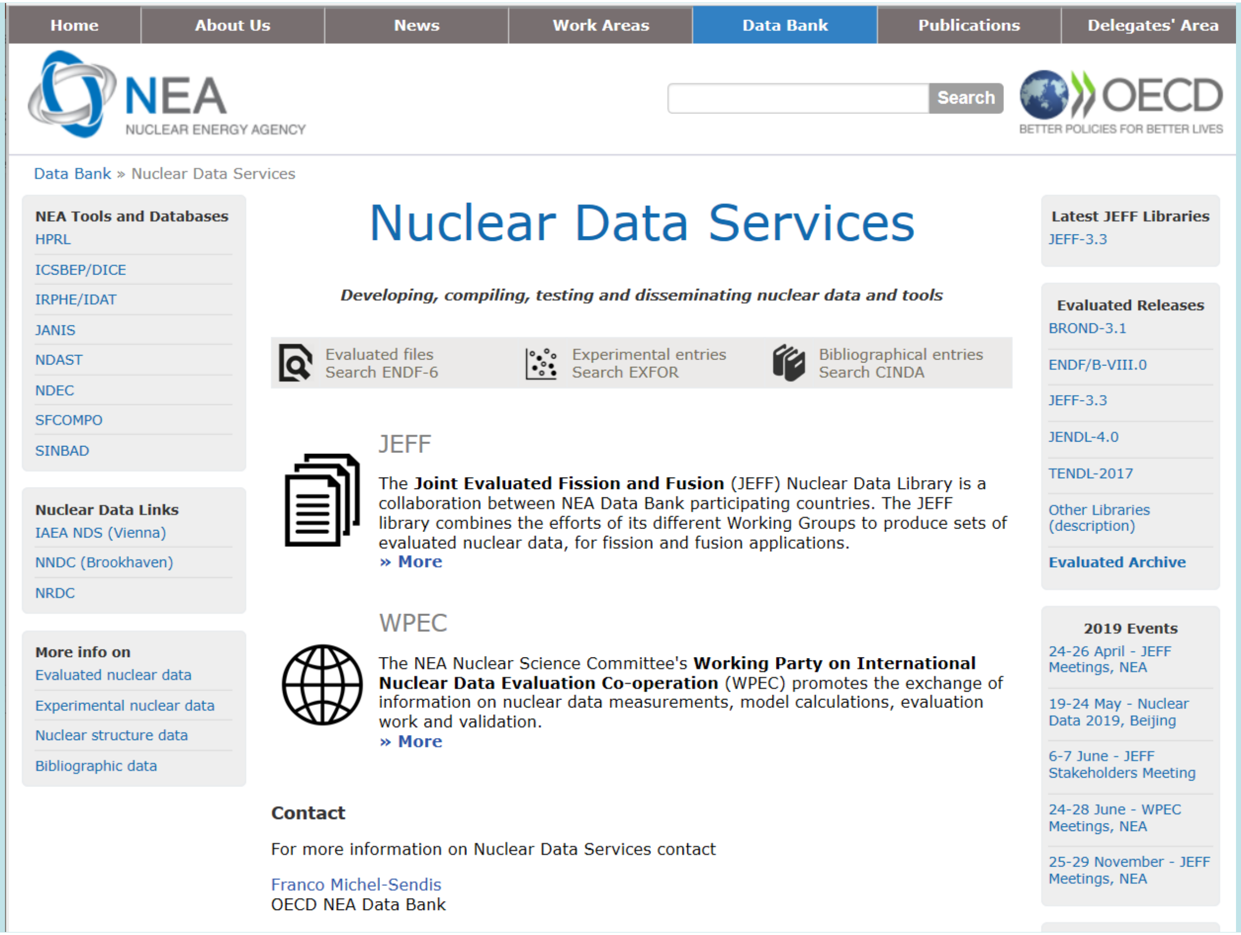


Java-based Nuclear Data Information System

- What is JANIS?
- Screen-shots
- **What's new in 4.0?** (Sept 2013)
- Content of the NEA database
- Help pages

JANIS Books

- Comparison of experimental and evaluated cross-sections



Data Bank » Nuclear Data Services

NEA Tools and Databases
- HPRL
- ICSBEP/DICE
- IRPHE/IDAT
- JANIS
- NDAST
- NDEC
- SFCOMPO
- SINBAD

Nuclear Data Links
- IAEA NDS (Vienna)
- NNDC (Brookhaven)
- NRDC

More info on
- Evaluated nuclear data
- Experimental nuclear data
- Nuclear structure data
- Bibliographic data

Nuclear Data Services

Developing, compiling, testing and disseminating nuclear data and tools

JEFF

The **Joint Evaluated Fission and Fusion** (JEFF) Nuclear Data Library is a collaboration between NEA Data Bank participating countries. The JEFF library combines the efforts of its different Working Groups to produce sets of evaluated nuclear data, for fission and fusion applications.
» More

WPEC

The NEA Nuclear Science Committee's **Working Party on International Nuclear Data Evaluation Co-operation** (WPEC) promotes the exchange of information on nuclear data measurements, model calculations, evaluation work and validation.
» More

Contact

For more information on Nuclear Data Services contact

Franco Michel-Sendis
OECD NEA Data Bank

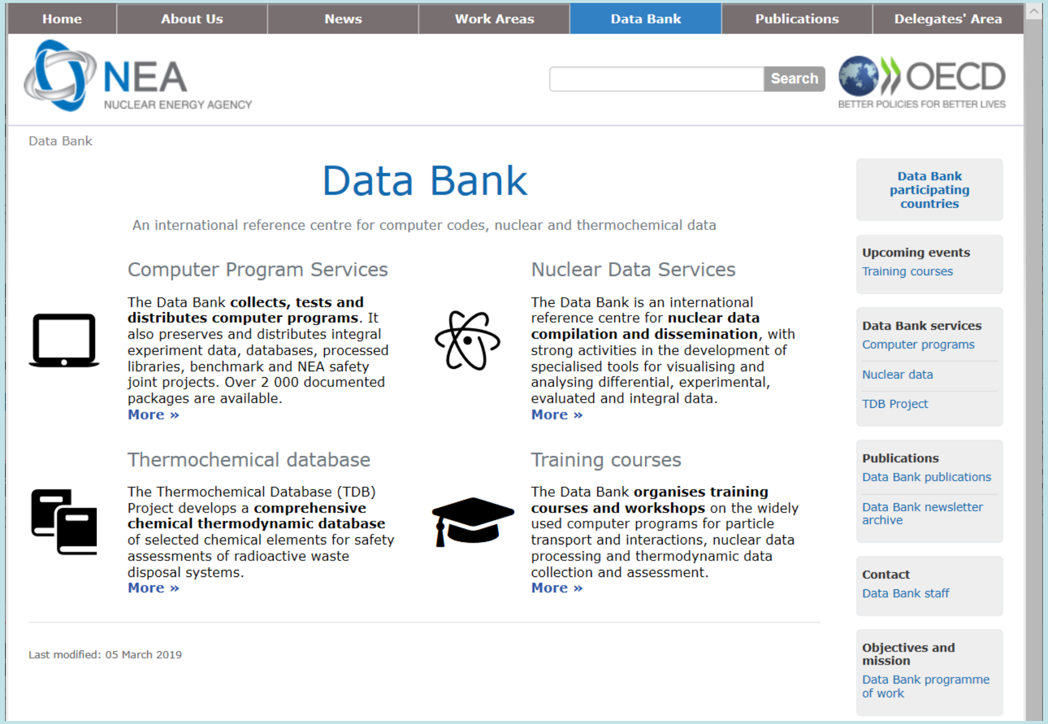
Latest JEFF Libraries
- JEFF-3.3

Evaluated Releases
- BROND-3.1
- ENDF/B-VIII.0
- JEFF-3.3
- JENDL-4.0
- TENDL-2017
- Other Libraries (description)
- **Evaluated Archive**

2019 Events
- 24-26 April - JEFF Meetings, NEA
- 19-24 May - Nuclear Data 2019, Beijing
- 6-7 June - JEFF Stakeholders Meeting
- 24-28 June - WPEC Meetings, NEA
- 25-29 November - JEFF Meetings, NEA

Website: NEA

Databank



Data Bank

Data Bank

An international reference centre for computer codes, nuclear and thermochemical data

Computer Program Services

The Data Bank **collects, tests and distributes computer programs**. It also preserves and distributes integral experiment data, databases, processed libraries, benchmark and NEA safety joint projects. Over 2 000 documented packages are available.
More »

Nuclear Data Services

The Data Bank is an international reference centre for **nuclear data compilation and dissemination**, with strong activities in the development of specialised tools for visualising and analysing differential, experimental, evaluated and integral data.
More »

Thermochemical database

The Thermochemical Database (TDB) Project develops a **comprehensive chemical thermodynamic database** of selected chemical elements for safety assessments of radioactive waste disposal systems.
More »

Training courses

The Data Bank **organises training courses and workshops** on the widely used computer programs for particle transport and interactions, nuclear data processing and thermodynamic data collection and assessment.
More »

Last modified: 05 March 2019

Data Bank participating countries

Upcoming events
Training courses

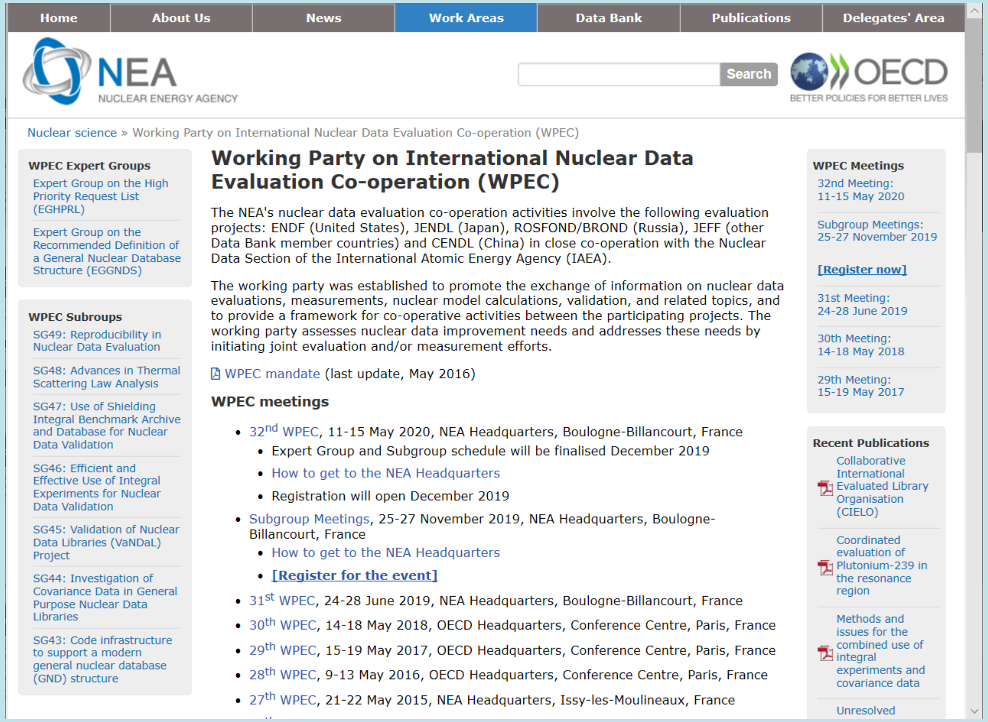
Data Bank services
Computer programs
Nuclear data
TDB Project

Publications
Data Bank publications
Data Bank newsletter archive

Contact
Data Bank staff

Objectives and mission
Data Bank programme of work

Working party on evaluation cooperation



Nuclear science » Working Party on International Nuclear Data Evaluation Co-operation (WPEC)

WPEC Expert Groups
Expert Group on the High Priority Request List (EGHPRL)
Expert Group on the Recommended Definition of a General Nuclear Database Structure (EGGNDS)

WPEC Subroups
SG49: Reproducibility in Nuclear Data Evaluation
SG48: Advances in Thermal Scattering Law Analysis
SG47: Use of Shielding Integral Benchmark Archive and Database for Nuclear Data Validation
SG46: Efficient and Effective Use of Integral Experiments for Nuclear Data Validation
SG45: Validation of Nuclear Data Libraries (VaNDaL) Project
SG44: Investigation of Covariance Data in General Purpose Nuclear Data Libraries
SG43: Code infrastructure to support a modern general nuclear database (GND) structure

Working Party on International Nuclear Data Evaluation Co-operation (WPEC)

The NEA's nuclear data evaluation co-operation activities involve the following evaluation projects: ENDF (United States), JENDL (Japan), ROSFOND/BROND (Russia), JEFF (other Data Bank member countries) and CENDL (China) in close co-operation with the Nuclear Data Section of the International Atomic Energy Agency (IAEA).

The working party was established to promote the exchange of information on nuclear data evaluations, measurements, nuclear model calculations, validation, and related topics, and to provide a framework for co-operative activities between the participating projects. The working party assesses nuclear data improvement needs and addresses these needs by initiating joint evaluation and/or measurement efforts.

WPEC mandate (last update, May 2016)

WPEC meetings

- 32nd WPEC, 11-15 May 2020, NEA Headquarters, Boulogne-Billancourt, France
  - Expert Group and Subgroup schedule will be finalised December 2019
  - How to get to the NEA Headquarters
  - Registration will open December 2019
- Subgroup Meetings, 25-27 November 2019, NEA Headquarters, Boulogne-Billancourt, France
  - How to get to the NEA Headquarters
  - **[Register for the event]**
- 31st WPEC, 24-28 June 2019, NEA Headquarters, Boulogne-Billancourt, France
- 30th WPEC, 14-18 May 2018, OECD Headquarters, Conference Centre, Paris, France
- 29th WPEC, 15-19 May 2017, OECD Headquarters, Conference Centre, Paris, France
- 28th WPEC, 9-13 May 2016, OECD Headquarters, Conference Centre, Paris, France
- 27th WPEC, 21-22 May 2015, NEA Headquarters, Issy-les-Moulineaux, France

WPEC Meetings
32nd Meeting: 11-15 May 2020
Subgroup Meetings: 25-27 November 2019
[Register now]
31st Meeting: 24-28 June 2019
30th Meeting: 14-18 May 2018
29th Meeting: 15-19 May 2017

Recent Publications
Collaborative International Evaluated Library Organisation (CIELO)
Coordinated evaluation of Plutonium-239 in the resonance region
Methods and issues for the combined use of integral experiments and covariance data
Unresolved

Website: IAEA

EXFOR: experimental data

LiveChart: Nuclide decay data browser

ENSDF: primary nuclear structure database (NUDAT-2)

RIPL: reaction model parameters

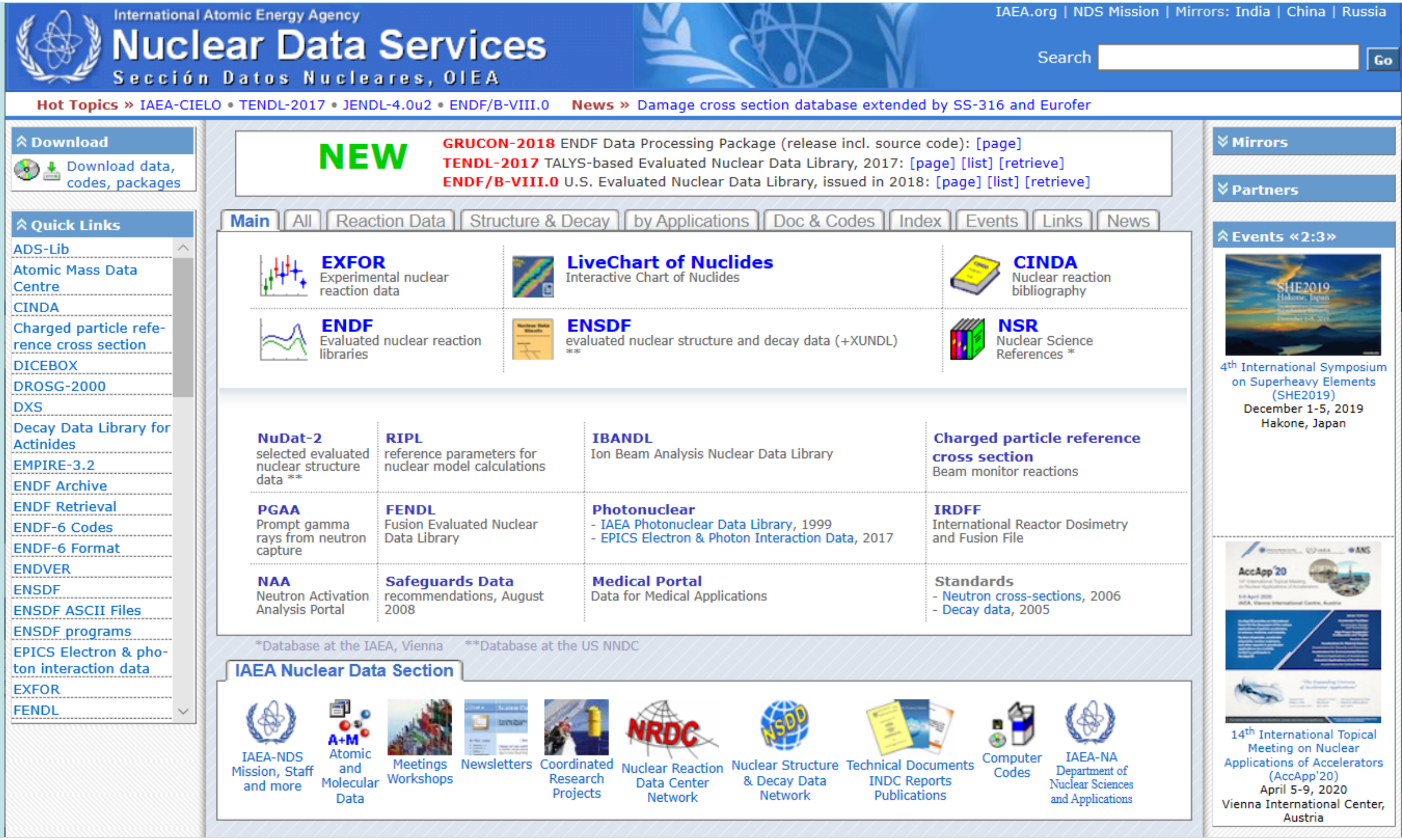
FENDL: fusion neutronics

PGAA, NAA: activation analysis

IBANDL: ion beam analysis

Medical Portal

IRDFF: Dosimetry



Hot Topics » IAEA-CIELO • TENDL-2017 • JENDL-4.0u2 • ENDF/B-VIII.0 **News** » Damage cross section database extended by SS-316 and Eurofer

Download data, codes, packages

GRUCON-2018 ENDF Data Processing Package (release incl. source code): [page]
TENDL-2017 TALYS-based Evaluated Nuclear Data Library, 2017: [page] [list] [retrieve]
ENDF/B-VIII.0 U.S. Evaluated Nuclear Data Library, issued in 2018: [page] [list] [retrieve]

Quick Links:

- ADS-Lib
- Atomic Mass Data Centre
- CINDA
- Charged particle reference cross section
- DICEBOX
- DROSG-2000
- DXS
- Decay Data Library for Actinides
- EMPIRE-3.2
- ENDF Archive
- ENDF Retrieval
- ENDF-6 Codes
- ENDF-6 Format
- ENDVER
- ENSDF
- ENSDF ASCII Files
- ENSDF programs
- EPICS Electron & photon interaction data
- EXFOR
- FENDL

EXFOR Experimental nuclear reaction data

LiveChart of Nuclides Interactive Chart of Nuclides

CINDA Nuclear reaction bibliography

ENDF Evaluated nuclear reaction libraries

ENSDF evaluated nuclear structure and decay data (+XUNDL) **

NSR Nuclear Science References *

NuDat-2 selected evaluated nuclear structure data **

RIPL reference parameters for nuclear model calculations

IBANDL Ion Beam Analysis Nuclear Data Library

Charged particle reference cross section Beam monitor reactions

PGAA Prompt gamma rays from neutron capture

FENDL Fusion Evaluated Nuclear Data Library

Photonuclear
- IAEA Photonuclear Data Library, 1999
- EPICS Electron & Photon Interaction Data, 2017

IRDFF International Reactor Dosimetry and Fusion File

NAA Neutron Activation Analysis Portal

Safeguards Data recommendations, August 2008

Medical Portal Data for Medical Applications

Standards
- Neutron cross-sections, 2006
- Decay data, 2005

*Database at the IAEA, Vienna **Database at the US NNDC

4th International Symposium on Superheavy Elements (SHE2019)
December 1-5, 2019
Hakone, Japan

14th International Topical Meeting on Nuclear Applications of Accelerators (AccApp'20)
April 5-9, 2020
Vienna International Center, Austria

Many more.

Website: NNDC

Some overlap with IAEA

AMDC/Q-value calculator

CapGam

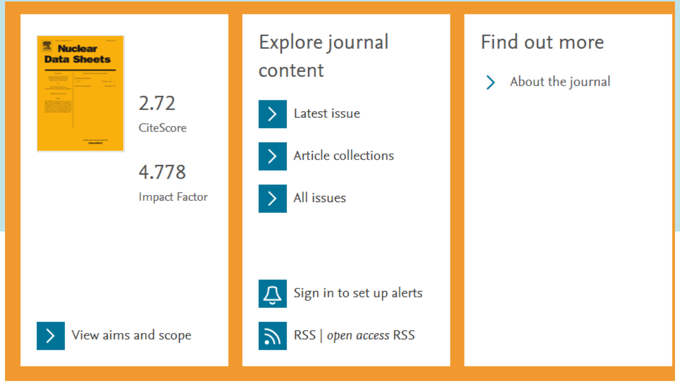
Atlas of Neutron Resonances

Nuclear wallet cards

Nuclear Data Sheets

Nuclear structure (ENSDF)

Nuclear data (special issues)



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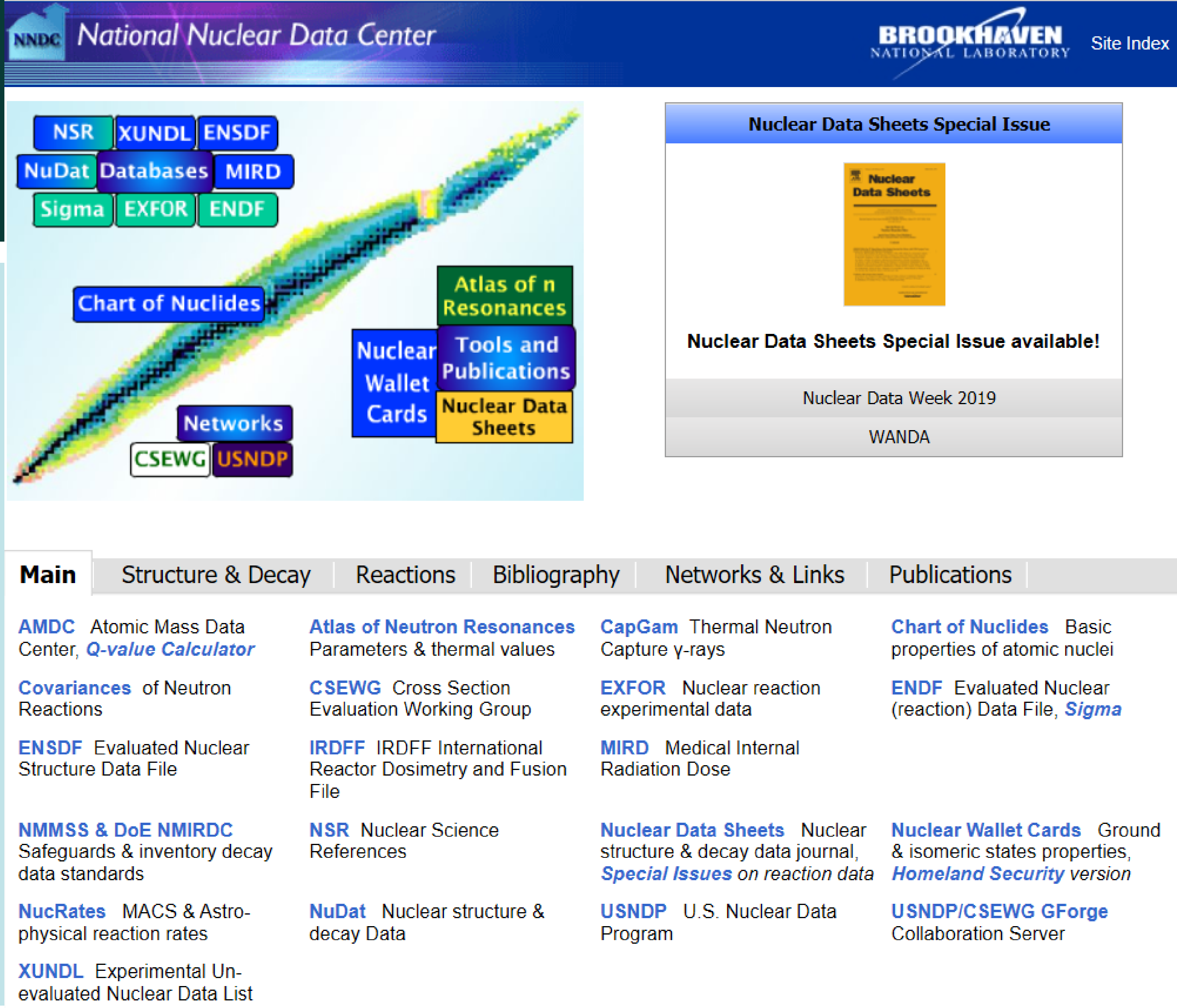


Nuclear Data Sheets Special Issue

Nuclear Data Sheets Special Issue available!

Nuclear Data Week 2019

WANDA

AMDC Atomic Mass Data Center, *Q-value Calculator*

Atlas of Neutron Resonances Parameters & thermal values

CapGam Thermal Neutron Capture γ-rays

Chart of Nuclides Basic properties of atomic nuclei

Covariances of Neutron Reactions

CSEWG Cross Section Evaluation Working Group

EXFOR Nuclear reaction experimental data

ENDF Evaluated Nuclear (reaction) Data File, *Sigma*

ENSDF Evaluated Nuclear Structure Data File

IRDFF IRDFF International Reactor Dosimetry and Fusion File

MIRD Medical Internal Radiation Dose

NMMSS & DoE NMIRDC Safeguards & inventory decay data standards

NSR Nuclear Science References

Nuclear Data Sheets Nuclear structure & decay data journal, *Special Issues* on reaction data

Nuclear Wallet Cards Ground & isomeric states properties, *Homeland Security* version

NucRates MACS & Astro-physical reaction rates

NuDat Nuclear structure & decay Data

USNDP U.S. Nuclear Data Program

USNDP/CSEWG GForge Collaboration Server

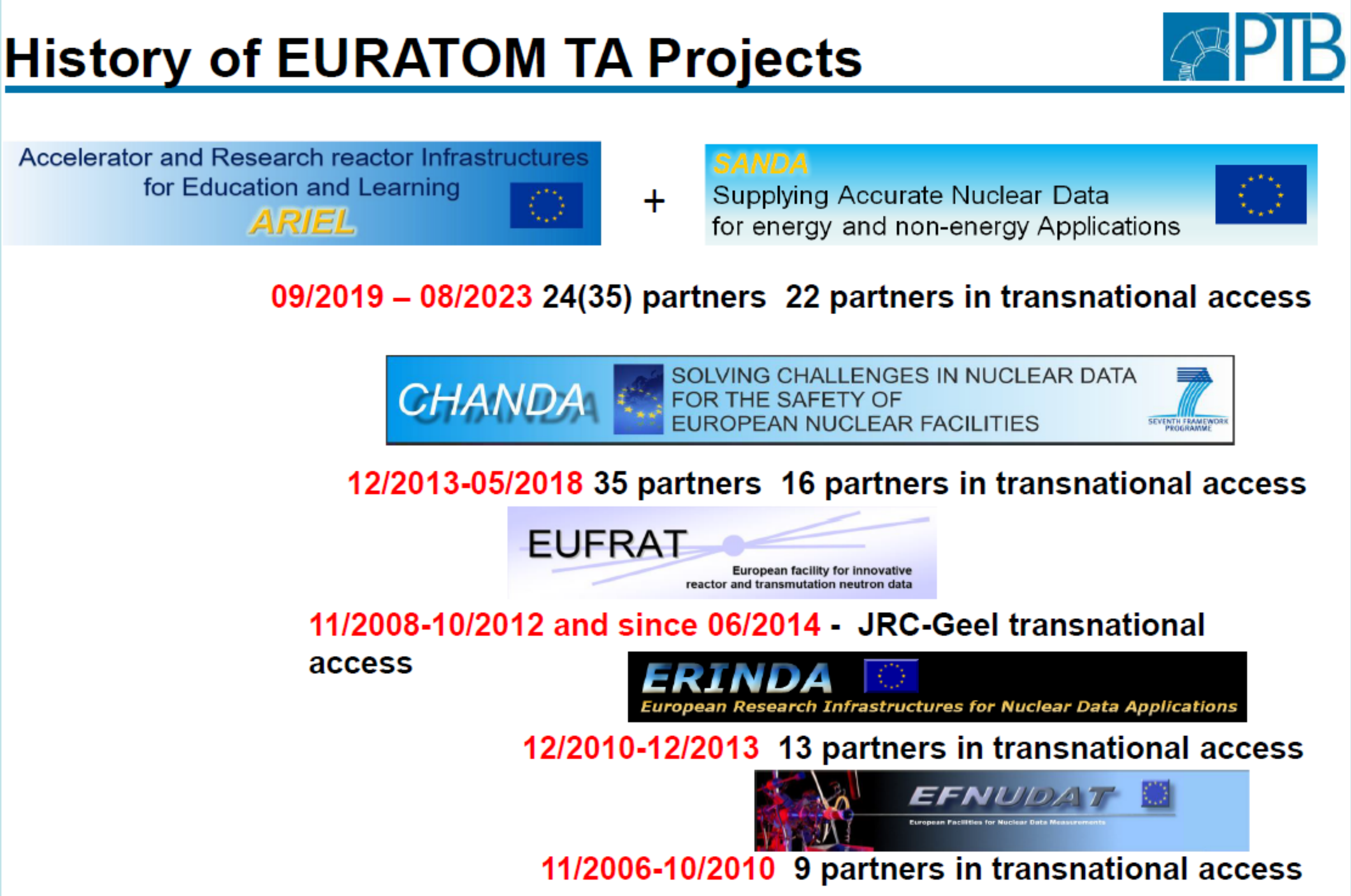
XUNDL Experimental Un-evaluated Nuclear Data List

EU Access to Research Infrastructure

Slides ARIEL kick-off meeting

Arnd Junghans (HZDR)

coordinator



History of EURATOM TA Projects

PTB

Accelerator and Research reactor Infrastructures for Education and Learning
ARIEL

\+

SANDA
Supplying Accurate Nuclear Data for energy and non-energy Applications

09/2019 – 08/2023 24(35) partners 22 partners in transnational access

CHANDA
SOLVING CHALLENGES IN NUCLEAR DATA FOR THE SAFETY OF EUROPEAN NUCLEAR FACILITIES

12/2013-05/2018 35 partners 16 partners in transnational access

EUFRAT
European facility for innovative reactor and transmutation neutron data

11/2008-10/2012 and since 06/2014 - JRC-Geel transnational access

ERINDA
European Research Infrastructures for Nuclear Data Applications

12/2010-12/2013 13 partners in transnational access

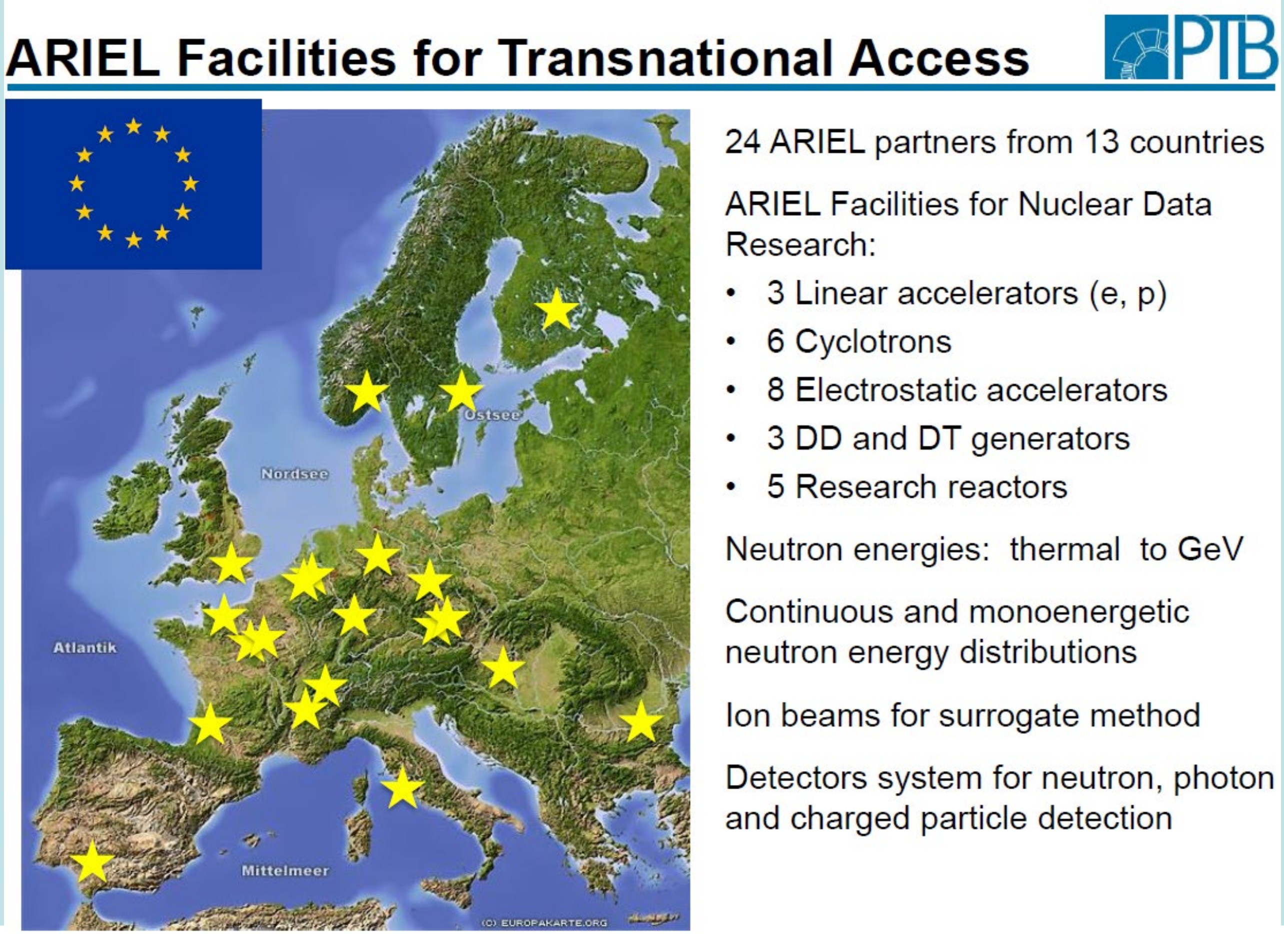
EFNUDAT
European Facilities for Nuclear Data Measurements

11/2006-10/2010 9 partners in transnational access

European Commission

EU Access to Research Infrastructure

Slides ARIEL kick-off meeting



ARIEL Facilities for Transnational Access

24 ARIEL partners from 13 countries

ARIEL Facilities for Nuclear Data Research:

- 3 Linear accelerators (e, p)
- 6 Cyclotrons
- 8 Electrostatic accelerators
- 3 DD and DT generators
- 5 Research reactors

Neutron energies: thermal to GeV

Continuous and monoenergetic neutron energy distributions

Ion beams for surrogate method

Detectors system for neutron, photon and charged particle detection

ARIEL Transnational Access Facilities

Many ARIEL facilities have a long record of EURATOM-funded TA projects:

HZDR, JRC Geel, n_TOF, CENRS-ALTO, CNRS-AIFIRA, CEA Ile de France, PTB, NPI, MTA-EK, IFIN, NPL, UU, OU

Some have new or significantly upgraded facilities:

JRC Geel, n_TOF, JYU, PTB, UU

… and some are the 'new kids on the block':

CNRS-GENESIS, NFS, ENEA, ILL, CNA, SCK*CEN, JGU, CVŘ

ARIL Kick-off

Criteria for Selection of ARIEL TA Projects

The PAC will select experiments based on scientific excellence and value to education and training:

- Focus on nuclear safety and on support of modelling and evaluation
- Provision of research experience for early-stage researchers
- Exchange of knowledge and methodologies for senior scientist and technical staff
- Coordination with ongoing EURATOM projects related to nuclear data
- Coordination with OECD/NEA: HPRL, JEFF, NEST, INDEN, SNETP.

The PAC will choose a facility for selected projects according to:

- Best match between needs of the experiment and capabilities of the facilities
- Availability of beam time
- Value for money

Accelerator and Research Reactor Infrastructures for Education and Learning: ARIEL

Open access to JRC facilities

(Geel, Karlsruhe, Petten – example shown is only Geel)

Website: https://ec.europa.eu/jrc/en/research-facility/open-access

- **EUFRAT-GELINA**
- **EUFRAT-MONNET**
- **EUFRAT-RADMET**
- **EUFRAT-HADES**

Free of charge

Same User Selection Committee

Same timing

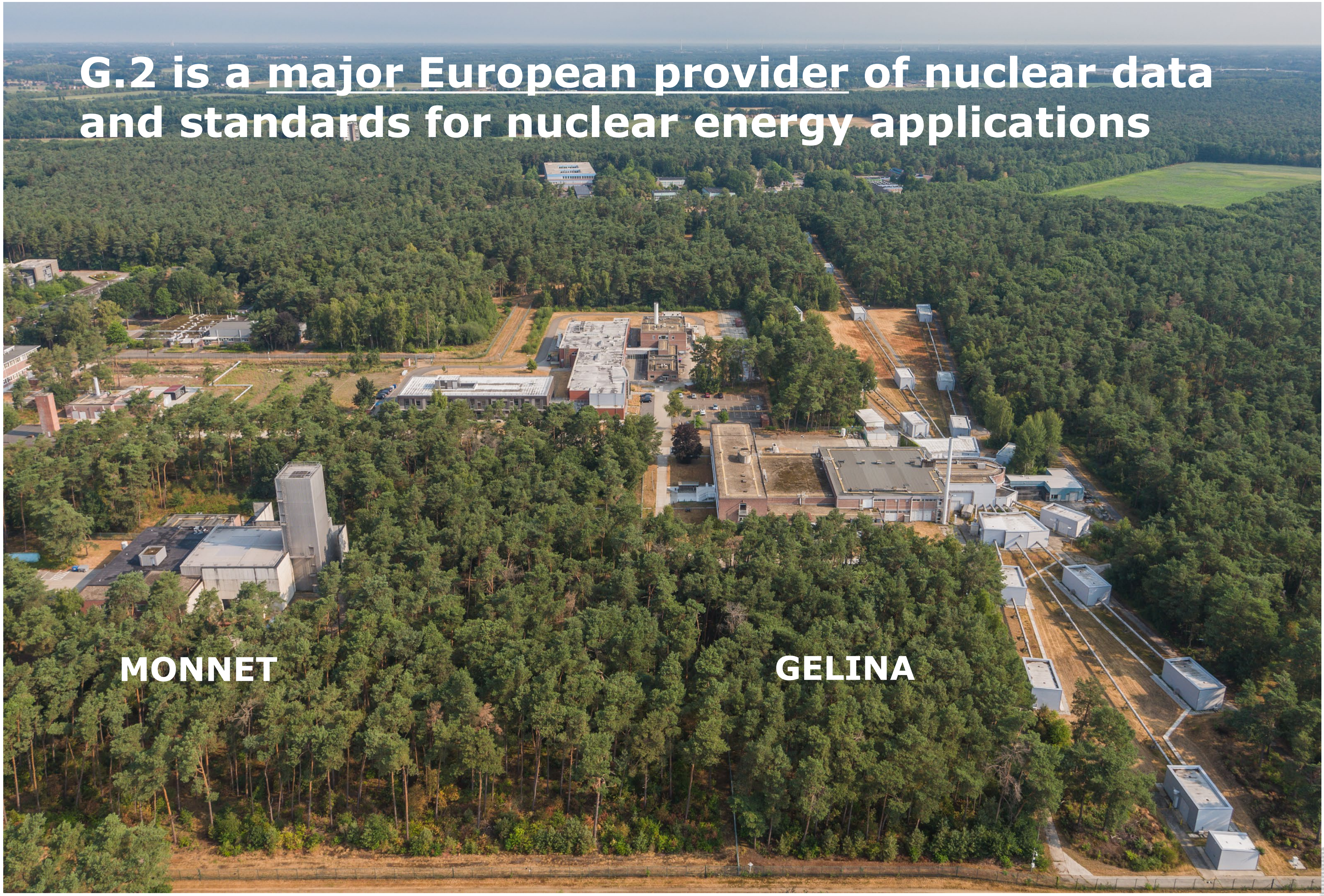
Eligibility criteria

- The **Lead User Institution** and **User Institutions** must be from an **EU Member State, candidate country** or **country associated to the Euratom Research Programme**.
- The **Lead User Institution** must be from a **university**, **research** or **public institution,** or **from a Small-Medium-Enterprise**.

