An Assessment of Nuclear Data for Fusion and the Need for New Experiments

Lee Bernstein
University of California - Berkeley
Lawrence Berkeley National Laboratory

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Fission and Fusion from a Nuclear Scientist/Data Person's Perspective

Fission

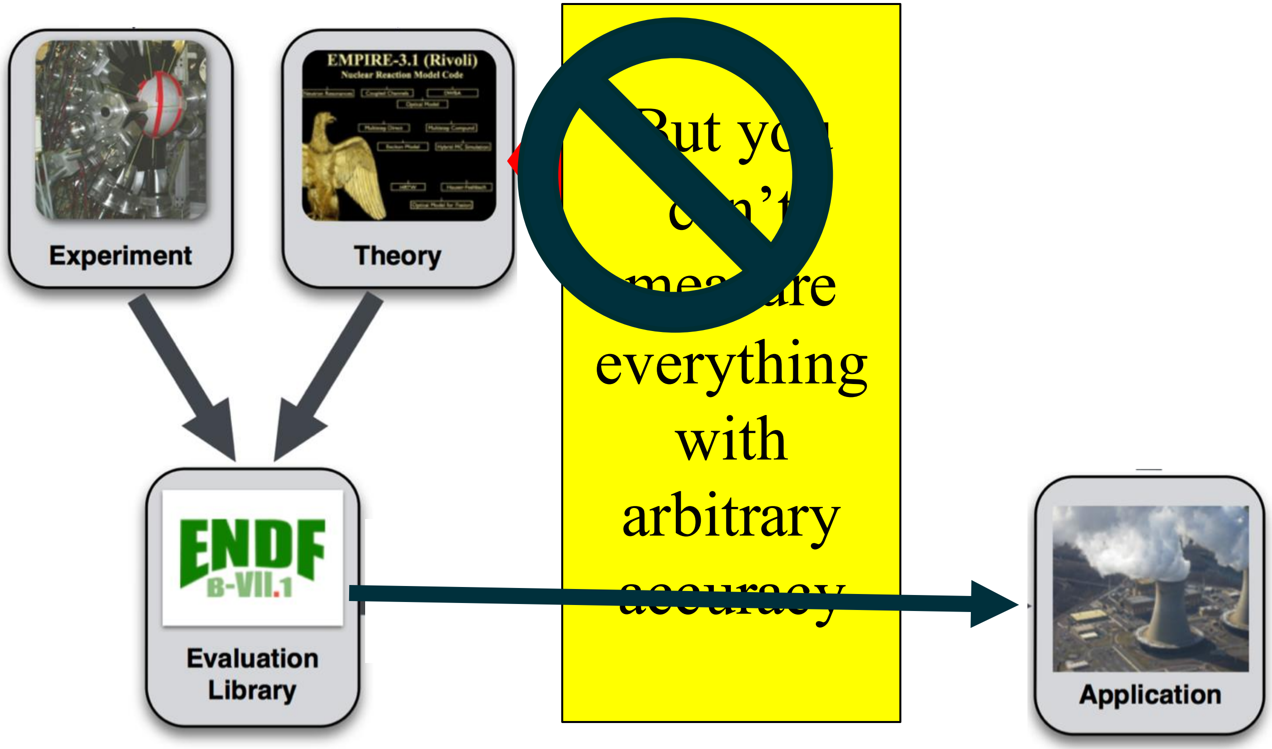
1. 85% of the energy is in the fission fragments, which can be stopped in ≈ a few μm via ***electronic stopping***.
2. Fuel needs to be dug up from the earth.
3. Reactors ***MUST lose most of the neutrons*** made per fission.
4. Generates some long-lived fission fragments ***and actinides with proliferation concerns (Pu)***

Fusion

1. A 14 MeV neutron contains 80% of the energy and needs 10's of cm to be stopped ***via nuclear scattering***
2. ½ of the fuel needs to be made
3. Reactor ***MUST use neutrons*** to create 1.1-12 tritons per fusion.
4. Generates ***some long-lived activation products and material with proliferation concerns (T)***

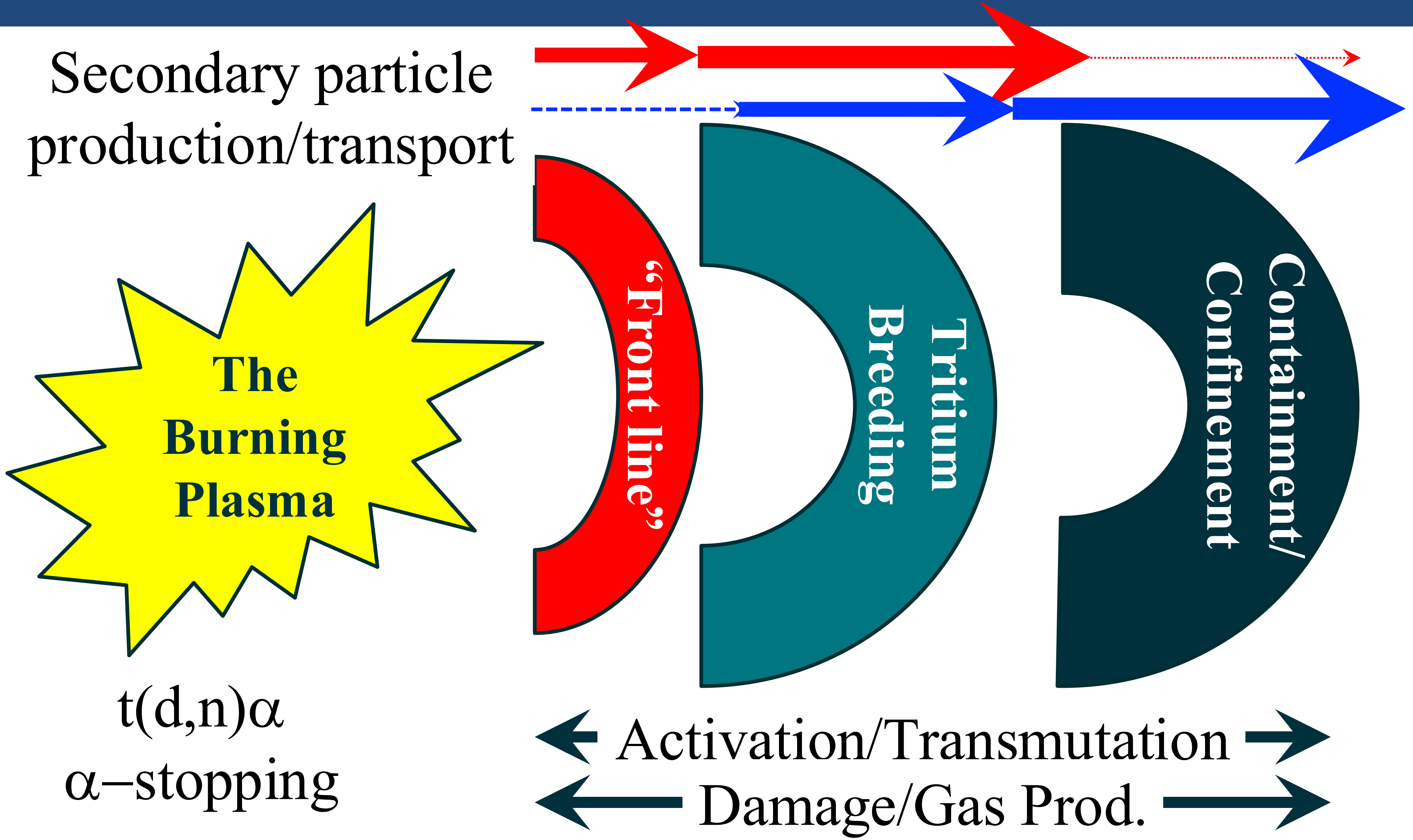
Neutron transport/capture are important to both

Reaction evaluation in a nutshell (Thanks to D. Brown!)



