FISPACT-II: an advanced simulation platform for inventory and nuclear observables

“a renaissance”

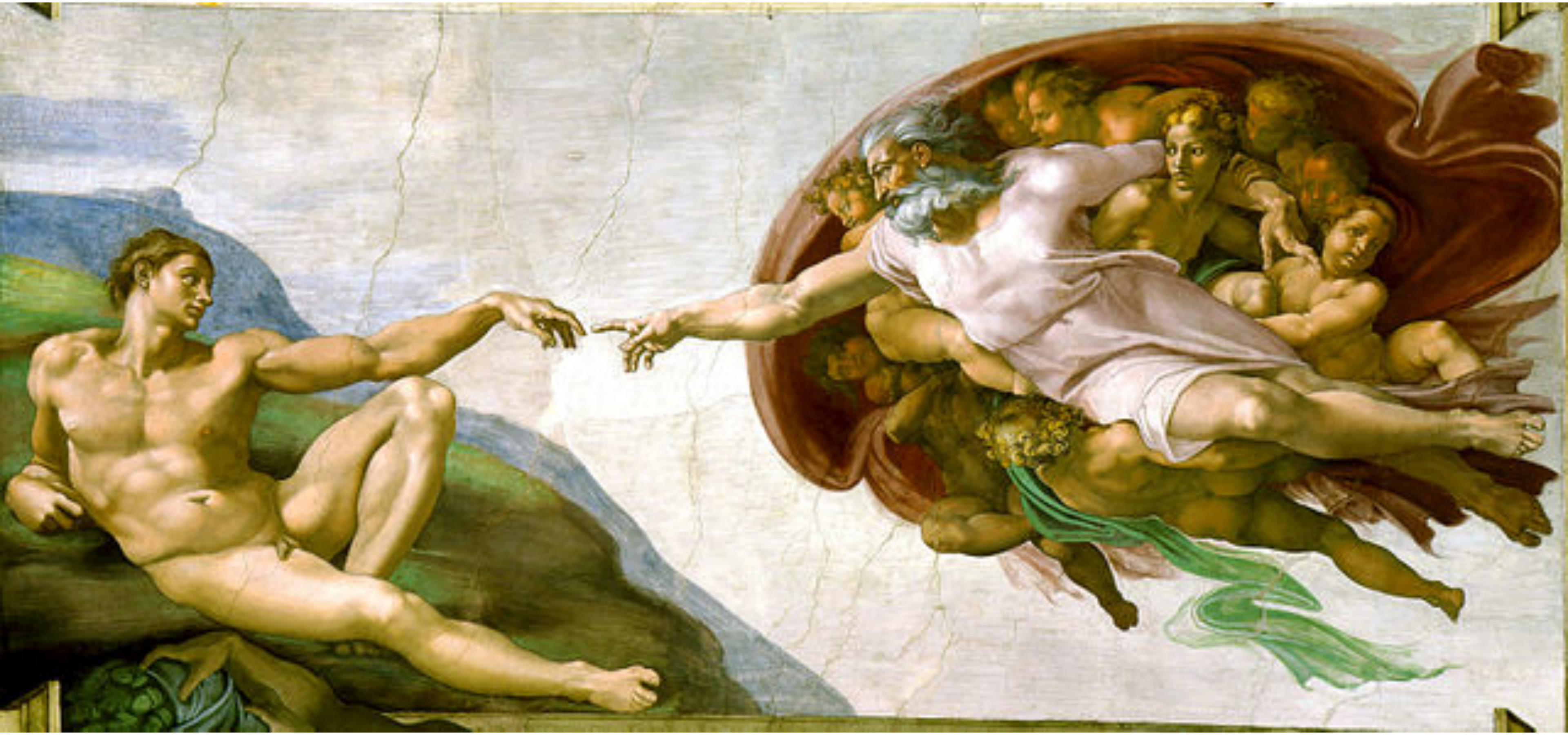
J-Ch. Sublet, M. Fleming and M. Gilbert

United Kingdom Atomic Energy Authority
Culham Science Centre
Abingdon OX14 3DB
United Kingdom

James W. Eastwood, J. Guy Morgan

Culham Electromagnetics Ltd

Italian renaissance



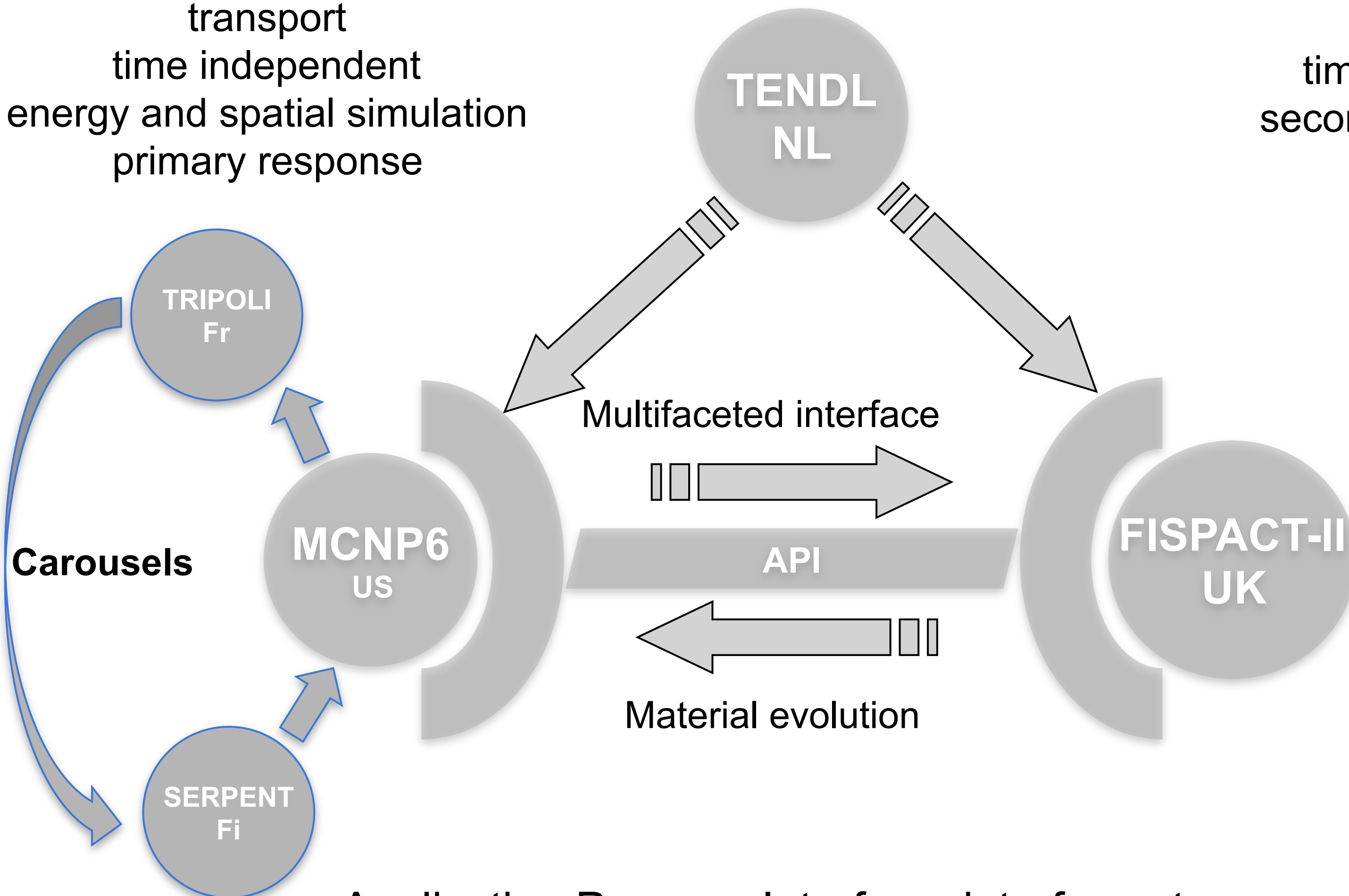
Michelangelo, (c. 1511) the Creation of Adam

Simulation in space, energy and time

Boltzmann equation
transport
time independent
energy and spatial simulation
primary response

Nuclear Data

Bateman equation
inventory
time dependent
secondary response



Application Program Interface: interfaces to connect Boltzmann and Bateman solvers for non-linear t- and T-dependent transport

Overview

Chapter 1

- Framework
- ODE solver
- Nuclear data processing steps and libraries
  - Particles induced reactions
  - DD, sFY, nFY, otherFY
  - Hazard, transport, clearance indices

Chapter 2

- Reaction rates uncertainty quantification and propagation, variance-covariance
- Self shielding of resonant channels
    - Probability tables, sub-group method
    - Thin and thick target yields
    - Real-world application

Overview

Chapter 3

- Extended pathways search
- Verification and Validation, V&V
  - Differential
  - Integral

Chapter 4

- Applications
  - Scoping studies of material response
    - Activation, transmutation and primary damage response functions
  - Fission
  - High energy
  - Input into materials science

Overview

Chapter 5

- FISPACT-II & Libraries simulation software
- Future Roadmap

Libraries distribution, access policy

- ENDF/B-VII.1, JENDL-4.0, JEFF-3.2, CENDL-3.1 nuclear data: available through the NNDC
  - https://www-nds.iaea.org/
- EAF-2010 in ENDF-6 format = n-FENDL-3.0/A; d-FENDL-3.0/A and p-FENDL-3.0/A = part of d-TENDL-2011 and p-TENDL-2011
  - http://www-nds.iaea.org/fendl3
- TENDL-2015 @
  - https://tendl.web.psi.ch/tendl_2015/tendl2015.html

  A project with yearly upgrade

framework

- FISPACT-II is a modern engineering prediction tool for activation-transmutation, depletion inventories at the heart of the an enhanced multi-physics platform that relies on the TALYS collaboration to provide the nuclear data libraries.
- FISPACT-II was designed to be a functional replacement for the code FISPACT-2007 but now includes many enhanced capabilities.
- d, p, α, γ, n-Transport Activation Library: TENDL-2015 from the TENDL collaboration, but also ENDF/B, JENDL, JEFF, CENDL and GEFY
- All nuclear data processing is handled by NJOY (LANL), PREPRO (LLNL) and CALENDF (UKAEA)

Development history (2009 - 2015)

- Phase I (*06-2006 – 03-2007*)
  - ODE solver selection, pre-programming ☑
- Phase II (*03-2009 – 03-2010*)
  - Release 0-20 alpha, 1-00 alpha, EASY-2010 benchmarking, CVS repository, software specification documents ☑
- Phase III (*06-2010 – 09-2011*)
  - FISPACT-II (12) 1.00, User manual, EAF-2010 full integration, PT's self shielding factor method, CCFE internal distribution ☑
- Phase IV (*10-2011 –* ***03-2012***)
  - EASY-II(12) R-2.00 first release ☑
- Phase V (*06-2012 –* ***06-2013***)
  - V&V suites, EASY-II (13) R-2.10 release ☑
- Phase VI (*06-2013 –* ***07-2014***)
  - V&V suites, EASY-II (14) R-2.20 release ☑
- Phase VII (*07-2014 –* ***09-2015***)
  - V&V suites, FISPACT-II R-3.00 & Libraries release ☑

Ordinary Differential Equation solver

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Theory: H. Bateman, Cambridge 1910

- Set of stiff Ordinary Differential Equations to be solved

$$\frac{dN_i}{dt} = -N_i(\lambda_i + \sigma_i \varphi) + \sum_{j \neq i} N_j(\lambda_{ij} + \sigma_{ij}\varphi)$$

- Here λ_i and σ_i are respectively the total decay constant and cross-section for reactions on nuclide i
- σ_{ij} is the cross-section for reactions on nuclide j producing nuclide i, and for fission it is given by the product of the fission cross-section and the fission yield fractions, as for radionuclide production yield
- λ_{ij} is the constant for the decay of nuclide j to nuclide i

Analytical and Numerical Models

- Analytical models are mathematical solutions expressed in closed form. The solution to the equations used to describe the time evolution of a system can be expressed in terms of well-known mathematical functions whose numerical values can be computed accurately, reliably and quickly. Then the numerical values of solutions at any required times may be computed in principle, but not always in practice. For example, the accuracy of a solution may be severely limited by rounding error in floating-point arithmetic.

