Studying Neutron-Induced Reactions for Basic Science and Societal Applications

Correlations in Hadronic and Partonic Interactions 2018

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28 September 2018

Outline

- An Introduction to Neutrons
- Why Study Neutrons and Neutron Interactions?
- Neutron Facilities and Techniques
- Outlook

From Elements to Nuclei

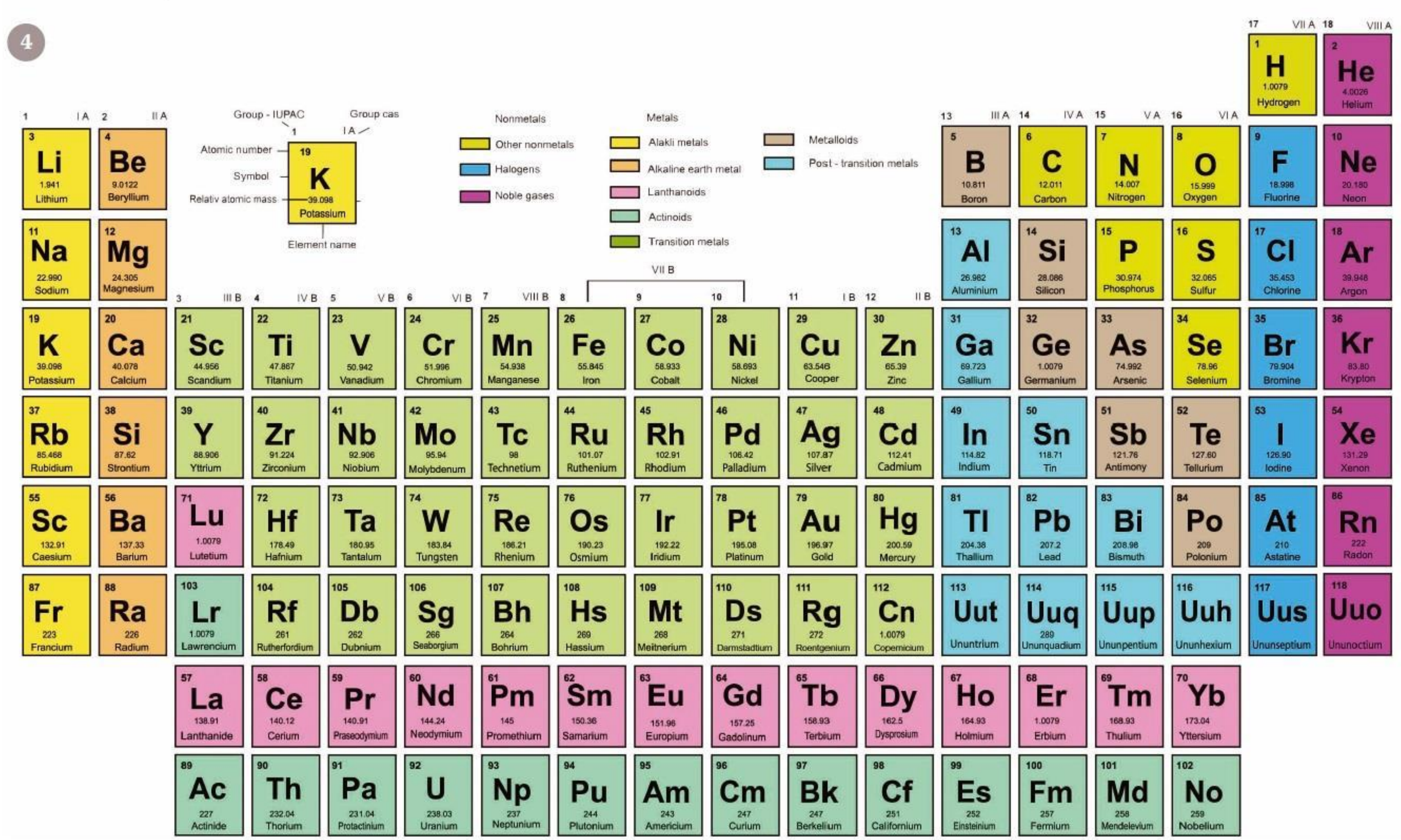
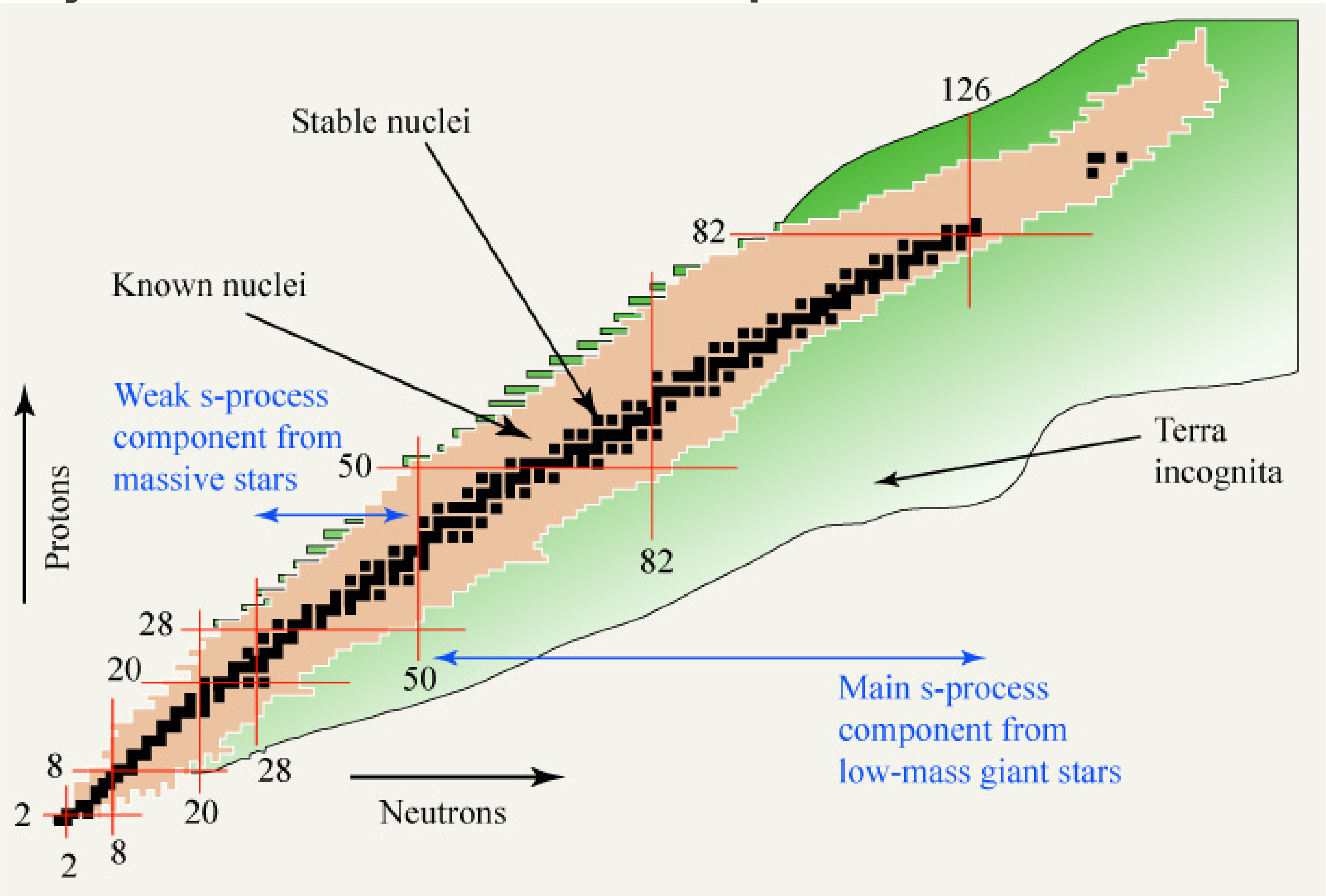