You shouldn't use integral benchmarks alone to gain confidence over your predictive capabilities if there is a lack of differential data to guide evaluation

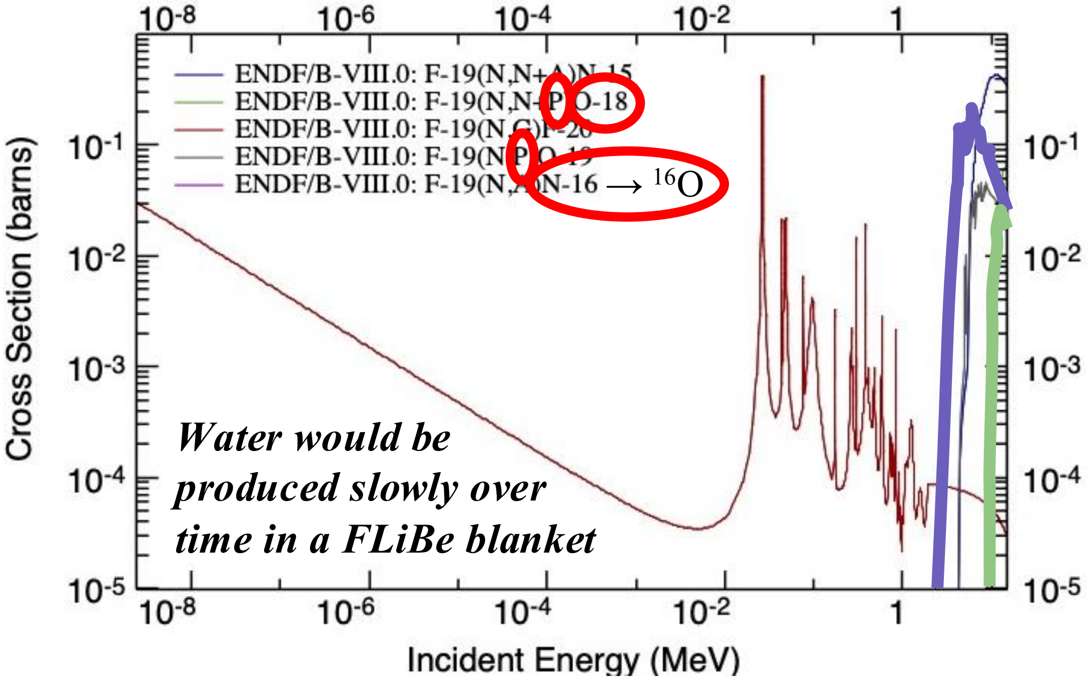
Where does Nuclear Data Play a role in a fusion energy system?



We'll examine a few examples of important data in several of these categories

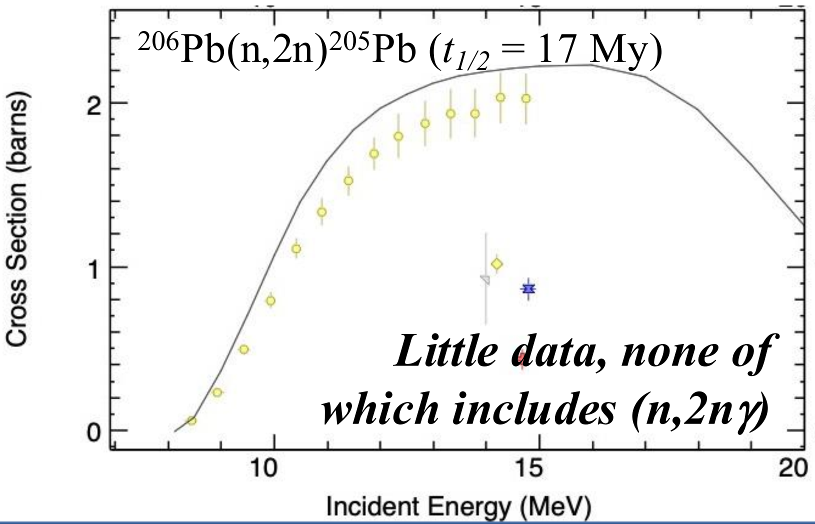
Transmutation/Activation & Gamma production is important through the fusion energy system

- Important Low-Z Nuclei: ***F***, Li, Be, B, O
  - Channels: (n,γ), (n,p), (n,pn), (n,α), (n,αn), (n,2n)
  - BUT: Most don't lead to long-lived radioactive nuclei
  - ***Chemical transformation could pose operational risks***



- Important High-Z Nuclei: ***Pb***, W, Ta, Bi
  - Channels: (n,γ), (n,2n), (n,3n)

Each High-Z (n,2n) reaction results in 1-3 γ-rays with a ΣE_γ= 3-8 MeV

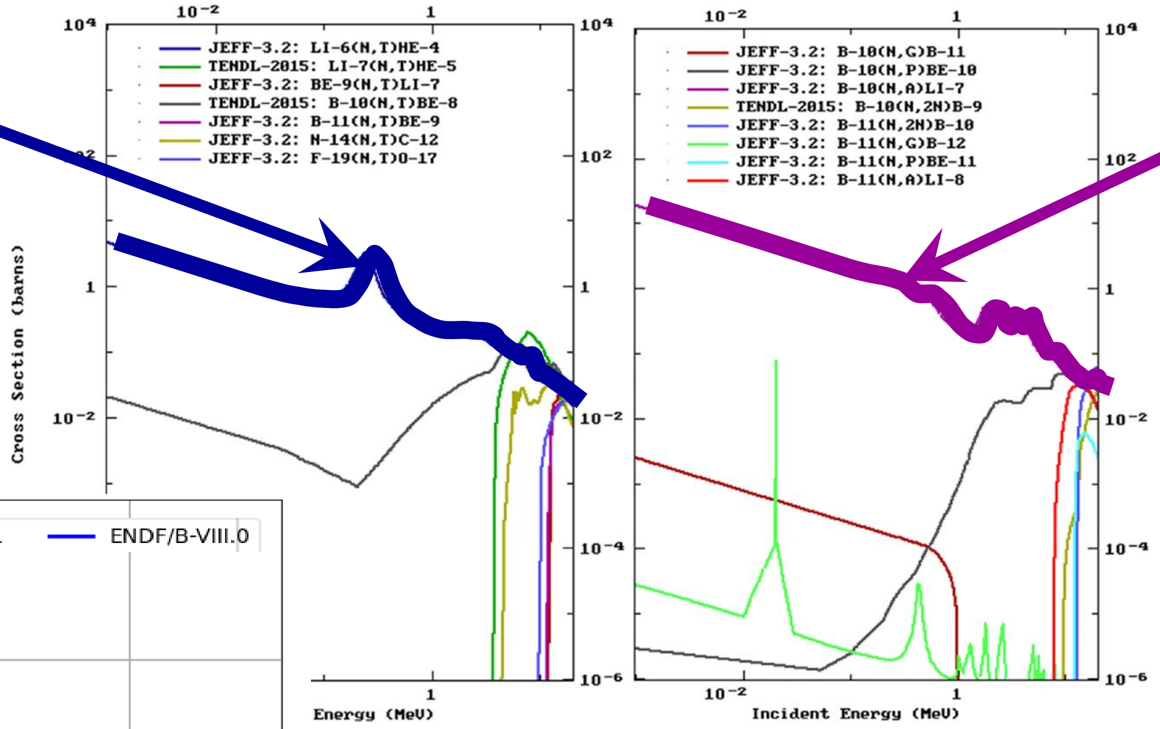


Tritium Breeding has focused on ^{6}Li(n,α)t but ^{10}B might be of interest too

First principles review of options for tritium breeder and neutron multiplier materials for breeding blankets in fusion reactors

