Nuclear Data in a Nutshell

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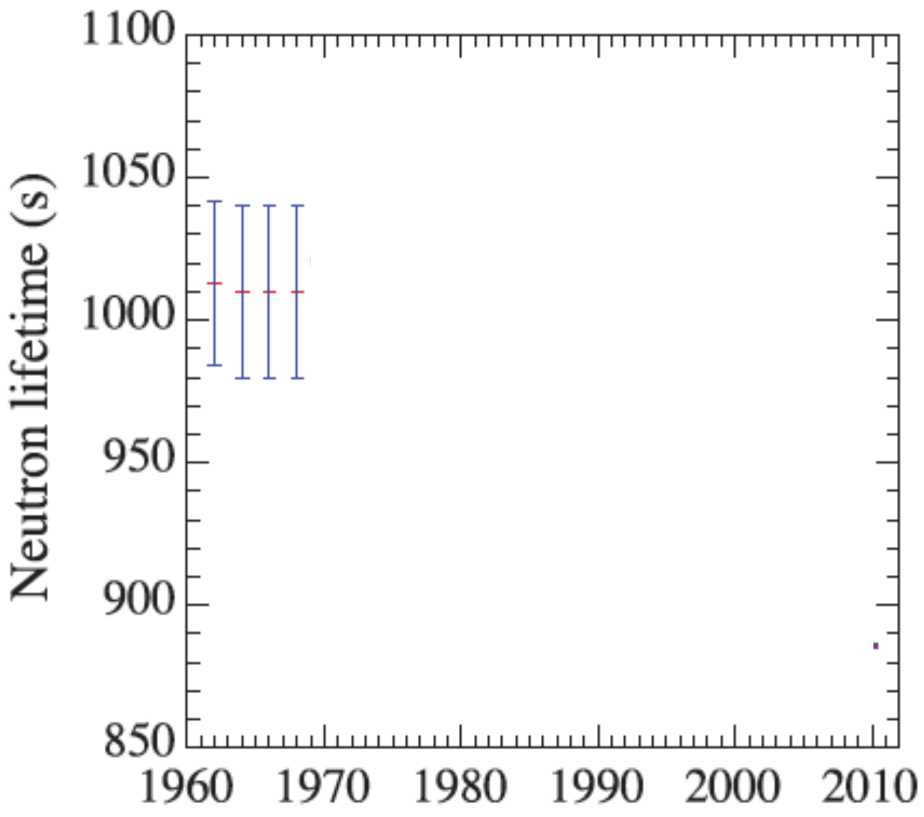
Let's start by considering "The Data Dilemma"

- If you don't have data, you get to make it up
- If you have one data set, it must be correct
- If you have two data sets, they are both wrong
  - *And everyone is just going to pick their favorite*
- When you have many data sets, you get to make it up again



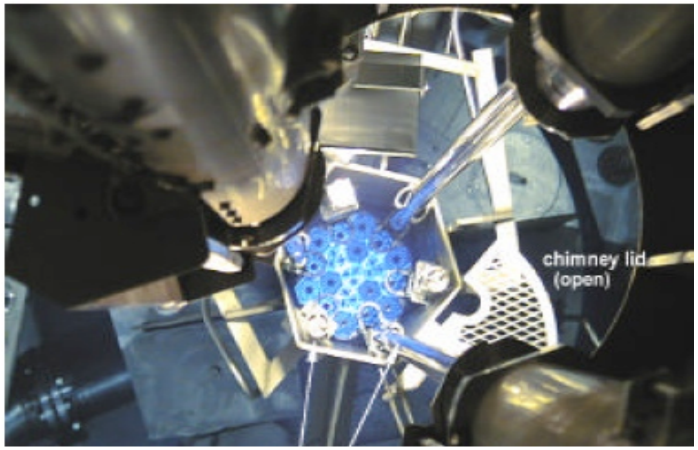
It's not enough to make the most accurate measurement since it will be viewed within the historical context

Thanks to Morgan White (LANL)

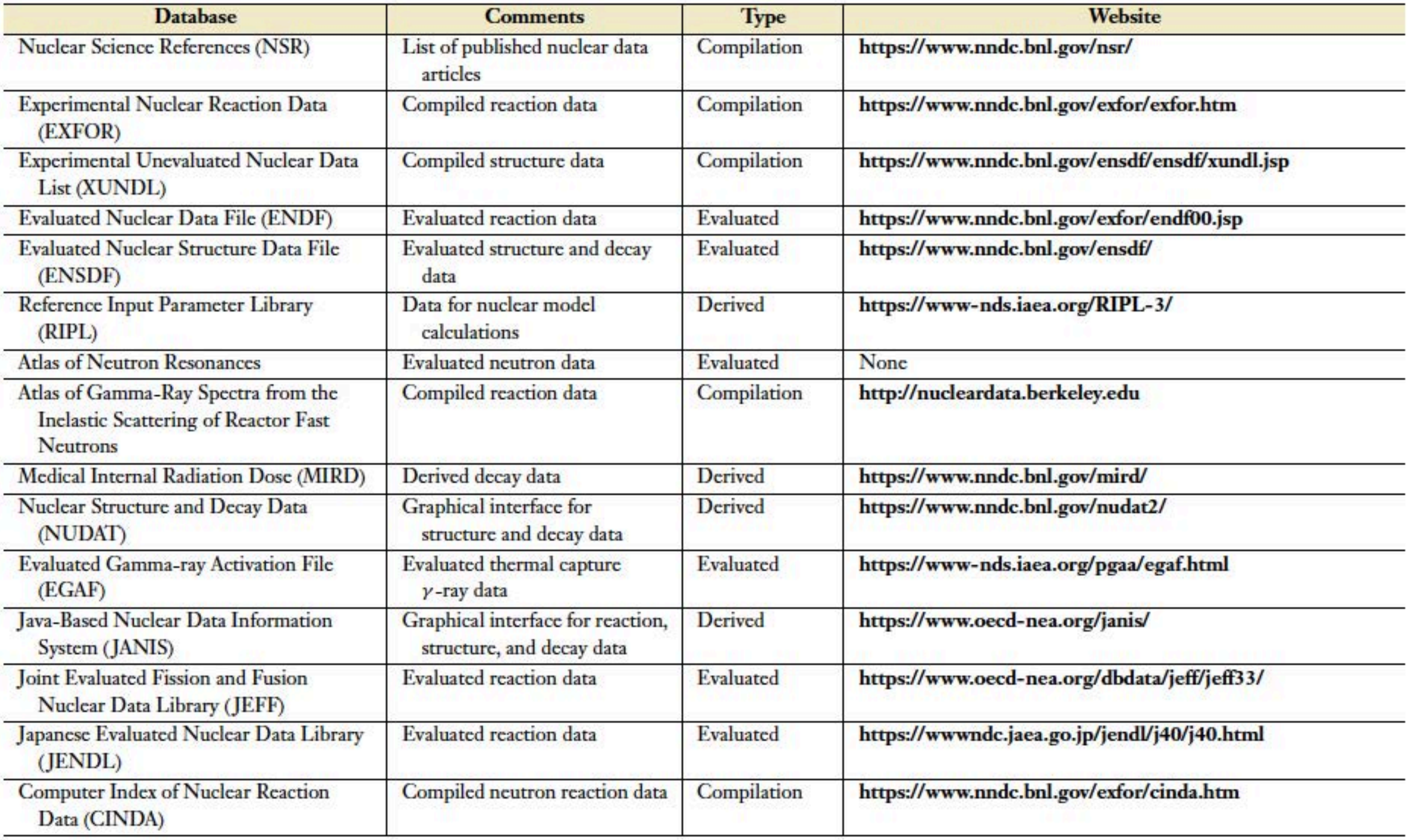
What happens when you ignore hidden compensating errors in nuclear data: The Maple reactor story

- The Maple reactors were dedicated medical isotope production reactors fueled with LEU using HEU targets
- AECL discovered that the reactor had a positive power coefficient of reactivity in June 2003.
- This behavior was deemed by the Canadian Nuclear Safety Commission to be a safety issue.
- AECL engaged the services of organizations such as BNL, INL, and INVAP, from 2005 to 2008 to identify the cause of the discrepancy.
- The cause was never determined and in May 2008,
- AECL discontinued the project.
- Following this decision, AECL was served with a *$1.6 billion lawsuit against for breach of contract*.

You run the risk of making bad decisions if you don't have trustworthy data



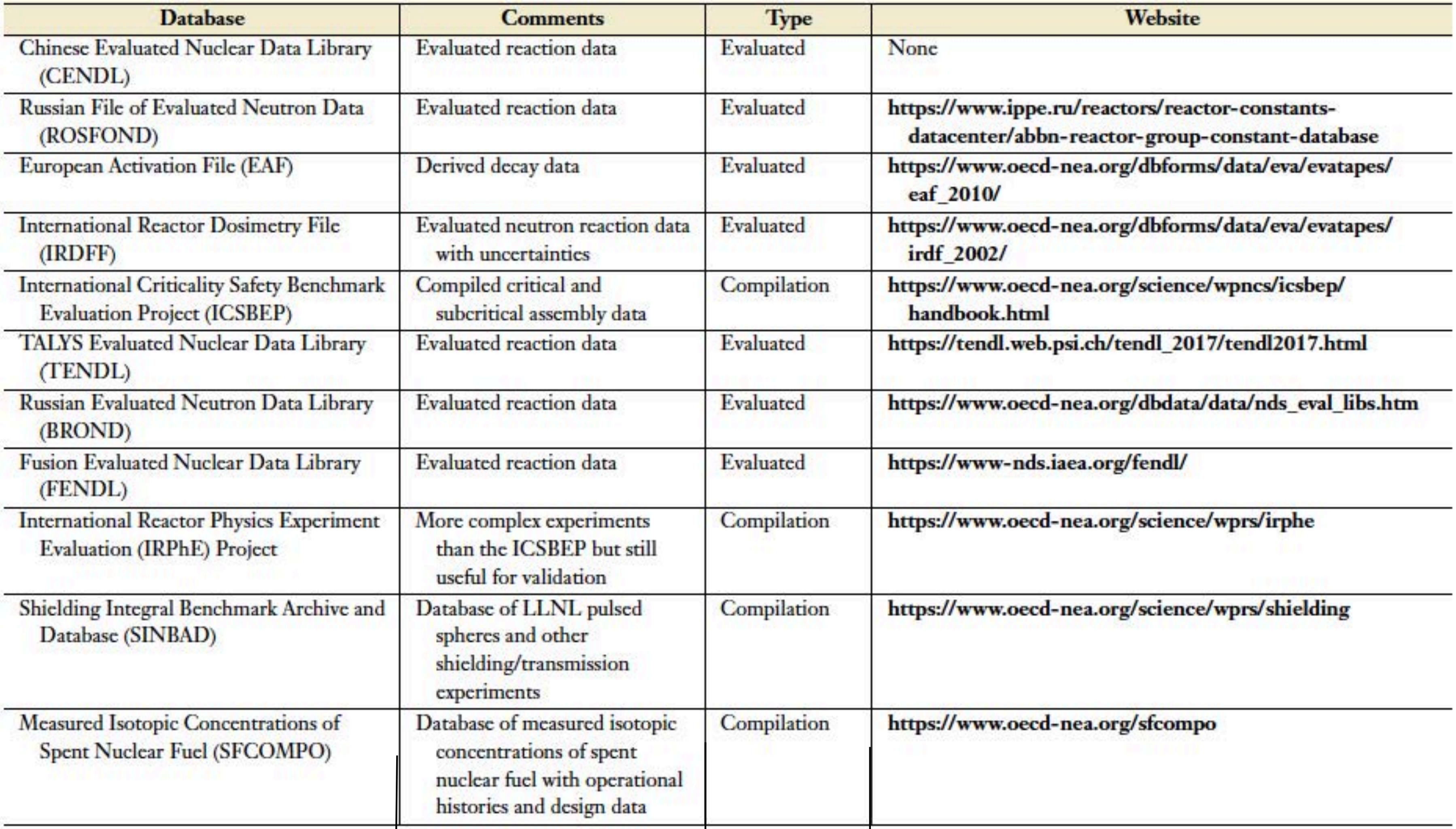
There are a VERY large body of complementary and/or competing nuclear databases*



