The European Commission’s science and knowledge service

Joint Research Centre
Nuclear Data

Arjan Plompen

Ecole Joliot Curie, 26 and 27 September 2019, Ile d’Oleron, France
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
Joint Research Centre
The European Commission's in-house scientific service
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
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".

A solid basis for contemporary engagements with the institutions, member states & international partners.
What do we work for?

• Nuclear science and technology applications to interests of a modern society
  o Main concerns: Nuclear safety and security & Climate change
  o 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
  o JRC Open Access to Research Infrastructure
  o Education and Training
  o Standardization
  o Exploratory Research
Nuclear facilities of JRC-Geel

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

GELINA

MONNET

TARGET

HADES

METRO
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

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

\[ E = \frac{1}{2} m v^2 \propto \left( \frac{L}{T} \right)^2 \]
Challenge: Climate Change - carbon free energy
Nuclear energy can be an important component in the mix

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

<table>
<thead>
<tr>
<th></th>
<th>CO2</th>
<th>CO2-free</th>
<th>Nuclear</th>
<th>Bio+waste</th>
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<td>Sweden</td>
<td>29%</td>
<td>71%</td>
<td>33%</td>
<td>25%</td>
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</tbody>
</table>

Countries with a high percentage CO₂-free energy use (nuclear) electricity for heating.
Still a lot to do for CO₂-free transport.

Data International Energy Agency, Total primary energy supply
Challenge: Climate Change - carbon free energy

Nuclear energy can be an important component in the mix

CO₂ reduction
• 2020-target -20%
• 2030-target -40%

Public IEA data

<table>
<thead>
<tr>
<th>region</th>
<th>1990 Mt CO2</th>
<th>2016 Mt CO₂</th>
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<tr>
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<td>38</td>
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<td>27%</td>
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<td>9.2</td>
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<tr>
<td>United States</td>
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<td>1.0</td>
<td>-1%</td>
<td>3.3E+08</td>
<td>14.8</td>
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<tr>
<td>China</td>
<td>2122</td>
<td>9102</td>
<td>4.3</td>
<td>-329%</td>
<td>1.4E+09</td>
<td>6.6</td>
</tr>
</tbody>
</table>
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

\[
\frac{1}{v} \frac{\partial f}{\partial t} + \mathbf{\Omega} \cdot \nabla f + \Sigma_T f = S + \int dE' d\Omega' \, f(E',\Omega') \Sigma_c(E'\rightarrow E,\Omega'\rightarrow\Omega)
\]

\[
S = S_{PF} + S_{dn} + S_{\alpha n} + S_{ext}
\]

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

\[
\Sigma_s(E\rightarrow E',\Omega\rightarrow\Omega') = \sum_i N_i \frac{d^2 \sigma_{s,i}}{dE'd\Omega'}(E, E', \Omega, \Omega')
\]

\[
\Sigma_T = \sum_i N_i \sigma_{T,i}
\]

\[
\frac{dN_i}{dt} = -\lambda_i N_i - r_i N_i + \sum_{j \neq i} \left( \lambda_{j \rightarrow i} + r_{j \rightarrow i} \right) N_j
\]

• **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

- **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, ...

\[
\frac{d}{dt} \frac{1}{v} \frac{df}{dt} + \Omega \cdot \nabla f + \Sigma_T f = S + \int dE'd\Omega' f(\Omega') \Sigma_{s(E\rightarrow E',\Omega\rightarrow \Omega')} \\
S = S_{PF} + S_{dn} + S_{an} + S_{ext} \\
S_{PF} = \sum_i N_i \int dE' f(\Omega') \bar{\nu_i}(E') \sigma_{F,i}(E') \bar{f}_{P,i}(E',E) \\
\Sigma_{s(E\rightarrow E',\Omega\rightarrow \Omega')} = \sum_i N_i \frac{d^2 \sigma_{s,i}}{dE'd\Omega'}(E, E', \Omega \cdot \Omega') \\
\Sigma_T = \sum_i N_i \sigma_{T,i} \\
\frac{dN_i}{dt} = -\lambda_i N_i - r_i N_i + \sum_{j \neq i} \left( \lambda_{j \rightarrow i} + r_{j \rightarrow i} \right) N_j
\]
Nuclear data in modeling