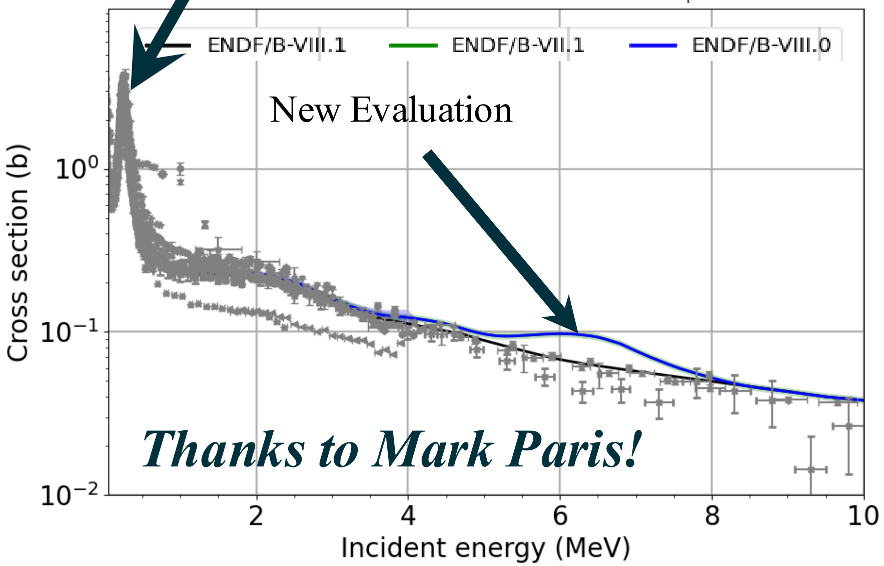
F.A. Hernandez*, P. Pereslavtsev

This peak in in ^{6}Li(n,t)α makes "fusion-eers" happy ☺

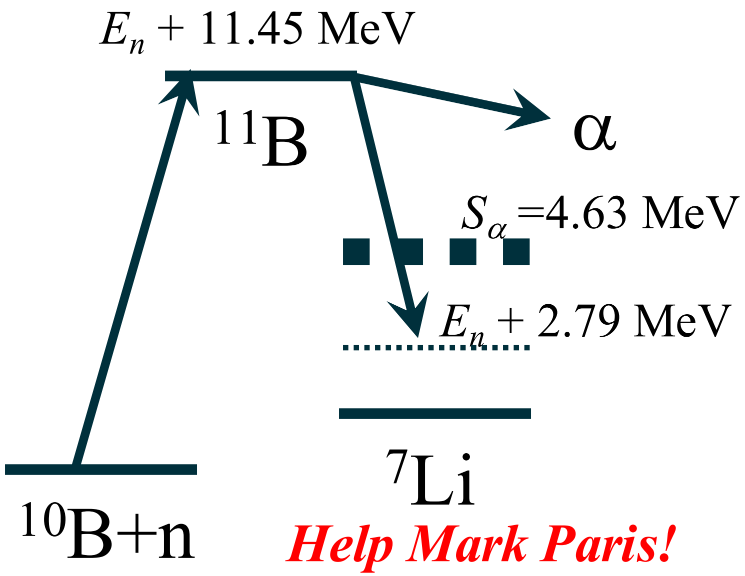


Is ^{11}B(n,α)^{7}Li REALLY that big?

Or does this curve have contributions from ^{11}B(n,α)^{7}Li*→ t+α ?



An activation experiment at 14 MeV and a coincident LENZ-style experiment might help tritium production



Help Mark Paris!

Tritium Breeding has focused on ^{6}Li(n,α)t but ^{10}B might be of interest too

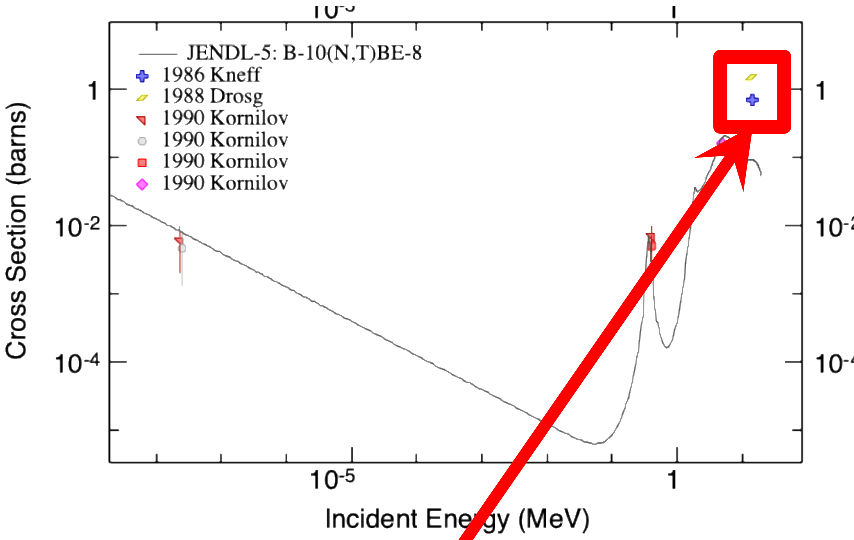
Here's all the available EXFOR data for ^{10}B(n,α)

No measurements above 6.52 MeV!

	n	Display	Year	Author-1	Energy range,eV		Points	Reference
1)		5-B-10(N,A)3-LI-7,,SIG Q(keV)=2757.222 C4: MF=3 MT=107 Op=0						
Quantity: [CS] Cross section								
	1	+ i X4 X4+± CSV+ T4 Cov	2019	Haoyu Jiang+	1.00e0	2.40e6	57	+ J,CPH/C,43,124[illegible]02,2019
	2	+ i X4 X4+± CSV+ T4 Cov	2017	R.Bevilacqua+	1.60e5	3.12e6	57	+ J,EPJ/CS,1[illegible],11010,2017
	3	+ i X4 X4+± CSV+ T4 Cov	2017	Zhimin Wang+	4.00e6	5.00e6	3	+ J,PR/C,[illegible]6,044621,2017
	4	A + i X4 X4+± CSV+ T4 Cov	2011	Zhang Guohui+	4.00e6	5.00e6	2	+ J,C[illegible],28,(8),082801,2011
	5	A + i X4 X4+± CSV+ T4 Cov	2008	Guohui Zhang+	4.00e6	5.00e6	2	+ [illegible],ARI,66,1427,2008
	6	+ i X4 X4+± CSV+ T4 Cov	2002	Guohui Zhang+	4.17e6	6.52e6	4	+ J,NSE,142,203,2002
	7	+ i X4 X4+± CSV+ T4 Cov	1975	S.J.Friesenhahn+	2.35e3	1.72e6	152	+ C,75WASH,1,232,197503
*	8	+ i X4 X4+± CSV+ T4 Cov	1969	D.Bogart+	2.90e4	8.17e5	27	+ J,NP/A,125,463,69
	9	+ i X4 X4+± CSV+ T4 Cov	1968	R.L.Macklin+	9.80e4	5.05e5	[illegible]	+ J,PR,165,1147,1968
	10	+ i X4 X4+± CSV+ T4 Cov	1967	S.A.Cox+	1.07e4	2.47e5	12	+ J,JNE,21,271,1967
	11	+ i X4 X4+± CSV+ T4 Cov	1964	F.P.Mooring+	1.15e4	7.71e4	3	+ P,ANL-6877,5,64
	12	+ i X4 X4+± CSV+ T4 Cov			1.15e4	7.71e4	3	
	13	+ i X4 X4+± CSV+ T4 Cov	1963	A.Prosdocimi+	6.01e-3	8.20e-2	50	+ J,JNE/AB,17,83,1963
	14	+ i X4 X4+± CSV+ T4 Cov			2.53e-2		2	
*	15	+ i X4 X4+± CSV+ T4 Cov	1960	E.G.Bilpuch+	3.00e3	6.80e4	32	+ J,AP,10,455,60
	16	A + i X4 X4+± CSV+ T4 Cov	1957	H.Bichsel+	2.00e4	4.78e6	98	+ J,PR,108,1025,57
	17	A + i X4 X4+± CSV+ T4 Cov	1944	C.L.Bailey+	5.80e5		1	+ R,LA-46,1944

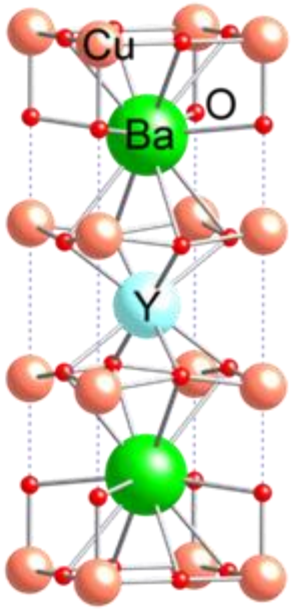
Additional measurements, especially between 6.5 & 14 MeV are needed