- Numerical models are used when analytical models are not available, or cannot be evaluated reliably. The approximate solution to a system of equations is obtained using an appropriate time-stepping procedure to evaluate the solution at a discrete sequence of desired times. Good procedures allow estimates of the numerical error to be obtained so that the accuracy of the solution is known. The mathematical solution is represented as a table of numbers generated by the numerical method and can be plotted as a graph.

Analytical and Numerical Models

- The choice of an appropriate numerical method for any particular problem cannot be made naively. Decades of research in the field of numerical analysis has yielded a wide variety of methods, each suited to specific classes of problems:

  Euler integration; exponential, matrix exponential, Newton-Krylov implicit integrators, Markovian chains, first to fifth-order Runge-Kutta, Chebyshev Rational Approximation, etc …

- In the case of the Bateman equations with constant coefficients:
  - an analytical solution is available in principle, but cannot be evaluated in practice
  - the solution can be expressed as a sum of exponential functions of time using the eigenvalues of the system matrix
  - unfortunately, these eigenvalues cannot be computed reliably because of ill-conditioning
  - if computable at all, the eigenvalues would take an unacceptably long time to evaluate

- For inventory calculations, key characteristics of the system of equations are
  - sparsity (most elements of the system matrix are zero)
  - stiffness (contrasting timescales between the rapid decay of some nuclides and the length of the desired time interval)

Rate equations: numerical aspects

- LSODES, Livermore Solver for Ordinary Differential Equations with general sparse Jacobian matrices

  - Backward Differentiation Formula (BDF) methods (Gear's method) in stiff cases to advance the inventory
  - Adams methods (predictor-corrector) in non stiff case
  - makes error estimates and automatically adjusts its internal time-steps
  - Yale sparse matrix efficiently exploits the sparsity
  - ability to handle time-dependent matrix
  - no need for equilibrium approximation
  - handles short (1ns) time interval and high fluxes

- LSODES wrapped in portable Fortran 95 code
  - dynamic memory allocation
  - minor changes to Livermore code to ensure portability

FISPACT-II advanced simulations

	FISPACT-II
Solver	Numerical - LSODES 2003
Incident particles	α, γ, d, p, n (5)
ENDF's libraries: TENDL-2015 & GEFY.5.2 ENDF/B-VII.1, JEFF-3.2, JENDL-4.0, CENDL-3.1 (~400 targets each)	✔ XS data (2809 targets) ✔ Decay data (3873 isotopes) ✔ nFY, sFY, otherFY ✔ Hazard, clearance indices, A2
Dpa, Kerma, Gas production, radionuclide yields	✔
PKA, recoil, emitted particles spectra	✔
Uncertainty quantification and propagation UQP	✔ Variance-covariance
Temperature (from reactor to astrophysics, plasma) 1 KeV ~ 12 million Kelvin	0, 294, 600, 900 K,…5, 30, 80 KeV
Self-shielding with probability tables and with resonance parameters	✔ Resolved and Unresolved Resonance Range
Energy range	1.0 10^{-5}eV – 30, 200 MeV, ..1GeV
Sensitivity	✔ Monte Carlo
Pathways analysis, routes of production	✔ multi steps
Thin, thick targets yields	✔

FISPACT-II features: ENDF's libraries

- Large number of targets: 2809 from H^1 to Fl^{289} (Flerovium, mass 114)
- Broad energy range: 1.0 10^{-5} eV – 200 MeV, 1 GeV
- Five incident particles: a, g, d, p, n

- Covariance information on neutron entrance channels, uncertainty
- Pathways analysis, production routes, dominant contributors
- Self-shielding effects: channels, isotopic, elemental

- Sensitivity analysis, (Monte Carlo)
- Isomeric states and branching ratio (g, m, n, o, p, q,…., from RIPL)
- Consistent decay data and cross section data: energy levels

- Transport A2, clearance, inhalation and ingestion indices
- DPA, Kerma (primary and secondary), gas and radionuclide production
- Temperatures: 0, 294, 600, 900 K,… and stellar 5 Kev, 30 KeV, 80 KeV (1 Kev = 12 10^6K)
- Thin, thick target yields
- V&V suites: fusion, fission, accelerator, astrophysics,..

For all nuclear applications

TALYS collaboration

Partners: IAEA, PSI, UKAEA, CEA DIF, Uppsala University,..

Objectives: To create a set of modern baseline general-purpose files aimed at satisfying the radiation transport and activation-transmutation requirements for facilities in support of nuclear technology.

- α, γ, d, p, n-TENDL libraries
- Multi applications, consistent libraries
- Complete variance-covariance information
- TALYS nuclear model
- T6 codes; TALYS, TAFIS, TANES, TARES, TEFAL and TASMAN, wrapped into a Total Monte-Carlo loop for uncertainty quantification

TALYS, T6 philosophy

- From model parameters to code result quantities
- Allow physical parameters to impact the basic nuclear data and not an engineered localized adjustment, unable to account for compensation effects.
- With variance-covariance data based on experimental data and nuclear models, allowing design optimization of nuclear technology.
- Account for the processing (non unique) steps.
- Include, account for V&V **V**erification and **V**alidation processes.
- Feedback of extensive validation and benchmark activities are automatically and rapidly, within a year not 10, taken into account.

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2016 periodic table

Periodic Table of the Elements

Atomic Number
Symbol
Name
Atomic Mass

1 IA 1A	2 IIA 2A	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8 VIII 8	9 VIII 8	10 VIII 8	11 IB 1B	12 IIB 2B	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
1 H Hydrogen 1.008																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305											13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.631	33 As Arsenic 74.922	34 Se Selenium 78.972	35 Br Bromine 79.904	36 Kr Krypton 84.798
37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.711	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.294
55 Cs Cesium 132.905	56 Ba Barium 137.328	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.085	79 Au Gold 196.967	80 Hg Mercury 200.592	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Fl Flerovium [289]	115 Uup Ununpentium unknown	116 Lv Livermorium [298]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown

Lanthanide Series	57 La Lanthanum 138.905	58 Ce Cerium 140.116	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.242	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.500	67 Ho Holmium 164.930	68 Er Erbium 167.259	69 Tm Thulium 168.934	70 Yb Ytterbium 173.055	71 Lu Lutetium 174.967
Actinide Series	89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]

Alkali Metal	Alkaline Earth	Transition Metal	Basic Metal	Semimetal	Nonmetal	Halogen	Noble Gas	Lanthanide	Actinide

