# Model evaluation of fast neutron reaction data for $^{238\text{-}242}$Pu

**Mihaela Sin**
**University of Bucharest, Romania**

# EMPIRE new developments

**EMPIRE team**

# Model evaluation of fast neutron reaction data for $^{238-242}$Pu

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## Status

**Exp. data**

(n,tot),(n,f),(n,g) $^{238-242}$Pu

(n,n'), (n,2n) $^{239}$Pu

**Independent recent evaluations**

$^{238-242}$Pu (ENDF/B-VIII.0, JENDL-5),

$^{239, 240,242}$Pu (+ JEFF-3.3), $^{239}$Pu (+ INDEN)

**Observations**

Significant discrepancies for channels with no experimental data: (n,n'), (n,2n), (n,3n).

Consistent calculations with a good DCCOMP, proper treatment of inelastic and accurate description of fission are required.

**Present calculations** - performed with EMPIRE 3.2 – Malta in the energy range 0.01 KeV – 30 MeV

**Models**

**DI** CC+DWBA, DCCOMP RIPL 2408

**PE** PCROSS – exciton model

**CN** HF + HRTW
EnhancedGSM LD
Optical model for fission
MLO1 photon strength function

Default parameters from RIPL-3 and internal systematics adjusted to fit the data.

**Results**

The results for all isotopes are available as ENDF-6 files ready to be used as priors for future evaluations.

Isotopic trends and sensitivity analysis have been done.

For $^{239}$Pu the calculations and the covariances generated Monte Carlo have been used by IAEA as prior for the GLSQ system GANDR to produce the INDEN evaluation. The (n,g) and (n,2n) cross sections were also adopted by ENDF/B-VIII.1

The differences between the evaluated and calculated cross sections are small, confirming the quality of the present calculations.

# n + $^{238}$Pu

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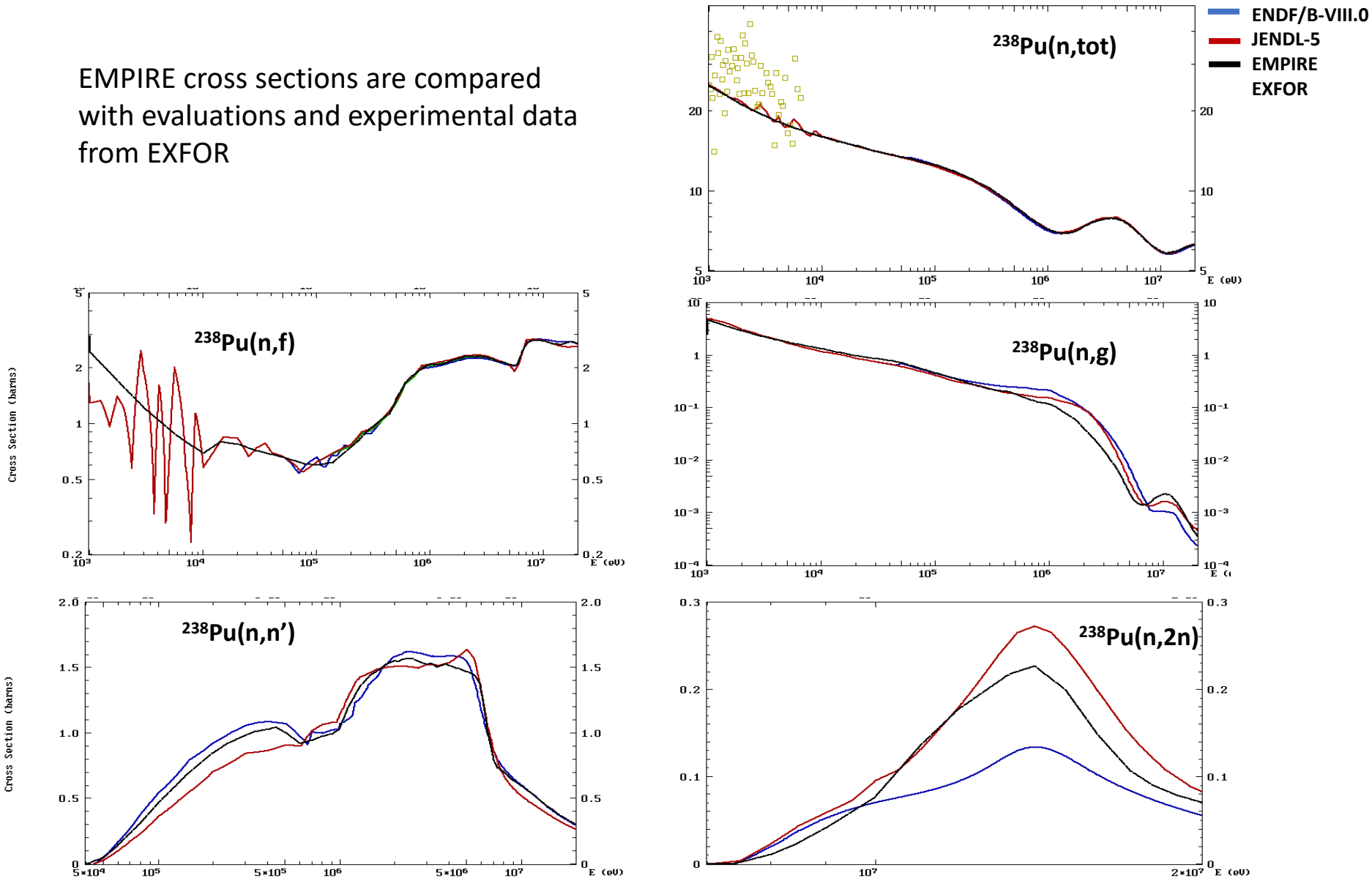
EMPIRE cross sections are compared with evaluations and experimental data from EXFOR