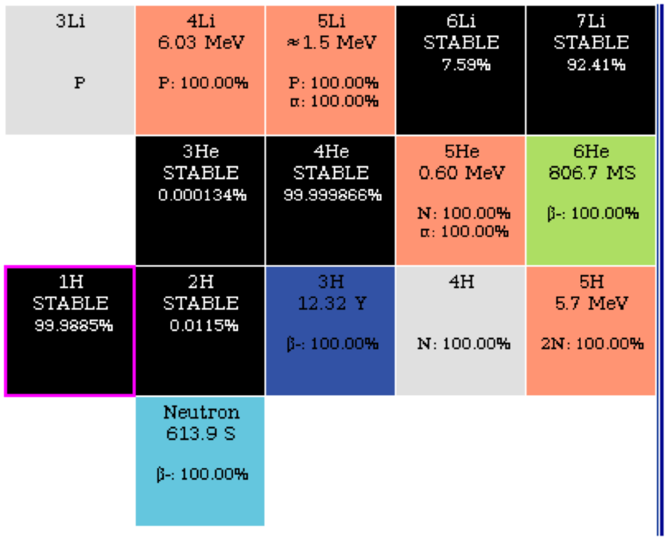
Image Credit:
Scherri, Royal Society of Chemistry (2012)

Chart of the Nuclides: A Low Energy Nuclear Physicist's View of the Landscape



Neutron Properties

- **Lifetime:**
  - 877.7 s (bottle value)
- **Mass:**
  - m_n = 939.57 MeV/c^2
    = 1.008664 u
- **Charge:**
  - No Charge!
- **Spin**
  - $J_\pi = \frac{1}{2}^+$
- **(+ 16 more pages in the Particle Data Book)**
  - http://pdg.lbl.gov/2018/listings/rpp2018-list-n.pdf



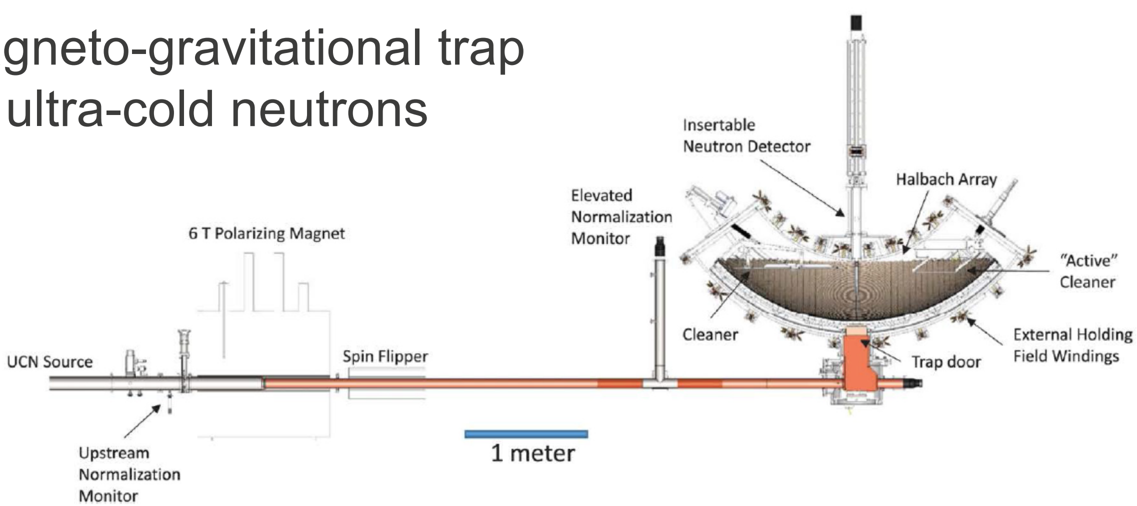
Nuclear Physics with Neutrons

- Studies of the weak force in a “simple” nuclear system
- Nuclear Astrophysics
- Neutron Resonances and Nuclear Structure
- Low-energy Neutron Imaging
- Fission Studies—Bringing it all together

The Neutron as a Laboratory for Fundamental Interactions

- **Neutron decay is a probe of the weak charge current**
- **The neutron is a "simple" to try to treat theoretically**
- **This both test the Standard Model and is needed for interpreting Big Bang Nucleosynthesis**
- **Different techniques give a 9.2 sec difference on a lifetime just under 900 s**

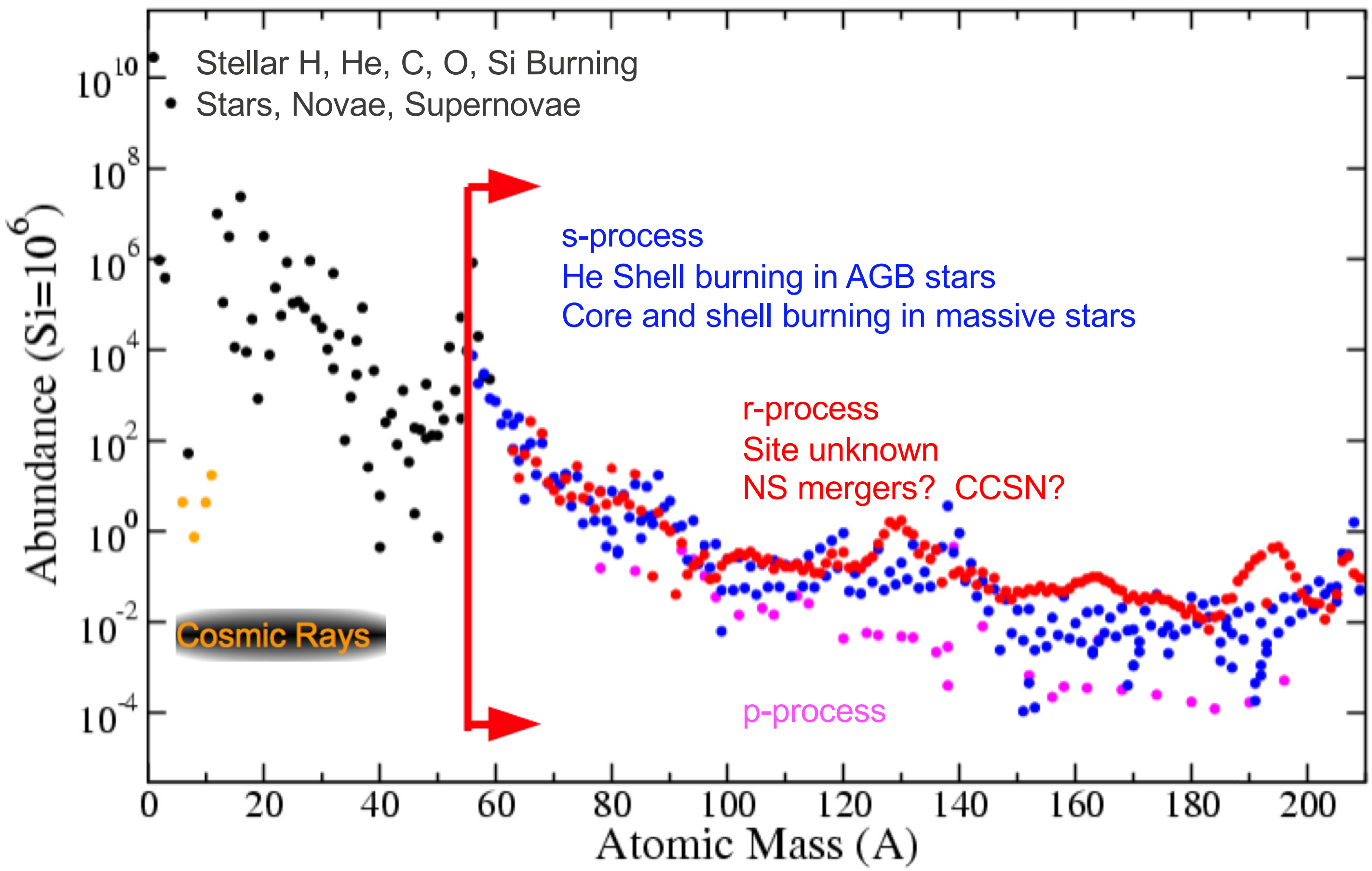
Magneto-gravitational trap for ultra-cold neutrons