Dawn Shaughnessy

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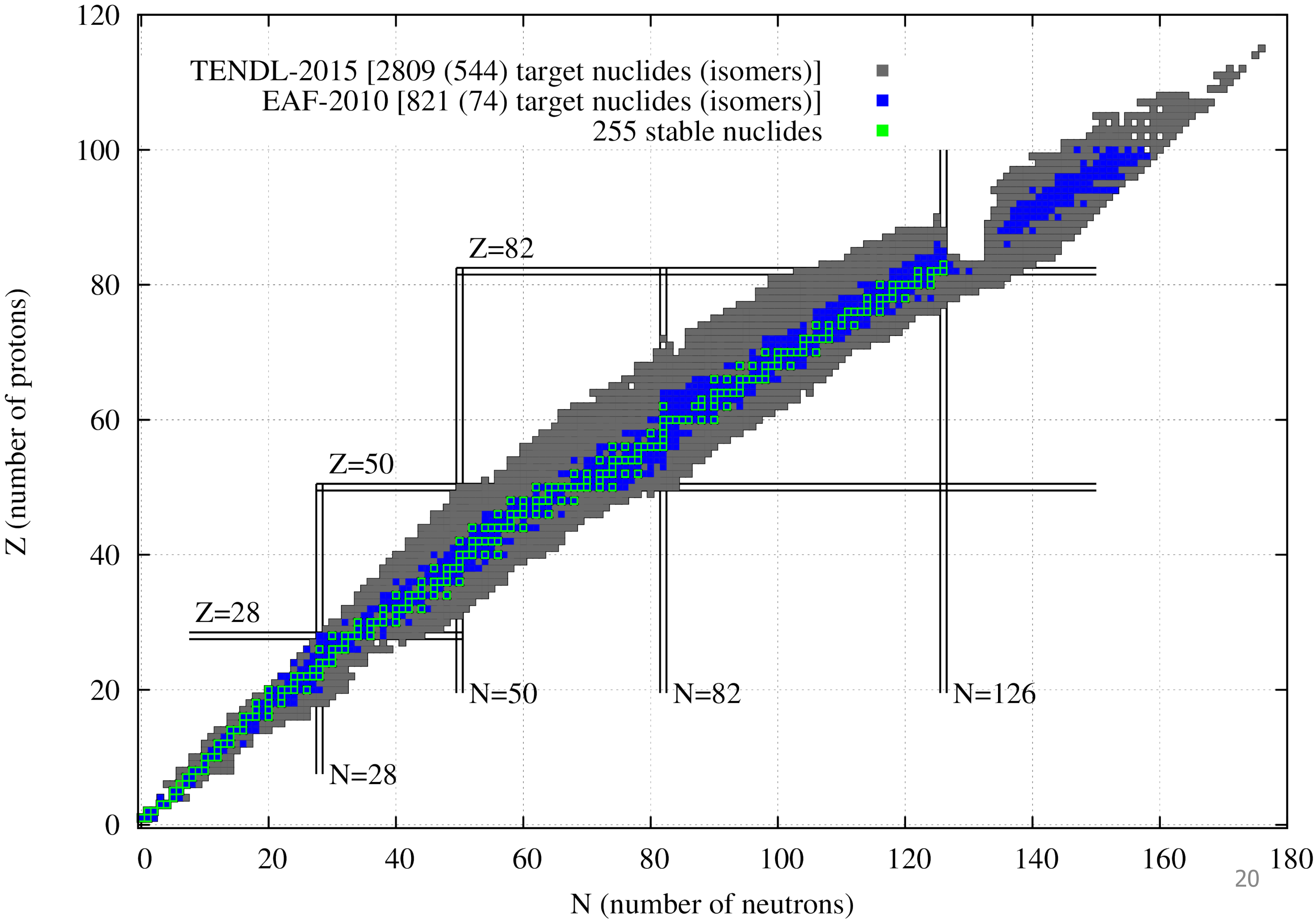
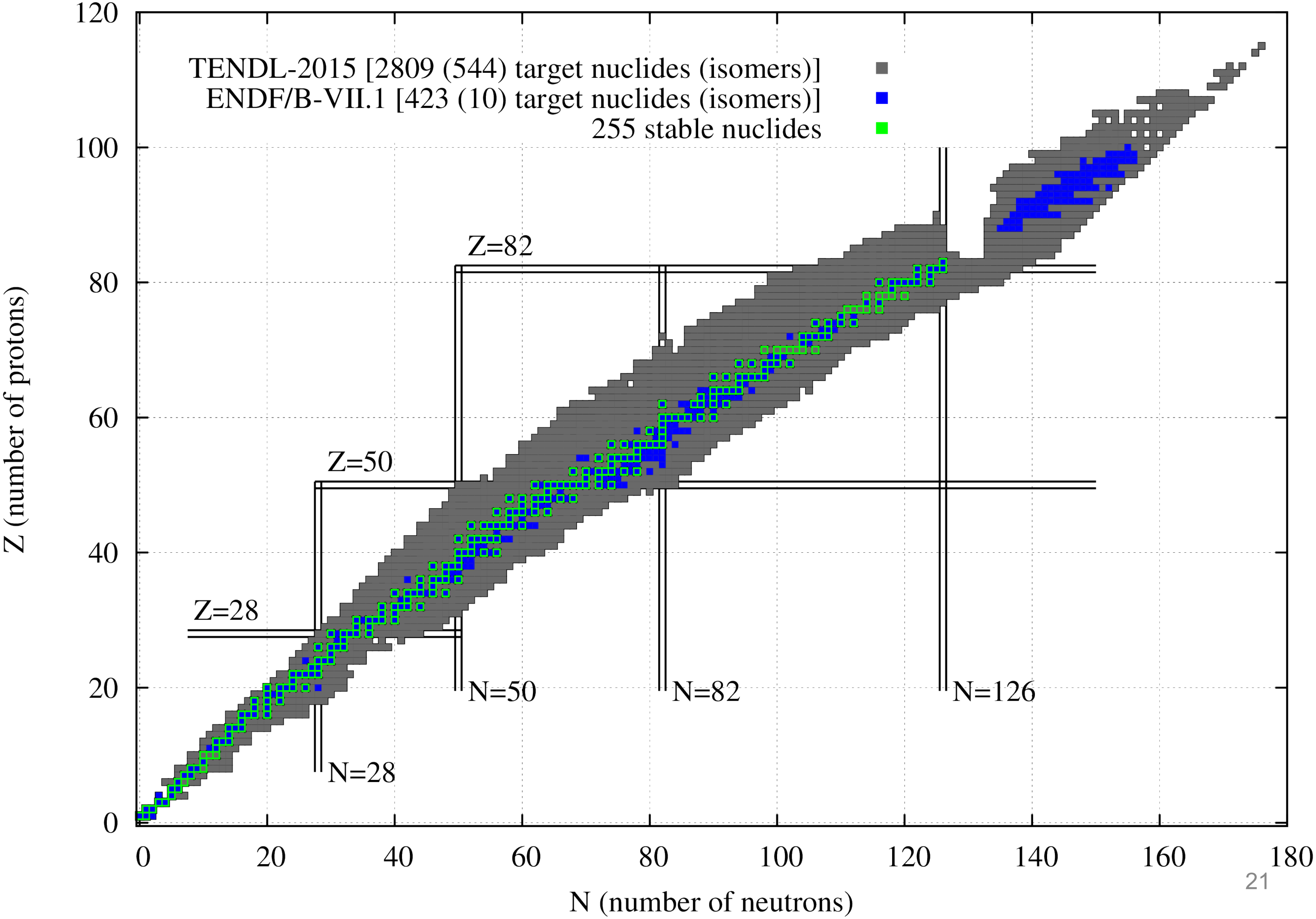
Isotopic targets



Isotopic targets



Nuclear data processing steps and libraries

Processing steps: burnup, transmutation

- Legacy EAF's format style libraries are being phased out, replaced by ENDF's style libraries, however the physics input streams remain
- This has been made possible because of:
  - November 2010 CSWEG ENDF-6 format extension
  - NJOY-12 extensions: mf8, reconr basic, acer, gaspr…
  - PREPRO-2015 extensions: sixpack, complot,…
  - TENDL-2015 enhanced GP format framework: unequivocal, clear format cutoff @ 30 then to 200 MeV, then to 1 GeV.
- The development of the FISPACT-II inventory code

FISPACT-II processing steps

- Uniquely, uses three processing codes to prepare, shape its nuclear data forms:
  - NJOY – kerma, dpa, matrix, gas production & crosschecking
  - PREPRO – ENDF data file preparation, high energy
  - CALENDF – probability table & crosschecking
- Advantages
  - Robustness, completeness
  - Redundancy
  - Portability, repeatability
  - Legacy and maturity
- Remarks: not all observables need processing to be usable

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Processing steps: three codes

ENDF file

- **NJOY12-064**
  - reconr
  - broadr
  - unresr
  - thermr
  - heatr
  - gaspr
    - purr
    - acer
    - groupr

cross-check

- **PREPRO-2015**
  - **linear**
  - **recent**
  - **sigma1**
  - **sixpack**
  - **activate**
  - **merger**
  - **dictin**
  - **groupie**

cross-check

- **CALENDF-2010**
  - calendf
  - regroutp
  - lecritp
  - ….

PT file

Single script for an entire library

ACE file

Processed ENDF file

Processing steps: three codes

- **NJOY-12.064**
  - 0 Kelvin run
  - Single temperature pendf
  - Two *heatr* runs (7 + 4 responses, gamma local)
  - *Groupr* 1025 groups @ 30 MeV; p, d, t, alpha and he-3 + residual nucleus (A>4) production matrix, recoil matrix

    - *thermr*, free gas
    - Two more *heatr* run (7 + 4 responses, gamma transported)
    - *purr* (nbin=20, ladders=64)
    - Two *acer* (new cumulative angle distribution (law 61) and one for checking and ace data forms display)

The MCNP routes

Processing steps: three codes

- **CALENDF-2010**
  - 0 Kelvin run
  - Single temperature pendf, statistical resonance in the URR
  - Single temperature Probability Tables
  - PT in the RR and URR from 0.1 eV to the end of the URR for each isotopes
  - Group structure 615 @ 10 eV, 900 @ 5 MeV

Those PT tables as they are stored can be used by either FISPACT-II and TRIPOLI-4.9. They allow self-shielding treatment in the URR to be accounted for (300 pcm on Bigten @ 20-150 KeV)

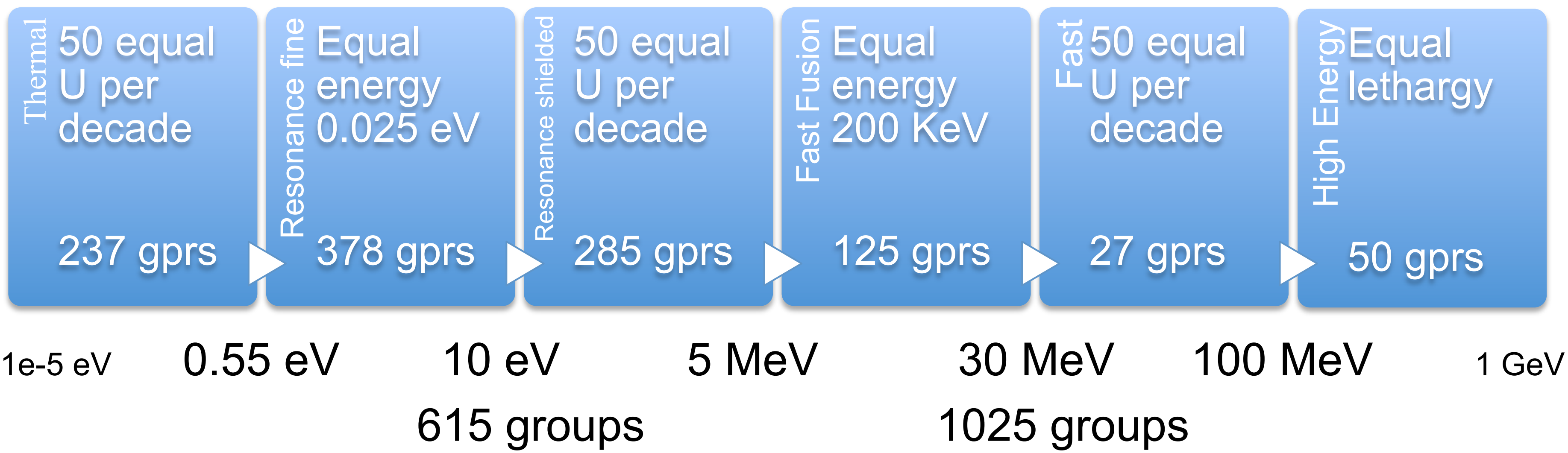
Processing steps: three codes

- **PREPRO-2015**
  - 0 Kelvin run
  - Single temperature pendf, 294 Kelvin to… 100 KeV
  - *SIXPACK*: unique mf3-mt5/mf6 high energy processing
  - *ACTIVATE*: unique mf9 processing
  - Merge NJOY-12 dpa, kerma pendf responses
  - *GROUPIE* to: 1102 gprs @ 1 GeV
    1067 gprs @ 200 MeV
    1025 gprs @ 30 MeV
    162 gprs @ 200 MeV (for charge particles)
  - mf-2 processed, but also kept in for further usage

The resulting pendf "tape" fully comply to the ENDF-6 format frame and many utilitarian process (display, merge, concatenate, etc.) can be performed on such data forms

