Neutron Detection

From MeV to neV energies

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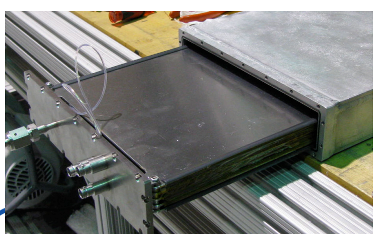
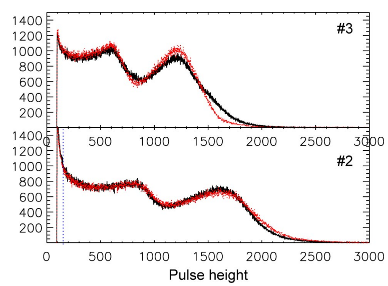
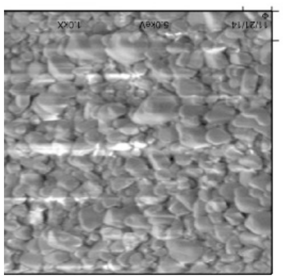
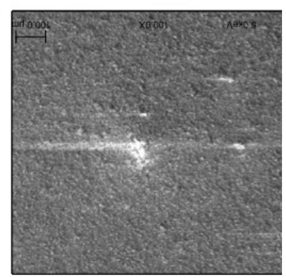
Los Alamos National Laboratory

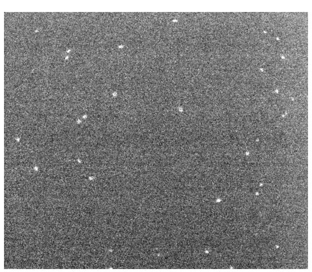
EDIT 2018, Fermilab





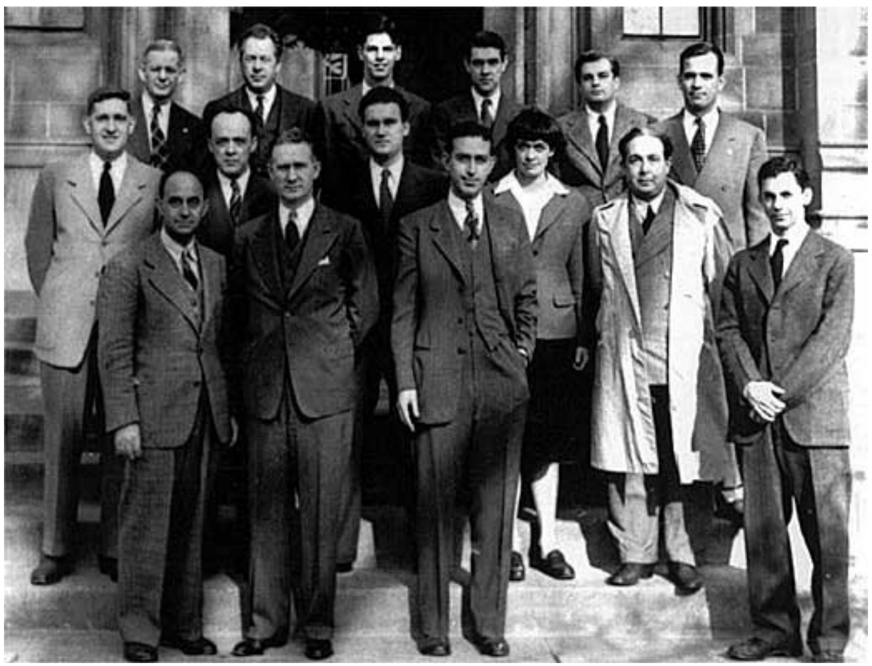


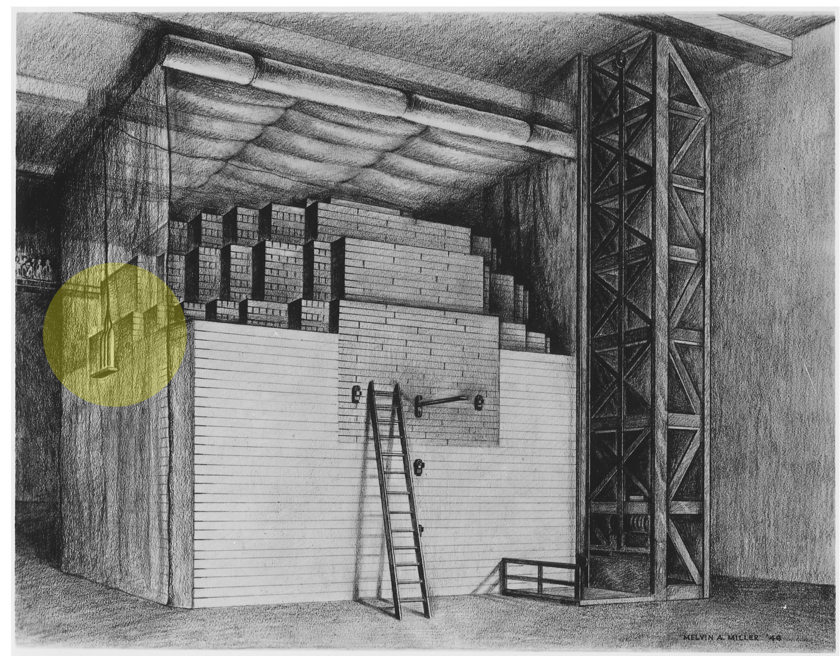




Fermi & neutron detection

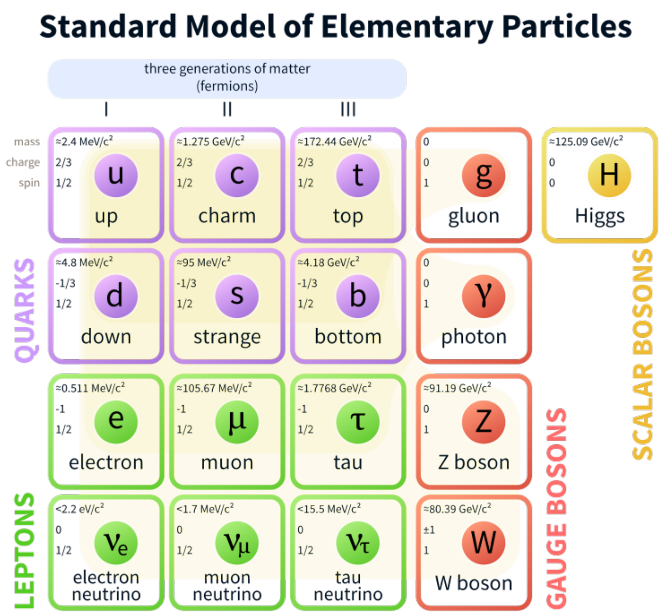
On Dec. 2, 1942, Fermi & his team achieved sustained chain reaction, and the first fission reactor. Key elements: fuel, neutron moderator, control rod, neutron detector, and radioactivity detector.

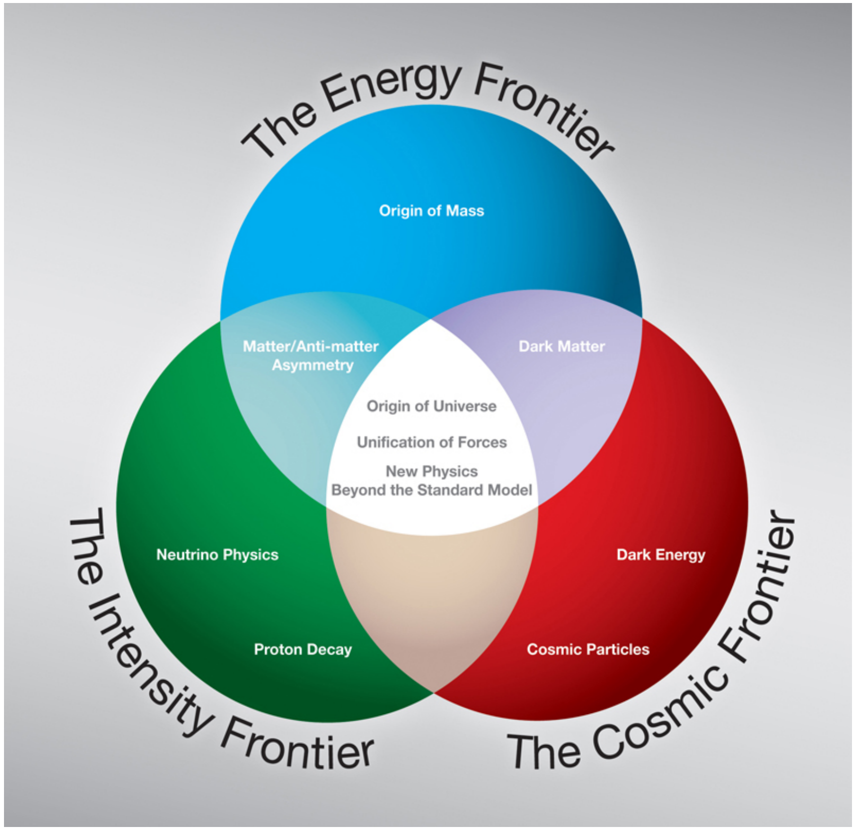


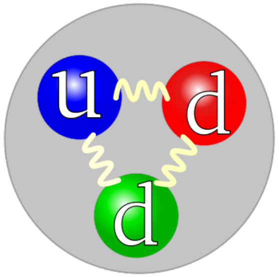


Chicago Pile-1 (CP-1)

What is a neutron?