Database	Comments	Type	Website
Nuclear Science References (NSR)	List of published nuclear data articles	Compilation	**https://www.nndc.bnl.gov/nsr/**
Experimental Nuclear Reaction Data (EXFOR)	Compiled reaction data	Compilation	**https://www.nndc.bnl.gov/exfor/exfor.htm**
Experimental Unevaluated Nuclear Data List (XUNDL)	Compiled structure data	Compilation	**https://www.nndc.bnl.gov/ensdf/ensdf/xundl.jsp**
Evaluated Nuclear Data File (ENDF)	Evaluated reaction data	Evaluated	**https://www.nndc.bnl.gov/exfor/endf00.jsp**
Evaluated Nuclear Structure Data File (ENSDF)	Evaluated structure and decay data	Evaluated	**https://www.nndc.bnl.gov/ensdf/**
Reference Input Parameter Library (RIPL)	Data for nuclear model calculations	Derived	**https://www-nds.iaea.org/RIPL-3/**
Atlas of Neutron Resonances	Evaluated neutron data	Evaluated	None
Atlas of Gamma-Ray Spectra from the Inelastic Scattering of Reactor Fast Neutrons	Compiled reaction data	Compilation	**http://nucleardata.berkeley.edu**
Medical Internal Radiation Dose (MIRD)	Derived decay data	Derived	**https://www.nndc.bnl.gov/mird/**
Nuclear Structure and Decay Data (NUDAT)	Graphical interface for structure and decay data	Derived	**https://www.nndc.bnl.gov/nudat2/**
Evaluated Gamma-ray Activation File (EGAF)	Evaluated thermal capture γ-ray data	Evaluated	**https://www-nds.iaea.org/pgaa/egaf.html**
Java-Based Nuclear Data Information System (JANIS)	Graphical interface for reaction, structure, and decay data	Derived	**https://www.oecd-nea.org/janis/**
Joint Evaluated Fission and Fusion Nuclear Data Library (JEFF)	Evaluated reaction data	Evaluated	**https://www.oecd-nea.org/dbdata/jeff/jeff33/**
Japanese Evaluated Nuclear Data Library (JENDL)	Evaluated reaction data	Evaluated	**https://wwwndc.jaea.go.jp/jendl/j40/j40.html**
Computer Index of Nuclear Reaction Data (CINDA)	Compiled neutron reaction data	Compilation	**https://www.nndc.bnl.gov/exfor/cinda.htm**

*L.A.B. *et al.*, Annu. Rev. Nucl. Part. Sci. 2019.69:109-136.

There are a VERY large body of complementary and/or competing nuclear databases (continued)*



Database	Comments	Type	Website
Chinese Evaluated Nuclear Data Library (CENDL)	Evaluated reaction data	Evaluated	None
Russian File of Evaluated Neutron Data (ROSFOND)	Evaluated reaction data	Evaluated	**https://www.ippe.ru/reactors/reactor-constants-datacenter/abbn-reactor-group-constant-database**
European Activation File (EAF)	Derived decay data	Evaluated	**https://www.oecd-nea.org/dbforms/data/eva/evatapes/eaf_2010/**
International Reactor Dosimetry File (IRDFF)	Evaluated neutron reaction data with uncertainties	Evaluated	**https://www.oecd-nea.org/dbforms/data/eva/evatapes/irdf_2002/**
International Criticality Safety Benchmark Evaluation Project (ICSBEP)	Compiled critical and subcritical assembly data	Compilation	**https://www.oecd-nea.org/science/wpncs/icsbep/handbook.html**
TALYS Evaluated Nuclear Data Library (TENDL)	Evaluated reaction data	Evaluated	**https://tendl.web.psi.ch/tendl_2017/tendl2017.html**
Russian Evaluated Neutron Data Library (BROND)	Evaluated reaction data	Evaluated	**https://www.oecd-nea.org/dbdata/data/nds_eval_libs.htm**
Fusion Evaluated Nuclear Data Library (FENDL)	Evaluated reaction data	Evaluated	**https://www-nds.iaea.org/fendl/**
International Reactor Physics Experiment Evaluation (IRPhE) Project	More complex experiments than the ICSBEP but still useful for validation	Compilation	**https://www.oecd-nea.org/science/wprs/irphe**
Shielding Integral Benchmark Archive and Database (SINBAD)	Database of LLNL pulsed spheres and other shielding/transmission experiments	Compilation	**https://www.oecd-nea.org/science/wprs/shielding**
Measured Isotopic Concentrations of Spent Nuclear Fuel (SFCOMPO)	Database of measured isotopic concentrations of spent nuclear fuel with operational histories and design data	Compilation	**https://www.oecd-nea.org/sfcompo**
Atomic Mass Evaluation and NUBASE2016	Atomic masses and decay properties	Evaluation	**http://amdc.impcas.ac.cn/web/masseval.html** **http://amdc.impcas.ac.cn/web/nubase_en.html**

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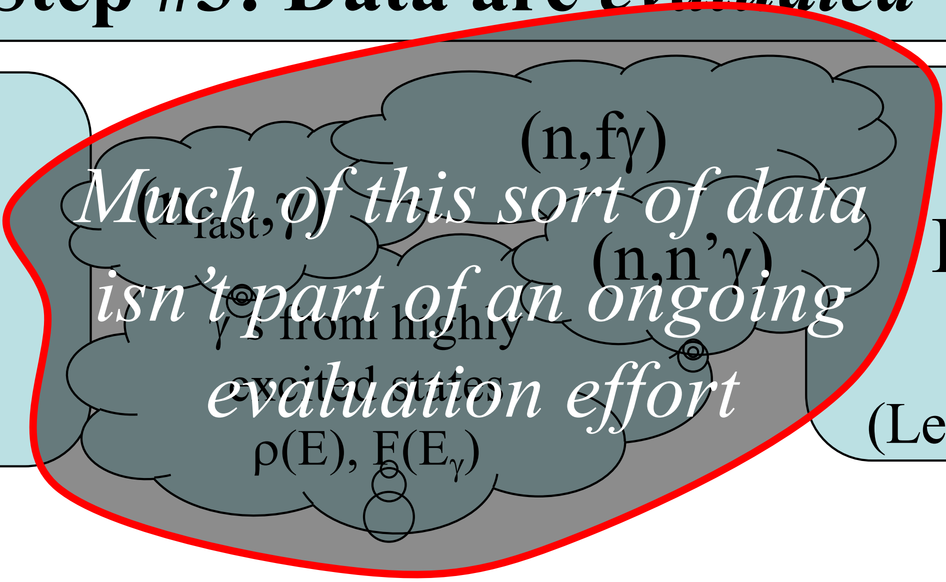
The Nuclear Data Pipeline in a Nutshell

Step #1: Measurements published

Step #2: Results are *compiled*

Step #3: Data are *evaluated*

ENDF
Reactions
(mostly cross sections)

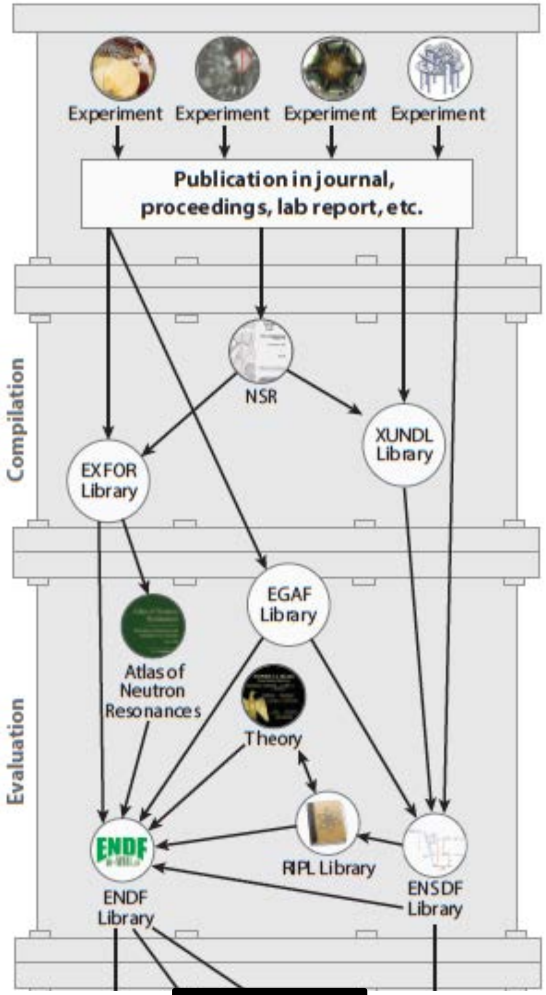


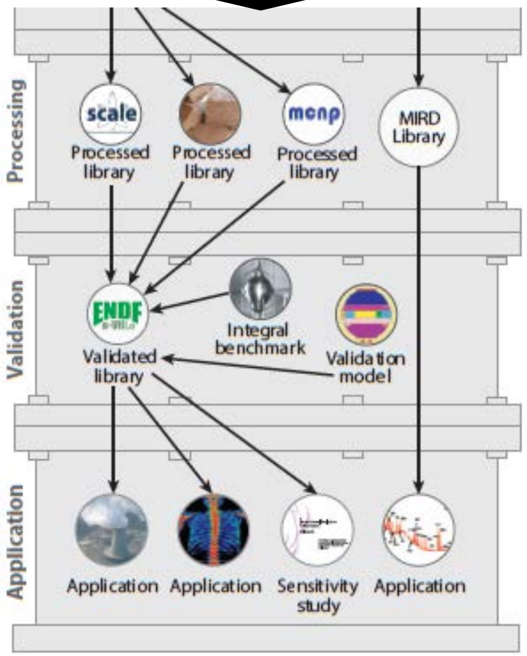
Much of this sort of data isn't part of an ongoing evaluation effort

ENSDF
Low-lying Structure
(Levels, gammas…)

A lot connections exist, but many aren't obvious to the casual user

The Nuclear Data "Pipeline" in most of its gory detail…





There's even more detail, but I don't want you screaming and running in fear…

The main nuclear structure database is the Evaluated Nuclear Structure Data File (ENSDF)

- Data from select peer-reviewed journals are compiled into the XUNDL (Unevaluated Nuclear Data List) database.
    - For many journals this is now done as a part of the review process
- The data from XUNDL are reviewed by expert evaluators on nuclide-by-nuclide basis or as part of an A-chain.
    - Data from decay and reactions *etc.* are combined to produce a list of recommended values called the *Adopted Levels and Gammas* file.
    - Vast majority of data is from γ-ray spectroscopy.
    - Only discrete levels are included (incomplete over $E_x \approx 0.5 - 2.0\ MeV$).
    - The ENSDF format is non-numeric with fixed length 80-character records and numerous text comments.
    - Results are published in *Nuclear Data Sheets* or *Nuclear Physics A* for nuclides with A<20.
    - The amount of data can vary dramatically from one nuclide to another.