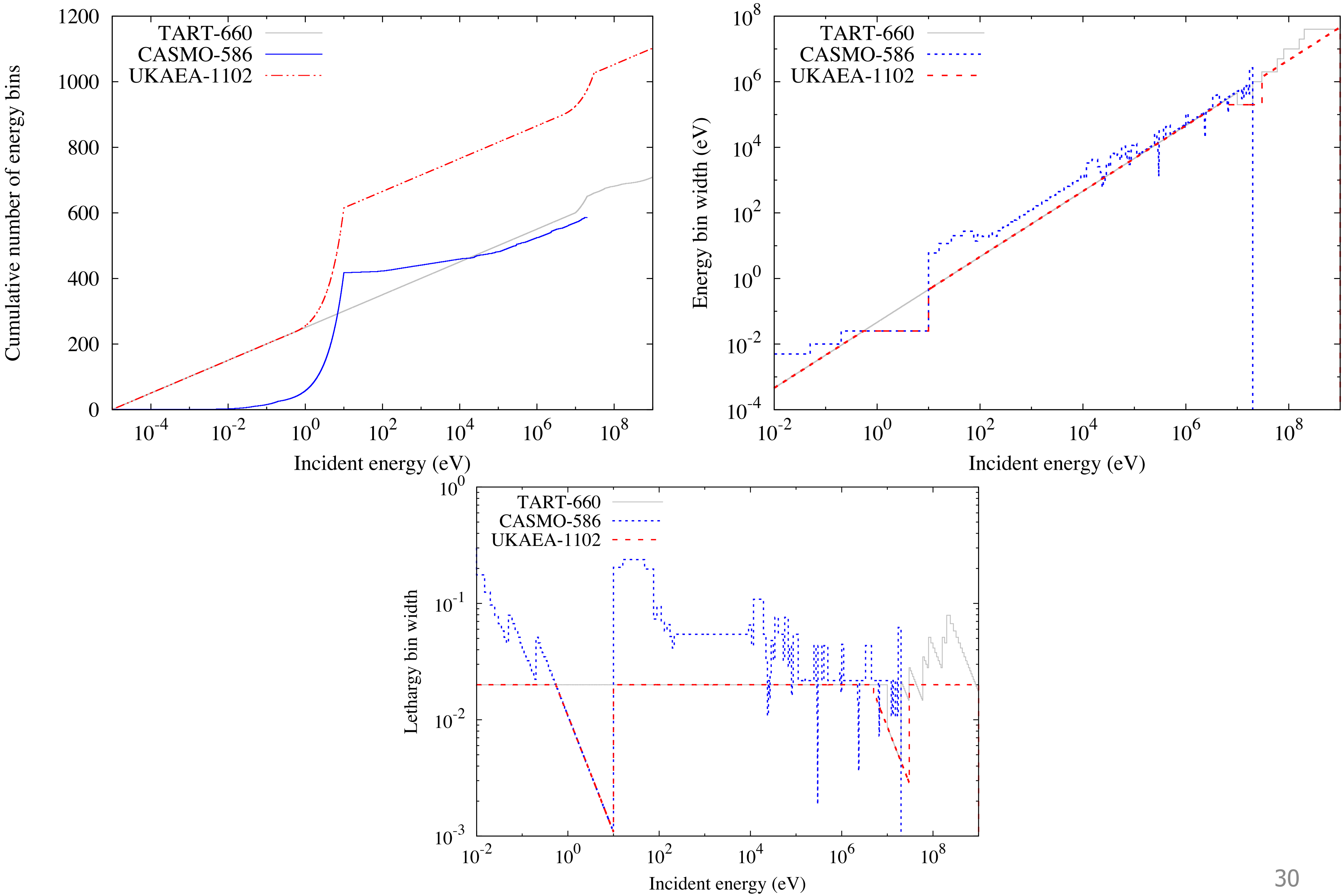
Group structures

- For all 2809 TENDL target nuclides
- 1102 energy groups for all applications alike

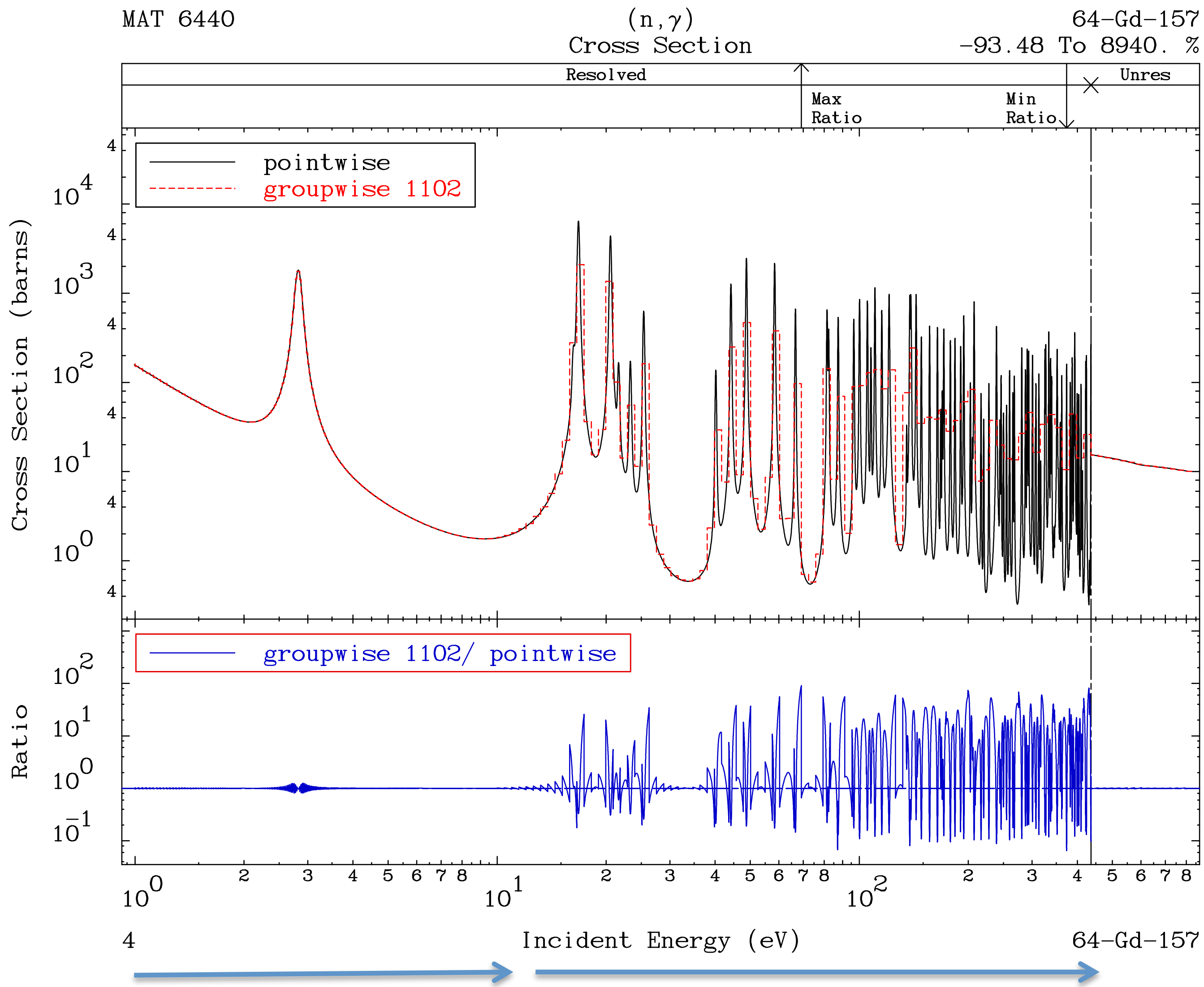


- 378 fine groups in the resonance range
- Resonance shielded data available in the RRR (0.1 eV) up to the end of the URR for all nuclides IDs
- Fast fine structure for accurate threshold reaction rate