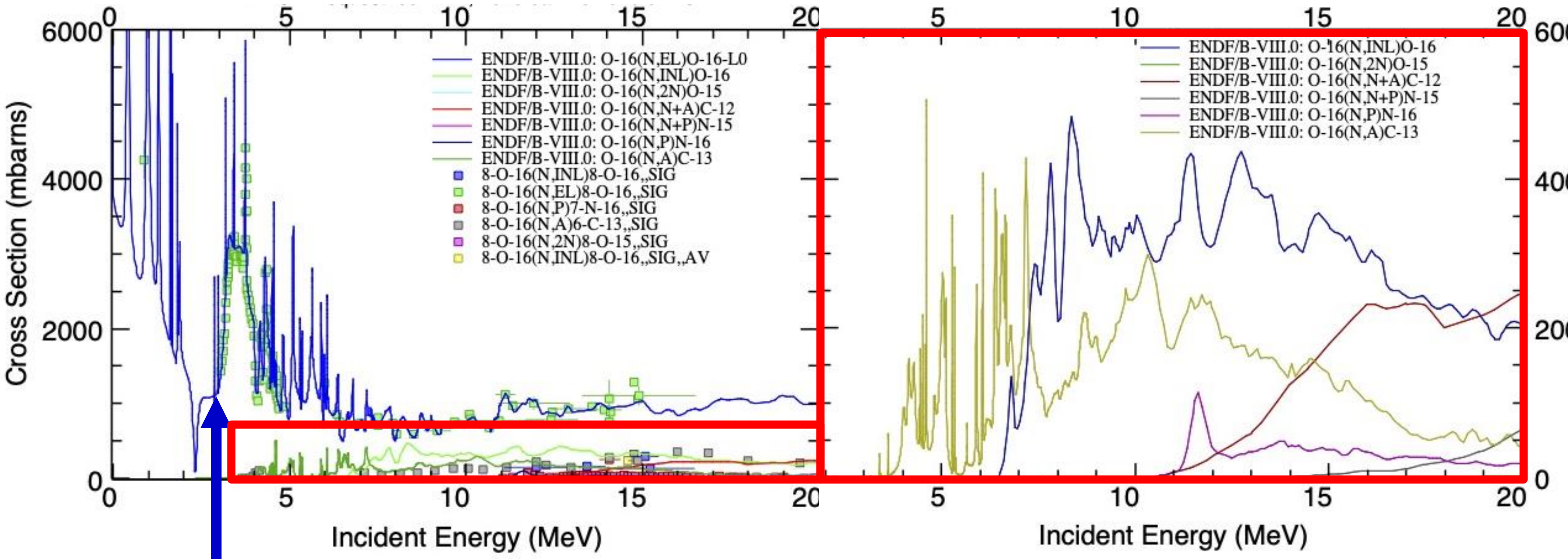
There's virtually no data for ^{10}B(n,t) itself



But 14 MeV looks promising

Let's look at an important materials damage data issue for MCF: ^{16}O for REBCO (MCF magnets)



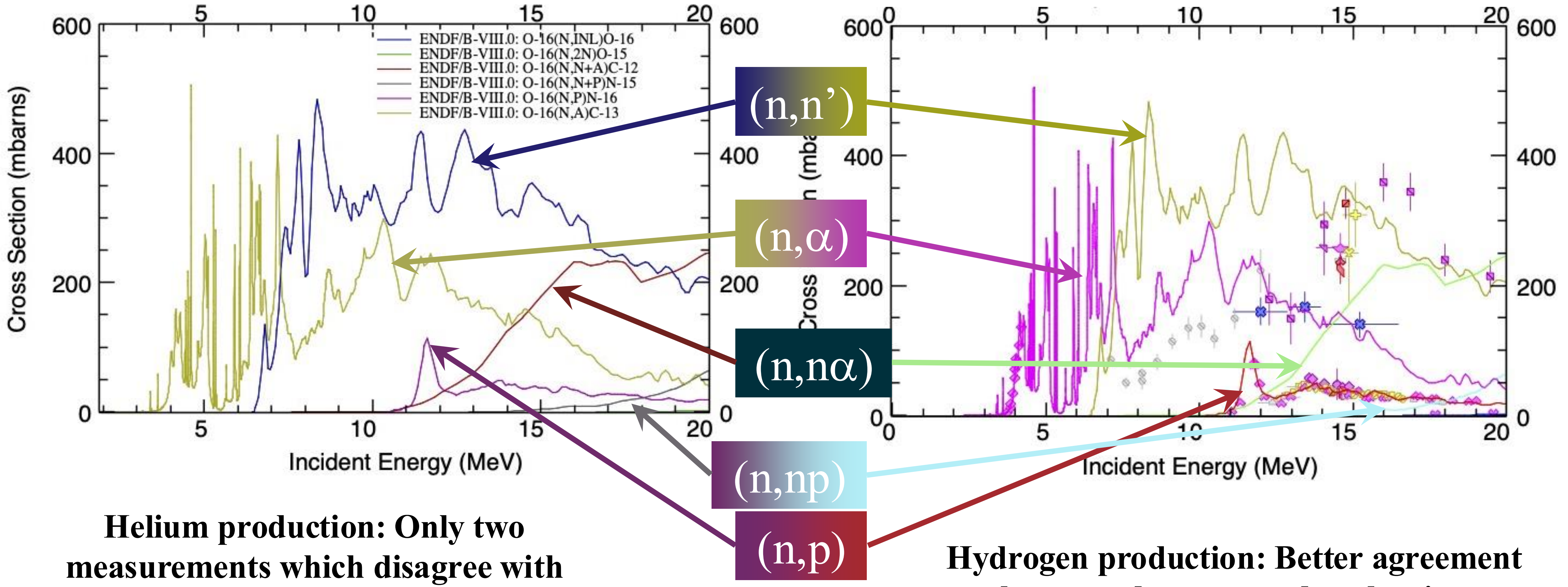


Elastic scatter (main constituent of σ_{DPA} at fast energies) has been measured for $E_n > 3$ MeV

The non-elastic channels are about as large at fast energies ($E_n > 3$ MeV) and they contribute to both σ_{DPA} AND gas production

What differential data exists for the ^{16}O non-elastic channels?

Inelastic scatter, including γ-ray production, is almost completely unmeasured)



Helium production: Only two measurements which disagree with each other and the evaluation

Hydrogen production: Better agreement between data sets and evaluation

Fortunately, parts of DOE have been investing in improving fast neutron scattering data, offering fusion a chance to address fusion needs incrementally

First Priority	Follow-up	Remaining	
H	He	F	Gd
C	Li	Mg	Bi
N	Be	P	Np
O	B	S	Am
Na	Cl	Ar	
Al	Cr	K	
Si	Mn	Ca	
Fe	Ni	Ti	
Cu	Ge	As	
Pb	Br	Kr	
W	Cd	Mo	
U	I	Sn	
Pu	Cs	Sb	
	La	Xe	