R. W. Pattie Jr. *et al. Science* (2018)

- **Pattie *et al.* bottle measurement**
  - 877.7 ± 0.7 (stat) +0.4/-0.2 (sys) s
- **Leading beam measurement**
  - 887.4 ± 2.2 s
- **Measurements are ongoing to resolve**

Nuclear Astrophysics: Synthesis of the heavy elements relies on neutron-induced reactions



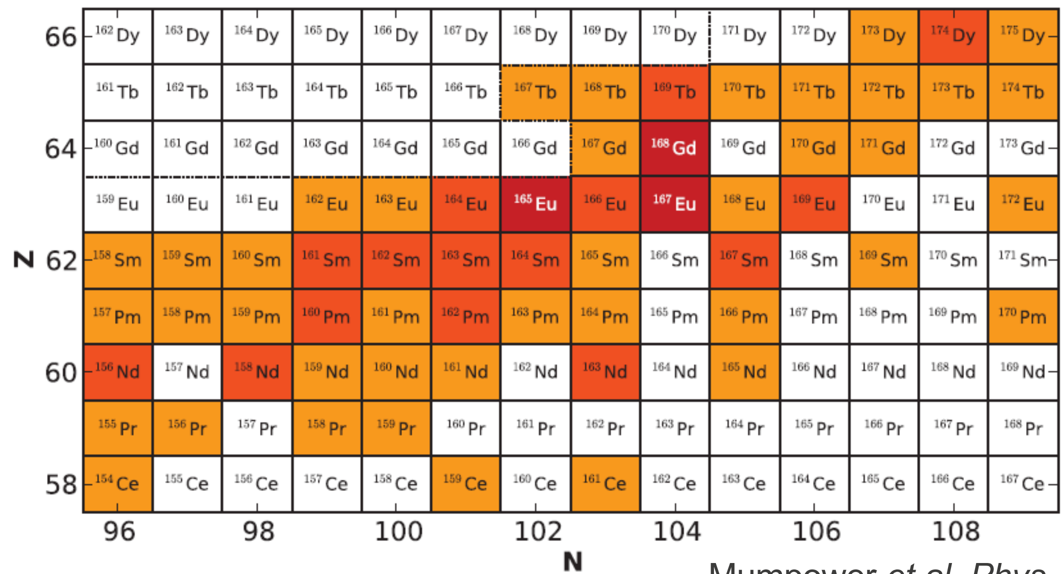
- **Heavy element synthesis dominated by neutron capture**
- **Knowledge of neutron capture reveals information about stellar evolution, neutron densities, and galactic history**

Abundances and Attribution from Anders & Grevasse, 1989
And Käppeler and Wisshak, 1989

Short-Lived Nuclei Drive Understanding of Stellar Environments and Astrophysical Sites

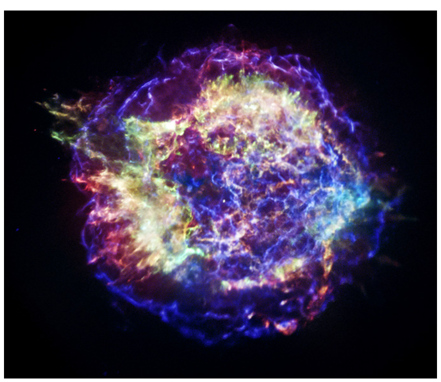
- **Mumpower *et al.* showed individual neutron capture rates impacted final abundances**
- **This demonstrated a need for (n,γ) rates far from stability**

r-process network (n,γ) sensitivity

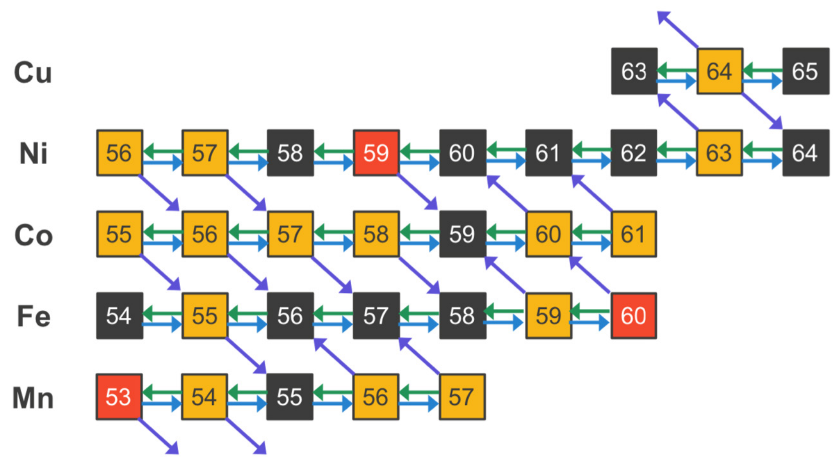


Mumpower *et al. Phys. Rev. C* **86** (2012)