Group structures



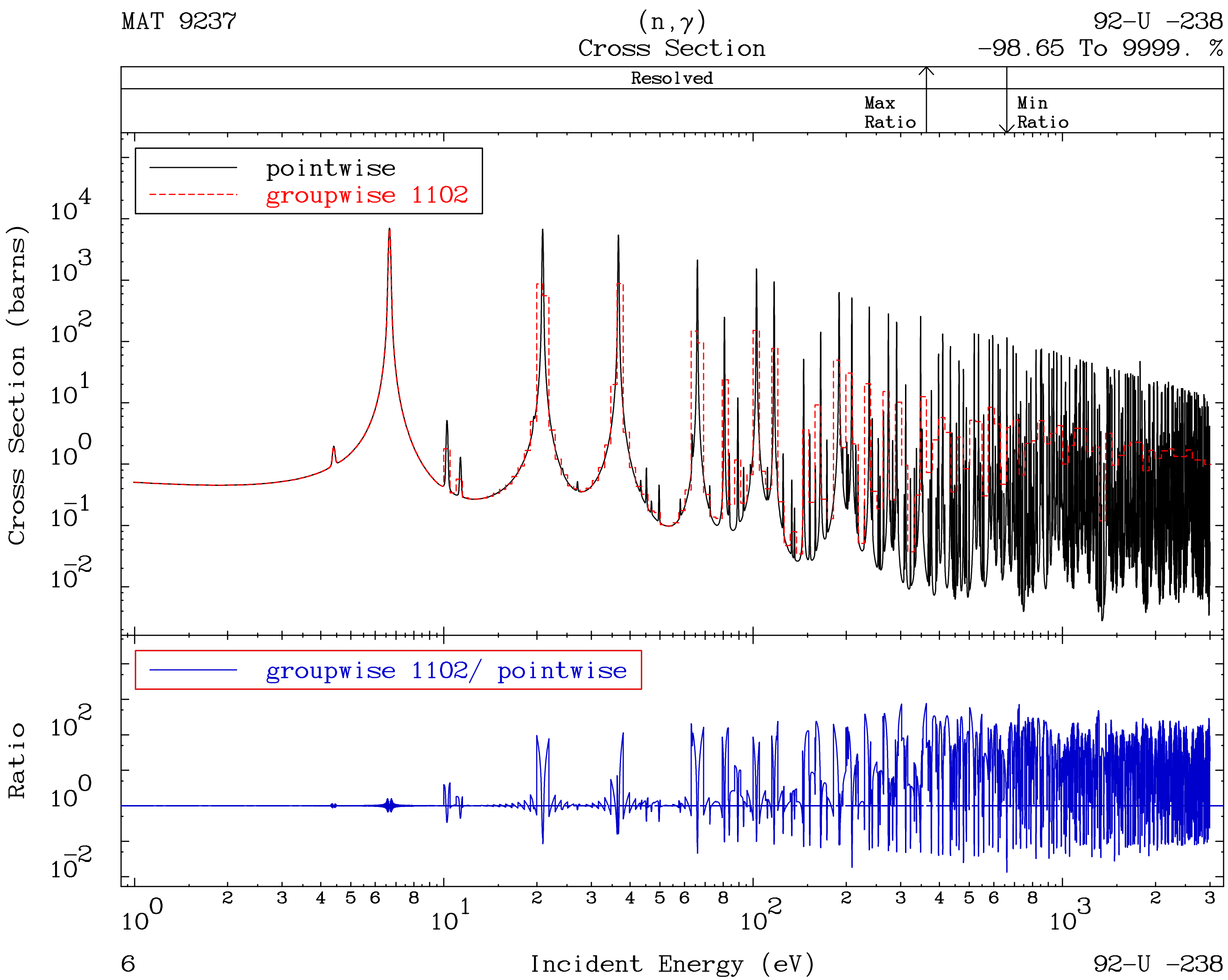
Group structure: 1102



Fine group to 10 eV

Resonance shielded to end of URR

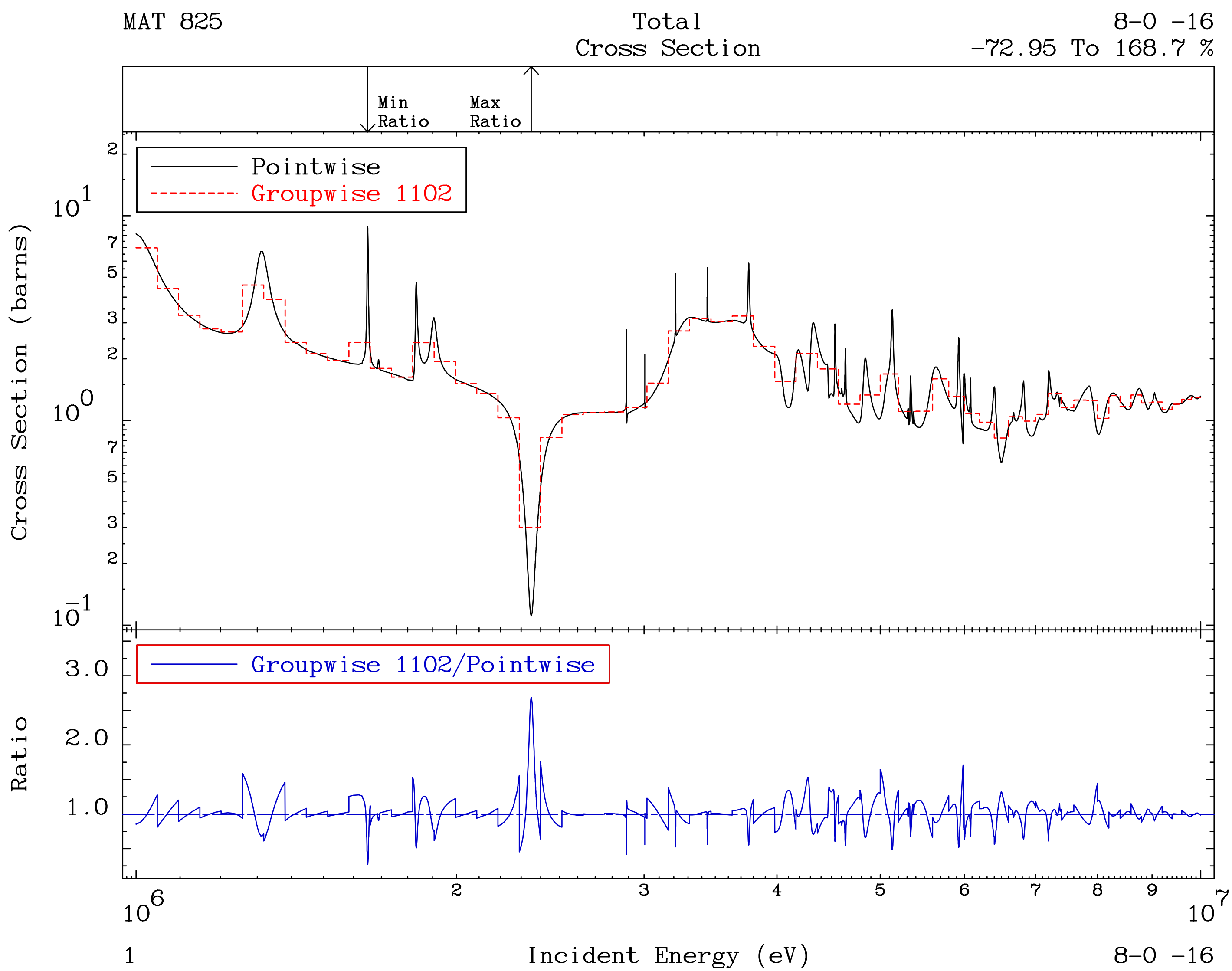
Group structure: 1102



Fine group to 10 eV

Resonance shielded to end of URR

Group structure: 1102



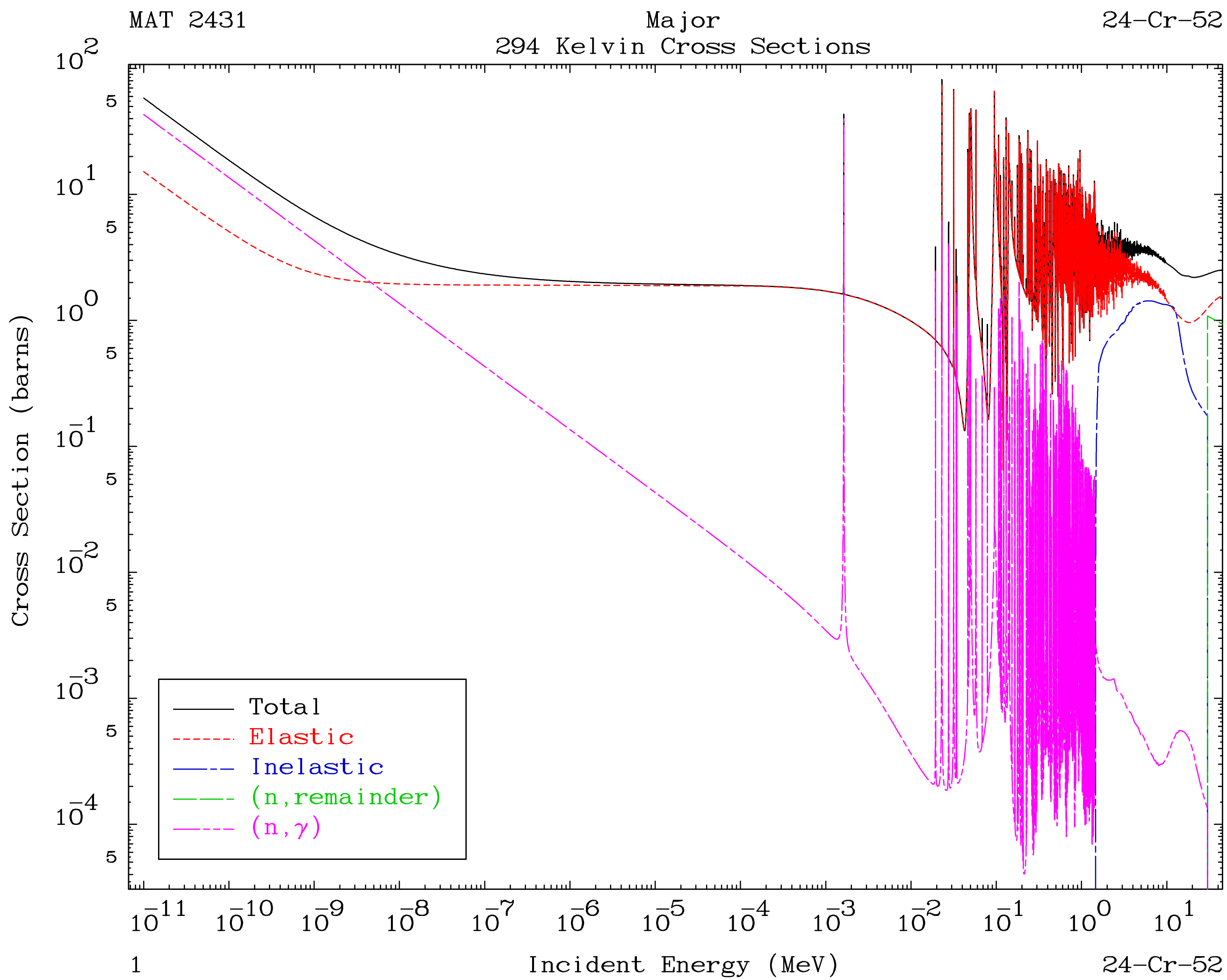
Peak and trough are well described

Applications forms

- Pointwise forms, Temperature dependent
- Groupwise, T and sigma zeroes dependent, PTs
- Variance and covariance (on cross section)
- MF-2 resonance widths for shielding
- Matrices: n-n, n-g, n-prod and recoil
- All partials and total Kerma (7), dpa (4), gas production (5)

- FISPACT-II & SPECTRA-PKA nuclear data forms, groupwise with probability tables, uncertainty, n-prod/recoil matrices, responses