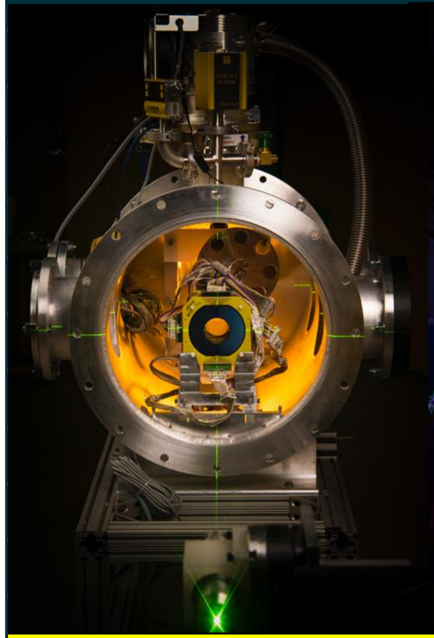
NA-22 has funded C & Na

NA-113 has funded Bi & ***Nb***

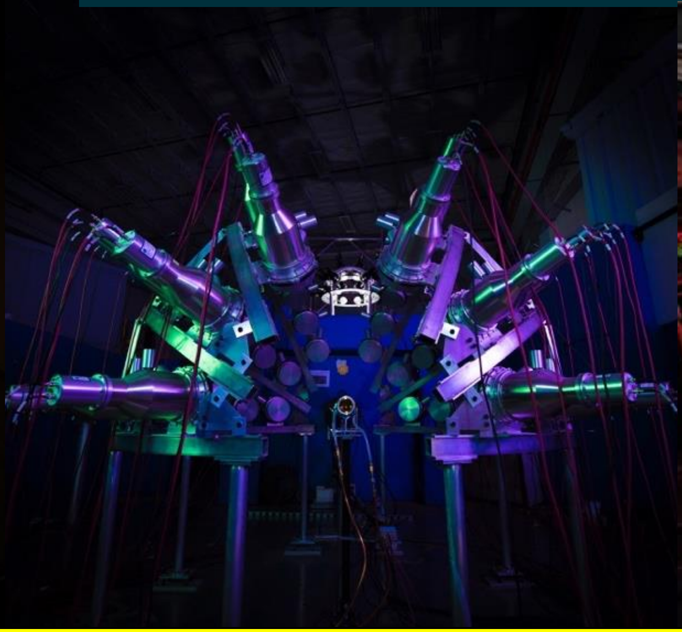
DOE-NE has funded Fe, Cl & U

Table 2 from the FY21 NA-22 portion of the Nuclear Data Interagency Working Group FOA

LENZ @ LANL
Gas Production Cross Sections



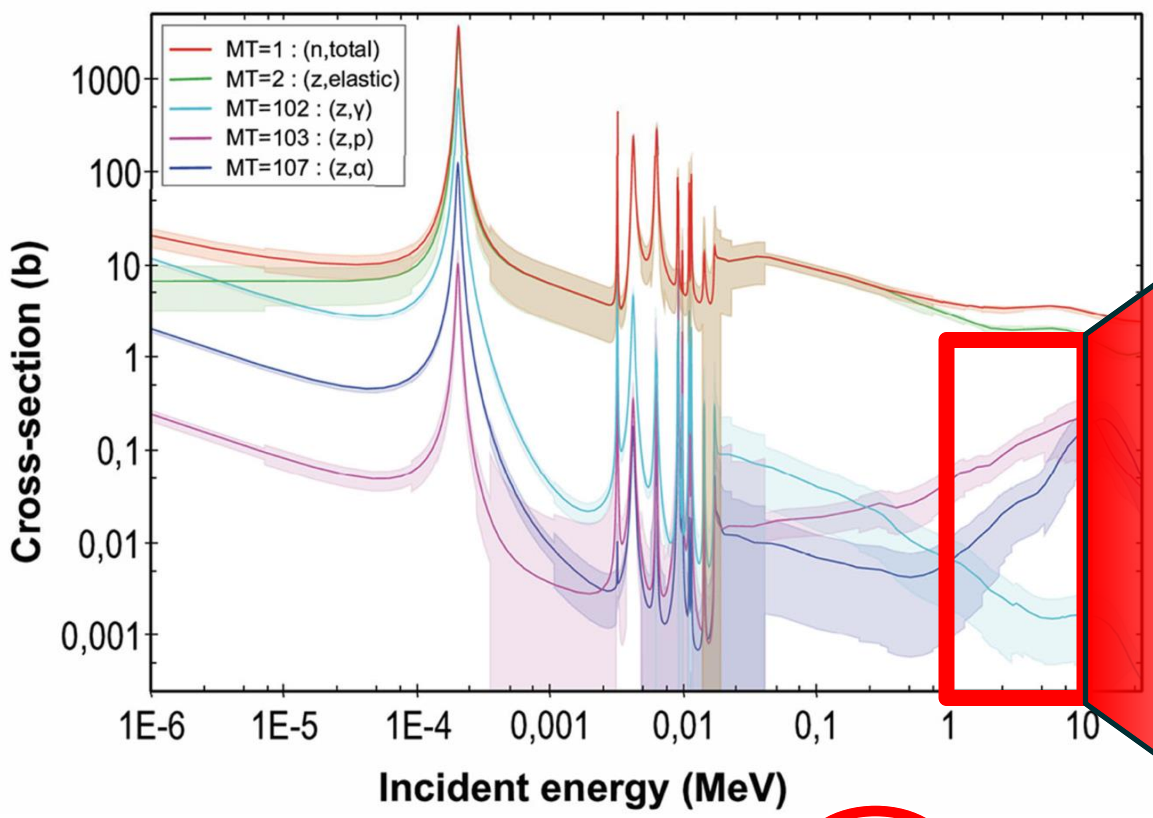
Chi-nu → CoGNAC @ LANL - Neutron Scatter Cross Sections



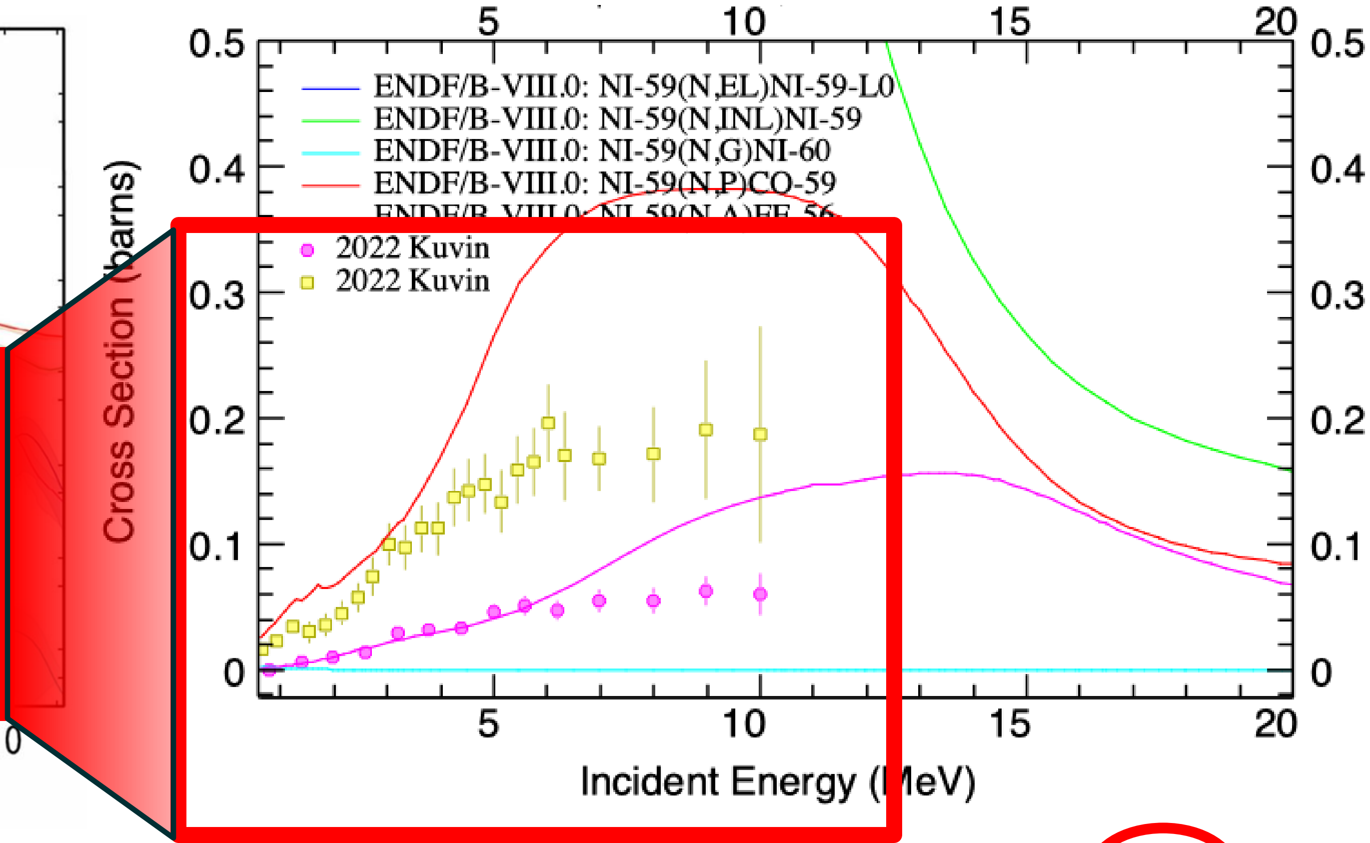
GENESIS @ LBNL
Neutron Scatter and γ-ray production Cross Sections

