Dispelling the Myth of Super-Moderators

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Outline

- **Introduction**
  - Motivation
- **Basic Theory**
  - Inelastic Scattering
  - (n, xn') reactions
  - Elastic Scattering
- **Application**

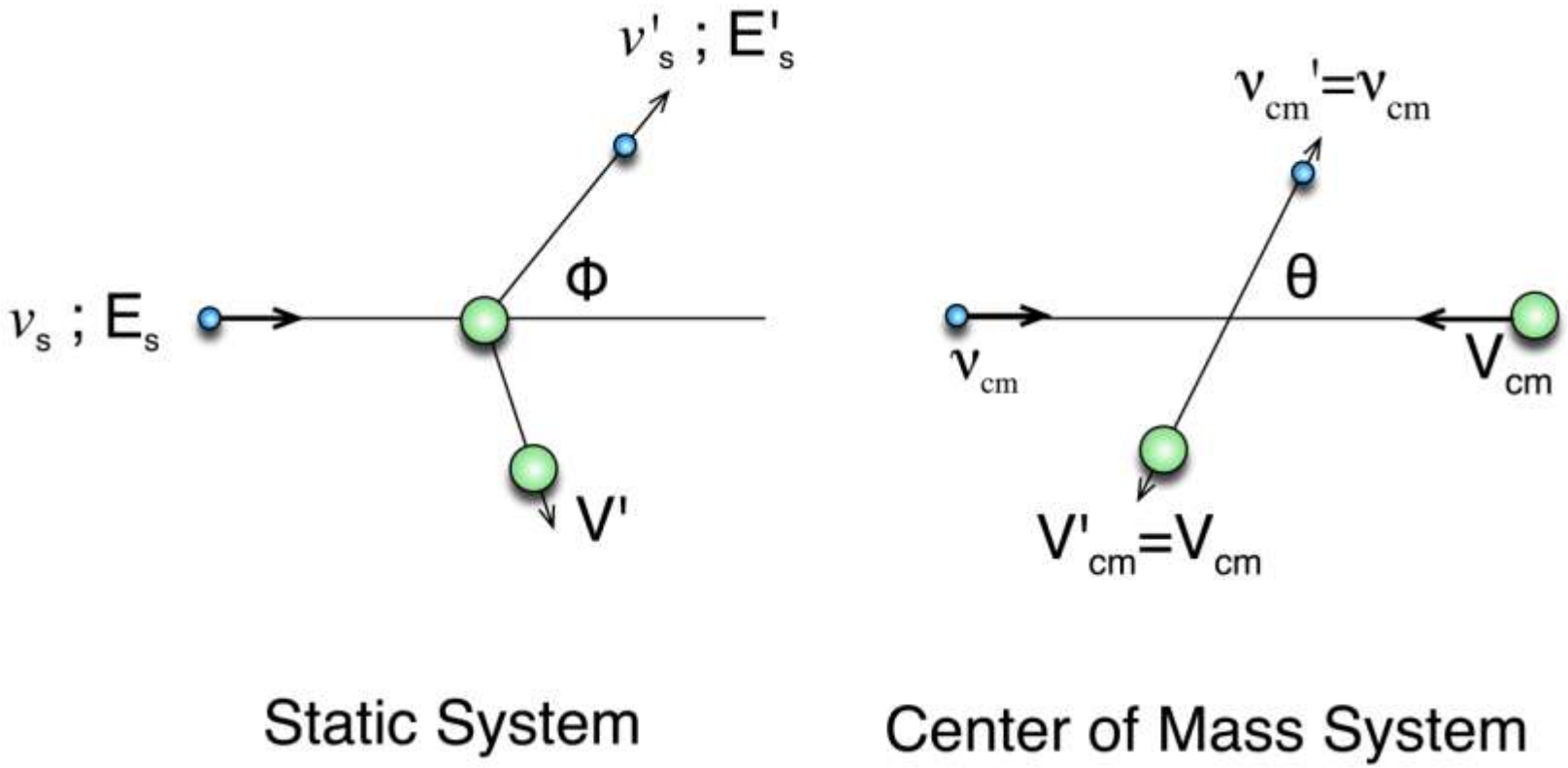
Introduction

- **Disturbing misuse of language**
  - Creeping into official review comments from auditing agencies
    - May lead to inappropriate response and redirection of already taxed and crucial resources
  - Case in point ***super-moderators***
- **Why should we care when presumably the intent is known**
  - We are professionals and as such we have an obligation to be technically accurate
  - Mentoring new staff is difficult enough without using inaccurate and incorrect terminology

Basic Theory of Moderation

- **Neutrons slow down via interactions with nuclei**
  - Compound nucleus interactions
    - Inelastic scattering, (n,n')
    - (n, xn') reactions
  - Elastic scattering
- **Compound nucleus reactions**
  - Colliding neutron is captured by the nucleus
  - Threshold reactions
  - For all but very energetic neutrons the inelastic spectrum is discrete
  - Regardless the inelastic spectrum does not include a thermal component

Reference Frames



Elastic Scattering Energy Loss

$$E'_s = \frac{1}{2} E_s \left[(1+\alpha) + (1-\alpha)\cos\theta \right]$$ In which $$\alpha = \left(\frac{A-1}{A+1} \right)^2$$

Therefore for forward scattering, i.e., no scatter

$\theta = 0$ $E'_s = E_s$ No Energy Loss

And for maximum scatter (head on)

$\theta = 180$ $E'_s = \alpha E_s$ Maximum Energy Loss

The Only Super Moderator

$$\alpha = \left(\frac{A-1}{A+1} \right)^2$$

- **For hydrogen A=1 and α=0**
- **$\alpha \Rightarrow 1$ as A increases**
- **A neutron can**
  - Lose all of its energy in a single collision with hydrogen
  - Lose only a fraction of its energy in collisions with all other nuclei

