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Analyses of criticality benchmark experiments with beryllium reflector

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Contents

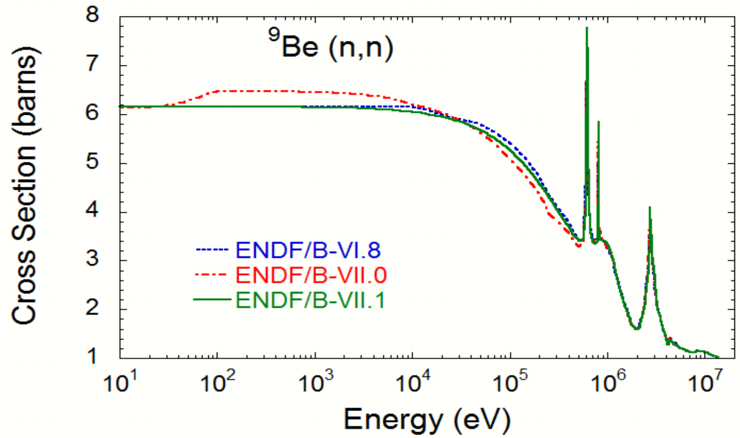
- Motivations
- Similarity analysis of benchmark experiments with beryllium reflector
- Conclusions

Applications of beryllium

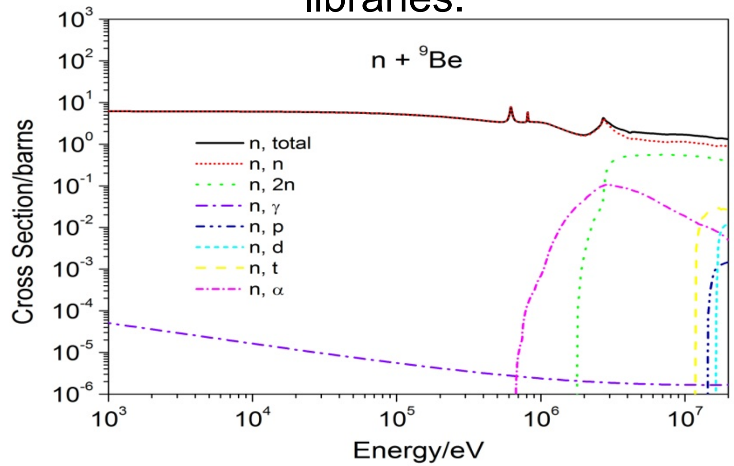
- Beryllium is important nuclear material, applied in
  - ITER breeder blanket, as multiplier
  - Thorium Molten Salt Reactor (TMSR), as coolant (BeF_2)
  - Moderator and reflector
  - Neutron source
- Beryllium nuclear data is of strong interest
  - A large number of beryllium bearing criticality benchmark experiments

Beryllium nuclear data in ENDF/B library

- **ENDF/B-VI (1986)**
  - experimental data before 1970s
  - for major reactions, some experimental data available
- **ENDF/B-VII.0 (2006)**
  - elastic scattering modified based on R-matrix analysis of measured data
- **ENDF/B-VII.1 (2011)**
  - revised again, with the new RPI experimental data
  - close to ENDF/B-VI.8



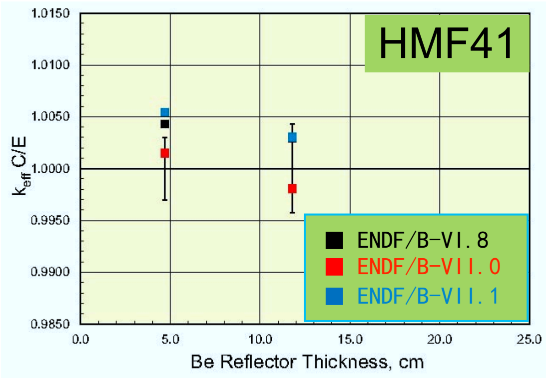
Elastic scattering from ENDF/B libraries.