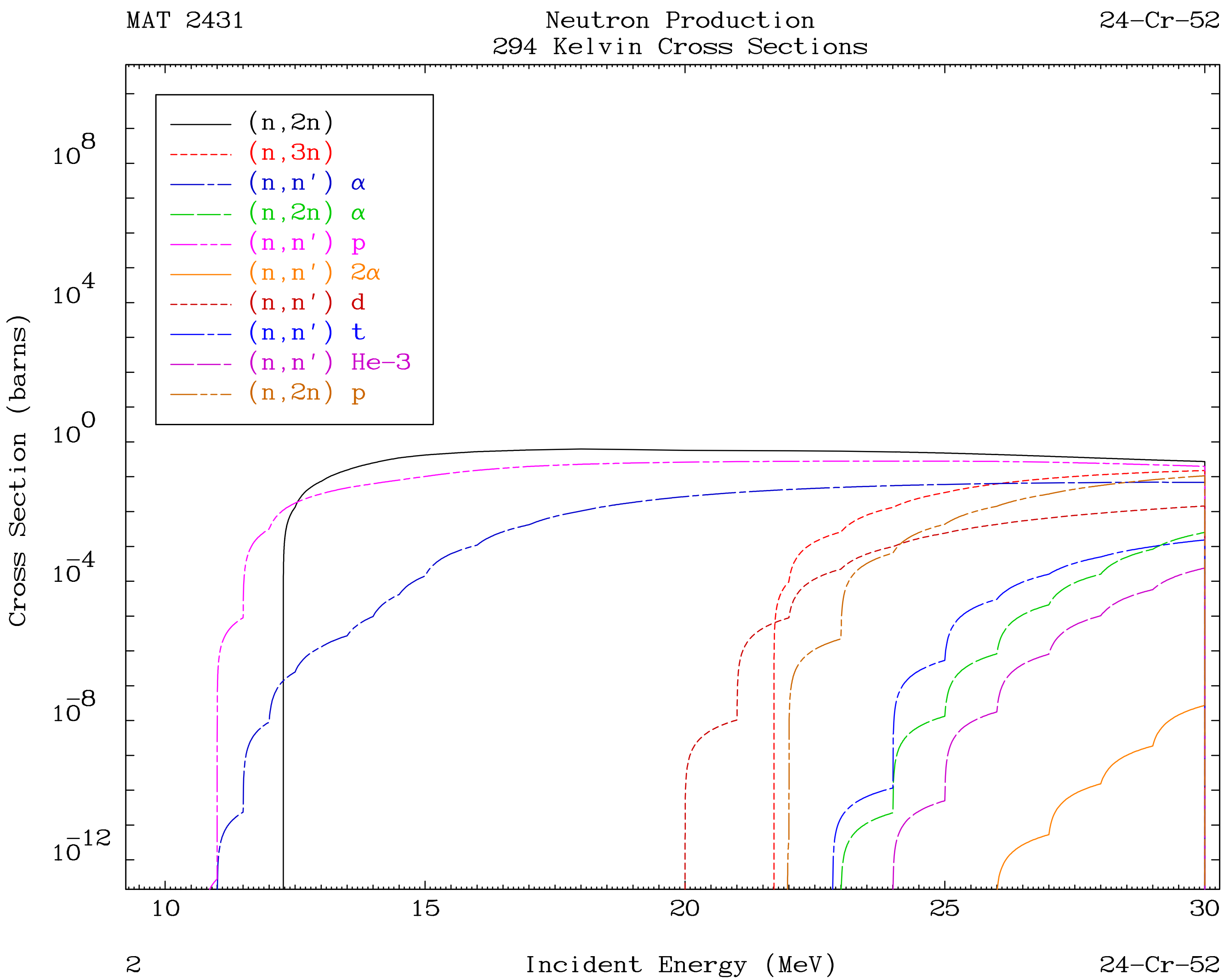
TENDL-2015 pendf, 200 MeV



90 reaction types

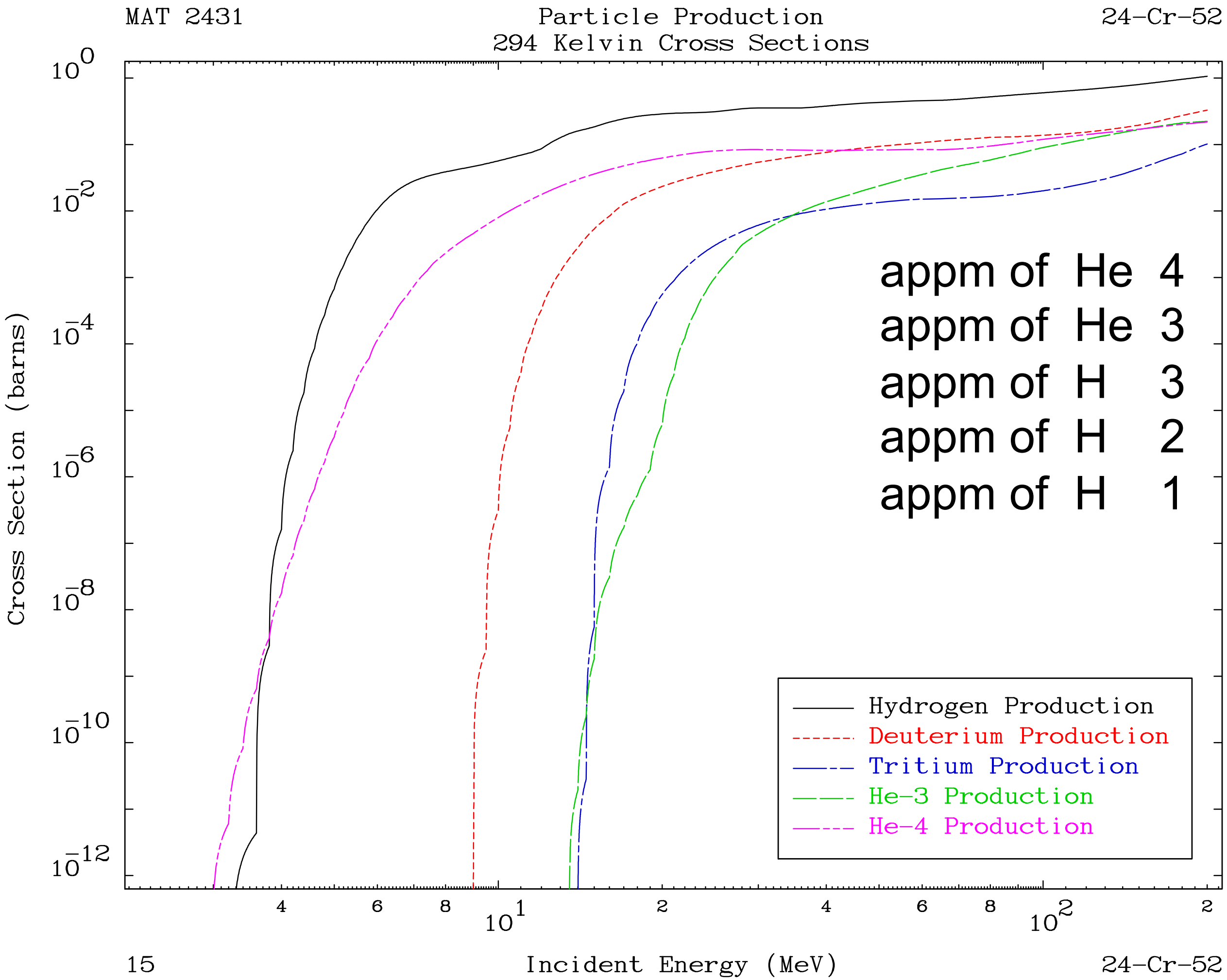
(n, remainder) =mf3-mt5*mf6 above 30 MeV

TENDL-2015 pendf, below 30 MeV



TENDL-2015 pendf, 200 MeV

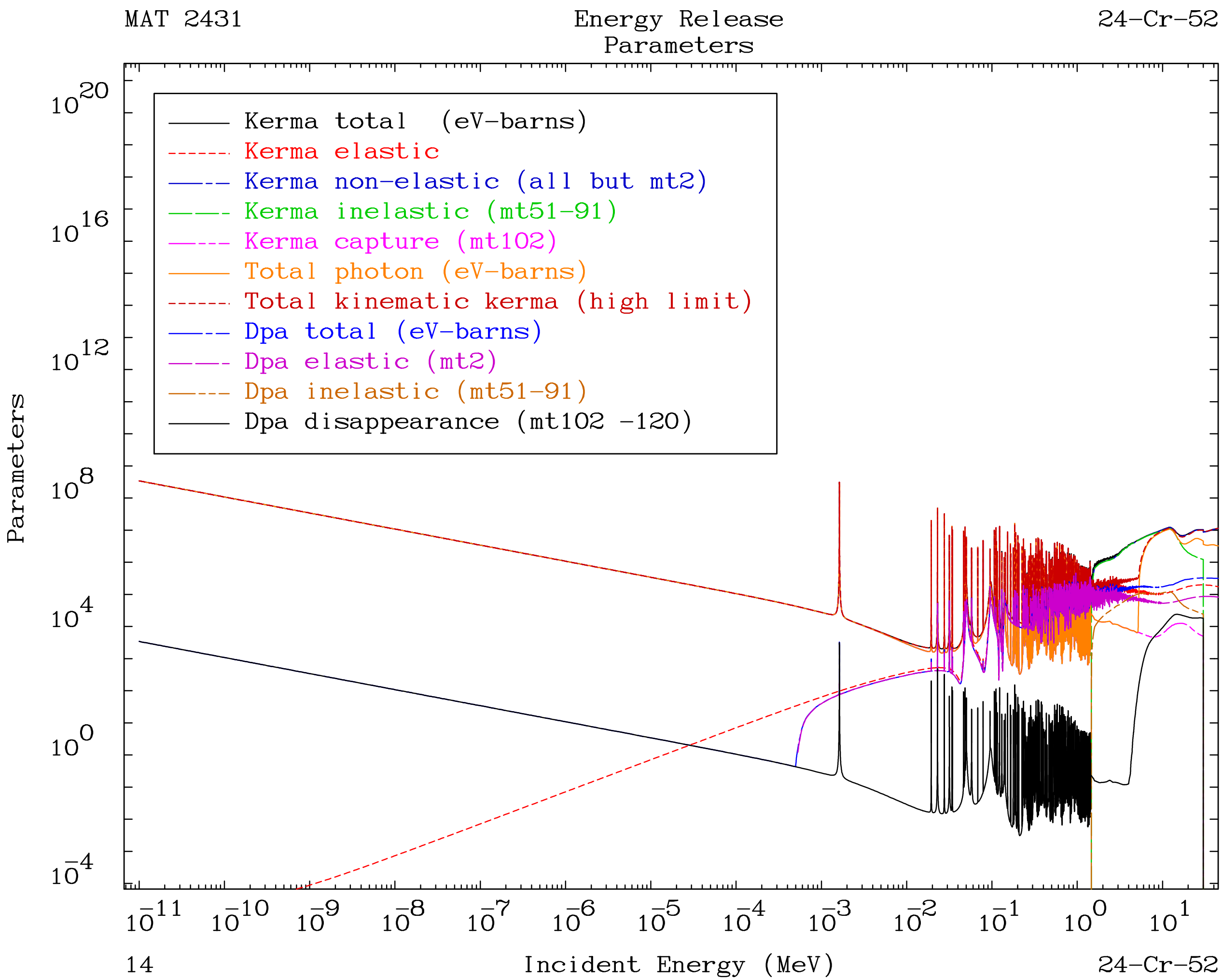
Gas production



appm of He 4 = 1.13E+03
appm of He 3 = 1.30E-02
appm of H 3 = 1.43E-18
appm of H 2 = 2.07E+01
appm of H 1 = 1.18E+03