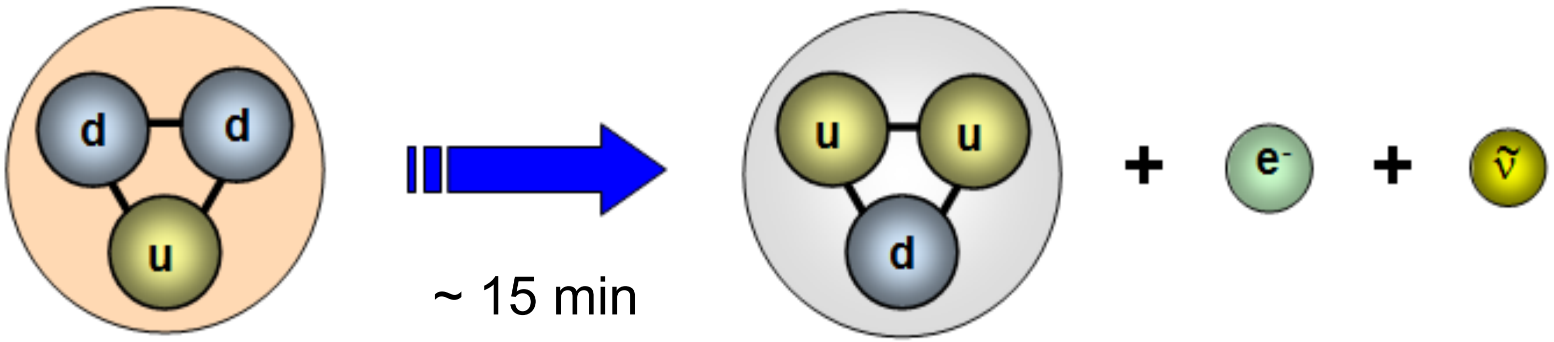






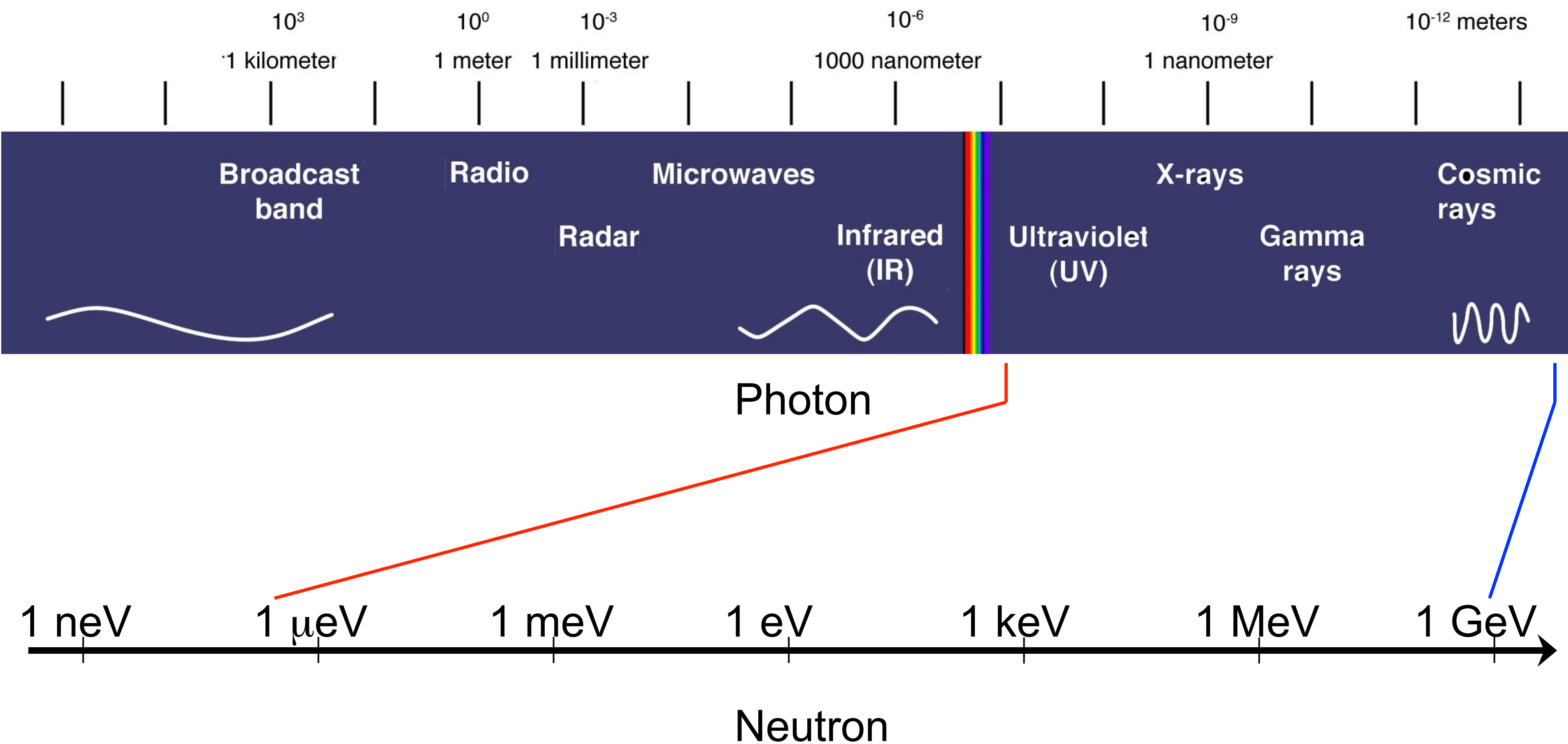
Physics beyond the standard model : Neutron approach

Beta$^-$ decay: $n \rightarrow p + \beta^- + \tilde{\nu}$



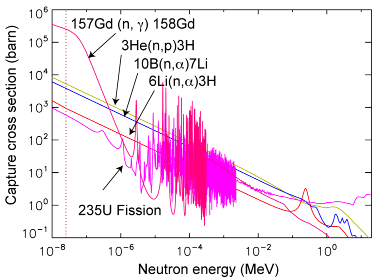
- Neutron β-decay
- Neutron EDM
- Neutron lifetime
- Matter-antimatter
- Dark matter
- …

Neutron detectors: illuminating the neutron world

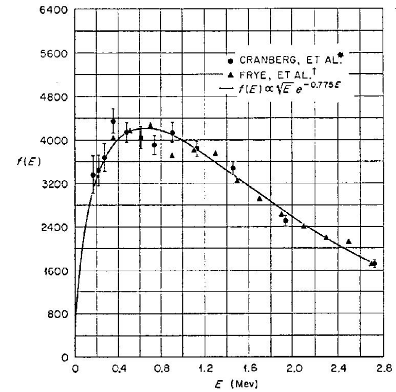


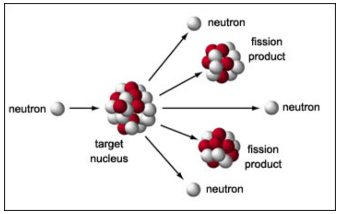
What does the world look like if eyes can see neutrons?

Neutron sources & detectors : mutually dependent



moderation

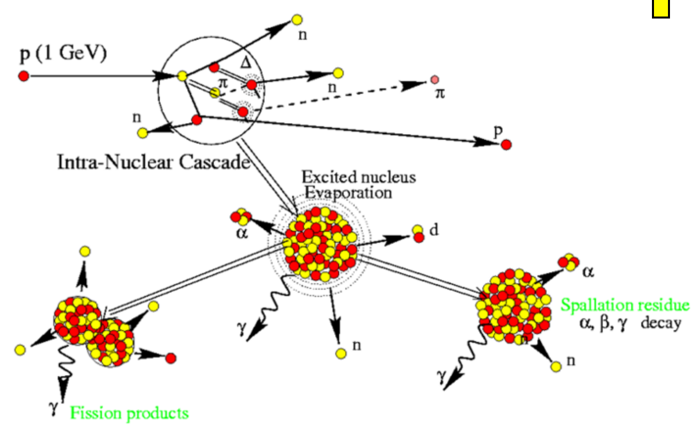




1 neV   1 μeV   1 meV   1 eV   1 keV   1 MeV   1 GeV

$1\text{x}10^2$ n/cm^2/s

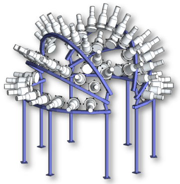
$1\text{x}10^{15}$ n/cm^2/s

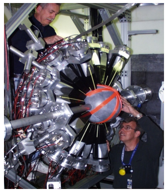


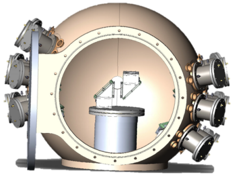
Outline

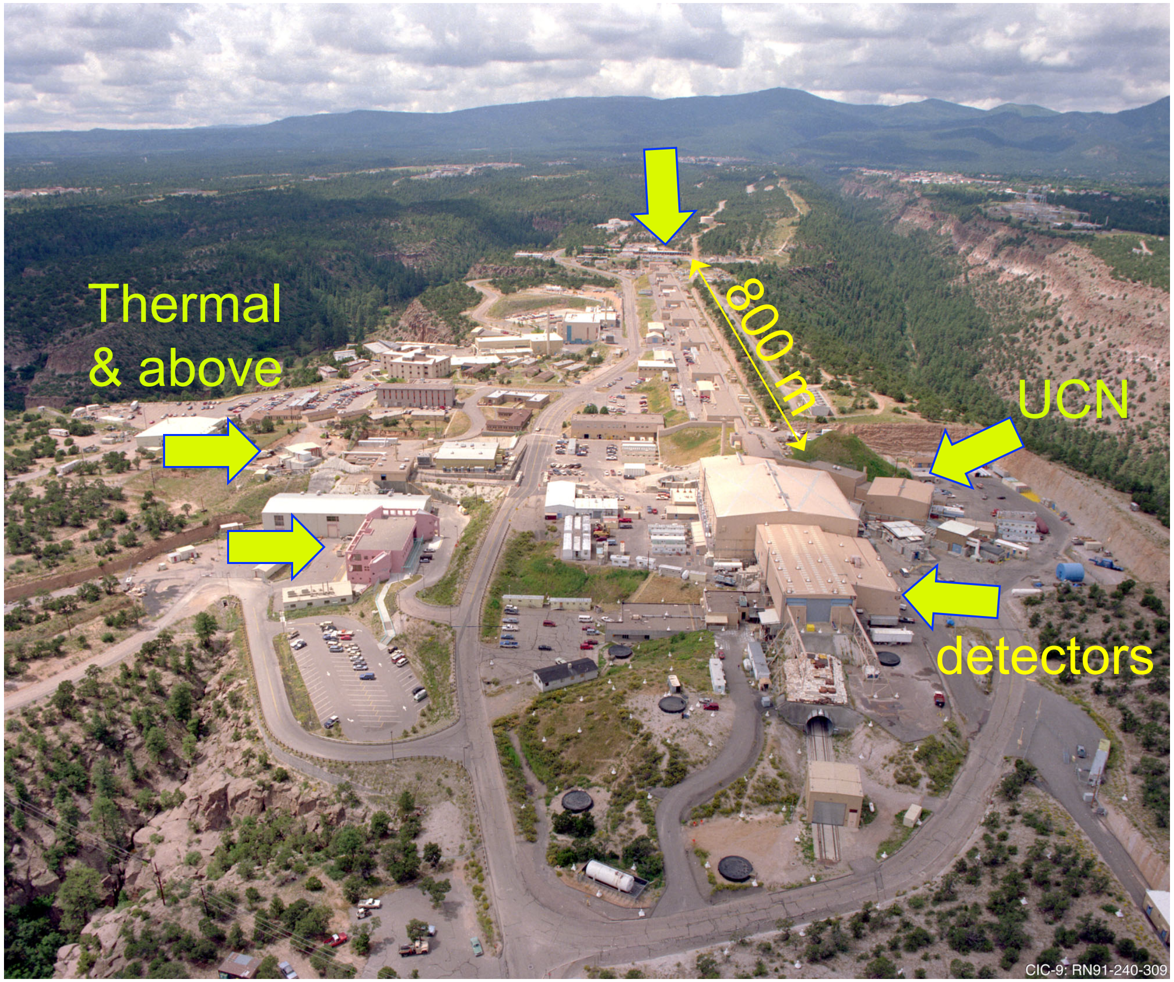
- LANSCE neutron source
- ^{10}B Detectors for ^{3}He replacement
- Ultracold neutron detectors and sciences
- Future perspectives

Los Alamos Neutron Science Center (LANSCE)

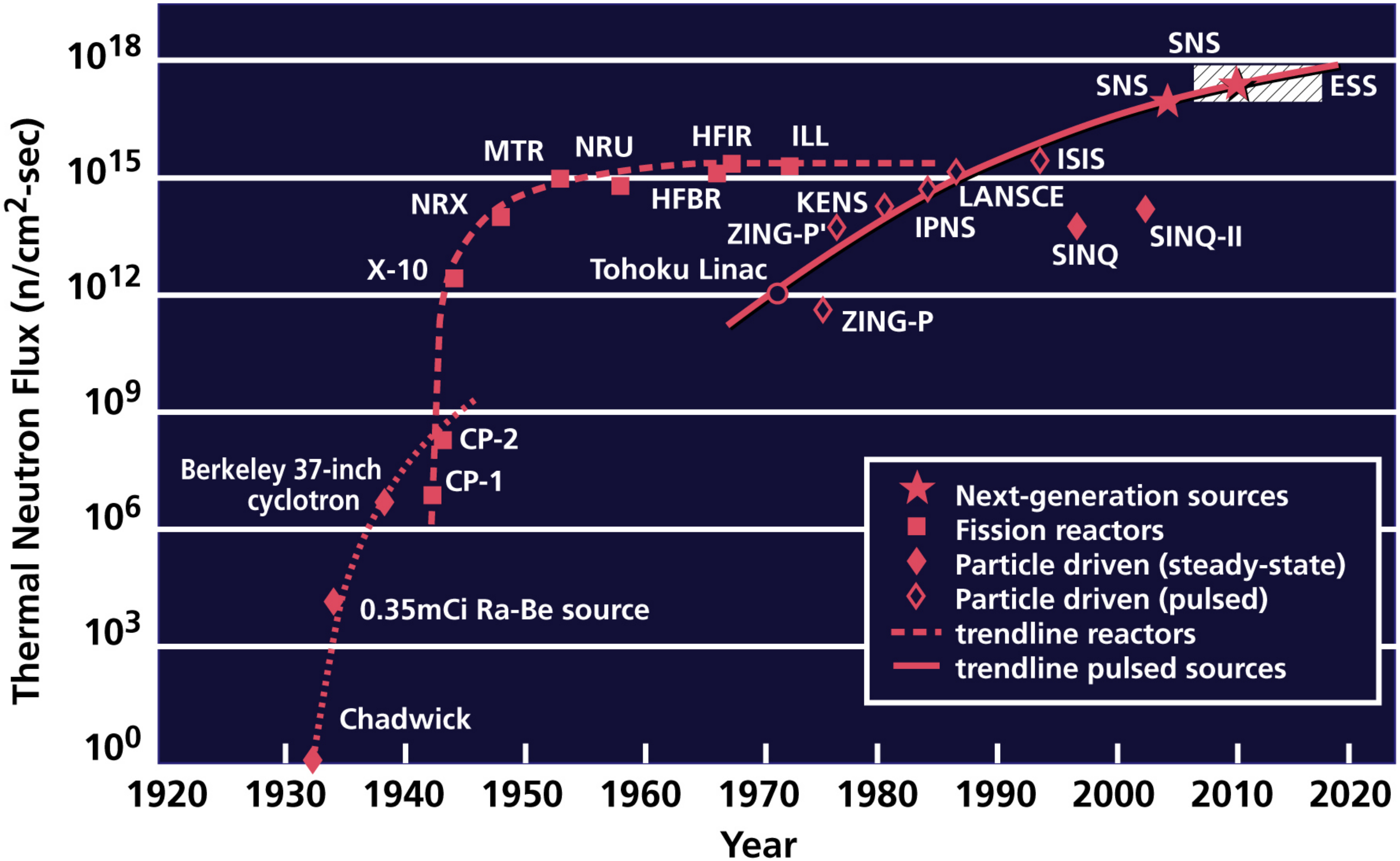








Evolution of neutron source



(Updated from *Neutron Scattering*, K. Skold and D. L. Price: eds., Academic Press, 1986)