Measurements and experiments

- Reaction data
  - Scattering
  - Fission
  - Transmission
  - Capture
- Structure and decay data
  - Half life
  - Emission probabilities
- Uncertainty in measurements
  - Measurement model
  - Guide to the expression of uncertainty

G.2 is a major European provider of nuclear data and standards for nuclear energy applications



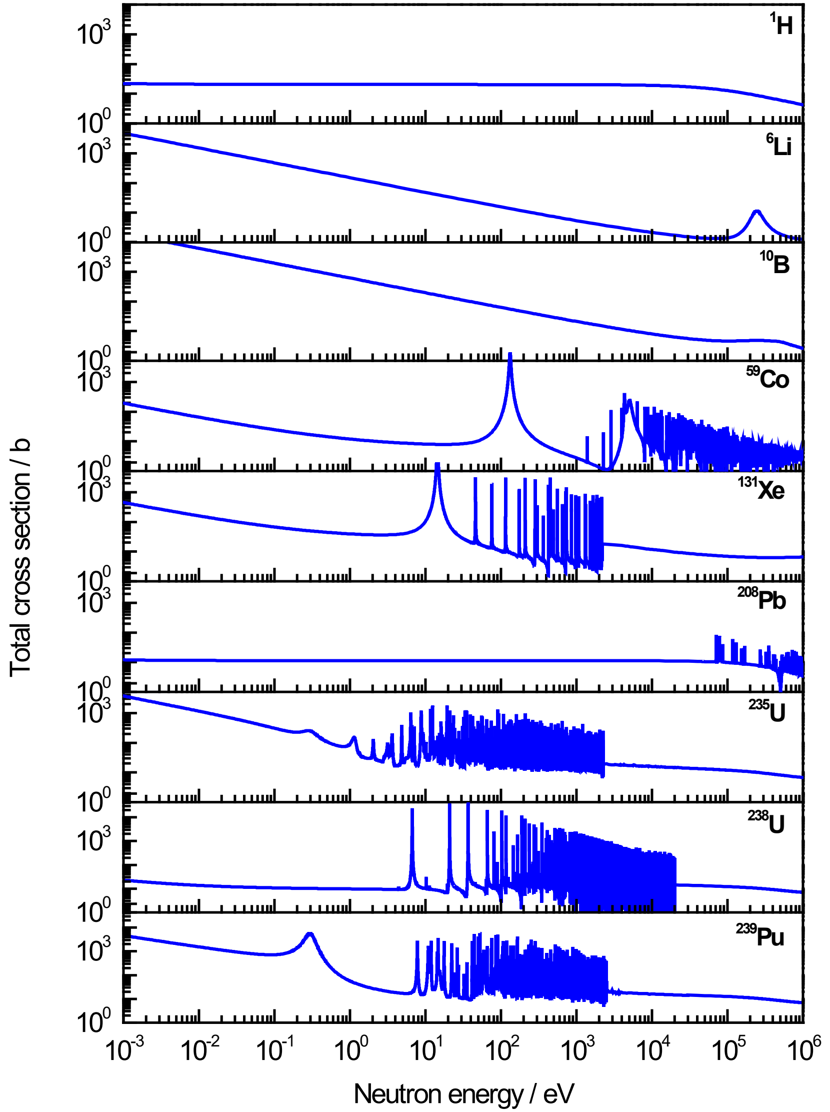
For and with

Member States,

OECD-NEA
IAEA

International
partners

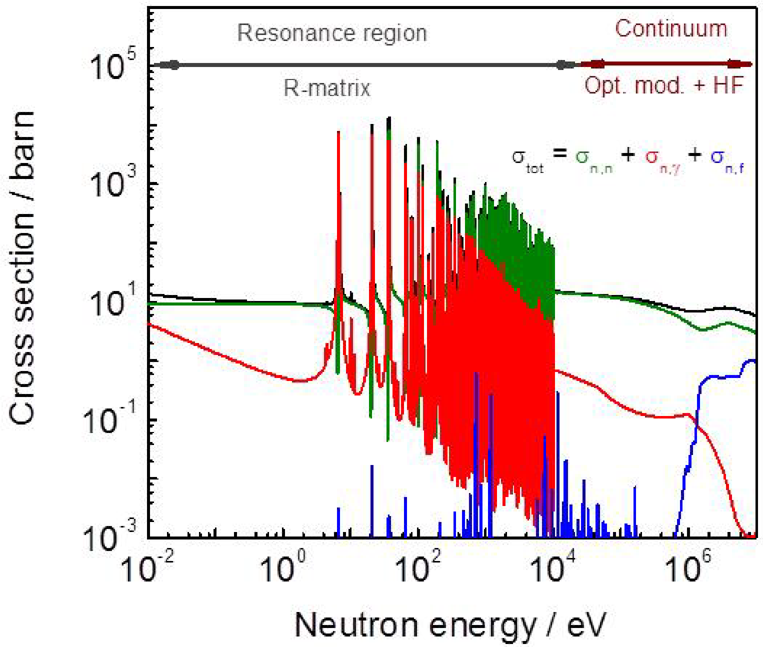
Neutron induced interaction cross sections

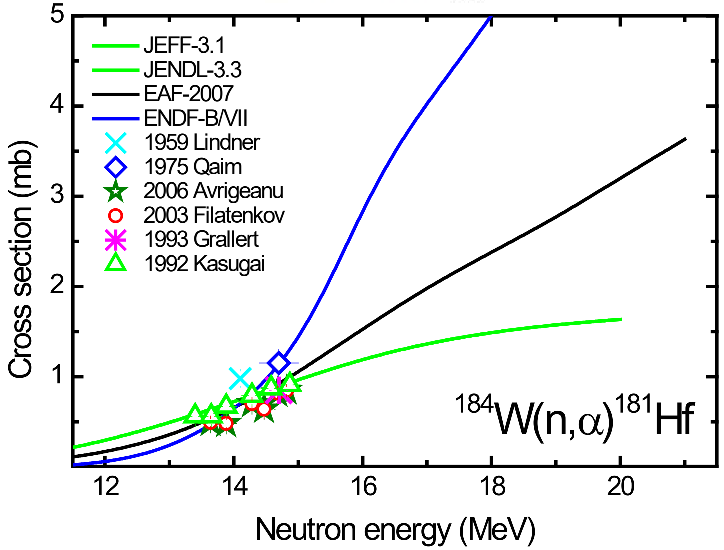


For most of the applications, i.e. nuclear energy, **theoretical cross sections are required**

- **Doppler** broadening
- Account for **self-shielding** in resonance region
- Ensures **full consistency**
- Consistency **between energy regions**
- **Inter- and extrapolation** in regions where no experimental data are available

Neutron induced interaction cross sections





- Cross sections **cannot be predicted** by nuclear theory from first principles
- Cross sections **can be parametrized** by nuclear reaction theory (formalisms)
- Model parameters are **adjusted to experimental data**

$\Rightarrow$ Experimental data are required

European Commission

Main principles of measurement (GELINA example)

Total cross section

$$T \cong e^{-n\,\sigma_{tot}}$$

Reaction cross section

$$Y_{\gamma} \approx (1 - e^{-n\,\sigma_{tot}})\frac{\sigma_{\gamma}}{\sigma_{tot}}$$

T = transmission

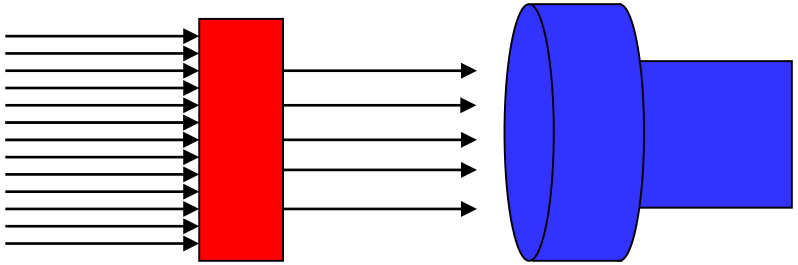
Fraction of the neutron beam traversing the sample **without any interaction**

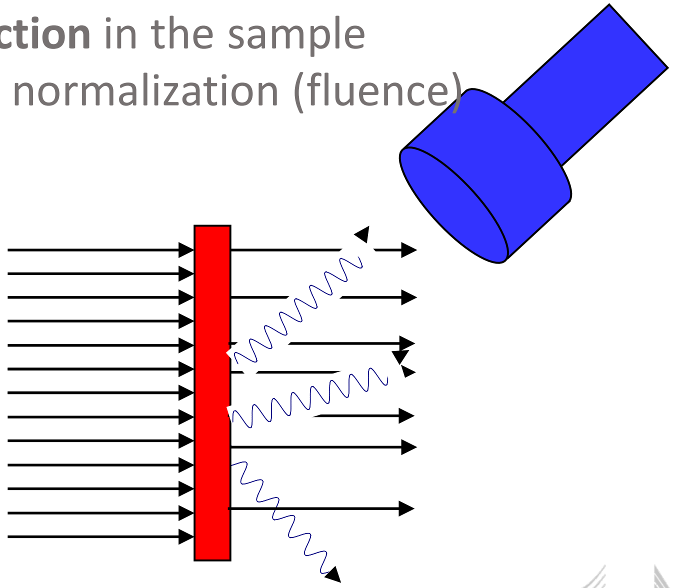
Need for normalization sample in/out

Y_r = reaction **yield**

Fraction of the neutron beam creating a **(n,γ) reaction** in the sample

Need for normalization (fluence)





GELINA - Cross section measurements

Total cross section

$$T \cong e^{-n\boxed{\sigma_{tot}}}$$

Reaction cross section

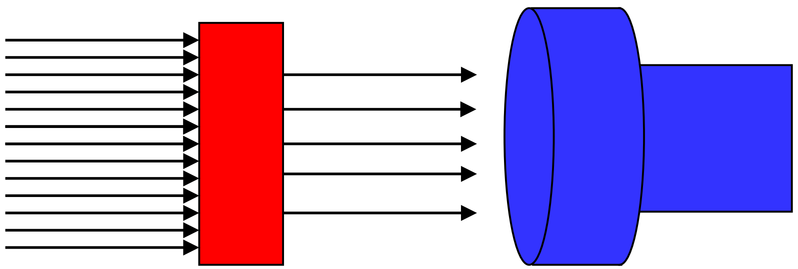
$$Y_\gamma \approx (1 - e^{-n\sigma_{tot}})\frac{\boxed{\sigma_\gamma}}{\sigma_{tot}}$$

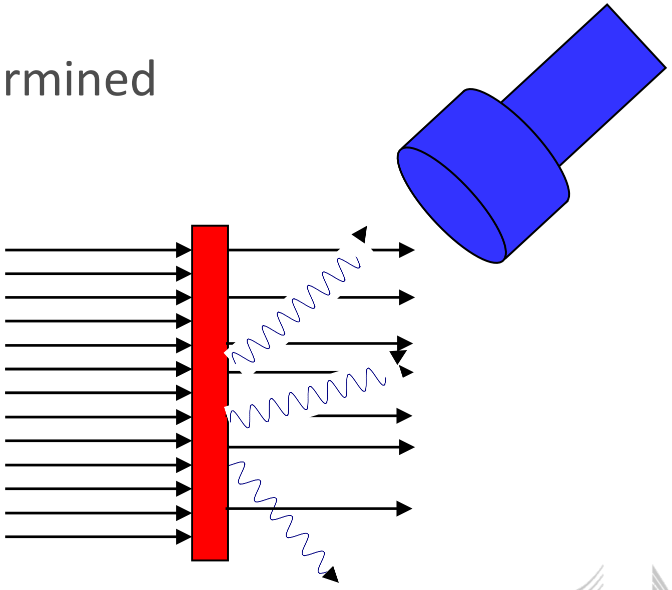
Well-characterised samples

n: areal density (total number of atoms per unit area) is well-known

⇓

accurate cross-sections can be determined





European Commission

Data taken in Geel, aim at better evaluated files

Other facilities contribute, similarly.

Experimental data

- Cross section for neutron induced reactions
- Fission fragment characteristics
- Neutron emission probabilities
- γ - ray emission probabilities
- Decay data
- Detector development
- Target production

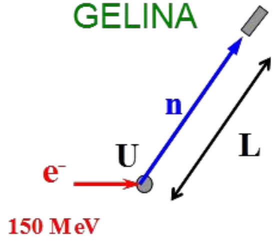
Theory/models

- Resonance shape analysis (RRR)
- Hauser-Feshbach formalism (URR)
- Fission process
- Level statistics

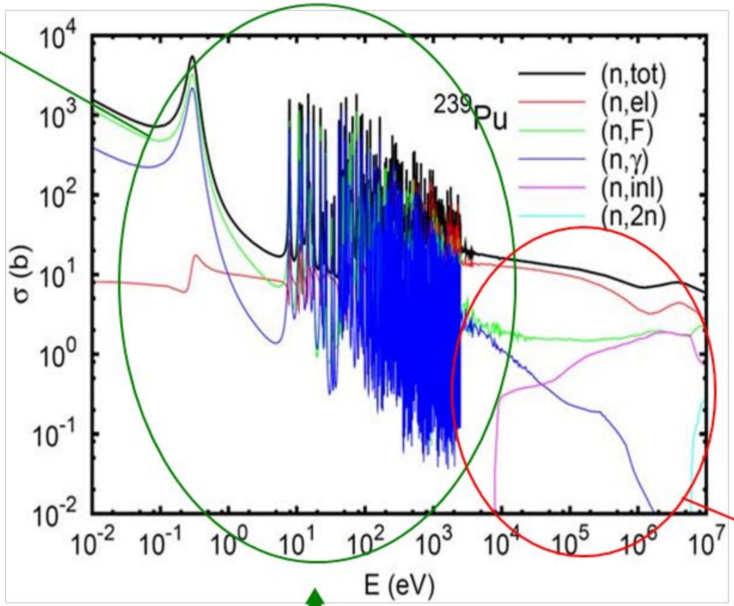
GELINA and MONNET accelerator laboratories

Time-of-flight measurements

GELINA

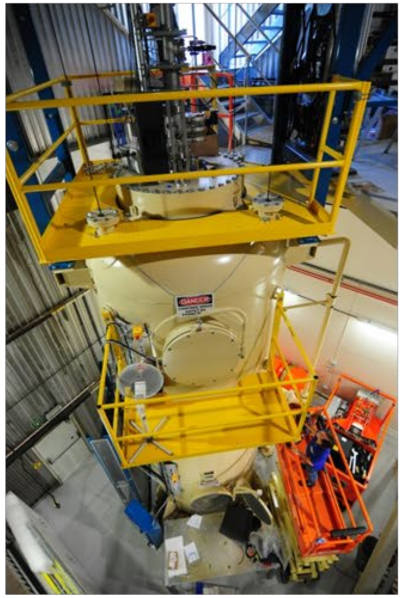


$$E = \frac{1}{2} m v^2 \propto \left(\frac{L}{T}\right)^2$$

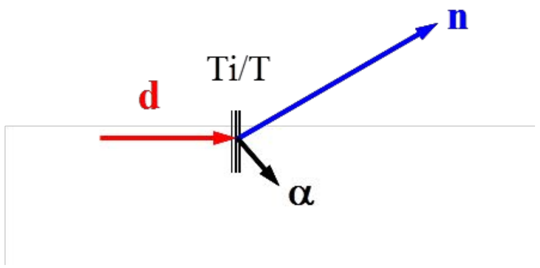


energy resolution

MONNET



Mono-energetic neutron beams



Nuclear science applications

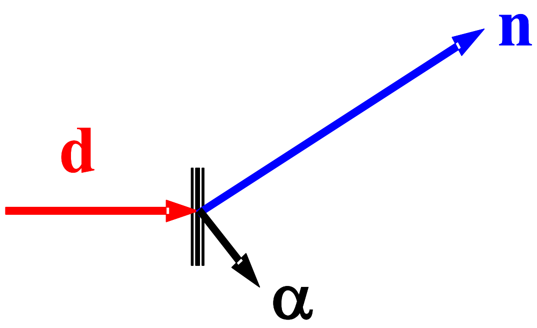
- Nuclear data research
- Non-destructive analysis
- Neutron and photon transport
- Detector characterisation
- Dosimetry
- Material science
- Medical applications
- Basic physics (fission, astrophysics, …)

- Cross-cutting disciplines

Mono-energetic neutron beams by (chp,n) reactions

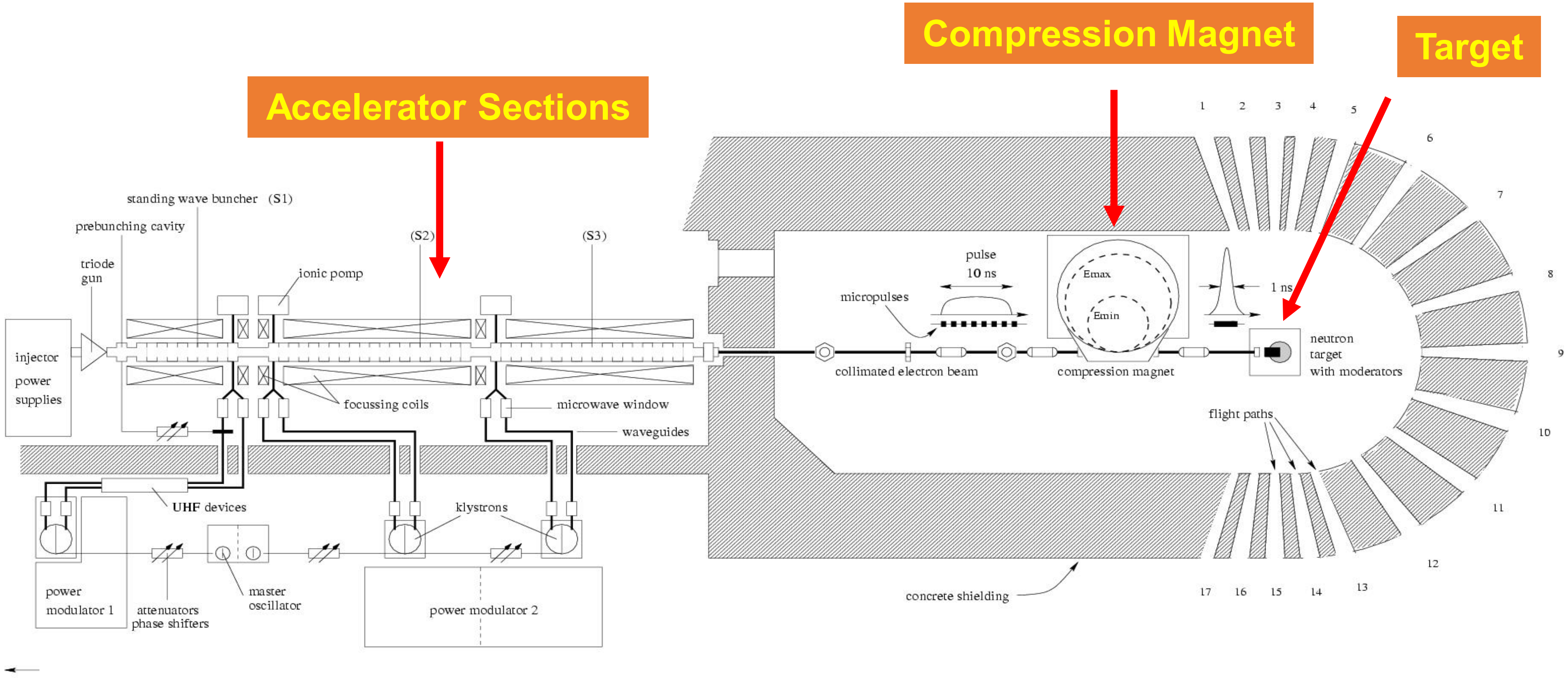
Quasi mono-energetic neutrons produced by charged-particle induced nuclear reactions

e.g. $T(d,n)^4He$



$^7Li(p,n)^7Be$	E_n: 0 - 5.3 MeV
$T(p,n)^3He$	E_n: 0 - 6.2 MeV
$D(d,n)^3He$	E_n: 1.8 - 10.1 MeV
$T(d,n)^4He$	E_n: 12.1 - 24.1 MeV

GELINA - Electron Linear Accelerator

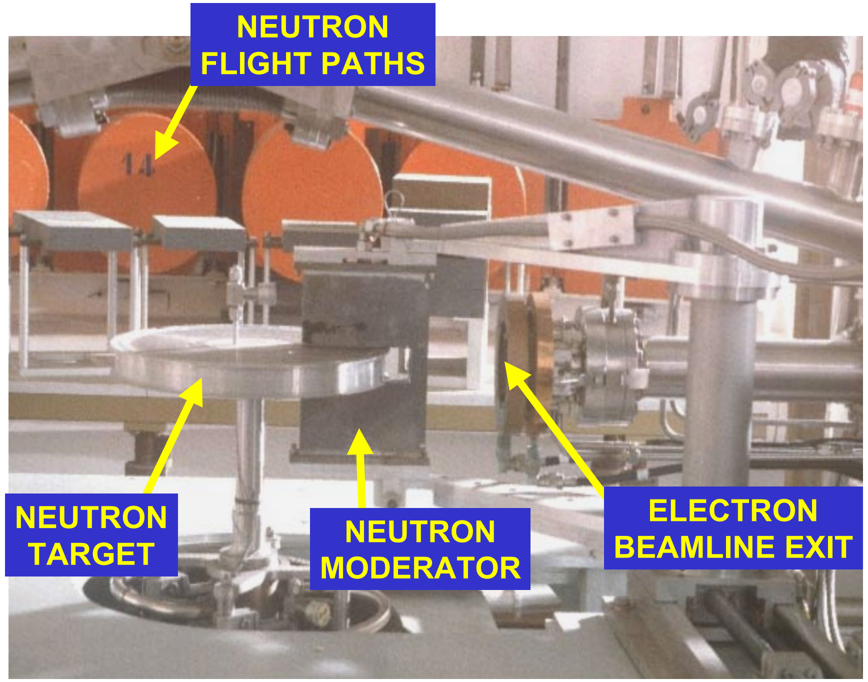


Normal Operating Parameters

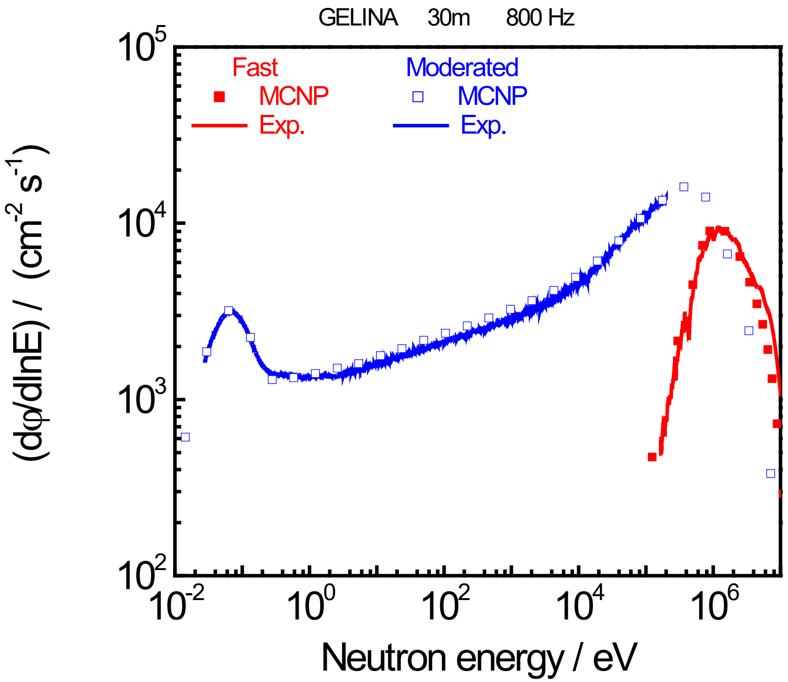
Average Current : 100 μA
Maximum Electron Energy : 150 MeV
Mean Power : 10 kW

Frequency : up to 800 Hz
Pulse Width : 1-2 ns
Neutron Flux : 2×10^{13} 1/s

GELINA - Neutron Production



- e^- **accelerated** to $E_{e^-,max} \approx 140$ MeV
- **Bremsstrahlung** in U-target
  (rotating & cooled with liquid Hg)
- **(γ, n), (γ, f)** in U-target
- Low energy neutrons by **moderation**
  (water moderator in Be-canning)



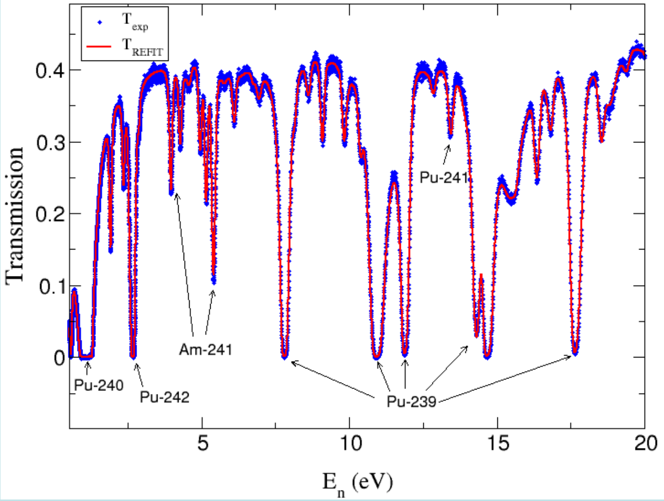
GELINA - Experimental set-ups

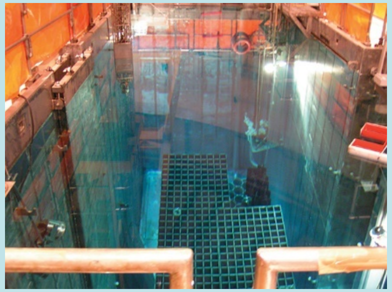
- Transcription
  - 10 m, 30m, 50 m
- Capture
  - 10 m, 30 m, 60 m
- Elastic scattering
  - 30 m
- In-elastic scattering
  - 30 m, 100 m
- Fission, (n,p), (n,α),
  - 10 m

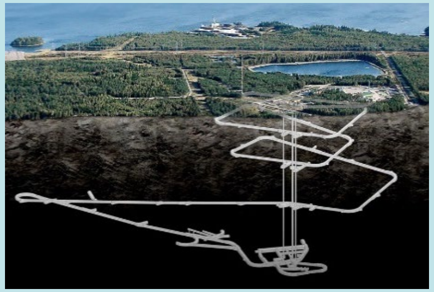
European Commission

Accurate non-destructive analysis

- Safeguards control of spent/accident fuel storage
- Use of neutron time-of-flight capture and transmission methods with accurate resonance parameters
- Method development JRC-JAEA
- Possible extensions under investigation



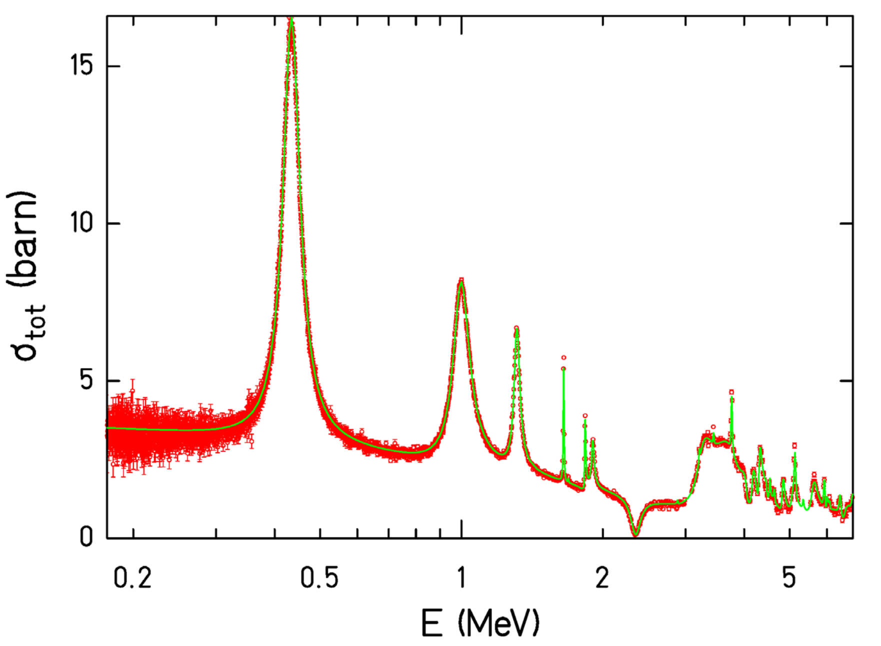


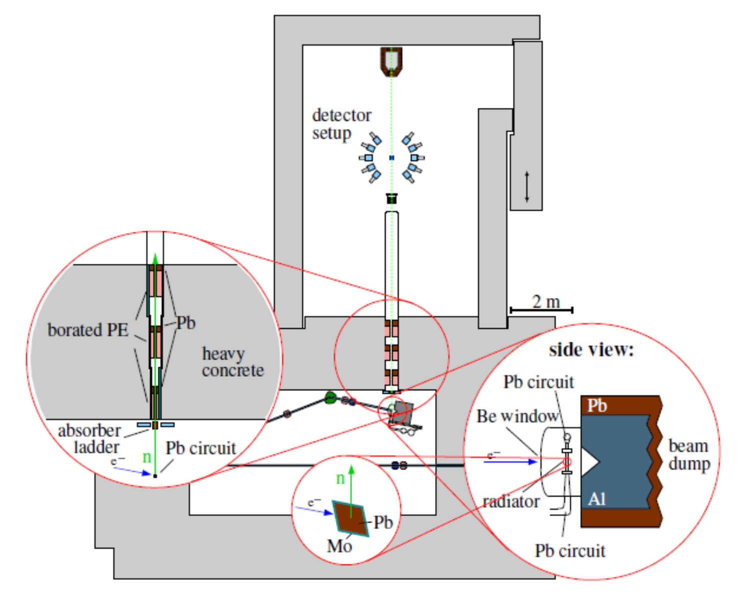


Pu-isotope	Declared %*	NRTA	Ratio
Pu-238	0.95174	0.979±0.018	1.029
Pu-239	62.6025	62.54±0.1	0.999
Pu-240	25.3526	26.25±0.02	1.039
Pu-241	1.5641	1.574±0.008	1.007
Pu-242	4.1489	3.983±0.008	0.960
Am-241	6.2870	6.316±0.008	1.005

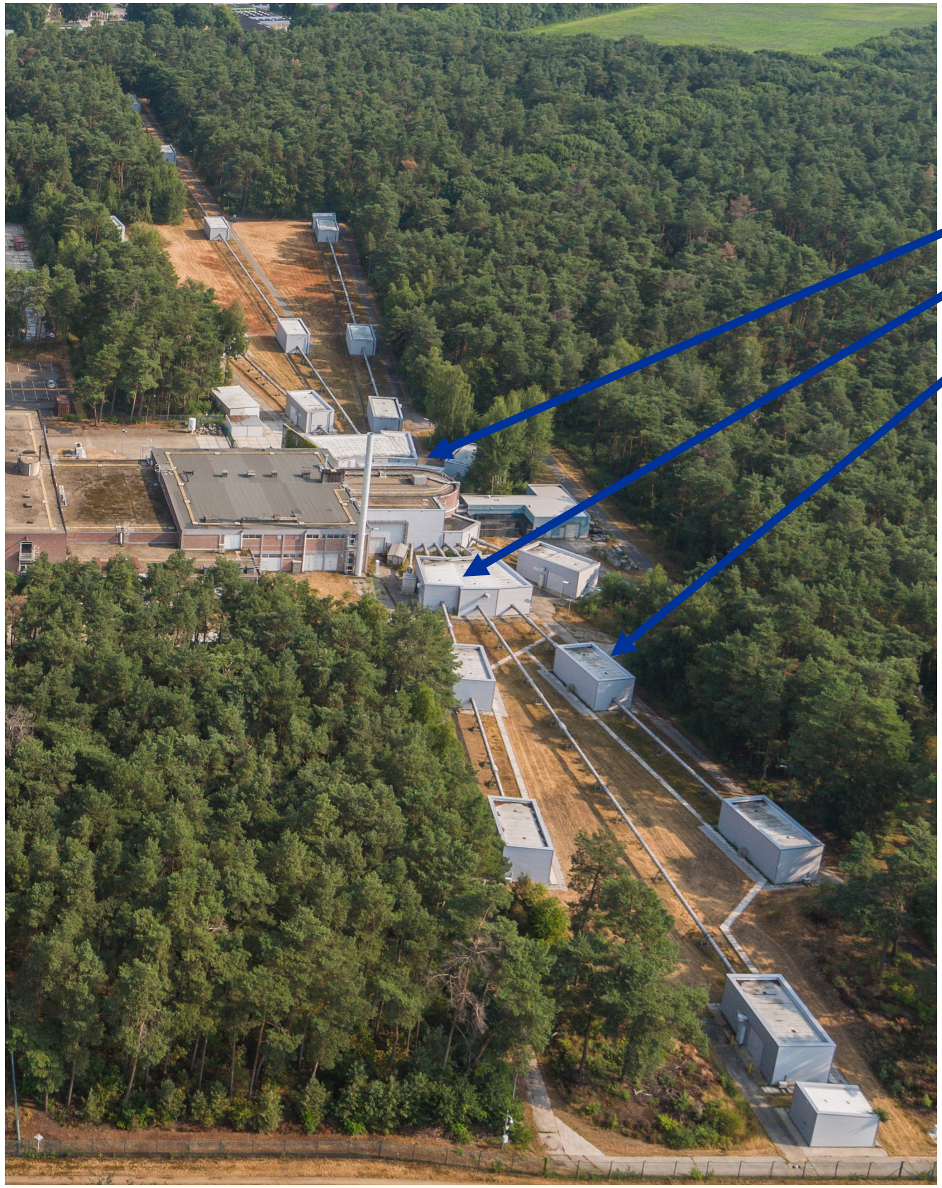
O(n,tot) – HZDR

- Transmission station HZDR – nELBE
- JEFF-3.2, response folded (green); data (red)



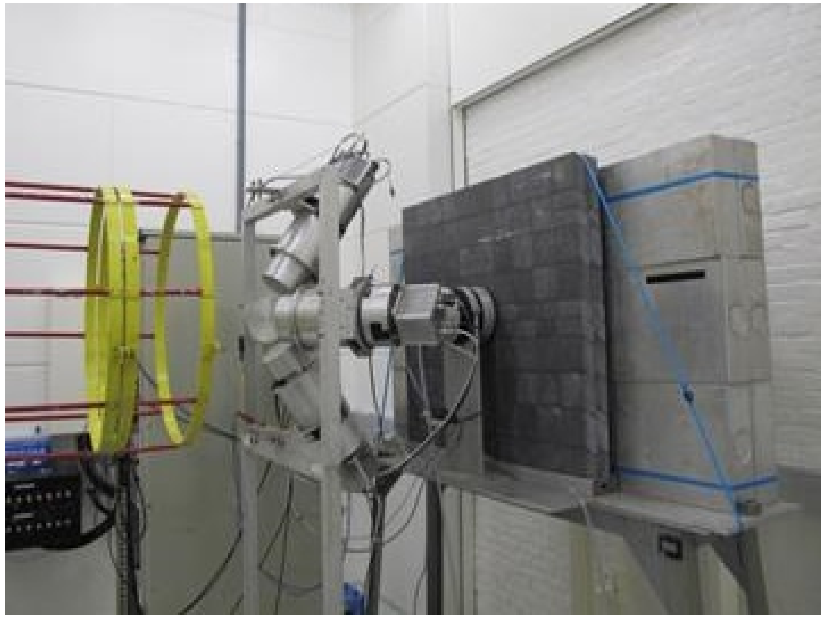


GELINA - Capture

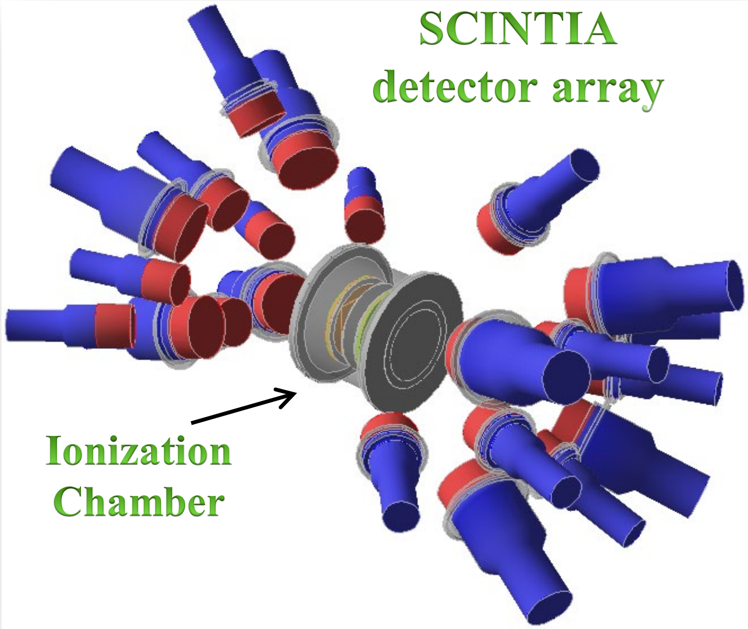


Capture – (n,gamma)

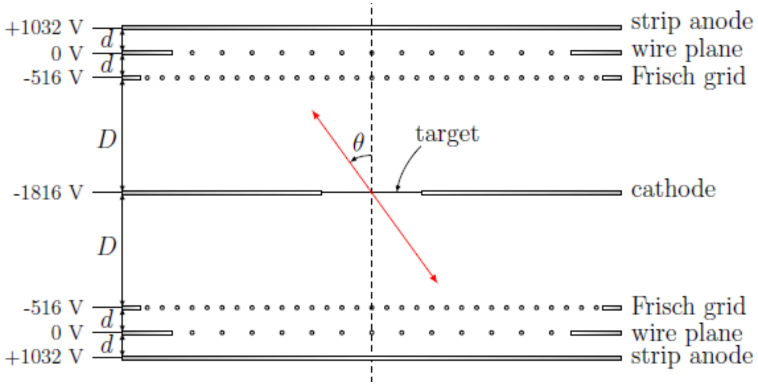
- 10 m, 30 m, 60 m



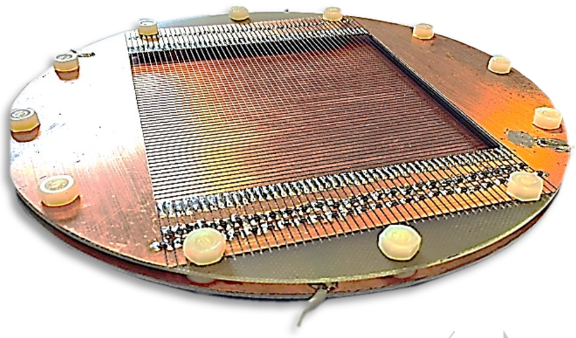
Fission fragment properties and prompt fission neutrons



- Fission fragments by **twin position sensitive IC** (2PIC)
  - Fragment energy
  - Fragment masses - 2E-technique
  - Fission axis orientation
- Prompt fission neutrons
  - 22 x **Scintillators**
  - Energy : time-of-flight

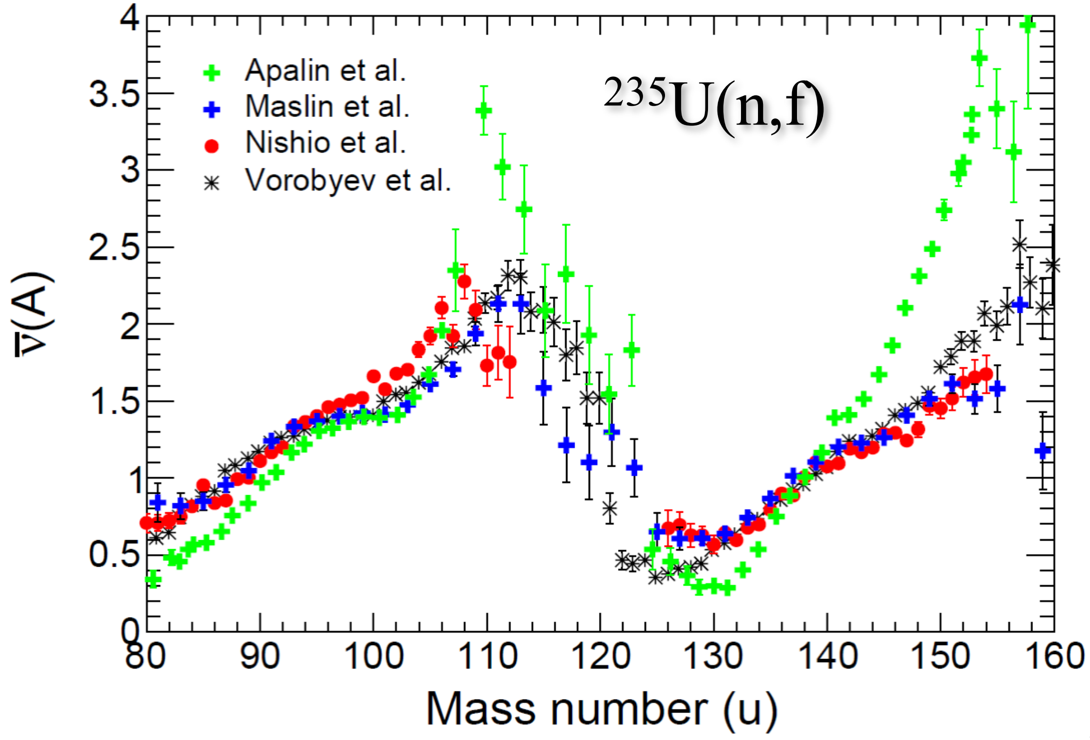


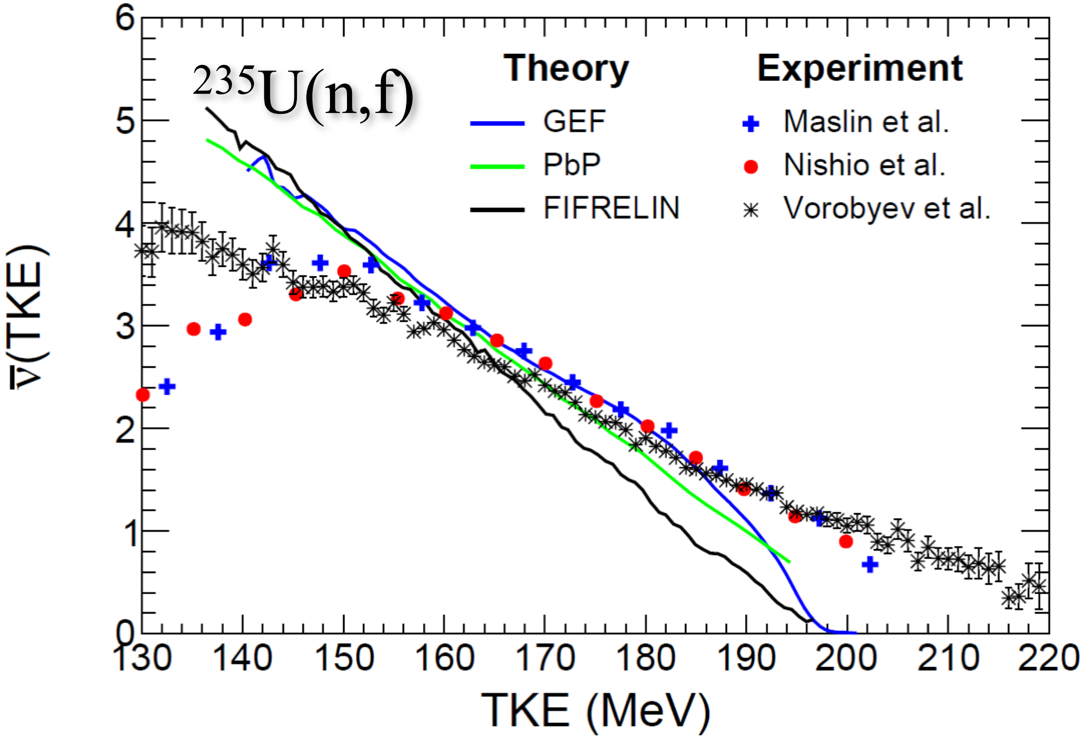
Position sensitive electrode



Neutron multiplicity
versus fragment mass and total kinetic energy

Available data on neutron multiplicity ν(A,TKE) show (strong) discrepancies

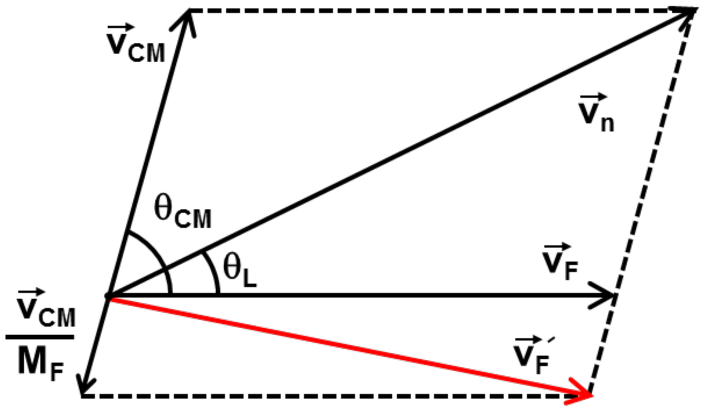




Experiment: ^{252}Cf(sf)