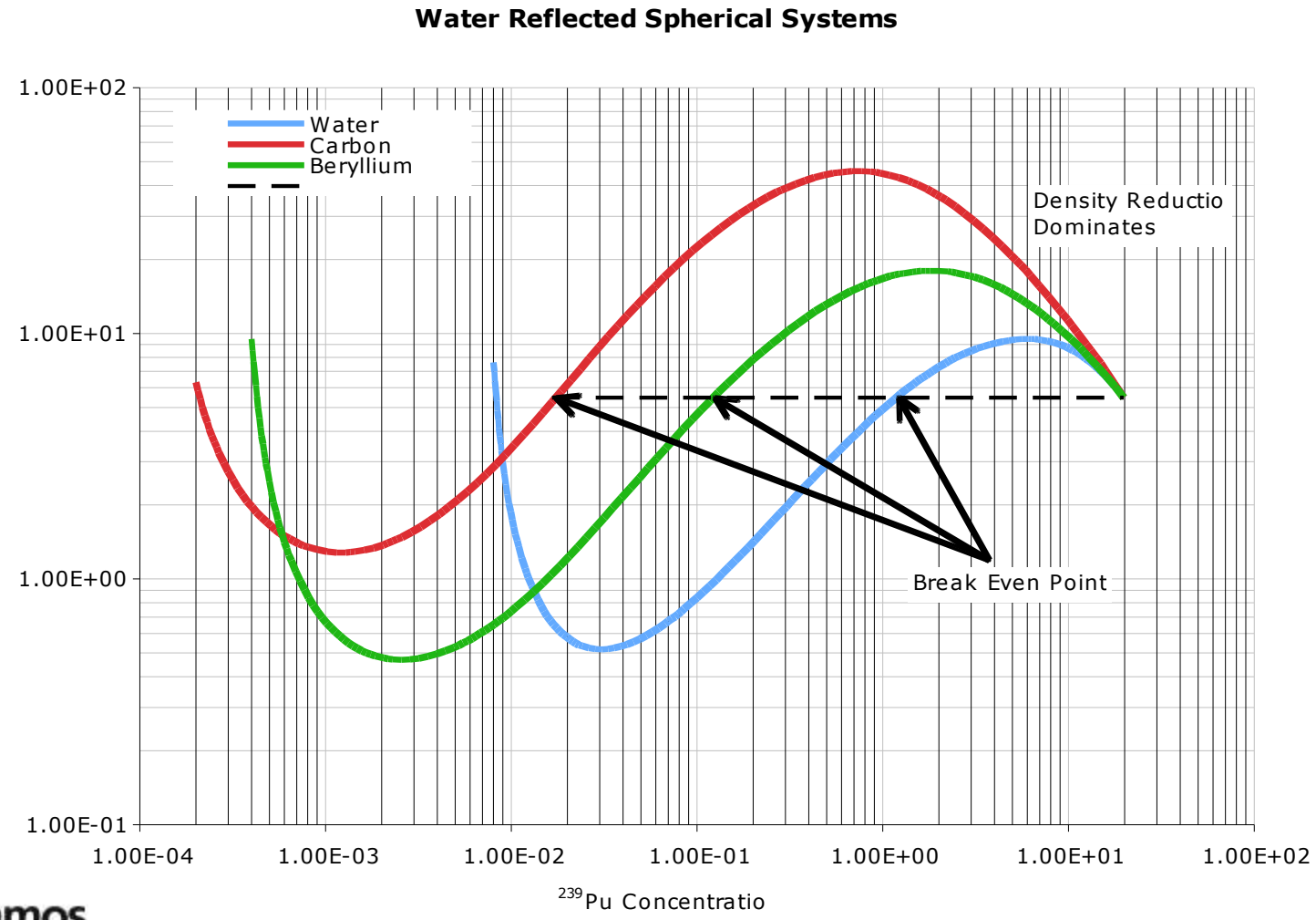
Hydrogen Is As Good As It Gets

Nucleus	Mass Number	α	Maximum Percent Loss	Average # Collisions 2 MeV to Thermal
Hydrogen	1	0	100.0	26
Deuterium	2	0.111	88.89	31
Beryllium	9	0.640	36.0	92
Carbon	12	0.716	28.4	118
Oxygen	16	0.779	22.14	155
Iron	56	0.931	6.9	518
^{239}Pu	239	0.983	1.7	2130

Sources of Confusion?

- **Be moderated systems can have a smaller minimum critical mass water moderated systems**
- **Moderation by Be and C can lead to lower limiting critical densities**
- **Poor Nomenclature has resulted from applying critical mass results as a "definition" of a physical process**
  - Moderation is a process governed by kinematics;
  - The definition is not linked to critical mass data;
  - If it were the definition would be variable

Critical Mass Curve Comparison



The Actual Cause

- **A function of 9 independent (but degenerate) factors only one of which is moderation**
- **For a smaller critical mass to result**
  - Fission (absorption) fraction must be higher, either
    - There is less leakage

      OR
    - Greater fraction of thermal neutrons are available
- **In fact both of these are true**

Values @ Minimum Critical Mass

Material	M_c (grams)	x/Pu ratio	Σ_a Mod	Mass (kg) Mod	Core Volume (L)
Hydrogen σ_a=0.332b	517 (30.6 g/L)	865	2.2×10^{-2}	16.9	16.9
Beryllium σ_a=0.0091b	469 (2.6 g/L)	19,140	1.1×10^{-3}	339	183
Carbon σ_a=0.0034b	1284 (1.3 g/L)	34,874	3.8×10^{-4}	2250	1000