The ^{235}U ENSDF adopted levels file

Adopted Levels, Gammas

History

Type	Author	Citation	Literature Cutoff Date
Full Evaluation	E. Browne, J. K. Tuli	NDS 122, 205 (2014)	1-Feb-2014

Q(β^-)=−124.0 *9*; S(n)=5297.5 *2*; S(p)=6709 *4*; Q(α)=4678.2 *7* 2012Wa38

Additional information 1.

Other reactions:

^{235}U(n,n′): E<20 MeV (2013He11,2005Ha23); E=0.14-15.2 MeV (2010Ha06); Others: 2009Ch24, 2009Mu14, 2004Du20.

^{235}U(n,n′γ): 2013Ke02, 2012LeZZ, 2008HuZW.

^{235}U(α,α′): 2011Bu11.

^{235}U(p,p): E= 1-200 MeV, calculated σ (2008Li05).

^{235}U(SF): 2013Ka26, 2012Fa12, 2012Ha06, 2005Re16. Measured σ using surrogate reaction (2012Hu01); calculated fission barrier and half-life (2012Ro34,2007Ro08).

^{238}U(n,4n): 2012Br11.

^{235}U(n,F) E=400 keV (2012PrZZ); E=2-8 MeV (2011Mu07); E=0.01 *30*30 MeV, calculated σ (2009Go05).

^{235}U(^{12}C,^{12}C) E=30-1000 MeV/nucleon; ^{235}U(^{20}C,^{20}C) E=30-1000 MeV/nucleon (2008Li05).

Cluster decay:

^{235}U(^{29}Mg): calculated half-life (2013Ta07).

^{235}U(^{24}Ne), ^{235}U(^{25}Ne): Calculated half-life (2013Zd01,2013Zd02).

^{235}U(^{24}Ne), ^{235}U(^{25}Ne),^{235}U(^{28}Mg): Calculated half-life (2012Ba35,2012Ku29). Others: ^{235}U(^{24}Ne), ^{235}U(^{25}Ne): 2010Ni13, 2004Ba64.

^{235}U(^{20}O), ^{235}U($^{22-26}$Ne), ^{235}U($^{28-30}$Mg) calculated Q(β^-)value, half-life (2012Sa31).

^{235}U(^{24}Mg): calculated half-life, isotope shift, Q(β^-)value (2005Bh02).

^{235}U(^{28}Mg): 2010Si12; calculated half-life (2009Ar11). Other: 2009Do16.

^{235}U(^{25}Ne), ^{235}U(^{29}Mg): calculated half-life (2011Sh13).

^{235}U(^{26}Ne), ^{235}U(^{29}Mg): 2005Ku32, 2005Ku04.

^{232}Th(^{16}O,^{13}C), ^{232}Th(^{19}F,^{16}N) (2000Si04): Measured excitation functions.

^{232}Th(α,xnF) (1997Er02): Measured fission fragments.

^{235}U(SF): calculated fission barrier and half-life (2012Ro34,2012Pa40,2011Hu06).

^{235}U isotopic abundance in natural uranium: 2012Qi02, 2011Be53, 2008We01.

Nuclear Structure: Level density parameters: 2006Fr21. Others: 2011Mu06, 2010Ni02, 2010Qu01, 2010To07, 2006Sa35. Quadrupole moment: 2005Ko18.

^{235}U Levels

Cross Reference (XREF) Flags

A	^{235}Pa β^- decay	F	^{234}U(n,γ) E=th	K	^{236}U(d,t)
B	^{235}Np ε decay	G	^{234}U(d,p)	L	^{236}U(^{3}He,α)
C	^{239}Pu α decay	H	^{235}U(n,n′)	M	Muonic atom
D	Coulomb excitation	I	^{235}U(n,n′γ)	N	^{235}U(γ,γ′)
E	^{233}U(t,p)	J	^{235}U(d,d′)		

E(level)[#]	J$^\pi$[@]	T$_{1/2}$	XREF	Comments
0.0[a]	7/2$^-$	7.04×10^8 y *1*	ABCD FGHIJK MN	%α=100; %SF=7×10^{-9} *2* %^{20}Ne=8×10^{-10} *4*; %^{25}Ne≈8×10^{-10} %^{28}Mg=8×10^{-10} μ=−0.38 *3* (1983Ni08,2011StZZ) Q=+4.936 *6* (1984Zu02,2011StZZ) μ(^{233}U)/μ(^{235}U)=− 1.5604 *14*, consistent with 5/2[633] and 7/2[743] configurations for ^{233}U and ^{235}U ground states, respectively (1990Ga28).

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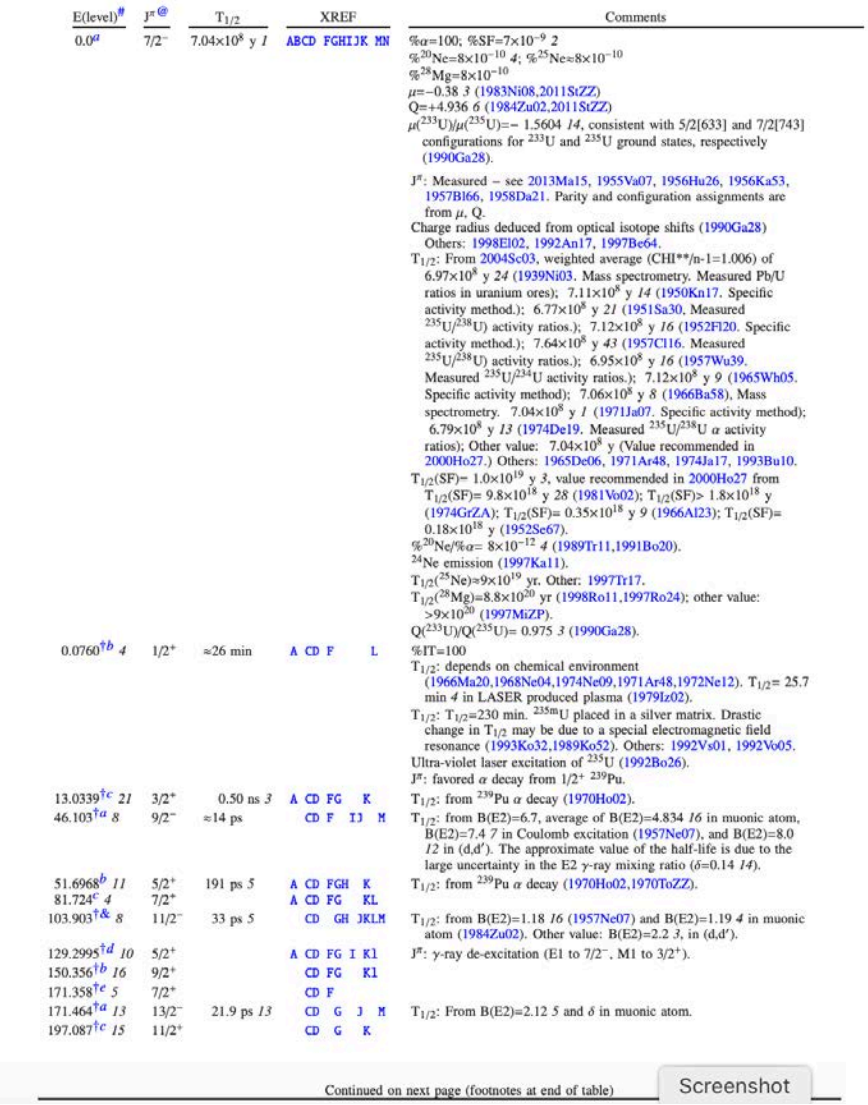
Screenshot



E(level)[#]	J$^\pi$[@]	T$_{1/2}$	XREF	Comments
0.0[a]	7/2$^-$	7.04×10^8 y *1*	ABCD FGHIJK MN	%α=100; %SF=7×10^{-9} *2* %^{20}Ne=8×10^{-10} *4*; %^{25}Ne≈8×10^{-10} %^{28}Mg=8×10^{-10} μ=−0.38 *3* (1983Ni08,2011StZZ) Q=+4.936 *6* (1984Zu02,2011StZZ) μ(^{233}U)/μ(^{235}U)=− 1.5604 *14*, consistent with 5/2[633] and 7/2[743] configurations for ^{233}U and ^{235}U ground states, respectively (1990Ga28). J$^\pi$: Measured – see 2013Ma15, 1955Va07, 1956Hu26, 1956Ka53, 1957Bl66, 1958Da21. Parity and configuration assignments are from μ, Q. Charge radius deduced from optical isotope shifts (1990Ga28) Others: 1998El02, 1992An17, 1997Be64. T$_{1/2}$: From 2004Sc03, weighted average (CHI**/n-1=1.006) of 6.97×10^8 y *24* (1939Ni03. Mass spectrometry. Measured Pb/U ratios in uranium ores); 7.11×10^8 y *14* (1950Kn17. Specific activity method.); 6.77×10^8 y *21* (1951Sa30. Measured ^{235}U/^{238}U) activity ratios.); 7.12×10^8 y *16* (1952Fl20. Specific activity method.); 7.64×10^8 y *43* (1957Cl16. Measured ^{235}U/^{238}U) activity ratios.); 6.95×10^8 y *16* (1957Wu39. Measured ^{235}U/^{234}U activity ratios.); 7.12×10^8 y *9* (1965Wh05. Specific activity method); 7.06×10^8 y *8* (1966Ba58), Mass spectrometry. 7.04×10^8 y *1* (1971Ja07. Specific activity method); 6.79×10^8 y *13* (1974De19. Measured ^{235}U/^{238}U α activity ratios); Other value: 7.04×10^8 y (Value recommended in 2000Ho27.) Others: 1965De06, 1971Ar48, 1974Ja17, 1993Bu10. T$_{1/2}$(SF)= 1.0×10^{19} y *3*, value recommended in 2000Ho27 from T$_{1/2}$(SF)= 9.8×10^{18} y *28* (1981Vo02); T$_{1/2}$(SF)> 1.8×10^{18} y (1974GrZA); T$_{1/2}$(SF)= 0.35×10^{18} y *9* (1966Al23); T$_{1/2}$(SF)= 0.18×10^{18} y (1952Se67). %^{20}Ne/%α= 8×10^{-12} *4* (1989Tr11,1991Bo20). ^{24}Ne emission (1997Ka11). T$_{1/2}$(^{25}Ne)≈9×10^{19} yr. Other: 1997Tr17. T$_{1/2}$(^{28}Mg)=8.8×10^{20} yr (1998Ro11,1997Ro24); other value: >9×10^{20} (1997MiZP). Q(^{233}U)/Q(^{235}U)= 0.975 *3* (1990Ga28).
0.0760[†b] *4*	1/2$^+$	≈26 min	A CD F L	%IT=100 T$_{1/2}$: depends on chemical environment (1966Ma20,1968Ne04,1974Ne09,1971Ar48,1972Ne12). T$_{1/2}$= 25.7 min *4* in LASER produced plasma (1979Iz02). T$_{1/2}$: T$_{1/2}$=230 min. ^{235m}U placed in a silver matrix. Drastic change in T$_{1/2}$ may be due to a special electromagnetic field resonance (1993Ko32,1989Ko52). Others: 1992Vs01, 1992Vo05. Ultra-violet laser excitation of ^{235}U (1992Bo26). J$^\pi$: favored α decay from 1/2$^+$ ^{239}Pu.
13.0339[†c] *21*	3/2$^+$	0.50 ns *3*	A CD FG K	T$_{1/2}$: from ^{239}Pu α decay (1970Ho02).
46.103[†a] *8*	9/2$^-$	≈14 ps	CD F IJ M	T$_{1/2}$: from B(E2)=6.7, average of B(E2)=4.834 *16* in muonic atom, B(E2)=7.4 *7* in Coulomb excitation (1957Ne07), and B(E2)=8.0 *12* in (d,d′). The approximate value of the half-life is due to the large uncertainty in the E2 γ-ray mixing ratio (δ=0.14 *14*).
51.6968[b] *11*	5/2$^+$	191 ps *5*	A CD FGH K	T$_{1/2}$: from ^{239}Pu α decay (1970Ho02,1970ToZZ).
81.724[c] *4*	7/2$^+$		A CD FG KL	
103.903[†&] *8*	11/2$^-$	33 ps *5*	CD GH JKLM	T$_{1/2}$: from B(E2)=1.18 *16* (1957Ne07) and B(E2)=1.19 *4* in muonic atom (1984Zu02). Other value: B(E2)=2.2 *3*, in (d,d′).
129.2995[†d] *10*	5/2$^+$		A CD FG I Kl	J$^\pi$: γ-ray de-excitation (E1 to 7/2$^-$, M1 to 3/2$^+$).
150.356[†b] *16*	9/2$^+$		CD FG Kl	
171.358[†e] *5*	7/2$^+$		CD F	
171.464[†a] *13*	13/2$^-$	21.9 ps *13*	CD G J M	T$_{1/2}$: From B(E2)=2.12 *5* and δ in muonic atom.
197.087[†c] *15*	11/2$^+$		CD G K	