# n + $^{239}$Pu

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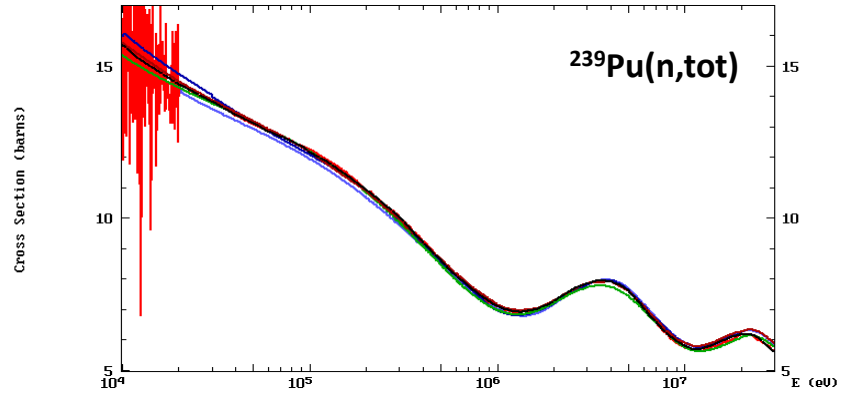
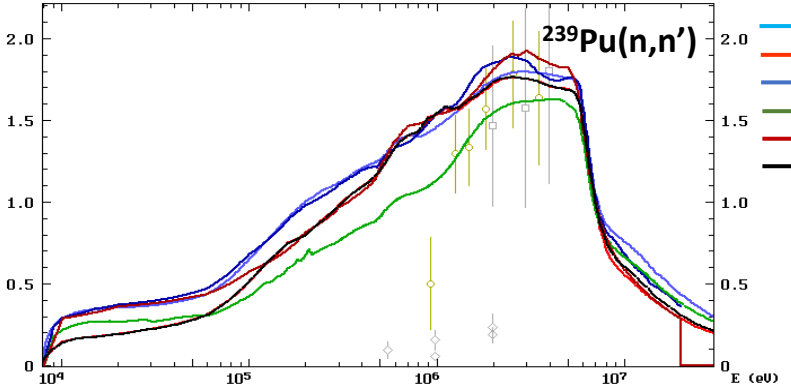
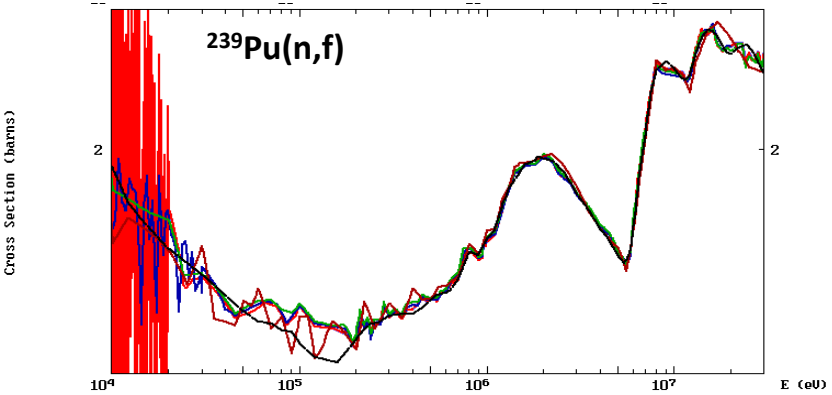
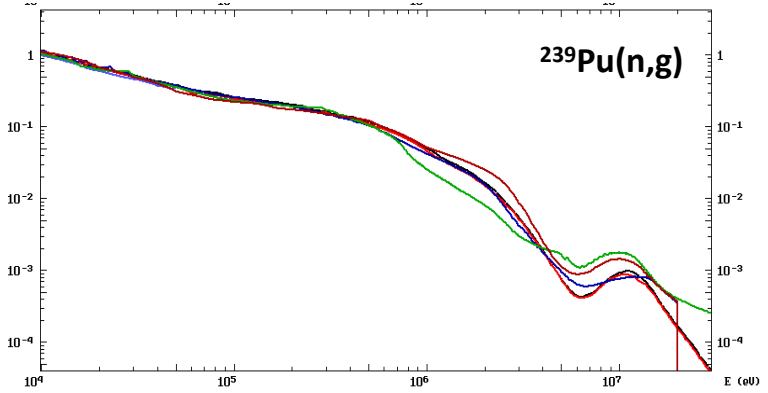
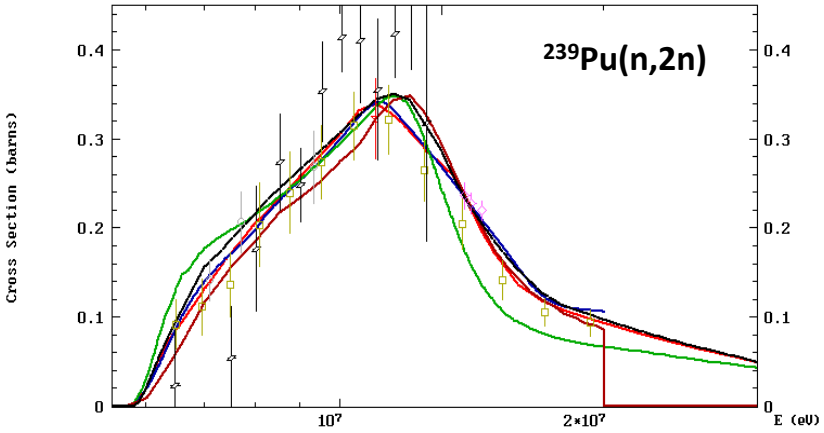