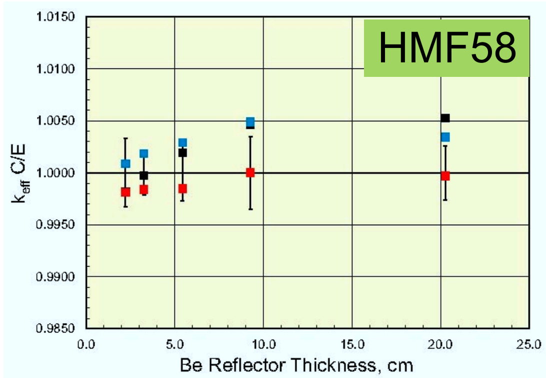


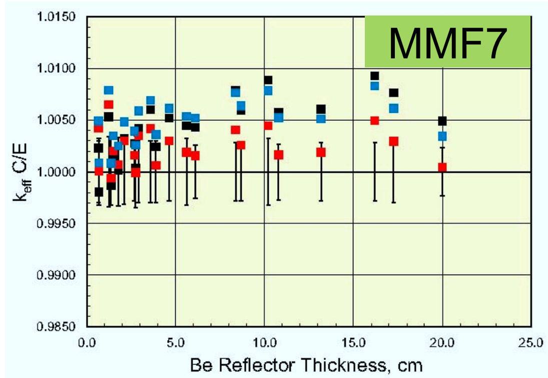
Cross sections from ENDF/B-VII.1.

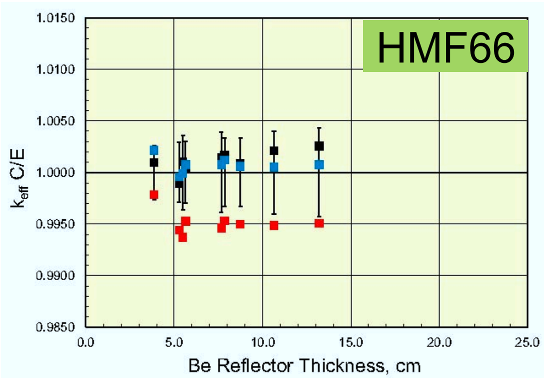
Beryllium data still thought to be **problematic**

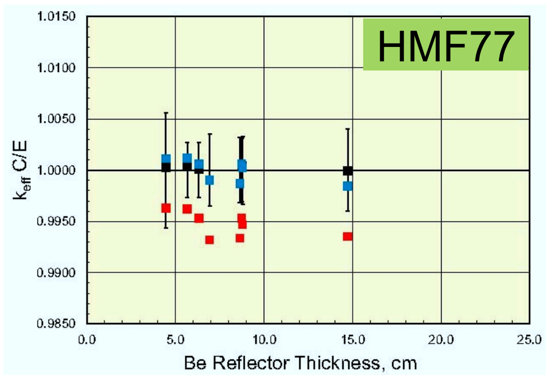
Calculated/Experimental (C/E) value for k_{eff} eigenvalue











- HMF41, HMF58 and MMF7 are better with **ENDF/B-VII.0**
- HMF66 and HMF77 are pretty well with **ENDF/B-VII.1, VI.8**

Figs. taken from ***A. Kahler, et al., Nuclear Data Sheets 112, 2997 (2011).***

Purpose of this work

Conflicting results of calculations across benchmarks are observed, then the question is:

Can we solve the conflict by improving nuclear data?

We perform similarity analyses for these benchmarks based on sensitivity coefficients of k_{eff} to nuclear data, trying to find a reasonable interpretation.

