The Experimental Side of the s Process

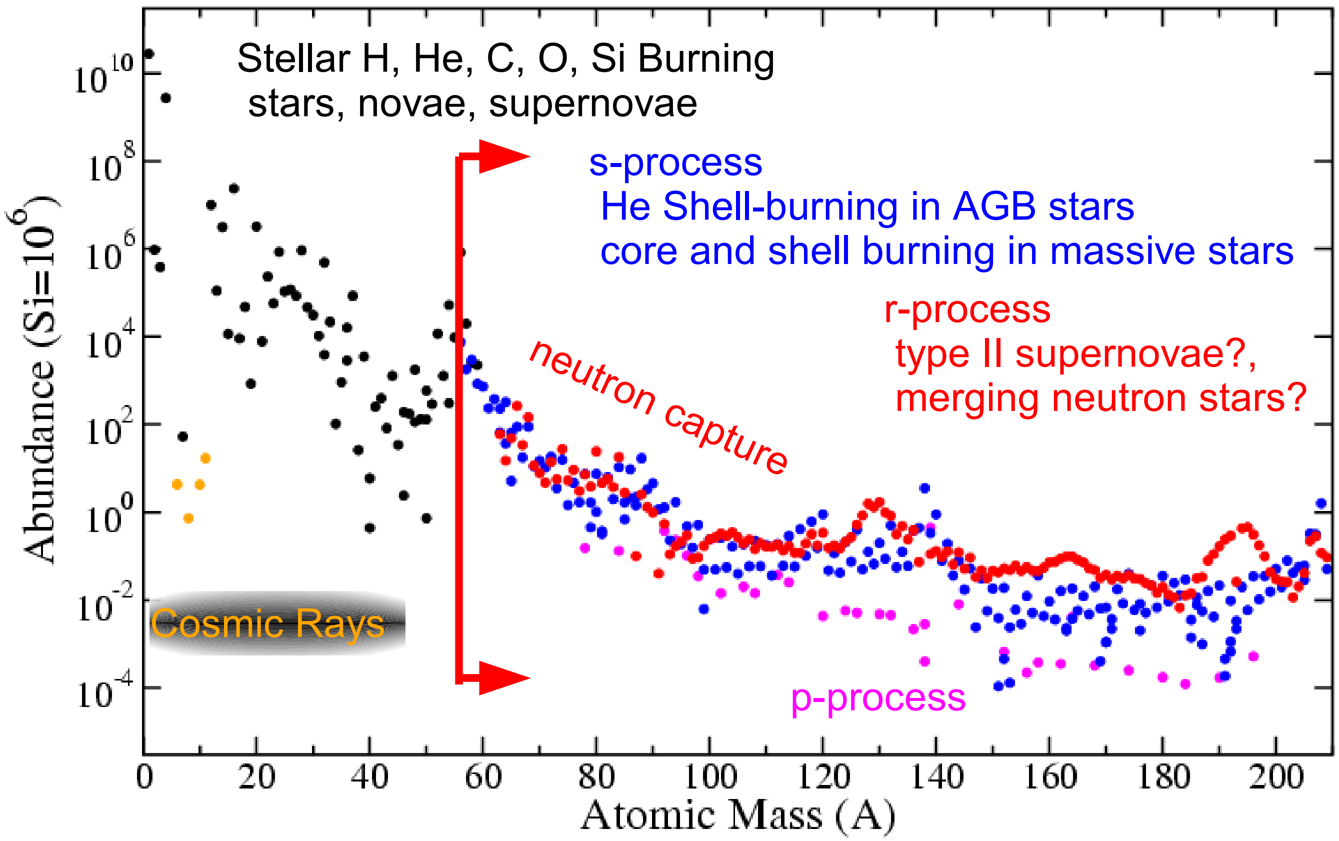
A. Couture

Nuclei in the Cosmos XI
21 July 2010
Heidelberg, Germany

Los Alamos
NATIONAL LABORATORY
EST. 1943

NNSA

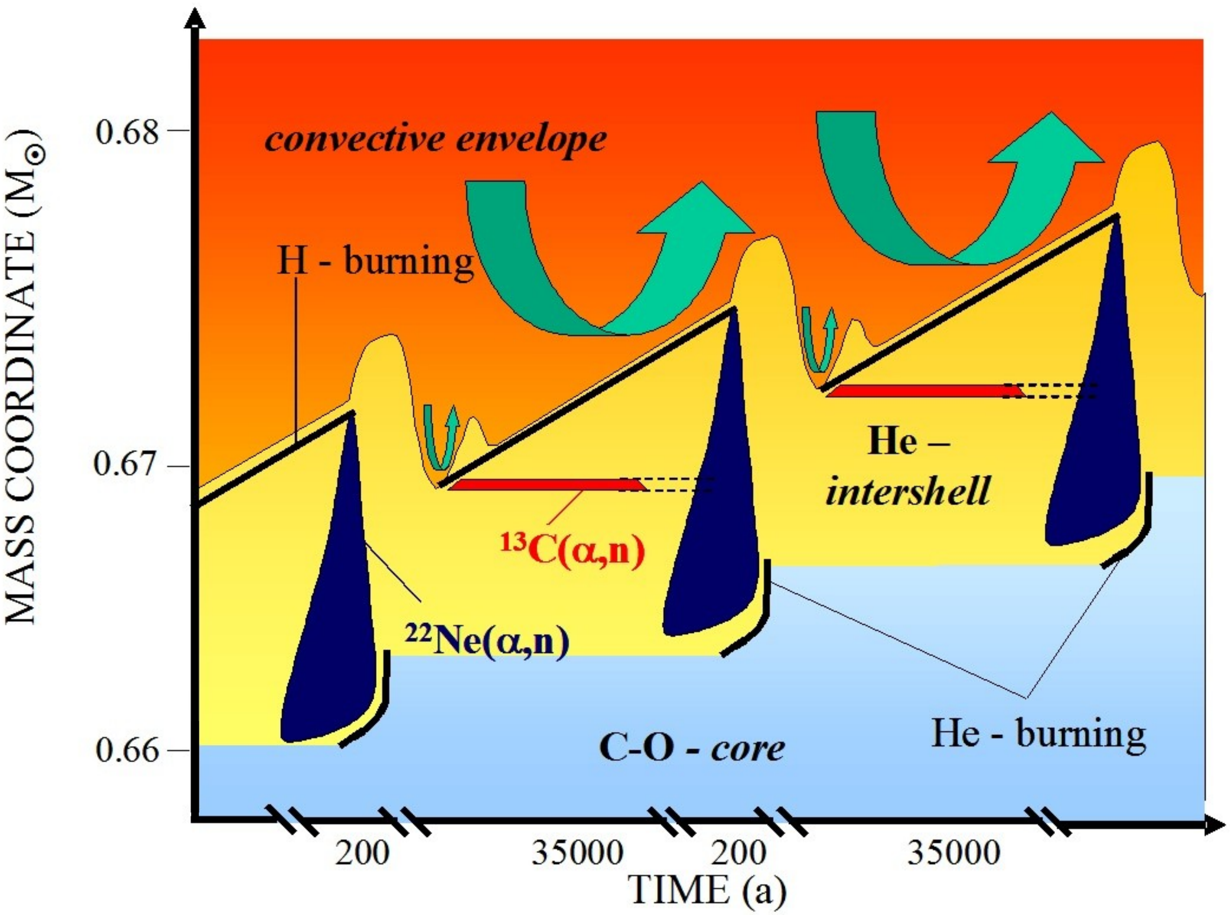
Half of the heavy elements are made through the *s* process



Abundances and Attribution from Anders & Grevesse, 1989
and Käppeler, Beer, and Wisshak, 1989

- Heavy element synthesis is dominated by neutron capture
- Reactions of interest lie near stability, making measurements experimentally tractable
- Historically, separation of *s* and *r* process synthesis based on *s* process contribution