BUT: the measurement → evaluation time scale takes years, so advance planning using the WANDA/NDIAWG process is *essential*

Some nice work from LANL are highlighting these uncertainties, but absolute normalization is tricky and it often doesn't cover the entire energy range



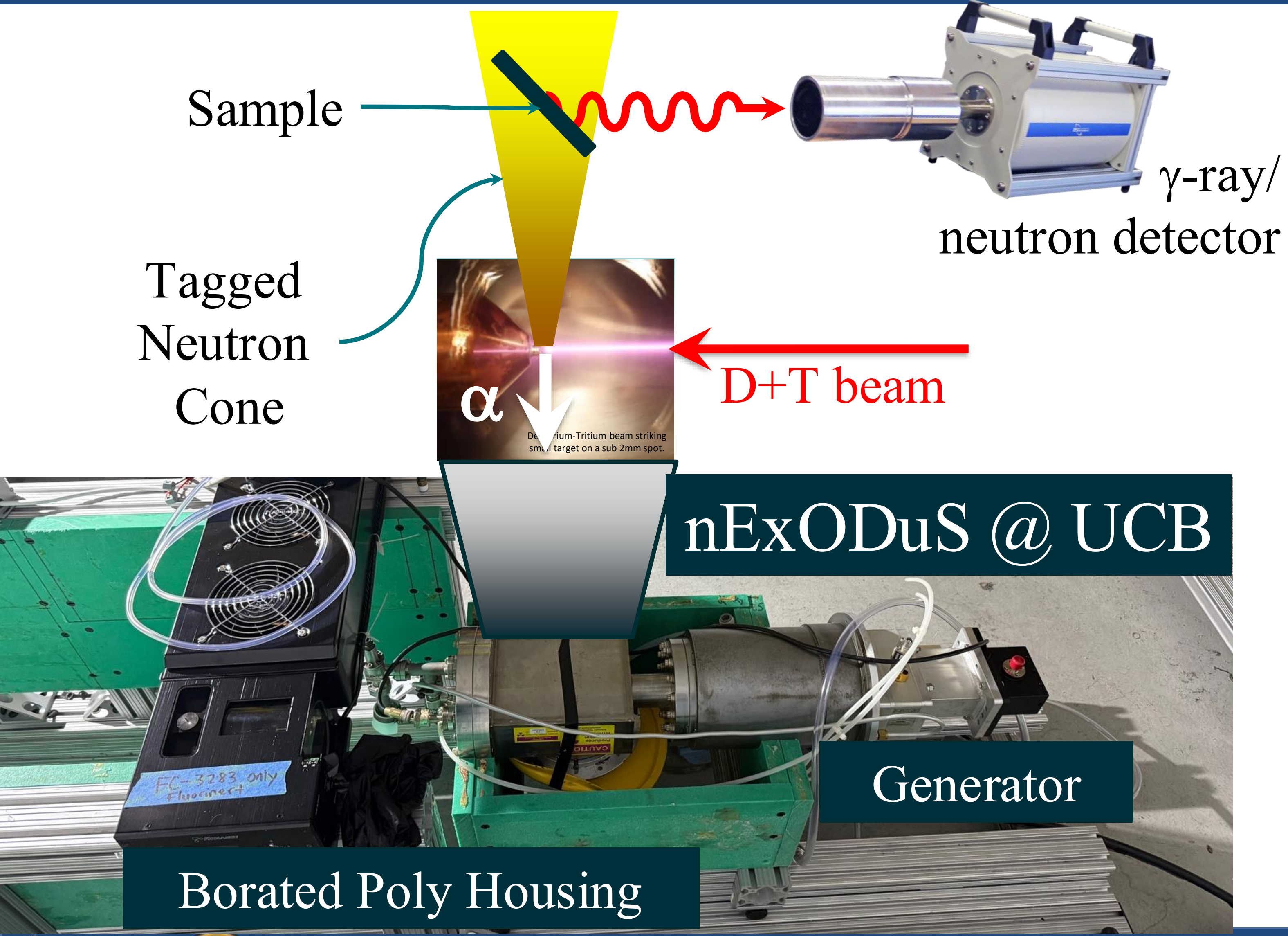
J.-Ch. Sublet *et al.*, Eur. Phys. J. Plus (2019) 134: 350



S.A. Kuvin *et al.*, Phys. Rev. C **105**, 044608 (2022)

Absolute measurements at 14 MeV are needed

A joint JHUAPL/NNDC/Berkeley team* are using a DT-API system to measure (n_{14},xnγ) cross sections *(Thanks Keegan for the advance advertisement!)*



Simple Count Rate Estimate

$$R_{\alpha-\gamma/n} = \sigma(N)_{sample}\Phi_n$$

For a 10 g sample 1 m away from a 1 cm scintillator @ 5 cm:

$$N_{sample} \approx 10^{23} atoms$$

$$\Phi_n \approx 10^8 \frac{n}{s} \times \frac{1}{100}^{2} \rightarrow\approx 10^9 \frac{n}{day}$$

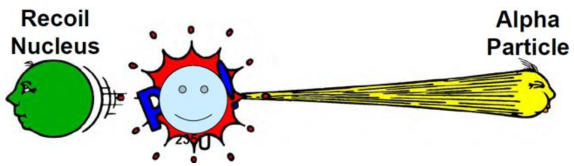
$$\rightarrow R_{\alpha-\gamma/n} = \frac{10^8}{\sigma\,(barn) \bullet day}$$

***10^5* peak counts/day for a 0.1% detection efficiency**

* Funded under a FY24 NDIAWG grant (PI: P. Peplowski)

For Materials Damage let's look WAY BACK to WANDA 2019: Materials Damage Session Findings/Recommendations (C. Romano)

- ENDF is missing data for recoils and (n,α)
  - Inaccurate (n,α) data caused serious miscalculation of materials lifetimes
- Need to understand how changed materials properties change the neutronics
  - Transmutation
  - Porosity
  - Chemical bonds



- Processing of the data in NJOY needs modernization to meet the needs of the fusion community
- Current models do not determine the size of vacancies
- Stopping Powers are not well understood
- Radionuclides produced under transmutation might create further Primary Knock-on Atoms (PKAs) as they decay, and so the rate of these must also be quantified.
  - Gilbert, Mark & Sublet, Jean-Christophe. (2016). PKA distributions: Contributions from transmutation products and from radioactive decay. Nuclear Materials and Energy. 9. 10.1016/j.nme.2016.02.006
- Inelastic Scatter cross sections need to be improved for fast neutron transport calculations
- Secondary particle production is not well known and requires measurement and theory development

For Materials Damage let's look WAY BACK to WANDA 2019: Materials Damage Session Findings/Recommendations (C. Romano)

- **There should there be a coordinated and comprehensive materials damage database for validation of calculations**

- Idaho National Laboratory has a database of irradiation materials available to borrow
  - Includes irradiation data but no post irradiation testing data
- Improved dosimetry standards will be necessary for 14 MeV neutrons
- Post Irradiation Testing
  - There are several capable laboratories with full suite of testing
  - Impossible to measure sigma-dpa due to annealing: Can look at crystalline structure, but not accurate measure of dpa

This may no longer be true!!!