T. E. Mason (SNS/ORNL)

Outline

- Introduction to LANSCE (a neutron source)
- **^{10}B Detectors for ^{3}He replacement**
- Ultracold neutron detectors and sciences
- Future perspectives

Fermi's neutron detector

PHYSICAL REVIEW VOLUME 72, NUMBER 3 AUGUST 1, 1947

A Thermal Neutron Velocity Selector and Its Application to the Measurement of the Cross Section of Boron

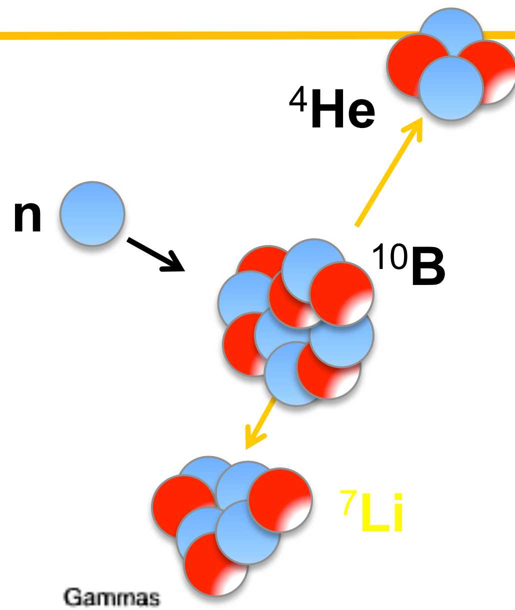
E. Fermi, J. Marshall, and L. Marshall
Argonne National Laboratory, University of Chicago, Chicago,** Illinois*

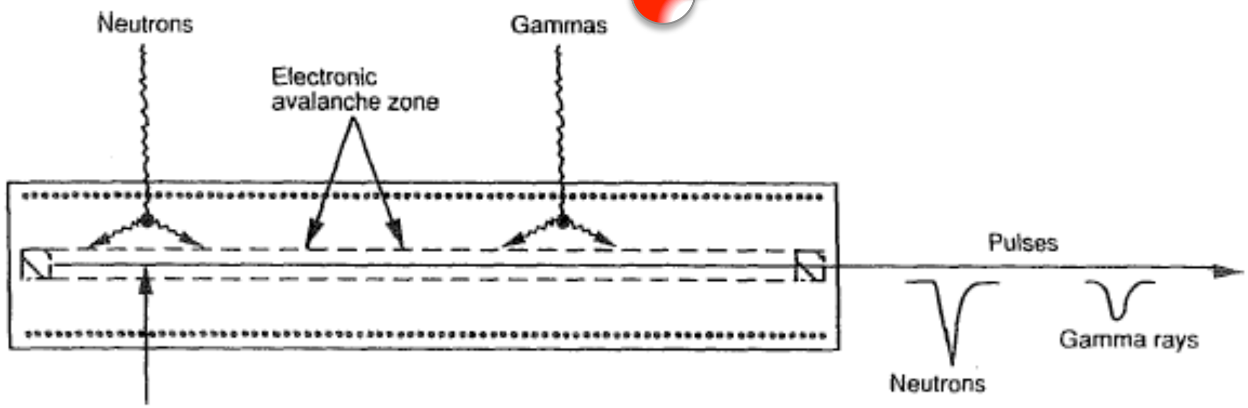
(Received April 25, 1947)

In all cases the detector was a proportional counter filled with BF_3 gas. By the use of cad-

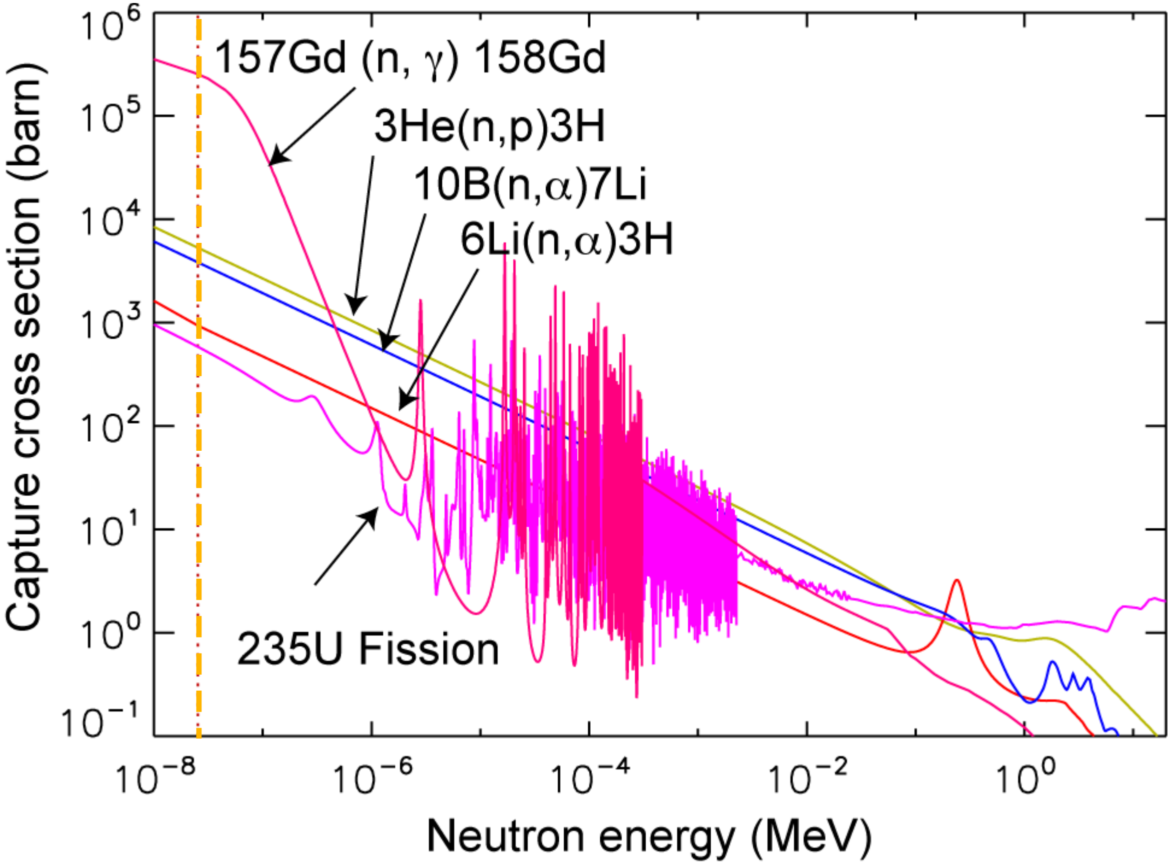
How does it work?

Natural boron
Has ~ 20% ^{10}B





^{10}B vs ^{3}He

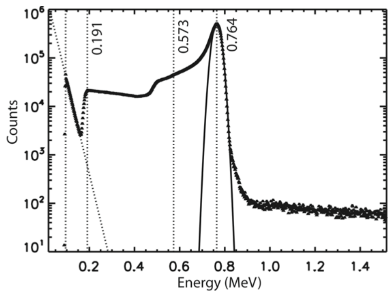


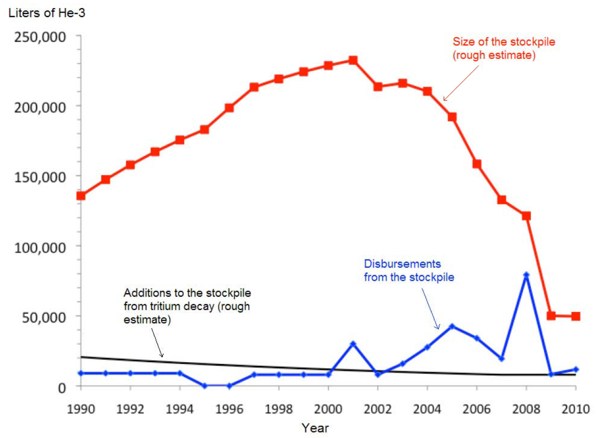
- Inert
- Non-toxic
- Gaseous state
- (Rare)

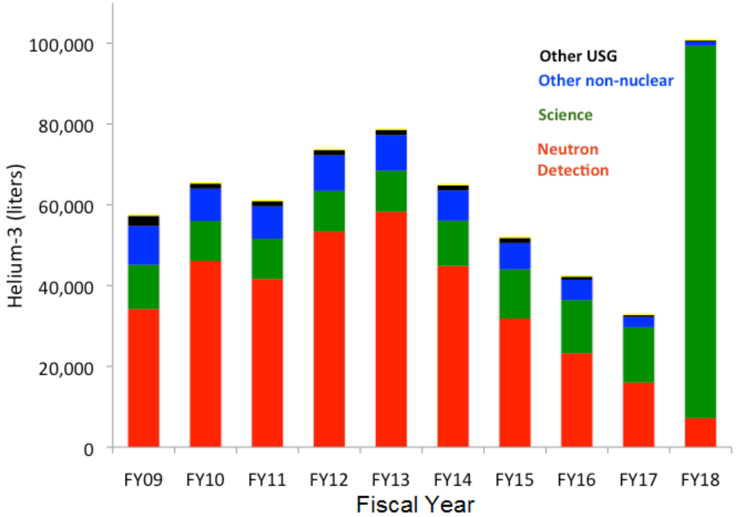
σ (^{10}B) ~ 72% σ (^{3}He)

^{3}He shortage

- **started in 1950s → buildup of tritium (^{3}H) for H-bombs**
  - Tritium β-decay, $^3H \rightarrow {}^3He + \beta\ (^-e)$
- **Neutron detection,**
  - $n + {}^3He \rightarrow p + {}^3H + 0.76$ MeV
- **^{3}He stockpile decline ~ 2001.**







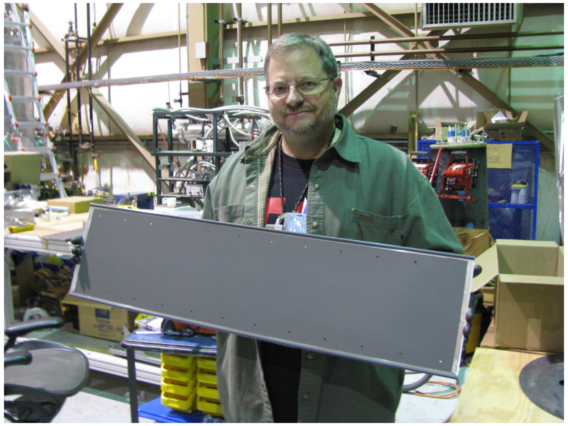
D. A. Shea & D. Morgan, *CRS Reort (2010).*

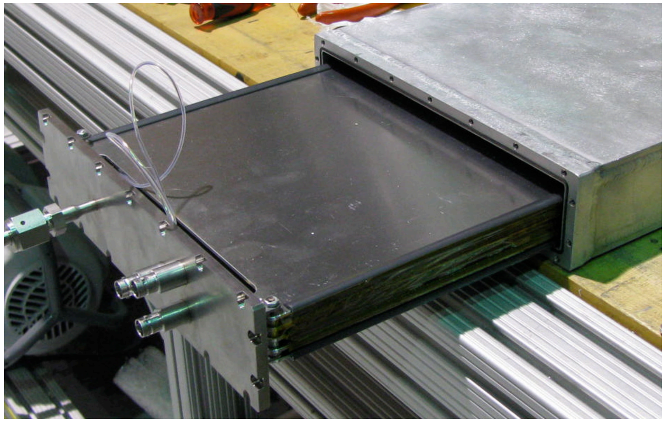
Alternative ^{3}He productions

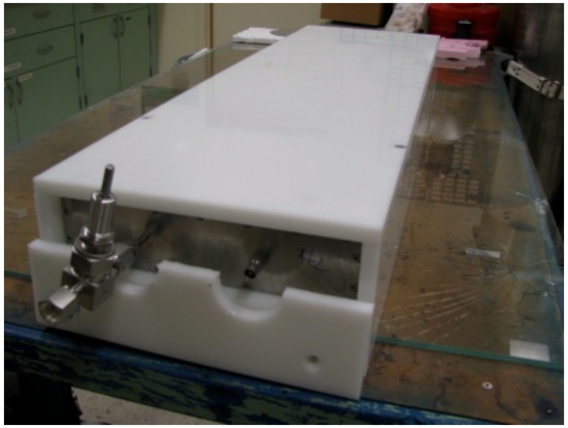
- **Natural ^{3}He, ~ 7 PPT(trillion) in th**
- **Tritium supply, ~ 20 kg**
  - Essentially single source
    - OPG (Canada)
  - High cost, \$100k - \$300k/g
    ~ \$27k – 80k/L
- **Moon mining (solar fusion)**
- **Tritium breeding (ITER)**