Main s Process: Thermally Pulsing AGB Stars



- Neutron exposures of 10^8 n/cm^3 and 10^{11} n/cm^3 are experienced during different phases
- Temperatures range from kT=8 keV up to kT=25 keV during the ^{13}C and ^{22}Ne phases
- Neutron capture cross-sections are critical for understanding the stellar sites and differentiating between stellar models

The Weak *s* Process: Massive stars

- The weak *s* process operates in massive stars ($M > 8M_{sun}$)
  - Responsible for majority of *s* process synthesis of $A<90$
- Neutron exposures are achieved during He burning and shell C burning
- Temperatures and neutron densities are quite different than for the main *s* process
  - He Burning: $^{22}Ne(\alpha,n)$
    - kT=25 keV, 10^6 n/cm^3
  - Carbon Shell burning: Various neutron sources
    - kT=90 keV, 10^{11} n/cm^3
- Unlike in low-mass AGB stars, later processing must be considered

The Weak *s* Process: Massive stars

- The weak *s* process operates in massive st 8M_{sun})
  - Responsible for majority of *s* process s
- Neutron exposures are ach d shell C burning
- Temperatures and neut e quite different than for the main *s* proce
  - He Burning: $^{22}Ne(\alpha,n)$
    - kT=25 keV, 10^6 n/cm^3
  - Carbon Shell burning: Various neutron sources
    - kT=90 keV, 10^{11} n/cm^3
- Unlike in low-mass AGB stars, later processing must be considered

For Details, see
M. Pignatari
NIC_XI_285

Los Alamos NATIONAL LABORATORY EST. 1943

NNSA

Where does this leave us?

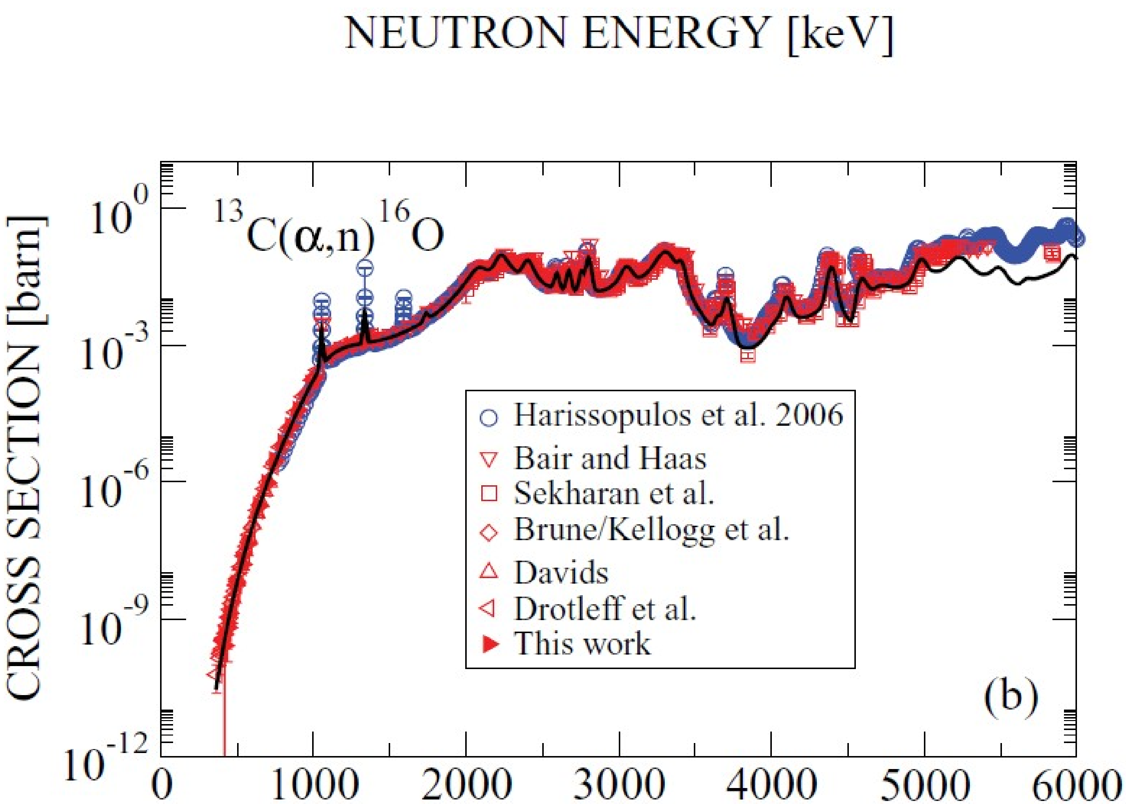
- Reaction rates, observations, and stellar modeling are quite mature
  - We can reliably diagnose where improved measurements are needed
  - Measurements can reveal detailed information about mixing, temperatures, and neutron density
  - We can potentially discriminate between competing stellar models
  - Precision measurements are often required
  - The "easy" measurements have already been done
- As an additional challenge, the measurements are needed over a range of energies, and many different isotopes play important roles in different scenarios