Cassiopeia A
10^{22} n/cm^2/sec



Weak s-Process Network

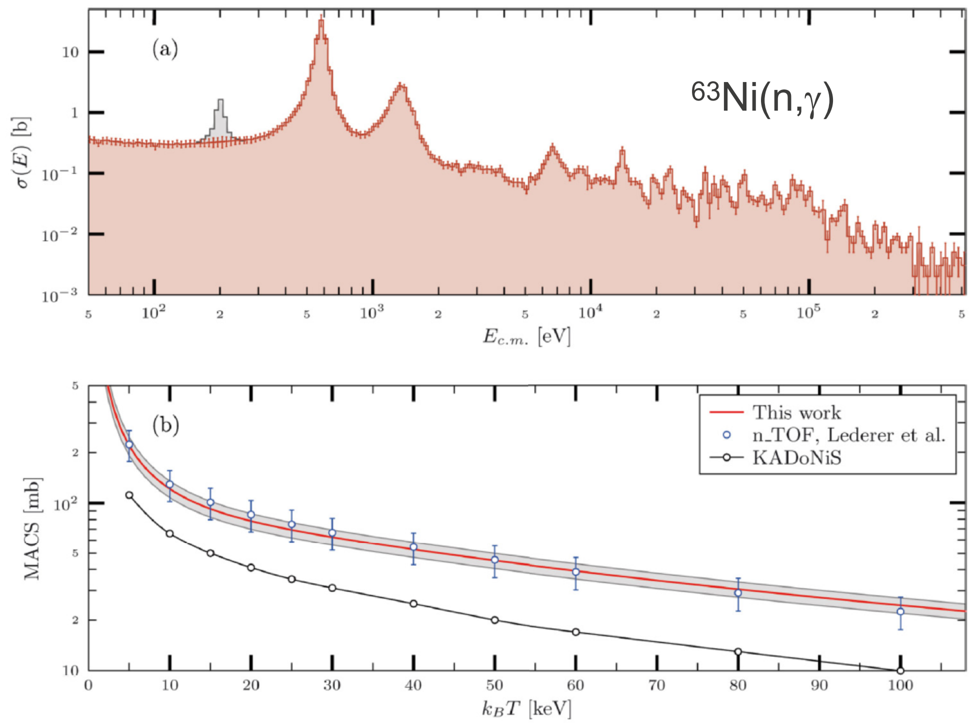


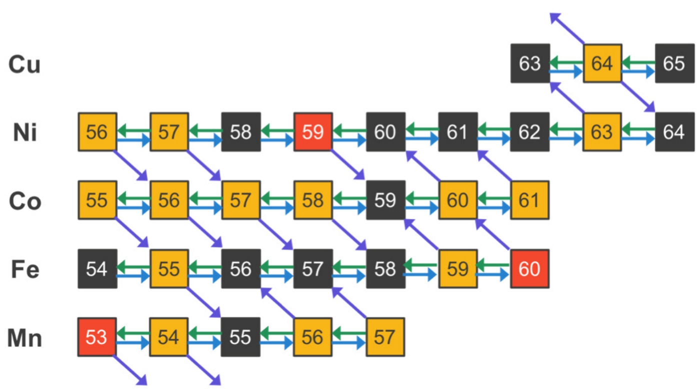
- Reactions on unstable isotopes are key for nucleosynthesis
- In particular, they provide information about the temperature and neutron density

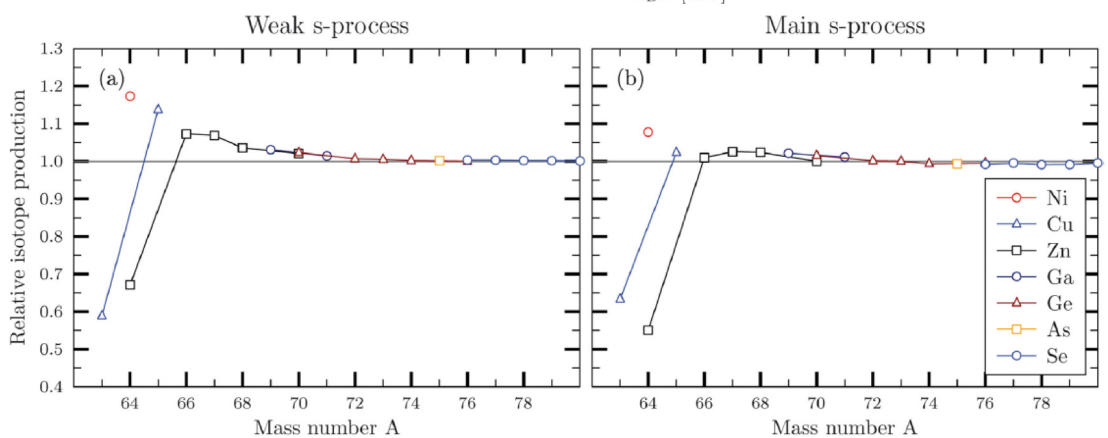
Neutron Capture on ^{63}Ni

- **Improved measurement of neutron capture cross sections, particularly on unstable isotopes inform nucleosynthesis**
- **^{63}Ni is one such case**
- **Increases in the neutron capture cross section bypass ^{63}Cu production, which is a calibration for the weak s-process**

Weigand *et al.* PRC **92** (2015)

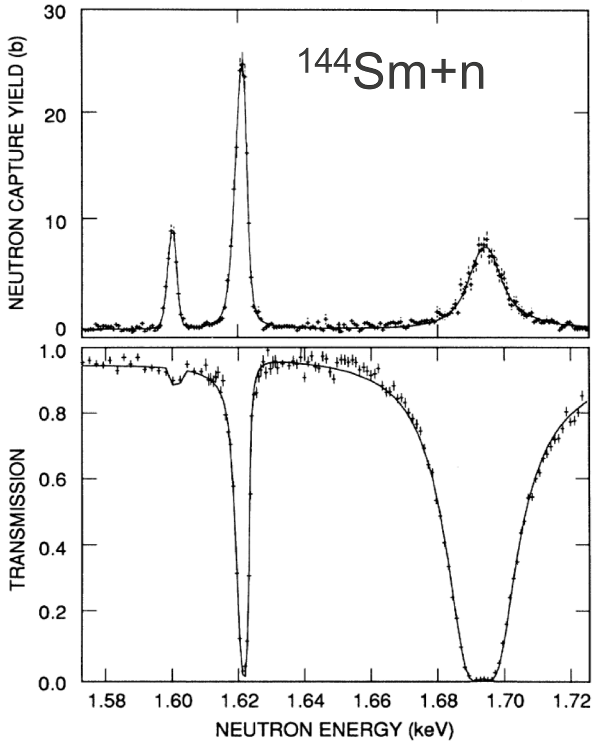




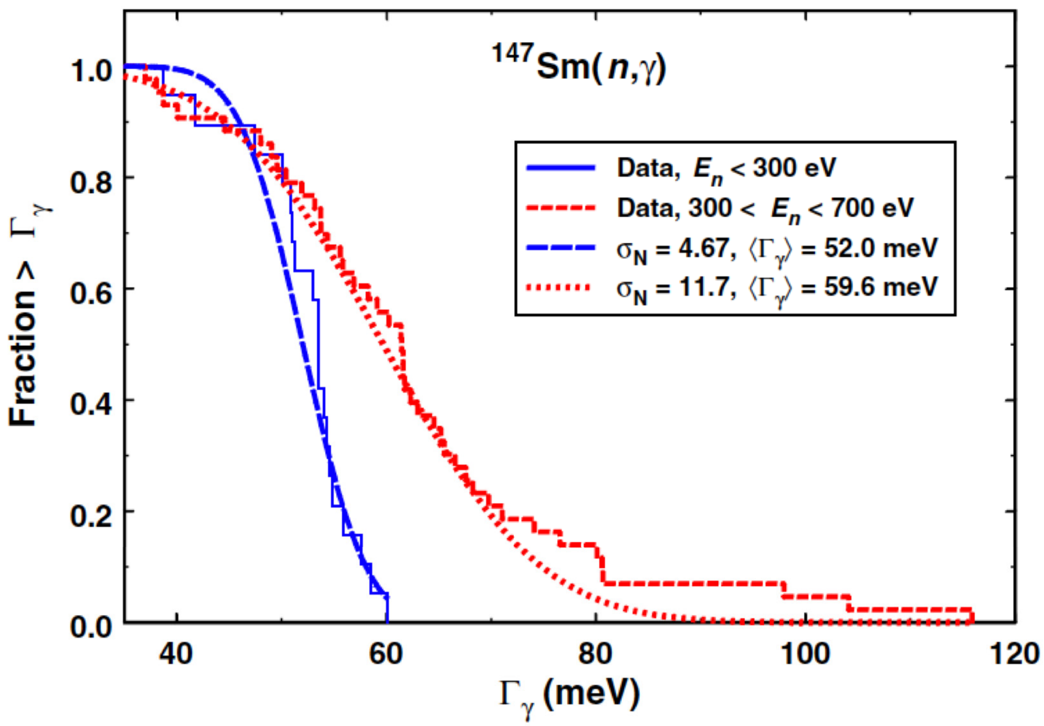


Neutrons allow resolved access to study structure at high excitation

Macklin *et al.* PRC **48** (1993)