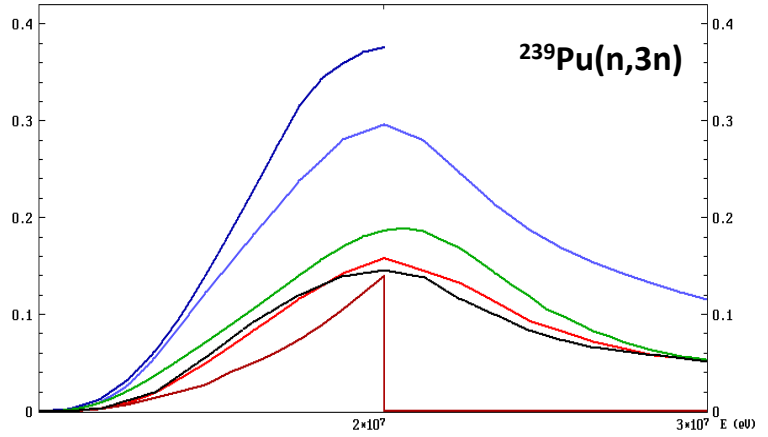




INDEN-2023
INDEN-2022
ENDF/B-VIII.0
JEFF-3.3
JENDL-5
EMPIRE
EXFOR



# n + $^{240}$Pu

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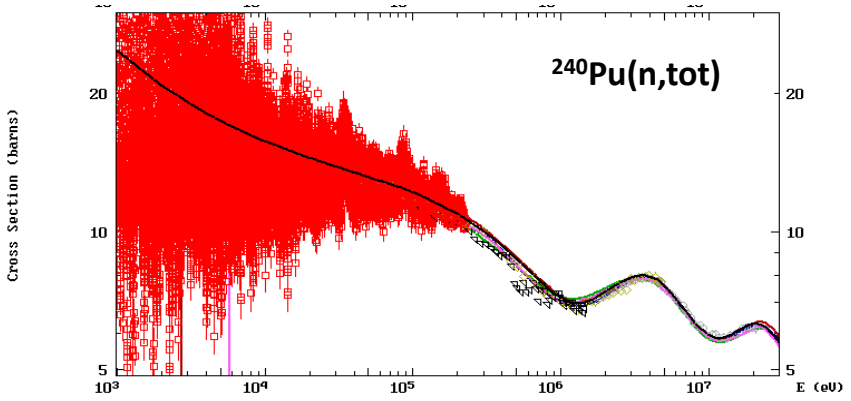
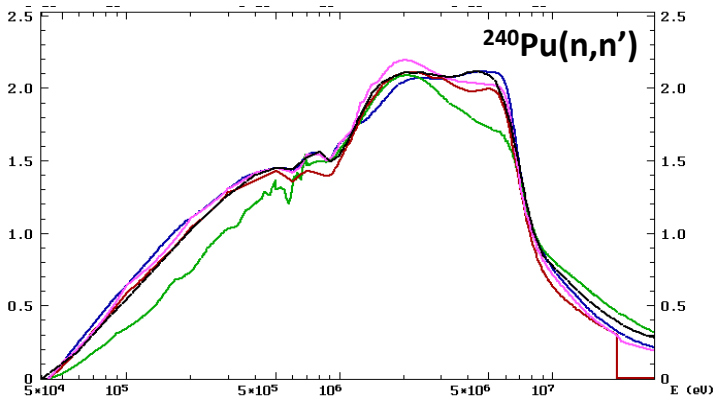
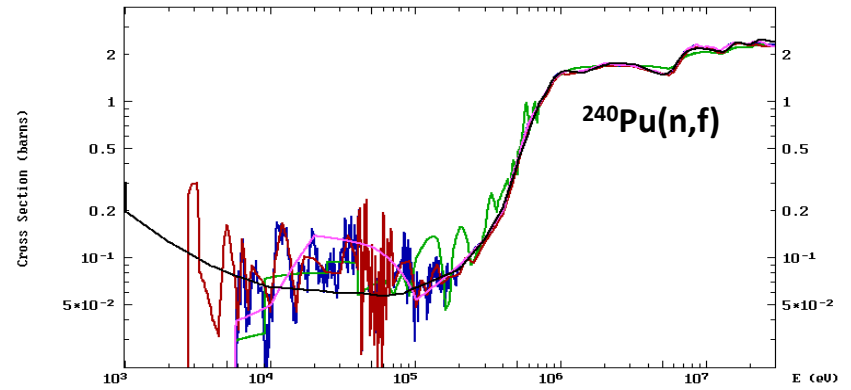
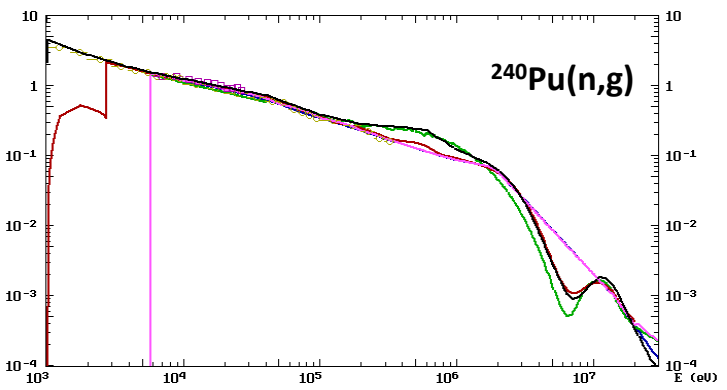
VIRTUTE ET SAPIENTIA