Contents

Beryllium reflected benchmarks

- A large number of beryllium criticality benchmarks available
  - HMF (HEU-MET-FAST) 41, HMF58, MMF(MIX-MET-FAST)7
  - HMF66, HMF77 used in beryllium data testing
- Try to find the most similar experiments for discussion
  - Consistent results could be expected for highly similar experiments
  - Check if the results are consistent

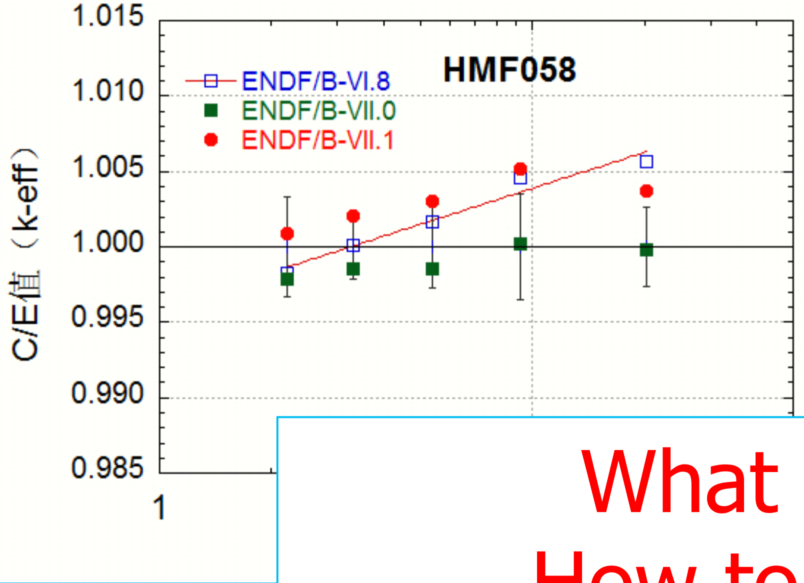
Beryllium reflected benchmarks

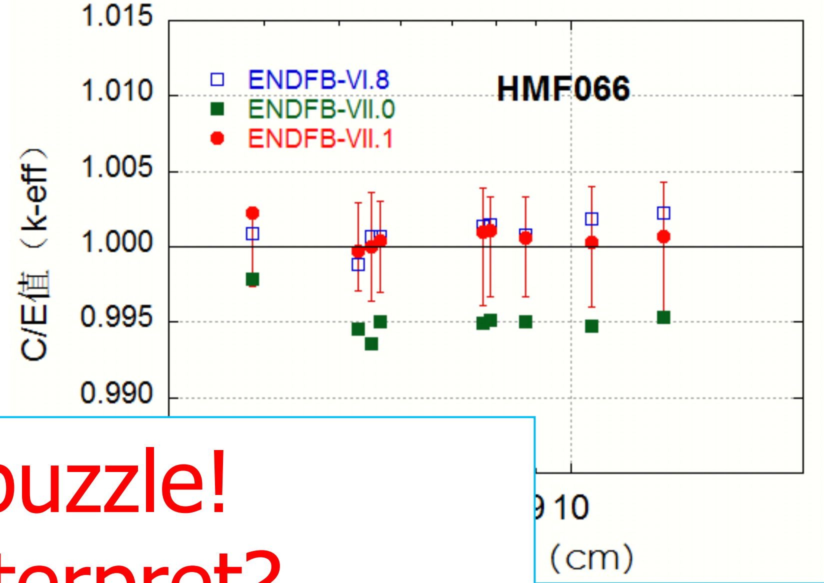
■ HMF58 and HMF66 are selected

Benchmark	Materials	Case	Be Shell Thickness, cm	Summary Description
HMF58	Be/HEU/Be	1	0.5//20.3	Internal and external radial reflector
		2	0.5//9.3	
		3	0.5//5.4	
		4	0.5//3.3	
		5	0.5//2.2	
HMF66	Be/Be/HEU/Be	1	0.5/2.6//8.7	Two nested internal Be shells and variable HEU shells plus an external Be reflector
		2	0.5/2.6//5.3	
		3	0.5/2.6//3.9	
		4	0.5/3.5//13.2	
		5	0.5/3.5//7.8	
		6	0.5/3.5//5.6	
		7	0.5/4.2//7.7	
		8	0.5/4.2//10.6	
		9	0.5/6.0//5.5	

- Similariry: common material compositions and similar geometric arrangements.
- Difference: HMF66 contains a larger internal beryllium sphere, varying in thickness.
- Consistent results of two benchmarks could be expected.