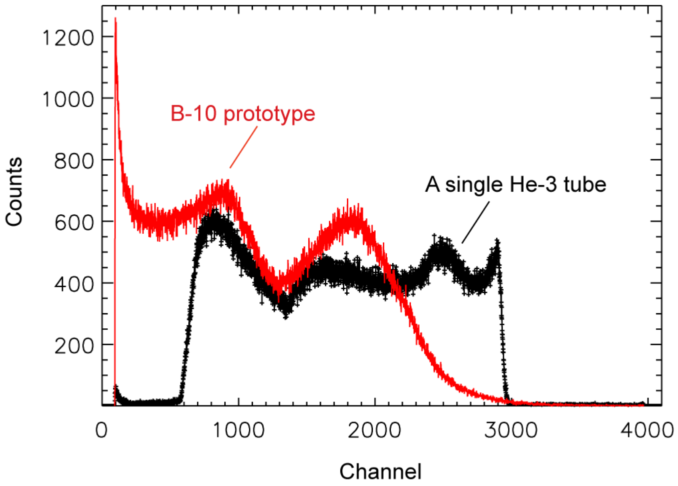
$$n + {}^6\mathrm{Li} \rightarrow {}^4\mathrm{He} + {}^3\mathrm{H} + 4.8\ \mathrm{MeV}$$

The ^{3}He shortage problem – our solution, ^{10}B powder

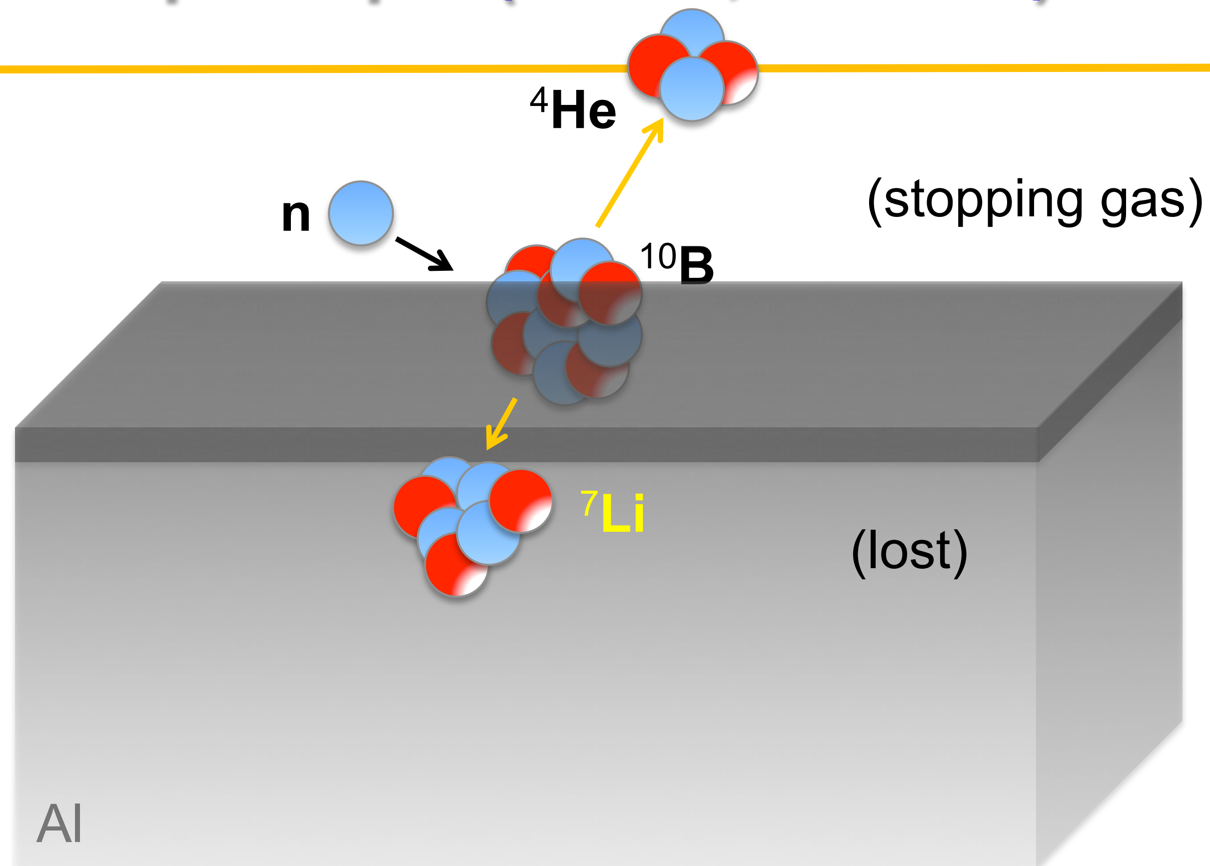








Detection principle (n → α, ^{7}Li → e$^-$)



$$^{10}B + n \rightarrow \begin{cases} ^7Li\,(0.84\text{ MeV}) + \alpha\,(1.47\text{ MeV}) + \gamma\,(0.48\text{ MeV}), & (94\%) \\ ^7Li\,(1.02\text{ MeV}) + \alpha\,(1.78\text{ MeV}), & (6\%) \end{cases}$$

Q = 2.79 MeV

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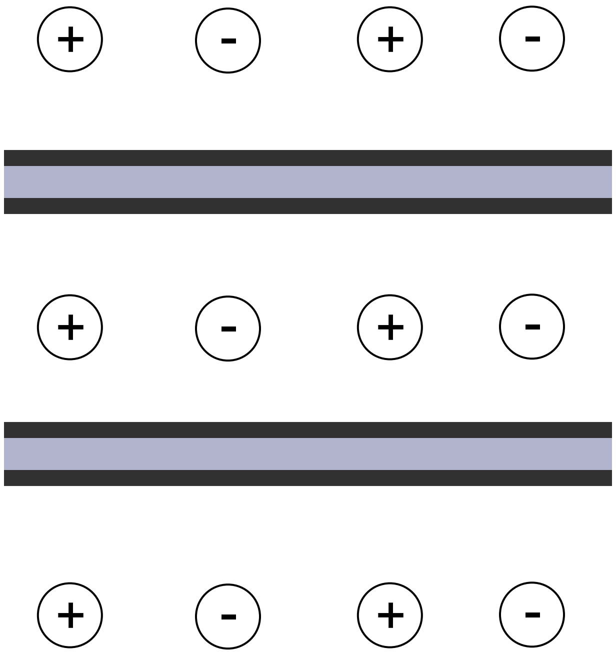
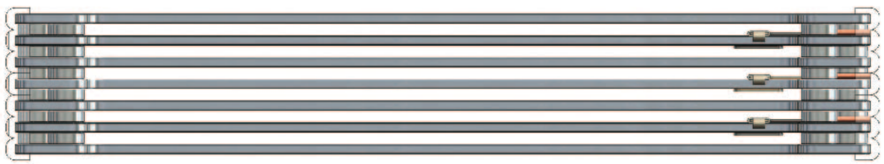
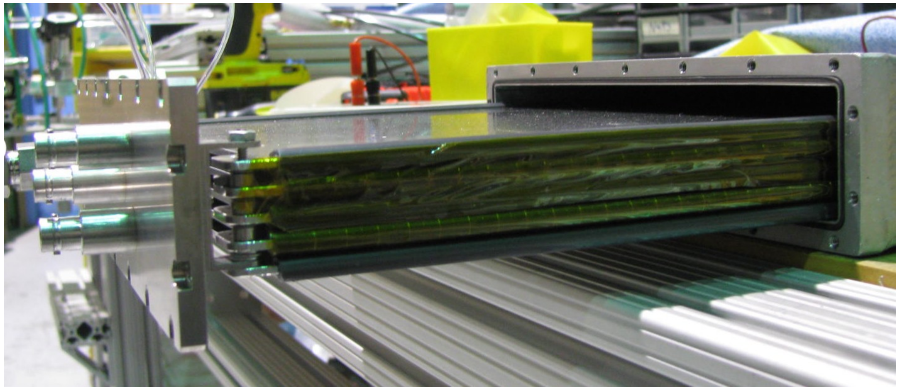
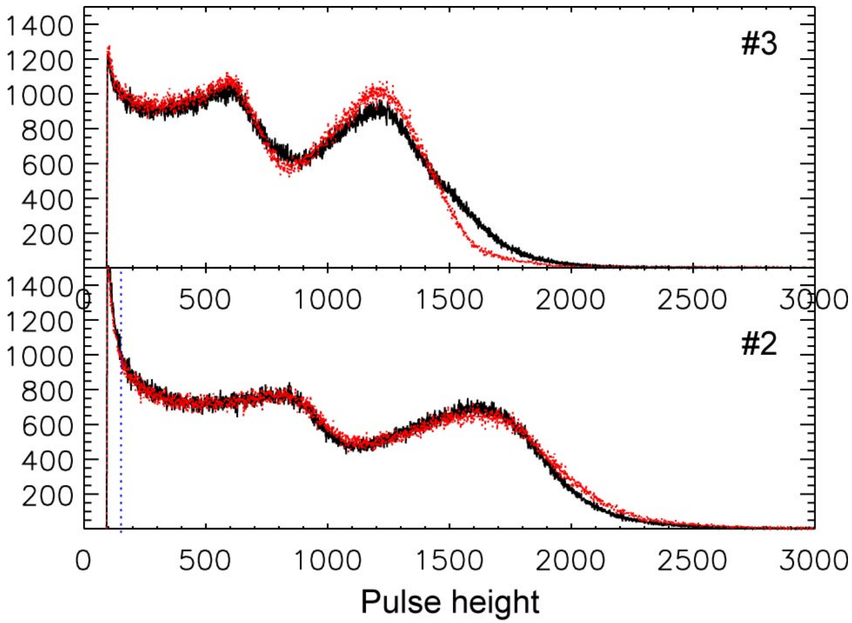
Charge collection: Double-helix electrode config.

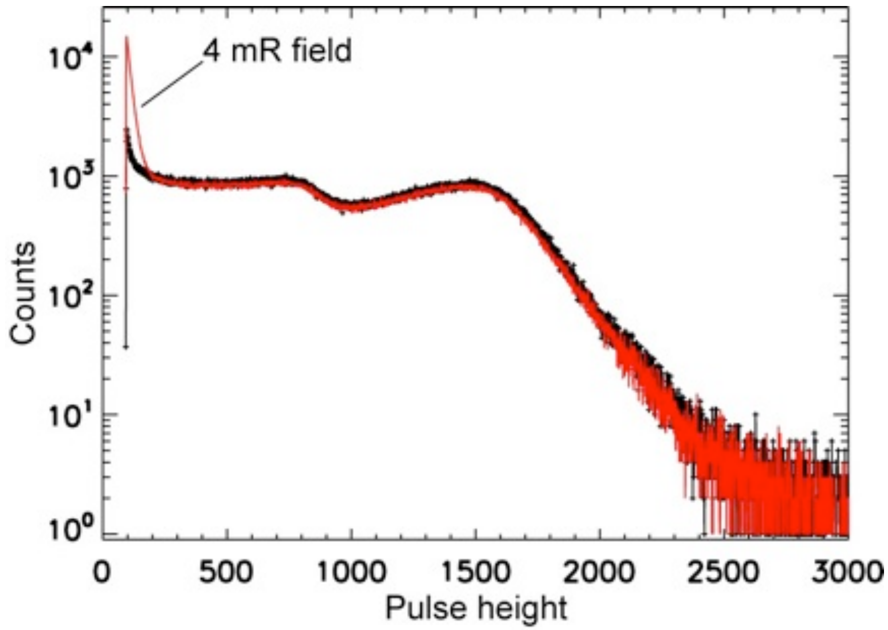






Performance (B): stability & γ-sensitivity





~ 18 months apart

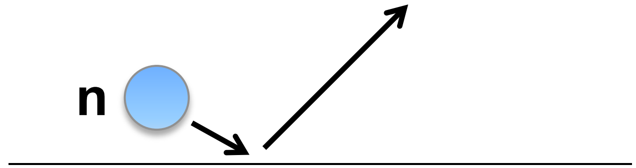
~ 10% efficiency loss

Outline

- Introduction to LANSCE (a neutron source)
- ^{10}B Detectors for ^{3}He replacement
- **Ultracold neutron detectors and science**
- Future perspectives

Fermi & ultracold neutrons

In 1936, Fermi realized first that the coherent scattering of slow neutrons would result in an effective interaction potential for neutrons traveling through matter; Experimental demonstration (1946, 1947);



How cold is ultracold ?