The effect of neutron recoil on experimental data

momentum transfer ❾change in fragment energy



$$E_f \approx E_i \frac{m_f}{m_i} - v_i p_{c.m.} \cos\theta_{c.m.}$$

No coincidence requirement (or 4π neutron detector)

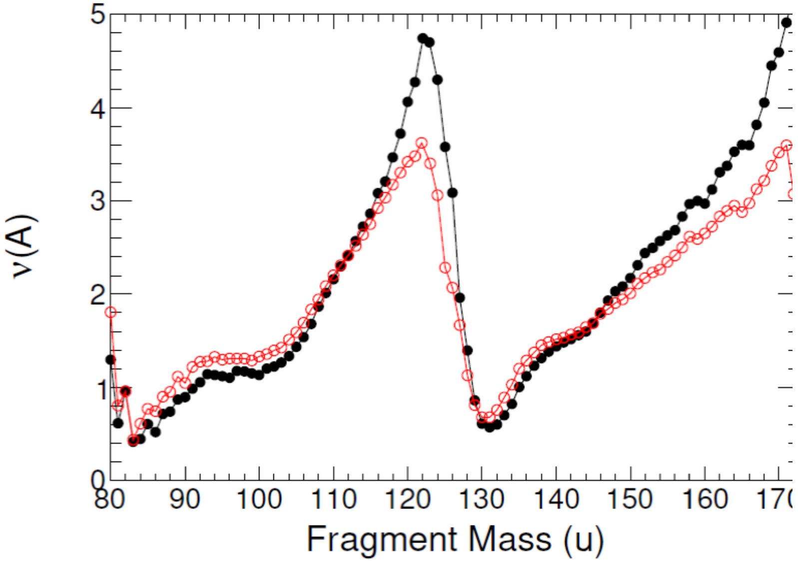
- ❾ 2nd term averages out

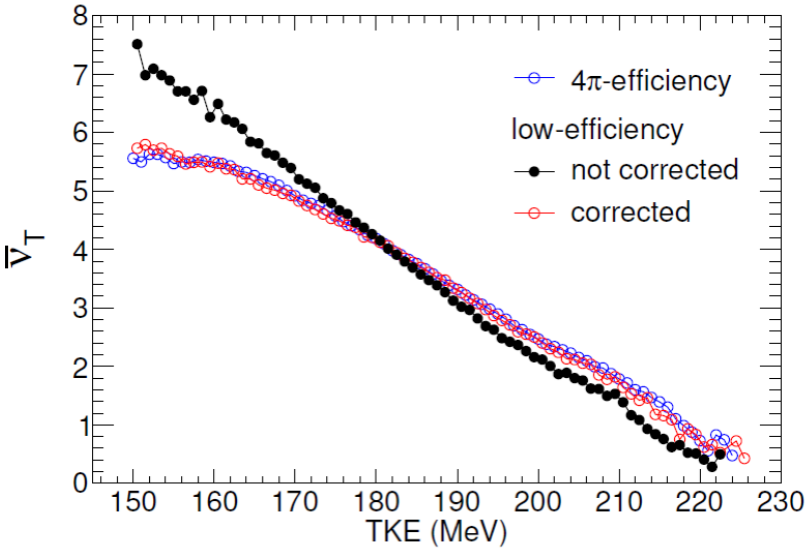
$$\langle \cos\theta_{CM} \rangle = 0$$

Fragment neutron coincidence

- ❾ biased selection

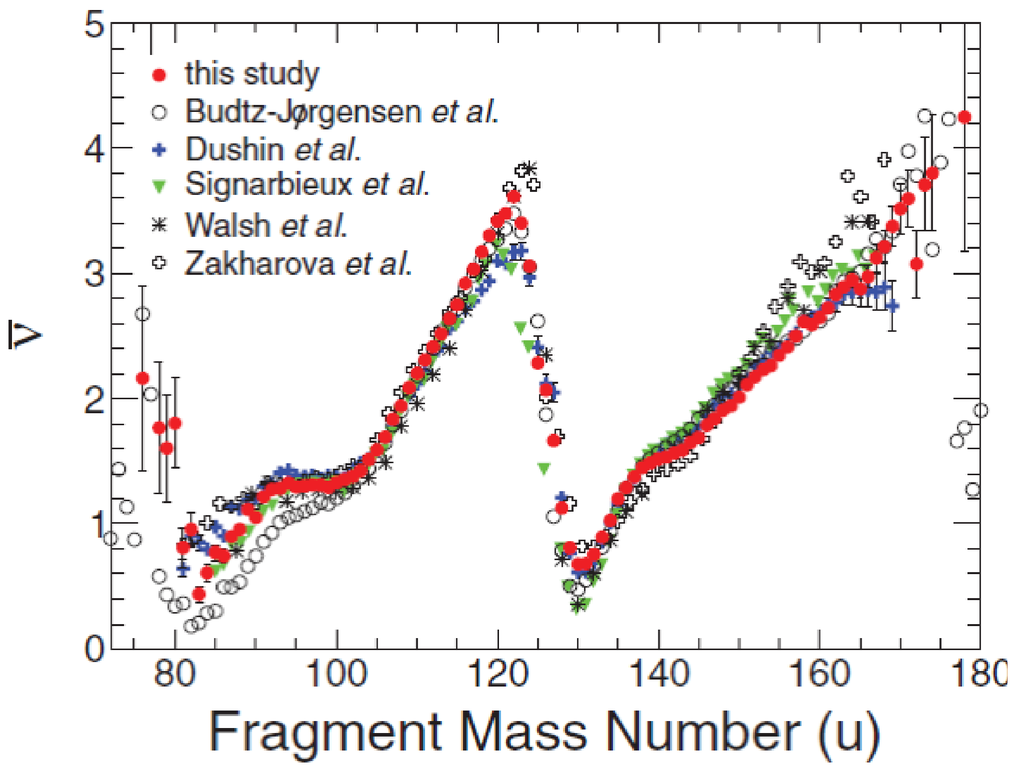
$$\langle \cos\theta_{CM} \rangle \neq 0$$

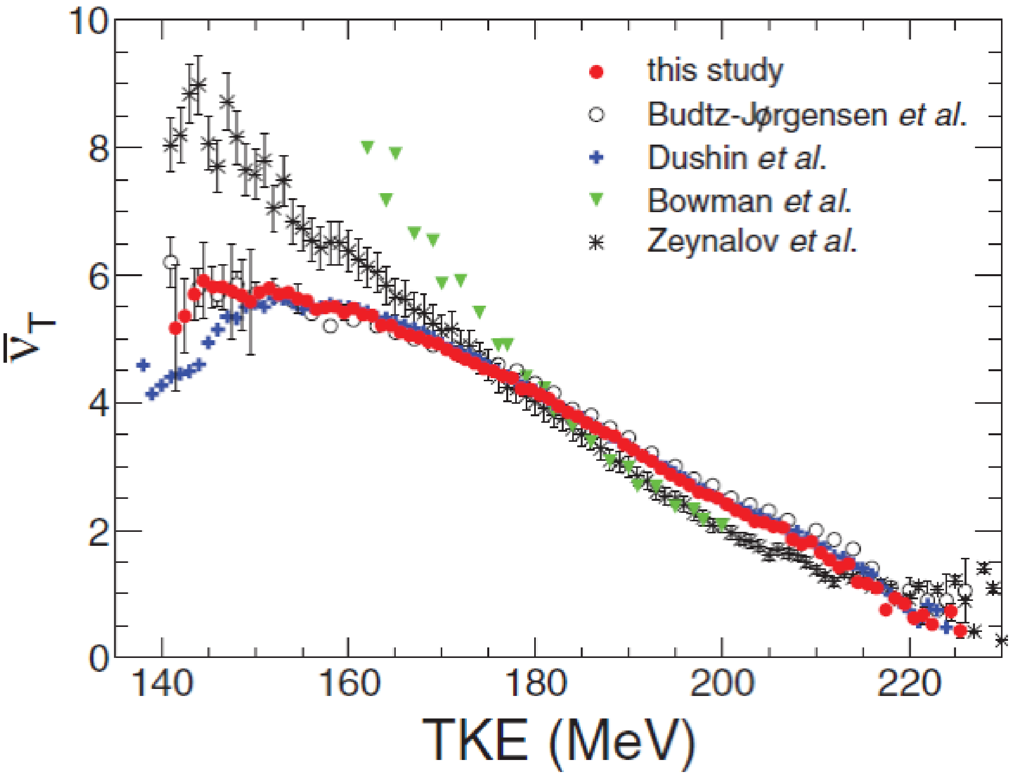




Experiment: ^{252}Cf(sf)

- υ(A,TKE) compares well literature
  - Specifically υ(TKE) with scintillation tank measurement (Dushin et al.)
- Discrepant data of Bowmann, (Zeynalov) due to recoil correction

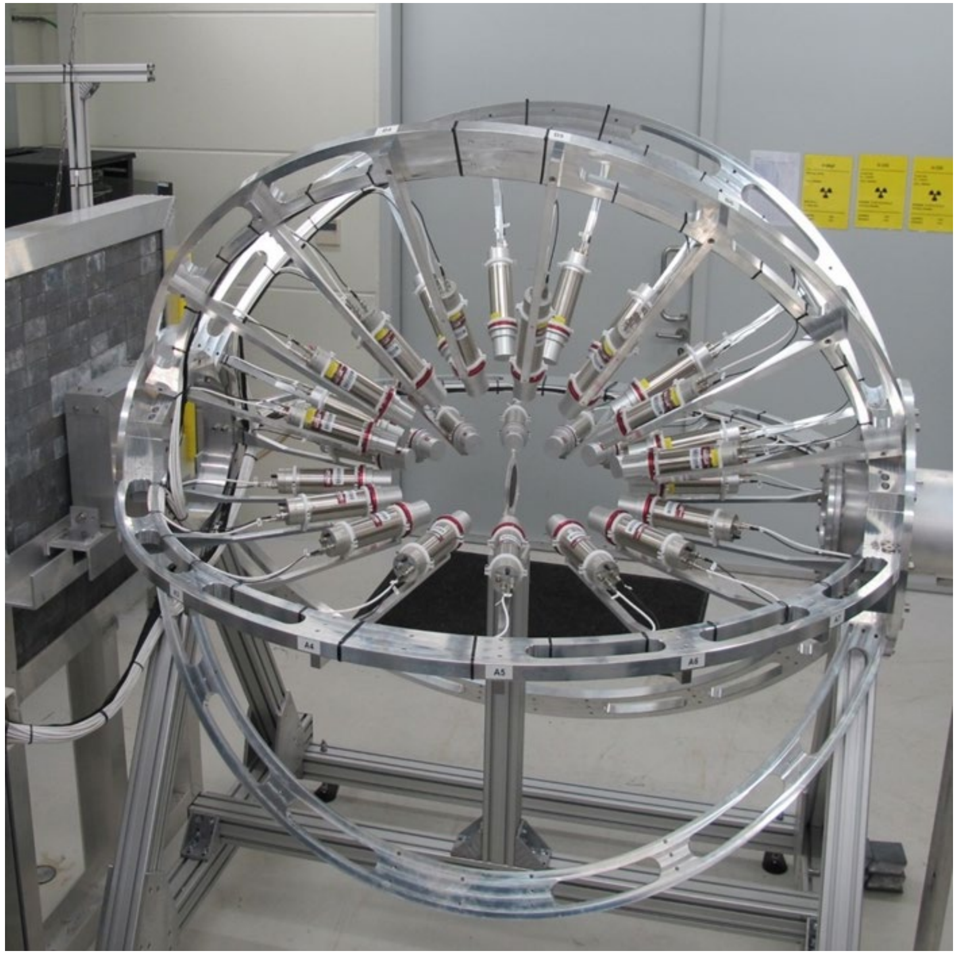


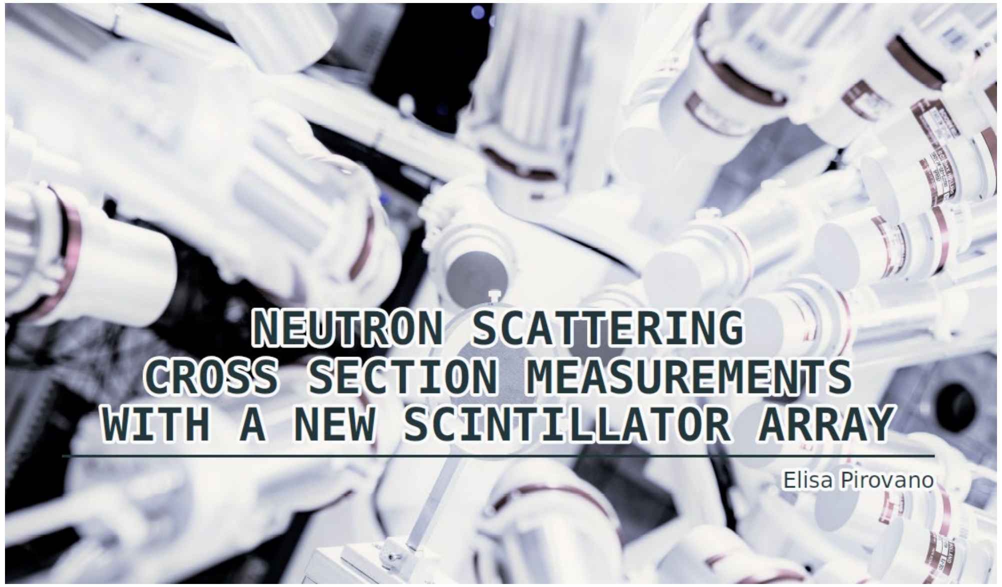


ELISA

ELastic and Inelastic Scattering Array

- 32 **liquid organic scintillators**
    - 16 EJ301 (NE213)
    - 16 EJ315 (C6D6)
- **n/g discrimination** via pulse shape discrimination
- Time resolution ~1 ns
- Neutron flux monitoring with a ^{235}U fission chamber





NEUTRON SCATTERING
CROSS SECTION MEASUREMENTS
WITH A NEW SCINTILLATOR ARRAY

Elisa Pirovano

Example of a scattering measurement with ELISA

n+^{56}Fe (thesis E. Pirovano, PRC99(2019)024601)

Fundamental physics:

- nucleon-nucleus potentials
- below 5 MeV the optical model does not reproduce the behaviour of the cross section

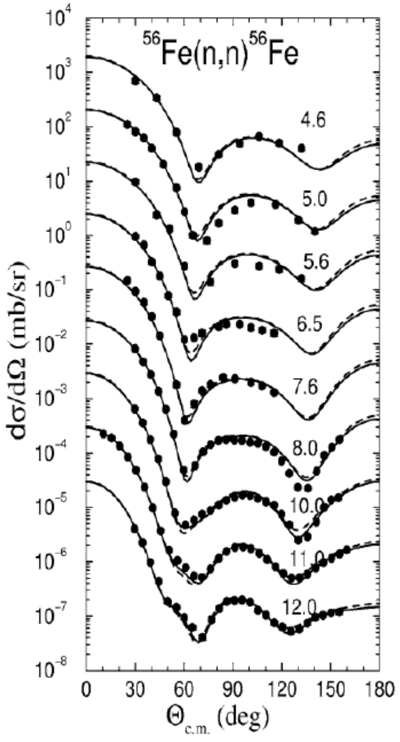
Applications:

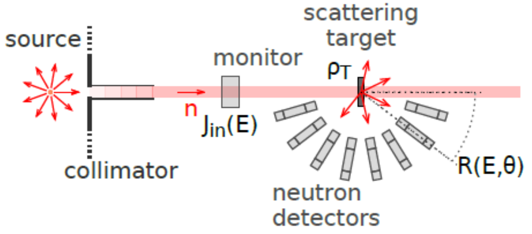
- dark matter detectors' calibration
- energy degrader for medical beam lines
- energy production

CIELO pilot project:

^{1}H, ^{16}O, ^{56}Fe, ^{235,238}U, ^{239}Pu

n-^{56}Fe scattering





- corrections
  - detected photons
  - background
  - multiple scattering
- separation elastic/inelastic events

scattering experiment

reaction rate

incoming neutron current

$$\frac{d\sigma}{d\Omega}(E,\theta) = \frac{R(E,\theta)}{\varepsilon(E')\,\Delta\Omega\, n_T J_{in}(E)}$$

efficiency

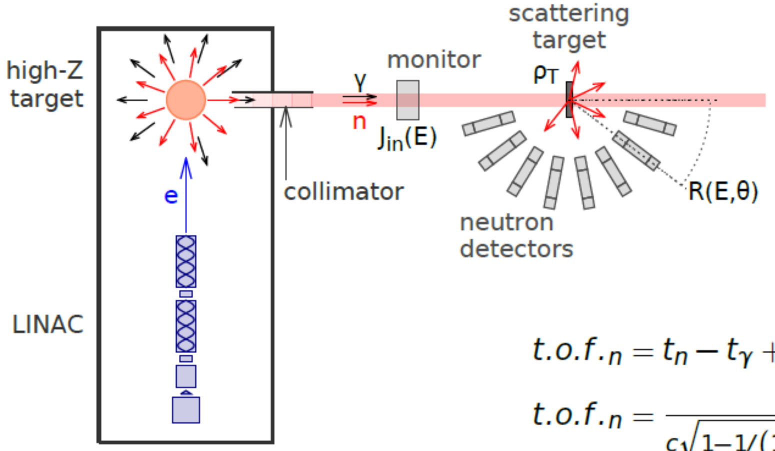
solid angle

target areal density

Example of a scattering measurement with ELISA

n+^{56}Fe (thesis E. Pirovano, PRC99(2019)024601)

neutron t.o.f. technique



$$t.o.f._n = t_n - t_\gamma + t.o.f._\gamma$$

$$t.o.f._n = \underbrace{\frac{L}{c\sqrt{1-1/(1+E/mc^2)^2}}}_{\text{before the collision}} + \underbrace{\frac{L'}{c\sqrt{1-1/(1+E'/mc^2)^2}}}_{\text{after the collision}}$$

$$2E'(Mc^2+mc^2) - 2E(Mc^2-mc^2) + 2E'E + E^*(2Mc^2+E^*) = 2c^2 p p' \cos\theta$$

detector array

Parallel plate ionization chamber
- 8 UF$_4$ deposits, 99.94%atom of ^{235}U
- 4.095(4) mg ^{235}U/cm^2

32 liquid organic scintillators
2×8 EJ301 (NE213)
2×8 EJ315 (C$_6$D$_6$)
→ n/γ discrimination via PSD
→ time resolution ~1 ns
→ consistency & repeatability checks

Example of a scattering measurement with ELISA

n+^{56}Fe (thesis E. Pirovano, PRC99(2019)024601)

8× organic scintillators

➡ coefficients for $P_1(\theta)$, $P_2(\theta)$, maybe $P_3(\theta)$

Numerical integration for the total cross-section:

$$\sigma = 2\pi \int_{-1}^{1} \frac{d\sigma}{d\Omega}(x)\,dx = 2\pi \sum_{i=1}^{8} w_i \frac{d\sigma}{d\Omega}(x$$

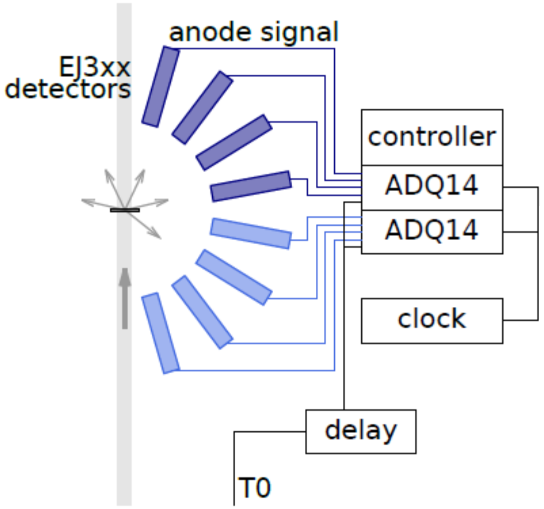
with

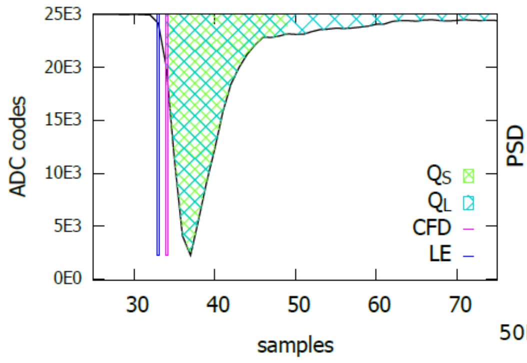
- $x_i = cos\theta_i$ zeros of the Legendre polynomial $P_8(x)$
- w_i weight factors

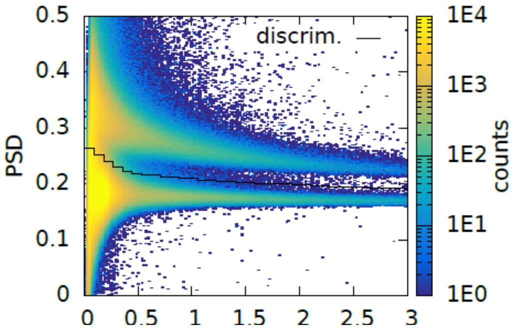
Exact result for polynomials of degree 15 or less

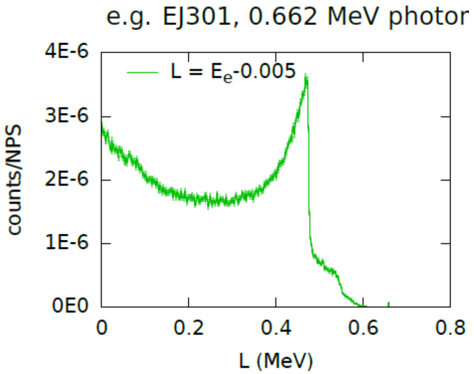
➡ ok for carbon, iron, deuterium up to 6 MeV

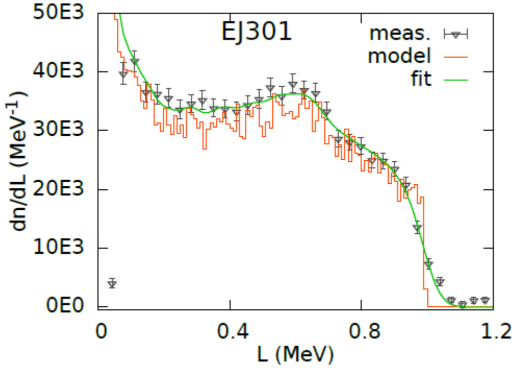
scintillator array

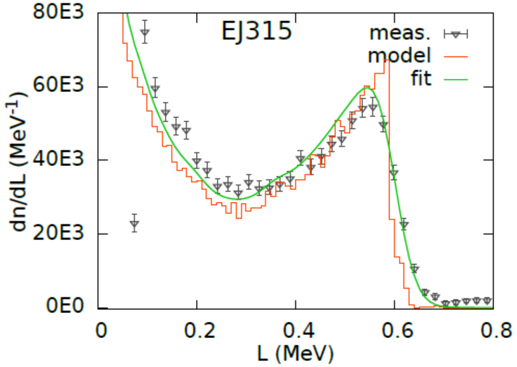


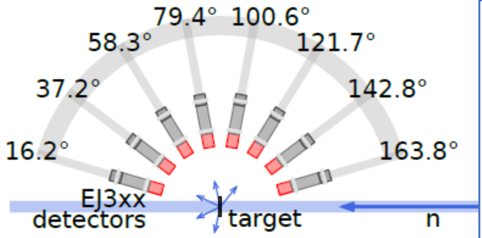












detector at θ = 163.8°

t.o.f. = 976–981 ns

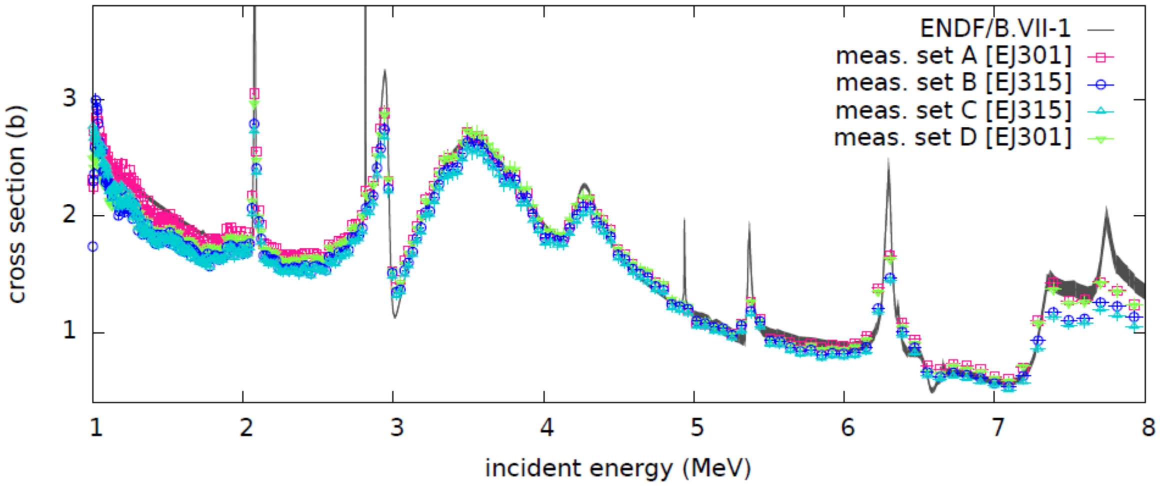
$$Y(t.o.f.,\theta) = \frac{1-F_{msc}(t.o.f.,\theta)}{\varepsilon(E')\big|_{L_{THR}}\,\Delta\Omega} \int_{L_{THR}} R_{fit}(L,E')\,dL$$

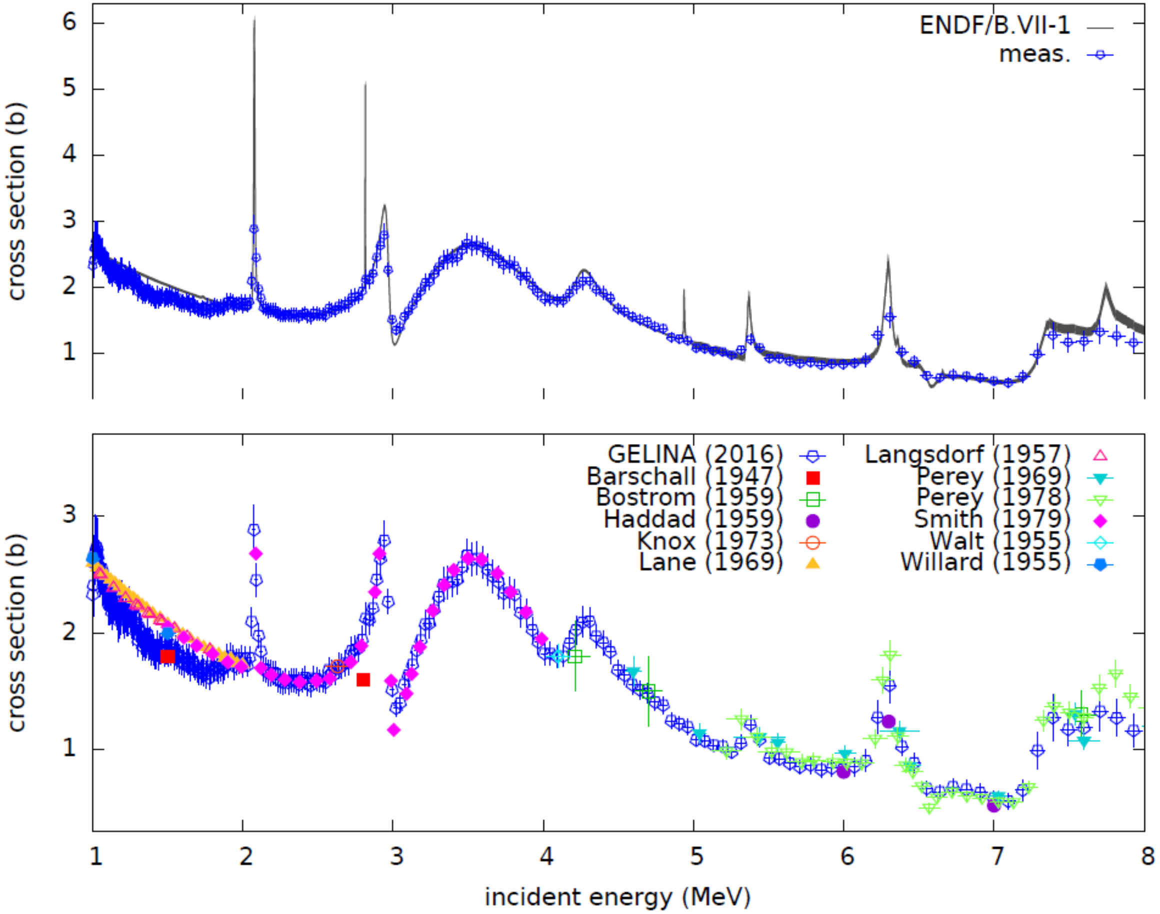
European Commission

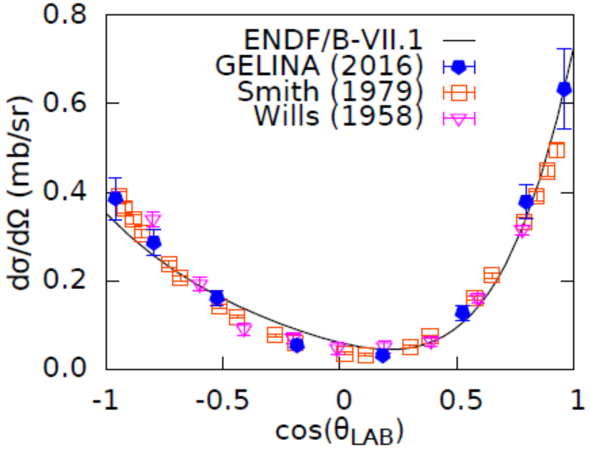
Example of a scattering measurement with ELISA

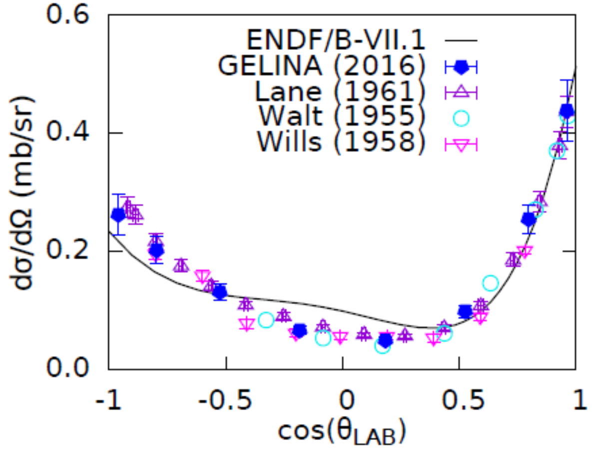
n+^{56}Fe (thesis E. Pirovano, PRC99(2019)024601)

four detector sets:



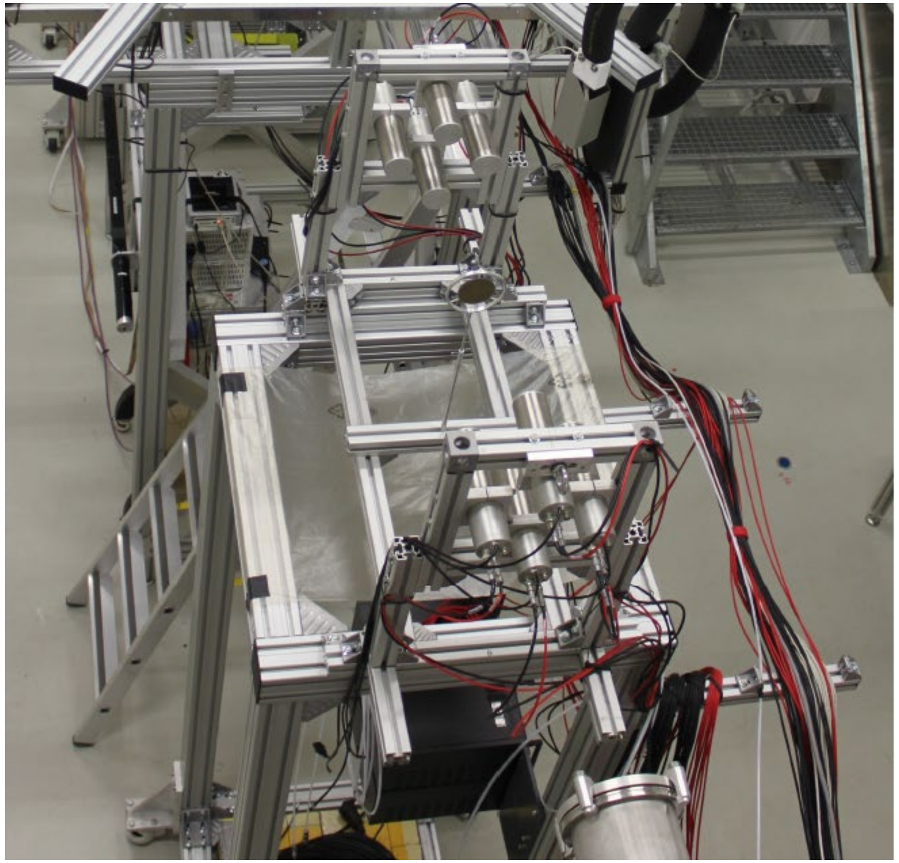






Example of a scattering measurement at nELBE (HZDR)

Thesis Elisa Pirovano, PRC95(2017)024601

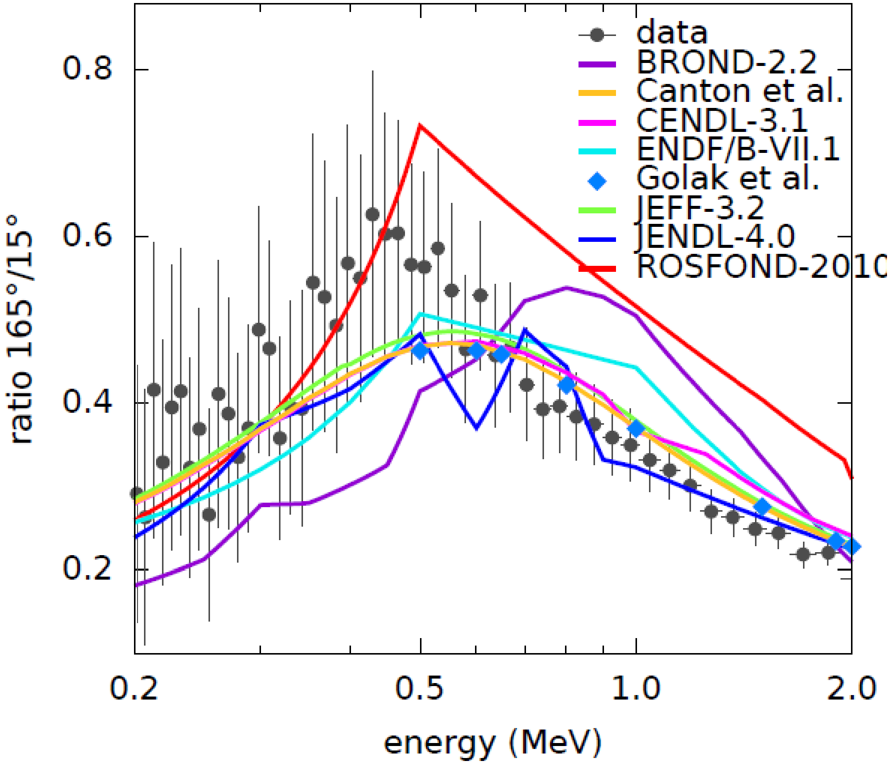


n-D scattering

- experiment at nELBE (HZDR, Dresden)
- energy range: 0.2 – 2 MeV
- ^{6}Li-glass detectors at 15° and 165°

to determine the ratio:

$$\left.\frac{d\sigma}{d\Omega}\right|_{165^\circ} \text{ over } \left.\frac{d\sigma}{d\Omega}\right|_{15^\circ}$$

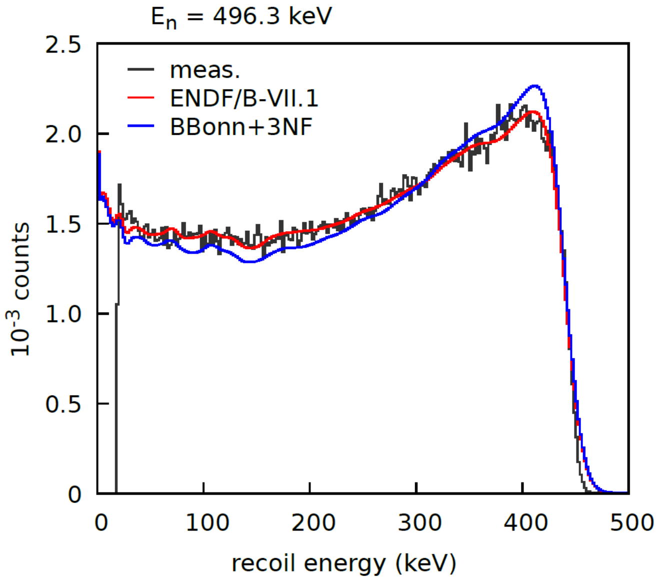


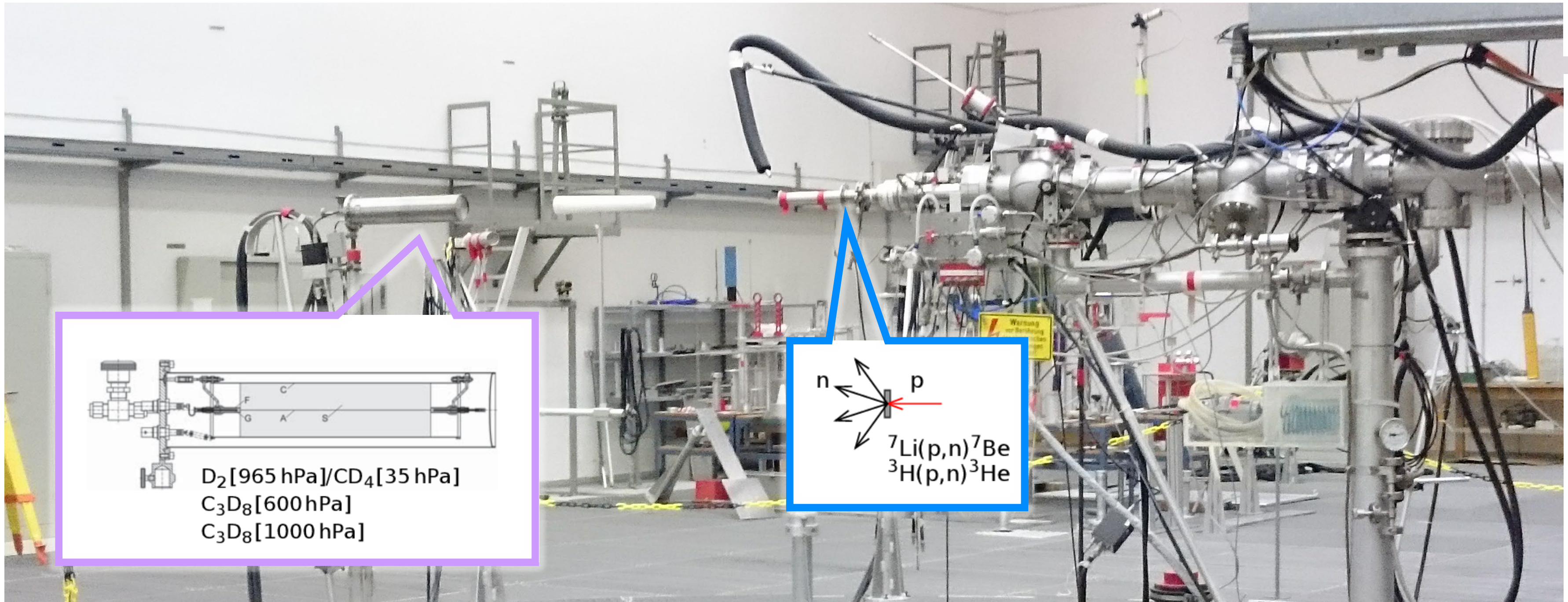
400 – 875 keV

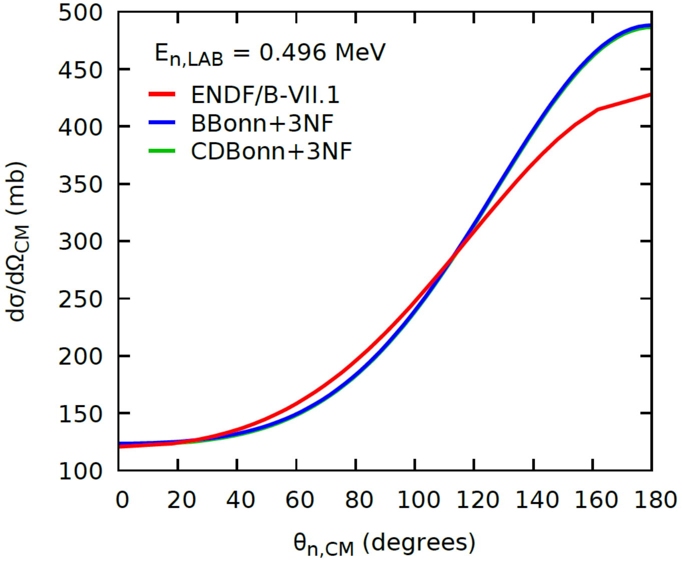
875 – 2500 keV

- measurement at the PTB VdG; Elisa Pirovano et al.
- quasi-monoenergetic neutrons via ^{7}Li(p,n) or ^{3}H(p,n)
- energy range 400 keV – 2.5 MeV
- different gas mixtures/pressures to limit the escape of recoil deuterons

	neutron energy:
D_2/CD_4	400 – 625 keV
C_3D_8 600 hPa	625 keV – 1.25 MeV
C_3D_8 1000 hPa	1.25 – 2.5 MeV