Experimental needs for the *s* process

- Half-lives
  - Needed for details of branch points
  - Thermally enhanced decay lifetimes particularly valuable
    - Presently we are still dependent on theory to predict them
- Charged particle reaction rates
  - Energy production (and convection/mixing)
  - Neutron production (primarily $^{13}C(\alpha,n)$ and $^{22}Ne(\alpha,n)$)
- Neutron induced reaction rates
  - Primarily neutron capture
  - Measurements on stable & unstable isotopes
  - Neutron poisons

Charged particle reactions

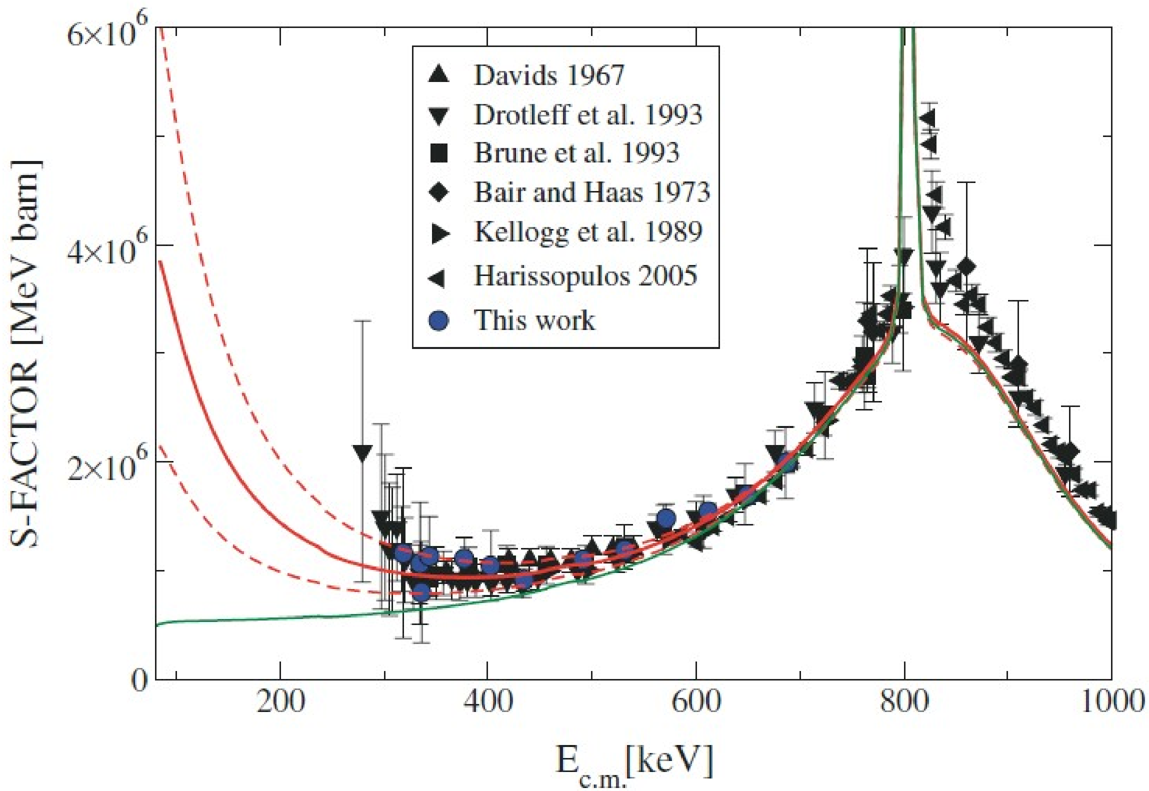
- Charged particle reaction rate measurements suffer from low temperatures and high Coulomb barriers
- In the recent work by Heil *et al.* the final analysis included 5 reaction channels, 11 data sets, and a resonance analysis of 80+ resonances
- Together, it brought the $^{13}C(\alpha,n)$ rate uncertainty down to ~20%.