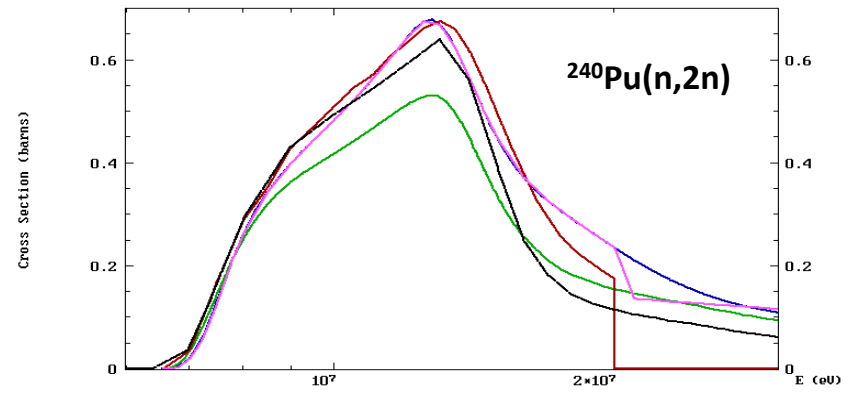


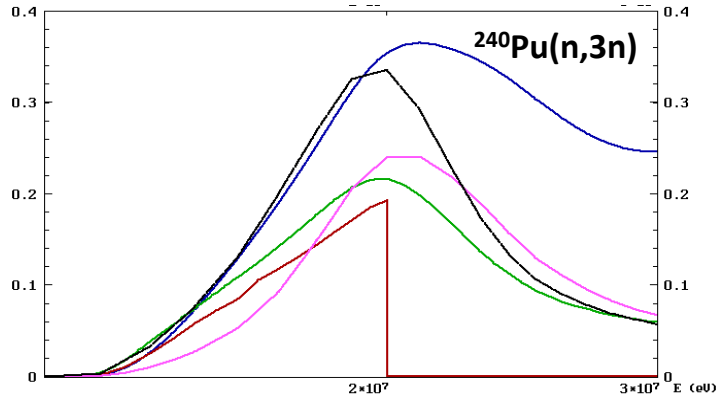




ENDF/B-VIII.0
JEFF-3.3
JENDL-5
TENDL
EMPIRE
EXFOR



# n + $^{241}$Pu

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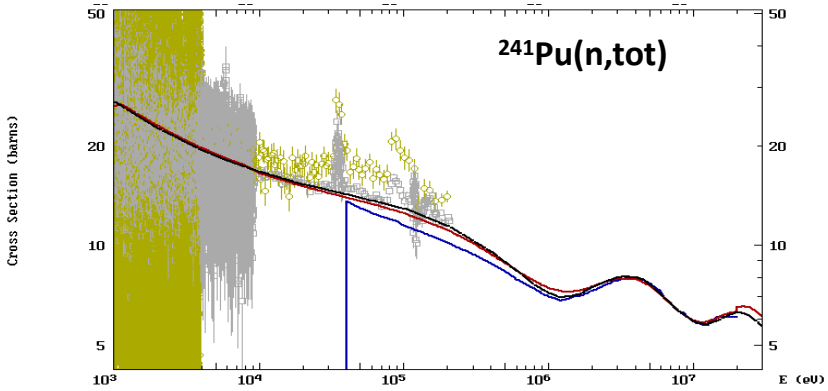