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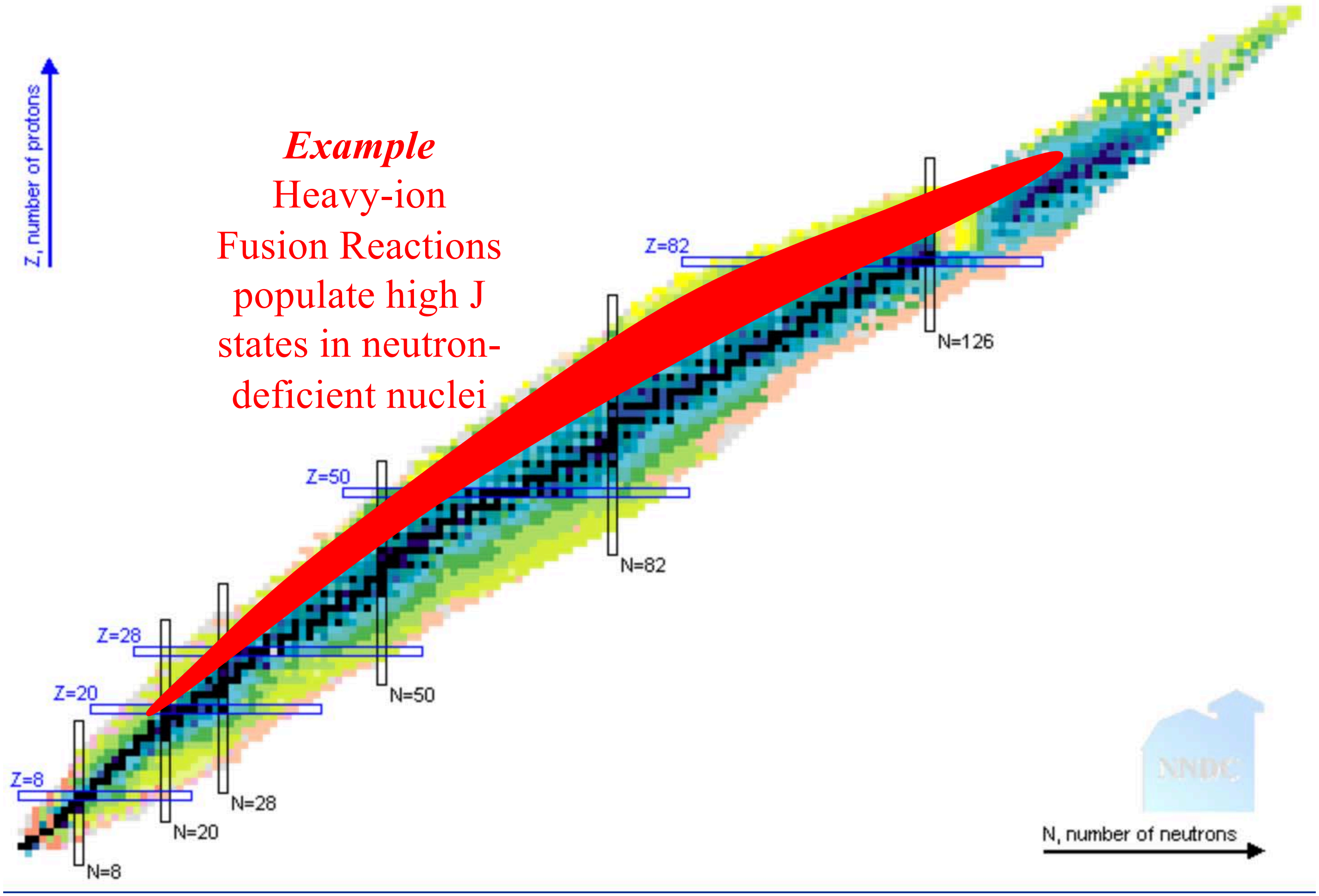
Screenshot

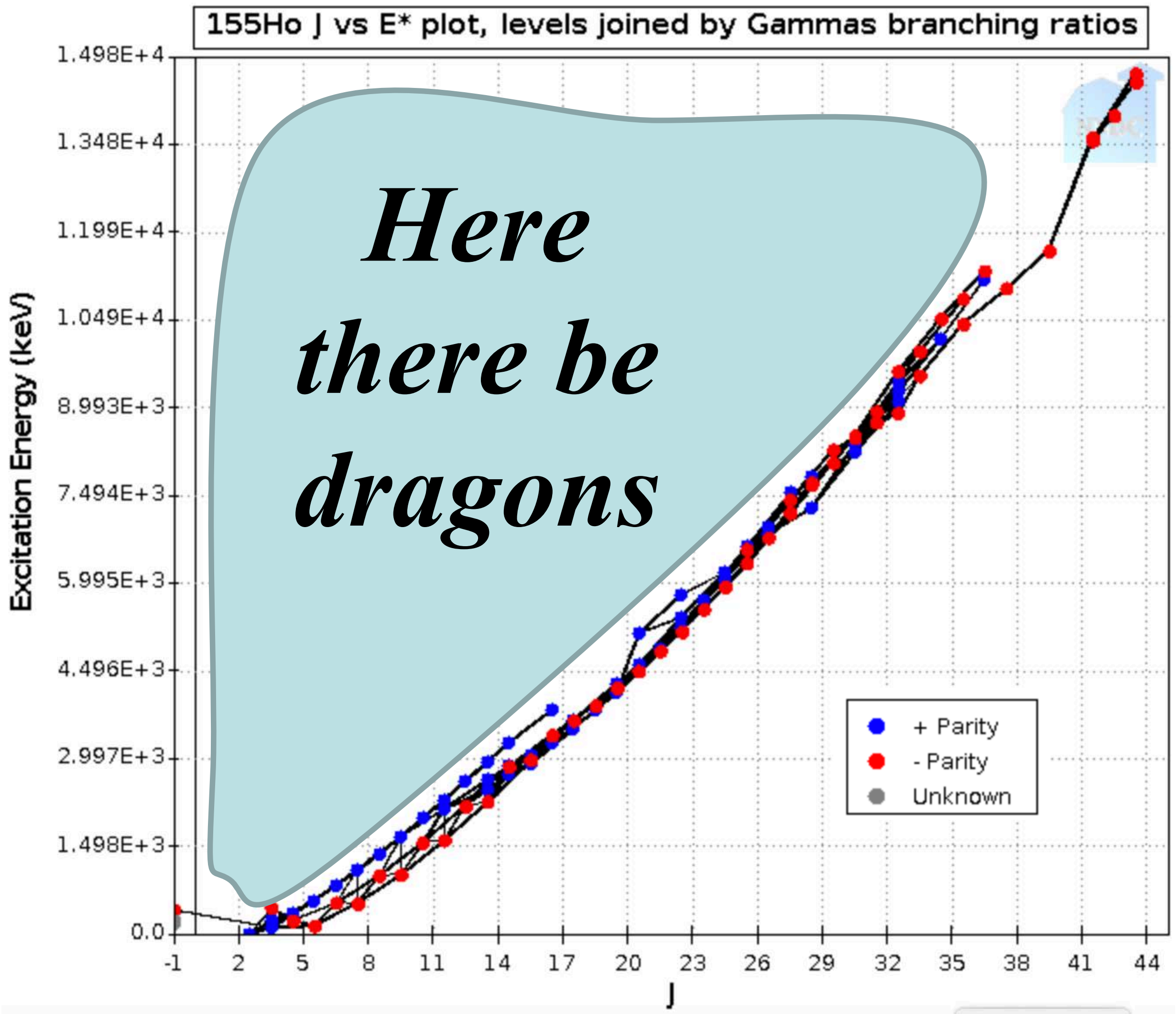
Nuclear structure data isn’t evenly spread out over the chart of nuclides