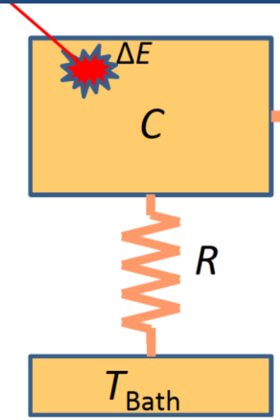
- Need to standardize materials analysis methods and format for irradiated materials data

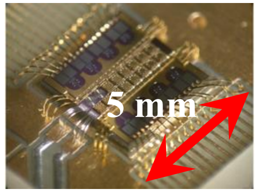
Thanks to Cathy Romano for taking on this topic for the first time!

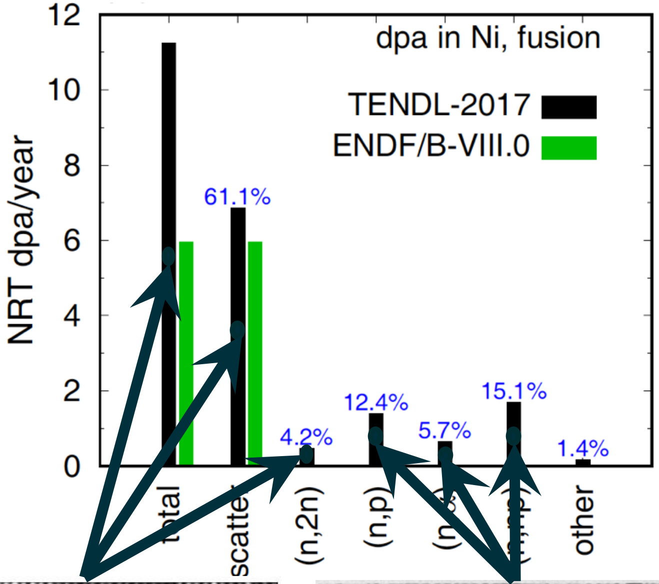
Differential σ_{DPA} and gas production measurements using a microcalorimeter coupled to a DT-API neutron generator

- Radiation is deposited in an absorber material and read out through a thermal resistance at low temperature.
- Source can be the absorber or embedded in it.

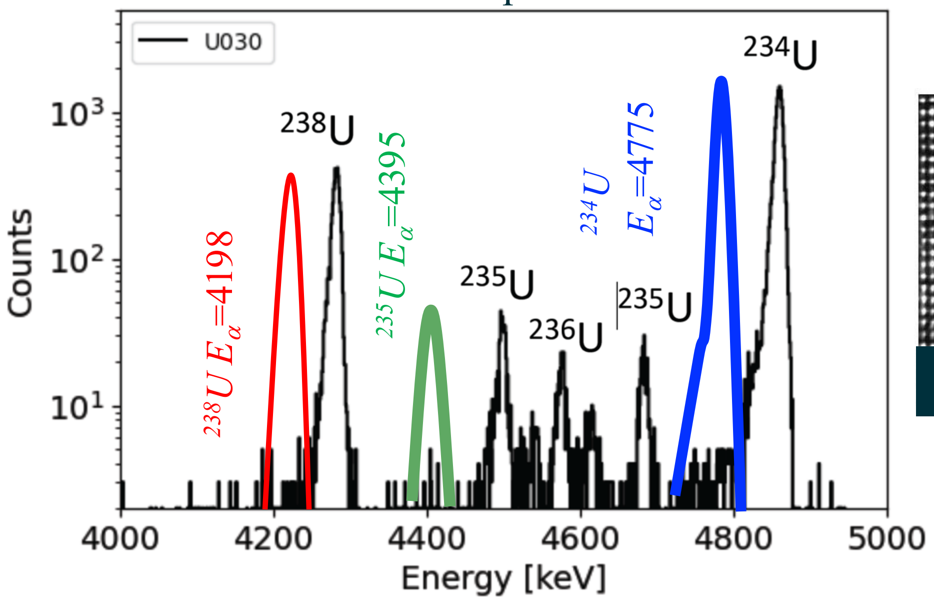
Radiation Threshold	
Silicon	3.6 eV
Germanium	2.9 eV
µCal	*≈30 µeV*

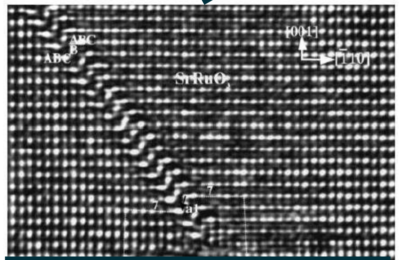




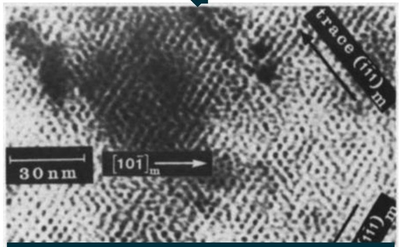


3% LEU Sample – α+*recoil!*[2]





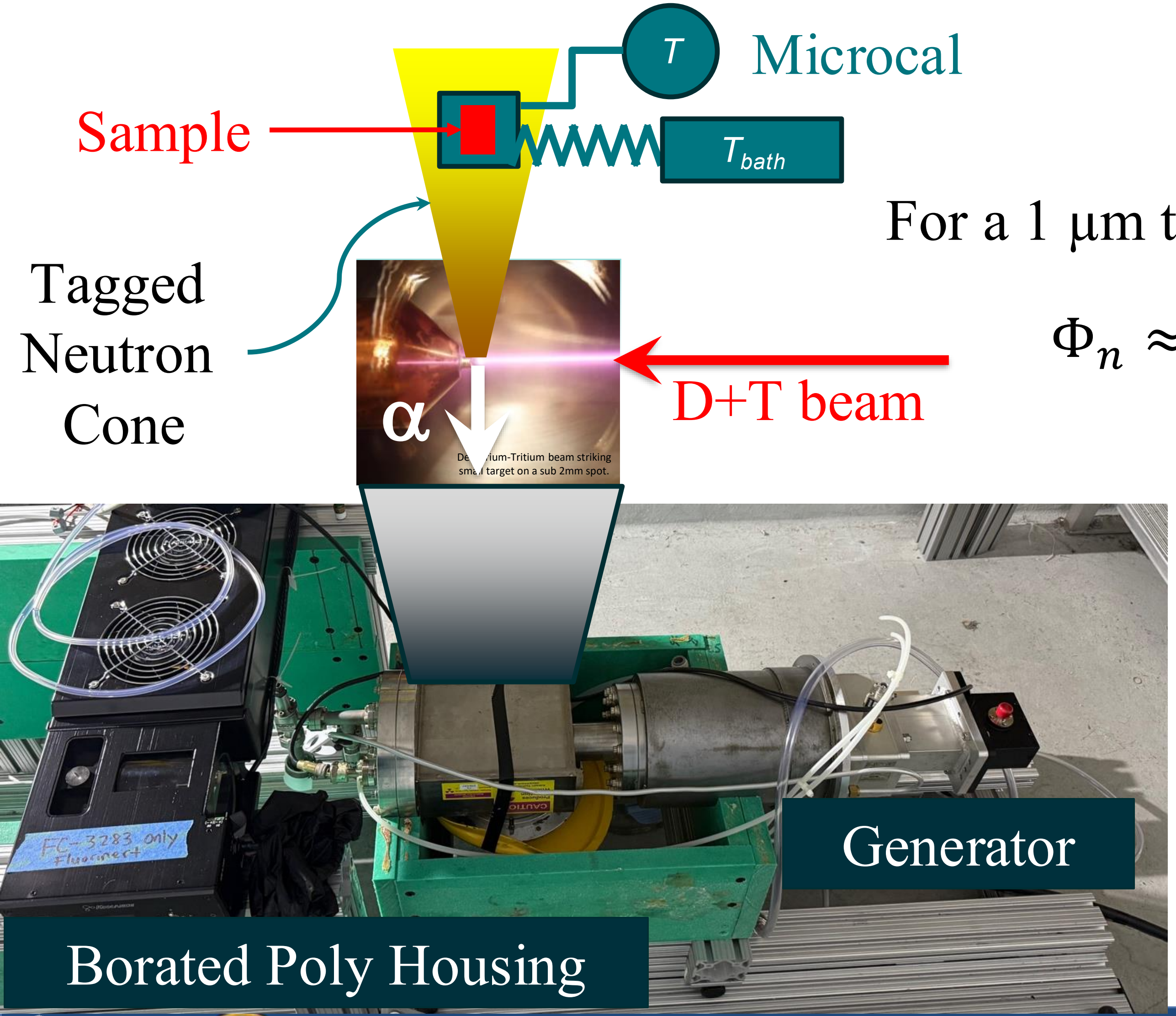
Displacement



Gas Production

See Keegan Kelly's talk from yesterday

Differential σ_{DPA} and gas production measurements using a microcalorimeter coupled to a DT-API neutron generator