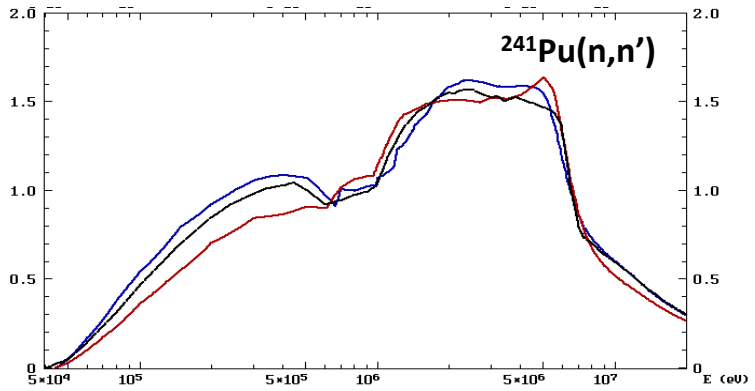


ENDF/B-VIII.0
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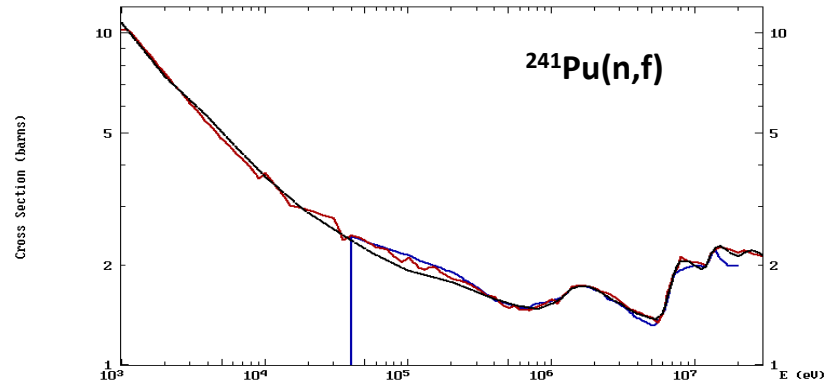
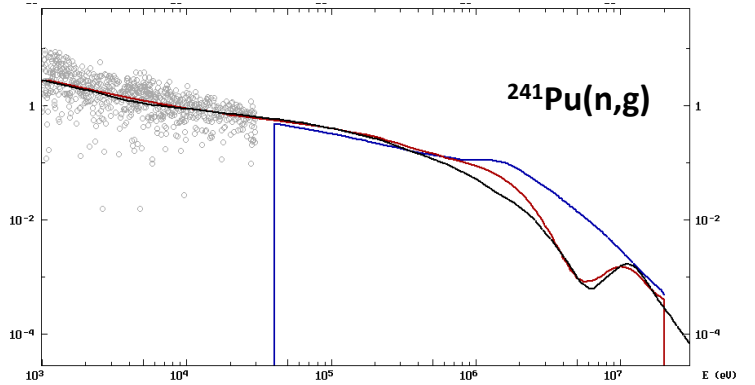
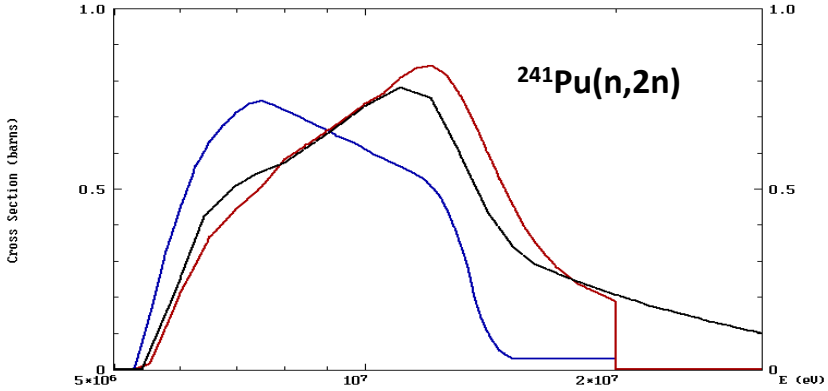
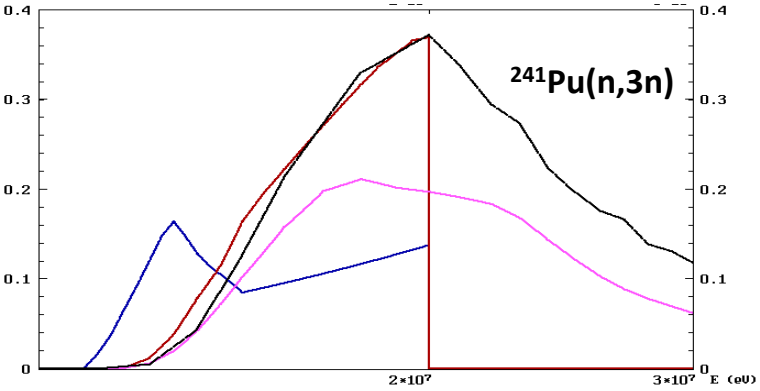
JENDL-5
TENDL
EMPIRE
EXFOR