Example

Heavy-ion
Fusion Reactions
populate high J
states in neutron-deficient nuclei

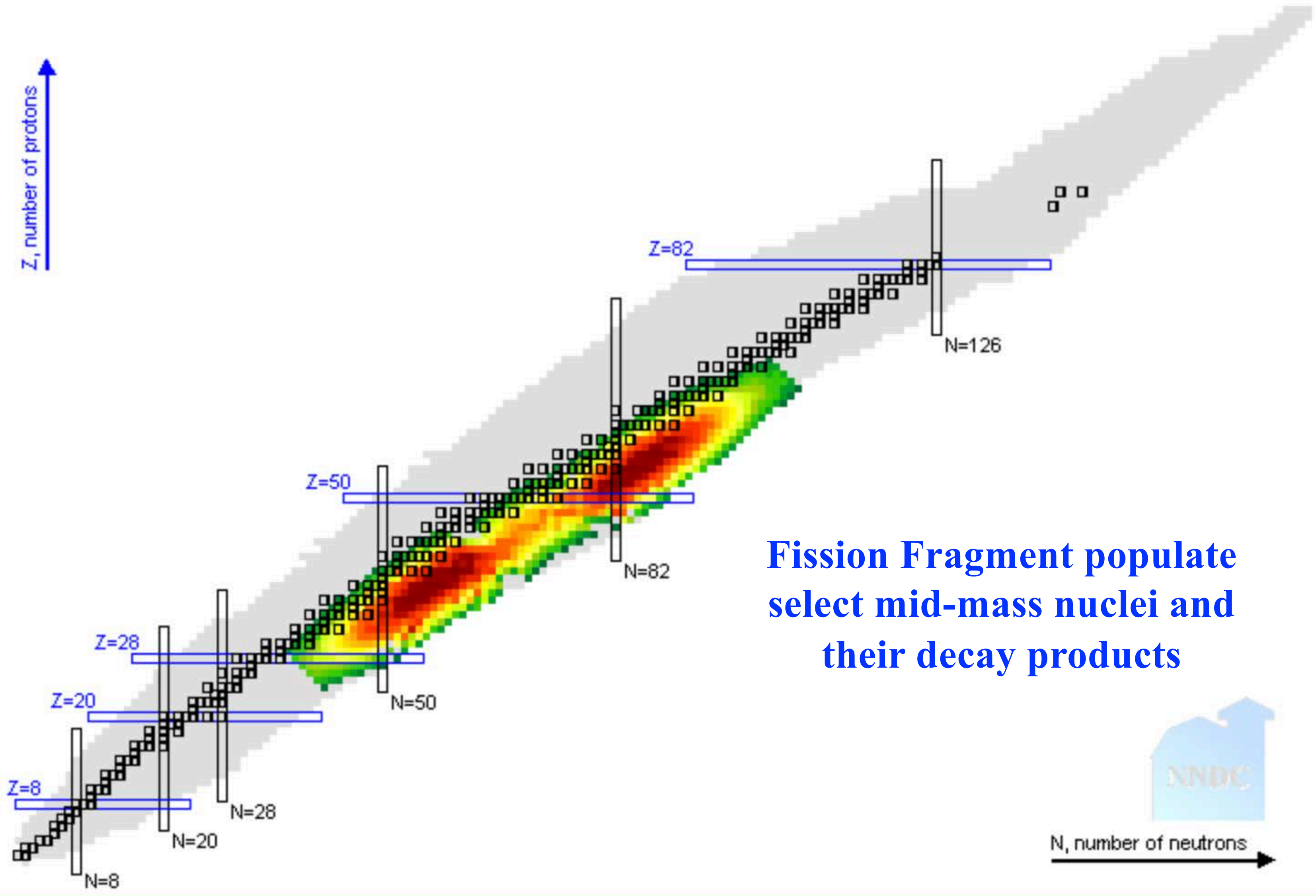
And heavy-ion fusion reactions only populate states near the yrast lines (maximum *J* per unit *E*)



Here there be dragons

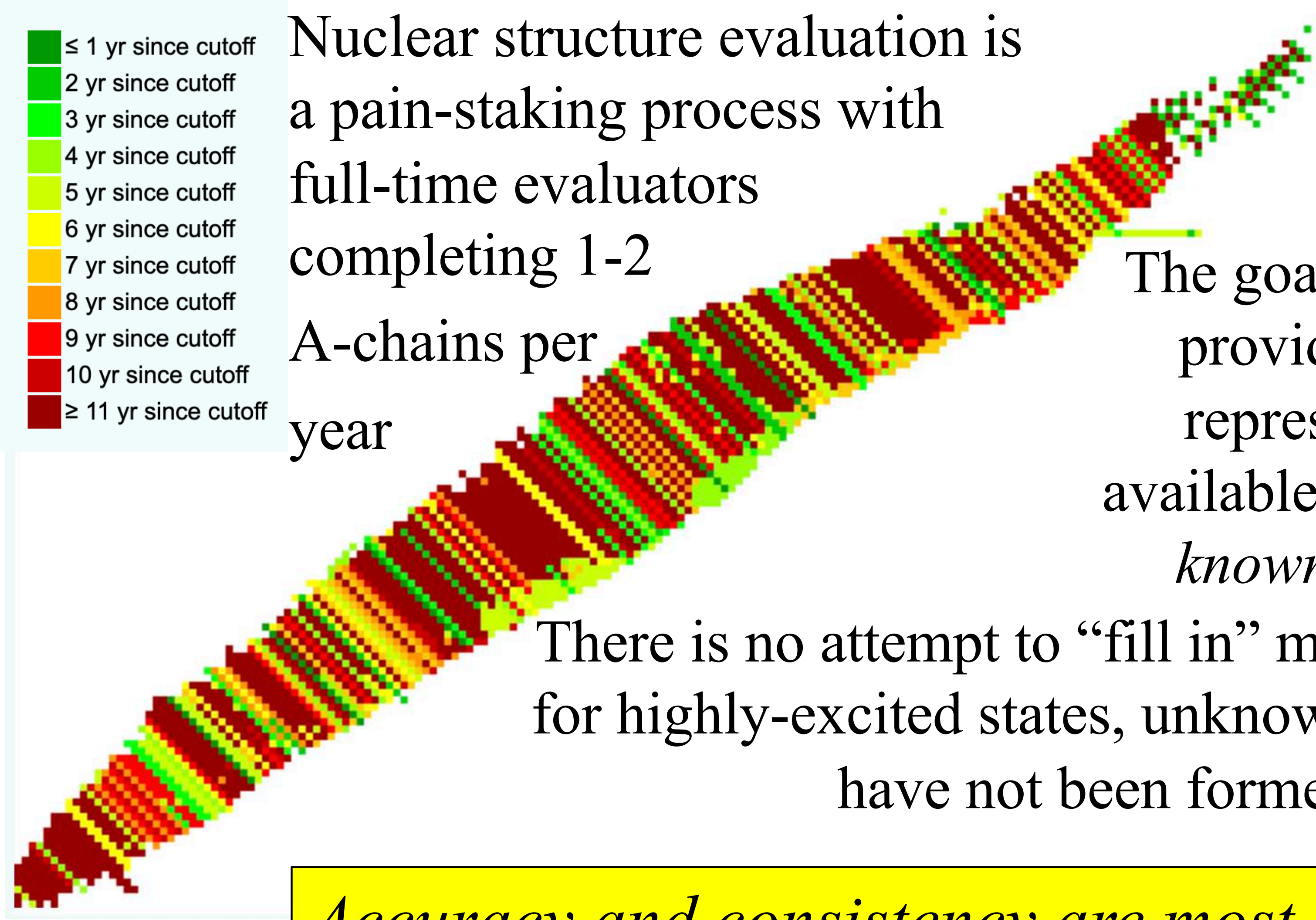
This is means that we are missing LOTS of information about off-yrast levels

Another source of information is the decay of fission fragments



Fission Fragment populate select mid-mass nuclei and their decay products

The ENSDF philosophy



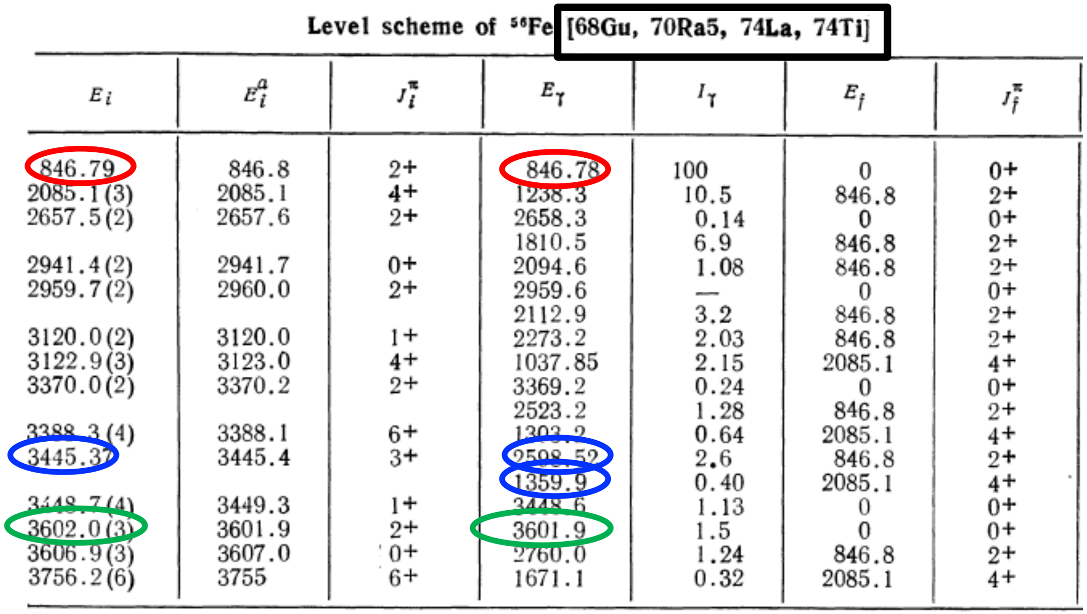
Nuclear structure evaluation is a pain-staking process with full-time evaluators completing 1-2 A-chains per year

The goal of ENSDF is to provide an objective representation of all available knowledge about *known* nuclear states

There is no attempt to "fill in" missing information for highly-excited states, unknown J^{π}, nuclei which have not been formed etc.