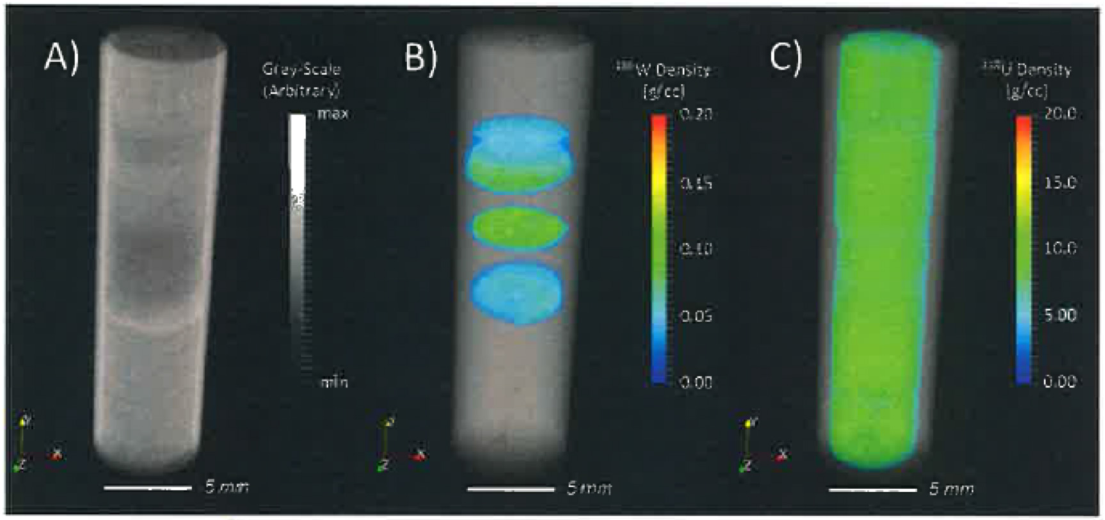
Koehler *et al.* PRL **108** (2012)



- **Neutron resonance spectroscopy allows measurements at eV resolution at several MeV excitation**
- **Cross section studies are only a small fraction of the available physics**

- **Detailed measurements of resonance widths in ^{147}Sm revealed an expected change at ~300 eV neutron energy**
  - Q-Value: 8.14139 MeV
- **This has implications for statistical interpretations of nuclear levels as well as cross sections and applications**

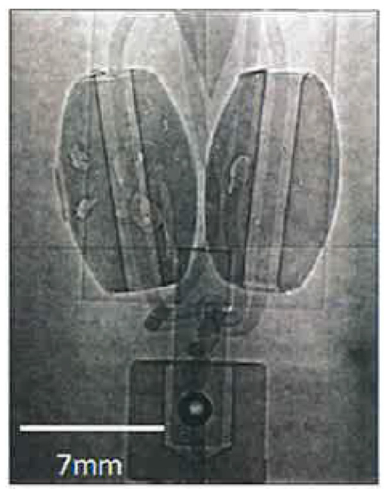
Low energy neutrons offer the ability to isolate isotopes (or elements) and edge features