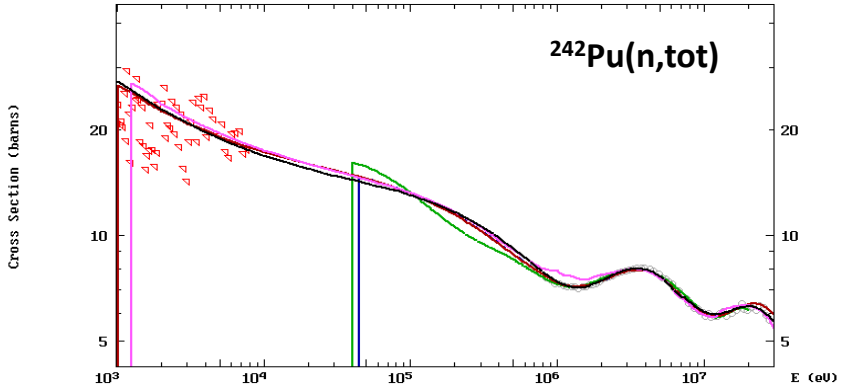


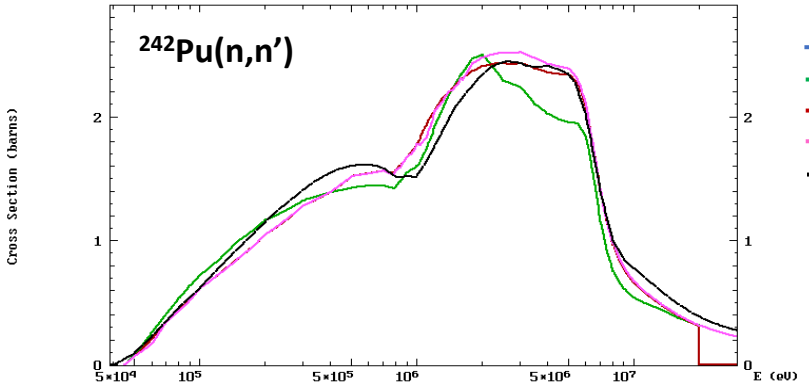



# n + $^{242}$Pu




ENDF/B-VIII.0
JEFF-3.3
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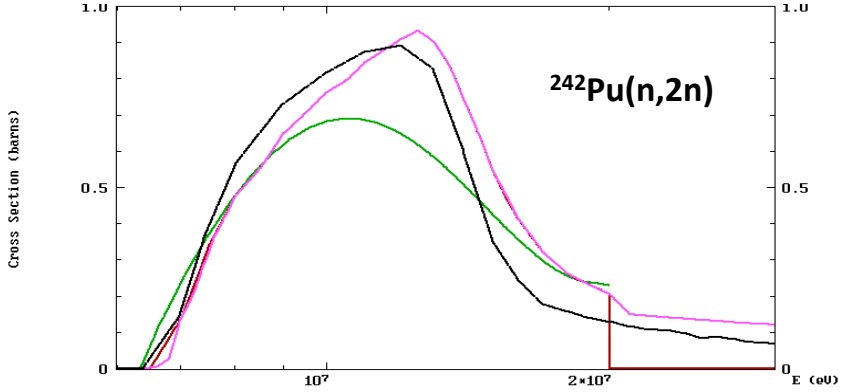
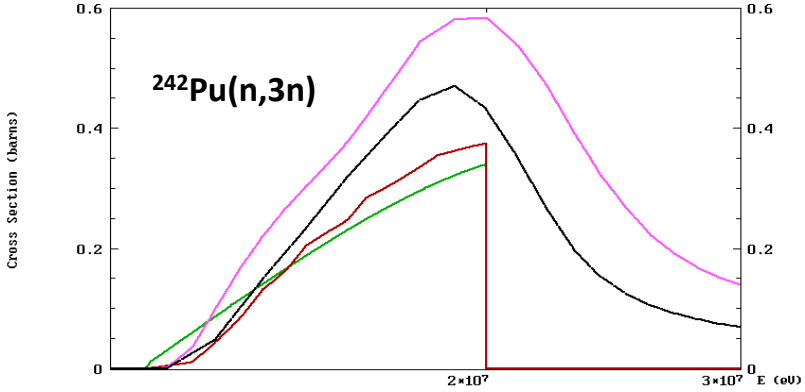
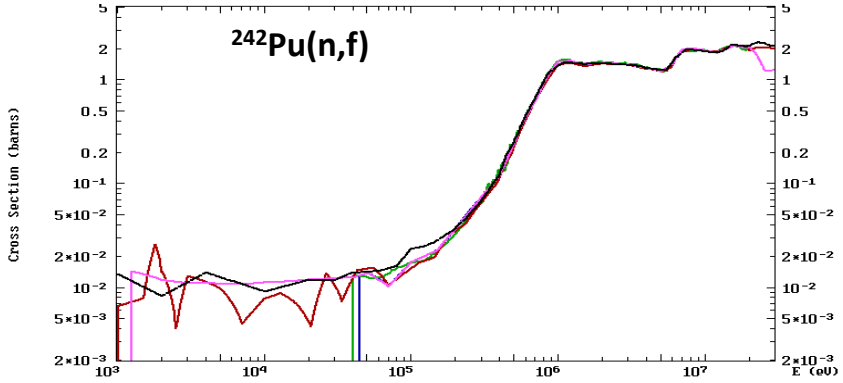
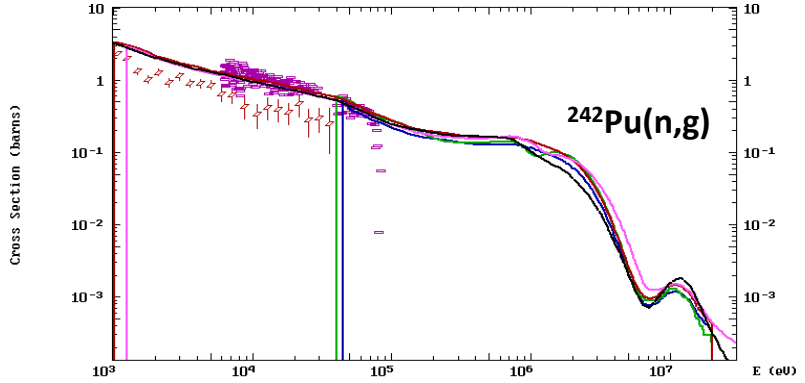
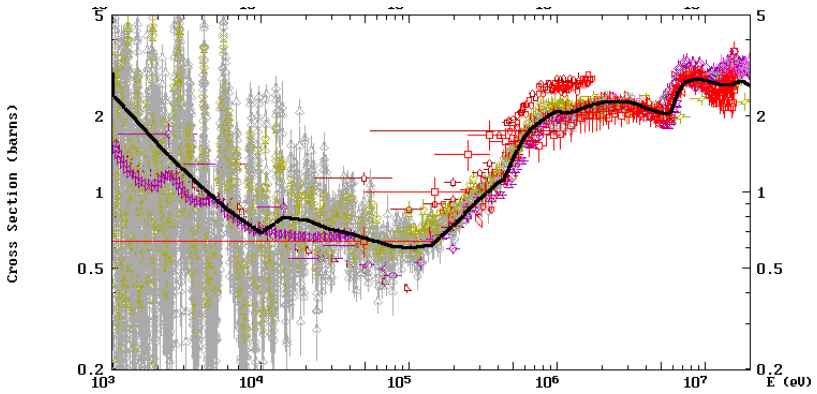