Accuracy and consistency are most important

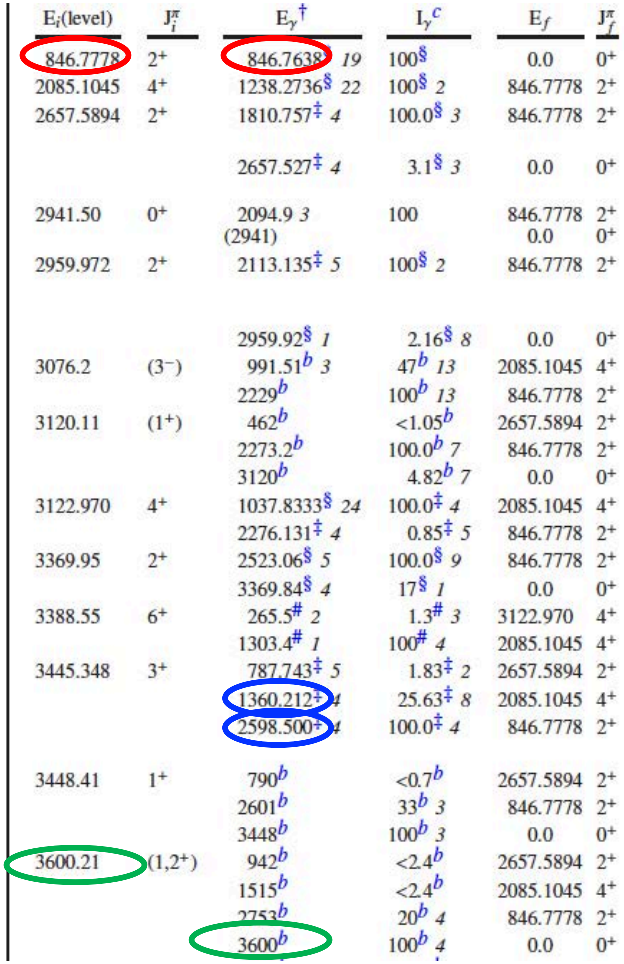
ENSDF evolves *slowly* on nuclei near stability – Example: ^{56}Fe circa 1974 vs 2009



Level scheme of ^{56}Fe [68Gu, 70Ra5, 74La, 74Ti]

E_i	E_i^a	J_i^π	E_γ	I_γ	E_f	J_f^π
846.79	846.8	2+	846.78	100	0	0+
2085.1(3)	2085.1	4+	1238.3	10.5	846.8	2+
2657.5(2)	2657.6	2+	2658.3	0.14	0	0+
			1810.5	6.9	846.8	2+
2941.4(2)	2941.7	0+	2094.6	1.08	846.8	2+
2959.7(2)	2960.0	2+	2959.6	—	0	0+
			2112.9	3.2	846.8	2+
3120.0(2)	3120.0	1+	2273.2	2.03	846.8	2+
3122.9(3)	3123.0	4+	1037.85	2.15	2085.1	4+
3370.0(2)	3370.2	2+	3369.2	0.24	0	0+
			2523.2	1.28	846.8	2+
3388.3(4)	3388.1	6+	1303.2	0.64	2085.1	4+
3445.37	3445.4	3+	2598.52	2.6	846.8	2+
			1359.9	0.40	2085.1	4+
3448.7(4)	3449.3	1+	3448.6	1.13	0	0+
3602.0(3)	3601.9	2+	3601.9	1.5	0	0+
3606.9(3)	3607.0	0+	2760.0	1.24	846.8	2+
3756.2(6)	3755	6+	1671.1	0.32	2085.1	4+

ENSDF 2009



E_i(level)	J_i^π	$E_\gamma^{\dagger}$	I_γ^{c}	E_f	J_f^π
846.7778	2^+	846.7638§ *19*	100§	0.0	0^+
2085.1045	4^+	1238.2736§ *22*	100§ *2*	846.7778	2^+
2657.5894	2^+	1810.757‡ *4*	100.0§ *3*	846.7778	2^+
		2657.527‡ *4*	3.1§ *3*	0.0	0^+
2941.50	0^+	2094.9 *3*	100	846.7778	2^+
		(2941)		0.0	0^+
2959.972	2^+	2113.135‡ *5*	100§ *2*	846.7778	2^+
		2959.92§ *1*	2.16§ *8*	0.0	0^+
3076.2	(3^-)	991.51^{b} *3*	47^{b} *13*	2085.1045	4^+
		2229^{b}	100^{b} *13*	846.7778	2^+
3120.11	(1^+)	462^{b}	<1.05^{b}	2657.5894	2^+
		2273.2^{b}	100.0^{b} *7*	846.7778	2^+
		3120^{b}	4.82^{b} *7*	0.0	0^+
3122.970	4^+	1037.8333§ *24*	100.0‡ *4*	2085.1045	4^+
		2276.131‡ *4*	0.85‡ *5*	846.7778	2^+
3369.95	2^+	2523.06§ *5*	100.0§ *9*	846.7778	2^+
		3369.84§ *4*	17§ *1*	0.0	0^+
3388.55	6^+	265.5$^{\#}$ *2*	1.3$^{\#}$ *3*	3122.970	4^+
		1303.4$^{\#}$ *1*	100$^{\#}$ *4*	2085.1045	4^+
3445.348	3^+	787.743‡ *5*	1.83‡ *2*	2657.5894	2^+
		1360.212‡ *4*	25.63‡ *8*	2085.1045	4^+
		2598.500‡ *4*	100.0‡ *4*	846.7778	2^+
3448.41	1^+	790^{b}	<0.7^{b}	2657.5894	2^+
		2601^{b}	33^{b} *3*	846.7778	2^+
		3448^{b}	100^{b} *3*	0.0	0^+
3600.21	$(1,2^+)$	942^{b}	<2.4^{b}	2657.5894	2^+
		1515^{b}	<2.4^{b}	2085.1045	4^+
		2753^{b}	20^{b} *4*	846.7778	2^+
		3600^{b}	100^{b} *4*	0.0	0^+

E_γ changed by < 0.1%

But…

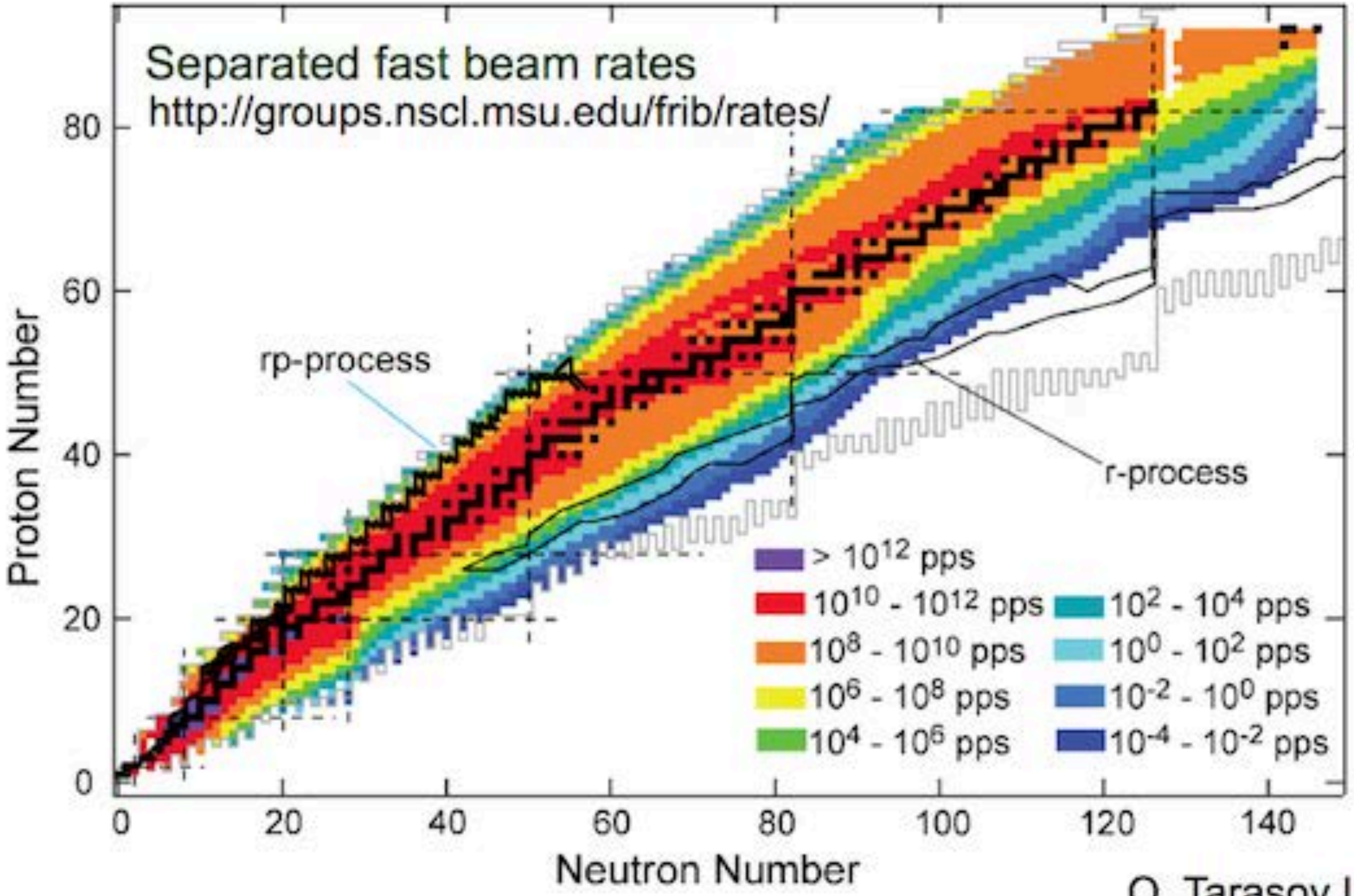
E_i < 3756 keV

- c 1970 – 18 γ-rays
- 2009 – 28 γ-rays

E_i < 4539 keV

- c 1970 – 36 γ-rays
- 2009 – 96 γ-rays

Radioactive ion beam facilities offer the possibility of learning about nuclei far from the valley of stability



O. Tarasov LISE++

Now, let's focus on the approach used on the reaction evaluation process

Let's say you want to design a reactor

1. First you put together a computer simulation
2. The simulation calls on nuclear data libraries to determine the right cross sections to use

But no one has measured one of the scattering cross sections as a function of angle, so…

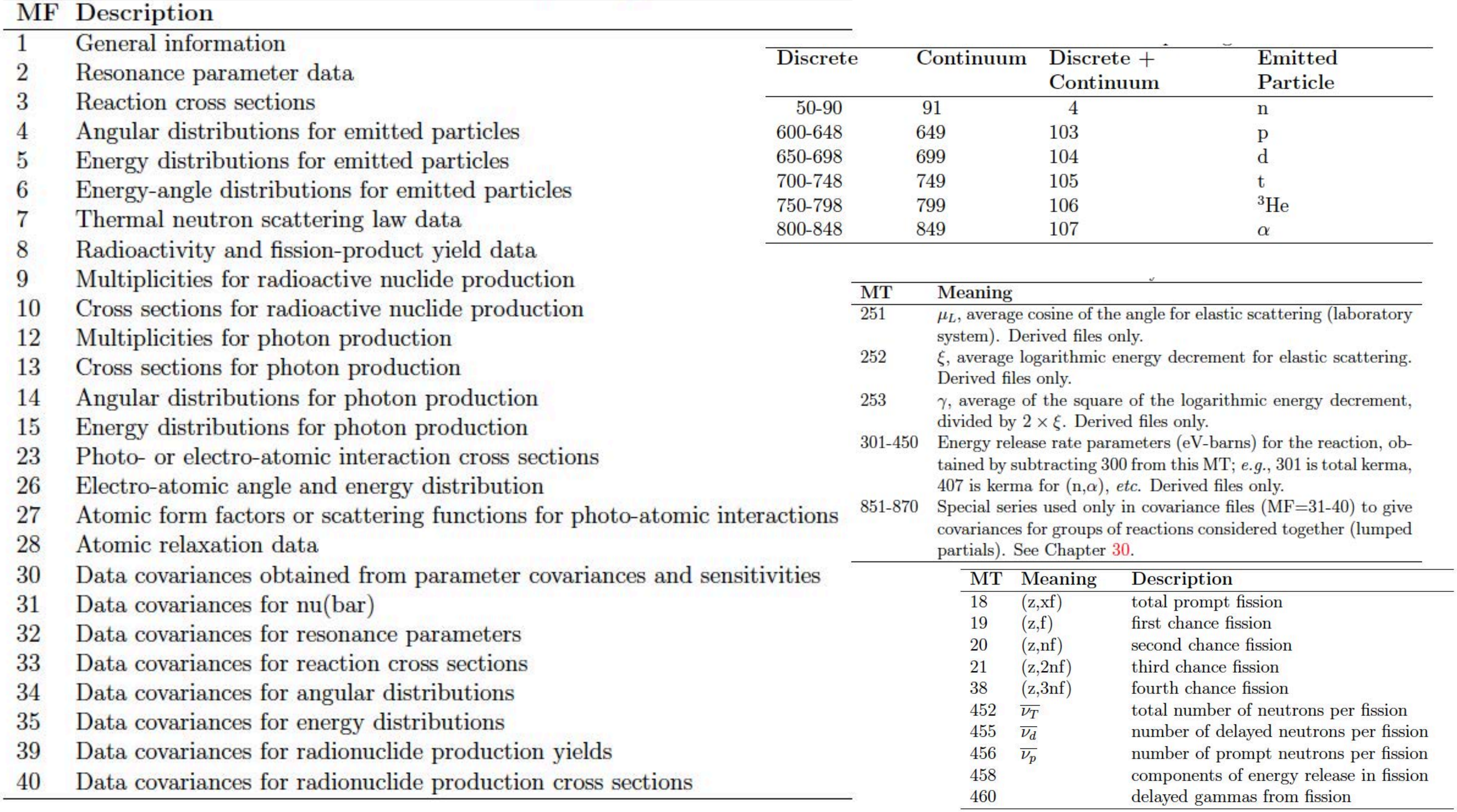
No reactor ☹

Of course we can't let that happen!!!