- **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

\[
\frac{1}{v} \frac{\partial f}{\partial t} + \Omega \cdot \nabla f + \Sigma_T f = S + \int dE' d\Omega' f(E', \Omega') \Sigma_\delta(E' \rightarrow E, \Omega' \rightarrow \Omega)
\]

\[
S = S_{PF} + S_{dn} + S_{an} + S_{ext}
\]

\[
S_{PF} = \sum_i N_i \int dE' \bar{f}(E') \sigma_{F,i}(E') f_P(E', E)
\]

\[
\Sigma_\delta(E \rightarrow E', \Omega \rightarrow \Omega') = \sum_i N_i \frac{d^2 \sigma_{s,i}}{dE' d\Omega'}(E, E', \Omega \cdot \Omega')
\]

\[
\Sigma_T = \sum_i N_i \sigma_{T,i}
\]

\[
\frac{dN_i}{dt} = - \lambda_i N_i - r_i N_i + \sum_{j \neq i} \left\{ \lambda_{j \rightarrow i} + r_{j \rightarrow i} \right\} N_j
\]
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
From science to application

Reactive versus proactive: ensure best science for every application
Alexey Stankovskiy

**MYRRHA $K_{\text{eff}}$ uncertainty and data priorities**

<table>
<thead>
<tr>
<th>Cov. data</th>
<th>$\Delta k_{\text{eff}}/k_{\text{eff}}$, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCALE-6.0m</td>
<td>0.945</td>
</tr>
<tr>
<td>COMMARA-2</td>
<td>~0.5</td>
</tr>
<tr>
<td>JENDL-4.0</td>
<td>0.553</td>
</tr>
</tbody>
</table>

**Target accuracy satisfactory:** $\frac{\Delta k_{\text{eff}}}{k_{\text{eff}}}$ ~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, $\chi$ and $\bar{\nu}$ 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: $\bar{\nu}$, (n,f), (n,γ) resonance and fast
- $^{209}$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: $\bar{\nu}$ fast
- $^{238}$Pu: (n,f) both resonance and fast

Increase of confidence by reducing the uncertainties is needed for

- Already covered by CIELO project
- Focus on
  - Not contributing essentially to $k_{\text{eff}}$ and $\beta_{\text{eff}}$ but impact fluxes, decay heat...
  - Impact burnup, decay heat
Nuclear data for safety

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

Strategic Research and Innovation Agenda
February 2013

European Commission
Nuclear data and nuclear power, today

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
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

Excellent example how good modeling may predict a cross section before the measurement
TALYS - BRC, ENDF/B-VII - LANL
Available nuclear data libraries

  Joint evaluated fission and fusion nuclear data library (JEFF-3.3, Nov. 2017)
  Nuclear Science/WPEC: CIELO - H, O, Fe, $^{235}\text{U}$, $^{238}\text{U}$, $^{239}\text{Pu}$
- JAEA Nuclear Data Center [wwwndc.jaea.go.jp/jendl, JENDL-4.0, 4.0+](http://wwwndc.jaea.go.jp/jendl)
- IAEA [www-nds.iaea.org](http://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
Databank

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.

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 experimental, differential, evaluated and integral data.

Thermochemical database

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

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 thermochemical data collection and assessment.

Working party on evaluation cooperation

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

The NEA’s nuclear data evaluation co-operation activities involve the following evaluation projects: NDA (United States), JENDL (Japan), RPS/FRONGB (Bulgaria), REF (other data bank member countries) and CNED (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 tools, 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 meeting (last update, May 2016)

WPEC meetings

1. 27th WPEC, 12-15 May 2015, NEA Headquarters, Boulogne-Billancourt, France
   - Expert Group and Subgroup schedule will be finalised December 2014
   - How to get to the NEA headquarters
   - Registration will open December 2014
   - Subgroup Meetings, 20-27 November 2015, NEA Headquarters, Boulogne-Billancourt, France
   - How to get to the NEA headquarters
   - Volunteers for the event

2. 26th WPEC, 24-29 June 2015, NEA Headquarters, Boulogne-Billancourt, France
   - Final WPEC, 14-18 May 2016, OECD Headquarters, Conferences Centre, Paris, France
   - 29th WPEC, 15-19 May 2017, OECD Headquarters, Conferences Centre, Paris, France
   - 27th WPEC, 22-26 May 2018, OECD Headquarters, Conferences Centre, Paris, France
   - 27th WPEC, 22-26 May, NEA Headquarters, Issy-les-Moulineaux, France
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