Lead sinkers+Al wire

Absorption contrast

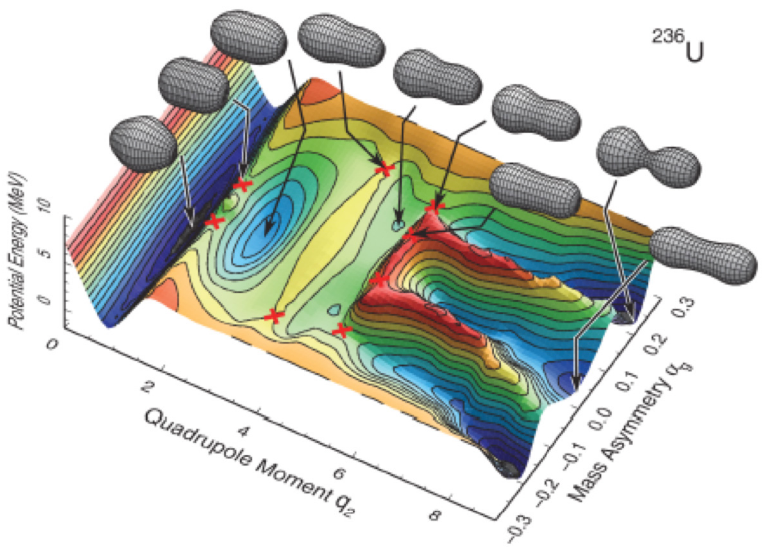
Phase contrast

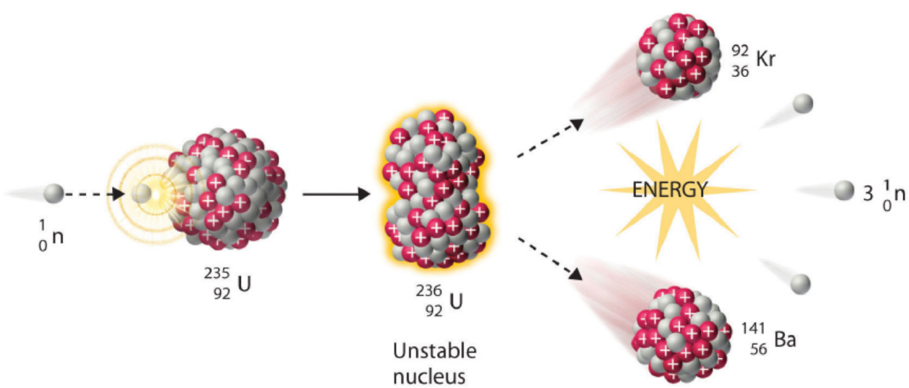


- **Energy Resolved Imaging**
  A. Thermal Image
  B. W gated
  C. ^{238}U gated

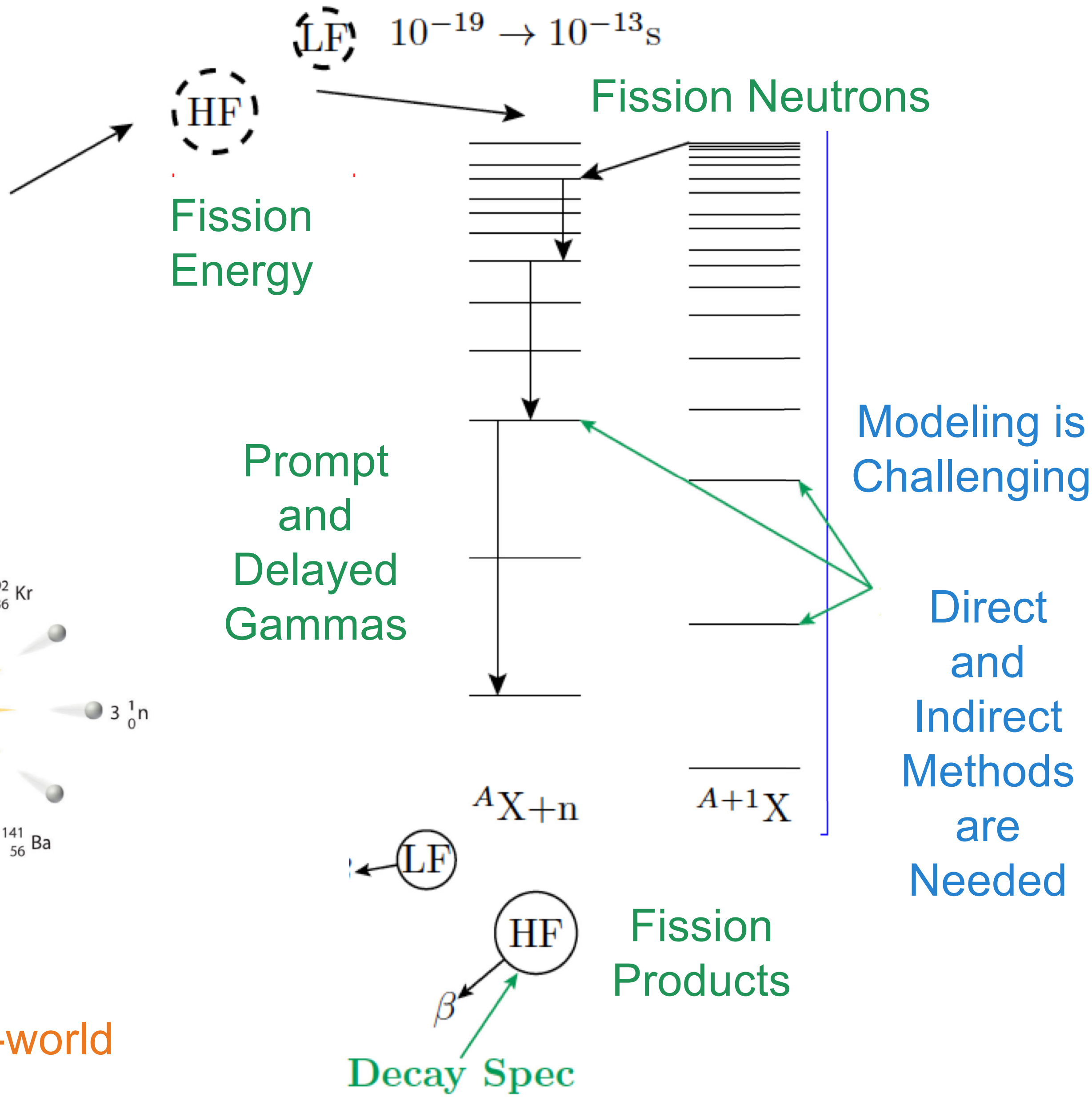
- **Phase-Contrast Imaging**
  - "cold" neutrons
  - Measurements at varying distance
  - Internal edge features become available

Fission: A Bane and Beauty of Nuclear Physics





Fission Cross Section



Direct tie of basic research to real-world applications in energy and safety

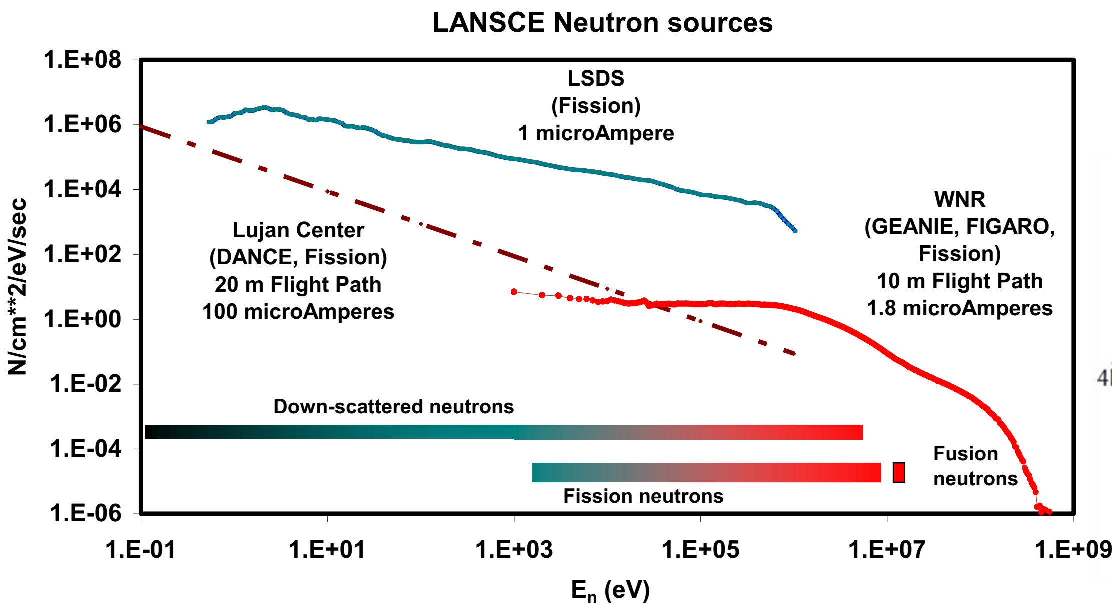
Neutron production facilities

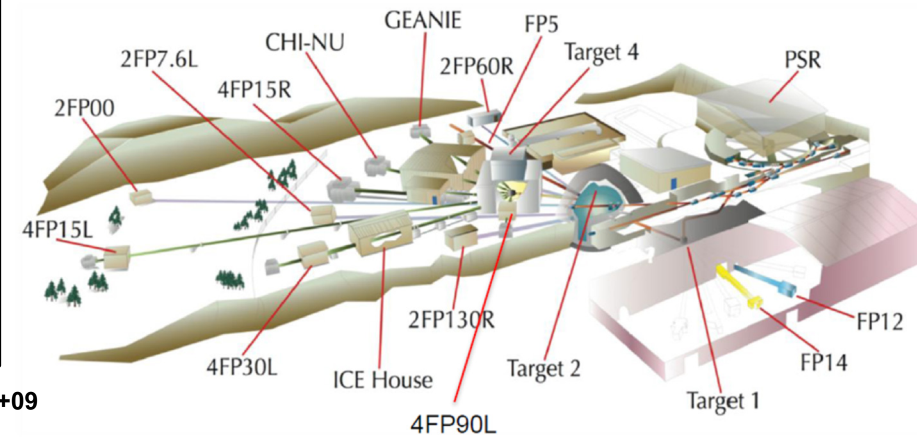
- **Neutron studies (unsurprisingly) require neutrons**
- **This presents challenges as they are**
  - Short lived
  - Cannot be directed/accelerated
  - Difficult to trap

- **Neutron facilities typically employ**
  - Spallation
  - Direct reactions
  - Reactor neutrons
    - I won't discuss reactor facilities further