We need to fill in any gaps in reaction data with the best information possible - This is the ENDF approach

Completeness is most important

The Evaluated Nuclear Data File (ENDF) contains "pre-digested" reaction data for use in applications



MF	Description
1	General information
2	Resonance parameter data
3	Reaction cross sections
4	Angular distributions for emitted particles
5	Energy distributions for emitted particles
6	Energy-angle distributions for emitted particles
7	Thermal neutron scattering law data
8	Radioactivity and fission-product yield data
9	Multiplicities for radioactive nuclide production
10	Cross sections for radioactive nuclide production
12	Multiplicities for photon production
13	Cross sections for photon production
14	Angular distributions for photon production
15	Energy distributions for photon production
23	Photo- or electro-atomic interaction cross sections
26	Electro-atomic angle and energy distribution
27	Atomic form factors or scattering functions for photo-atomic interactions
28	Atomic relaxation data
30	Data covariances obtained from parameter covariances and sensitivities
31	Data covariances for nu(bar)
32	Data covariances for resonance parameters
33	Data covariances for reaction cross sections
34	Data covariances for angular distributions
35	Data covariances for energy distributions
39	Data covariances for radionuclide production yields
40	Data covariances for radionuclide production cross sections

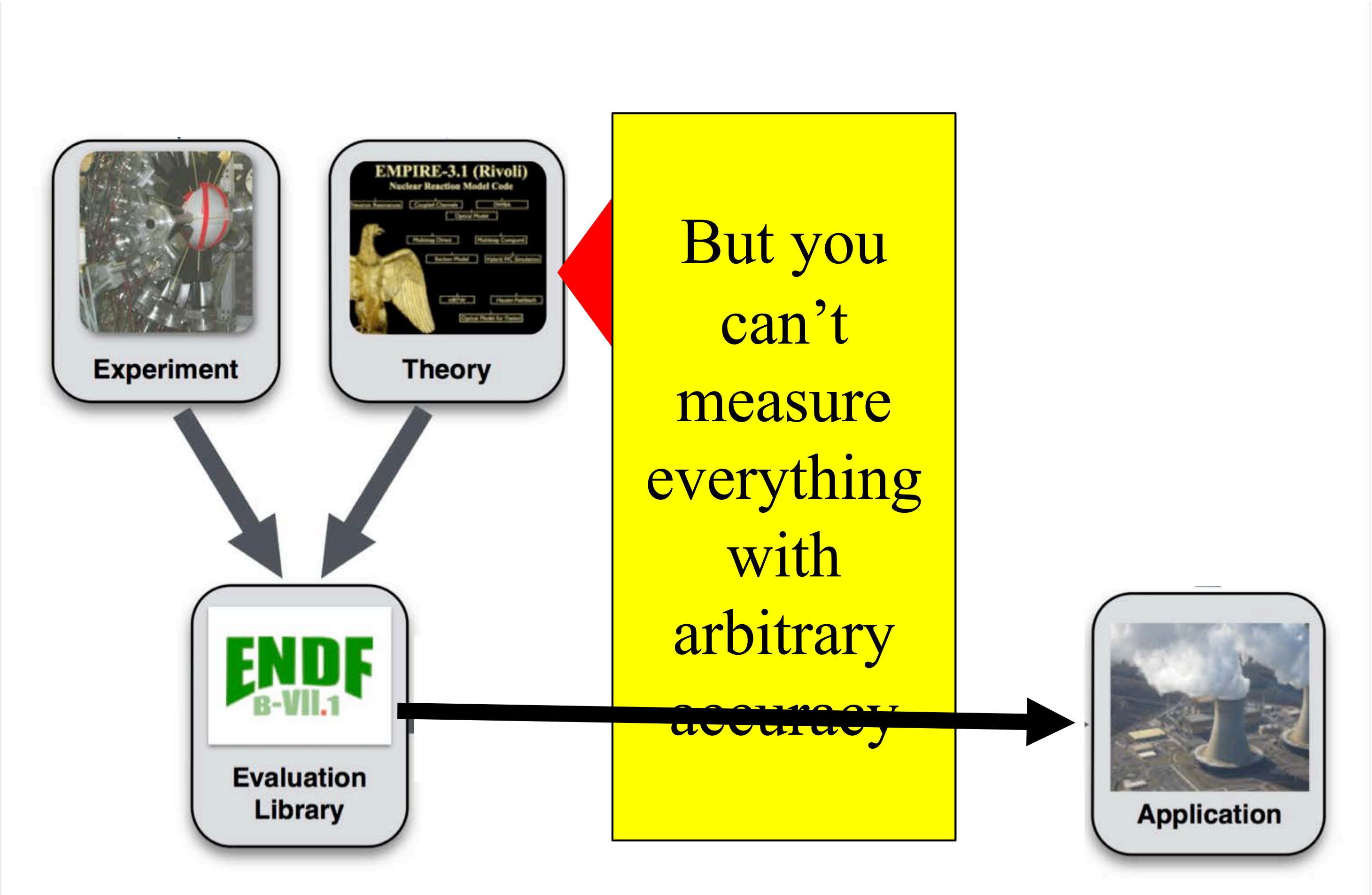
Discrete	Continuum	Discrete + Continuum	Emitted Particle
50-90	91	4	n
600-648	649	103	p
650-698	699	104	d
700-748	749	105	t
750-798	799	106	^{3}He
800-848	849	107	α

MT	Meaning
251	μ_L, average cosine of the angle for elastic scattering (laboratory system). Derived files only.
252	ξ, average logarithmic energy decrement for elastic scattering. Derived files only.
253	γ, average of the square of the logarithmic energy decrement, divided by $2 \times \xi$. Derived files only.
301-450	Energy release rate parameters (eV-barns) for the reaction, obtained by subtracting 300 from this MT; *e.g.*, 301 is total kerma, 407 is kerma for (n,α), *etc.* Derived files only.
851-870	Special series used only in covariance files (MF=31-40) to give covariances for groups of reactions considered together (lumped partials). See Chapter 30.

MT	Meaning	Description
18	(z,xf)	total prompt fission
19	(z,f)	first chance fission
20	(z,nf)	second chance fission
21	(z,2nf)	third chance fission
38	(z,3nf)	fourth chance fission
452	$\overline{\nu_T}$	total number of neutrons per fission
455	$\overline{\nu_d}$	number of delayed neutrons per fission
456	$\overline{\nu_p}$	number of prompt neutrons per fission
458		components of energy release in fission
460		delayed gammas from fission

The reaction evaluation process

ENDF uses theory tuned to reproduce energy-differential and integral data



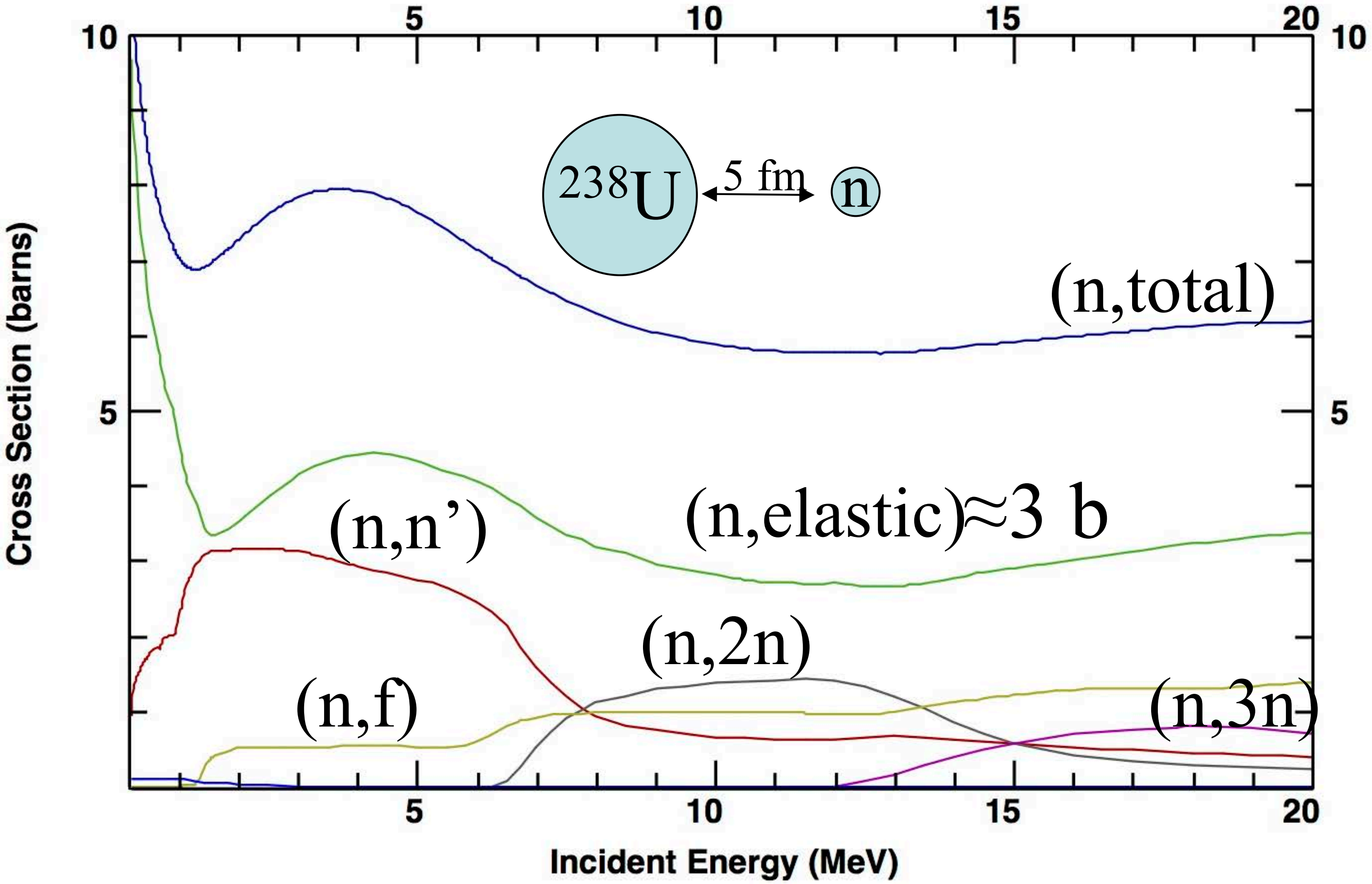
But you can’t measure everything with arbitrary accuracy