Heil *et al.* PRC (2008)

Charged particle reactions

- Charged particle reaction rate measurements suffer from low temperatures and high Coulomb barriers
- In the recent work by Heil *et al.* the final analysis included 5 reaction channels, 11 data sets, and a resonance analysis of 80+ resonances
- Together, it brought the $^{13}C(\alpha,n)$ rate uncertainty down to ~20%.



Heil *et al.* PRC (2008)

Los Alamos NATIONAL LABORATORY EST. 1943

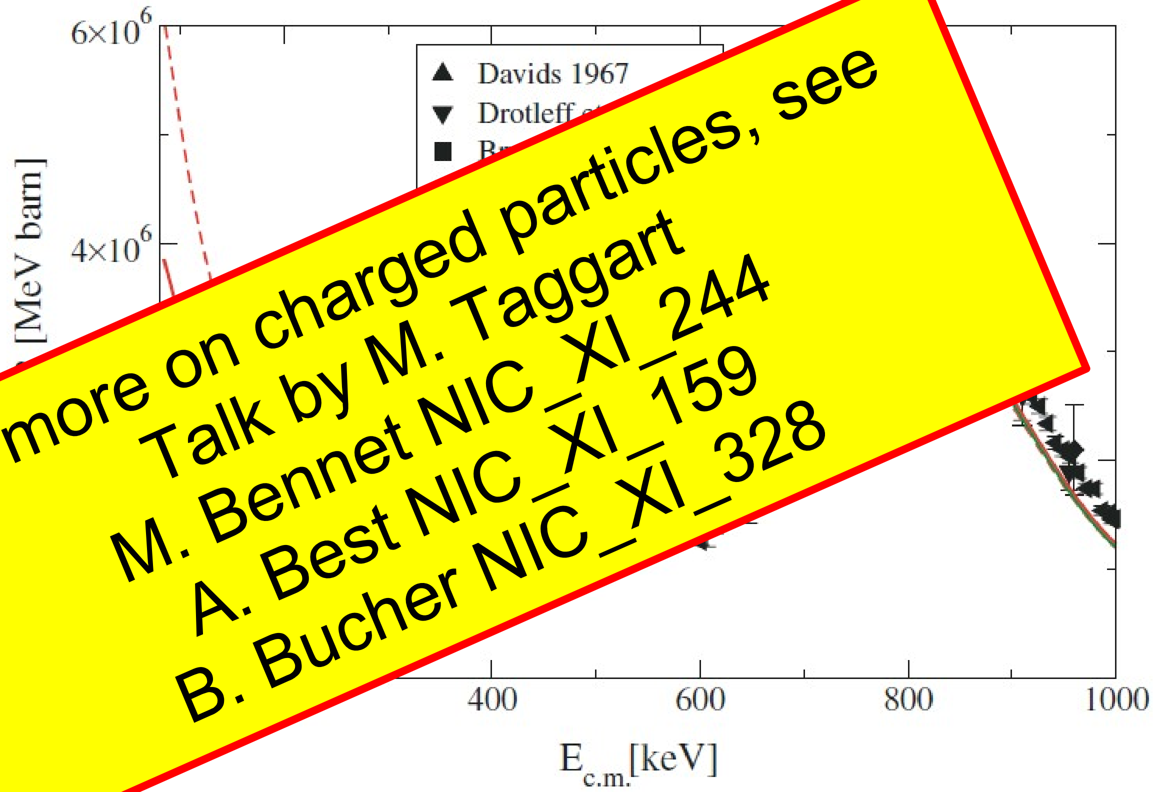
NNSA

Charged particle reactions

- Charged particle reaction rate measurements suffer from low temperatures and high Coulomb barriers

- In the recent work by Heil *et al.* the final analysis included *E* reaction channel data sets, and a resonance analysis 80+ resonances

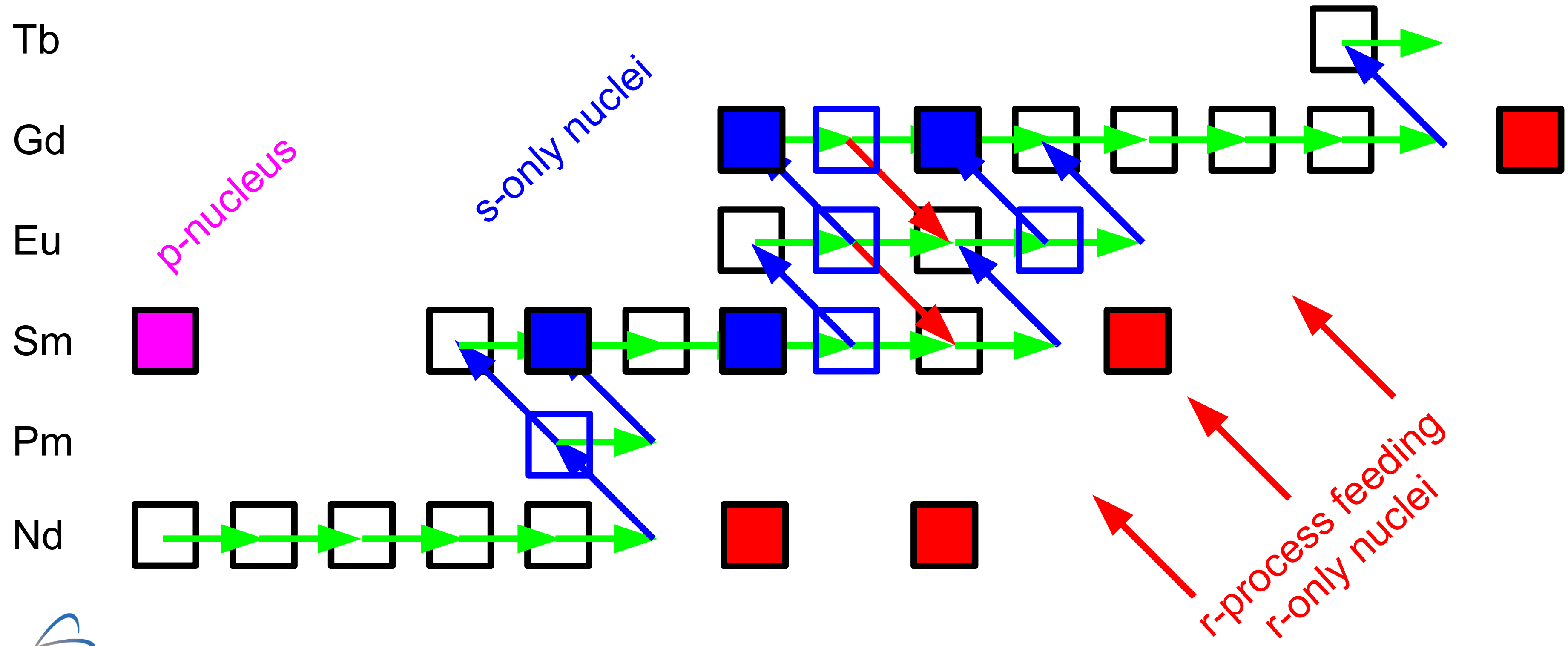
- Together, it brought th ^{13}C(α,n) rate uncertaint down to ~20%.