Calculations of HMF58 and HMF66





What a puzzle!
How to interpret?

- HMF58:
  – VI.8 and VII.1 data, obvious beryllium reflector bias for C/E value for k_{eff}
  ✓VII.0 data, pretty good results
- HMF66:
  ✓VII.1, calculated very well; VI.8, calculated pretty well
  –VII.0, underestimated significantly

Sensitivity of k_{eff} to nuclear data

- Sensitivity coefficient $\mathbf{S_k}$ of k_{eff} to nuclear data σ

$$S_{k,\sigma_i} = \frac{\partial k_{eff}}{\partial \sigma_i} \frac{\sigma_i}{k_{eff}}$$

Sensitivity coefficient $\mathbf{S_k}$ and nuclear data σ could be thought as vectors

Change of k_{eff} due to changes of σ

$$\Delta k_{eff} / k_{eff} \cong \mathbf{S_k} \cdot \Delta \sigma / |\sigma|$$

Similarity index

- Similarity indices
  - Accessing the degree of similarity for nuclear systems
  - C_k, G, E, etc., using sensitivity and uncertainty data
- E index
  - Cosine of two sensitivity vectors of system i and j

$$E \equiv \frac{\mathbf{S}_i^T \cdot \mathbf{S}_j}{|\mathbf{S}_i||\mathbf{S}_j|} \qquad |\mathbf{S}_i| = \sqrt{\mathbf{S}_i^T \cdot \mathbf{S}_i}$$

E = 1, completely similar; E = 0, completely dissimilar

More close to 1, more similar!

Similarity analyses

- Similarity indices for experiments from HMF58 and HMF66

	HMF58.1	HMF58.2	HMF58.3	HMF58.4	HMF58.5
HMF66.1	**0.9940**	0.9976	0.9873	0.9699	0.9558
HMF66.2	0.9829	**0.9977**	**0.9983**	0.9900	0.9810
HMF66.3	0.9722	0.9928	**0.9995**	**0.9968**	**0.9911**
HMF66.4	0.9916	0.9779	0.9534	0.9244	0.9040
HMF66.5	**0.9929**	0.9947	0.9821	0.9623	0.9468
HMF66.6	0.9880	**0.9980**	0.9933	0.9801	0.9682
HMF66.7	0.9918	0.9912	0.9758	0.9536	0.9367
HMF66.8	0.9894	0.9785	0.9546	0.9258	0.9054
HMF66.9	0.9889	0.9880	0.9717	0.9484	0.9310

Sensitivity coefficient and similarity indices calculated by SURE code.