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)
EU Access to Research Infrastructure

Slides ARIEL kick-off meeting

Arnd Junghans (HZDR)
coordinator

History of EURATOM TA Projects

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

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

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

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

11/2006-10/2010 9 partners in transnational access
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*CENT, JGU, CVR
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
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  Free of charge
- EUFRAT-MONNET  Same User Selection Committee
- EUFRAT-RADMET  Same timing
- EUFRAT-HADES

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

⇒ **Experimental data are required**
Main principles of measurement (GELINA example)

**Total cross section**

\[ T \approx e^{-n \sigma_{\text{tot}}} \]

**Reaction cross section**

\[ Y_{\gamma} \approx (1 - e^{-n \sigma_{\text{tot}}}) \frac{\sigma_{\gamma}}{\sigma_{\text{tot}}} \]

**Transmission**

Fraction of the neutron beam traversing the sample without any interaction

Need for normalization sample in/out

**Reaction yield**

Fraction of the neutron beam creating a \((n,\gamma)\) reaction in the sample

Need for normalization (fluence)
GELINA - Cross section measurements

**Total cross section**

\[ T \approx e^{-n\sigma_{\text{tot}}} \]

**Reaction cross section**

\[ Y_\gamma \approx (1 - e^{-n\sigma_{\text{tot}}}) \frac{\sigma_\gamma}{\sigma_{\text{tot}}} \]

**Well-characterised samples**

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

\[ \downarrow \]

**accurate cross-sections** can be determined
Data taken in Geel, aim at better evaluated files
Other facilities contribute, similarly.

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

Experimental data

Theory/models

- Resonance shape analysis (RRR)
- Hauser-Feshbach formalism (URR)
- Fission process
- Level statistics
GELINA and MONNET accelerator laboratories

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. \( T(d,n)^4\text{He} \)

\[
\begin{align*}
^{7}\text{Li}(p,n)^7\text{Be} & \quad E_n: 0 - 5.3 \text{ MeV} \\
T(p,n)^3\text{He} & \quad E_n: 0 - 6.2 \text{ MeV} \\
D(d,n)^3\text{He} & \quad E_n: 1.8 - 10.1 \text{ MeV} \\
T(d,n)^4\text{He} & \quad E_n: 12.1 - 24.1 \text{ MeV}
\end{align*}
\]
GELINA - Electron Linear Accelerator

Accelerator Sections

Compression Magnet

Target

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 : $2 \times 10^{13}$ 1/s
**GELINA - Neutron Production**

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

![Diagram of GELINA setup with labeled components: Neutron Target, Neutron Flight Paths, Neutron Moderator, Electron Beamline Exit](image)

![Graph showing neutron energy distribution](image)
GELINA - Experimental set-ups

- Transmission
  - 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
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 $\nu(A,TKE)$ show (strong) discrepancies.
Experiment: $^{252}\text{Cf}(sf)$

The effect of neutron recoil on experimental data

momentum transfer $\delta$ change 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)

$\delta$ 2nd term averages out

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

Fragment neutron coincidence

$\delta$ biased selection

$$\langle \cos \theta_{CM} \rangle \neq 0$$
Experiment: $^{252}\text{Cf}(sf)$

- $\nu(A,\text{TKE})$ compares well literature
  - Specifically $\nu(\text{TKE})$ 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
Example of a scattering measurement with ELISA $n + {}^{56}\text{Fe}$ (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:
- $^1\text{H}$, $^{16}\text{O}$, $^{56}\text{Fe}$, $^{235,238}\text{U}$, $^{239}\text{Pu}$

Corrections:
- detected photons
- background
- multiple scattering
- separation elastic/inelastic events