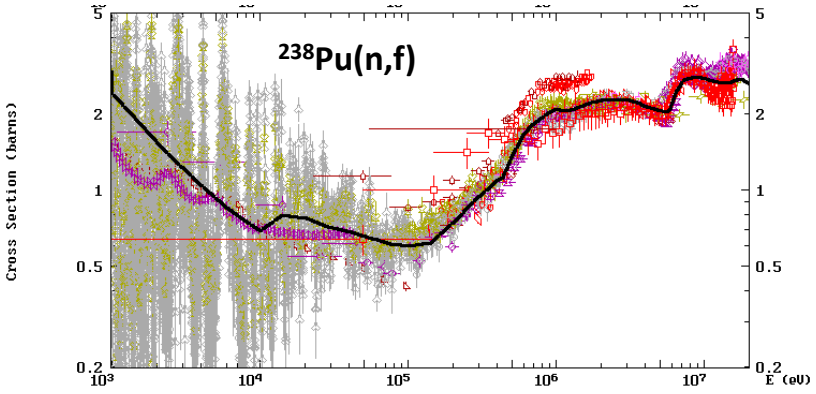



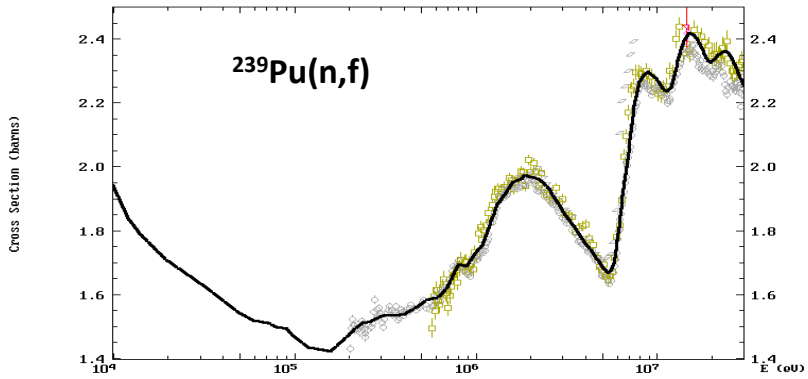



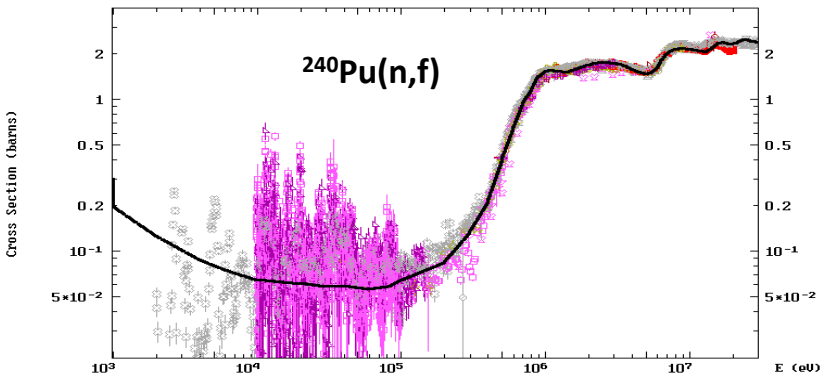



# 238-242Pu(n,f)


Cross Section (barns)
E (eV)


238Pu(n,f)
Cross Section (barns)
E (eV)