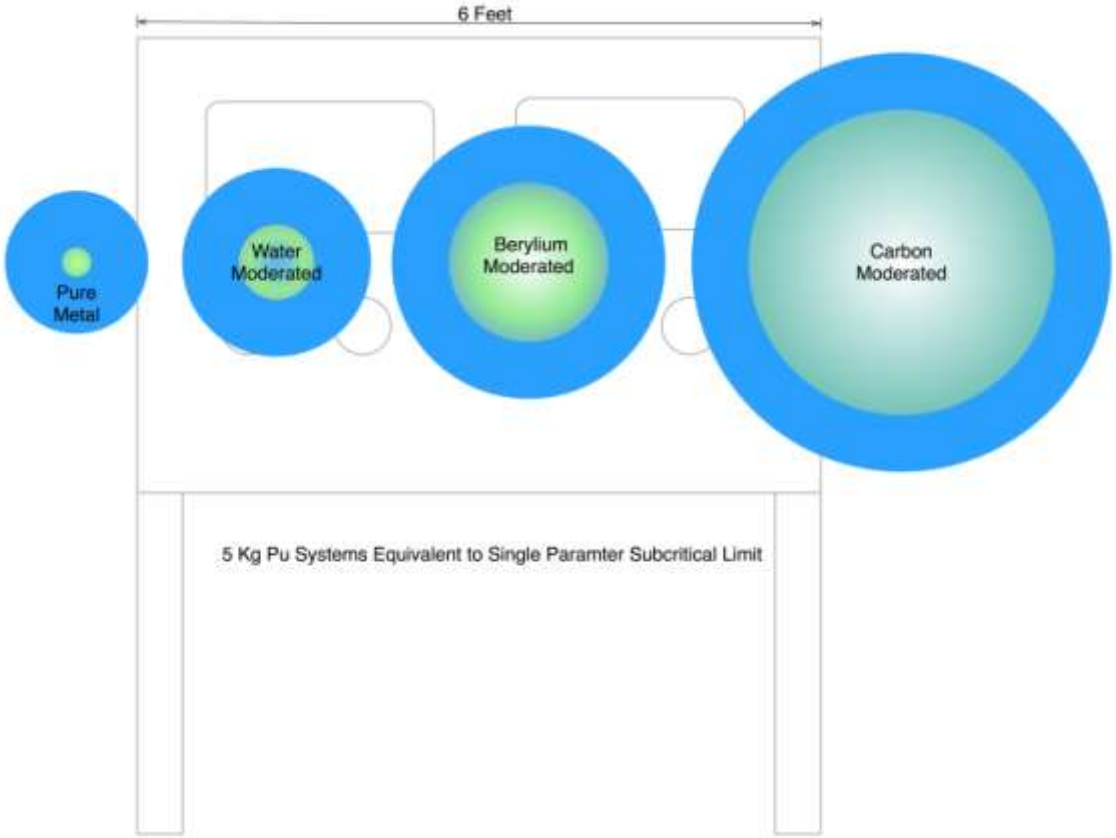
Break Even Point Values (M_c=5.49 Kg)

Material	ρ_c (g/L)	x/Pu ratio	Mass (kg) Mod	Core Volume (L)	System Volume (L)
Hydrogen	1019	21.1	4.36	4.63	70
Beryllium	122.4	399	82.4	44.8	217
Carbon	17.4	2578	709	315	794

Application

- **The fact that Be moderated systems has a marginally lower critical mass is of no practical importance**
- **The amount of material required just to re-establish the reactivity to undiluted system is very large**
  - Processes that would encounter such situations are very rare
    - Experiments designed to test this very attribute
    - Exotic fuel manufacturing that does not exist as of now

5 kg Single Parameter Subcritical Limit Unit Size Comparison



Reflectors

- **There are conditions in which there are reflecting materials superior to water**
  - Generalizations are just a imprudent in the case of reflectors as in the case of moderators
  - There are the same multiple competing factors of scattering that effects leakage, moderation, and absorption

Conclusion

- The language used by professionals needs to be correct, particularly in a safety discipline
- Basic collision dynamics demonstrates there is no better moderator than hydrogen
- Smaller critical masses for Be are not due to superior moderation but less absorption and leakage
- In all but esoteric applications it is not a practical concern