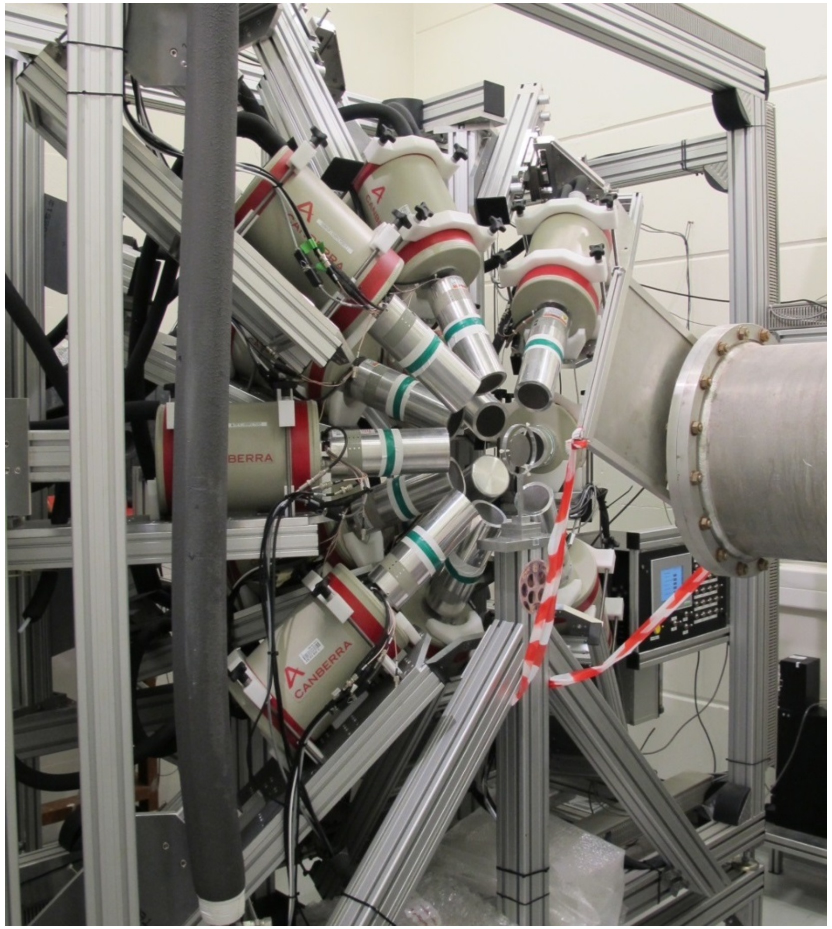




GAINS

Gamma Array for Inelastic Neutron Scattering

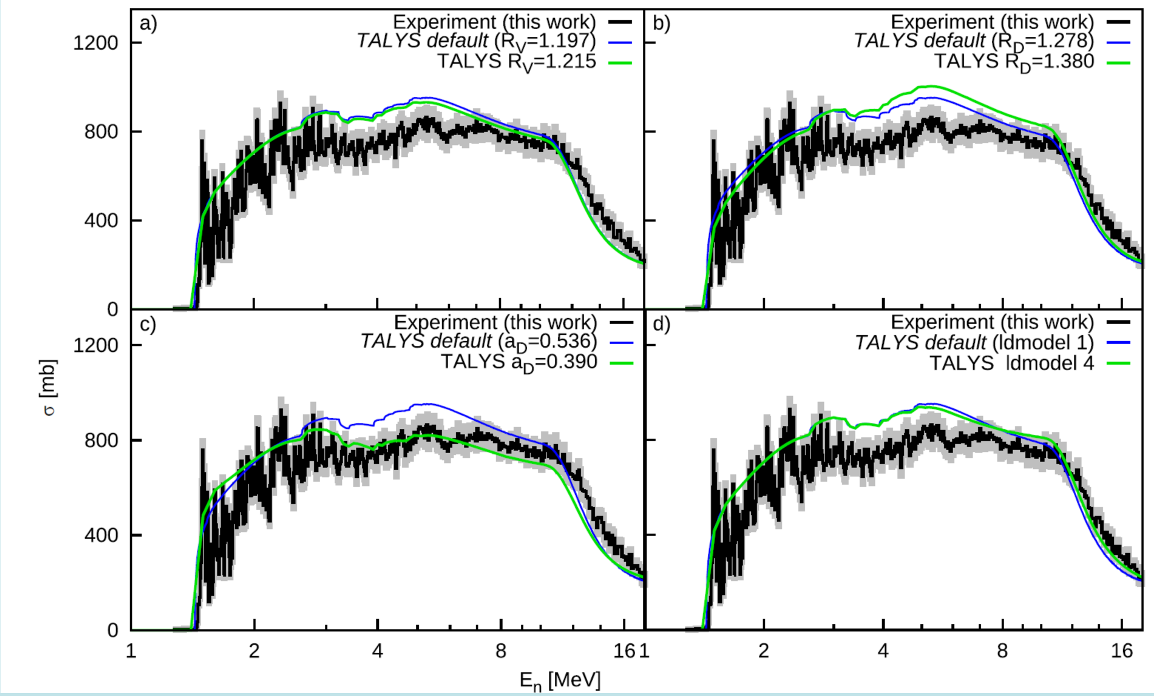
- 12 **HPGe** detectors
- Neutron flux monitoring with a ^{235}U fission chamber
- ^{7}Li, ^{12}C, **^{16}O**, ^{23}Na, ^{24}Mg, ^{28}Si, ^{nat}Ti, ^{nat}Mo, ^{52}Cr, **^{54}Fe**, ^{56}Fe, ^{57}Fe, **^{58}Ni, ^{60}Ni**, ^{76}Ge, ^{nat}Zr, ^{206,207,208}Pb, ^{209}Bi, ^{54}Fe



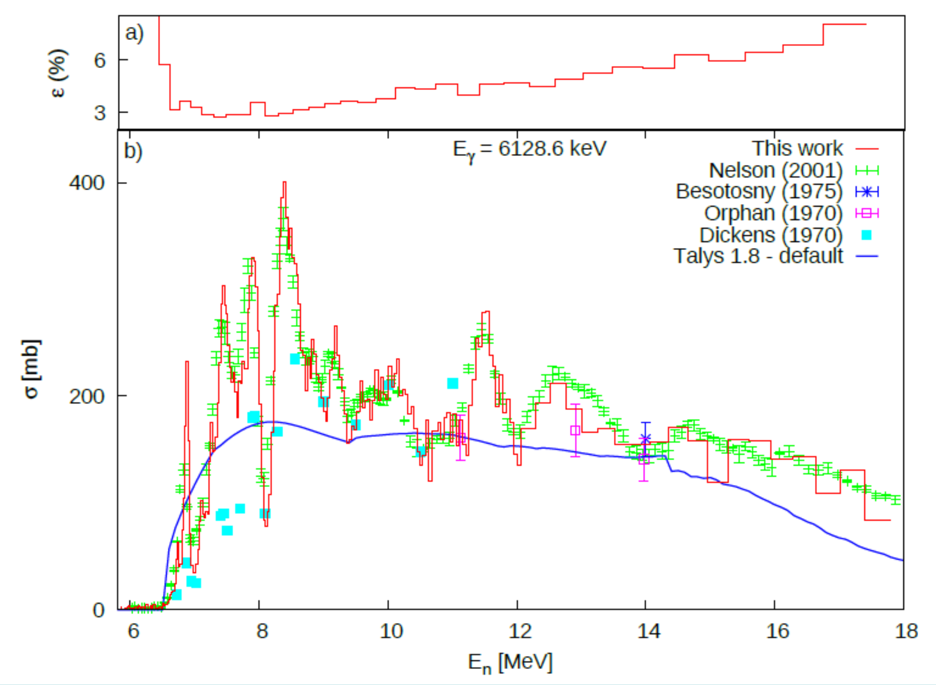
Inelastic scattering with GAINS & Grapheme

Collaboration with CNRS-IPHC, HZDR, IFIN-HH, PTB

^{54}Fe: 2+ to g.s. decay - Adina Olacel



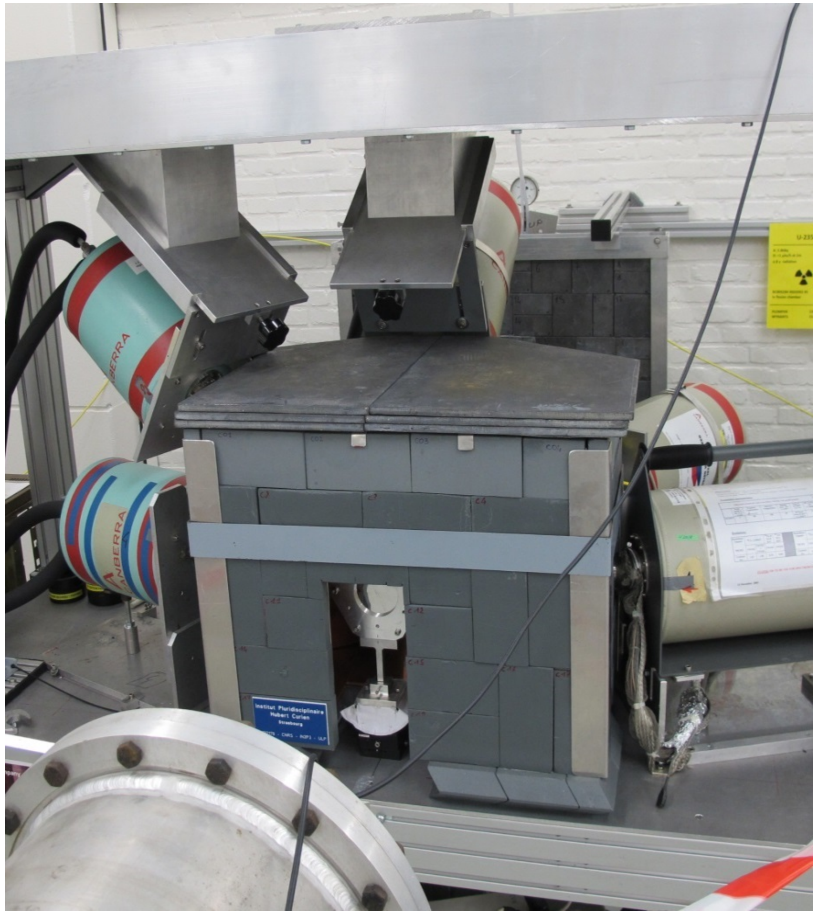
^{16}O: 3- to g.s. decay – Marian Boromiza



GRAPhEME

(GeRmanium array for Actinides PrEcise MEasurements)

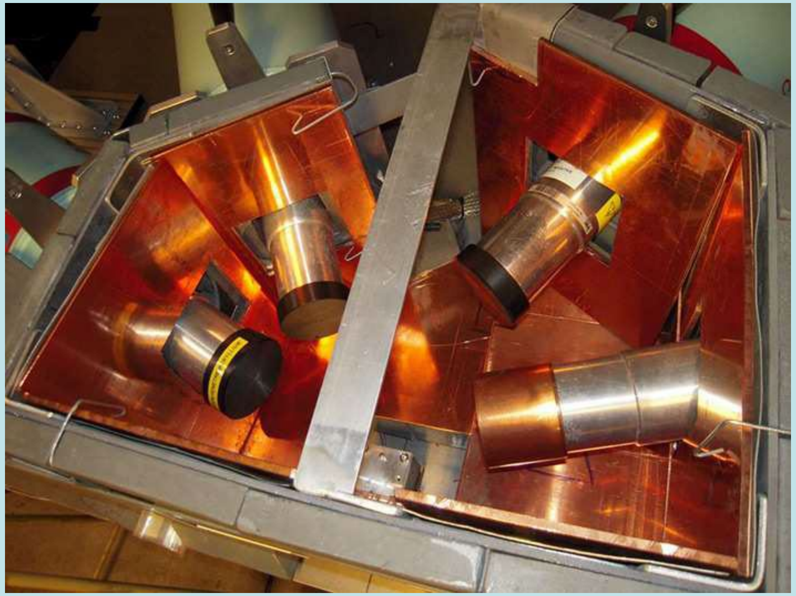
- **Inelastic** scattering set-up
- 5 planar **HPGe** detectors, one segmented (36 pixels)
- Neutron flux monitoring with a ^{235}U fission chamber

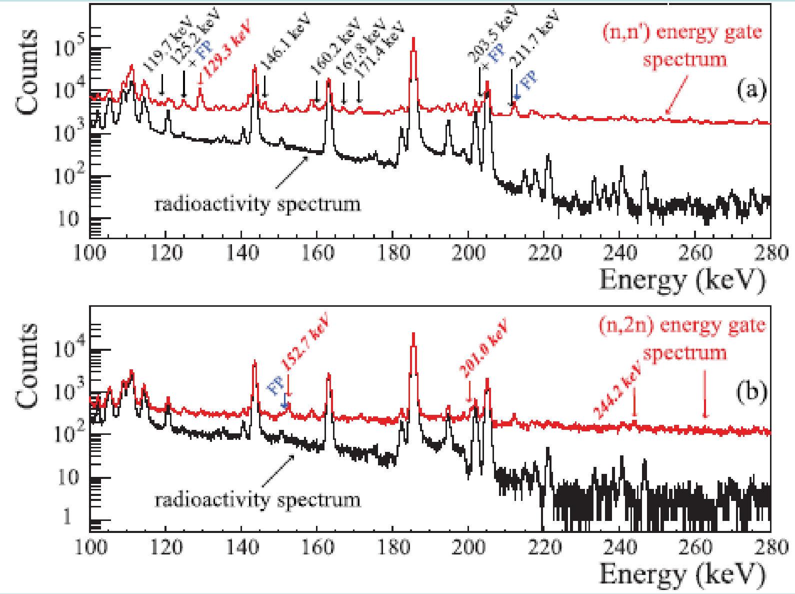


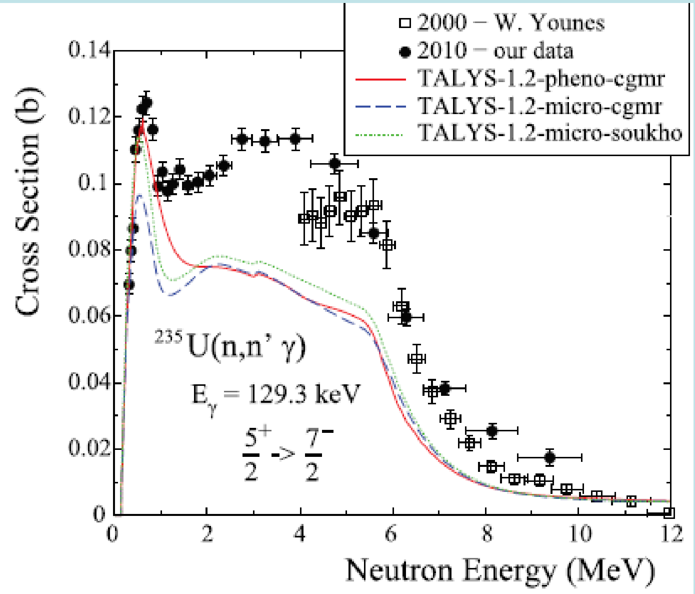
Inelastic scattering with GAINS & Grapheme

Collaboration with CNRS-IPHC, HZDR, IFIN-HH, PTB

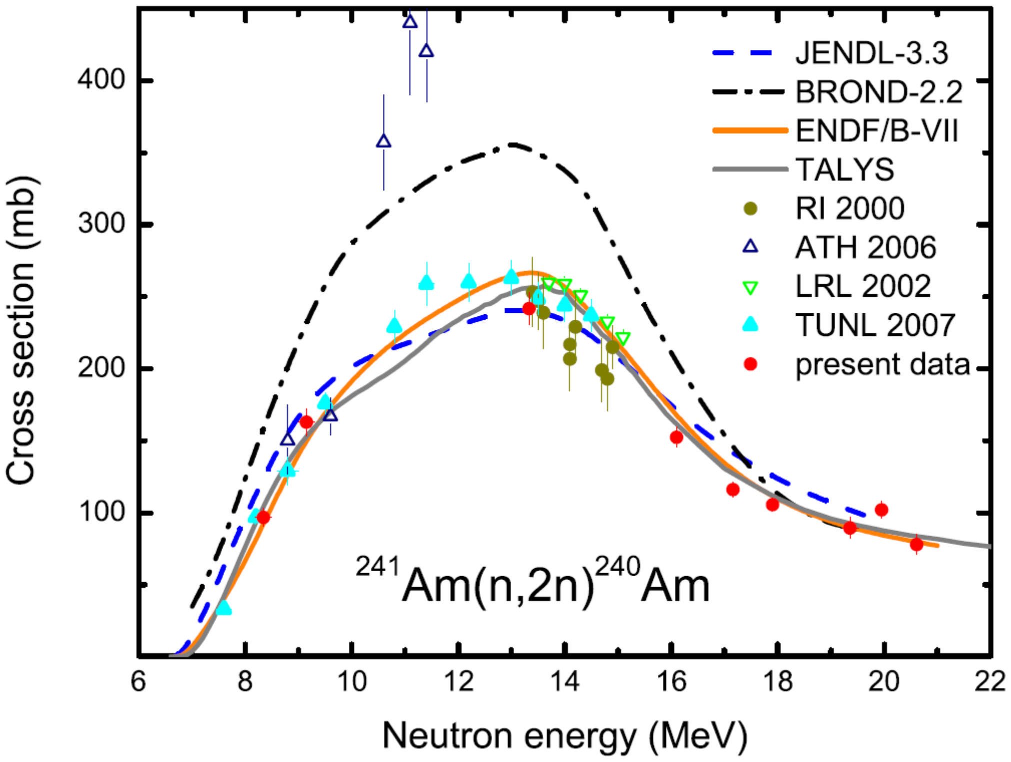
M. Kerveno et al., European Physical Journal A 51 (2015) 167







Uncertainties of measurements



Methodology

“Evaluation of measurement data - Guide to the expression of uncertainty in measurement”

Joint Committee for Guides in Metrology, *JCGM 100:2008, www.bipm.org (2008)*

Developed by experts for measurements relied upon in application (SI system)

General

Systematic

Standardized

Uncertainties

Error

Every measurement is in error

All measurements are imperfect

- imperfect realization of quantity
- random variations
- inadequate corrections
- incomplete knowledge
- *number of nuclei*
- *detection efficiency*
- *fluence measurement*
- *multiple scattering*
- *standard cross section*
- *calibration sources*
- *statistics*

- *Error is unknowable*
- *Sources of error may be recognized and should be corrected for:*

Measurement result = corrected result

- Systematic error

  Mean error that would result from infinitely many measurements under repeatability conditions

- Correction (factor)

  Value added (multiplied) to compensate for systematic error

- Random error

  Error minus systematic error

European Commission

Procedure

1. Set up mathematical relation measured quantity (Y) and input quantities (X)
2. Estimate the inputs (x)
3. Estimate the standard uncertainties for the inputs: u(x)
4. Estimate covariances of input uncertainties: $u(x_i,x_j)$
5. Find the measured quantity (y) from the inputs
6. Estimate the combined standard uncertainties and covariances $u_c(y_k)$ and $u_c(y_k,y_l)$
7. Report result with standard uncertainties and covariances and uncertainty budget.

$$Y_k = f_k(X_1, X_2, ...X_N)$$

$$X_i \rightarrow x_i$$

$$\rightarrow u(x_i)$$

$$\rightarrow u(x_i, x_j) = C(x_i, x_j)u(x_i)u(x_j)$$

$$y_k = f_k(x_1, x_2, ...x_N)$$

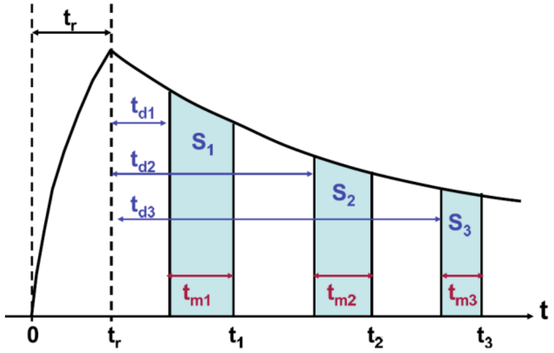
$$u_c^2(y_k) = \sum_{i=1}^{N}\sum_{j=1}^{N} \frac{\partial f_k}{\partial x_i}\frac{\partial f_k}{\partial x_j} u(x_i, x_j)$$

$$u_c(y_k, y_l) = \sum_{i=1}^{N}\sum_{j=1}^{N} \frac{\partial f_k}{\partial x_i}\frac{\partial f_l}{\partial x_j} u(x_i, x_j)$$

$$u_c(y_k, y_l) = \sum_{i=1}^{N}\sum_{j=1}^{N} S_{ki} S_{lj} C(x_i, x_j) r(x_i) r(x_j)$$

Activation data evaluation

$$\sigma_{\mathrm{Am}} = \sigma_{\mathrm{Al}} \frac{S_{\mathrm{Am}}}{S_{\mathrm{Al}}} \frac{\left[I \epsilon f_{\Sigma} f_r n \Phi_0 \right]_{\mathrm{Al}}}{\left[I \epsilon f_{\Sigma} f_r n \Phi_0 \right]_{\mathrm{Am}}} \cdot \prod_k \frac{C_{\mathrm{k,Am}}}{C_{\mathrm{k,Al}}}$$



σ_{Al}	Reference cross section
S	Counts for gamma
I	gamma-ray intensity
ε	absolute detection efficiency
f_{Σ}	cooling time factor
f_r	irradiation time factor
n	number of nuclides
Φ_0	mean neutron flux
C_k	correction factors for * low energy neutrons * intensity fluctuations

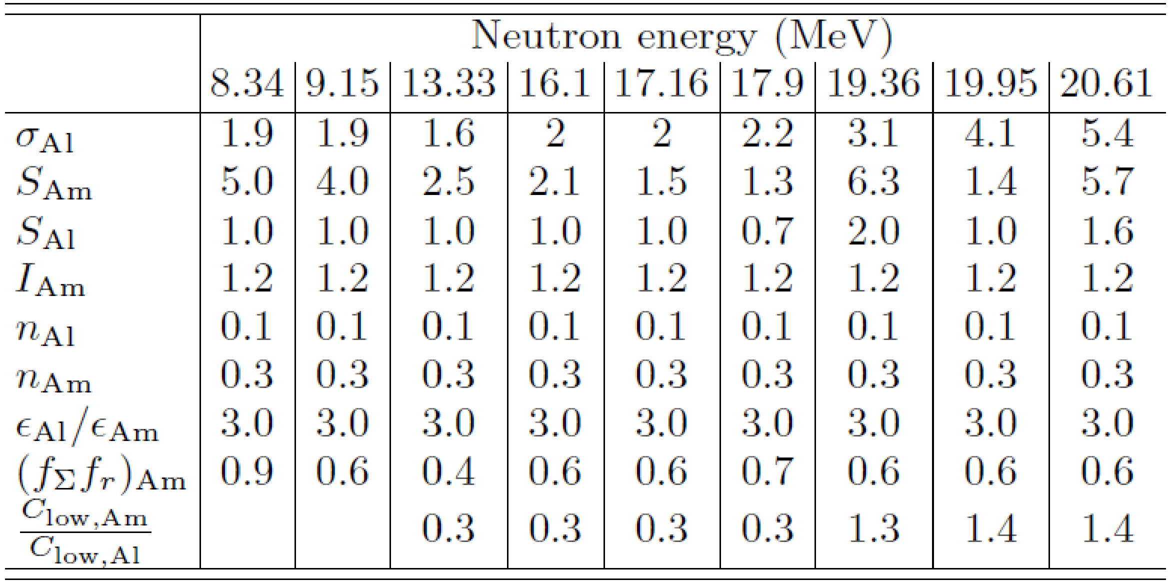
$$f_{\Sigma} = \frac{1}{\lambda} \sum e^{-\lambda t_{d_i}} \left(1 - e^{-\lambda t_{m_i}}\right)$$

$$f_r = 1 - e^{-\lambda t_r}$$

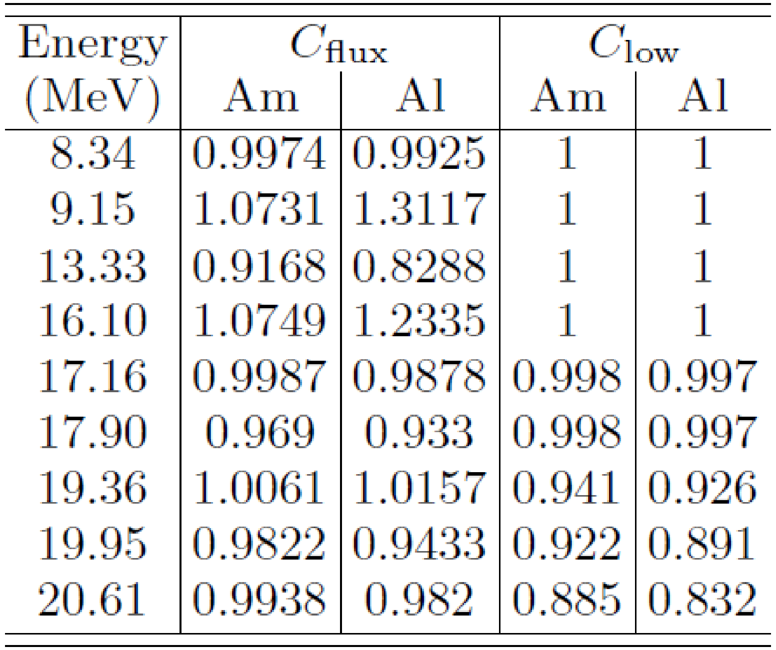
$$C_{\mathrm{flux}} = \frac{\bar{\Phi}\left(1 - e^{-\lambda t_r}\right)}{\sum_{i=1}^{m} \Phi_i \left(1 - e^{-\lambda \Delta t}\right) e^{-\lambda (m-i) \Delta t}}$$

$$C_{\mathrm{low}} = 1 - \frac{\int_0^{E_c} \Phi(E) \sigma(E) dE}{\int_0^{\infty} \Phi(E) \sigma(E) dE}.$$

Activation data reporting



	Neutron energy (MeV)								
	8.34	9.15	13.33	16.1	17.16	17.9	19.36	19.95	20.61
σ_{Al}	1.9	1.9	1.6	2	2	2.2	3.1	4.1	5.4
S_{Am}	5.0	4.0	2.5	2.1	1.5	1.3	6.3	1.4	5.7
S_{Al}	1.0	1.0	1.0	1.0	1.0	0.7	2.0	1.0	1.6
I_{Am}	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
n_{Al}	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
n_{Am}	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
$\epsilon_{\mathrm{Al}}/\epsilon_{\mathrm{Am}}$	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
$(f_{\Sigma} f_r)_{\mathrm{Am}}$	0.9	0.6	0.4	0.6	0.6	0.7	0.6	0.6	0.6
$\frac{C_{\mathrm{low,Am}}}{C_{\mathrm{low,Al}}}$			0.3	0.3	0.3	0.3	1.3	1.4	1.4



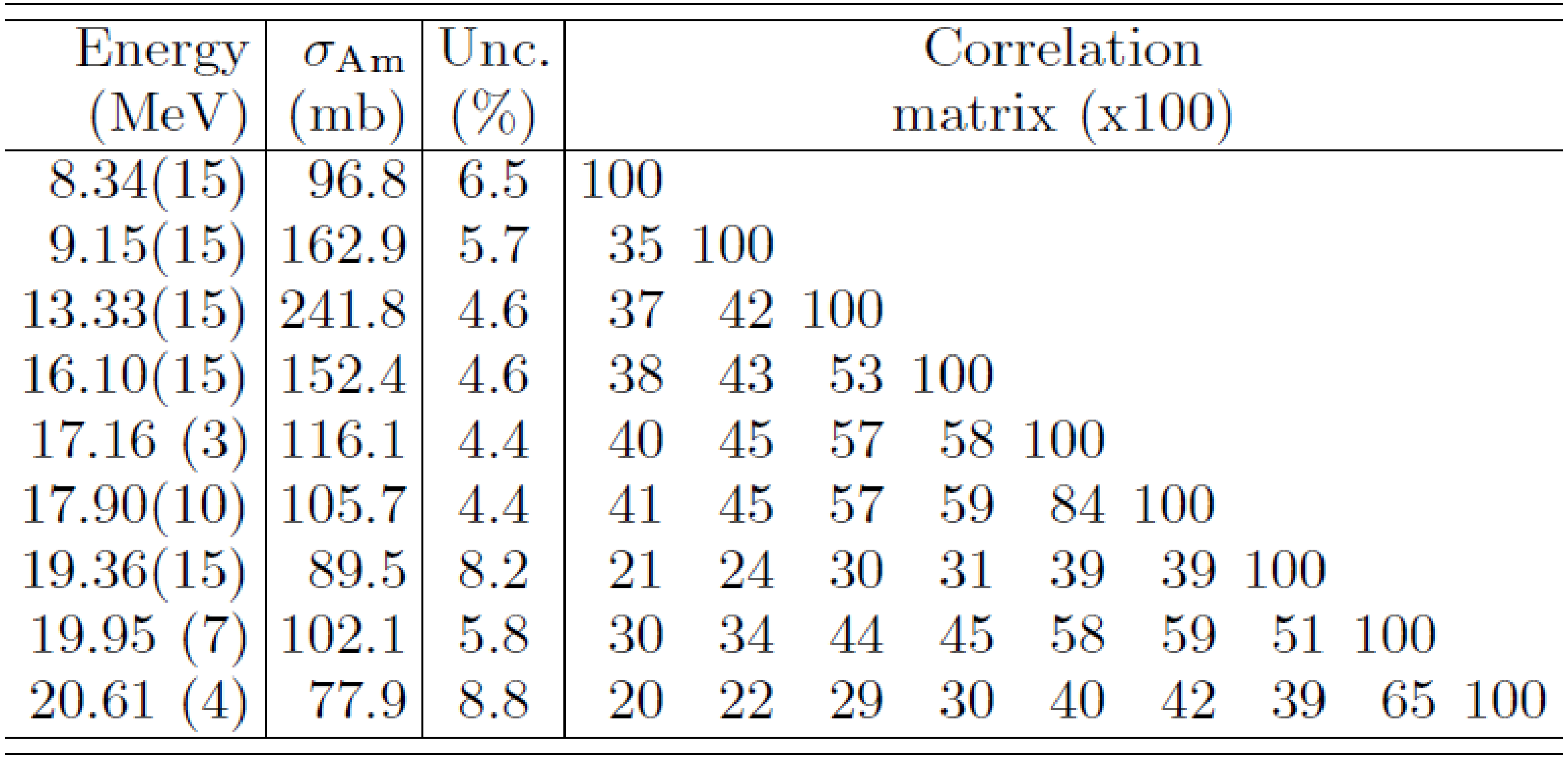
Energy (MeV)	C_{flux}		C_{low}	
	Am	Al	Am	Al
8.34	0.9974	0.9925	1	1
9.15	1.0731	1.3117	1	1
13.33	0.9168	0.8288	1	1
16.10	1.0749	1.2335	1	1
17.16	0.9987	0.9878	0.998	0.997
17.90	0.969	0.933	0.998	0.997
19.36	1.0061	1.0157	0.941	0.926
19.95	0.9822	0.9433	0.922	0.891
20.61	0.9938	0.982	0.885	0.832

% uncertainties for components in the activation formula

σ_{Al} uncertainty correlations taken from the evaluation

$\varepsilon_{\mathrm{Al}}/\varepsilon_{\mathrm{Am}}$ uncertainty fully correlated w. neutron energy

Activation reporting



Energy (MeV)	σ_{Am} (mb)	Unc. (%)	Correlation matrix (x100)								
8.34(15)	96.8	6.5	100								
9.15(15)	162.9	5.7	35	100							
13.33(15)	241.8	4.6	37	42	100						
16.10(15)	152.4	4.6	38	43	53	100					
17.16 (3)	116.1	4.4	40	45	57	58	100				
17.90(10)	105.7	4.4	41	45	57	59	84	100			
19.36(15)	89.5	8.2	21	24	30	31	39	39	100		
19.95 (7)	102.1	5.8	30	34	44	45	58	59	51	100	
20.61 (4)	77.9	8.8	20	22	29	30	40	42	39	65	100

Uncertainties in measurement

Summary

There is an excellent guide on what to do

Its use should be promoted

Reporting should be as complete as possible

Correlations make this a challenge in data storage for large data sets, but there are solutions (AGS)

- Cautions

- A small uncertainty does not guarantee a small error: incomplete knowledge ⇨ incomplete corrections
- Do not over- or underestimate uncertainties! Use all your current knowledge as best as possible.

1. overestimation leads to needless caution of users, attempts to remeasure, disregard for your hard work, difficulty identifying incomplete knowledge
2. underestimation leads to misplaced trust, undue weight of the result in evaluations, biased predictions

When the model doesn’t cover reality: examples in radionuclide metrology

Stefaan Pomme, Metrologia 53 (2016) S55-S64

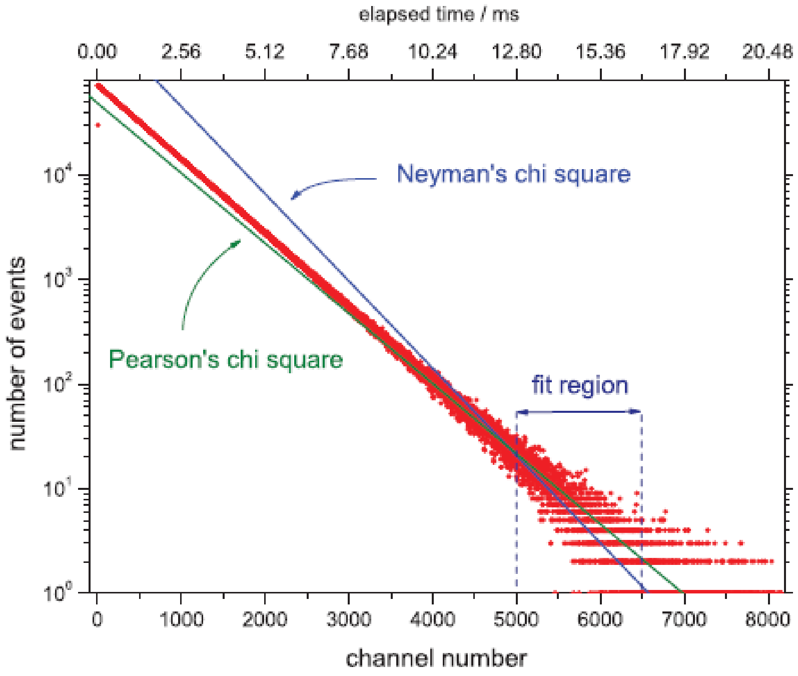


Figure 6. Least-squares fit of an exponential function to Poisson-distributed data from channel 5000 to 6500, using Neyman’s and Pearson’s χ^2. Both weighting strategies lead to biased results [70].

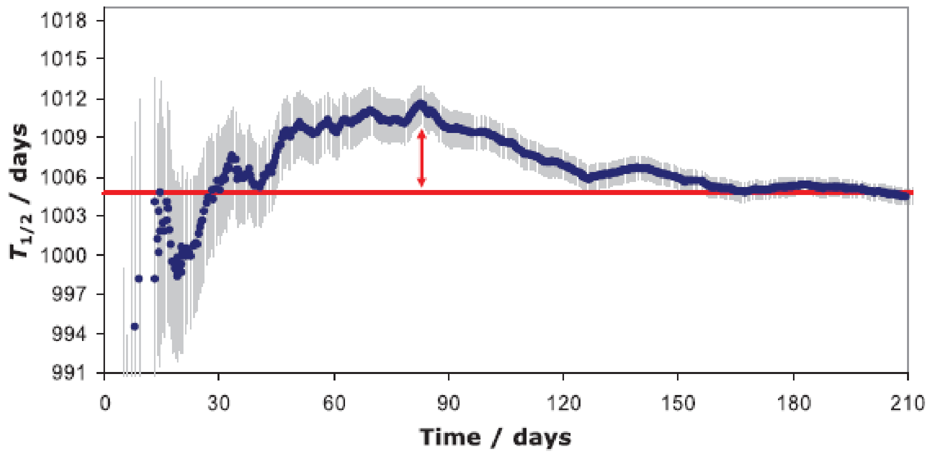
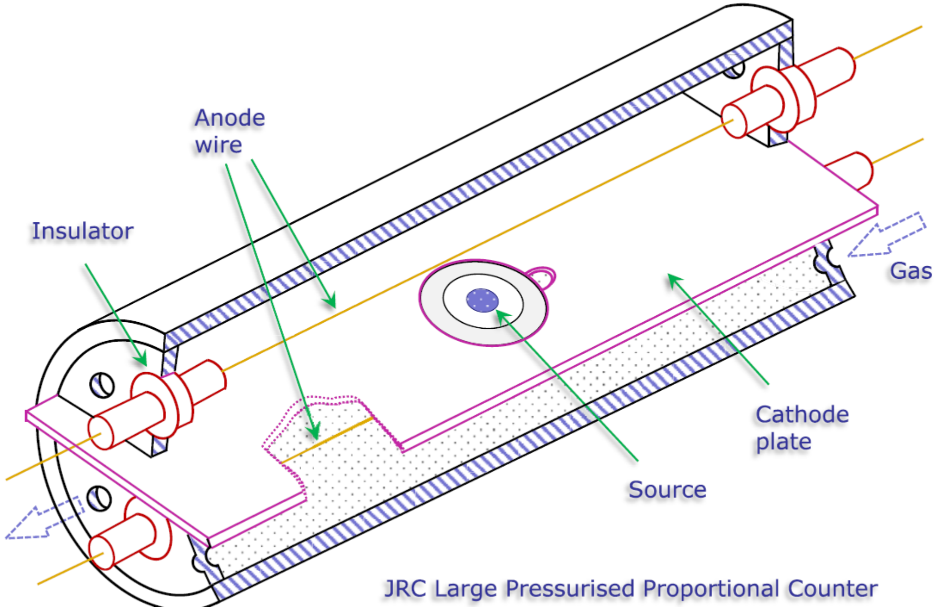


Figure 7. Daily updates of fitted ^{55}Fe half-life values to a growing data set. Intermediate values are discrepant with the final result, which proves that the uncertainty from the least-squares fit is unrealistically low [74].

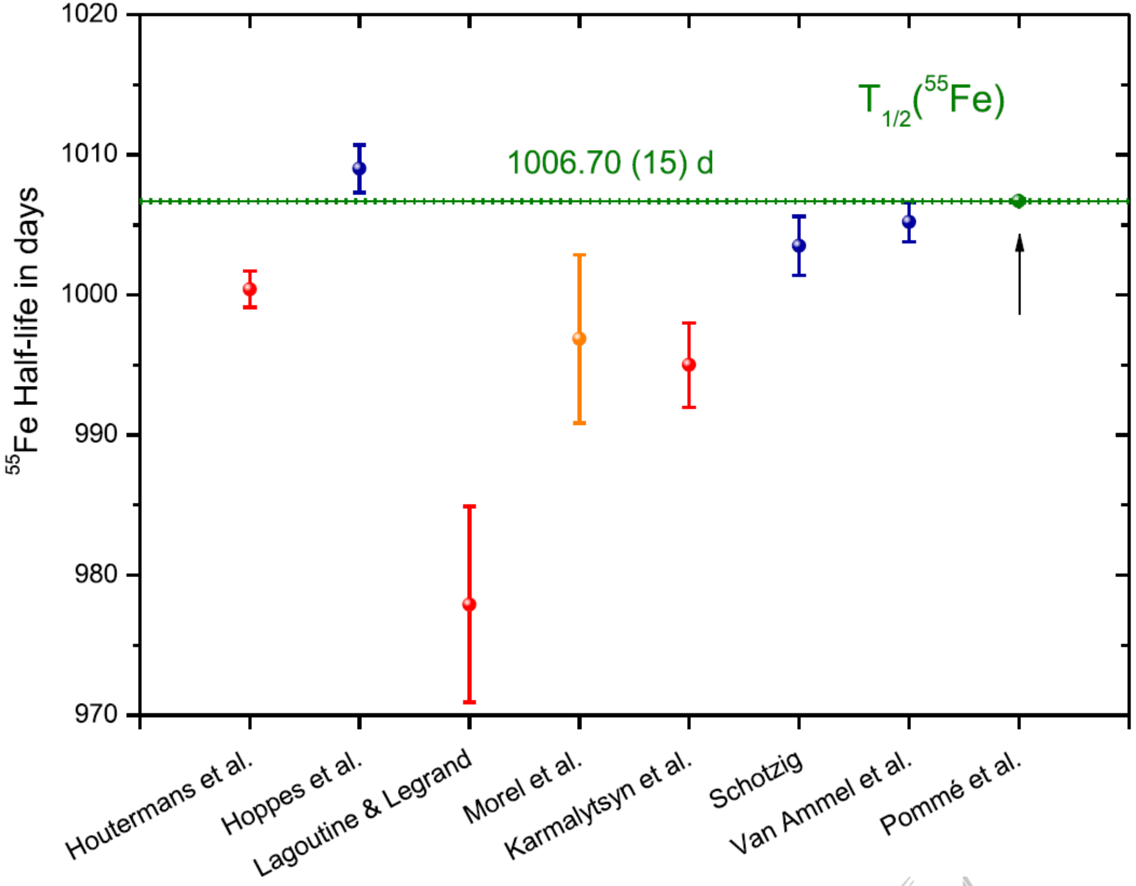
Examples in radionuclide metrology; ^{55}Fe half life

Biases in values and uncertainties

Stefaan Pomme, Applied Radiation and Isotopes 148 (2019) 27



JRC Large Pressurised Proportional Counter



Theory, experiments, evaluation


R.P. Feynman
1918-1988

“It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong”

“We have learned a lot from experience about how to handle some of the ways we fool ourselves. One example:

Millikan measured the charge of the electron by an experiment with falling oil drops and got an answer which we know not to be quite right.

It’s interesting to look at the history of measurements of the charge of the electron, after Millikan. If you plot them as a function of time, you find that one is a little bigger than Millikan’s, and the next one’s a little bit bigger... until finally they settle down to a number which is higher.”