Neutron Spallation at the Los Alamos Neutron Science Center

LANSCE at Los Alamos opens the door to many new measurements



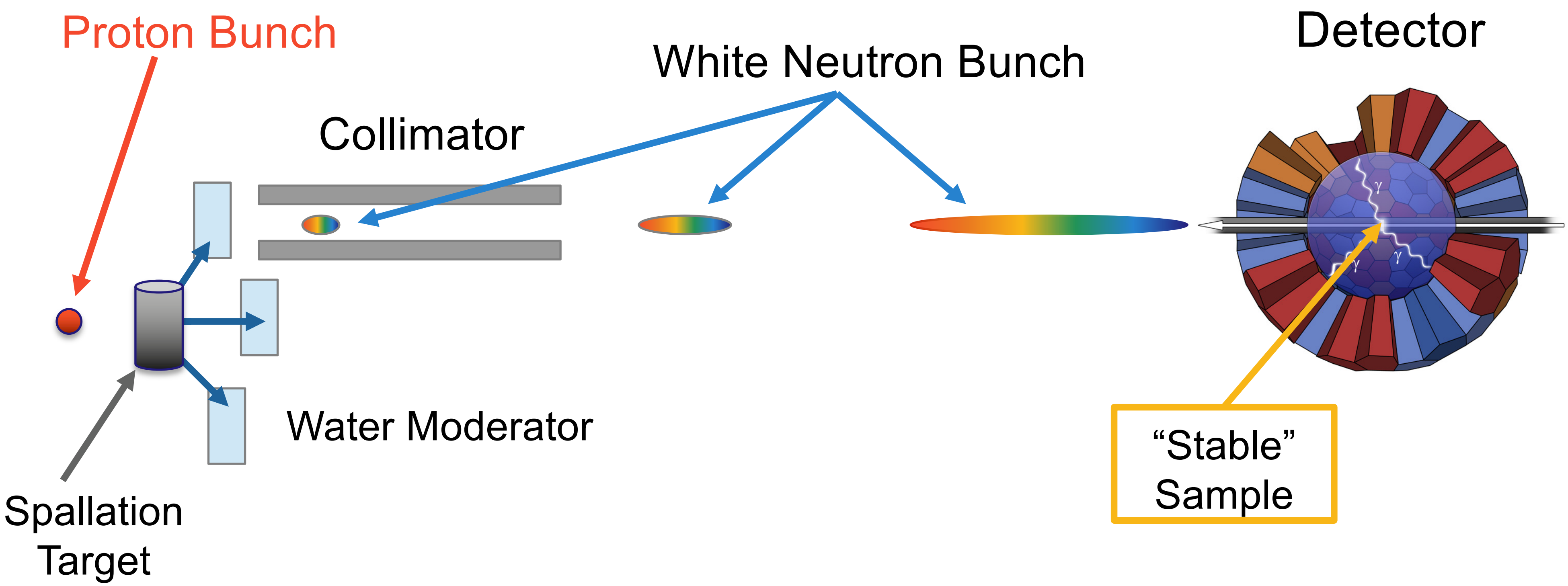


800 MeV linear accelerator: H+ beams for isotope production and H- beams to drive two neutron beam facilities

Lujan center: moderated spallation source, three flight paths devoted to nuclear science sub-thermal ≤ En ≤ 500 keV

WNR: unmoderated spallation target, generating neutrons with 100 keV ≤ En ≤ 600 MeV

How are neutron measurements traditionally performed at time-of-flight facilities?



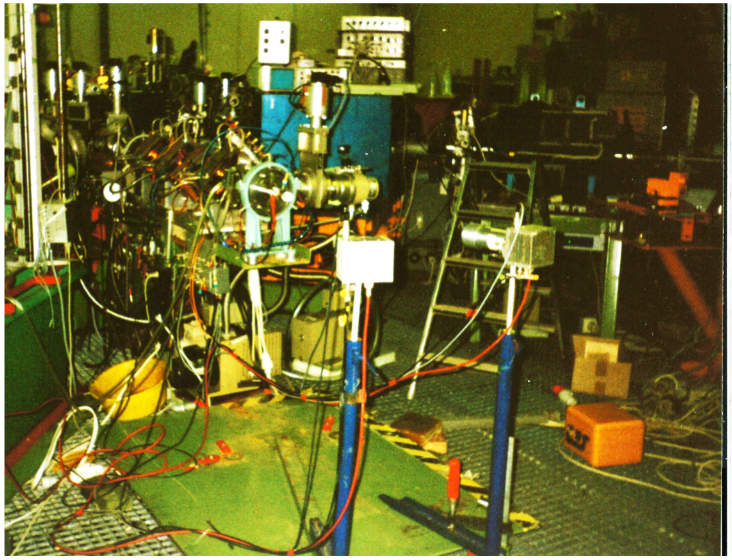
E_p= 800 MeV ν_p=20 Hz 10 meV < E_n < 500 keV

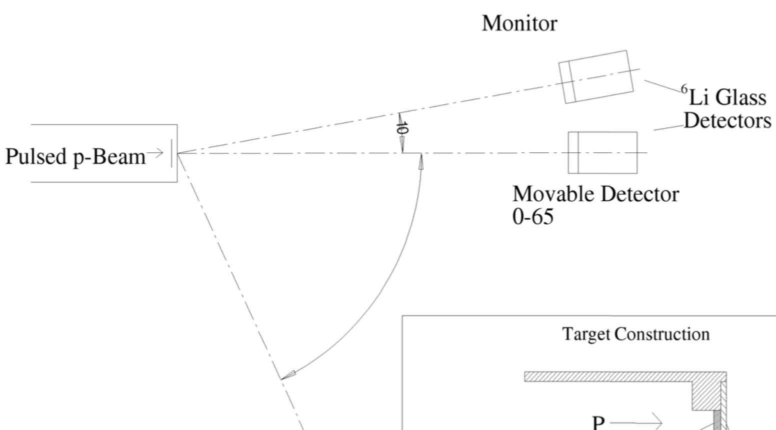
$\phi_n = 3 \cdot 10^5$ n/s/cm^2/decade

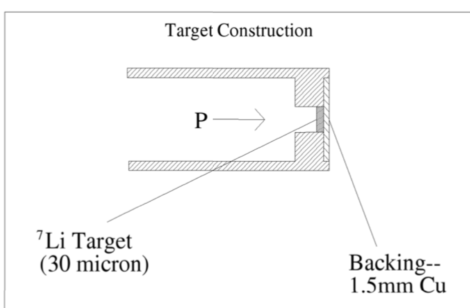
Details vary with facility, but the basic principles are the same

Direct Reactions from $^{7}Li(p,n)$

Measuring neutron spectra at Karlsruhe, circa 1997







Neutrons from $^{7}Li(p,n)$

Figure 3

Energy Spectra versus Emission Angle

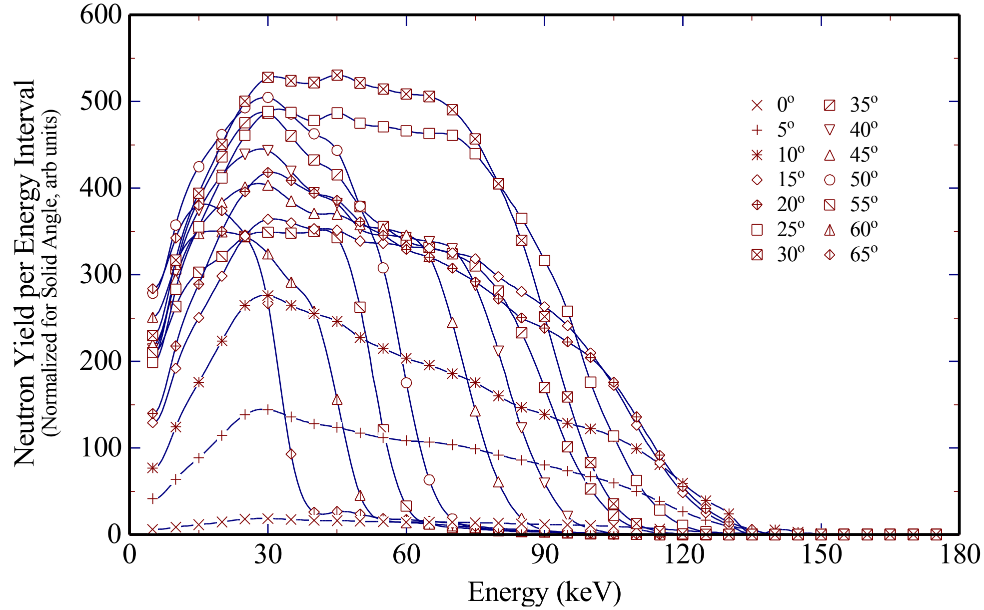
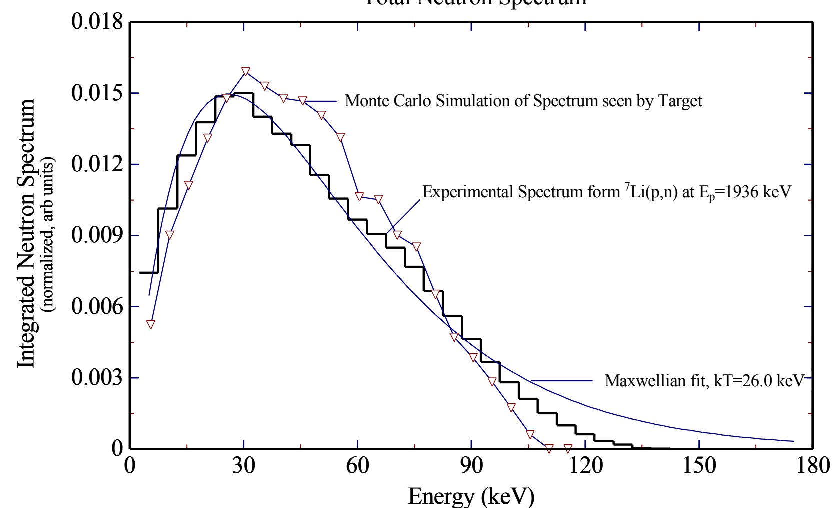