Simple Count Rate Estimate

$$R_{\alpha-\gamma/n} = \sigma(N)_{sample}\Phi_n$$

For a 1 µm thick sample ($N_{sample} \approx 10^{20} atoms$) @ 10 cm:

$$\Phi_n \approx 10^8 \, {}^{n}/_{s} \times {}^{1}/_{10}{}^{2} \longrightarrow \Phi_n \approx 10^{11} \, {}^{n}/_{day}$$

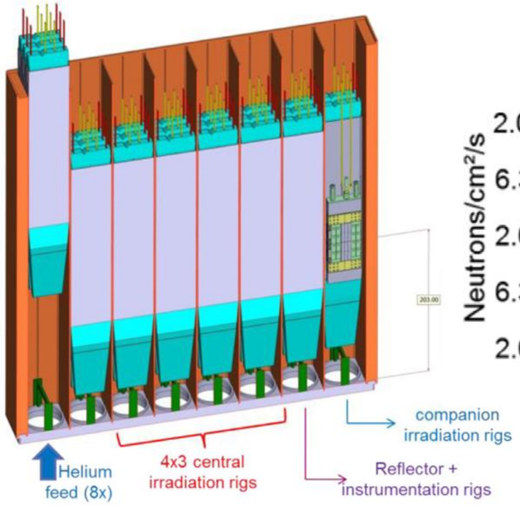
$$\rightarrow R_{\alpha-\gamma/n} = 10^7/\sigma\,(barn) \bullet day$$

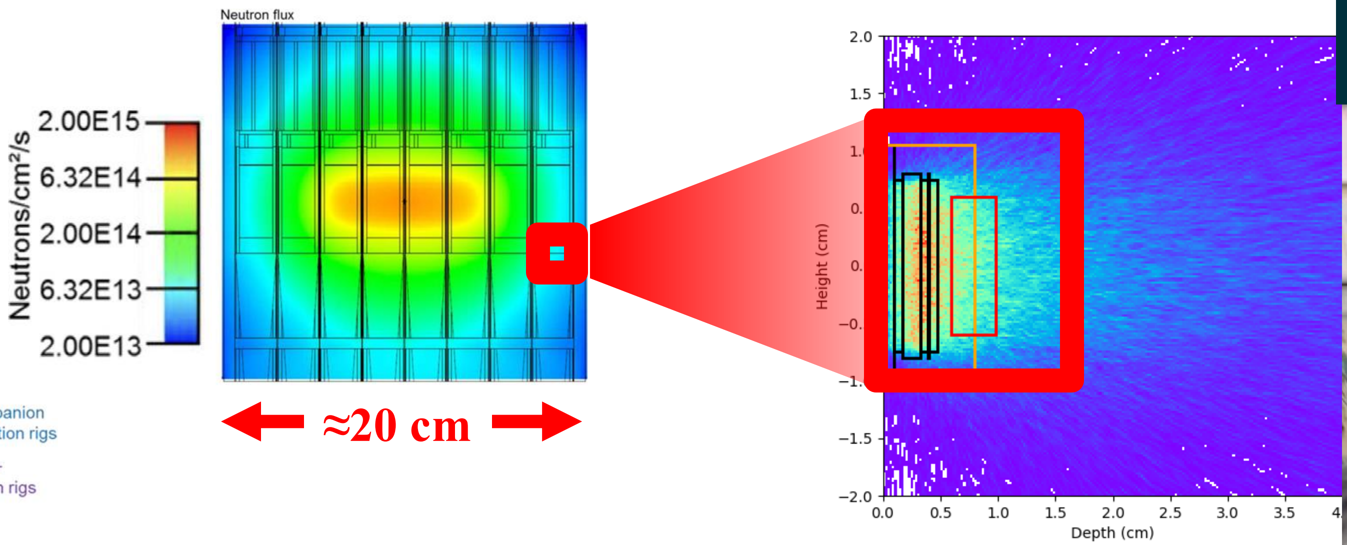
Energy deposited in ^{56}Fe by a 14.1 MeV neutron		
(n,el) or (n,inl)	≤ 247 keV	$\sigma_{14}^{max} \approx 0.6\ b$
(n,p) (Q=-3.0 MeV)	≤11,38 keV	$\sigma_{14}^{max} \approx 0.1\ b$
(n,α) (Q=+0.32 MeV)	≤14.7 MeV	$\sigma_{14}^{max} \approx 0.1\ mb$
(n,pn) (Q=-10.2 MeV)	≤ 4.2 MeV	$\sigma_{14}^{max} \approx 0.1\ b$

All major parts of σ_{DPA} are resolvable

How about integral measurements using high-flux neutron beams from thick target deuteron breakup (IFMIF etc.)?

Future Facilities (IFMIF[1]/FPNS)

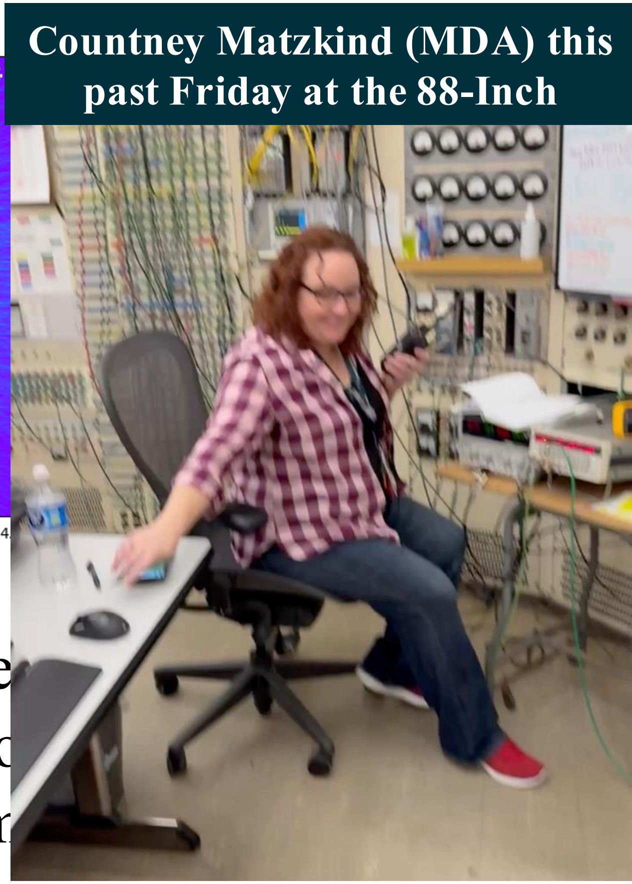




- IFMIF/FPNS plan to achieve multi-DPA damage in 100+ cm^3 volumes using thick target deuteron breakup

Cost: ≈10^{8\text{-}9}$ + years to design & build

Current Facilities



- The same spectrum is
neutron single-event e
radioisotope productic
% of the flux in ≈1 cm

Integral tests can be performed now, but they are <u>NOT</u> a substitute for differential data

Conclusions

- Many nuclear data needs for fusion energy overlap with other programs, allowing them to benefit from work being done by DOE/NP, the NNSA, DOE-NE, BUT numerous gaps exist
  - Differential data is lacking for tritium breeding, materials damage and gamma-ray production
- The combination of DT neutron generators with Associated Particle Imaging and Microcalorimetry offers a chance to address nuclear data gaps relevant to fusion:
- Opportunities exist for fusion energy to partner with other nuclear data users to accelerate progress and mitigate risk.

Thanks for your attention!