239Pu(n,f)
Cross Section (barns)
E (eV)


240Pu(n,f)
Cross Section (barns)
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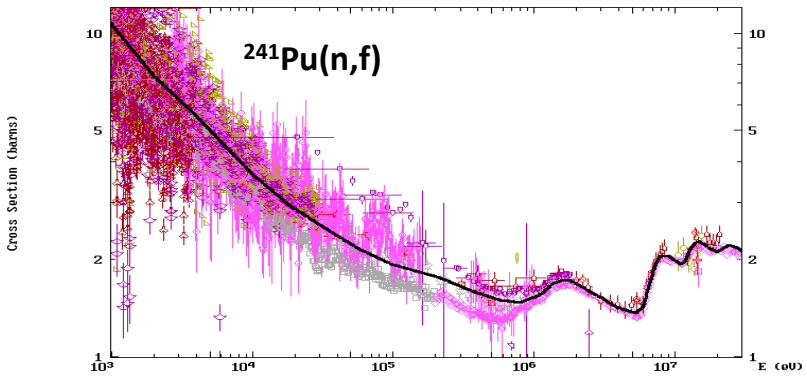
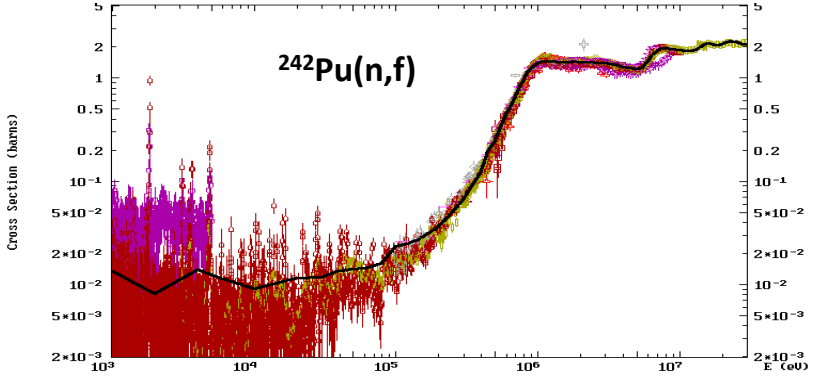
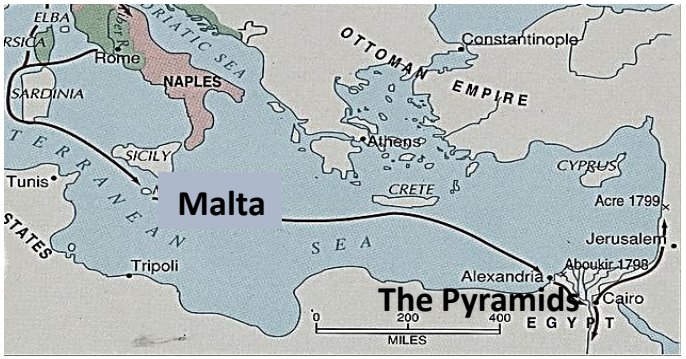

241Pu(n,f)
Cross Section (barns)
E (eV)


242Pu(n,f)
Cross Section (barns)
E (eV)

# EMPIRE
# new developments




The present version EMPIRE 3.2 – Malta will be replaced soon by EMPIRE 3.3 – The Pyramids

It is a team effort to maintain and develop all the components of such a complex code as EMPIRE.

## Examples of modeling updates

**Direct interaction** – ECIS-2006, OPTMAN, DCCOMP, DWBA, multi-band couplings are employed to improve the direct contribution with effects on the neutron emission channels and indirectly on fission.

**Deuteron-induced reaction –** full treatment including the competition between elastic breakup, inelastic breakup with absorption of only a neutron or a proton, and complete absorption. These breakup-fusion reactions are particularly complex, forming compound nuclei with a wide range of excitation energies and angular momenta.

**Fission –** the optical model for fission extended to be valid at deep sub-barrier energies can provide accurate cross sections in special cases such as triple humped barriers with very narrow third well, photofission, and now for (d,pf) probabilities.

**Level density –** a new model "Constant Temperature + EGSM Fermi Gas" was added to the existing Gilbert-Cameron, GSM, EGSM, HFB.

**Preequilibrium** – work on: generalizing DDHMS and boosting MSC without giving up gradual absorption.

# EMPIRE new developments

## Other improvements

**Covariances** (e.g. distinguish incoming and outgoing channel in sensitivity calculations),

**New formatting capabilities** (e.g. ENDF formatting of discrete gamma lines, discrete level cross sections in (n,d), (n,t), (n,He3), Kalman produced covariances including cross-reaction correlations),

**Input** (e.g. defining automatic elemental-evaluation loops, updates for the mass table, constants, and resonances, completing the gamma decay schemes),

**Plotting and comparison with the experimental data** (e.g. better manipulation of c4 files, plotting guided by the ENDF-file contents),

**New GUI** – under development.

**Contributions to nuclear data libraries**: INDEN, ENDF/B-VIII, IAEA PD2019, RIPL-4

Complete, self-contained and install-free packages for Windows, Linux and Mac OS at https://www-nds.iaea.org/empire/index.html