Scattering experiment:
- reaction rate
- incoming neutron current
- efficiency
- target areal density
- solid angle
Example of a scattering measurement with ELISA $n+^{56}\text{Fe}$ (thesis E. Pirovano, PRC99(2019)024601)

$$t_{o.f.\, n} = t_n - t_\gamma + t_{o.f.\, \gamma}$$

$$t_{o.f.\, n} = \frac{L}{c\sqrt{1-1/(1+E/mc^2)^2}} + \frac{L'}{c\sqrt{1-1/(1+E'/mc^2)^2}}$$

before the collision  
after the collision

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

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

32 liquid organic scintillators
- 2x8 EJ301 (NE213)
- 2x8 EJ315 (C$_6$D$_6$)
- $n/\gamma$ discrimination via PSD
- time resolution $\sim$1 ns
- consistency & repeatability checks
Example of a scattering measurement with ELISA

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

8x 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

Detector at \( \theta = 163.8^\circ \)
- t.o.f. = 976–981 ns

\[
Y(t.o.f., \theta) = \frac{1 - F_{\text{mSc}}(t.o.f., \theta)}{\varepsilon(E')|_{L_{\text{THR}}} \Delta \Omega} \int_{L_{\text{THR}}}^{R_{\text{fit}}(L, E')} dL
\]
Example of a scattering measurement with ELISA
\( \text{n} + ^{56}\text{Fe} \) (thesis E. Pirovano, PRC99(2019)024601)
Example of a scattering measurement at nELBE (HZDR)
Thesis Elisa Pirovano, PRC95(2017)024601

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

To determine the ratio:

$$\frac{\frac{d\sigma}{d\Omega}}{165^\circ} \text{ over } \frac{d\sigma}{d\Omega} \text{ at } 15^\circ$$
-measurement at the PTB VdG; Elisa Pirovano et al.
- quasi-monoenergetic neutrons via $^7\text{Li}(p,n)$ or $^3\text{H}(p,n)$
- energy range 400 keV – 2.5 MeV
- different gas mixtures/pressures to limit the escape of recoil deuterons

$D_2/CD_4$  
$C_3D_8$ 600 hPa  
$C_3D_8$ 1000 hPa

neutron energy:  
400 – 625 keV  
625 keV – 1.25 MeV  
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”


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
Procedure

1. Set up mathematical relation measured quantity (Y) and input quantities (X)
   \[ Y_k = f_k(X_1, X_2, \ldots X_N) \]
2. Estimate the inputs (x)
   \[ X_i \rightarrow x_i \]
3. Estimate the standard uncertainties for the inputs: u(x)
   \[ \rightarrow u(x_i) \]
4. Estimate covariances of input uncertainties: u(x_i, x_j)
   \[ \rightarrow u(x_i, x_j) = C(x_i, x_j)u(x_i)u(x_j) \]
5. Find the measured quantity (y) from the inputs
   \[ y_k = f_k(x_1, x_2, \ldots x_N) \]
6. Estimate the combined standard uncertainties and covariances u_c(y_k) and u_c(y_k, y_l)
   \[ u_c^2(y_k) = \sum_{i=1}^{N} \sum_{j=1}^{N} \frac{\partial f_k}{\partial x_i} \frac{\partial f_k}{\partial x_j} u(x_i, x_j) \]
   \[ u_c(y_k, y_l) = \sum_{i=1}^{N} \sum_{j=1}^{N} \frac{\partial f_k}{\partial x_i} \frac{\partial f_l}{\partial x_j} u(x_i, x_j) \]
7. Report result with standard uncertainties and covariances and uncertainty budget.
   \[ u_c(y_k, y_l) = \sum_{i=1}^{N} \sum_{j=1}^{N} S_{ki}S_{lj}C(x_i, x_j)r(x_i)r(x_j) \]
Activation data evaluation

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

- \(\sigma_{\text{Al}}\): Reference cross section
- \(S\): Counts for gamma
- \(I\): Gamma-ray intensity
- \(\epsilon\): Absolute detection efficiency
- \(f_{\Sigma}\): Cooling time factor
- \(f_r\): Irradiation time factor
- \(n\): Number of nuclides
- \(\Phi_0\): Mean neutron flux
- \(C_k\): Correction factors for
  * Low energy neutrons
  * Intensity fluctuations

\[
f_{\Sigma} = \frac{1}{\lambda} \sum e^{-\lambda t_{d_i}} (1 - e^{-\lambda t_{m_i}})
\]

\[
f_r = 1 - e^{-\lambda t_r}
\]

\[
C_{\text{flux}} = \frac{\bar{\Phi}(1 - e^{-\lambda t_r})}{\sum_{i=1}^{m} \Phi_i (1 - e^{-\lambda \Delta t}) e^{-\lambda (m-i) \Delta t}}
\]

\[
C_{\text{low}} = 1 - \frac{\int_0^{E_c} \Phi(E) \sigma(E) dE}{\int_0^{\infty} \Phi(E) \sigma(E) dE}
\]
Activation data reporting