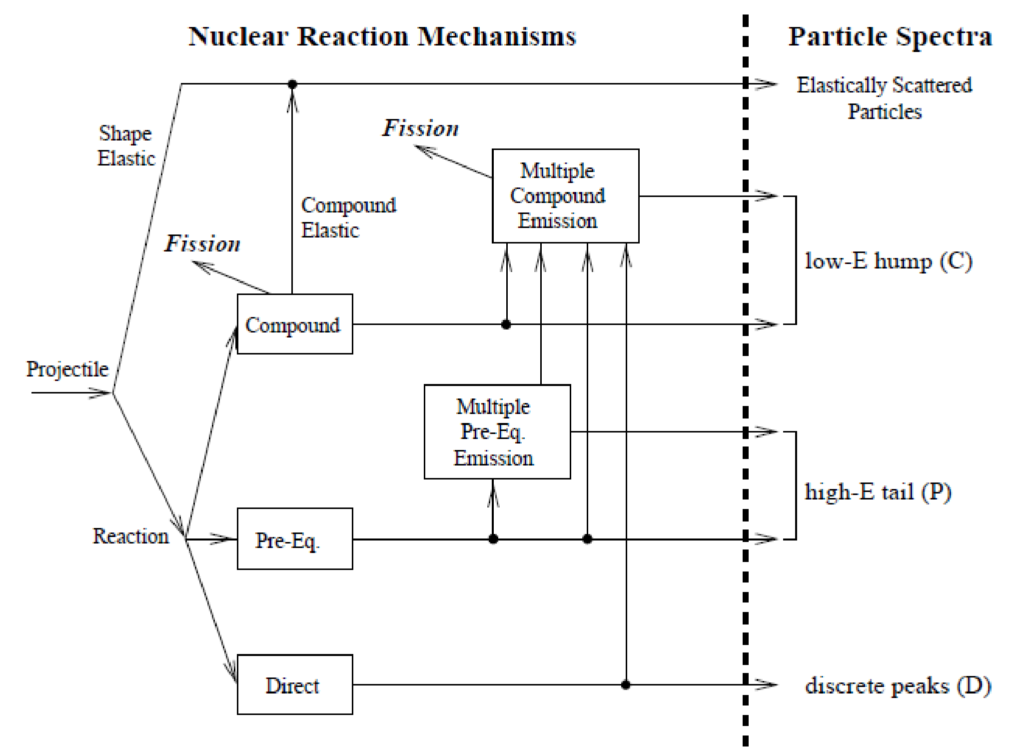
“... when you have a wide range of people who contribute without looking carefully at it, you don’t improve your knowledge of the situation by averaging.”

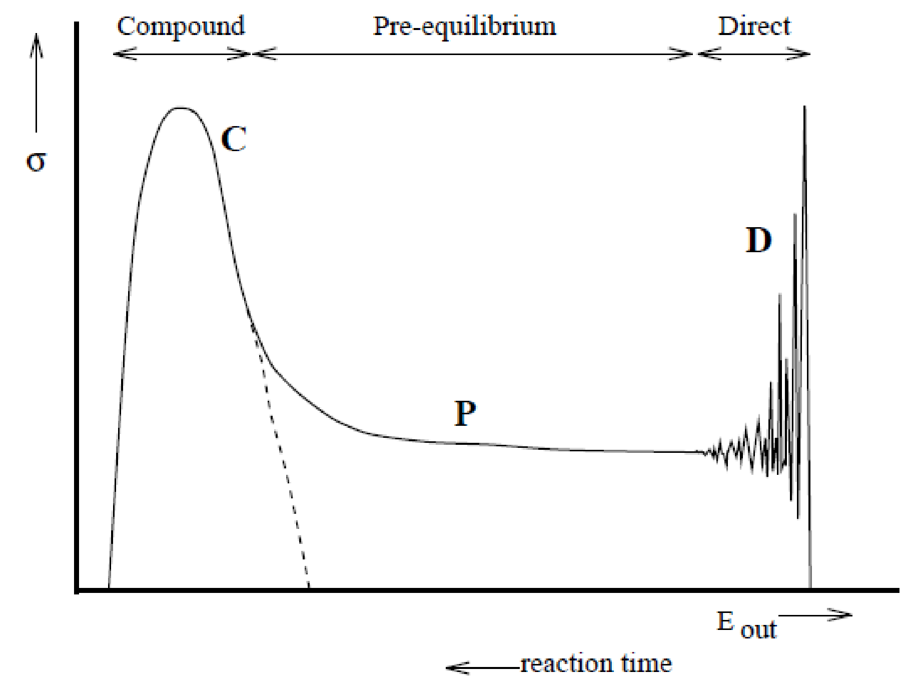
Modeling and evaluation

- Nuclear reaction modeling
  - Hauser-Feshbach-Moldauer
  - R-matrix
    - Resonance shape analysis
    - Physical R-matrix for light nuclei
- An actual evaluation: JEFF-3.3

Hauser Feshbach modeling (TALYS, EMPIRE, …)

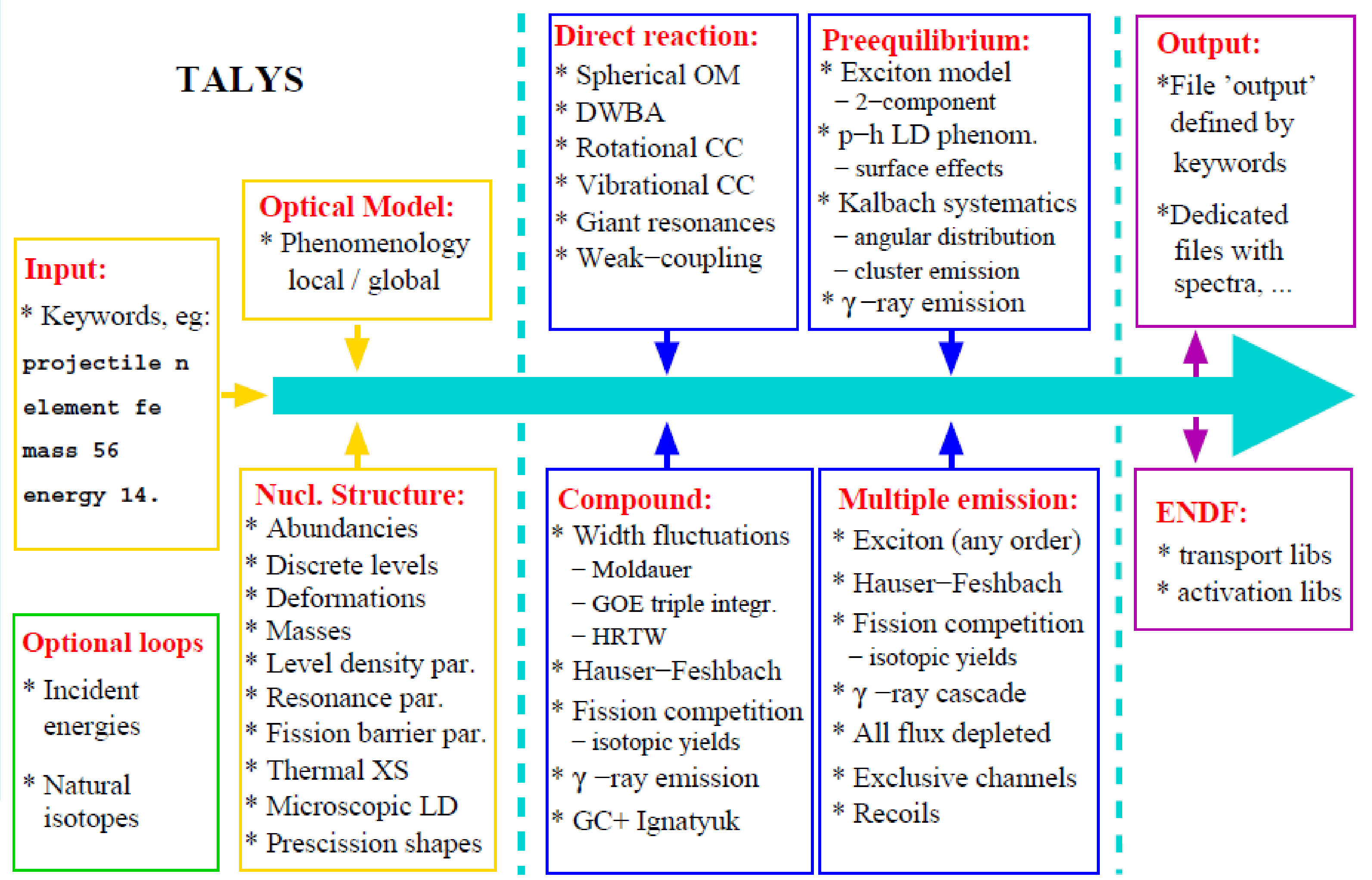
Source: Talys manual





Hauser Feshbach modeling (TALYS, EMPIRE, …)

Source: Talys manual



TALYS

Input:
- Keywords, eg:

```
projectile n
element fe
mass 56
energy 14.
```

Optical Model:
- Phenomenology local / global

Nucl. Structure:
- Abundancies
- Discrete levels
- Deformations
- Masses
- Level density par.
- Resonance par.
- Fission barrier par.
- Thermal XS
- Microscopic LD
- Prescission shapes

Optional loops
- Incident energies
- Natural isotopes

Direct reaction:
- Spherical OM
- DWBA
- Rotational CC
- Vibrational CC
- Giant resonances
- Weak–coupling

Preequilibrium:
- Exciton model
  - 2–component
- p–h LD phenom.
  - surface effects
- Kalbach systematics
  - angular distribution
  - cluster emission
- γ –ray emission

Compound:
- Width fluctuations
  - Moldauer
  - GOE triple integr.
  - HRTW
- Hauser–Feshbach
- Fission competition
  - isotopic yields
- γ –ray emission
- GC+ Ignatyuk

Multiple emission:
- Exciton (any order)
- Hauser–Feshbach
- Fission competition
  - isotopic yields
- γ –ray cascade
- All flux depleted
- Exclusive channels
- Recoils

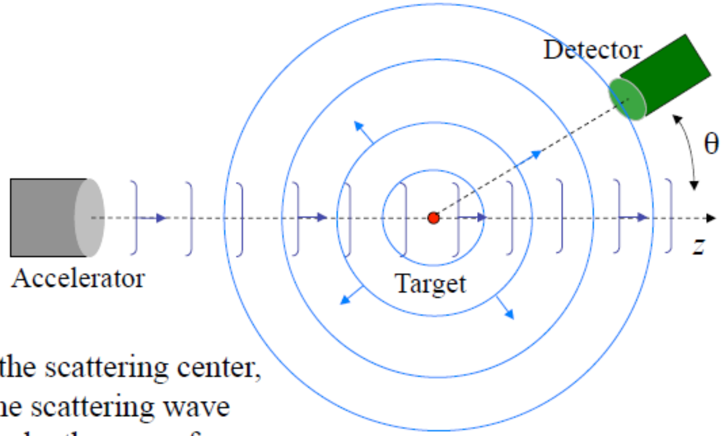
Output:
- File 'output' defined by keywords
- Dedicated files with spectra, ...

ENDF:
- transport libs
- activation libs

Hauser Feshbach modeling (TALYS, EMPIRE, …)

Source: Talys manual & lecture notes Brett Carlson, ICTP 2014.

The quantum view of scattering



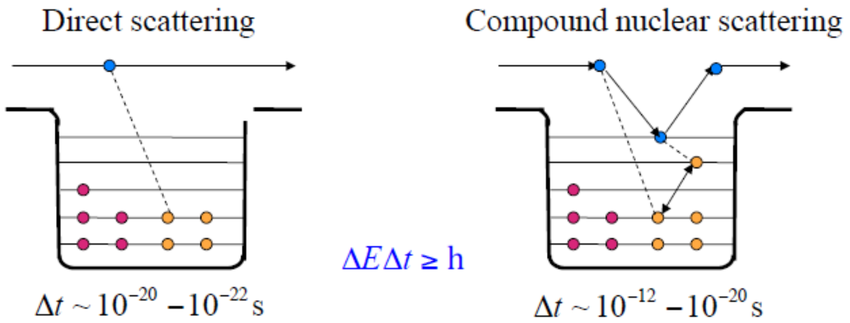
Far from the scattering center, we take the scattering wave function to be the sum of a plane wave and a scattered outgoing spherical wave,

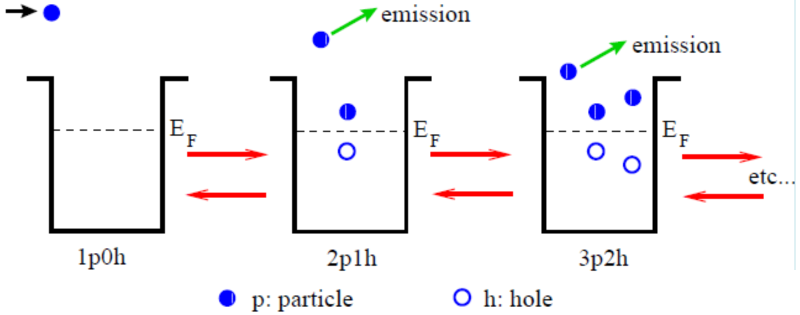
$$\psi(\vec{r}) \approx e^{ikz} + f(\theta)\frac{e^{ikr}}{r}$$

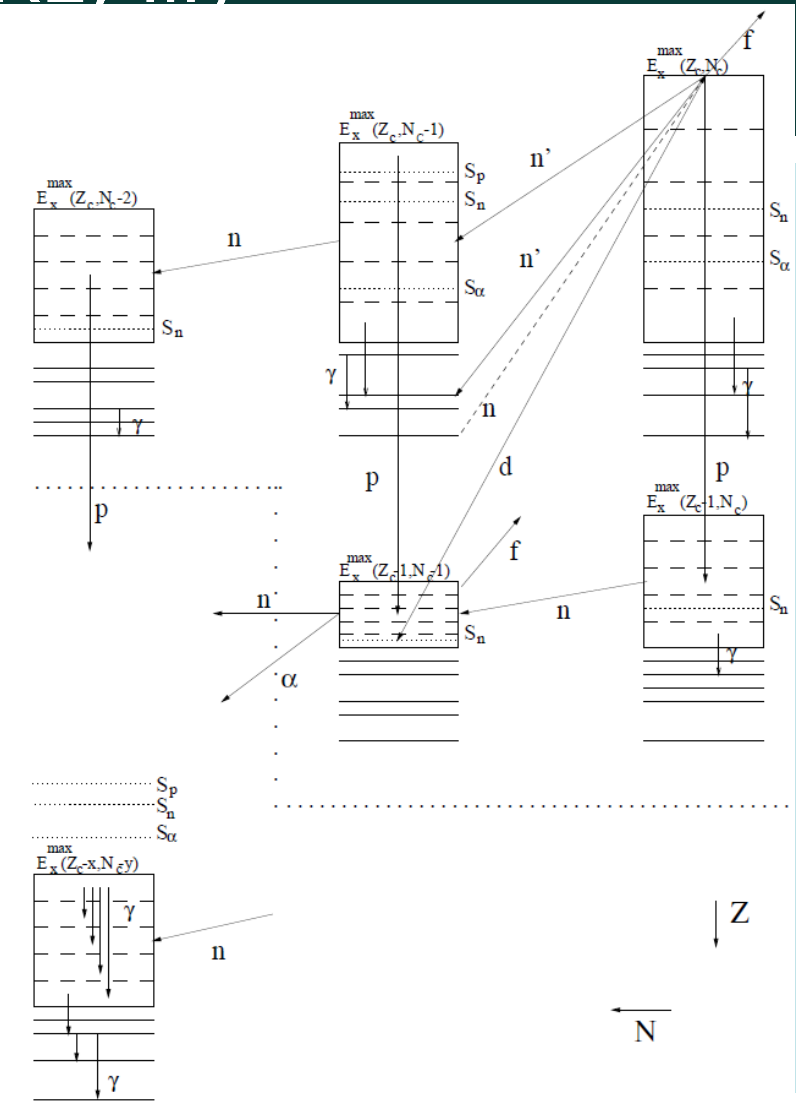
when $r \to \infty$. ($k^2 = 2\mu E_{cm}/\hbar^2$)

The differential cross section is the squared magnitude of the scattering amplitude,

$$\frac{d\sigma}{d\Omega} = |f(\theta)|^2$$

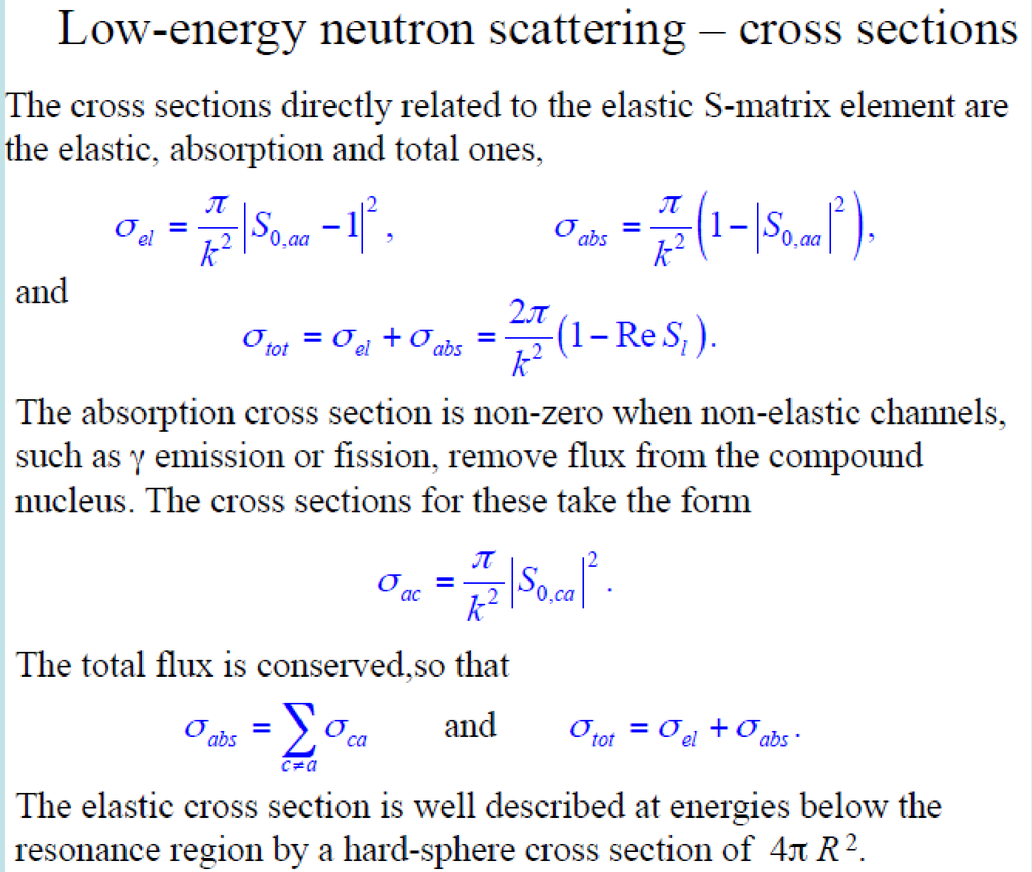






Hauser Feshbach modeling (TALYS, EMPIRE, …)

Source: lecture notes Brett Carlson, ICTP 2014.



Low-energy neutron scattering – cross sections

The cross sections directly related to the elastic S-matrix element are the elastic, absorption and total ones,

$$\sigma_{el} = \frac{\pi}{k^2}\left|S_{0,aa} - 1\right|^2 , \qquad \sigma_{abs} = \frac{\pi}{k^2}\left(1 - \left|S_{0,aa}\right|^2\right),$$

and

$$\sigma_{tot} = \sigma_{el} + \sigma_{abs} = \frac{2\pi}{k^2}\left(1 - \mathrm{Re}\, S_l\right).$$

The absorption cross section is non-zero when non-elastic channels, such as γ emission or fission, remove flux from the compound nucleus. The cross sections for these take the form

$$\sigma_{ac} = \frac{\pi}{k^2}\left|S_{0,ca}\right|^2 .$$

The total flux is conserved,so that

$$\sigma_{abs} = \sum_{c \neq a} \sigma_{ca} \qquad \text{and} \qquad \sigma_{tot} = \sigma_{el} + \sigma_{abs} .$$

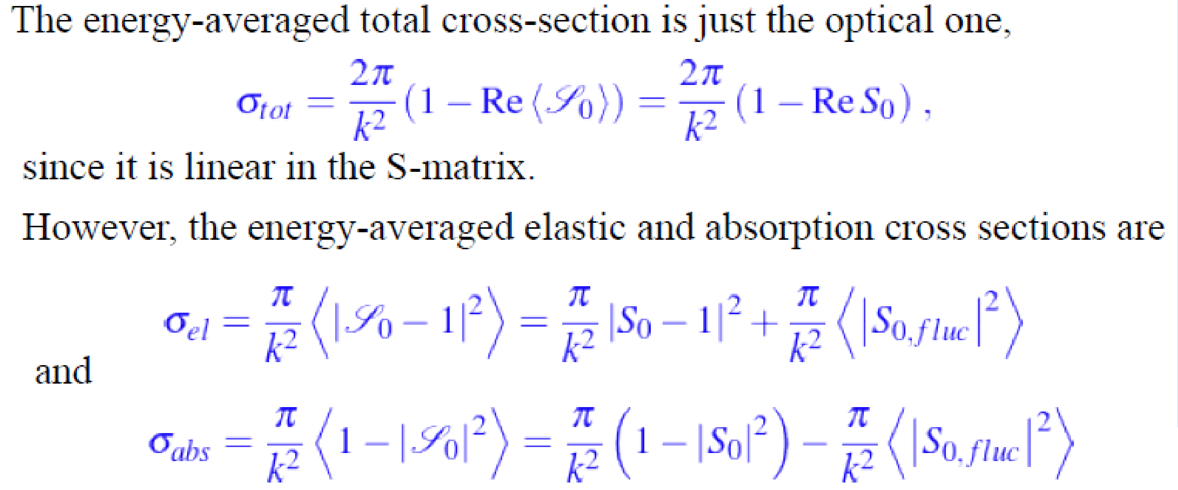
The elastic cross section is well described at energies below the resonance region by a hard-sphere cross section of $4\pi R^2$.

The optical model potential is an energy-averaged interaction

We know about fluctuations known as resonances.

An optical model works well if there are many resonances in the energy-interval.

This implies residual fluctuations that don’t average out: width fluctuations (Moldauer)



The energy-averaged total cross-section is just the optical one,

$$\sigma_{tot} = \frac{2\pi}{k^2}\left(1 - \mathrm{Re}\left\langle \mathscr{S}_0 \right\rangle\right) = \frac{2\pi}{k^2}\left(1 - \mathrm{Re}\, S_0\right) ,$$

since it is linear in the S-matrix.

However, the energy-averaged elastic and absorption cross sections are

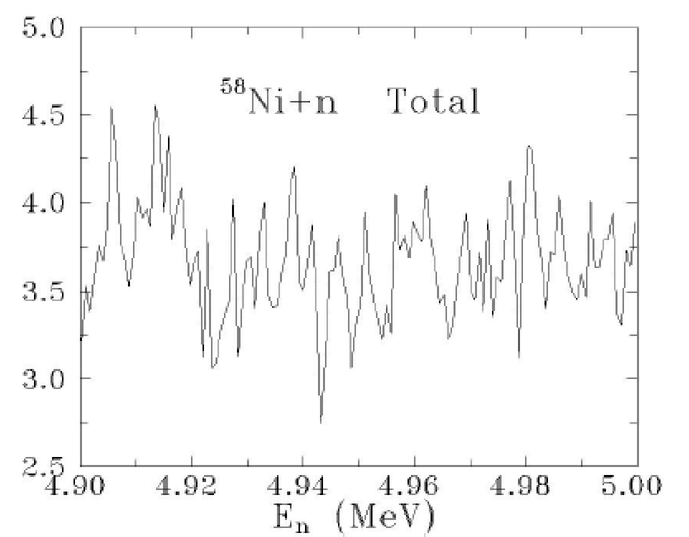
$$\sigma_{el} = \frac{\pi}{k^2}\left\langle \left|\mathscr{S}_0 - 1\right|^2 \right\rangle = \frac{\pi}{k^2}\left|S_0 - 1\right|^2 + \frac{\pi}{k^2}\left\langle \left|S_{0,fluc}\right|^2 \right\rangle$$

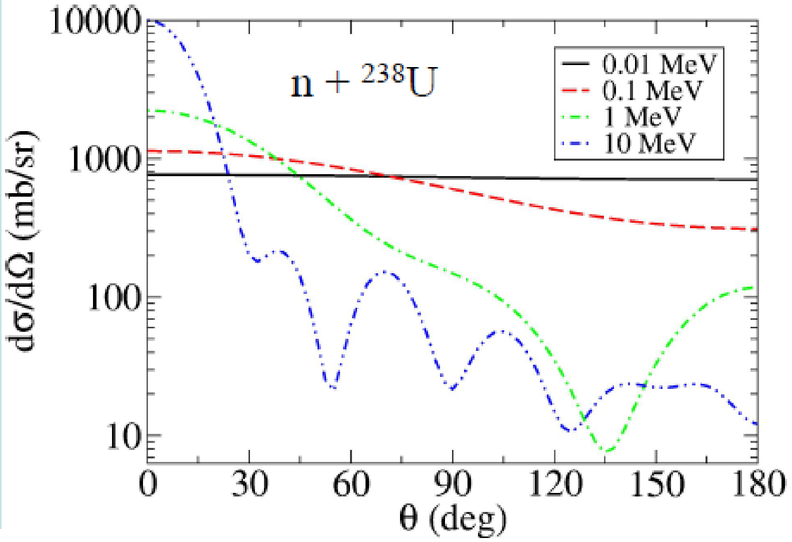
and

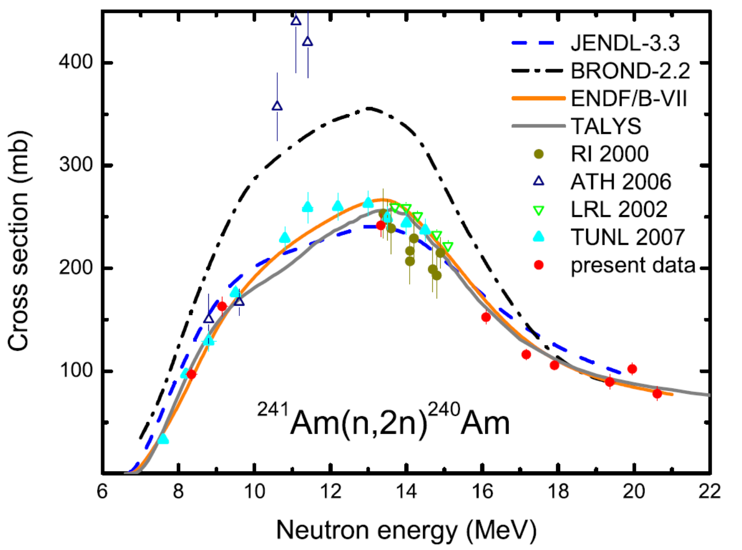
$$\sigma_{abs} = \frac{\pi}{k^2}\left\langle 1 - \left|\mathscr{S}_0\right|^2 \right\rangle = \frac{\pi}{k^2}\left(1 - \left|S_0\right|^2\right) - \frac{\pi}{k^2}\left\langle \left|S_{0,fluc}\right|^2 \right\rangle$$

Hauser Feshbach modeling (TALYS, EMPIRE, …)

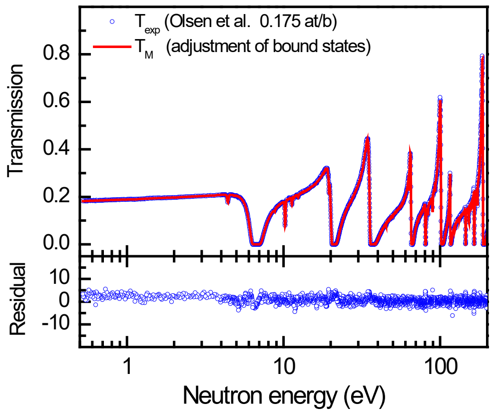
- Requires many model choices and parameters.
- TALYS and EMPIRE have preferred model choices and parameter sets and allow a range of choices.
- IAEA has the Reference Input Parameter Library (RIPL) to which you can turn if improvements or other options should be looked for.

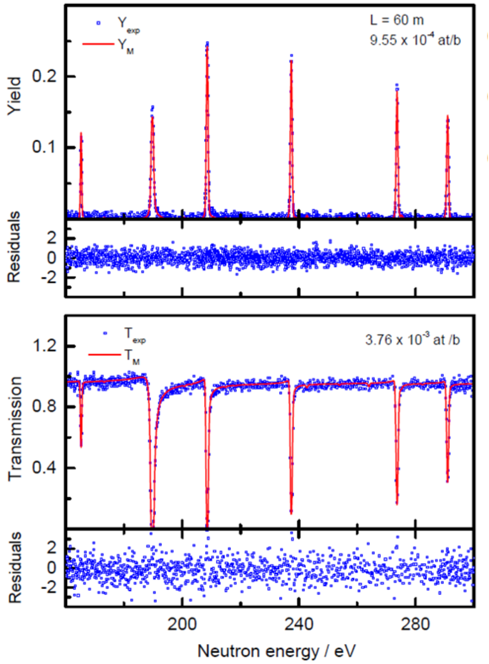


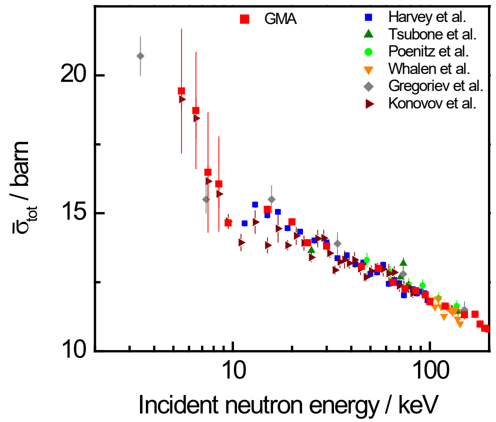


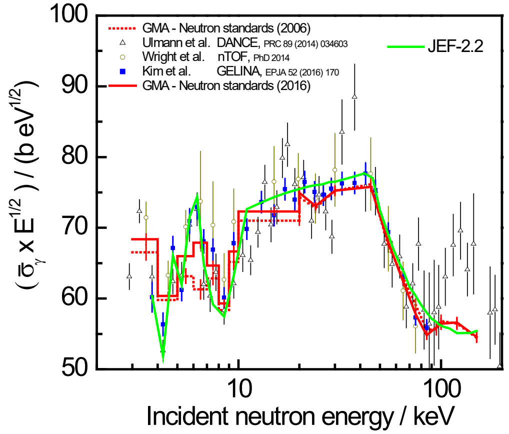


Evaluation of n+^{238}U in the resonance region;









⇒ RRR: R-matrix (RM)

⇒ URR: GLSQ to experimental data (GMA) - The standards method

- **Only based on energy dependent and spectrum averaged microscopic cross section data**

- Without any additional normalization or background correction on experimental data
- Without any adjustment to integral benchmark data

- **General purpose evaluated data file that is fully consistent with integral data**

R-matrix

$$R_{cc'}(E)=\sum_{\lambda}\frac{\gamma_{\lambda c}\gamma_{\lambda c'}}{E_{\lambda}-E},$$

Theory initially developed by Wigner and Eisenbud

Review paper by Lane and Thomas (RMP 1958).

Allows an exact parametrization of binary reactions with constant real parameters.

Employed in various approximations to parametrize/model resonances in reactions.

Codes: REFIT, SAMMY, CONRAD, EDA (standards), …

Recently used extensively for light nuclei and charged particle reactions in astrophysics (AZUR

Evaluations disting nresolved

$$d\sigma_{\alpha s\nu,\,\alpha' s'\nu'}=\left|A_{\alpha' s'\nu',\,\alpha s\nu}(\Omega_{\alpha'})\right|^2 d\Omega_{\alpha'}$$

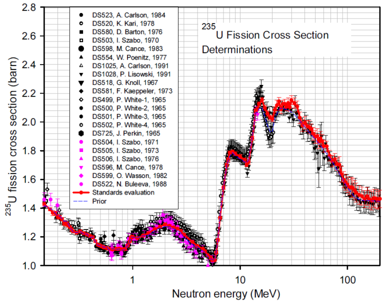
$$A_{\alpha' s'\nu',\,\alpha s\nu}(\Omega_{\alpha'})=\frac{\pi^{\frac{1}{2}}}{k_\alpha}\Big\{-C_{\alpha'}(\theta_{\alpha'})\delta_{\alpha' s'\nu',\,\alpha s\nu}+i\sum_{l'm'l}(2l+1)^{\frac{1}{2}}\big[e^{2i\omega_{\alpha' l'}}\delta_{\alpha' s' l'\nu' m',\,\alpha s l\nu 0}-U_{\alpha' s' l'\nu' m',\,\alpha s l\nu 0}\big]Y_m^{(l)}(\Omega_{\alpha'})\Big\}.$$

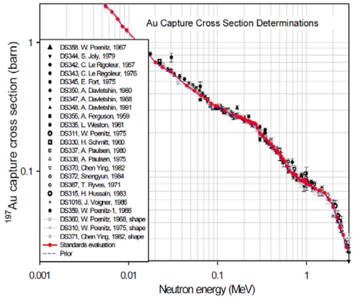
$$\mathbf{U}^J=(\mathbf{O}\varrho^{-\frac{1}{2}}-\mathbf{R}^J\mathbf{O}^{0\prime}\varrho^{\frac{1}{2}})^{-1}(\mathbf{I}\varrho^{-\frac{1}{2}}-\mathbf{R}^J\mathbf{I}^{0\prime}\varrho^{\frac{1}{2}})$$

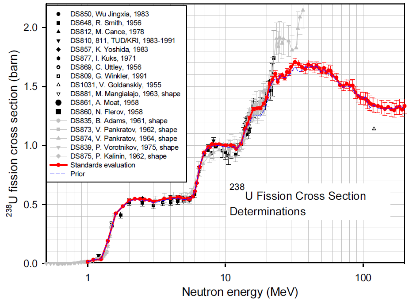
Success stories in our field

Standards

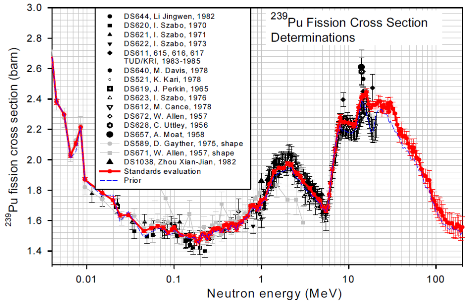
Carlson et al. NDS110(2009)3324

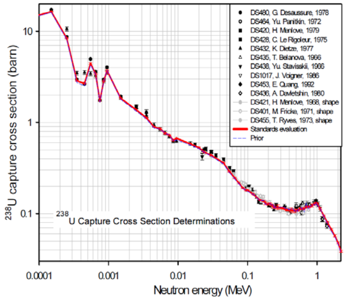






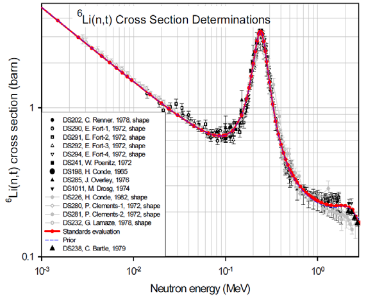
GLSQ of tables to many data sets

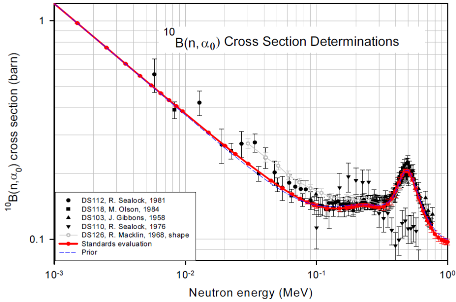




R-matrix

Phase-shift analysis – Wigner style





GLSQ of R-matrix model to many data sets

^{235}U(n,f) ^{197}Au(n,g) ^{6}Li(n,t) ^{10}B(n,α_0)

^{238}U(n,f)

^{239}Pu(n,f) ^{238}U(n,g)

European Commission

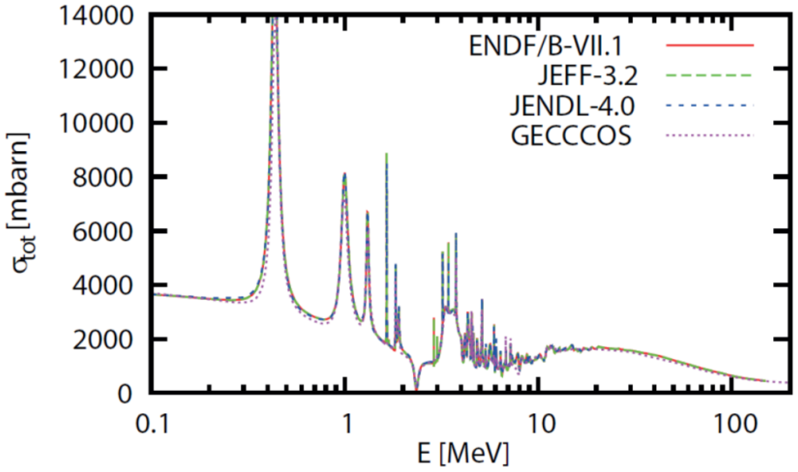
Evaluation of n + ^{16}O cross-section data using Hybrid R-Matrix approach

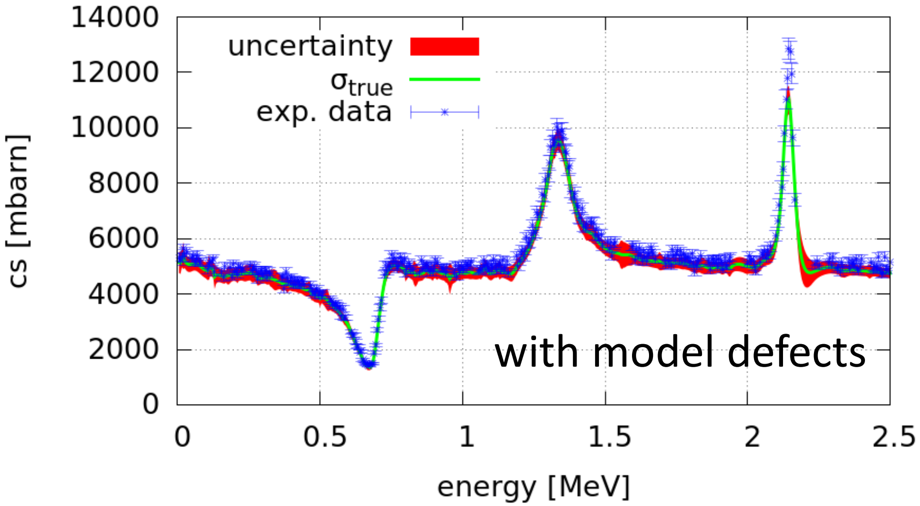
- ***Hybrid R-matrix fit*** *in energy range 1 keV – 14 MeV using TUW code system* ***GECCCOS***
- *Statistical model fit using TALYS with optimized optical potentials (1 keV – 200 MeV)*
- *Unified Bayesian evaluation* ***accounting for model defects*** *(in resonance and statistical energy range) providing co-variance matrices*

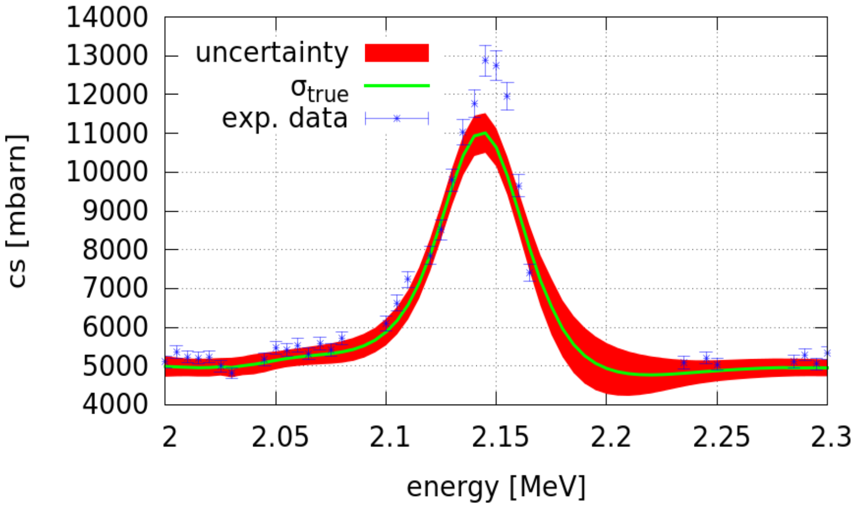
⇒ *Production of full ENDF prototype data file for use in benchmark analyses*

⇒ H. Leeb, R046

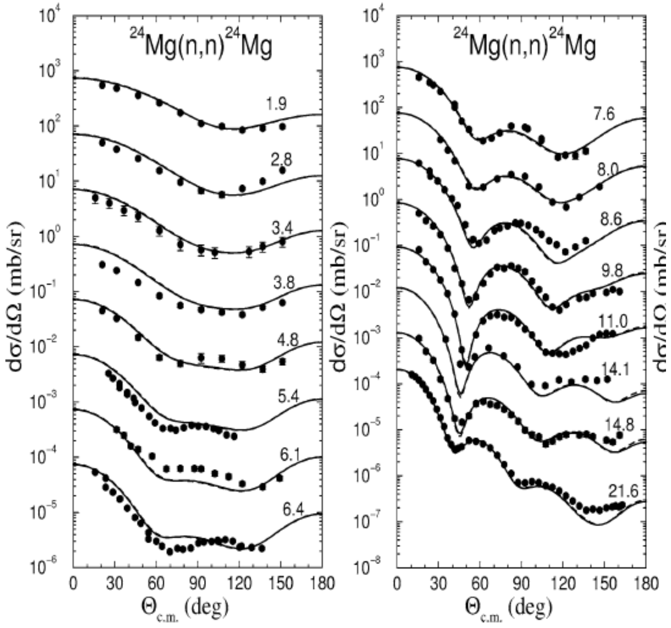
Total cross-section n + ^{16}O





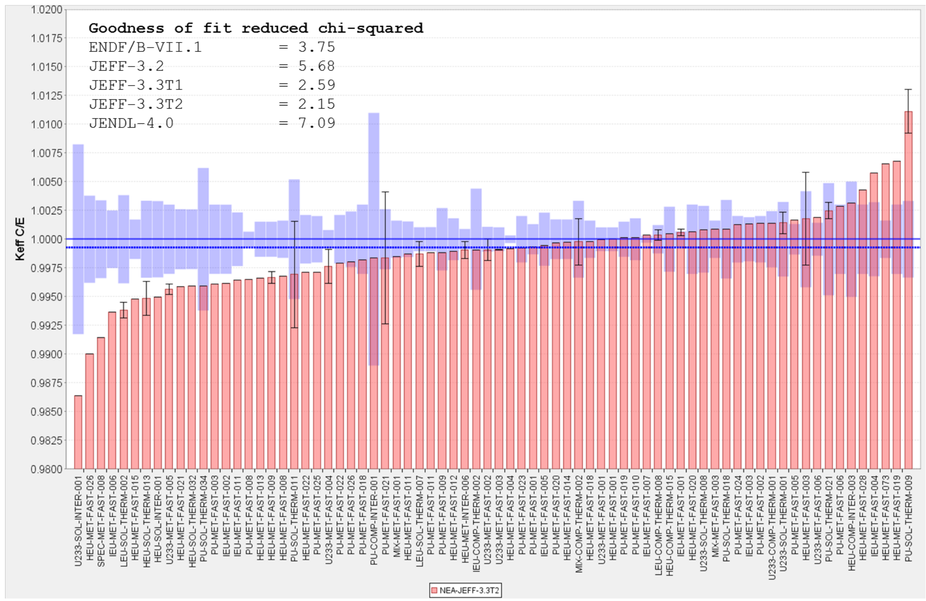


Present status of nuclear physics and engineering in our field



Example KD potential

JEFF-3.3T2. NEA Validation Suite 123 cases



Courtesy Oscar Cabellos

The best we can do presently is deal with discrepancies or
Study cases carefully: experiment and well-known GLSQ / R-matrix

Fully statistical approaches work when there are no discrepancies.
With discrepancies we are certain to find a case where we are wrong!
Murphy

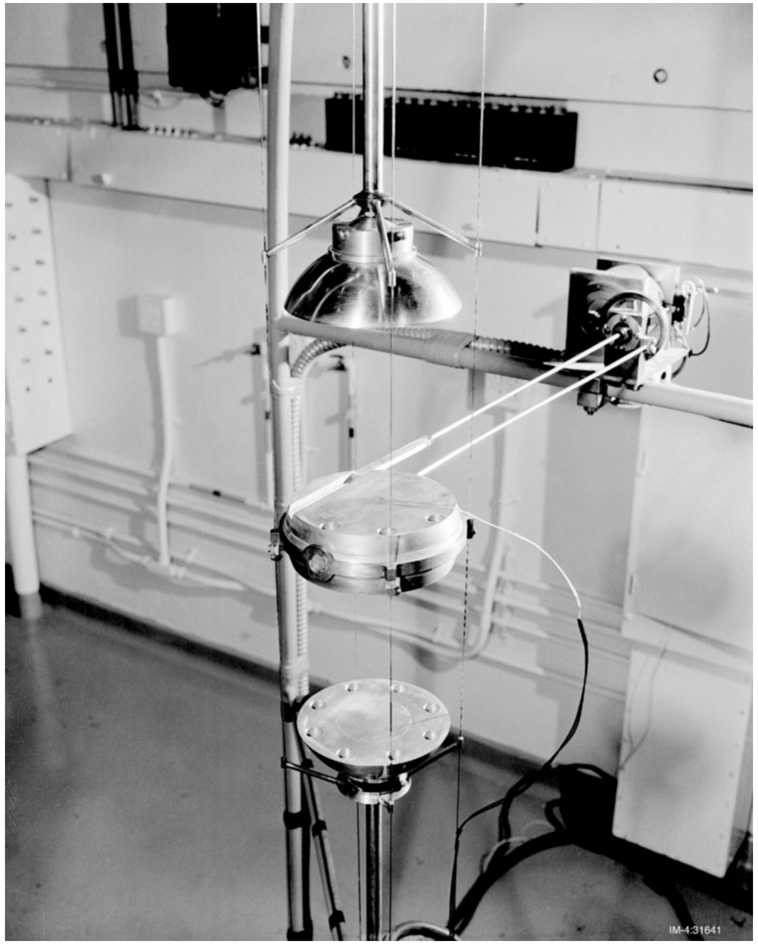
An example of a critical assembly

JEZEBEL
Criticality benchmark
k=1 (about)
One nuclide

Modeled as a Pu sphere

One of the Mosteller suite of 123 cases used for ND library development.