Material:	V_F[8]	v_C[9]	η (10^{-4})[9]
Beryllium	252 neV	6.89 m/s	2.0-8.5
BeO	261 neV	6.99 m/s	
Nickel	252 neV	6.84 m/s	5.1
Diamond	304 neV	7.65 m/s	
Graphite	180 neV	5.47 m/s	
Iron	210 neV	6.10 m/s	1.7-28
Copper	168 neV	5.66 m/s	2.1-16
Aluminium	54 neV	3.24 m/s	2.9-10

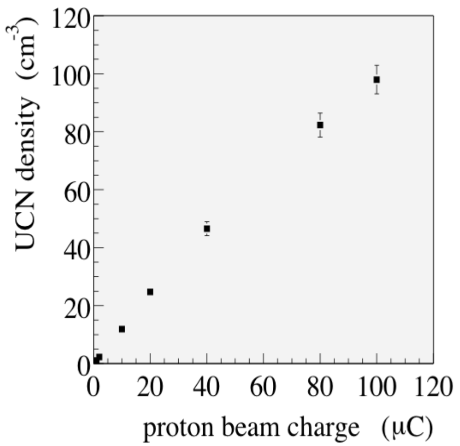
Fermi potential

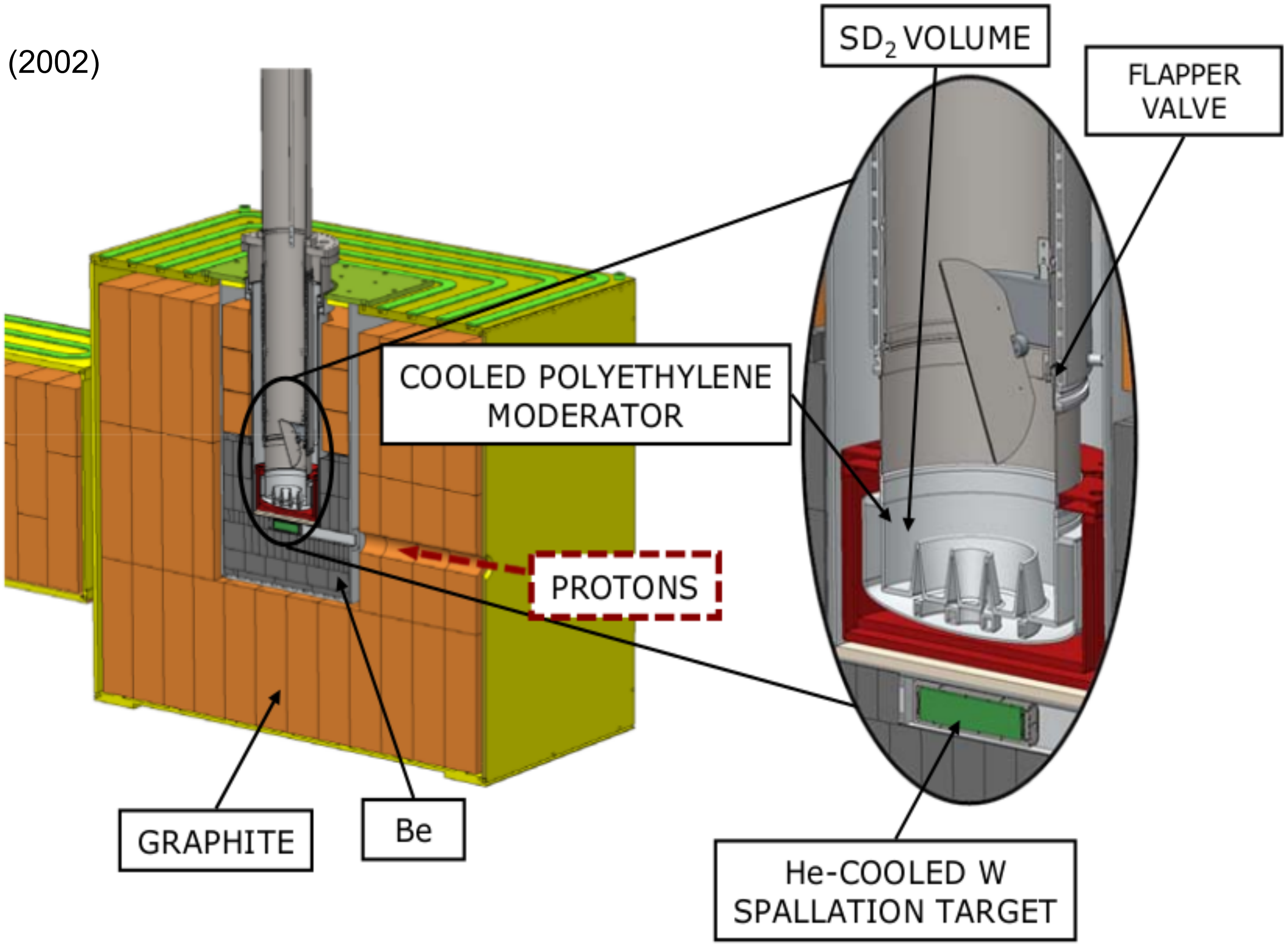
^{58}Ni = 335 neV

Gravity: 1 m ~ 102 neV
Magnetic field: 1 T ~ 60 neV

The LANL UCN Source

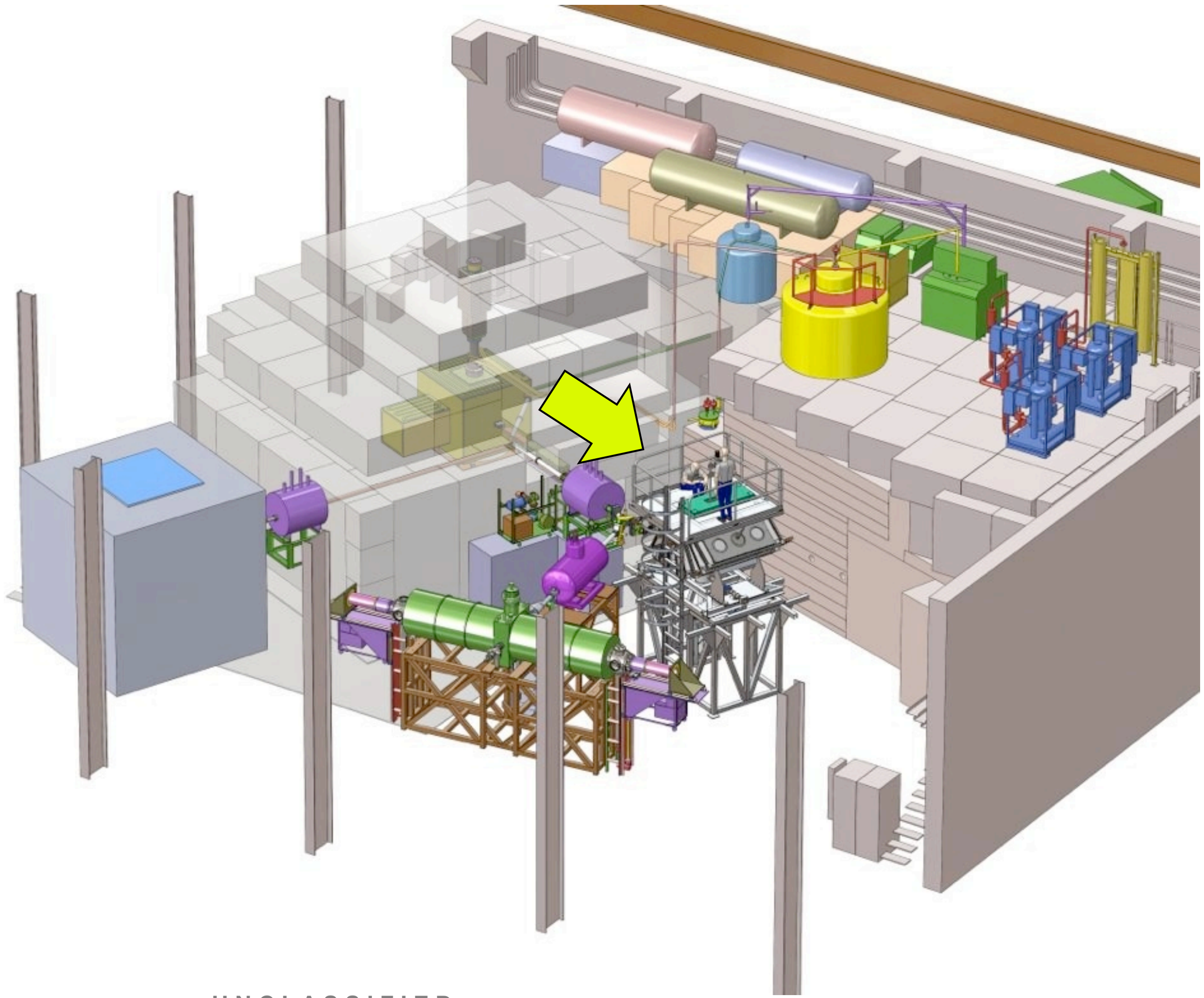
C. Morris et al., PRL 89, 272501 (2002)





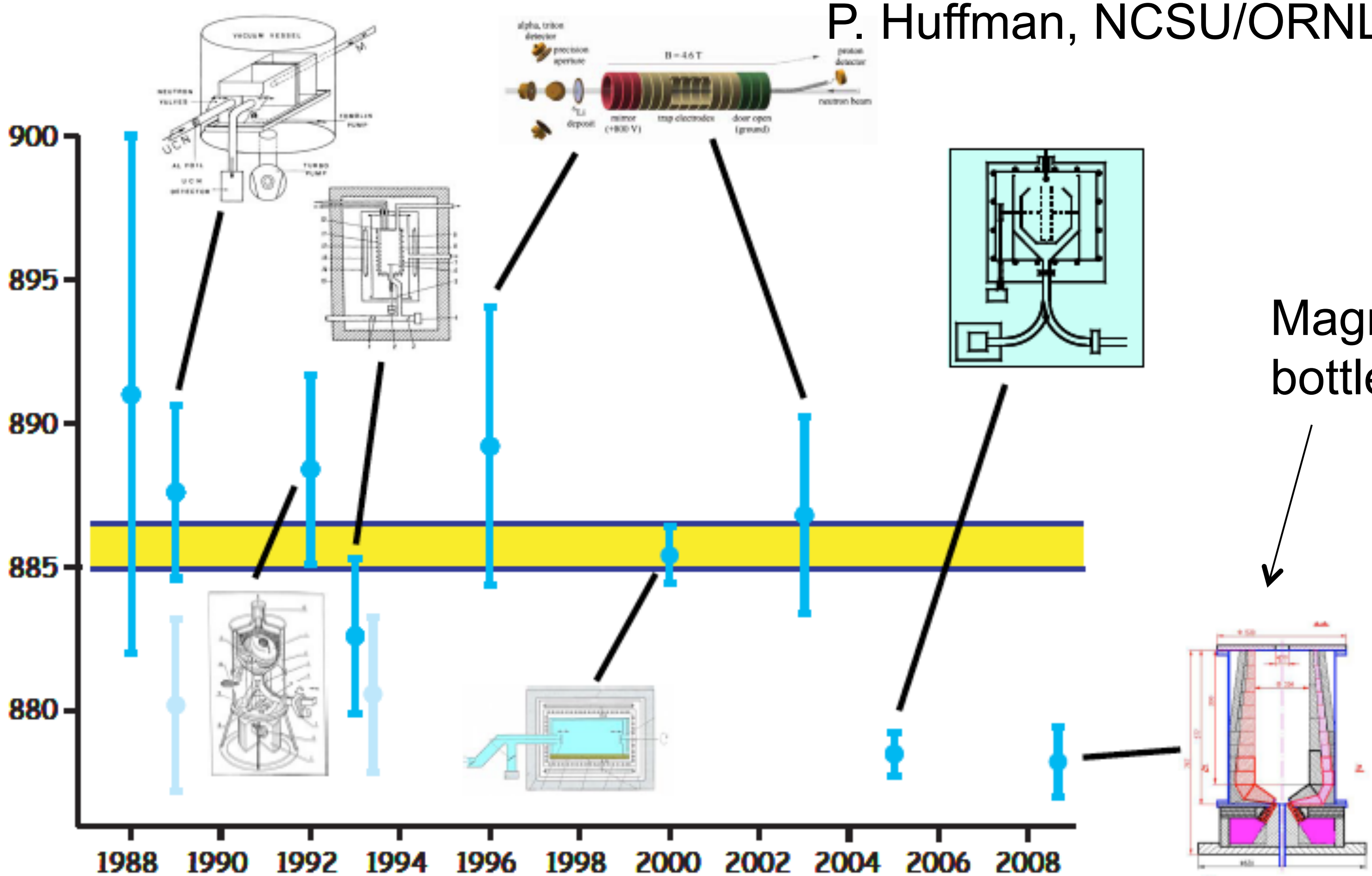
UCN science → Physics beyond the Standard Model