% uncertainties for components in the activation formula

$\sigma_{\text{Al}}$ uncertainty correlations taken from the evaluation

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

<table>
<thead>
<tr>
<th>Neutron energy (MeV)</th>
<th>Activation data reporting</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.34</td>
<td>9.15</td>
</tr>
<tr>
<td>$\sigma_{\text{Al}}$</td>
<td>1.9</td>
</tr>
<tr>
<td>$S_{\text{Am}}$</td>
<td>5.0</td>
</tr>
<tr>
<td>$S_{\text{Al}}$</td>
<td>1.0</td>
</tr>
<tr>
<td>$I_{\text{Am}}$</td>
<td>1.2</td>
</tr>
<tr>
<td>$n_{\text{Al}}$</td>
<td>0.1</td>
</tr>
<tr>
<td>$n_{\text{Am}}$</td>
<td>0.3</td>
</tr>
<tr>
<td>$\varepsilon_{\text{Al}}/\varepsilon_{\text{Am}}$</td>
<td>3.0</td>
</tr>
<tr>
<td>$(f_{\Sigma} f_p)_{\text{Am}}$</td>
<td>0.9</td>
</tr>
<tr>
<td>$C_{\text{low Am}}$</td>
<td>0.3</td>
</tr>
<tr>
<td>$C_{\text{low Al}}$</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>$C_{\text{Hux}}$</th>
<th>$C_{\text{Low}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.34</td>
<td>0.9974</td>
<td>0.9925</td>
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<tr>
<td>9.15</td>
<td>1.0731</td>
<td>1.3117</td>
</tr>
<tr>
<td>13.33</td>
<td>0.9168</td>
<td>0.8288</td>
</tr>
<tr>
<td>16.10</td>
<td>1.0749</td>
<td>1.2335</td>
</tr>
<tr>
<td>17.16</td>
<td>0.9987</td>
<td>0.9878</td>
</tr>
<tr>
<td>17.90</td>
<td>0.969</td>
<td>0.933</td>
</tr>
<tr>
<td>19.36</td>
<td>1.0061</td>
<td>1.0157</td>
</tr>
<tr>
<td>19.95</td>
<td>0.9822</td>
<td>0.9433</td>
</tr>
<tr>
<td>20.61</td>
<td>0.9938</td>
<td>0.9823</td>
</tr>
</tbody>
</table>

European Commission
## Activation reporting

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>$\sigma_{Am}$ (mb)</th>
<th>Unc. (%)</th>
<th>Correlation matrix ($\times 100$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.34(15)</td>
<td>96.8</td>
<td>6.5</td>
<td>100</td>
</tr>
<tr>
<td>9.15(15)</td>
<td>162.9</td>
<td>5.7</td>
<td>35 100</td>
</tr>
<tr>
<td>13.33(15)</td>
<td>241.8</td>
<td>4.6</td>
<td>37 42 100</td>
</tr>
<tr>
<td>16.10(15)</td>
<td>152.4</td>
<td>4.6</td>
<td>38 43 53 100</td>
</tr>
<tr>
<td>17.16 (3)</td>
<td>116.1</td>
<td>4.4</td>
<td>40 45 57 58 100</td>
</tr>
<tr>
<td>17.90(10)</td>
<td>105.7</td>
<td>4.4</td>
<td>41 45 57 59 84 100</td>
</tr>
<tr>
<td>19.36(15)</td>
<td>89.5</td>
<td>8.2</td>
<td>21 24 30 31 39 39 100</td>
</tr>
<tr>
<td>19.95 (7)</td>
<td>102.1</td>
<td>5.8</td>
<td>30 34 44 45 58 59 51 100</td>
</tr>
<tr>
<td>20.61 (4)</td>
<td>77.9</td>
<td>8.8</td>
<td>20 22 29 30 40 42 39 65 100</td>
</tr>
</tbody>
</table>
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 $\chi^2$. 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

“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
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,

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

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.