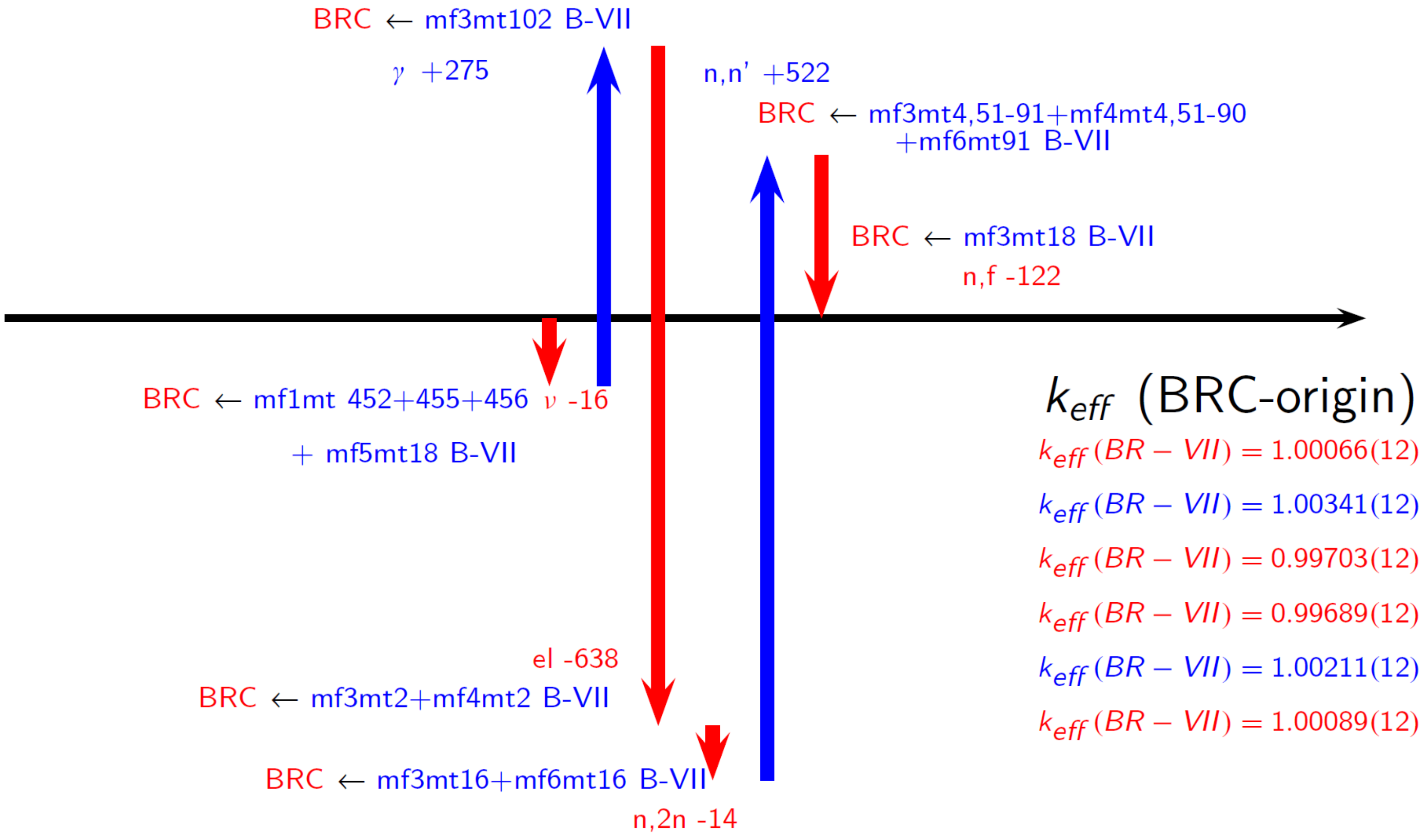
Much wider suite: ICSBEP
www.oecd-nea.org/science/wpncs/icsbep/



K-eff is a (delicate) balance

JEZEBEL $k_{eff}(BRC) = 1.00082(11)$ $k_{eff}(B\text{-}VII) = 1.00060(12)$

B. Morillon, slide courtesy P. Romain (CEA),
INDC(NDS)-0597, A. Plompen, T. Kawano, R. Capote Eds. (2011).



BRC ← mf3mt102 B-VII

γ +275

n,n' +522

BRC ← mf3mt4,51-91+mf4mt4,51-90
+mf6mt91 B-VII

BRC ← mf3mt18 B-VII

n,f -122

BRC ← mf1mt 452+455+456 ν -16

+ mf5mt18 B-VII

el -638

BRC ← mf3mt2+mf4mt2 B-VII

BRC ← mf3mt16+mf6mt16 B-VII

n,2n -14

k_{eff} (BRC-origin)

$k_{eff}(BR - VII) = 1.00066(12)$

$k_{eff}(BR - VII) = 1.00341(12)$

$k_{eff}(BR - VII) = 0.99703(12)$

$k_{eff}(BR - VII) = 0.99689(12)$

$k_{eff}(BR - VII) = 1.00211(12)$

$k_{eff}(BR - VII) = 1.00089(12)$

Theory, experiments, evaluation

R.P. Feynman
1918-1988

“It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong”

“We have learned a lot from experience about how to handle some of the ways we fool ourselves. One example:

Millikan measured the charge of the electron by an experiment with falling oil drops and got an answer which we know not to be quite right.

It’s interesting to look at the history of measurements of the charge of the electron, after Millikan. If you plot them as a function of time, you find that one is a little bigger than Millikan’s, and the next one’s a little bit bigger... until finally they settle down to a number which is higher.”

“... when you have a wide range of people who contribute without looking carefully at it, you don’t improve your knowledge of the situation by averaging.”

European Commission

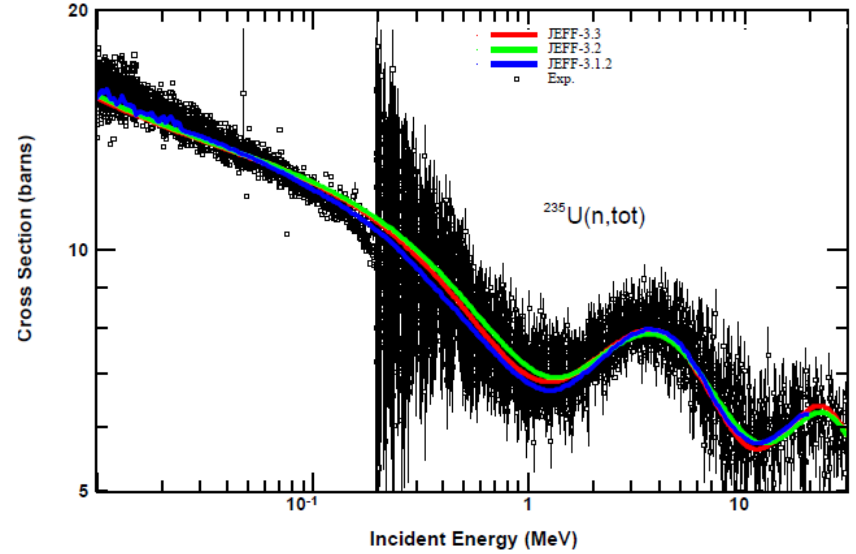
The JEFF collaboration

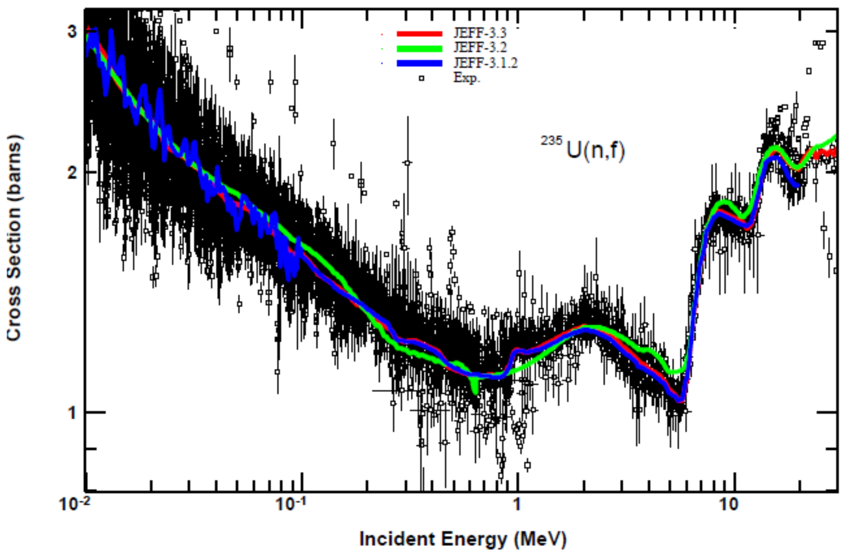
- NEA Databank member countries
- Large fraction of contributors is from Europe
- 2 meetings per year
- 40-100 participants
- Voluntary contributions: resources of contributors
- Maintain close links with data projects in Europe
- Joint meetings.

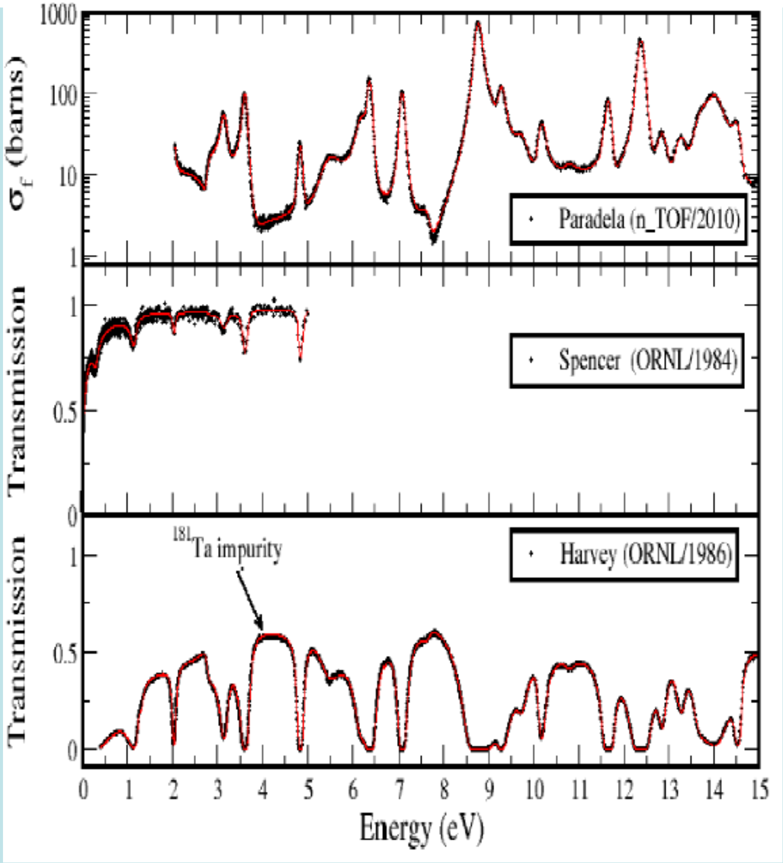
JEFF – 3.3, 20 November 2017

- New major actinides (CEA Cadarache & Bruyeres-le-Chatel, IRSN)
- FY beta file UKFY3.7 (NNL)
- Radioactive Decay Data File (CEA Saclay)
- New covariances
- Increased reliance on TENDL for completeness and decay heat (D. Rochman, M. Fleming)
- New Cu files (Pereslavtsev, Leal) solved important issue with JEFF-3.2
- Improved gamma-emission data (C. Jouanne, R. Perry, G. Noguere, O. Serot, …)
- Restoration of 8 group structure for delayed neutrons (P. Leconte)
- New thermal scattering data (Cantargi, Granada, Marquez Damian, Noguere)
- Removal of legacy files, update of adopted files to latest release
- Many issues resolved (many contributors)

JEFF-3.3 U-235







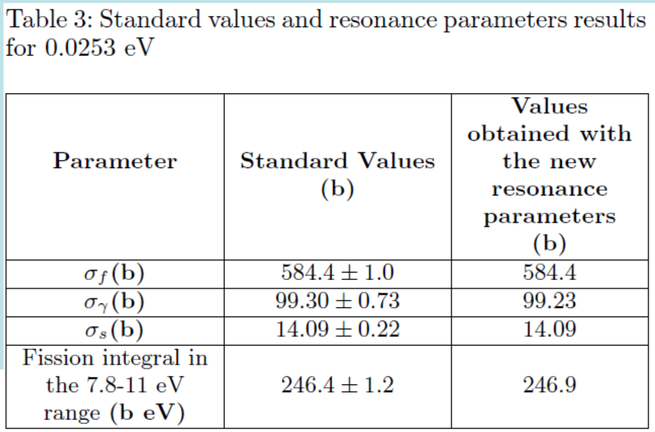
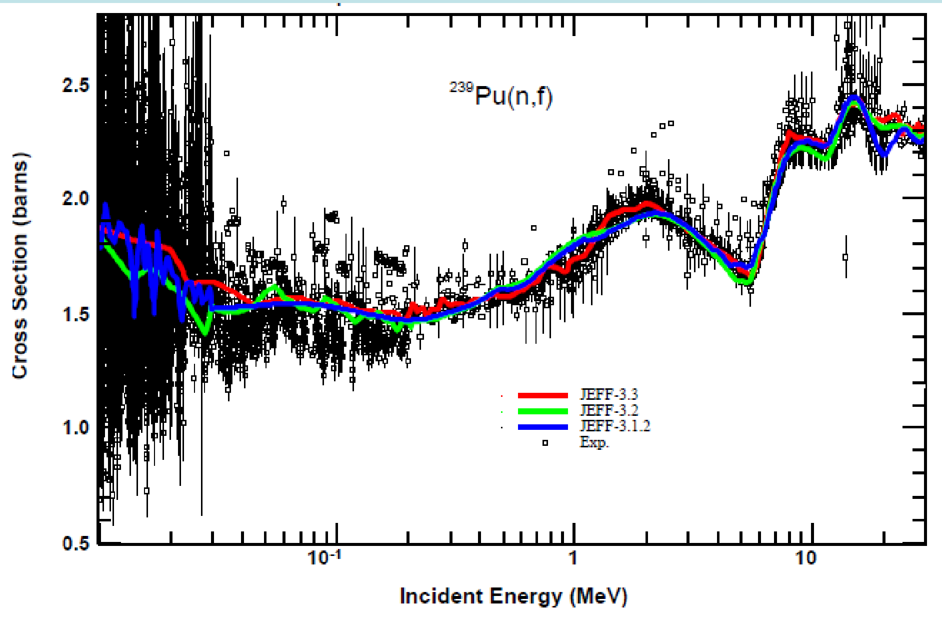


Table 3: Standard values and resonance parameters results for 0.0253 eV

Parameter	Standard Values (b)	Values obtained with the new resonance parameters (b)
σ_f(b)	584.4 ± 1.0	584.4
σ_γ(b)	99.30 ± 0.73	99.23
σ_s(b)	14.09 ± 0.22	14.09
Fission integral in the 7.8-11 eV range (b eV)	246.4 ± 1.2	246.9

European Commission

JEFF-3.3 Pu-239



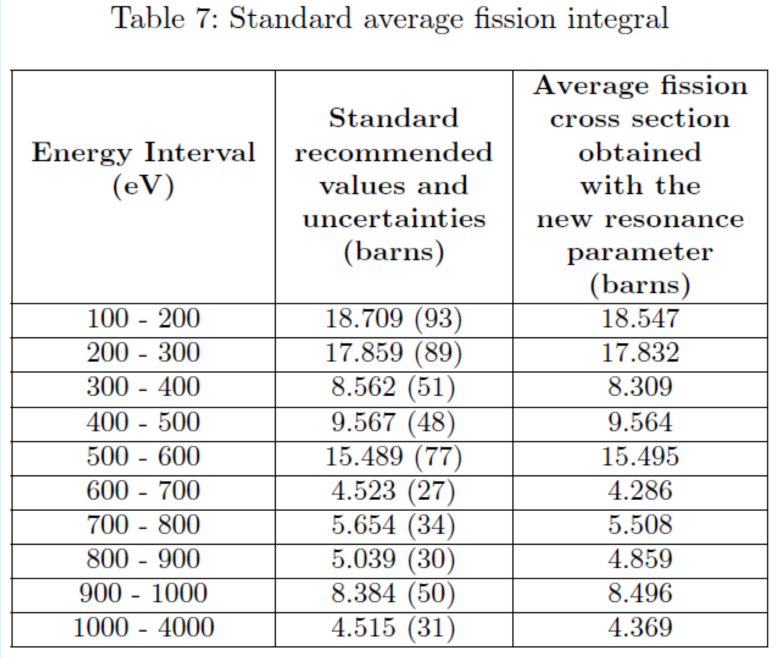
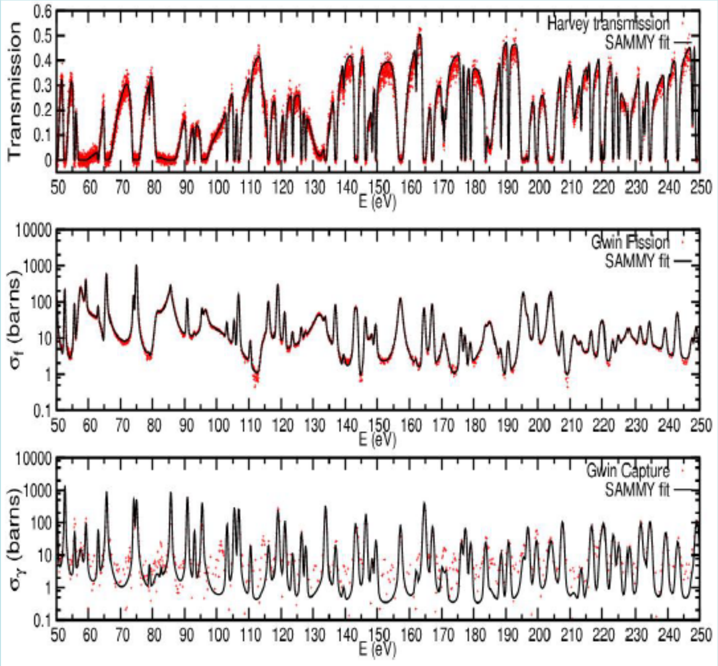
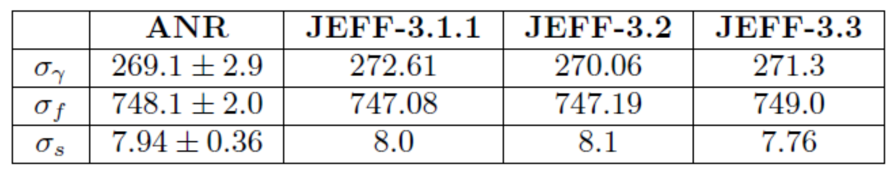


Table 7: Standard average fission integral

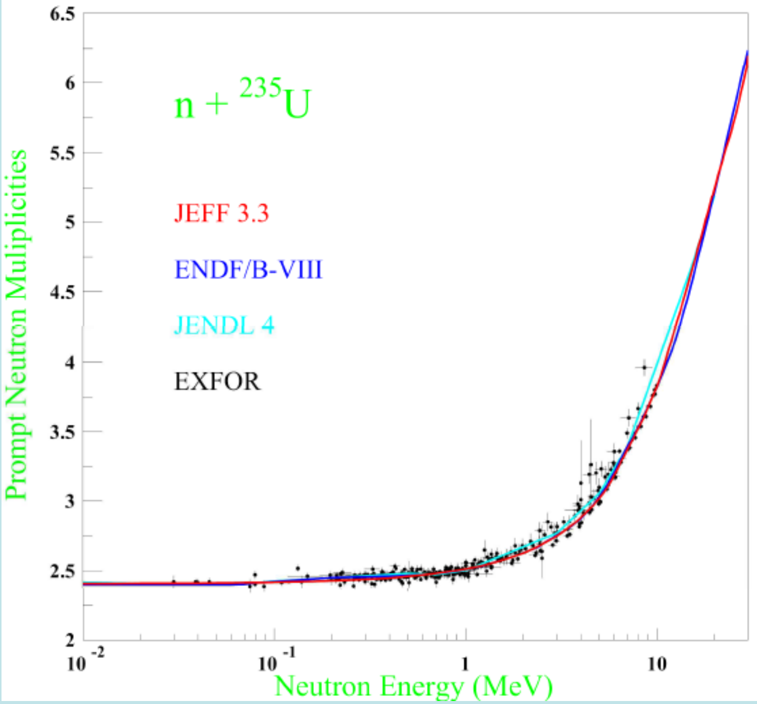
Energy Interval (eV)	Standard recommended values and uncertainties (barns)	Average fission cross section obtained with the new resonance parameter (barns)
100 - 200	18.709 (93)	18.547
200 - 300	17.859 (89)	17.832
300 - 400	8.562 (51)	8.309
400 - 500	9.567 (48)	9.564
500 - 600	15.489 (77)	15.495
600 - 700	4.523 (27)	4.286
700 - 800	5.654 (34)	5.508
800 - 900	5.039 (30)	4.859
900 - 1000	8.384 (50)	8.496
1000 - 4000	4.515 (31)	4.369

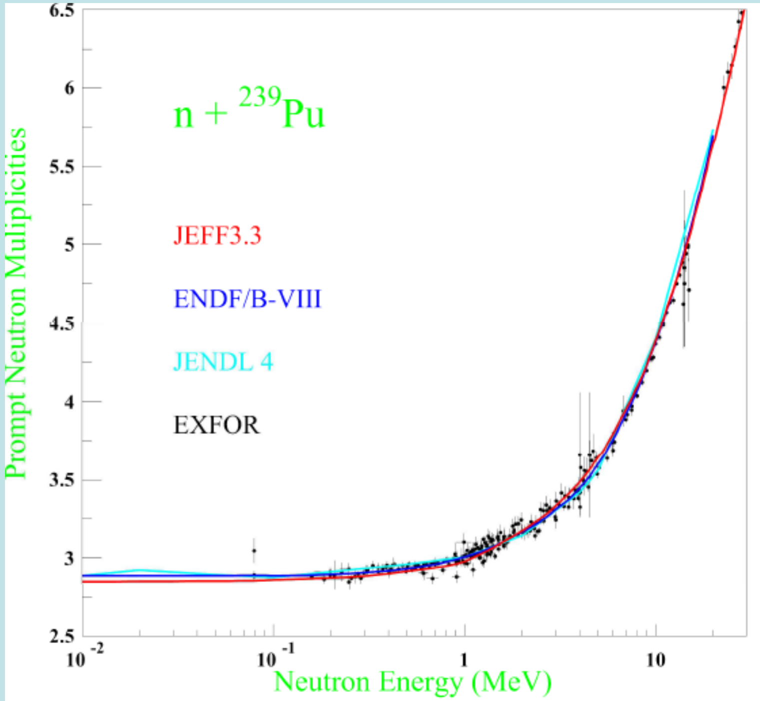


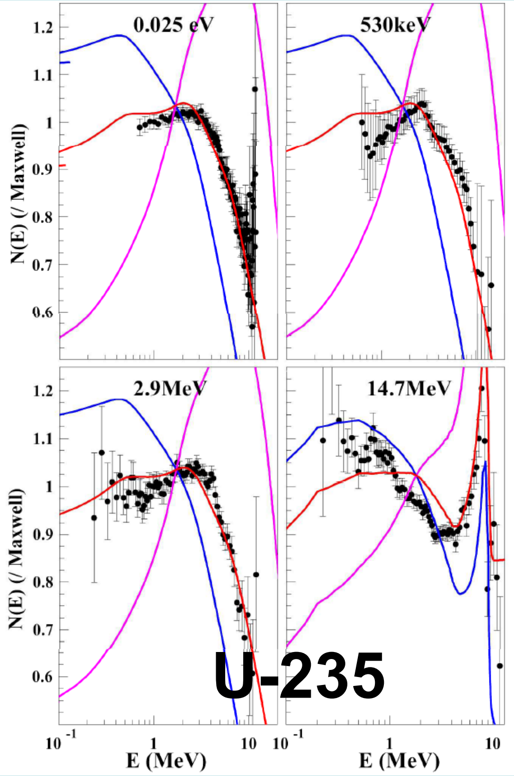


	ANR	JEFF-3.1.1	JEFF-3.2	JEFF-3.3
σ_γ	269.1 ± 2.9	272.61	270.06	271.3
σ_f	748.1 ± 2.0	747.08	747.19	749.0
σ_s	7.94 ± 0.36	8.0	8.1	7.76

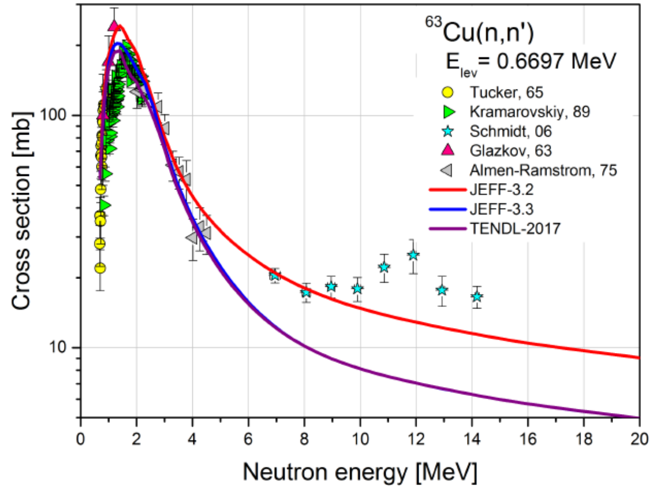
U-235, Pu-239 nu-bar and pfns

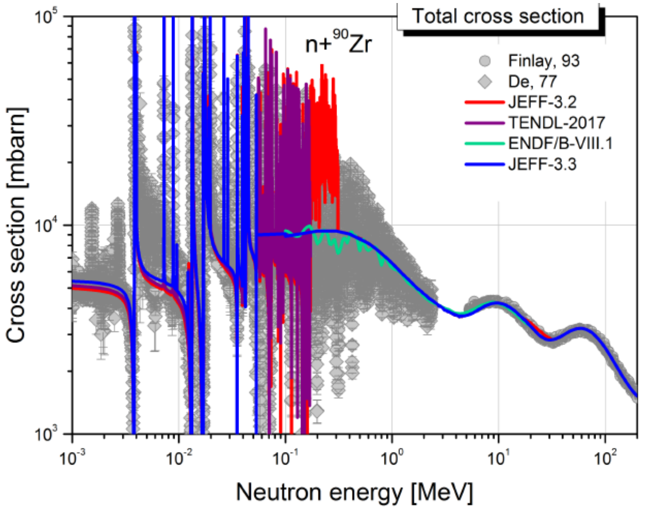






Structural materials, coolants





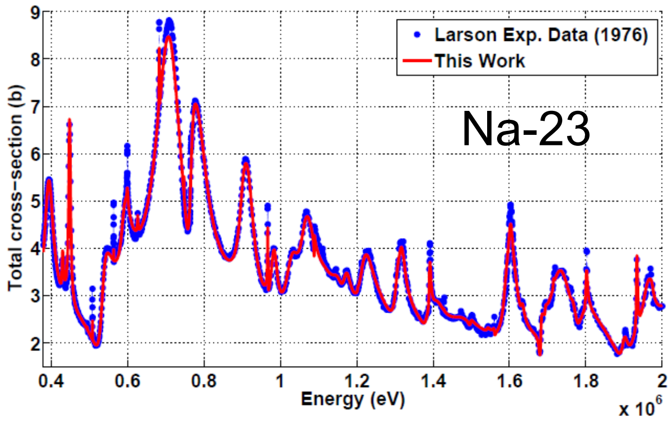
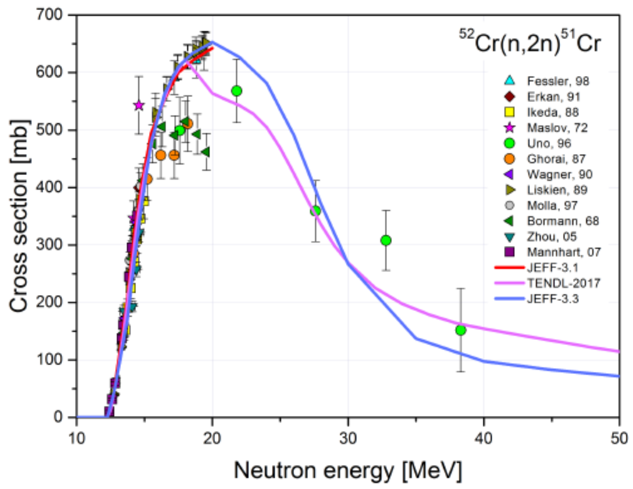
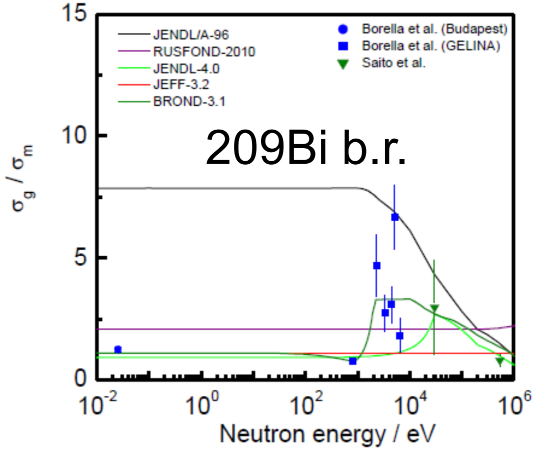
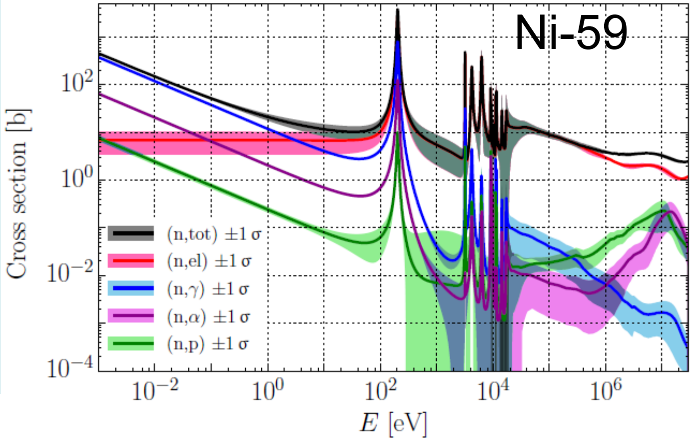


Fig. 31: Evaluated ^{23}Na total cross-section (red) compared to Larson experimental data (blue dots)





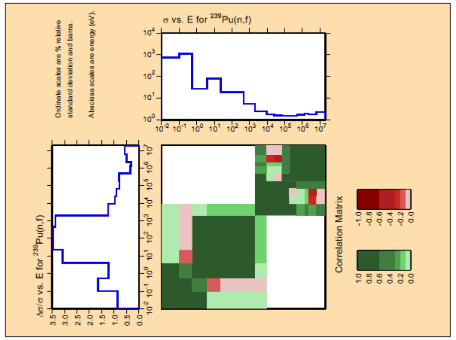


European Commission

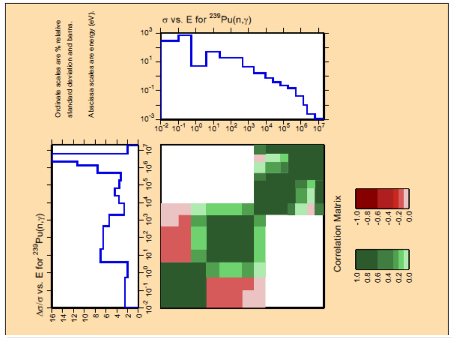
Cyrille De Saint Jean

^{239}Pu

(n,f)

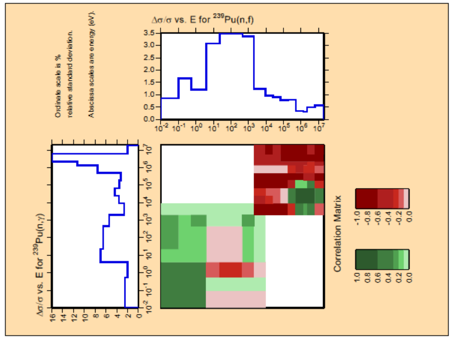


(n,g)



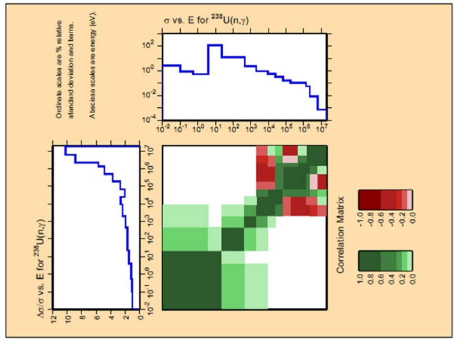
(n,f) x

(n,g)

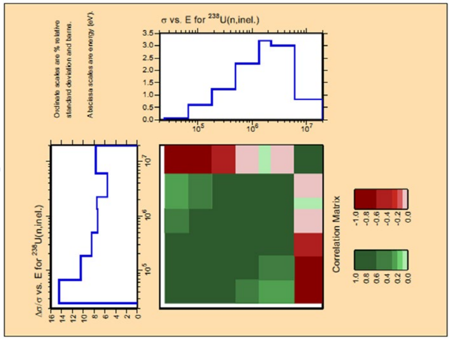


^{238}U

(n,g)

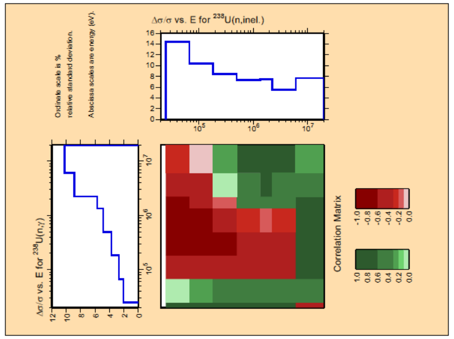


(n,inl)



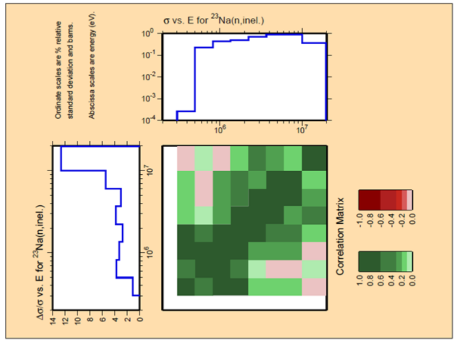
(n,g) x

(n,inl)



^{23}Na

(n,inl)

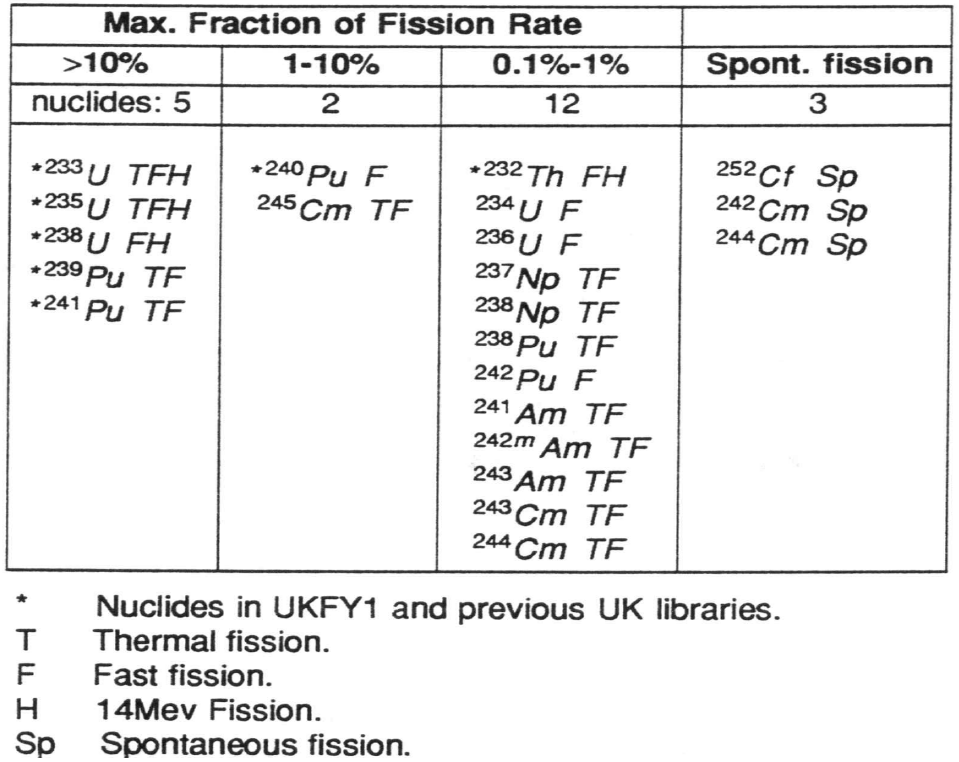


Further covariances for Hf

Many from TENDL (D. Rochman)

European Commission

Robert Mills, NNL, UKFY-3.7 = JEFF-3.3 FY



Max. Fraction of Fission Rate			
>10%	1-10%	0.1%-1%	Spont. fission
nuclides: 5	2	12	3
*^{233}U TFH *^{235}U TFH *^{238}U FH *^{239}Pu TF *^{241}Pu TF	*^{240}Pu F ^{245}Cm TF	*^{232}Th FH ^{234}U F ^{236}U F ^{237}Np TF ^{238}Np TF ^{238}Pu TF ^{242}Pu F ^{241}Am TF ^{242m}Am TF ^{243}Am TF ^{243}Cm TF ^{244}Cm TF	^{252}Cf Sp ^{242}Cm Sp ^{244}Cm Sp

* Nuclides in UKFY1 and previous UK libraries.
T Thermal fission.
F Fast fission.
H 14Mev Fission.
Sp Spontaneous fission.