- Neutron EDM
- Neutron β-decay
- Neutron lifetime
- Dark matter
- …

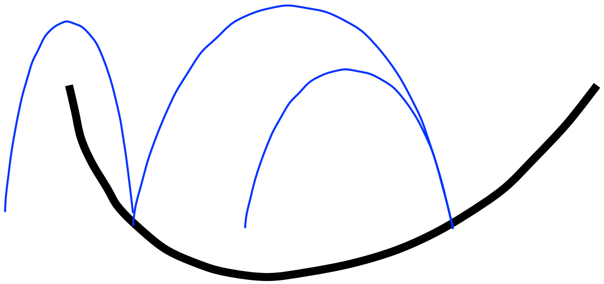


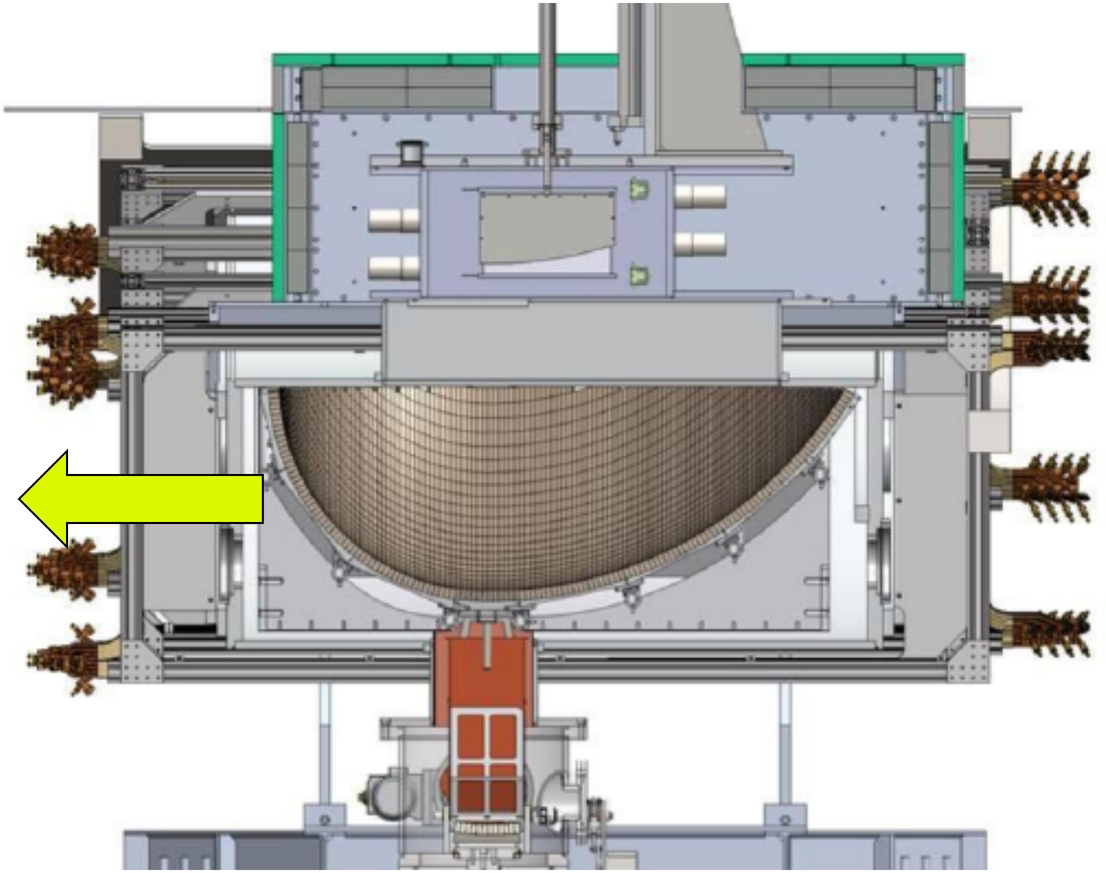
The neutron lifetime crisis → 1-3 sec resolution

P. Huffman, NCSU/ORNL (2009)



Neutron lifetime (UCNτ) experiment



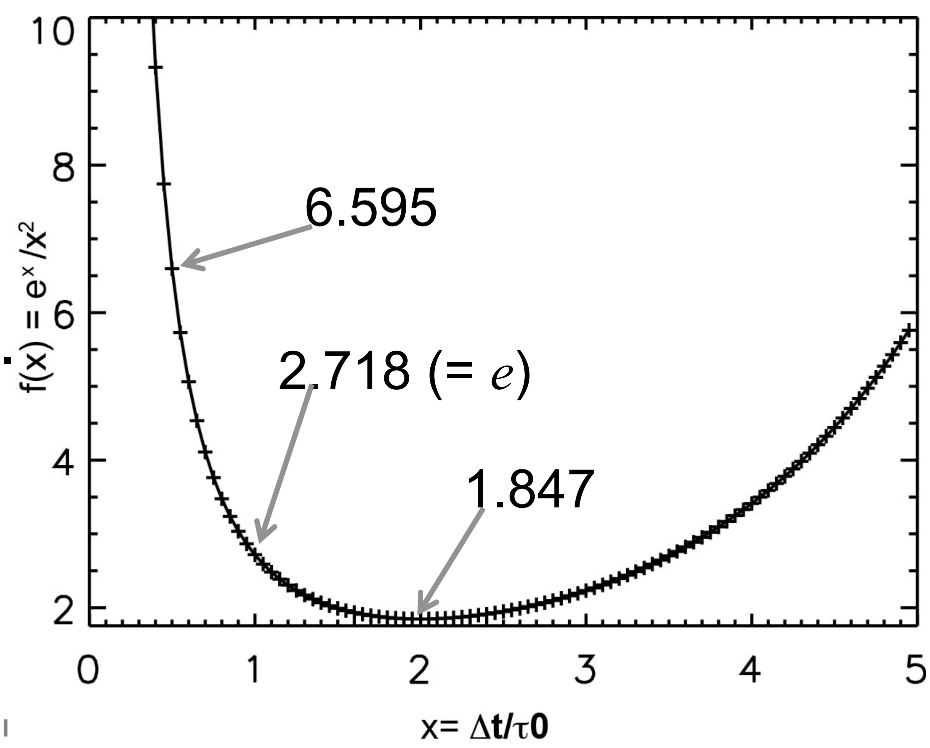


Detector design is important for accuracy

$$N_0 \geq \frac{K}{f\epsilon}\frac{\tau_0^2}{\delta\tau_0^2}\left(\frac{\tau_0}{\Delta t}\right)^2 \exp\left(\frac{\Delta t}{\tau_0}\right)$$

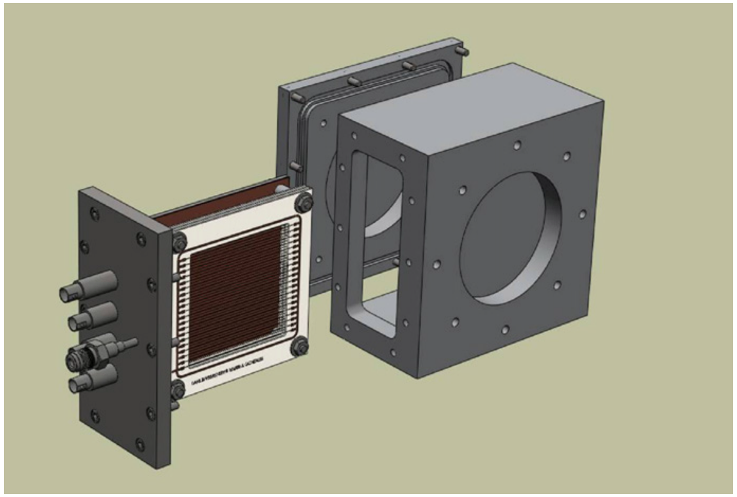
- **1 sec → $\tau_0/\delta\tau_0 \sim 10^3$.**
- ***K*= 1 - 2; *Δt*, waiting time;**
- ***f*ε, detection efficiency > 0.5;**
- **F(*Δt/*τ_0), a minimum exists (next slide).**
- **Phase-space dependence,**