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,

\[ \sigma_{tot} = \frac{2\pi}{k^2} (1 - \text{Re} \langle \mathcal{Y}_0 \rangle) = \frac{2\pi}{k^2} (1 - \text{Re} S_0) \]

since it is linear in the S-matrix.

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

\[ \sigma_{el} = \frac{\pi}{k^2} (|\mathcal{Y}_0|^2) = \frac{\pi}{k^2} |S_0 - 1|^2 + \frac{\pi}{k^2} |S_{0,\text{fluc}}|^2 \]

and

\[ \sigma_{abs} = \frac{\pi}{k^2} (1 - |\mathcal{Y}_0|^2) = \frac{\pi}{k^2} (1 - |S_0|^2) - \frac{\pi}{k^2} |S_{0,\text{fluc}}|^2 \]
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 $n+^{238}\text{U}$ in the resonance region;

- 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

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, physical R-matrix – ULB, …).
Evaluations distinguish 1) Resolved Resonance Region, 2) Unresolved Resonance Region, 3) Fast region.

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

\[
A_{\alpha',s',v'},_{\alpha s v}(\Omega_{\alpha'}) = \frac{1}{2} \left\{ -C_{\alpha'}(\theta_{\alpha'}) \delta_{\alpha',s',v'},_{\alpha s v} + i \sum_{l' m'} (2l + 1) \frac{1}{k_{\alpha}} [e^{2i \omega_{\alpha'}(l')} \delta_{\alpha',s',l' v', m'},_{\alpha s l' v'} - U_{\alpha',s',l' v', m'},_{\alpha s l' v'}] Y_{m'}^{(l)}(\Omega_{\alpha'}) \right\}.
\]

\[
U^J = (O_{\varphi}^{\frac{1}{2}} - R^J O^{0'} \varphi^{\frac{1}{2}})^{-1}(I_{\varphi}^{\frac{1}{2}} - R^J I^{0'} \varphi^{\frac{1}{2}})
\]
Success stories in our field

**Standards**
Carlson et al. NDS110(2009)3324

**R-matrix**
Phase-shift analysis – Wigner style

GLSQ of tables to many data sets

GLSQ of R-matrix model to many data sets

$^{235}\text{U}(n,f)$  $^{197}\text{Au}(n,g)$  $^{6}\text{Li}(n,t)$  $^{10}\text{B}(n,\alpha_0)$  
$^{238}\text{U}(n,f)$  $^{239}\text{Pu}(n,f)$  $^{238}\text{U}(n,g)$
Evaluation of $n + {^{16}\text{O}}$ cross-section data using Hybrid R-Matrix approach

- **Hybrid R-matrix fit** in energy range 1 keV – 14 MeV using TUW code system **GECCOS**
- 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

$\Rightarrow$ Production of full ENDF prototype data file for use in benchmark analyses

$\Rightarrow$ H. Leeb, R046

**Total cross-section $n + {^{16}\text{O}}$**

![Graph showing total cross-section and energy]
Present status of nuclear physics and engineering in our field

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

Example KD potential Courtesy Oscar Cabellos

Jeff-3.3T2, NEA Validation Suite 123 cases

Goodness of fit reduced chi-squared

- ENDF/B-VII.1 = 3.75
- JEFF-3.2 = 5.68
- JEFF-3.1P1 = 2.59
- JEFF-3.1P2 = 2.15
- JENDL-6.0 = 7.09
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/wpnbs/icsbep/
K-eff is a (delicate) balance

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

“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:

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“... 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.”
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.
• 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)
Table 3: Standard values and resonance parameters results for 0.0253 eV

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Standard Values (b)</th>
<th>Values obtained with the new resonance parameters (b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_f$ (b)</td>
<td>584.4 ± 1.0</td>
<td>584.4</td>
</tr>
<tr>
<td>$\sigma_i$ (b)</td>
<td>99.90 ± 0.78</td>
<td>99.23</td>
</tr>
<tr>
<td>$\sigma_r$ (b)</td>
<td>14.09 ± 0.22</td>
<td>14.09</td>
</tr>
<tr>
<td>Fission integral in</td>
<td>246.4 ± 1.2</td>
<td>246.9</td>
</tr>
<tr>
<td>the 7.8-11 eV range (b eV)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 7: Standard average fission integral