NJOY generated MT's displayed by PREPRO

TENDL-2015 pendf, 200 MeV

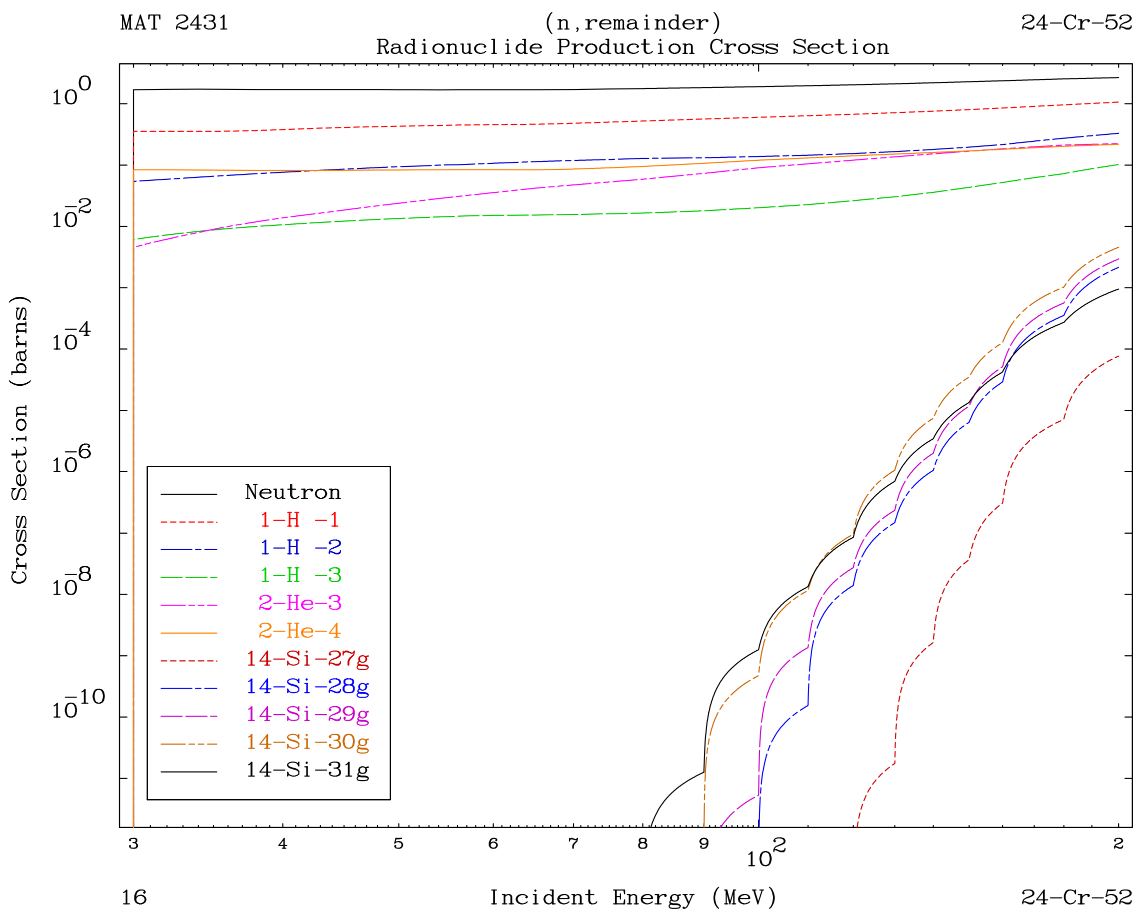


Total, partial Kerma

Total, partial Dpa

NJOY generated MT's displayed by PREPRO

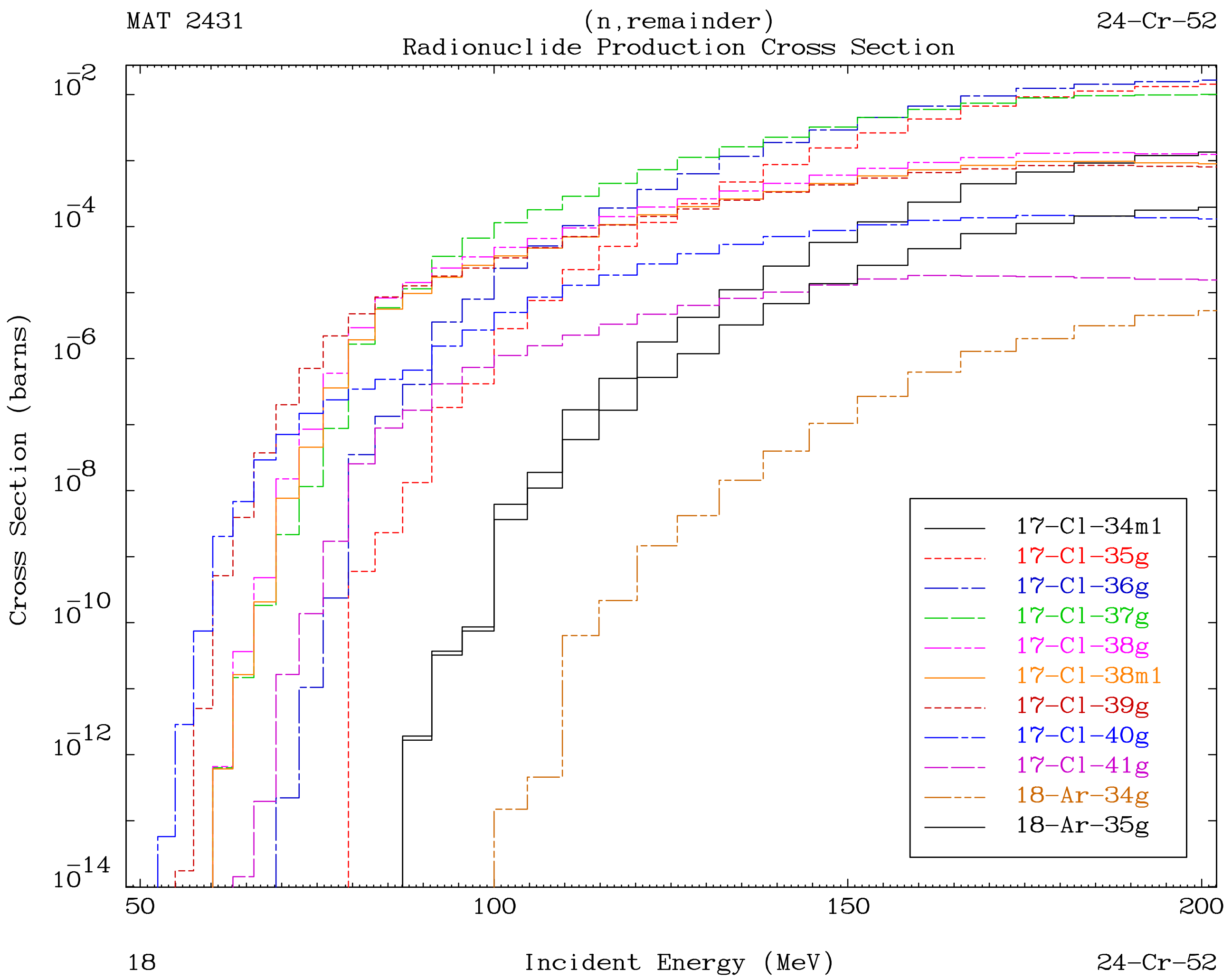
TENDL-2015 pendf from mf3*mf6



Cross section channels above 30 MeV

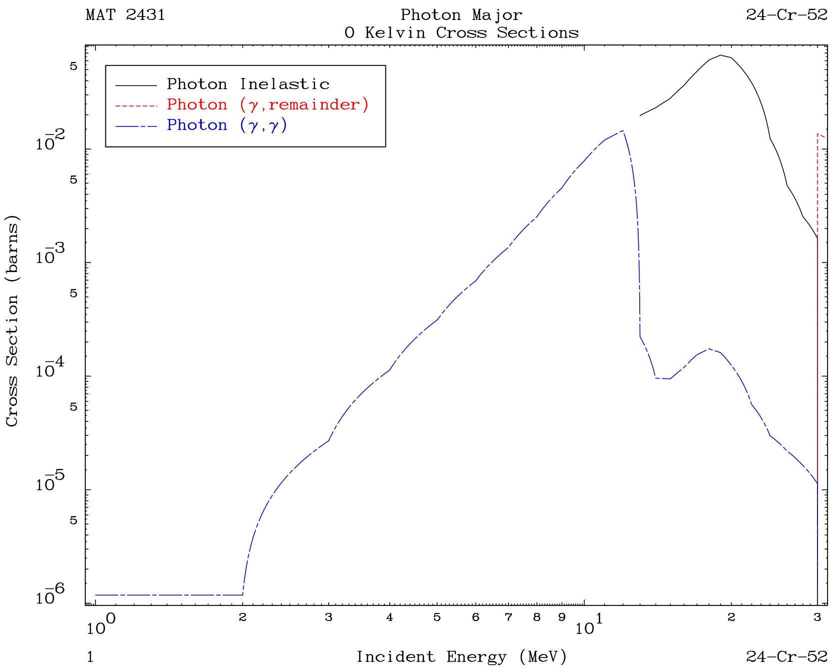
Unique to PREPRO mf10-mt5

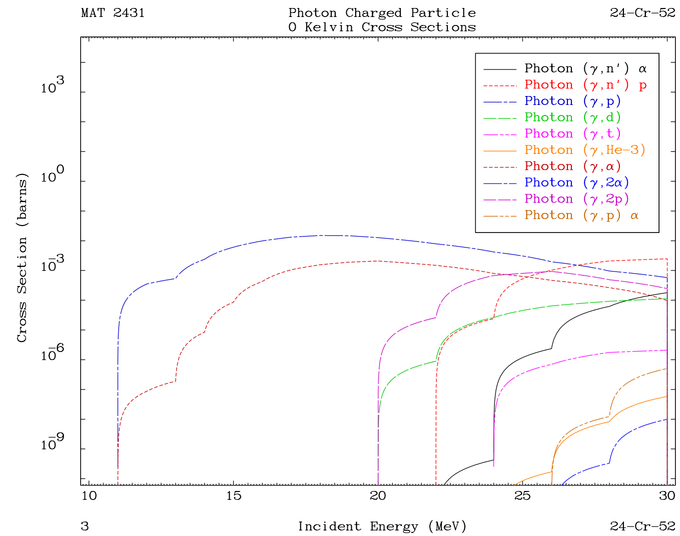
TENDL-2015 gendf, 200 MeV

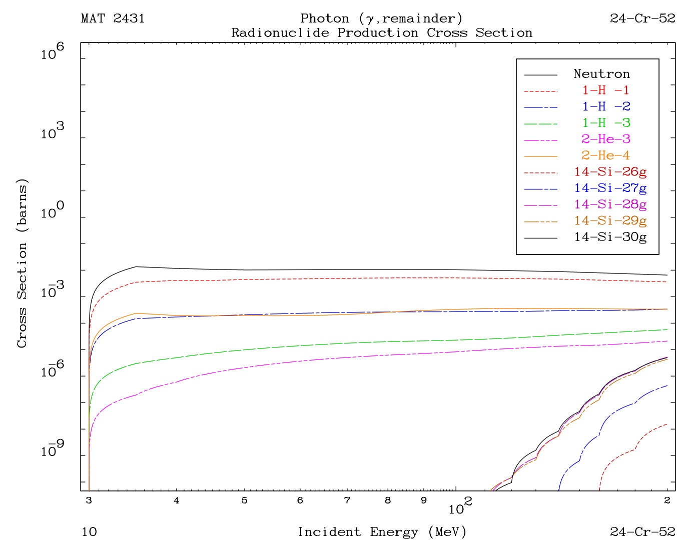


Groupwise data from PREPRO-2015, MF-10 with isomers

TENDL-2015 gamma pendf, 200 MeV







Processing steps: burnup, transmutation

- Multi-particle groupwise, multi-temperature libraries with NJOY12-064, PREPRO-2015, probability tables in the RRR & URR with CALENDF-2010
  - For the inventory code FISPACT-II
- From α, γ, p, d, n-TENDL-2015 & ENDF/B-VII.1, JEFF-3.2, JENDL-4.0u, CENDL-3.1
- FISPACT-II parses directly the TENDL's covariance complex information
- Transport and activation application libraries now stem from unique, truly general purpose files

FISPACT-II TENDL's libraries – 200 MeV

- n-tendl-2015, multi temperatures, 1102 groups library for 2809 targets
  - ✓ full set of covariance
  - ✓ probability tables in the RRR and URR
  - ✓ xs, dpa, kerma, gas, radionuclide production

- JENDL-4.0u, ENDF/B-VII.1, JEFF-3.2, CENDL-3.1, 1102 groups libraries for circa 400 targets each

- γ-tendl-2015, 162 groups xs library, 2804 targets
- p-tendl-2015, 162 groups xs library, 2804 targets
- d-tendl-2015, 162 groups xs library, 2804 targets
- α-tendl-2015, 162 groups xs library, 2804 targets

FISPACT-II other libraries

- ✓ UKDD-2012, 3873 isotopes (23 decay modes; 7 single and 16 multi-particle ones)
- ✓ Ingestion and inhalation, clearance and transport indices libraries, 3873 isotopes
- ✓ GEFY 5.2, JEFF-3.1.1, UKFY4.2 fission yields
- ✓ ENDF/B-VII.1 DD and FY
- ✓ JENDL-4.0 DD and FY

Kept for compatibility, but with less capabilities:

- ✓ EAF-2010 decay data: 2233 isotopes
- ✓ EAF-2010 ingestion and inhalation, clearance and transport indices libraries, 2233 isotopes
  - ✓ EAF-2010 libraries; 293K, 816 targets (55 MeV)
  - ✓ EAF's uncertainty files

Response functions

- γ-dose rate
  - From either contact (default) or point source
  - Contact: dose rate at surface of semi-infinite slab

$$D = \frac{CB}{2} \sum_{i=1}^{N_\gamma} \frac{\mu_a(E_i)}{\mu_m(E_i)} S_\gamma(E_i)$$

N_γ = number of γ energy groups,
μ_a = mass energy absorption,
μ_m = mass energy attenuation,
B = build-up factor,
S_γ = rate of γ emission,
C = conversion from MeV/kg/s to Sv/h