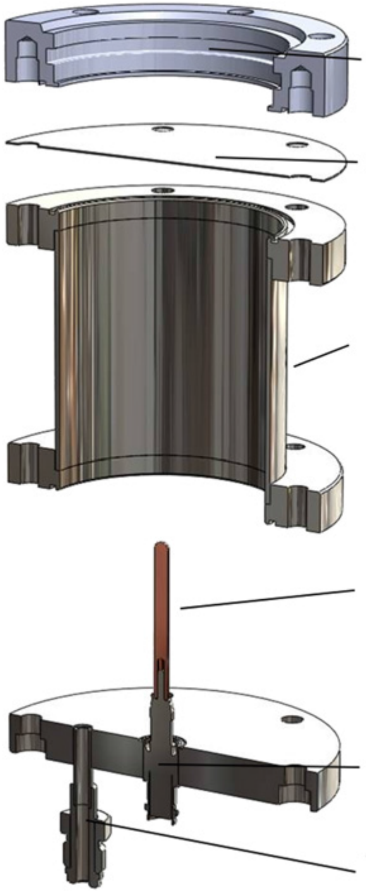
finite UCN trapping time,… ignored



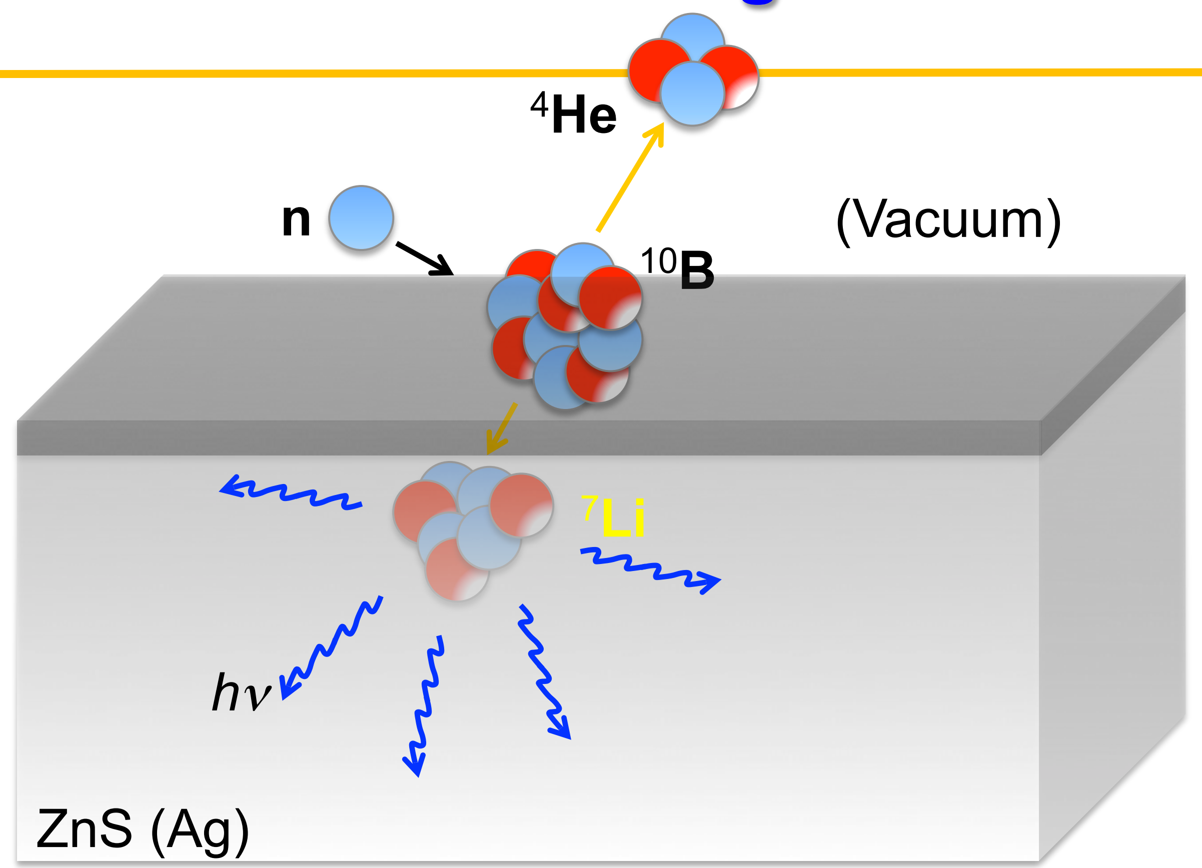
Gas detectors won't work

- ^{3}He-based
- ^{10}B –based





A solid-state detector using ^{10}B



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Q = 2.79 MeV

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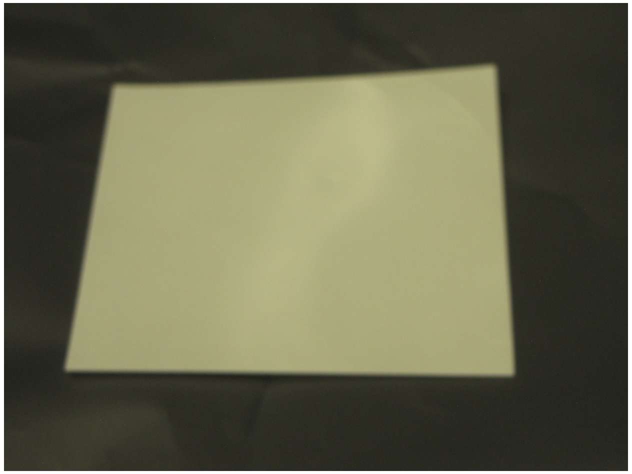
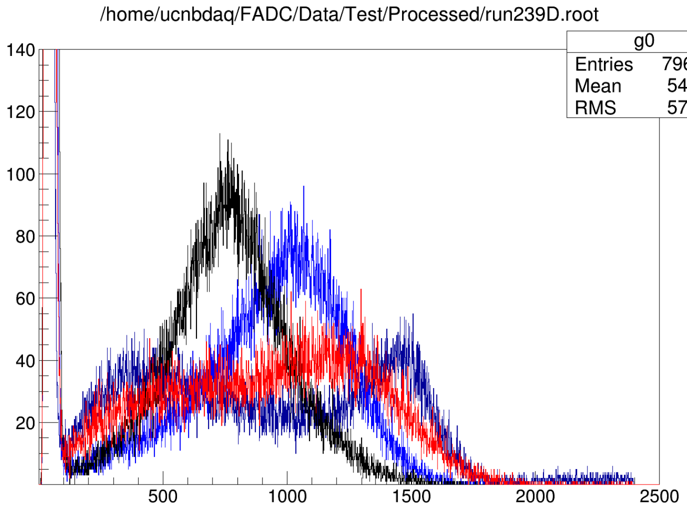
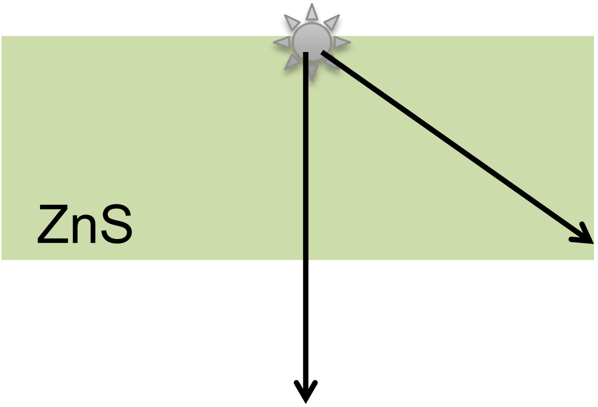
Operated by Los Alamos National Security, LLC for the U.S. Department of Energy's NNSA

Thin-film ZnS:Ag ~ old material (low cost)







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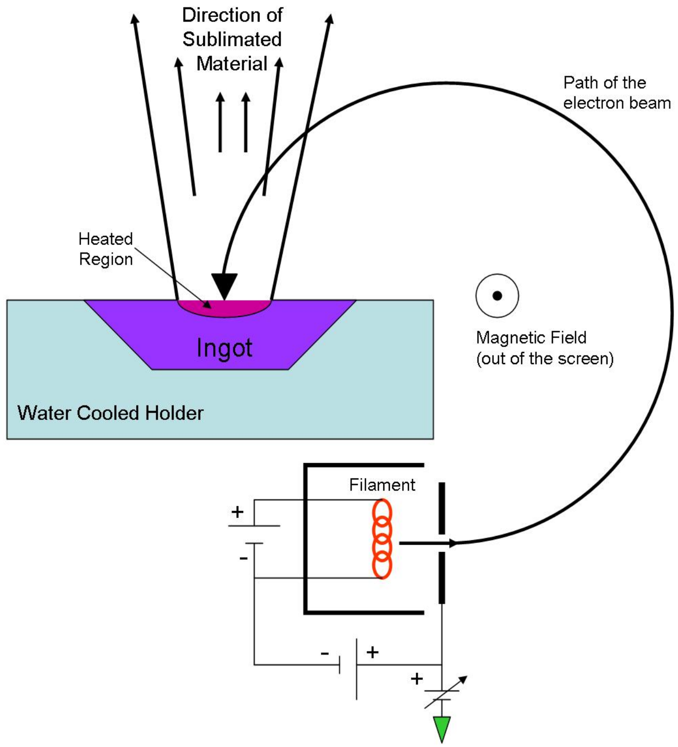
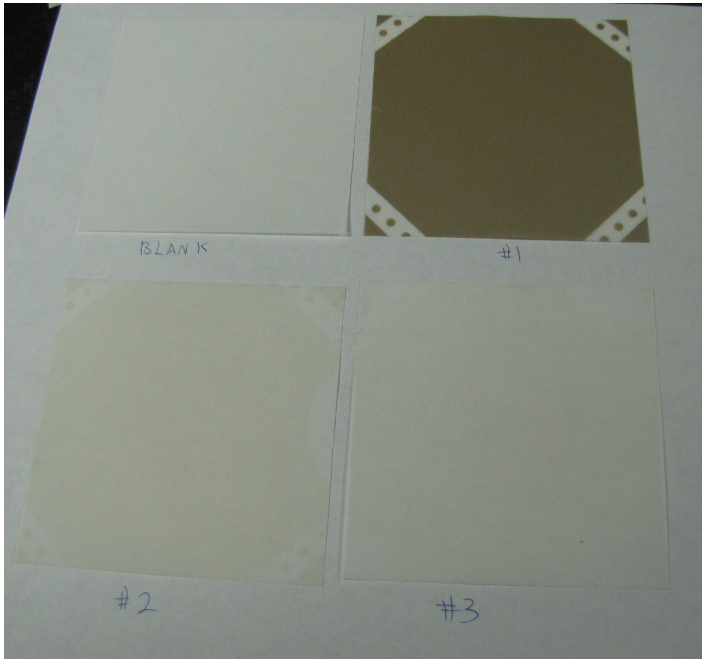
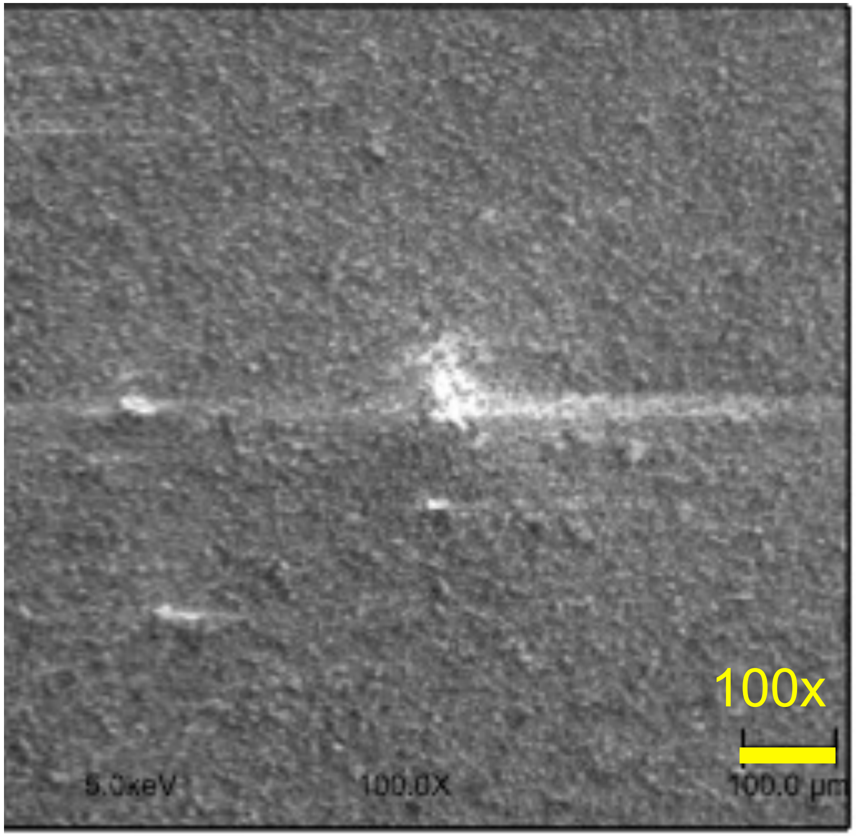
os National Security, LLC for the U.S. Department of Energy's NNSA