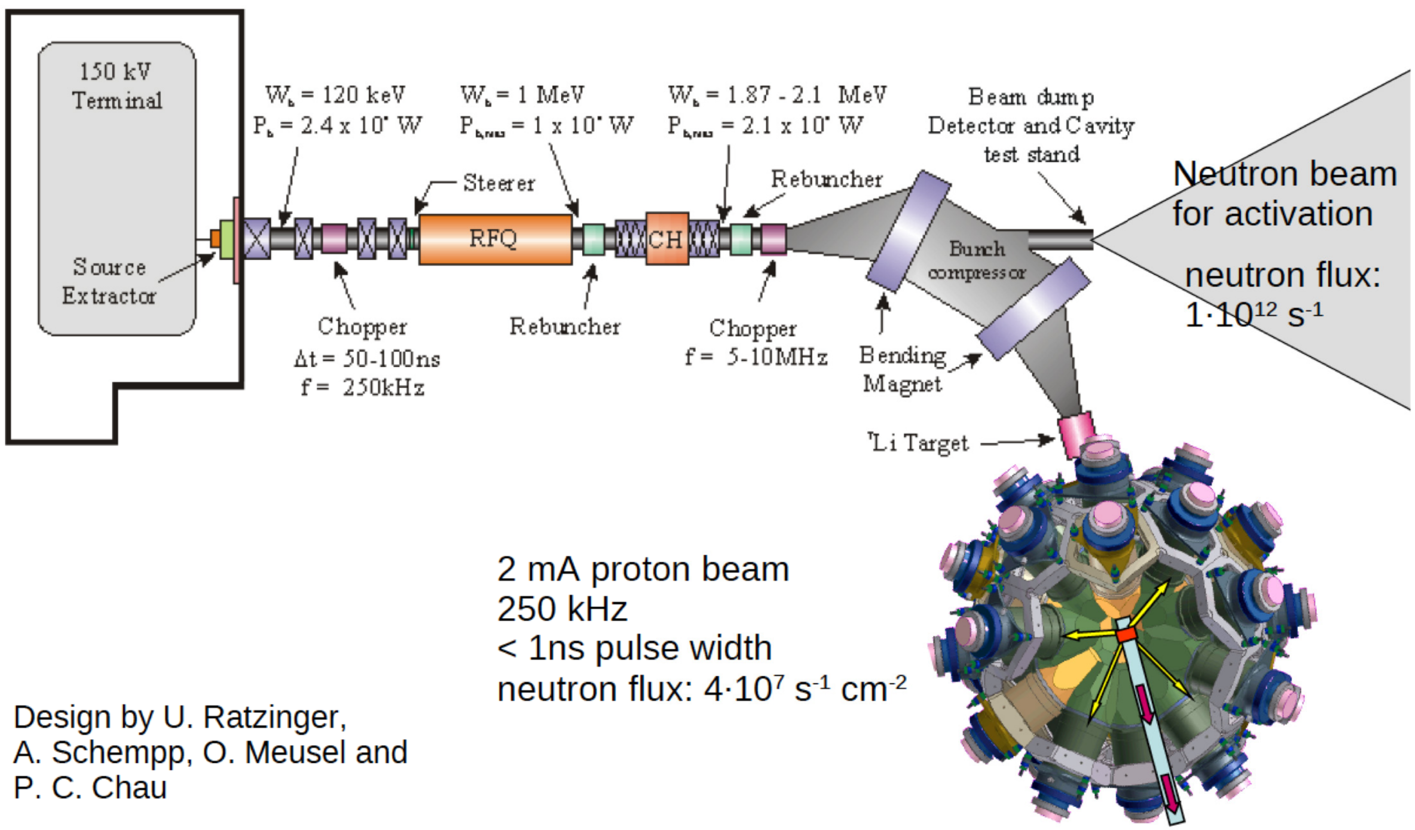
Figure 5

Total Neutron Spectrum



FRANZ in Germany and SARAF in Israel are extending this to high power

The Frankfurt neutron source at the Stern-Gerlach-Zentrum (FRANZ)



2 mA proton beam
250 kHz
< 1ns pulse width
neutron flux: $4 \cdot 10^{7}$ s^{-1} cm^{-2}

Design by U. Ratzinger, A. Schempp, O. Meusel and P. C. Chau

- Advances in accelerator technology and targetry enable new facilities
- Neutron flux enhancements of orders of magnitude over existing facilities
- This will open new measurements on unstable isotopes
- SARAF-I is in production with keV neutrons
- SARAF-II will offer beams up to 40 MeV

Slide Credit: R. Reifarth

Neutron Facilities for Nuclear Physics Exist Around the World and are Growing

Facility	Neutron Spectrum	Detection
DANCE/LANSCE	Spallation TOF white	BaF_2 (calorimeter)
nTOF (CERN)	Spallation TOF white	C_6D_6, BaF_2
~~ORELA (ORNL)~~	e^- LINAC, TOF white	C_6D_6, BaF_2
GELINA (IRMM)	e^- LINAC, TOF white	C_6D_6
~~FZK (Karlsruhe)~~	(p,n) TOF 25 keV Maxwellian	BaF_2, Activation
SARAF (Israel)	(p,n) 25 keV Maxwellian (*MeV Coming*)	Activation
FRANZ (Germany)	(p,n) 25 keV Maxwellian *(planned)*	BaF_2, Activation
TUNL (USA)	(d,d), (d,t) “Monoenergetic”	Activation

- RPI, Tokyo Tech, ~~IPNS (Argonne)~~, Ohio Univ., Univ. of Kentucky, nELBE, others

Outlook

- **Neutron physics offers a rich set of science**
  - Much of this physics is, at best, difficult to access with other probes
- **Advances in accelerator technology, beam transport , and targetry are making ever more powerful facilities available**
- **Much work remains to be done, particularly on unstable isotopes**
- **Surprising gaps in knowledge exist, even on stable isotopes**
- **Neutron science has direct impacts on a range of applied fields in addition to basic science**

Orion's Belt seen from Los Alamos, NM

Photo Courtesy of Shannon Scott