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

\[
\begin{array}{|c|c|c|c|}
\hline
\text{ANR} & \text{JEFF-3.1.1} & \text{JEFF-3.2} & \text{JEFF-3.3} \\
\hline
\sigma_f & 269.1 \pm 2.9 & 272.61 & 270.06 & 271.3 \\
\sigma_f & 748.1 \pm 2.0 & 747.08 & 747.19 & 749.0 \\
\sigma_s & 7.94 \pm 0.36 & 8.0 & 8.1 & 7.76 \\
\hline
\end{array}
\]
U-235, Pu-239 nu-bar and pfns
Structural materials, coolants

- $^{63}$Cu(n,n')
  - $E_n = 0.6697$ MeV
  - Cross section [mb]
  - Neutron energy [MeV]

- Total cross section
  - $^{95}$Zr
  - Neutron energy [MeV]
  - Cross section [mbarn]
  - Energy [eV]

- $^{209}$Bi b.r.

- $^{23}$Na total cross-section (red) compared to Larson experimental data (blue dots)

- $^{52}$Cr(n,2n)$^{51}$Cr
  - Cross section [mb]
  - Neutron energy [MeV]

- Ni-59
Further covariances for Hf
Many from TENDL (D. Rochman)
### Neutron spectra

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

- 20 files, 14 new, first covariances for H in H$_2$O.
- Cantargi, Granada, Marquez Damian
  - D in D$_2$O, Ortho D$_2$, Para D$_2$
  - H in ice, mesitylene, Ortho H$_2$, Para H$_2$, toluene
  - O-16 in D$_2$O, Al$_2$O$_3$
  - Al in Al$_2$O$_3$
  - Si in Si
- Mg in Mg (Mounier)
- H in CaH$_2$, Ca in CaH$_2$ (Serot)
- Keinert, Mattes
  - H in H$_2$O, CH$_2$, ZrH (Keinert, Mattes)
  - Be in Be (Keinert, Mattes)
  - C in graphite (Keinert, Mattes)
Delayed neutrons – 8 groups structure
Benchmarking

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
Additional critical experiments

![Graph showing k\text{eff} (C – E) [pcm] for Fast-Na, UOx, and MOx.](chart)

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

<table>
<thead>
<tr>
<th>Library</th>
<th>$k_{\text{eff}}$</th>
<th>Library</th>
<th>$k_{\text{eff}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>JEFF-3.1.2</td>
<td>1.0059</td>
<td>JENDL-4.0</td>
<td>1.0031</td>
</tr>
<tr>
<td>JEFF-3.2</td>
<td>1.0083</td>
<td>ENDF/B-VII.1</td>
<td>1.0069</td>
</tr>
<tr>
<td>JEFF-3.3</td>
<td>1.0073</td>
<td>ENDF/B-VIII.0</td>
<td>1.0054</td>
</tr>
</tbody>
</table>
Application to PWR – UPM – SEANAP