Similarity analyses

- Most similar experiments from HMF66 to each in HMF58

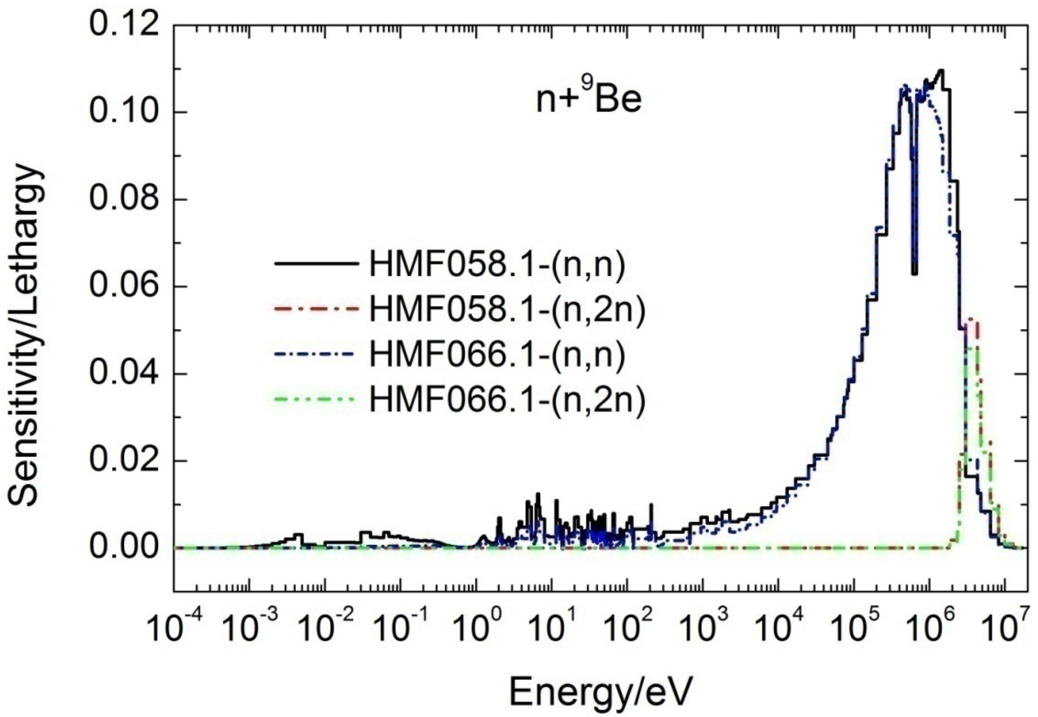
	Similarity suite 1	Similarity suite 2	Similarity suite 3	Similarity suite 4	Similarity suite 5
HMF58	HMF58.1	HMF58.2	HMF58.3	HMF58.4	HMF58.5
HMF66 E index	HMF66.1 0.9940	HMF66.6 0.9980	HMF66.3 0.9995	HMF66.3 0.9968	HMF66.3 0.9911
HMF66 E index	HMF66.5 0.9929	HMF66.2 0.9977	HMF66.2 0.9983	HMF66.2 0.9900	-- --

Each suite : 1 from HMF58 and 1-2 from HMF66

Suites 1-3 with thicker reflector are selected for analyses.

Similarity analyses

■ Sensitivity data for HMF58 case 1 and HMF66 case 1



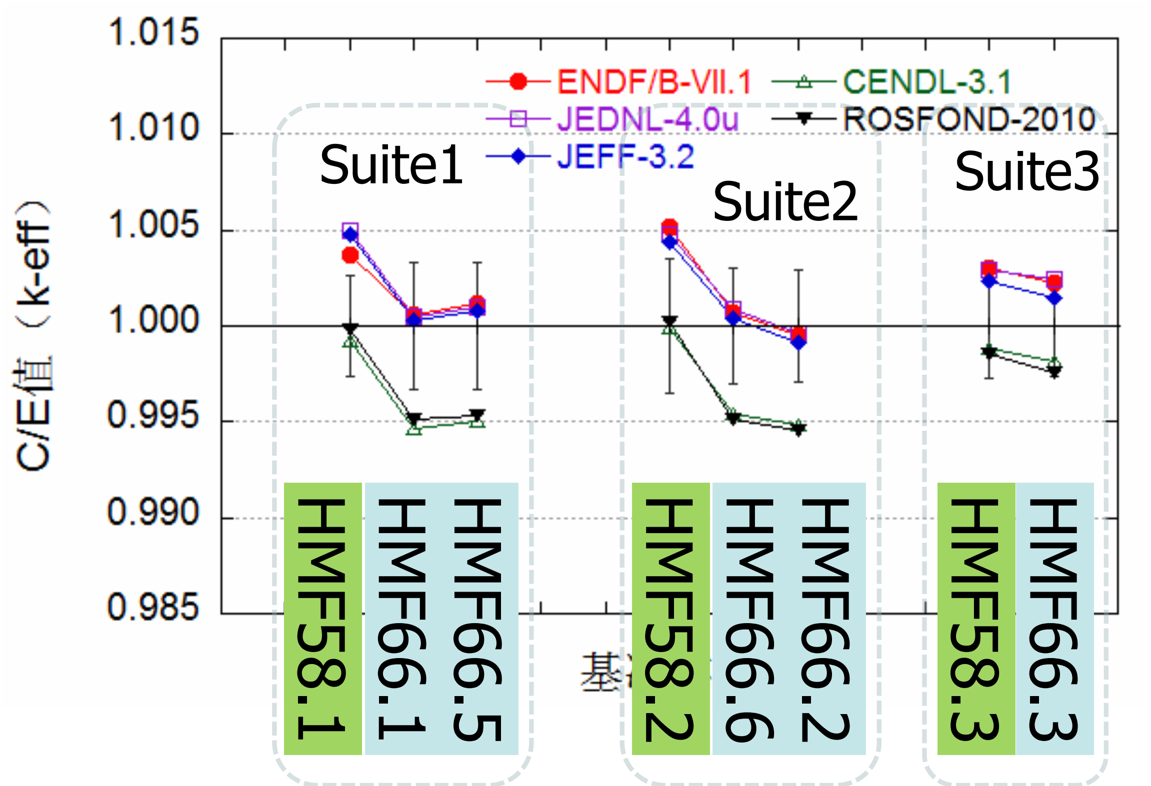
Systems with E index close to 1, having similar sensitivities.