Neutron spectra	Fissioning nuclide	UKFY3.6	New data	UKFY3.7
Thermal	Th229	337	72	409
Thermal	U233	757	188	945
Thermal	U235	2390	151	2541
Thermal	Np238	115	63	178
Thermal	Pu239	861	225	1086
Thermal	Pu241	334	63	397
Thermal	Cm245	161	219	380
Thermal	Cf249	305	239	544
Fast	U235	724	5	729
Fast	Pu239	390	5	395
Fast	Pu241	111	5	116

New JEFF-3.3 DD file, Mark Kellett, CEA Saclay

• FROM JEFF-3.1.1 TO JEFF-3.3

JEFF-3.3 (released October 2016):

Complete re-assessment and update to all 900 evaluations coming from ENSDF

Assessment of IAEA actinide decay data (85 nuclei)

Assessment of IRDFF decay data library (~80 nuclei)

Inclusion of updated UKPADD-6.12 library (~50 additional nuclei)

Assessment of new DDEP evaluations (~30 additional nuclei)

Inclusion of initial TAGS results from University of Valencia *(2010)*

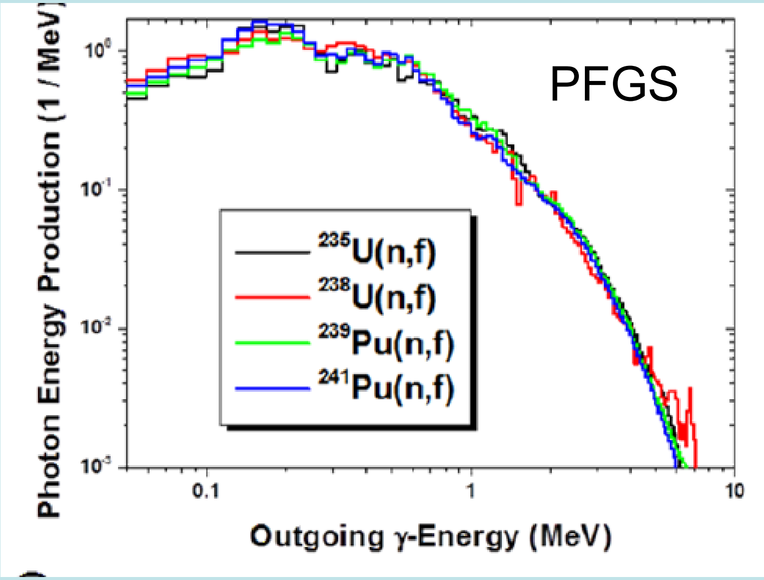
Inclusion of first TAGS results from University of Nantes *(2015)*

Inclusion of further TAGS results from University of Valencia *(2016)*

Corrections based on limited feedback to JEFF-3.1.1

JEFF-3.3 Gamma yields

- Prompt fission (Serot)
- Capture (Perry, Noguere, Serot)
- Inelastic (Jouanne)



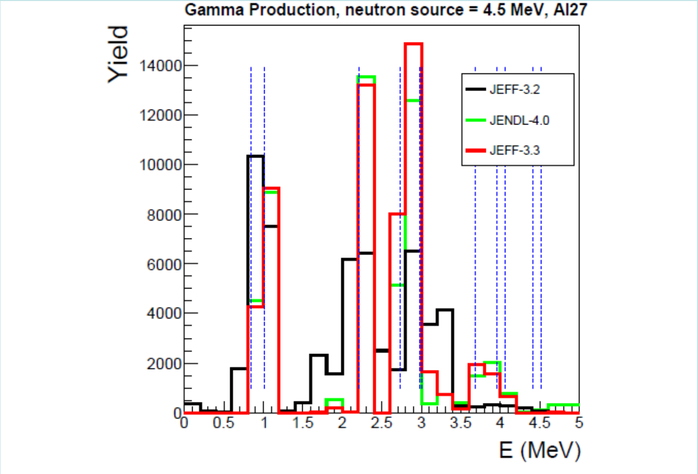
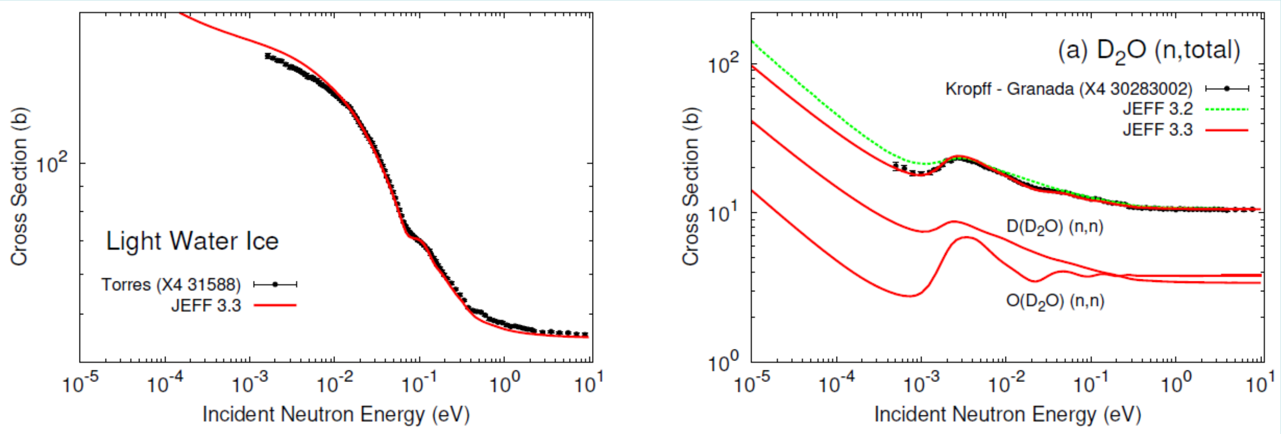


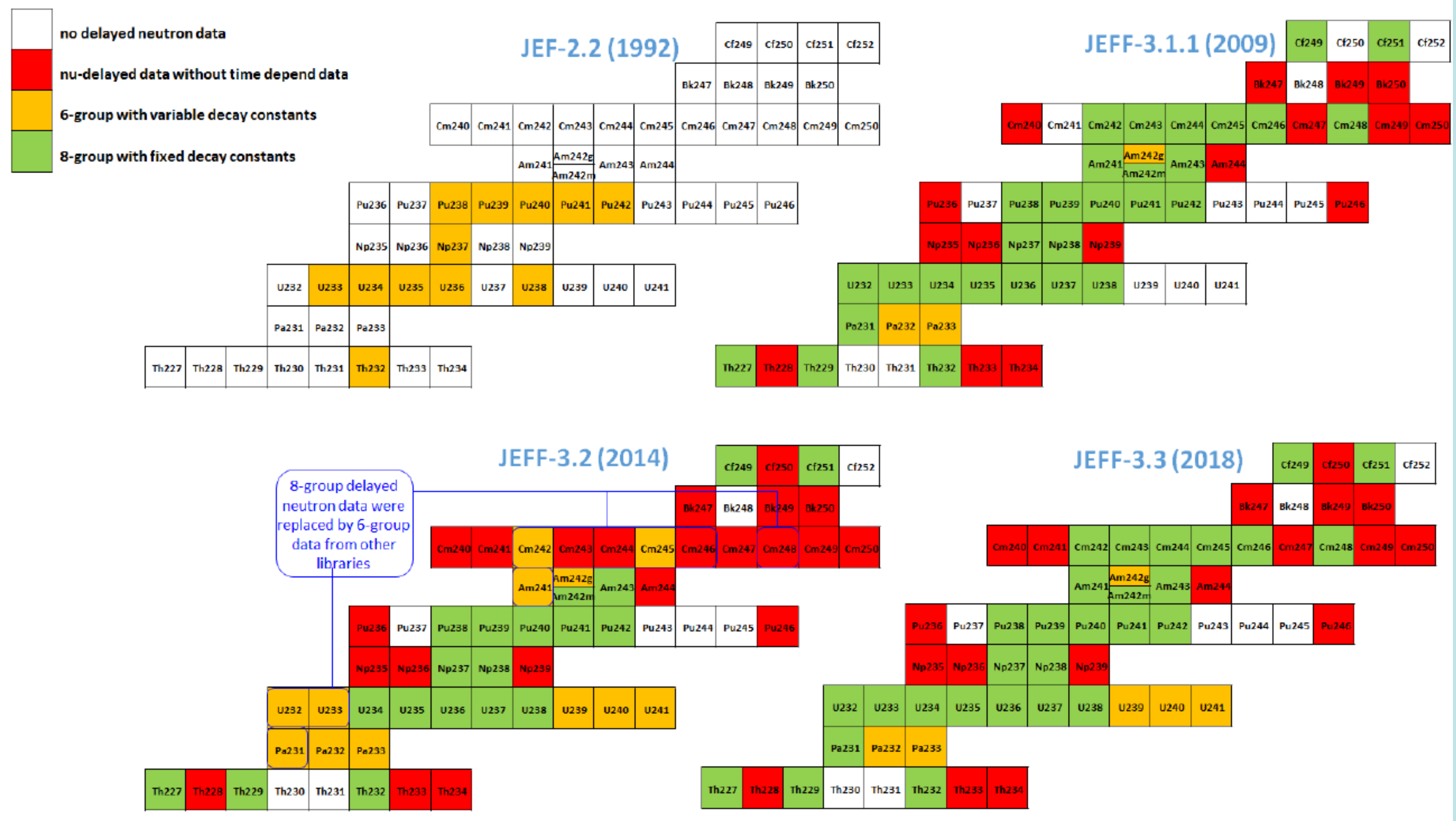
Fig. 71: Monte-Carlo simulations of gamma spectra from Al-27 inelastic scattering with 4.5 MeV neutrons, with excited level energies of Al-27 shown in blue.

Thermal scattering

- 20 files, 14 new, first covariances for H in H_2O.
- Cantargi, Granada, Marquez Damian
    - D in D_2O, Ortho D_2, Para D_2
    - H in ice, mesitylene, Ortho H_2, Para H_2, toluene
    - O-16 in D_2O, Al_2O_3
    - Al in $Al2O_3$
    - Si in Si
- Mg in Mg (Mounier)
- H in CaH_2, Ca in CaH_2 (Serot)
- Keinert, Mattes
    - H in H_2O, CH_2, ZrH (Keinert, Mattes)
    - Be in Be (Keinert, Mattes)
    - C in graphite (Keinert, Mattes)



Delayed neutrons – 8 groups structure



⬜ no delayed neutron data
🟥 nu-delayed data without time depend data
🟨 6-group with variable decay constants
🟩 8-group with fixed decay constants

JEF-2.2 (1992)

⬜ Cf249 ⬜ Cf250 ⬜ Cf251 ⬜ Cf252
⬜ Bk247 ⬜ Bk248 ⬜ Bk249 ⬜ Bk250
⬜ Cm240 ⬜ Cm241 ⬜ Cm242 ⬜ Cm243 ⬜ Cm244 ⬜ Cm245 ⬜ Cm246 ⬜ Cm247 ⬜ Cm248 ⬜ Cm249 ⬜ Cm250
⬜ Am241 ⬜ Am242g / ⬜ Am242m ⬜ Am243 ⬜ Am244
⬜ Pu236 ⬜ Pu237 🟨 Pu238 🟨 Pu239 🟨 Pu240 🟨 Pu241 🟨 Pu242 ⬜ Pu243 ⬜ Pu244 ⬜ Pu245 ⬜ Pu246
⬜ Np235 ⬜ Np236 🟨 Np237 ⬜ Np238 ⬜ Np239
⬜ U232 🟨 U233 🟨 U234 🟨 U235 🟨 U236 ⬜ U237 🟨 U238 ⬜ U239 ⬜ U240 ⬜ U241
⬜ Pa231 ⬜ Pa232 ⬜ Pa233
⬜ Th227 ⬜ Th228 ⬜ Th229 ⬜ Th230 ⬜ Th231 🟨 Th232 ⬜ Th233 ⬜ Th234

JEFF-3.1.1 (2009)

🟩 Cf249 ⬜ Cf250 🟩 Cf251 ⬜ Cf252
🟥 Bk247 ⬜ Bk248 🟥 Bk249 🟥 Bk250
🟥 Cm240 ⬜ Cm241 🟩 Cm242 🟩 Cm243 🟩 Cm244 🟩 Cm245 🟩 Cm246 🟥 Cm247 🟩 Cm248 🟥 Cm249 🟥 Cm250
🟩 Am241 🟨 Am242g / 🟩 Am242m 🟩 Am243 🟥 Am244
🟥 Pu236 ⬜ Pu237 🟩 Pu238 🟩 Pu239 🟩 Pu240 🟩 Pu241 🟩 Pu242 ⬜ Pu243 ⬜ Pu244 ⬜ Pu245 🟥 Pu246
🟥 Np235 🟥 Np236 🟩 Np237 🟩 Np238 🟥 Np239
🟩 U232 🟩 U233 🟩 U234 🟩 U235 🟩 U236 🟩 U237 🟩 U238 ⬜ U239 ⬜ U240 ⬜ U241
🟩 Pa231 🟨 Pa232 🟨 Pa233
🟩 Th227 🟥 Th228 🟩 Th229 ⬜ Th230 ⬜ Th231 🟩 Th232 🟥 Th233 🟥 Th234

JEFF-3.2 (2014)

8-group delayed neutron data were replaced by 6-group data from other libraries

🟩 Cf249 🟥 Cf250 🟩 Cf251 ⬜ Cf252
🟥 Bk247 ⬜ Bk248 🟥 Bk249 🟥 Bk250
🟥 Cm240 🟥 Cm241 🟨 Cm242 🟥 Cm243 🟥 Cm244 🟨 Cm245 🟥 Cm246 🟥 Cm247 🟥 Cm248 🟥 Cm249 🟥 Cm250
🟨 Am241 🟨 Am242g / 🟩 Am242m 🟩 Am243 🟥 Am244
🟥 Pu236 ⬜ Pu237 🟩 Pu238 🟩 Pu239 🟩 Pu240 🟩 Pu241 🟩 Pu242 ⬜ Pu243 ⬜ Pu244 ⬜ Pu245 🟥 Pu246
🟥 Np235 🟥 Np236 🟩 Np237 🟩 Np238 🟥 Np239
🟨 U232 🟨 U233 🟩 U234 🟩 U235 🟩 U236 🟩 U237 🟩 U238 🟨 U239 🟨 U240 🟨 U241
🟨 Pa231 🟨 Pa232 🟨 Pa233
🟩 Th227 🟥 Th228 🟩 Th229 ⬜ Th230 ⬜ Th231 🟩 Th232 🟥 Th233 🟥 Th234

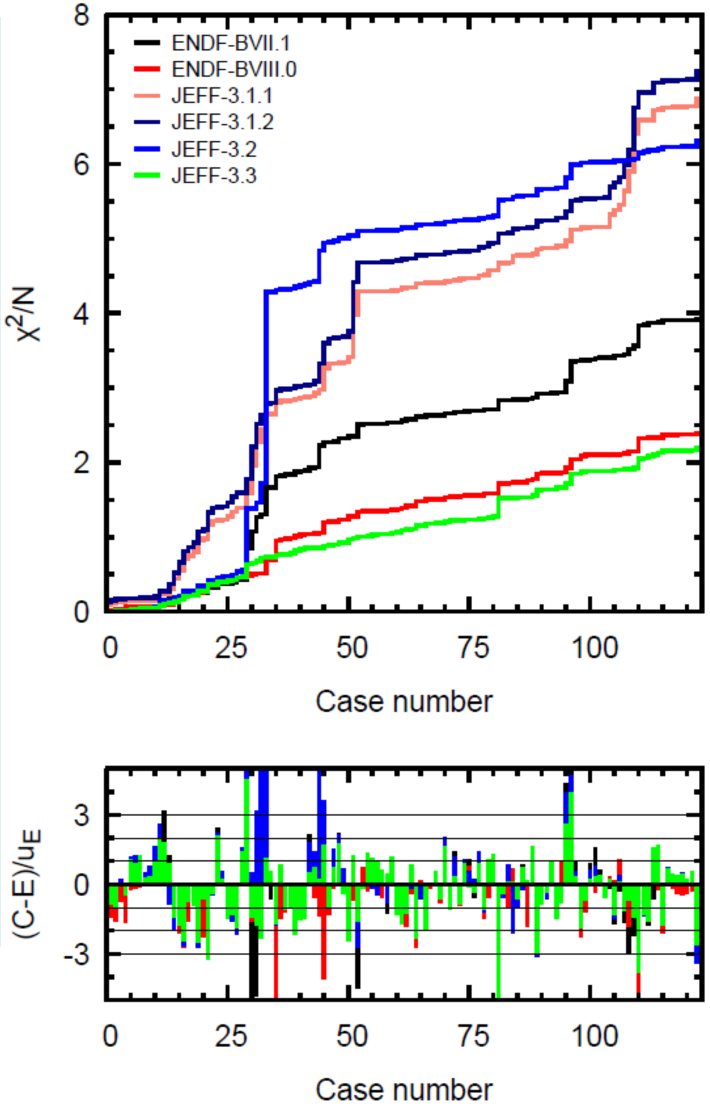
JEFF-3.3 (2018)

🟩 Cf249 🟥 Cf250 🟩 Cf251 ⬜ Cf252
🟥 Bk247 ⬜ Bk248 🟥 Bk249 🟥 Bk250
🟥 Cm240 🟥 Cm241 🟩 Cm242 🟩 Cm243 🟩 Cm244 🟩 Cm245 🟩 Cm246 🟥 Cm247 🟩 Cm248 🟥 Cm249 🟥 Cm250
🟩 Am241 🟨 Am242g / 🟩 Am242m 🟩 Am243 🟥 Am244
🟥 Pu236 ⬜ Pu237 🟩 Pu238 🟩 Pu239 🟩 Pu240 🟩 Pu241 🟩 Pu242 ⬜ Pu243 ⬜ Pu244 ⬜ Pu245 🟥 Pu246
🟥 Np235 🟥 Np236 🟩 Np237 🟩 Np238 🟥 Np239
🟩 U232 🟩 U233 🟩 U234 🟩 U235 🟩 U236 🟩 U237 🟩 U238 🟨 U239 🟨 U240 🟨 U241
🟩 Pa231 🟨 Pa232 🟨 Pa233
🟩 Th227 🟥 Th228 🟩 Th229 ⬜ Th230 ⬜ Th231 🟩 Th232 🟥 Th233 🟥 Th234

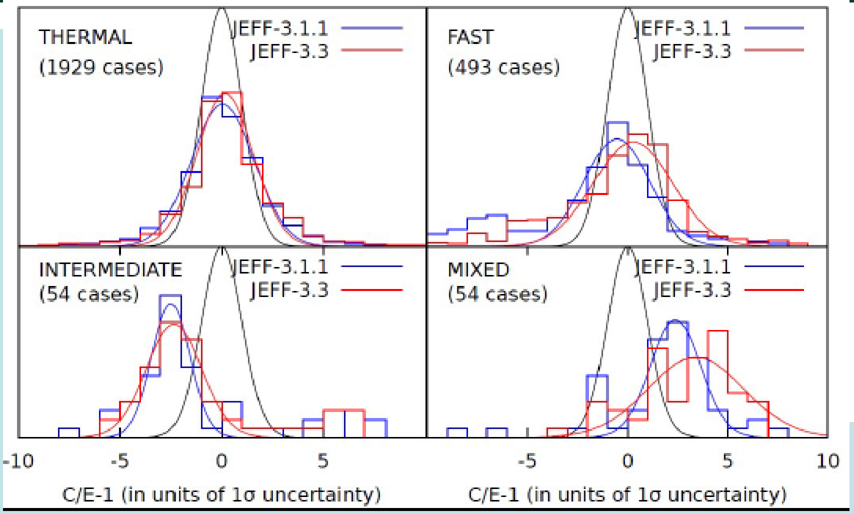
European Commission

Benchmarking

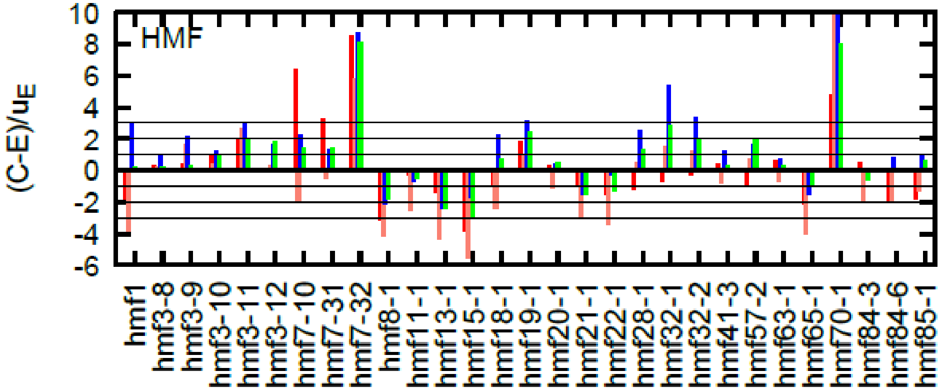
NEA-Mosteller

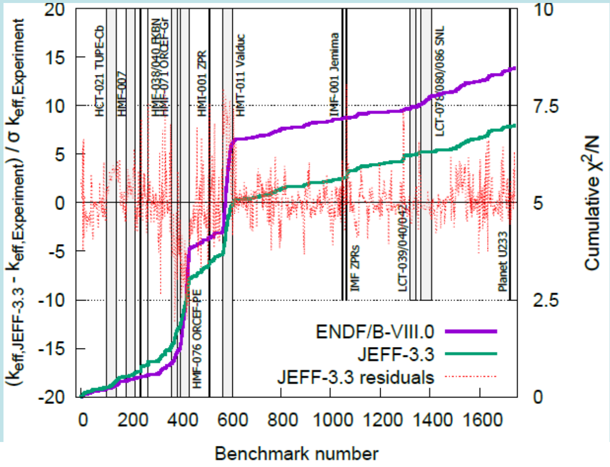


NRG - Van der Marck



IRSN - Leclaire





Trkov - Fleming

JEFF-3.3 is considerably better than JEFF-3.2 and JEFF-3.1.1&2

JEFF-3.3 is comparable to ENDF/B-VIII.1

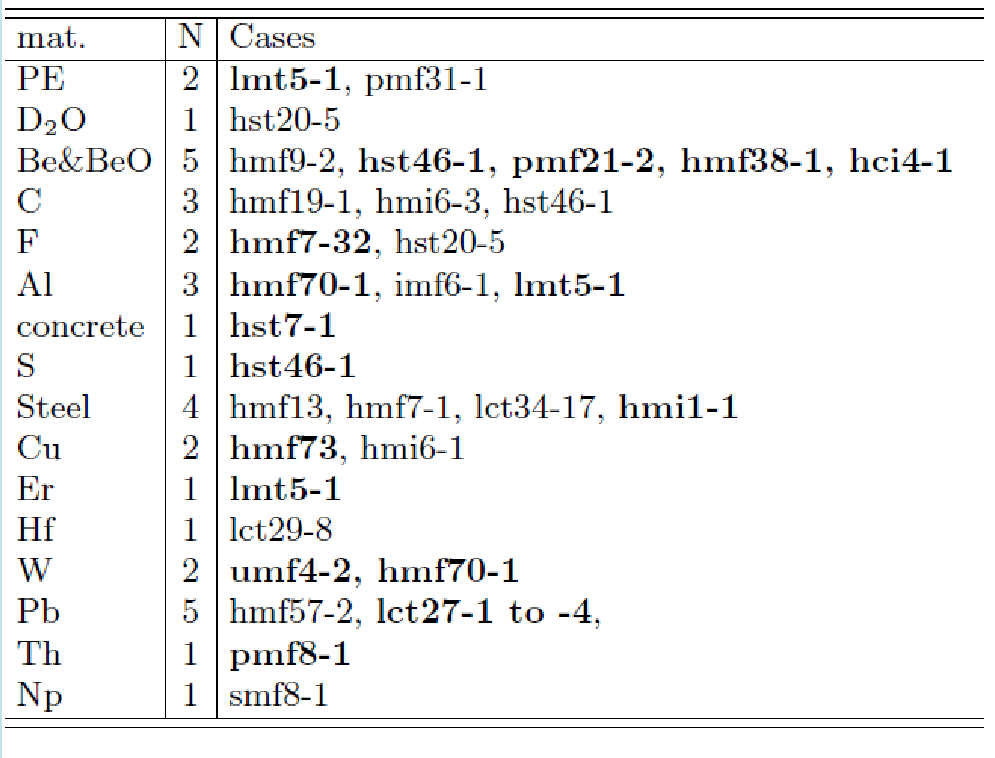
Distributions over benchmarks are strongly affected by outliers

Leads to a non-Gaussian distribution!

Outlier analysis

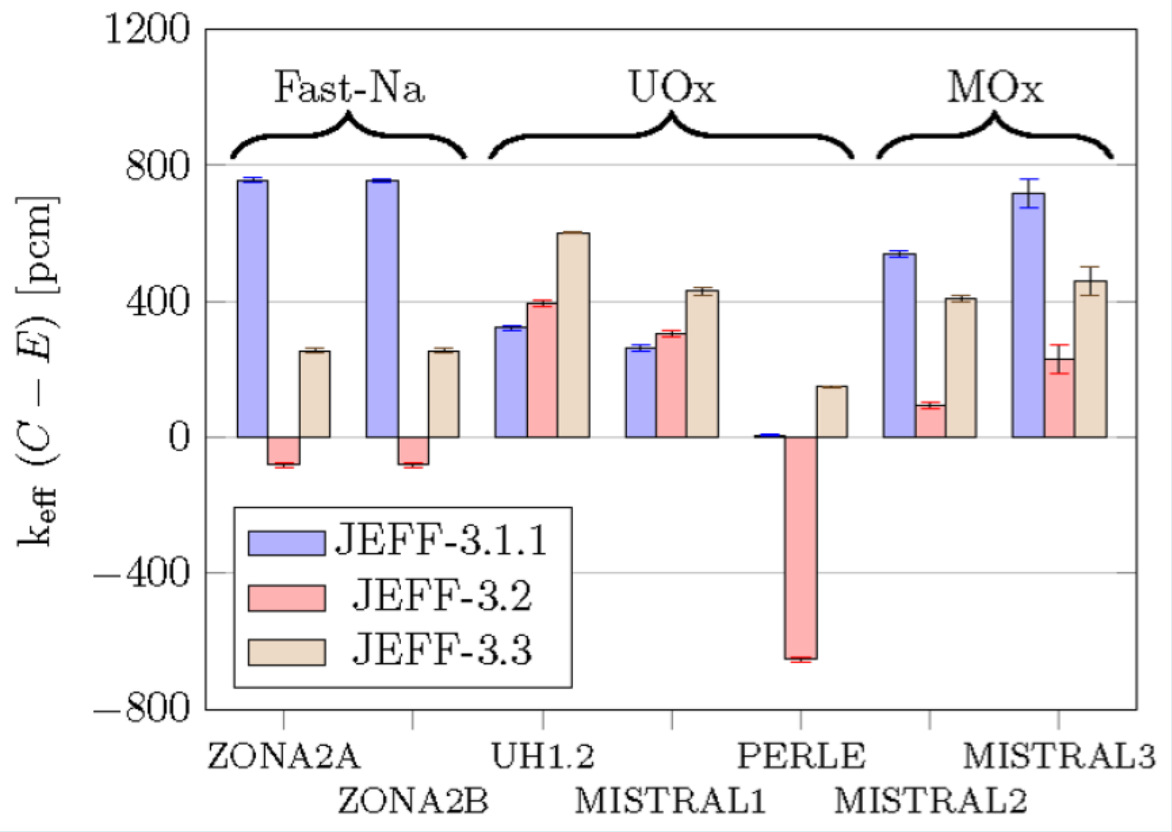
- NEA+IRSN suite implied materials other than actinides (2-3s and **>3s**)
- The remainder of outliers (16 out of 45) are **actinide+water+oxygen** only.
- IAEA suite: 1/3 of cases is an outlier > 2s. Many due to small benchmark unc.
- PE, Be/BeO, F, Al, concrete, S, steel, Cu, Er, W, Pb, Th
- (D2O, C, Hf, Np) … (Gd, Cr).

- Most important remain the major actinides

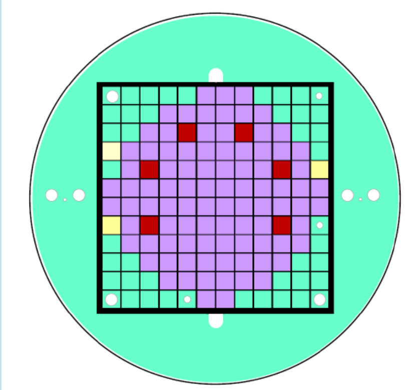


mat.	N	Cases
PE	2	**lmt5-1**, pmf31-1
D_2O	1	hst20-5
Be&BeO	5	hmf9-2, **hst46-1**, **pmf21-2**, **hmf38-1**, **hci4-1**
C	3	hmf19-1, hmi6-3, hst46-1
F	2	**hmf7-32**, hst20-5
Al	3	**hmf70-1**, imf6-1, **lmt5-1**
concrete	1	**hst7-1**
S	1	**hst46-1**
Steel	4	hmf13, hmf7-1, lct34-17, **hmi1-1**
Cu	2	**hmf73**, hmi6-1
Er	1	**lmt5-1**
Hf	1	lct29-8
W	2	**umf4-2**, **hmf70-1**
Pb	5	hmf57-2, **lct27-1 to -4**,
Th	1	**pmf8-1**
Np	1	smf8-1

Additional critical experiments



VENUS-F



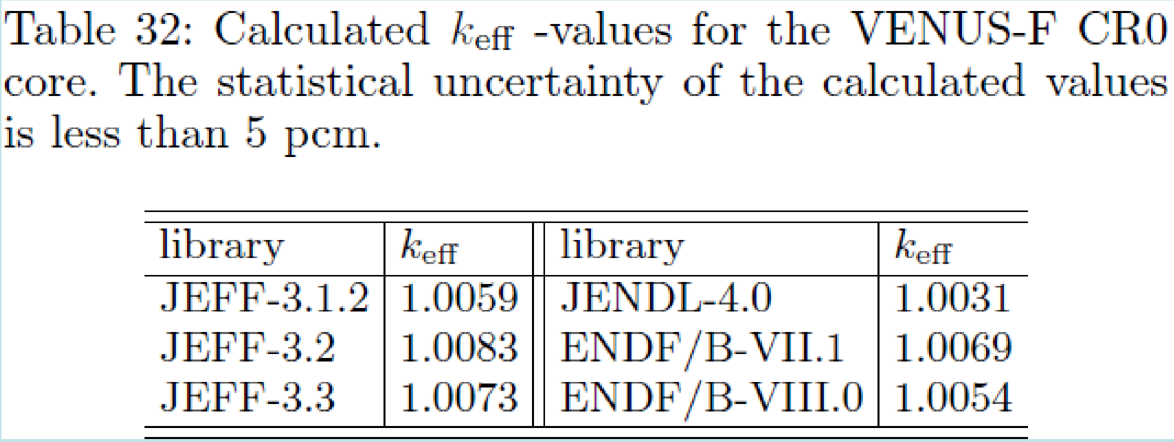
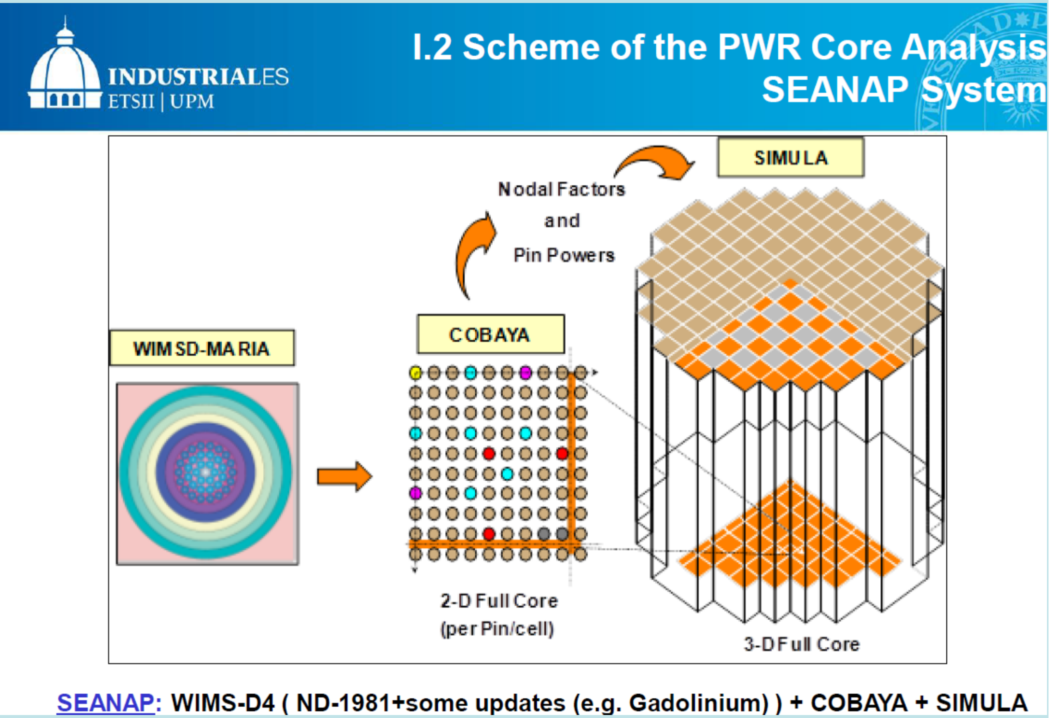


Table 32: Calculated k_{eff} -values for the VENUS-F CR0 core. The statistical uncertainty of the calculated values is less than 5 pcm.

library	k_{eff}	library	k_{eff}
JEFF-3.1.2	1.0059	JENDL-4.0	1.0031
JEFF-3.2	1.0083	ENDF/B-VII.1	1.0069
JEFF-3.3	1.0073	ENDF/B-VIII.0	1.0054

Application to PWR – UPM – SEANAP

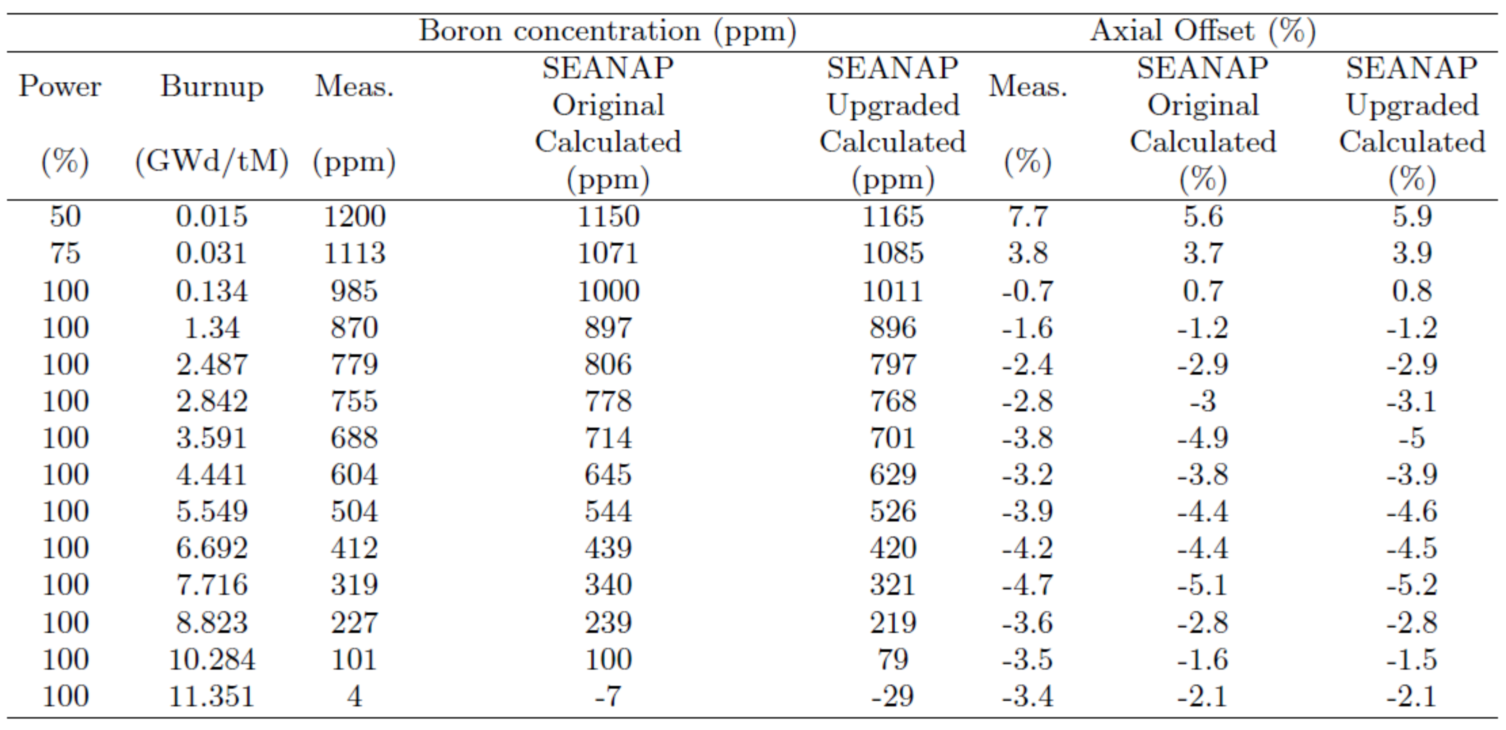
Boron concentration and axial offset



INDUSTRIALES ETSII | UPM

I.2 Scheme of the PWR Core Analysis SEANAP System

SEANAP: WIMS-D4 (ND-1981+some updates (e.g. Gadolinium)) + COBAYA + SIMULA

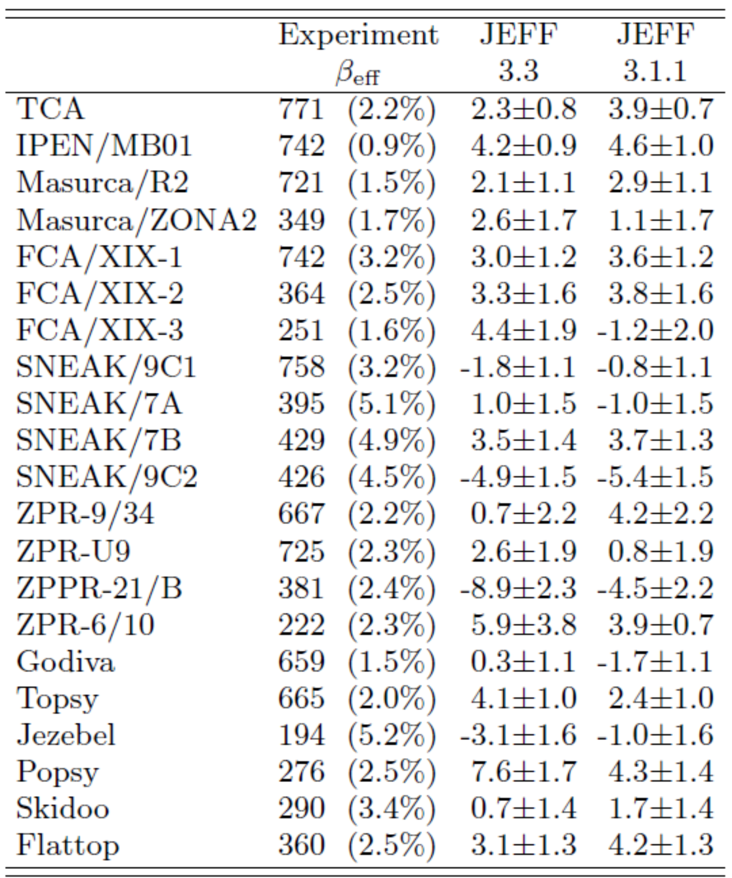


		Boron concentration (ppm)			Axial Offset (%)		
Power (%)	Burnup (GWd/tM)	Meas. (ppm)	SEANAP Original Calculated (ppm)	SEANAP Upgraded Calculated (ppm)	Meas. (%)	SEANAP Original Calculated (%)	SEANAP Upgraded Calculated (%)
50	0.015	1200	1150	1165	7.7	5.6	5.9
75	0.031	1113	1071	1085	3.8	3.7	3.9
100	0.134	985	1000	1011	-0.7	0.7	0.8
100	1.34	870	897	896	-1.6	-1.2	-1.2
100	2.487	779	806	797	-2.4	-2.9	-2.9
100	2.842	755	778	768	-2.8	-3	-3.1
100	3.591	688	714	701	-3.8	-4.9	-5
100	4.441	604	645	629	-3.2	-3.8	-3.9
100	5.549	504	544	526	-3.9	-4.4	-4.6
100	6.692	412	439	420	-4.2	-4.4	-4.5
100	7.716	319	340	321	-4.7	-5.1	-5.2
100	8.823	227	239	219	-3.6	-2.8	-2.8
100	10.284	101	100	79	-3.5	-1.6	-1.5
100	11.351	4	-7	-29	-3.4	-2.1	-2.1

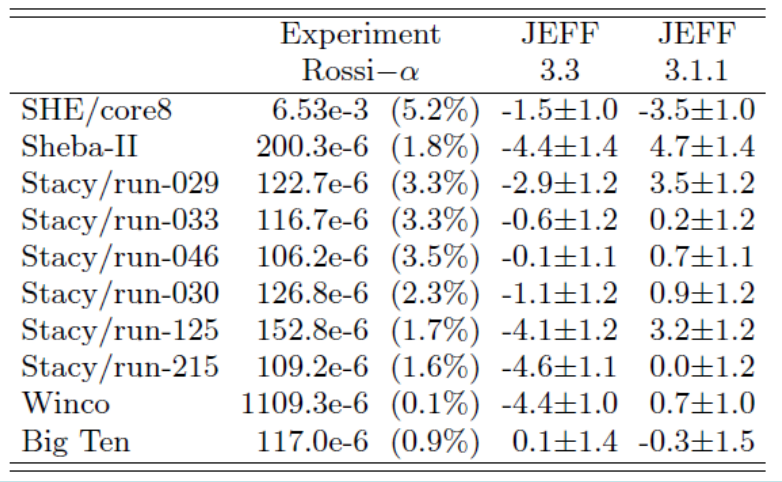
- JEFF-3.3 does very well when applied to an actual PWR code system

Delayed neutron testing

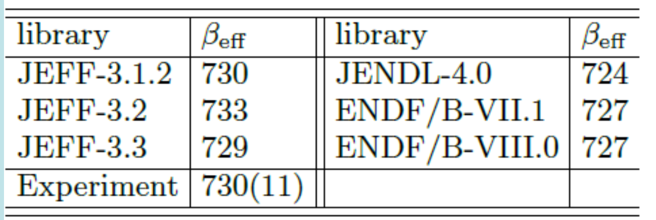
- Beta-eff versus 20 cases in literature and VENUS-F
- JEFF-3.3 comes out well (JEFF-3.1.1 somewhat better)



	Experiment β_{eff}	JEFF 3.3	JEFF 3.1.1
TCA	771 (2.2%)	2.3±0.8	3.9±0.7
IPEN/MB01	742 (0.9%)	4.2±0.9	4.6±1.0
Masurca/R2	721 (1.5%)	2.1±1.1	2.9±1.1
Masurca/ZONA2	349 (1.7%)	2.6±1.7	1.1±1.7
FCA/XIX-1	742 (3.2%)	3.0±1.2	3.6±1.2
FCA/XIX-2	364 (2.5%)	3.3±1.6	3.8±1.6
FCA/XIX-3	251 (1.6%)	4.4±1.9	-1.2±2.0
SNEAK/9C1	758 (3.2%)	-1.8±1.1	-0.8±1.1
SNEAK/7A	395 (5.1%)	1.0±1.5	-1.0±1.5
SNEAK/7B	429 (4.9%)	3.5±1.4	3.7±1.3
SNEAK/9C2	426 (4.5%)	-4.9±1.5	-5.4±1.5
ZPR-9/34	667 (2.2%)	0.7±2.2	4.2±2.2
ZPR-U9	725 (2.3%)	2.6±1.9	0.8±1.9
ZPPR-21/B	381 (2.4%)	-8.9±2.3	-4.5±2.2
ZPR-6/10	222 (2.3%)	5.9±3.8	3.9±0.7
Godiva	659 (1.5%)	0.3±1.1	-1.7±1.1
Topsy	665 (2.0%)	4.1±1.0	2.4±1.0
Jezebel	194 (5.2%)	-3.1±1.6	-1.0±1.6
Popsy	276 (2.5%)	7.6±1.7	4.3±1.4
Skidoo	290 (3.4%)	0.7±1.4	1.7±1.4
Flattop	360 (2.5%)	3.1±1.3	4.2±1.3