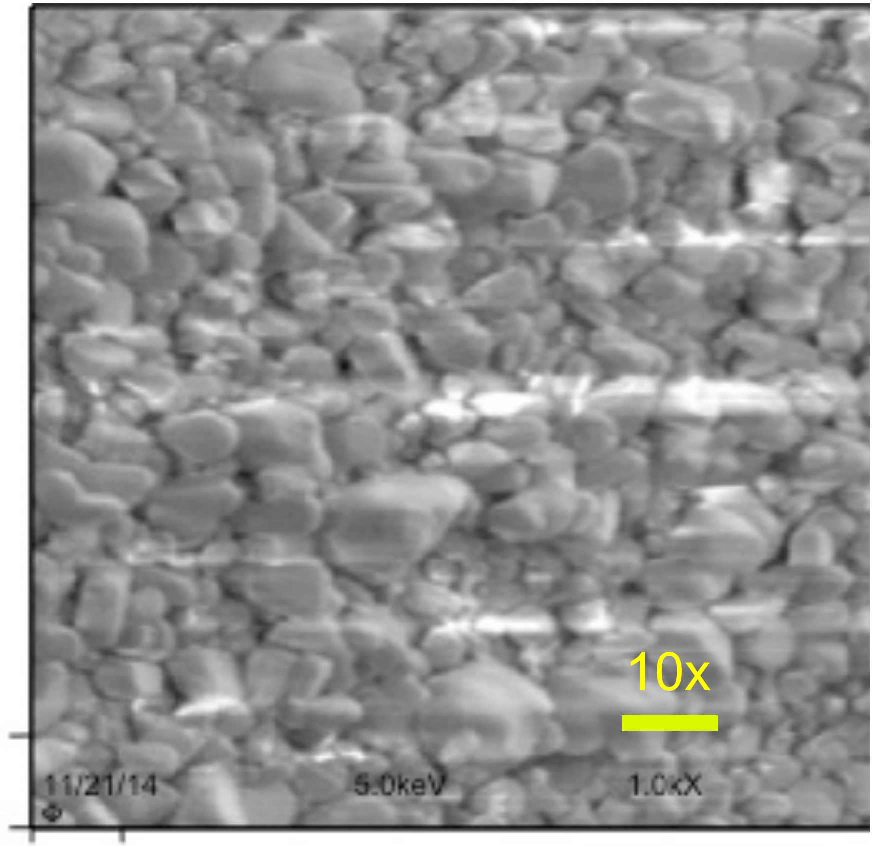
Fabrication: e-beam coating



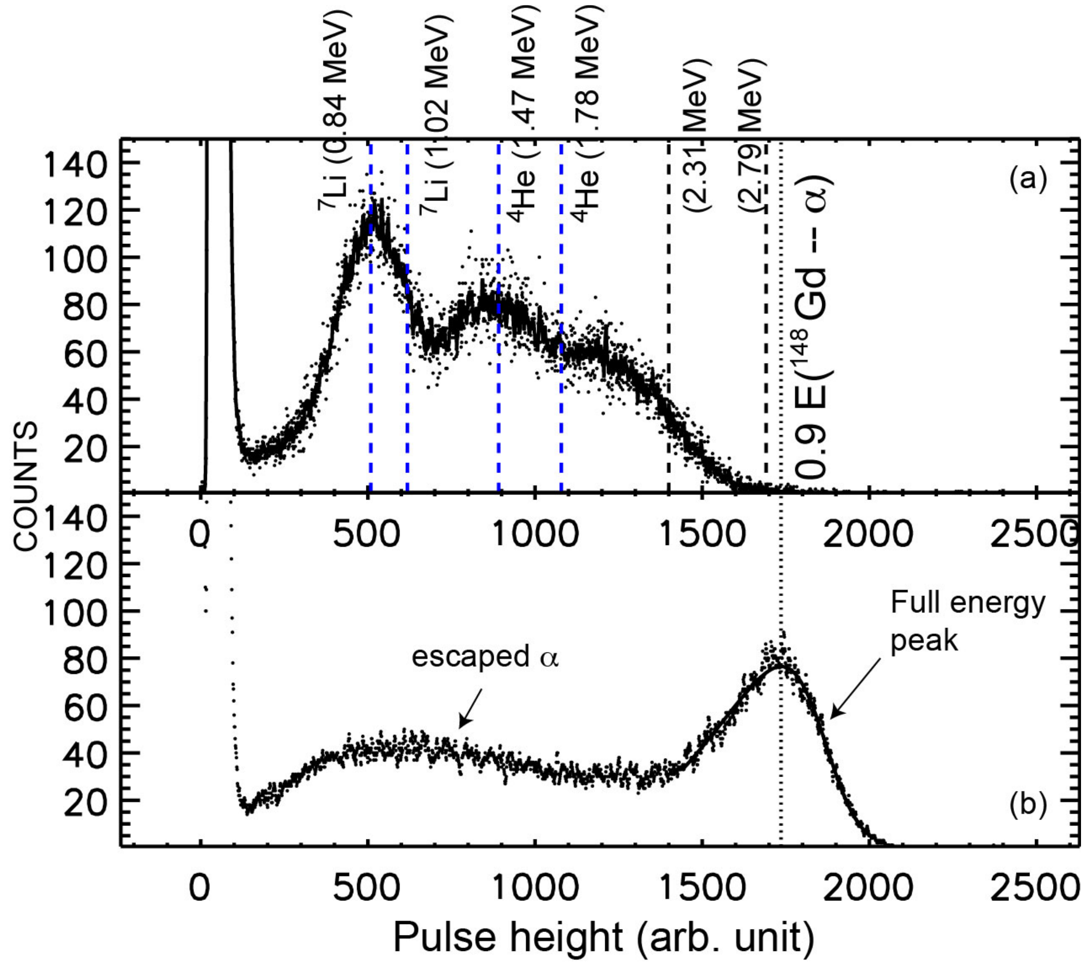


Surface textures



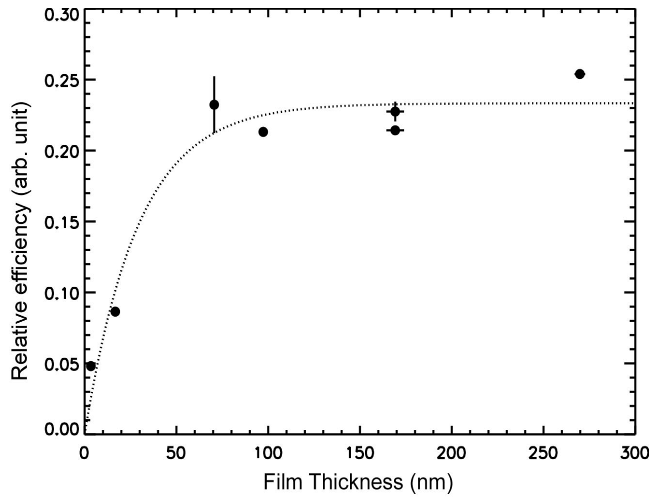


UCN (Charged particle) spectrum



^{10}B thickness determined by Beer's law

- $\lambda_a = \lambda_0 \, u_a/u_0 \rightarrow$ 36 nm @ 4 m/s
- T = 3 λ_a (95%), 4λ_a (98%)
- ^{7}Li signals needed for > 50% efficiency



3 λ_a ~ 100 nm (single layer sufficient for high efficiency)

Outline

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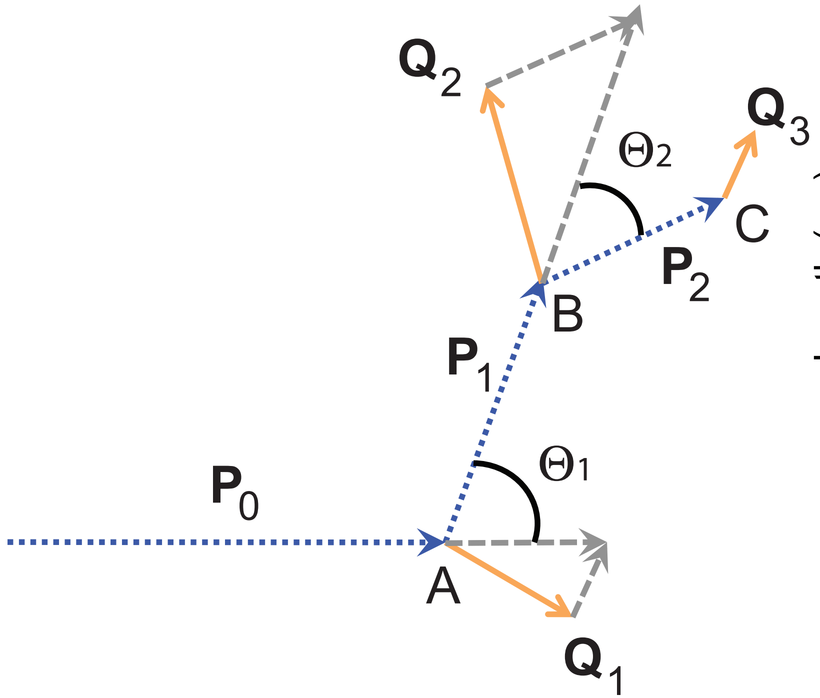
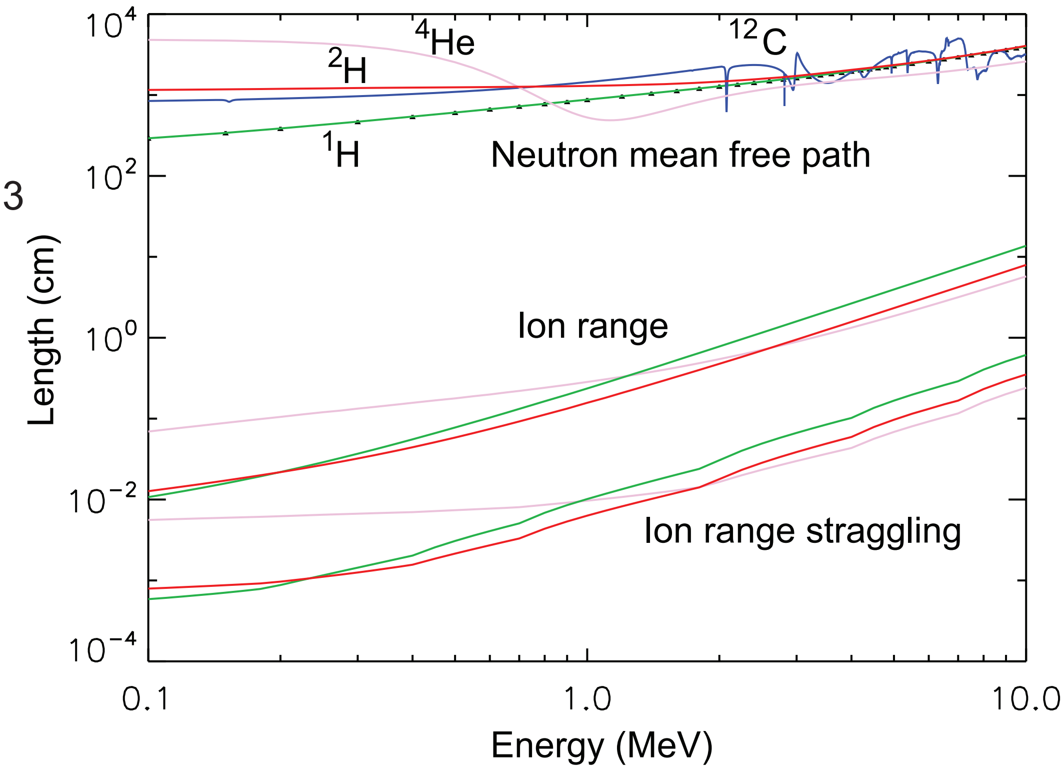
- ^{10}B Detectors for ^{3}He replacement
- Ultracold neutron detector and applications
- **Future perspectives**
  - Neutron Telescope
  - Neutron Microscope
  - Ideal neutron detectors
  - …

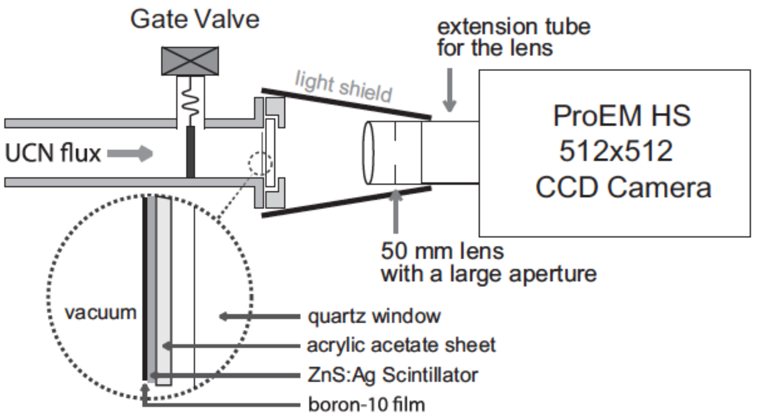
Neutron telescope





Challenge: large spatial dynamic range, 10^6

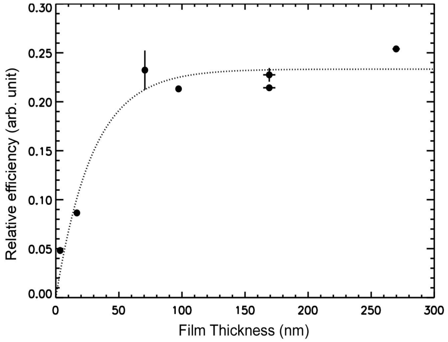
Microscope: using CCD cameras

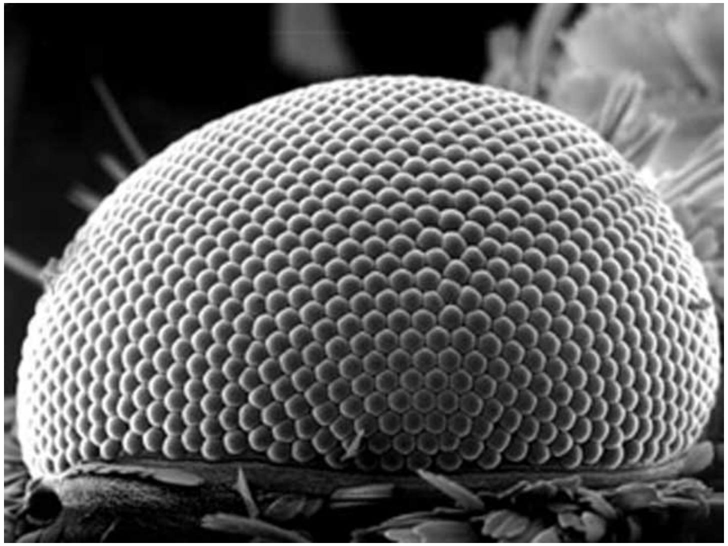


W. Wei et al, NIMA 830 (2016) 36-43.

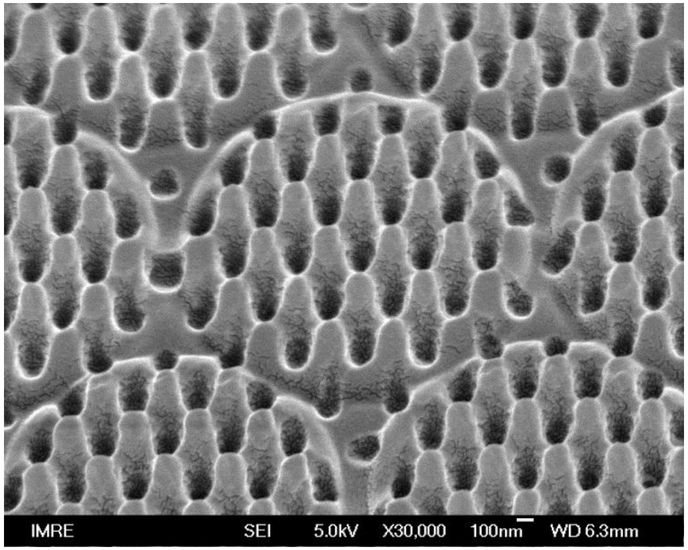
A perfect neutron absorber

- **Absolute efficiency (hard to prove exp.)**
- **UCN/Surface interactions (rough surface)**
  - Rough surface → difficult theor./comput. problem
  - An ideal absorbing surface for UCNs ??





Moth's eye



http://www.a-star.edu.sg

Summary

- **Neutron detector development driven by**
  - Basic science (UCN, nuclear science, physics beyond the standard model)
  - Applications (Homeland security, user facilities -- SNS)
- **Neutron measurements always limited by neutron flux**
- **Signal-to-noise is important**
  - Gamma background (pulse shape discrimination);
  - Correlating different signals (timing);
  - Material use;
  - Low-noise electronics/digitizers;
- **New materials, structures and data extraction/processing provide new opportunities for innovative neutron detectors**

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