k_{eff} calculations for similar experiments

- Nuclear data libraries
  - ENDF/B-VII.1
  - JEDNL-4.0
  - JEFF-3.2
  - CENDL-3.1
  - ROSFOND-2010
- Transport calculation
  - OpenMC 0.6 (with continue energy cross sections)
  - $\sigma < 10$ pcm

k_{eff} calculations for similar experiments

■ C/E (Calculated/Experimental) values for k_{eff}s



- Suite1:
  - Exps. from different benchmarks, deviations of C/E 400-500 pcm;
  - Same benchmarks, consistent result
- Suite2:
  - different benchmarks, deviations ~500 pcm;
  - Same benchmarks, consistent result
- Suite3:
  - different benchmarks, consistent result

Suites 1-2 : significant deviations

Solve the conflict by improving nuclear data?

If nuclear data are improved as

$$\boldsymbol{\sigma} \rightarrow \boldsymbol{\sigma}' = \boldsymbol{\sigma} + \Delta\boldsymbol{\sigma}$$

So the k_{eff} for two system 1 and 2 are changed to

$$k_{eff}^{1\,\prime} = k_{eff}^{1} + \Delta k_{eff}^{1} \qquad\qquad k_{eff}^{2\,\prime} = k_{eff}^{2} + \Delta k_{eff}^{2}$$

Where

$$\Delta k_{eff}^{1} / k_{eff}^{1} \cong \mathbf{S}_{k,\sigma}^{1} \cdot \Delta\boldsymbol{\sigma} / |\boldsymbol{\sigma}| \qquad\qquad \Delta k_{eff}^{2} / k_{eff}^{2} \cong \mathbf{S}_{k,\sigma}^{2} \cdot \Delta\boldsymbol{\sigma} / |\boldsymbol{\sigma}|$$

Since $\mathbf{S}_{k,\sigma}^{1} \sim \mathbf{S}_{k,\sigma}^{2}$, $\Delta k_{eff}^{1} \sim \Delta k_{eff}^{2}$.

C/E for k_{eff}^{1} and k_{eff}^{2} are not consistent, then C/E for $k_{eff}^{1\,\prime}$ and $k_{eff}^{1\,\prime}$ are not consistent.

Solve the conflict by improving nuclear data?

There is little (no?) chance to calculate all experiments in HMF58 and HMF66 very well by improving nuclear data.

How about re-evaluating the experimental values for k_{eff}?

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conclusions

- There are experiments of high similarity from HMF58 and HMF66 respectively , accessed by E index.
- The deviations up to 500 pcm between C/E values for k_{eff} for experiments of high similarity from different benchmarks are observed. The reliability of beryllium nuclear data can not be checked by these benchmarks.
- It may be impossible mission to improve the k_{eff} calculations for both HMF58 and HMF66 benchmark experiments by revising relevant nuclear data.
- We suggest that some of beryllium reflected criticality benchmarks be re-evaluated. And new criticality experiments similar to the two benchmarks are valuable for testing beryllium nuclear data.

Thank you for your attention!