Boron concentration and axial offset

- 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)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>JEFF 3.3</th>
<th>JEFF 3.1.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCA</td>
<td>2.3±0.8</td>
<td>3.9±0.7</td>
</tr>
<tr>
<td>IPEN/MB01</td>
<td>4.2±0.9</td>
<td>4.6±1.0</td>
</tr>
<tr>
<td>Masurea/R2</td>
<td>2.1±1.1</td>
<td>2.9±1.1</td>
</tr>
<tr>
<td>Masurea/ZONEA2</td>
<td>2.6±1.7</td>
<td>1.1±1.7</td>
</tr>
<tr>
<td>FCA/XIX-1</td>
<td>3.0±1.2</td>
<td>3.6±1.2</td>
</tr>
<tr>
<td>FCA/XIX-2</td>
<td>3.3±1.6</td>
<td>3.8±1.6</td>
</tr>
<tr>
<td>FCA/XIX-3</td>
<td>4.4±1.9</td>
<td>-1.2±2.0</td>
</tr>
<tr>
<td>SNEAK/9C1</td>
<td>-1.8±1.1</td>
<td>-0.8±1.1</td>
</tr>
<tr>
<td>SNEAK/7A</td>
<td>1.0±1.5</td>
<td>-1.0±1.5</td>
</tr>
<tr>
<td>SNEAK/7B</td>
<td>3.5±1.4</td>
<td>3.7±1.3</td>
</tr>
<tr>
<td>SNEAK/9C2</td>
<td>-4.9±1.5</td>
<td>-5.4±1.5</td>
</tr>
<tr>
<td>ZPR-9/34</td>
<td>0.7±2.2</td>
<td>4.2±2.2</td>
</tr>
<tr>
<td>ZPR-U9</td>
<td>2.6±1.9</td>
<td>0.8±1.9</td>
</tr>
<tr>
<td>ZPPR-21/B</td>
<td>-8.9±2.3</td>
<td>-4.5±2.2</td>
</tr>
<tr>
<td>ZPR-6/10</td>
<td>5.9±3.8</td>
<td>3.9±0.7</td>
</tr>
<tr>
<td>Godiva</td>
<td>0.3±1.1</td>
<td>-1.7±1.1</td>
</tr>
<tr>
<td>Topsy</td>
<td>4.1±1.0</td>
<td>2.4±1.0</td>
</tr>
<tr>
<td>Jezebel</td>
<td>-3.1±1.6</td>
<td>-1.0±1.6</td>
</tr>
<tr>
<td>Popsy</td>
<td>7.6±1.7</td>
<td>4.3±1.4</td>
</tr>
<tr>
<td>Skidoo</td>
<td>0.7±1.4</td>
<td>1.7±1.4</td>
</tr>
<tr>
<td>Flattop</td>
<td>3.1±1.3</td>
<td>4.2±1.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Experiment</th>
<th>JEFF 3.3</th>
<th>JEFF 3.1.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHE/core8</td>
<td>-1.5±1.0</td>
<td>-3.5±1.0</td>
</tr>
<tr>
<td>Sheba-II</td>
<td>-4.4±1.4</td>
<td>4.7±1.4</td>
</tr>
<tr>
<td>Stacy/run-029</td>
<td>-2.9±1.2</td>
<td>3.5±1.2</td>
</tr>
<tr>
<td>Stacy/run-033</td>
<td>-0.6±1.2</td>
<td>0.2±1.2</td>
</tr>
<tr>
<td>Stacy/run-046</td>
<td>-0.1±1.1</td>
<td>0.7±1.1</td>
</tr>
<tr>
<td>Stacy/run-030</td>
<td>-1.1±1.2</td>
<td>0.9±1.2</td>
</tr>
<tr>
<td>Stacy/run-125</td>
<td>-4.1±1.2</td>
<td>3.2±1.2</td>
</tr>
<tr>
<td>Stacy/run-215</td>
<td>-4.6±1.1</td>
<td>0.0±1.2</td>
</tr>
<tr>
<td>Winco</td>
<td>-4.4±1.0</td>
<td>0.7±1.0</td>
</tr>
<tr>
<td>Big Ten</td>
<td>0.1±1.4</td>
<td>-0.3±1.5</td>
</tr>
</tbody>
</table>
Shielding benchmarks - SINBAD

Cf-252 leakage spectra
Fe and U - IPPE

ASPIR PULL-88

FNS Oxygen
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
“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, $\Gamma_\gamma$, 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, $\Gamma_\gamma$, fission transmission

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

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

Comparative study between experiment, evaluation and GEF

B.Voirin\textsuperscript{12}, G.Kessedjian\textsuperscript{1}, A.Chebbouni\textsuperscript{2} & O.Serot\textsuperscript{2}

Karl-Heinz Schmidt
Subatech, Nantes
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.
• Accelerator production routes for Mo-99: neutrons
• Y. Nagai
• Two accelerators for Japan

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

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

Energy distribution of neutrons
Lhersonneau et al. NIM (2009)

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
• Accelerator production routes for Mo-99: electrons & photons
• LightHouse, Northstar, Canadian Light Source Inc.
European nuclear data initiatives

- SANDA: Supplying accurate nuclear data for energy and non-energy applications, 35 participating organizations, 4 years from 1 Sep. 2019.
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.
European nuclear data initiatives, training opportunities
ARIOEL – www.ariel-h2020.eu

Training of early stage researchers 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