  - Dose from a point source
    - `DOSE 2 x`
    - Point source of 1 g of material at a distance *x* (m)

UK Atomic Energy Authority

Response functions

- Biological hazard – `HAZARDS`
  - Estimates the biological impact to human beings
  - library of dose coefficients
    - determine the dose following ingestion or inhalation of 1 Bq of activity from each radionuclide
    - From ICRP and NRPB where available
    - Uses an approximation otherwise (1209 nuclides)
- Clearance indices – `CLEAR`
  - IAEA data coefficients determining when a radionuclide can be disposed of as if non-radioactive (clearance=1)

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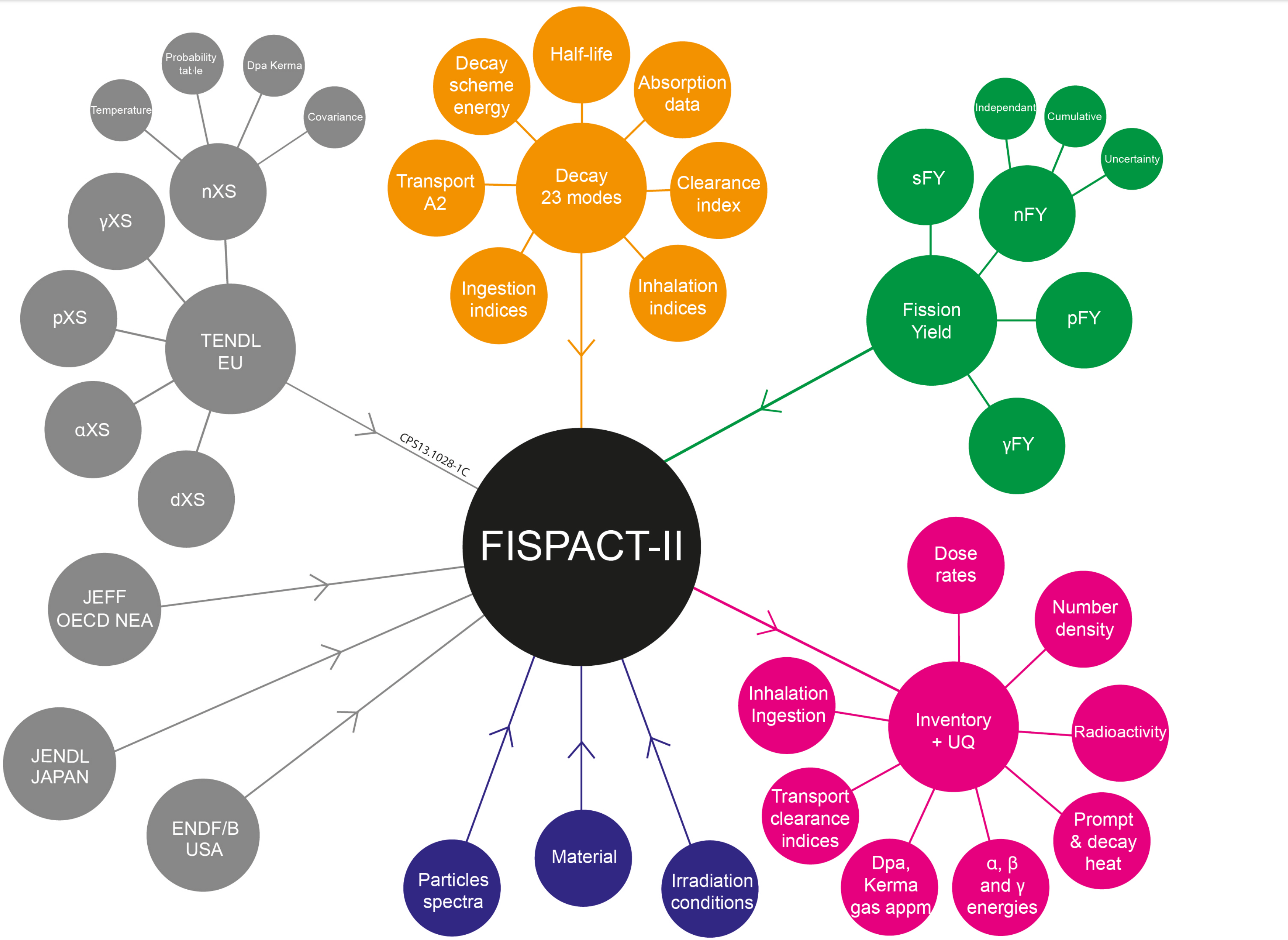
FISPACT-II &TENDL & ENDF/B, JENDL, JEFF



FISPACT-II roadmap

UK Atomic Energy Authority

① FISPACT-2007+ & EAF-2010 in EAF format processed by SAFEPAQ-II ☑ 08/2010

② FISPACT-II(11) & EAF-2010 in EAF format processed by SAFEPAQ-II ☑ 01/2011

③ FISPACT-II(11) & EAF-2010 + CALENDF PT's ssf method, ENDF's format and processing framework ☑ 09/2011

④ EASY-II(12) = FISPACT-II(12) & EAF's and TENDL-2011 ENDF's libraries processed by NJOY, PREPRO & CALENDF ☑ 03/2012

⑤ EASY-II(13) = FISPACT-II & EAF's and TENDL's V&V libraries processed by NJOY, PREPRO & CALENDF ☑ 06/2013

⑥ EASY-II(14) =FISPACT-II & EAF's, TENDL's, ENDF's libraries, automated V&V processes ☑ 07/2014

⑦ FISPACT-II & TENDL's, ENDF's libraries, automated V&V processes ☑ 09/2015

Vigilant, thorough V&V stepped approach, weathered in five years

MT Values

- Grid of reactions, MT numbers defined in ENDF-6 format

Ni	**Z+2**			(α,3n)	(α,2n)	(α,n)	
Co	**Z+1**			(p,n) β^-	(p, γ) (d,n)	(t,n)	
Fe	**Z**	(n,4n) 37	(n,3n) 17	(n,2n) (γ,n) 16	(n,n') 4	(n,γ) 102	(t,p)
Mn	**Z-1**	(n,2nt) 154	(n,nt; 3np) 33, 42	(n,t; nd; 2np) 105, 32, 41	(n,d; np) 104, 28	(n,p); β^+ 103	
Cr	**Z-2**	(n,2na) 24	(n,n'a) 22	(n,a; nh; pt) 107, 34, 116	(n,h; n2p; pd) 106, 44, 115	(n,2p) 111	
V	**Z-3**	(n,2npa) 159	(n,da; npa) 117, 45	(n,pa) 112		(n,3p) 197	
Ti	**Z-4**	(n,2a) 108					
		N-3	**N-2**	**N-1**	**N**	**N+1**	**N+2**
		53	**54**	**55**	**56**	**57**	**58**

target Fe^{56}

n in ➔ Z always decrease
p, d, a in ➔ Z may increase
The emitted particles may differ, not the residual
The residual product may be another element

Tungsten transmutation with FISPACT-II

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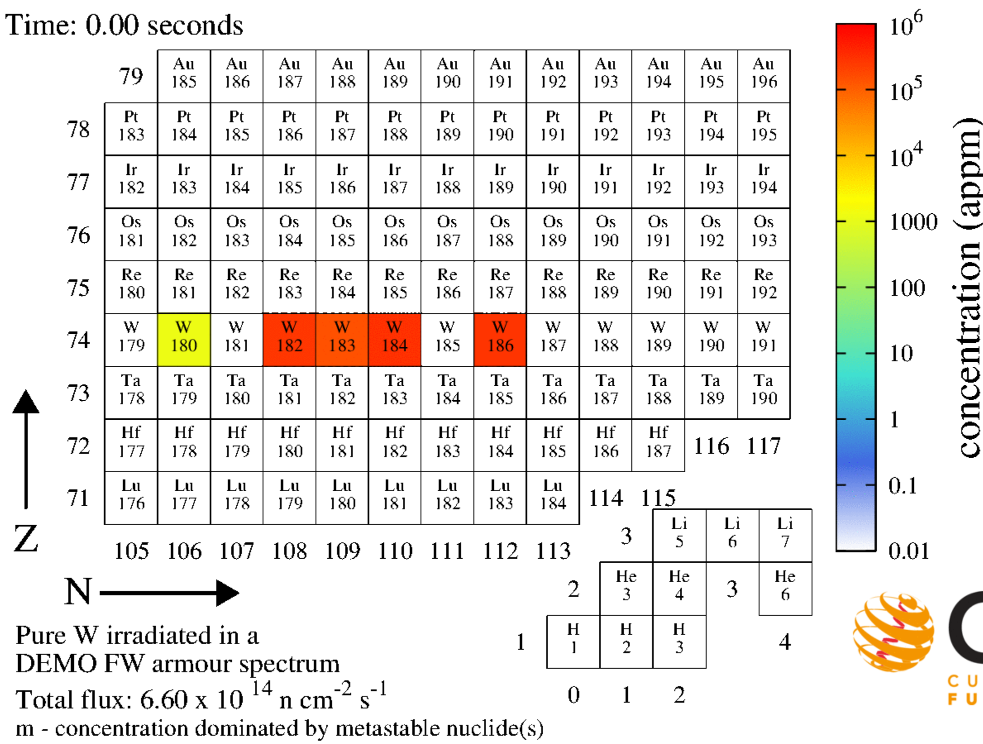

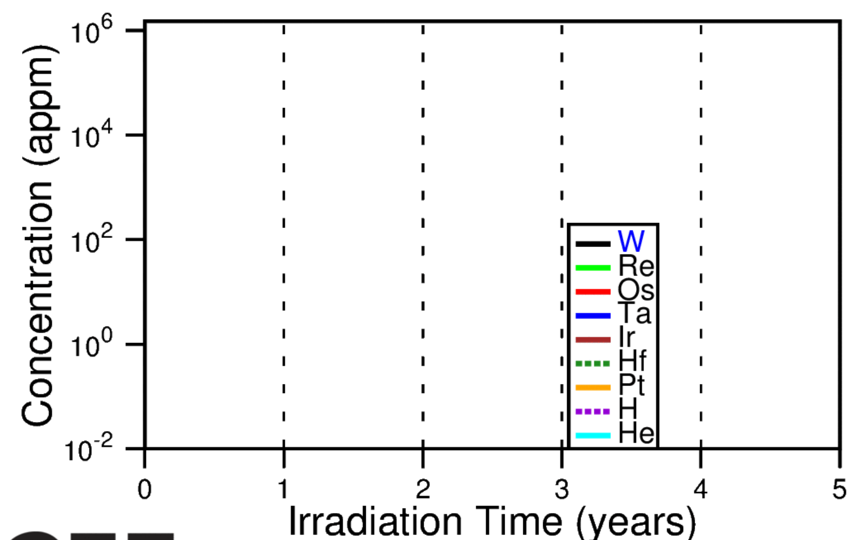

CCFE
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M. R. Gilbert et al., *Nucl. Sci. Eng* (2013)
M.R. Gilbert et al., *Nucl. Fusion* **51** (2011) 043005 & **52** (2012) 083019

Tungsten transmutation with FISPACT-II