Reaction evaluation combines experiment with reaction theory and modeling to build a consistent picture

Thanks to Dave Brown (BNL/NNDC)

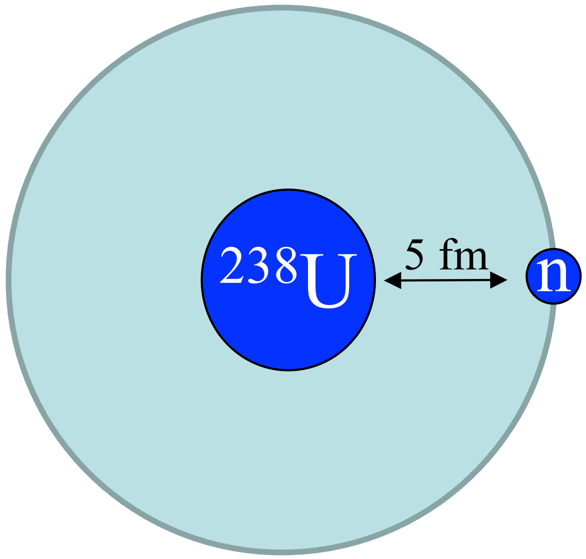
The total reaction cross section is fixed creating a connection between different channels

Evaluation is performed for a given projectile+target+energy combination

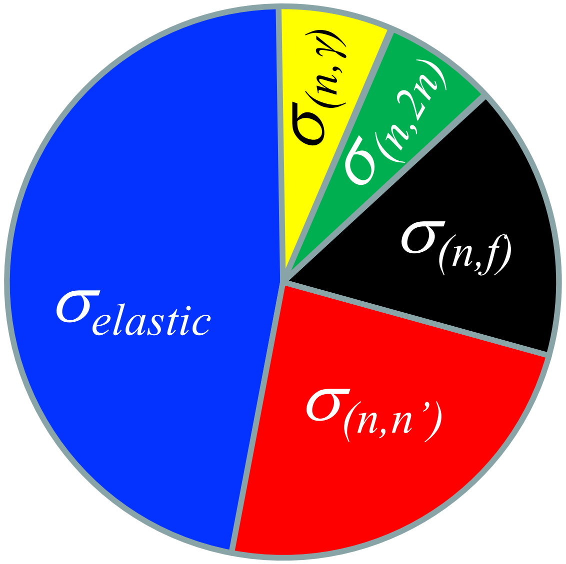


An increase in one cross section requires a decrease in another

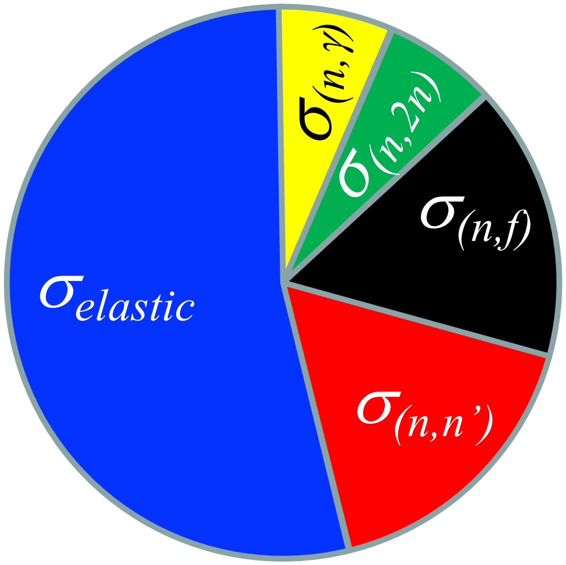
Since σ_{total} is fixed for a given projectile + target system at a given energy there are *covariances* between reaction channels



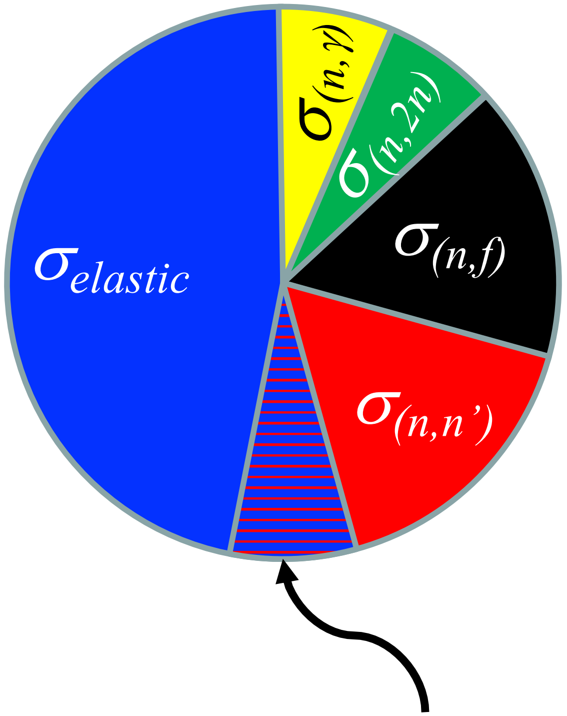
Evaluator #1



Evaluator #2



These uncertainties are most likely to involve reactions channels where there is little data available to guide the evaluator



Compensating uncertainties

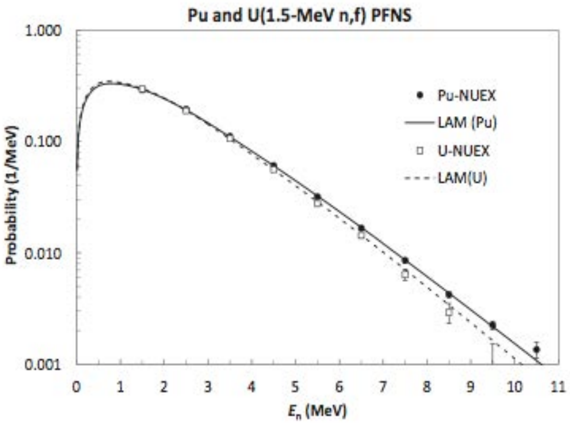
Case study: the Jezebel critical assembly
Which piece(s) of nuclear data is most important???

*E. Bauge *et al.*,
Eur. Phys. J. A (2012) 48: 113

Not too bad…

Fission cross sectio

-122 p.c.r



-> BRC

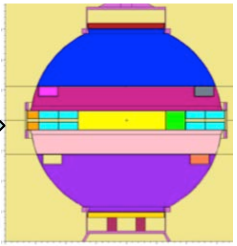
Good News!!!

VII –> BRC

275 p.c.m.

Worrisome

Experiment vs. Model (ENDF-B7.1 & BRC **databases)**



Inelastic BVII –> BRC

+522 *p.c.m*

Yikes!

Elastic BVII –> BRC

-638 p.c.m.

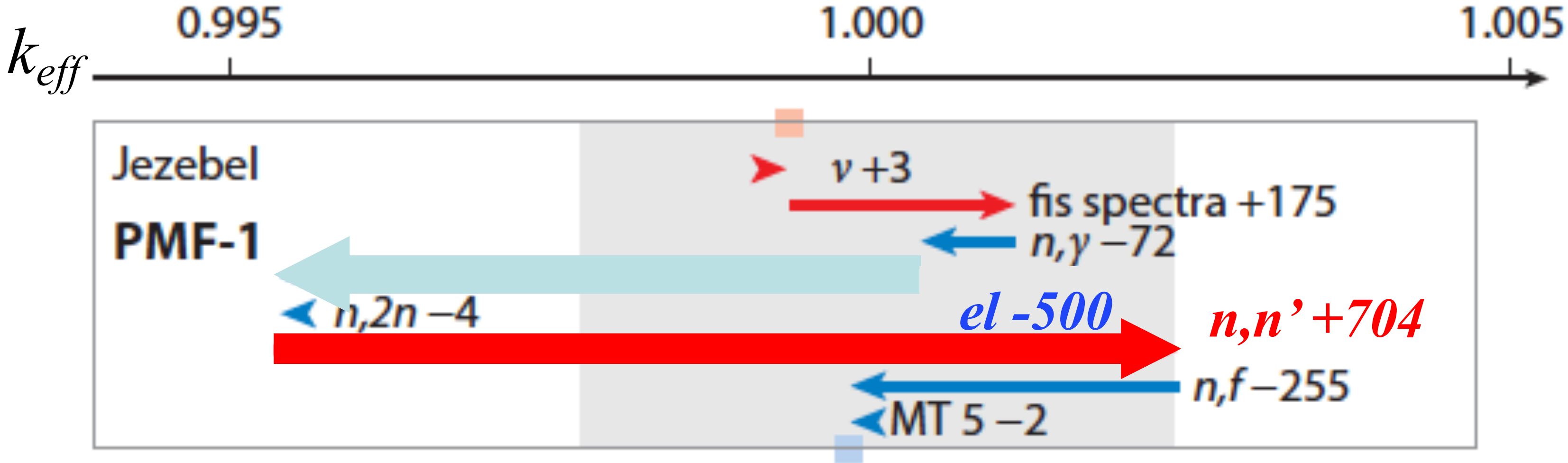
(n,2n) reaction BVII –> BRC

-14 p.c.m.

As expected

Compensating errors can mask bad data

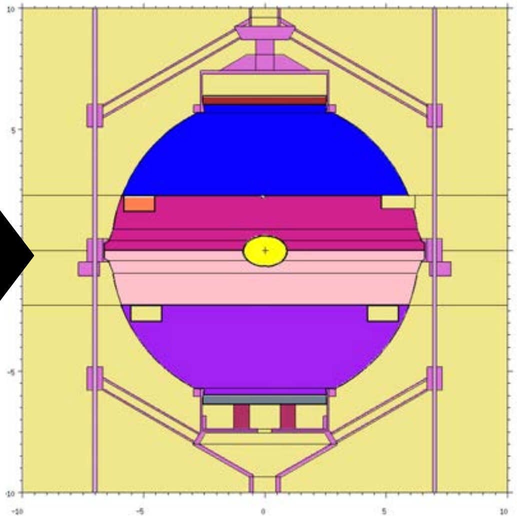
This problem is still present 7 years later



Jezebel (^{239}Pu)
critical assembly

ENDF/B-VIII.0 vs. JEFF-3.3

Neutrons from (n,f) are indistinguishable from (n,n')



*L.A.B. *et al.*, Annu. Rev. Nucl. Part. Sci. 2019.69:109-136.