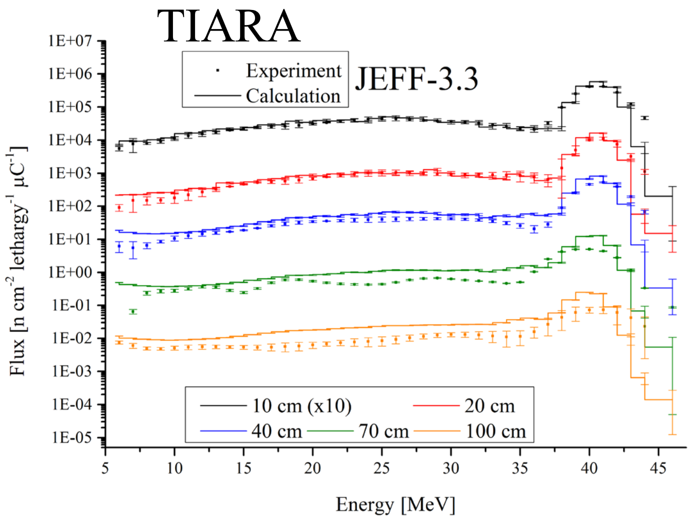


	Experiment Rossi−α	JEFF 3.3	JEFF 3.1.1
SHE/core8	6.53e-3 (5.2%)	-1.5±1.0	-3.5±1.0
Sheba-II	200.3e-6 (1.8%)	-4.4±1.4	4.7±1.4
Stacy/run-029	122.7e-6 (3.3%)	-2.9±1.2	3.5±1.2
Stacy/run-033	116.7e-6 (3.3%)	-0.6±1.2	0.2±1.2
Stacy/run-046	106.2e-6 (3.5%)	-0.1±1.1	0.7±1.1
Stacy/run-030	126.8e-6 (2.3%)	-1.1±1.2	0.9±1.2
Stacy/run-125	152.8e-6 (1.7%)	-4.1±1.2	3.2±1.2
Stacy/run-215	109.2e-6 (1.6%)	-4.6±1.1	0.0±1.2
Winco	1109.3e-6 (0.1%)	-4.4±1.0	0.7±1.0
Big Ten	117.0e-6 (0.9%)	0.1±1.4	-0.3±1.5

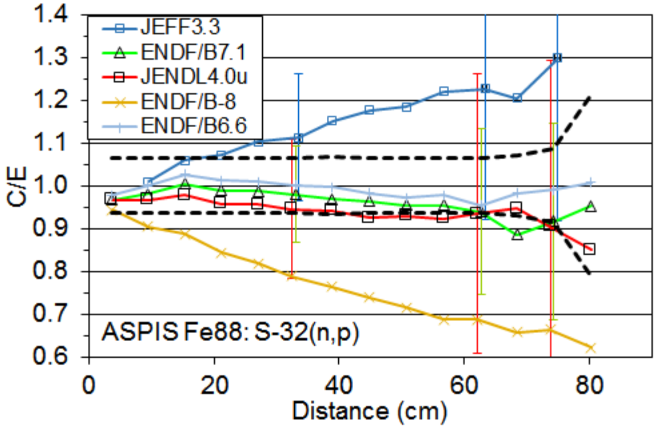


library	β_{eff}	library	β_{eff}
JEFF-3.1.2	730	JENDL-4.0	724
JEFF-3.2	733	ENDF/B-VII.1	727
JEFF-3.3	729	ENDF/B-VIII.0	727
Experiment	730(11)		

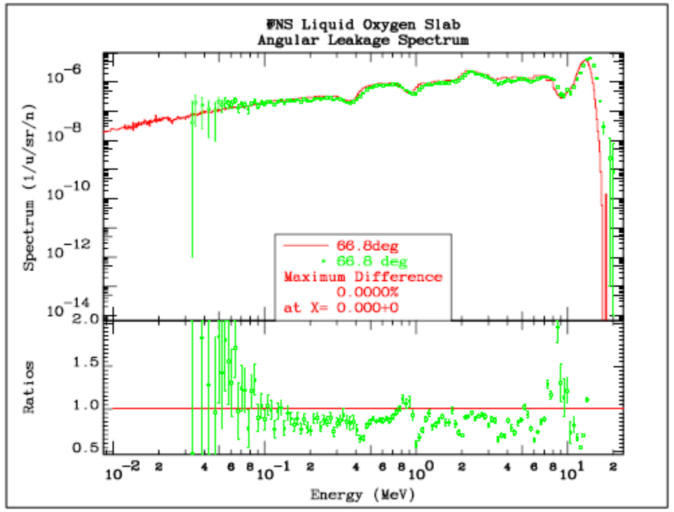
Shielding benchmarks - SINBAD



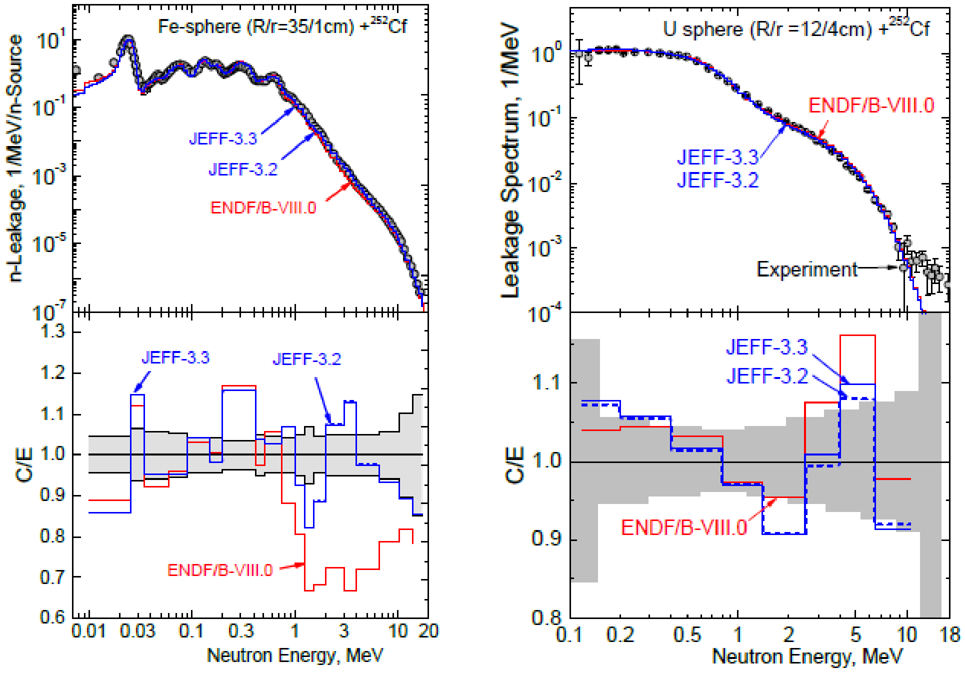
ASPIS IRON-88



FNS Oxygen



Cf-252 leakage spectra
Fe and U - IPPE



Decay Heat, Pu-239 & Inconel-600 examples

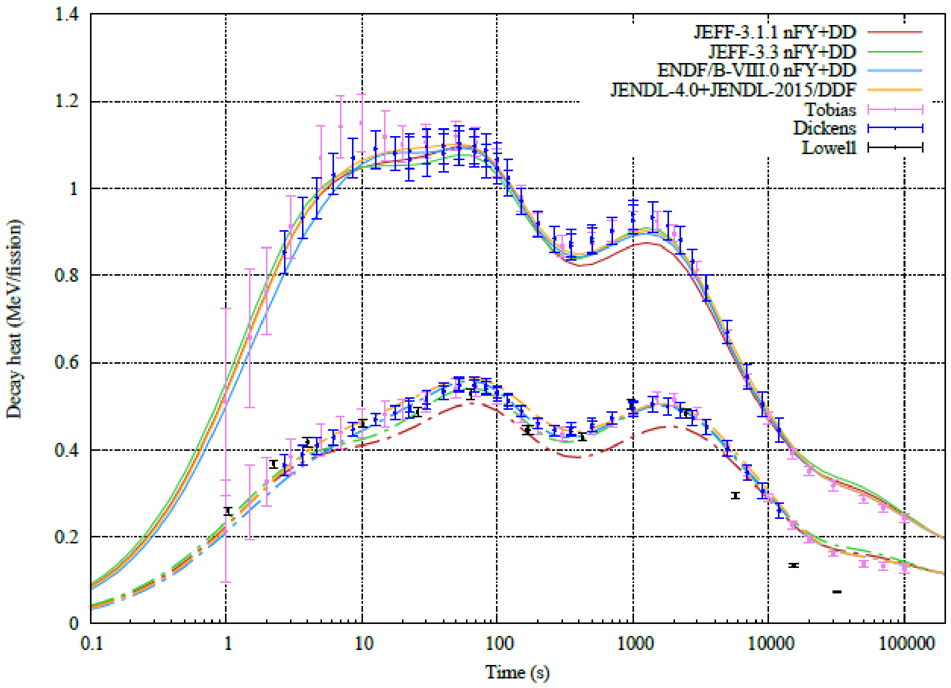


Fig. 98: Total and gamma fission decay heat pulse for ^{239}Pu, showing simulations with a range of nuclear data files, as calculated by FISPACT-II. Note the significant under-prediction of gamma heat for JEFF-3.1.1, over a range of cooling periods from 10 to 2000 seconds.

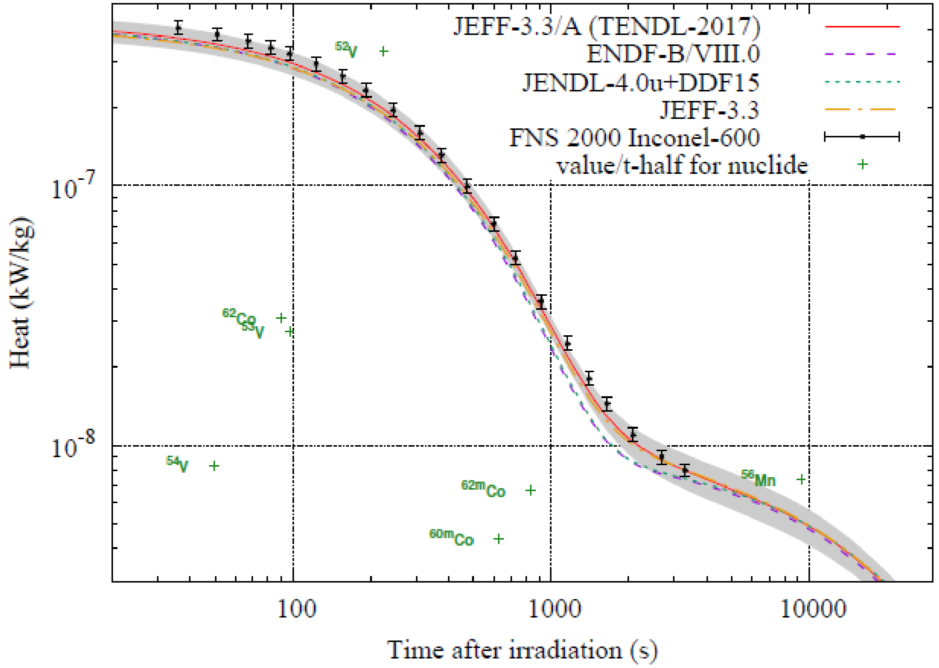


Fig. 100: Decay heat simulations and measurements from the JAEA Fusion Neutron Source, considering Inconel-600 irradiation and the most recent nuclear data libraries. Dominant nuclides are labeled at (x,y) coordinates that are their half-life and post-irradiation quantity, respectively.

The future of JEFF: JEFF-4

- We want JEFF-4 to be a major change
- Wide range of applications
- Make nuclear science knowledge and knowhow as available as possible
- Systematic inclusion of uncertainties and their correlations
- Improve the quality assurance of evaluations
- Increase the range of validation
- Improve interaction with users
- Foster the developer and scientific community

Theory, experiments, evaluation

R.P. Feynman
1918-1988

“It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong”

“We have learned a lot from experience about how to handle some of the ways we fool ourselves. One example:

Millikan measured the charge of the electron by an experiment with falling oil drops and got an answer which we know not to be quite right.

It’s interesting to look at the history of measurements of the charge of the electron, after Millikan. If you plot them as a function of time, you find that one is a little bigger than Millikan’s, and the next one’s a little bit bigger... until finally they settle down to a number which is higher.”

“... when you have a wide range of people who contribute without looking carefully at it, you don’t improve your knowledge of the situation by averaging.”

Summary

- Using better models allows to better reproduce experimental data
  Ex: OMP, Statistical models, Level densities, Γγ, fission transmission

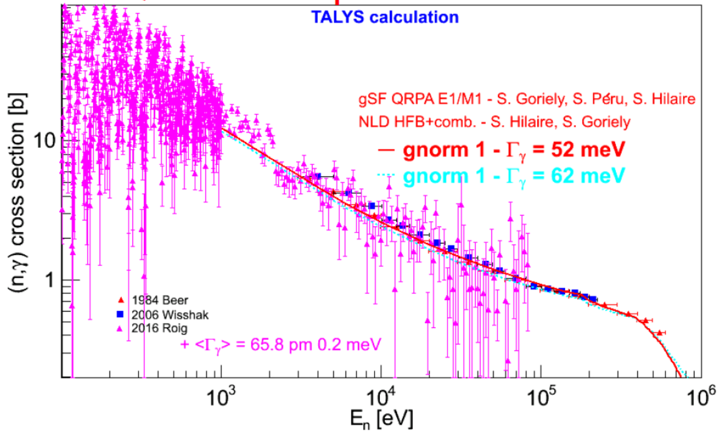
- Microscopic models are able to compute model ingredients from nuclear interaction + many body formalism (no adjustment)

- Use of better (more microscopic) reduce the dynamics of model parameter adjustment.
  - \+ parameter values more physical
  - \- fine adjustments still needed for optimal agreement with data

  Ex: OMP, level densities, Γγ, fission transmission

- Examples shown for cross sections in the continuum
  but conclusions also relevant for PFNS, PFGS, and in the resonance region

What about QRPA microscopic calculations?



Quantification of model defects into the covariance matrix is needed
BUT using better models will reduce the amplitude of such defects.

Resonance range evaluations

JRC & partners

- Au (500 eV <->5 keV)

CEA/Cadarache

- Lu
- Ag

KAERI

- Rh
- Gd (+ INFN Bologna + ENEA)

JAEA

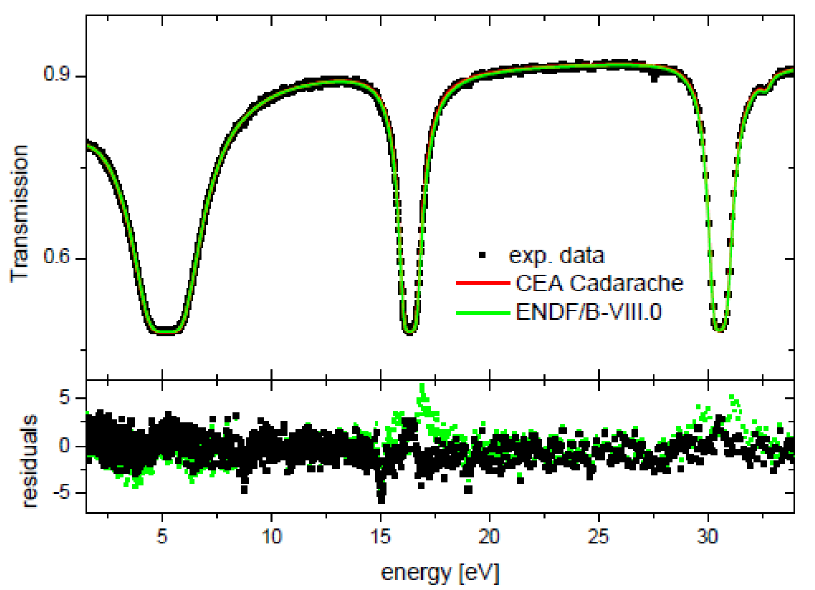
- Cu
- Bi (+SCK-CEN)

INFN Bari

- Y
- Zr

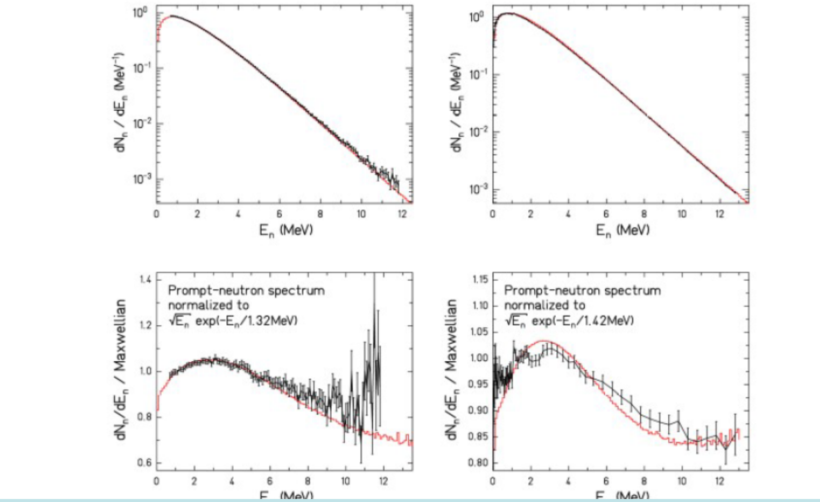
IRSN priority list ***(to be completed)***

Pu-239
Pu-240, Pu-241, Am-241,
U-235, U-238, U-234
Gd isotopes, Mo isotopes, Fe-54, Fe56, Pb-204, Pb-206, Pb-207, Pb-208
Cl-35, Cl-37, F-19, Nickel isotopes, Sm-149, Sm-152, Cs-133, Si isotopes,
Ca isotopes, Mn-55, Nd-143

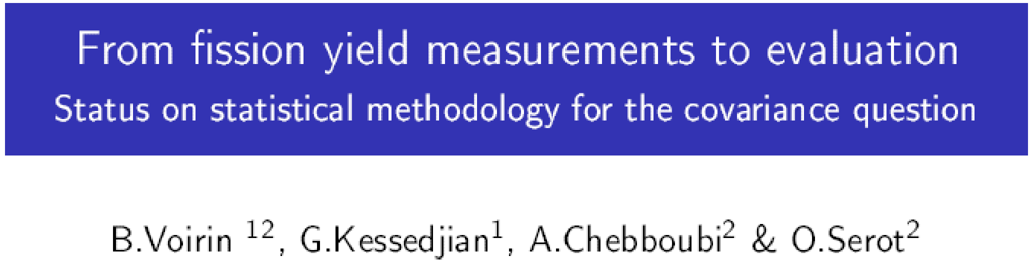


- CEA Cadarache
- ^{237}Np,
- ^{240,242}Pu,
- ^{241,243}Am,
- ^{103}Rh,
- ^{99}Tc,
- ^{234}U,
- ^{235,238}U,
- ^{239}Pu

Fission yields



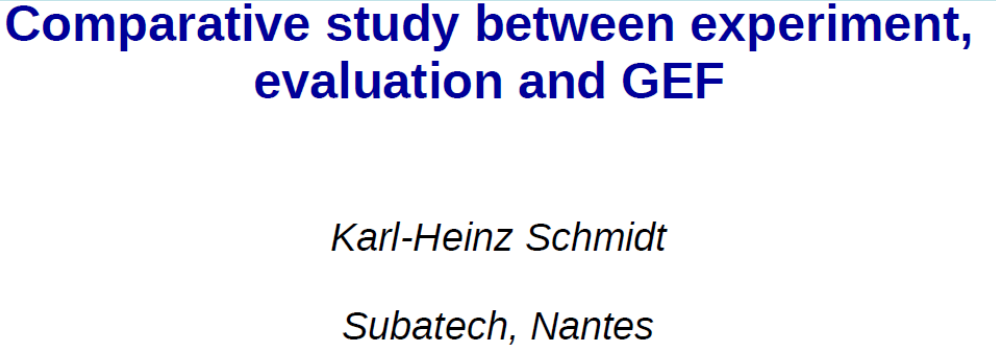
- Support for new evaluation was very fragile
- Considerable new experimental and modeling efforts
- Database needs to be secured
- Evaluation process needs to be secured
- Alignment with radioactive decay data evaluation
- Completeness is possible using FIFRELIN & GEF
- Resolution needed between accuracy from experiment and complete modeling (similar to reaction evaluations)



From fission yield measurements to evaluation

Status on statistical methodology for the covariance question

B.Voirin [12], G.Kessedjian[1], A.Chebboubi[2] & O.Serot[2]



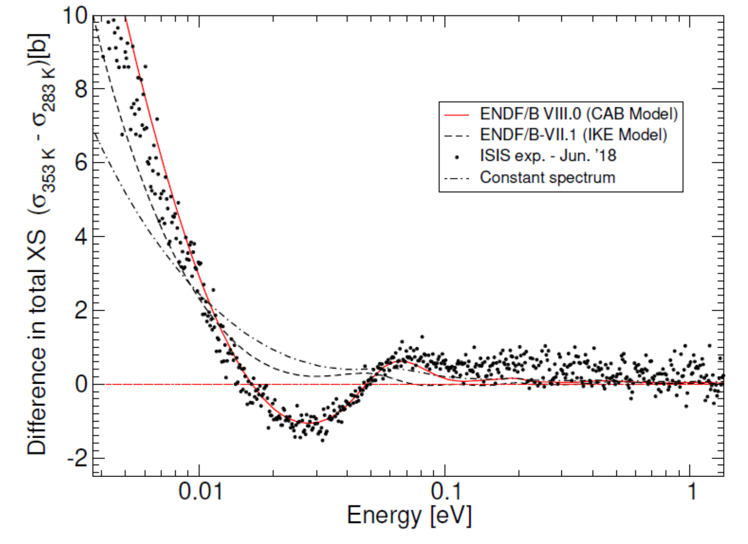
Comparative study between experiment, evaluation and GEF

Karl-Heinz Schmidt

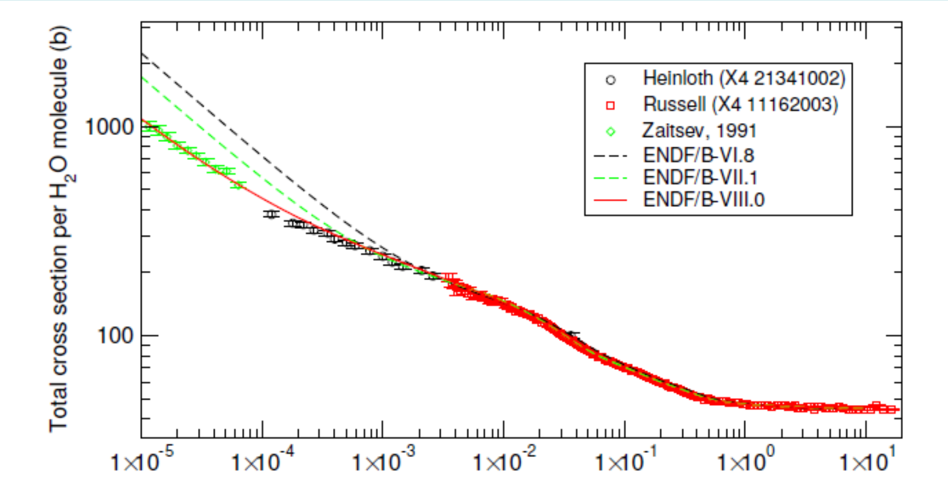
Subatech, Nantes

European Commission

Thermal scattering



- Important new modeling developments.
- New experimental data.
- Only partly on board in JEFF-3.3.
- We should fully adopt the new modeling as it is supported by old and new data, better than JEFF-3.3.
- Use covariance information.

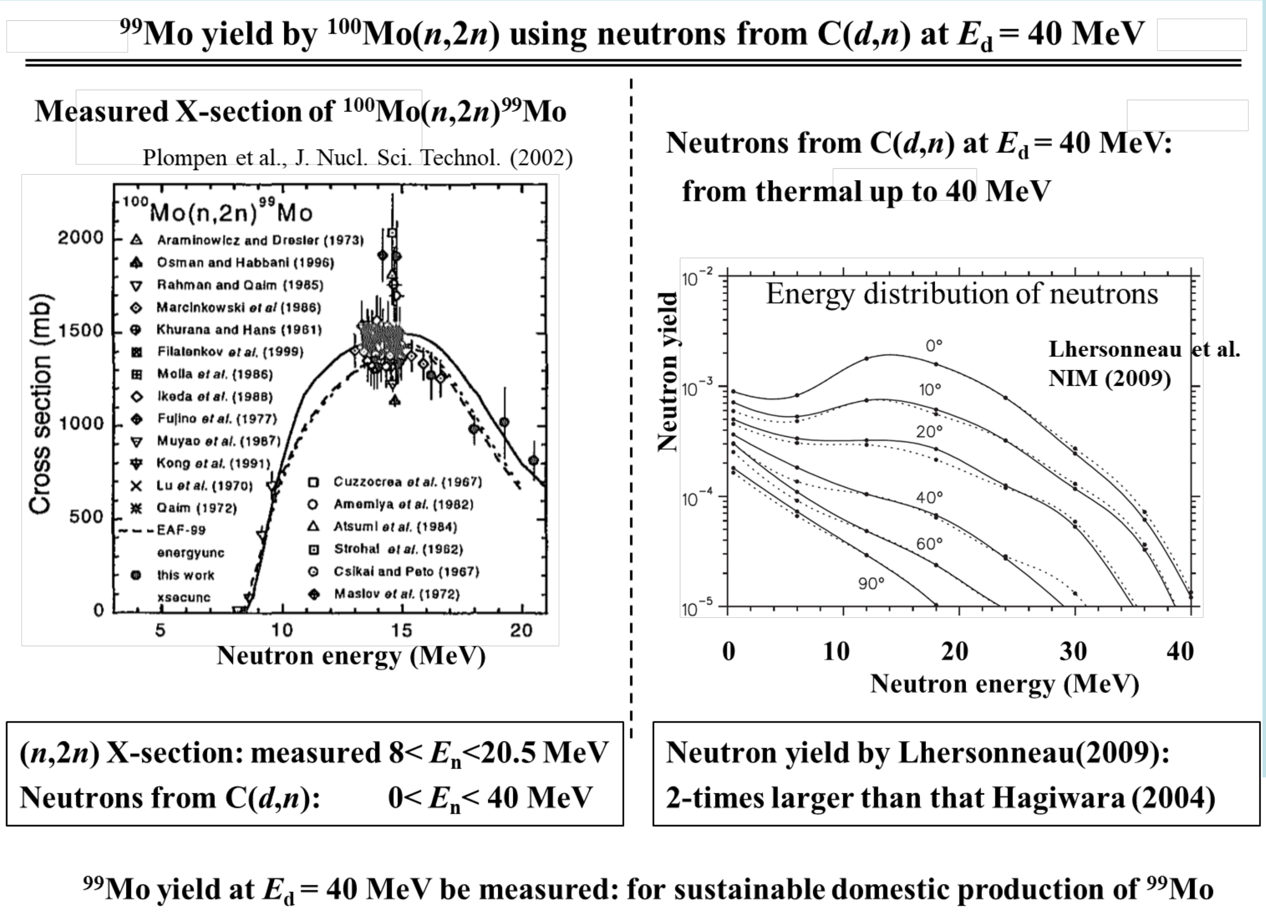


Medical isotopes GELINA, MONNET, RADMET?

- Potential for decay data, cross section and yield studies.
- Physics of targets and separation (irNano, exploratory, if funded).
- Relevant for major developments centered on accelerator production of medical radionuclides. Distributed production.
- Diagnostics (SPECT, PET): established & prospective isotopes.
- Therapy: alpha, beta, auger-electron emitters.
- Good potential for cross-site collaboration as well as inter-institutional with MS, international partners. Networking is critical for meaningful results.
- Excellent example is TAT by Alfred Morgenstern and collaborators. Highly regarded also by those (CERN, ILL, PSI, …) that are after alternatives by theranostics (^{149}Tb – TAT+PET, ^{152}Tb - PET, ^{155}Tb - SPECT).
- All very well, but 1 AD, 2 CAs for a meaningful activity, even if Open Access etc.

Illustrations

- Accelerator production routes for Mo-99: neutrons
- Y. Nagai
- Two accelerators for Japan



^{99}Mo yield by ^{100}Mo(n,2n) using neutrons from C(d,n) at E_d = 40 MeV

Measured X-section of ^{100}Mo(n,2n)^{99}Mo

Plompen et al., J. Nucl. Sci. Technol. (2002)

Neutrons from C(d,n) at E_d = 40 MeV:

from thermal up to 40 MeV

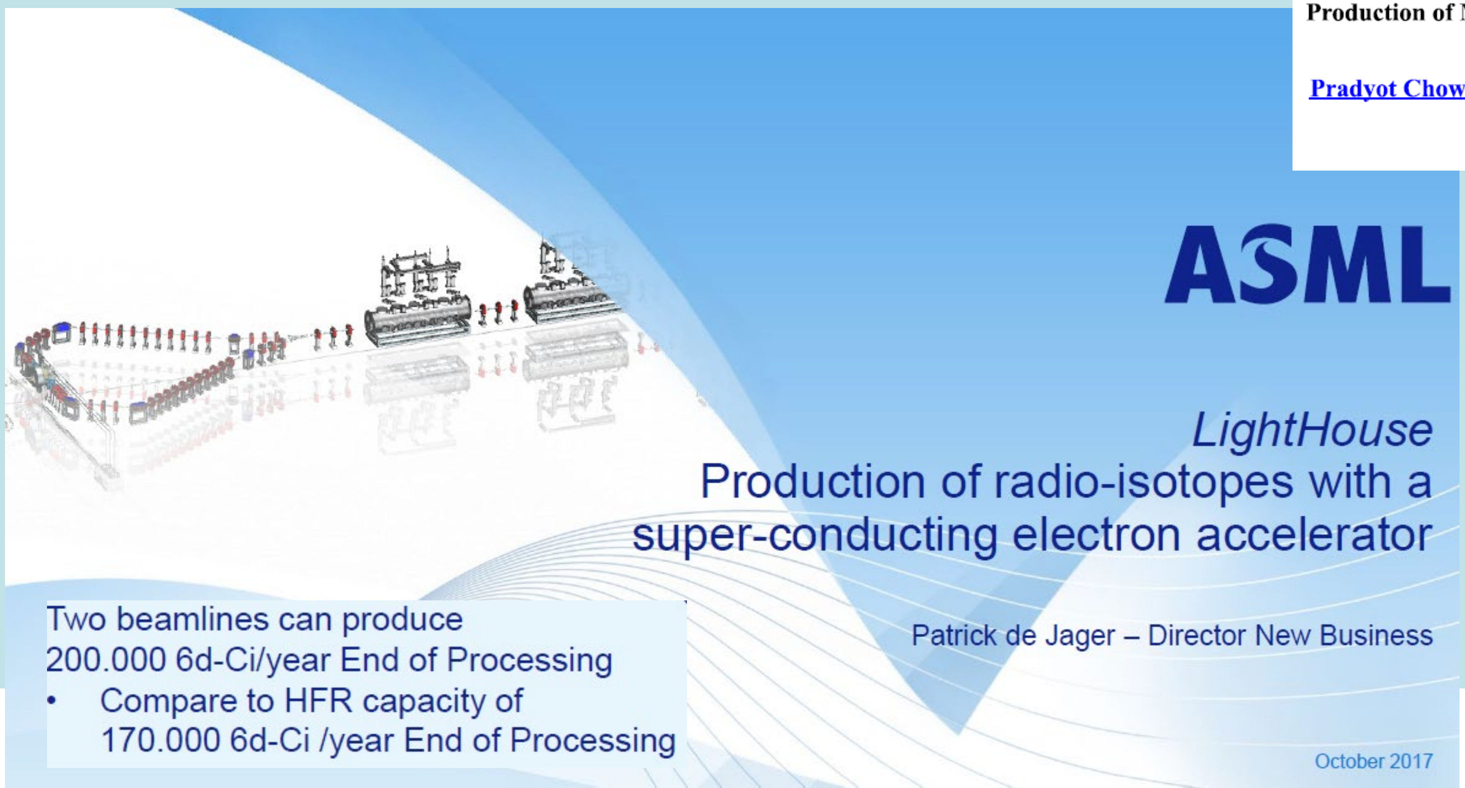
(n,2n) X-section: measured 8< E_n<20.5 MeV
Neutrons from C(d,n): 0< E_n< 40 MeV

Neutron yield by Lhersonneau(2009):
2-times larger than that Hagiwara (2004)

^{99}Mo yield at E_d = 40 MeV be measured: for sustainable domestic production of ^{99}Mo

Illustrations

- Accelerator production routes for Mo-99: electrons & photons
- LightHouse, Northstar, Canadian Light Source Inc.



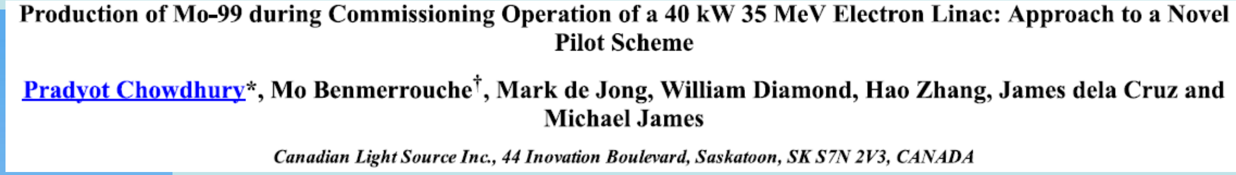
LightHouse

Production of radio-isotopes with a super-conducting electron accelerator

Patrick de Jager – Director New Business

October 2017

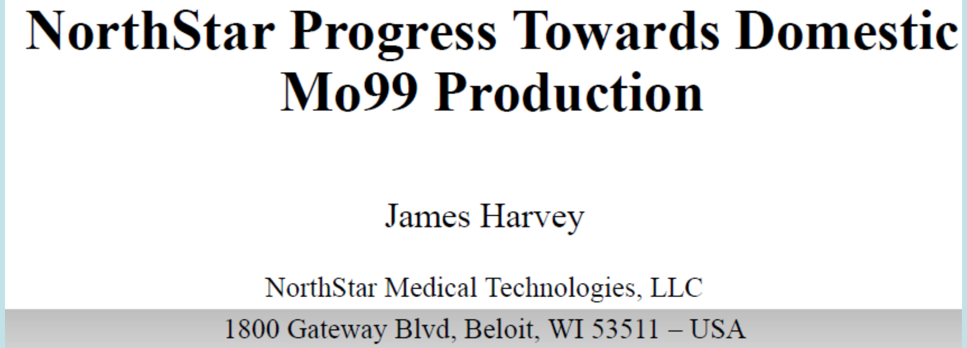
Two beamlines can produce
200.000 6d-Ci/year End of Processing
- Compare to HFR capacity of
  170.000 6d-Ci /year End of Processing



Production of Mo-99 during Commissioning Operation of a 40 kW 35 MeV Electron Linac: Approach to a Novel Pilot Scheme

Pradyot Chowdhury*, Mo Benmerrouche†, Mark de Jong, William Diamond, Hao Zhang, James dela Cruz and Michael James

Canadian Light Source Inc., 44 Inovation Boulevard, Saskatoon, SK S7N 2V3, CANADA

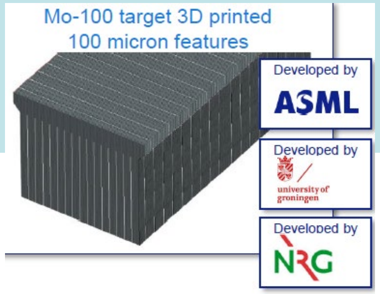


NorthStar Progress Towards Domestic Mo99 Production

James Harvey

NorthStar Medical Technologies, LLC

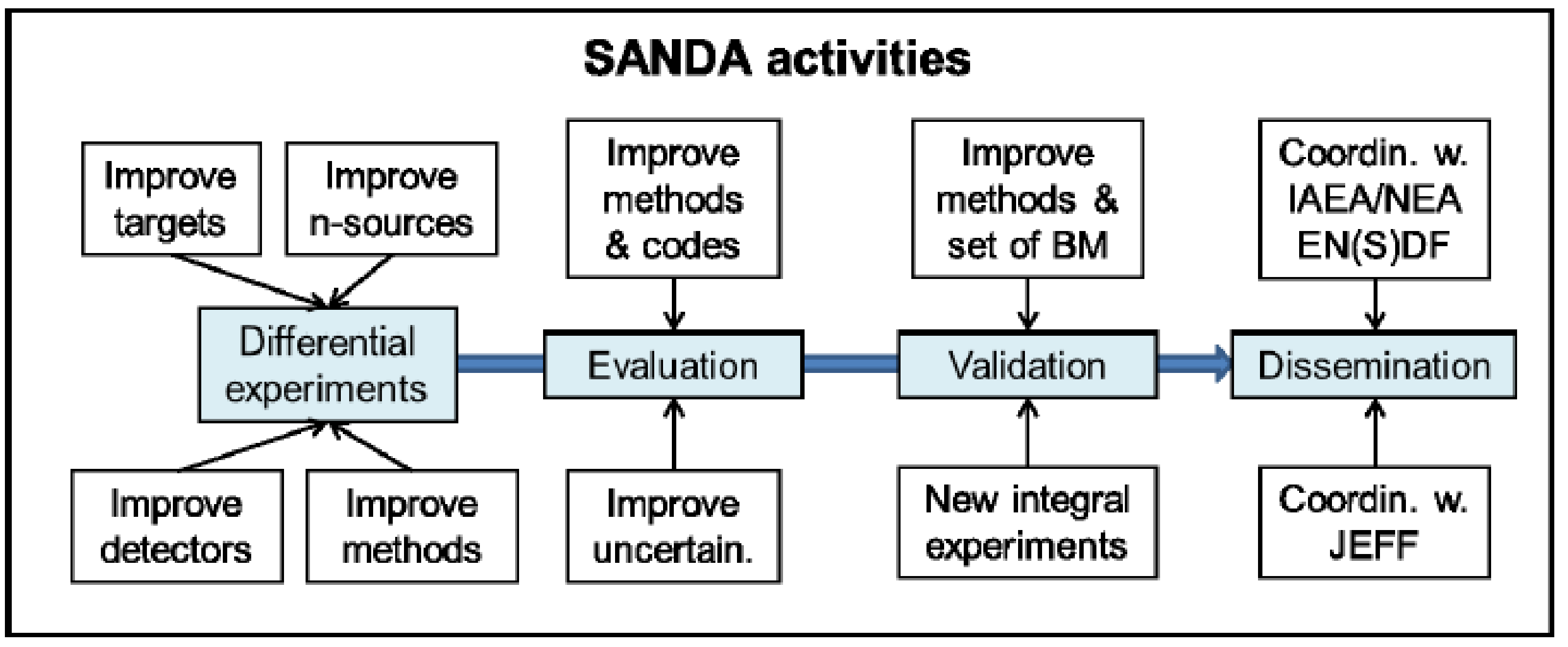
1800 Gateway Blvd, Beloit, WI 53511 – USA



European Commission

European nuclear data initiatives

- SANDA Supplying accurate nuclear data for energy and non-energy applications, 35 participating organizations, 4 years from 1 Sep. 2019.



SANDA activities

Improve targets

Improve n-sources

Improve methods & codes

Improve methods & set of BM

Coordin. w. IAEA/NEA EN(S)DF

Differential experiments

Evaluation

Validation

Dissemination

Improve detectors

Improve methods

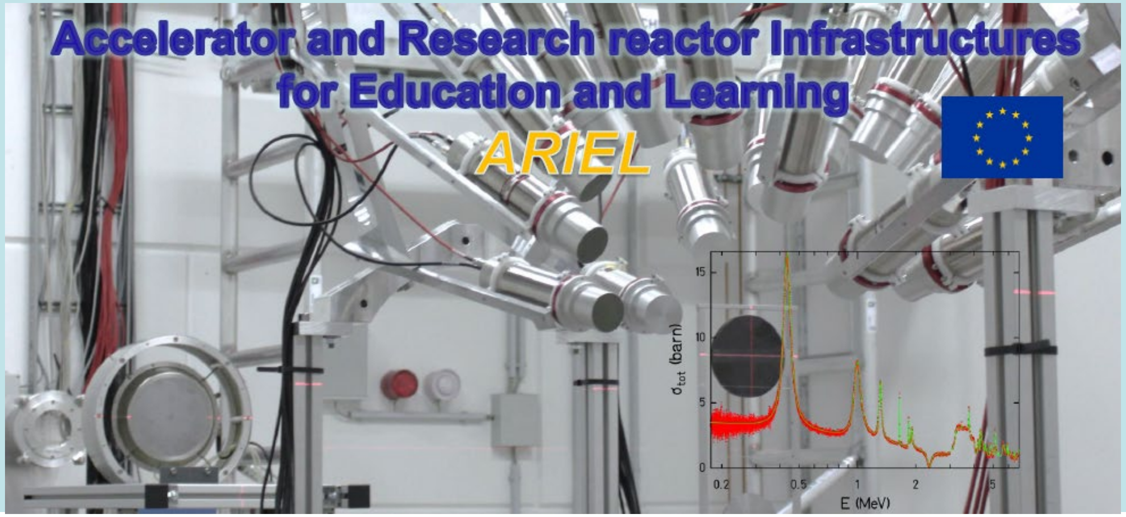
Improve uncertain.

New integral experiments

Coordin. w. JEFF

European nuclear data initiatives
ARIEL – www.ariel-h2020.eu

- ARIEL, 23 participating organizations, 4 years from 1 Sep. 2019.
- 27 research infrastructures, 22 accelerators, 5 research reactors
- Open access: one PAC evaluates proposals for all facilities
- Support to the proposers and the facilities.



Accelerator and Research Reactor Infrastructures for Education and Learning: ARIEL

European Commission

European nuclear data initiatives, training opportunities
ARIEL – www.ariel-h2020.eu

Training of early stage reseachers and scientific visits

- Up to 30 research stays for up to 12 weeks:
  Early stage researchers + short term visitors
- Full spectrum of experimental capacities of the consortium resulting in a high potential of competence building.
- Support student graduate education +
  training of engineers and technicians +
  sharing knowledge between experienced researchers.
- Participation of IAEA, JEFF(NEA), GRS and IRSN essential
- Selection by the Project Advisory Committee based on scientific excellence and relevance to the ARIEL objectives in collaboration with ENEN

Summer schools

- Hands-on school on the production, detection and use of neutron beams, University of Seville (18-24 participants)
- Lab course in Reactor Operation and Nuclear Chemistry, University of Mainz (10 participants)
- Nuclear data: the path from the detector to the reactor calculation, CIEMAT, Madrid (20 participants)
- EXTEND’2022 summer school at Uppsala University (20-25 participants)
- Dissemination and advertisement through ENEN