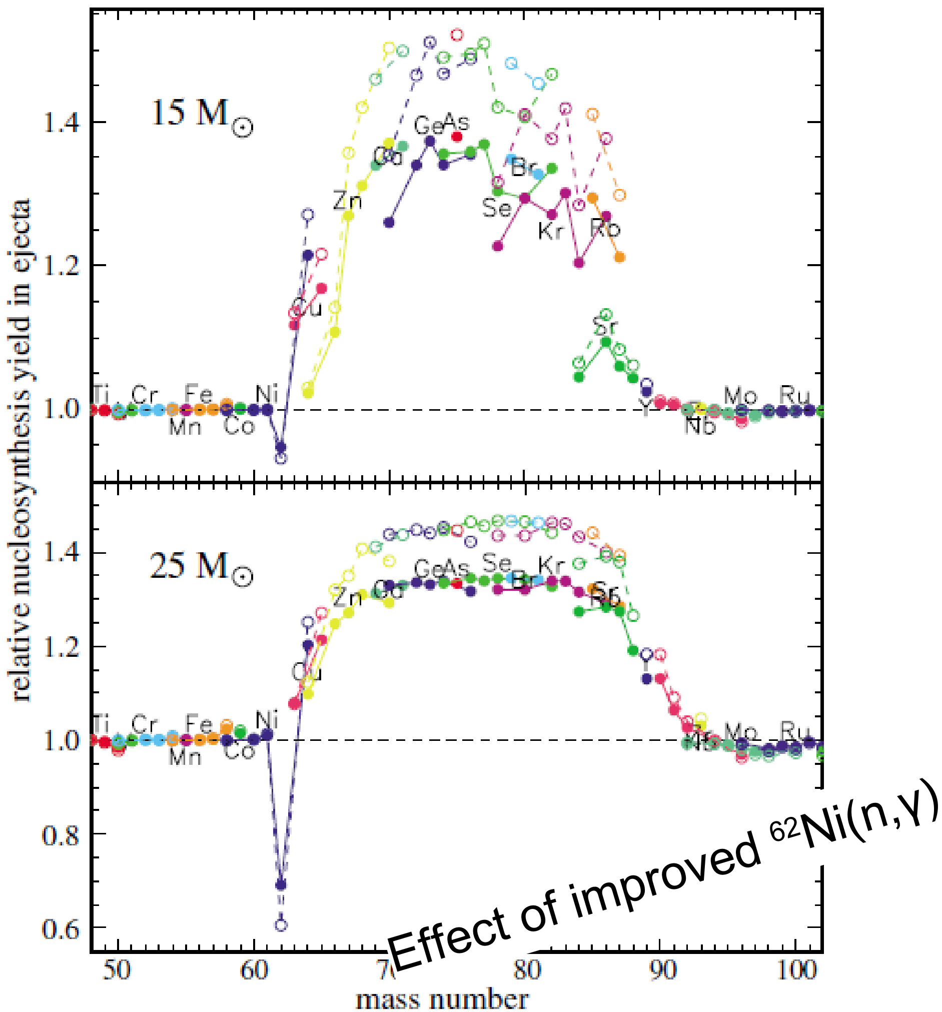
For more on charged particles, see
Talk by M. Taggart
M. Bennet NIC_XI_244
A. Best NIC_XI_159
B. Bucher NIC_XI_328

Heil *et al.* PRC (2008)

Neutron capture in the *s* process



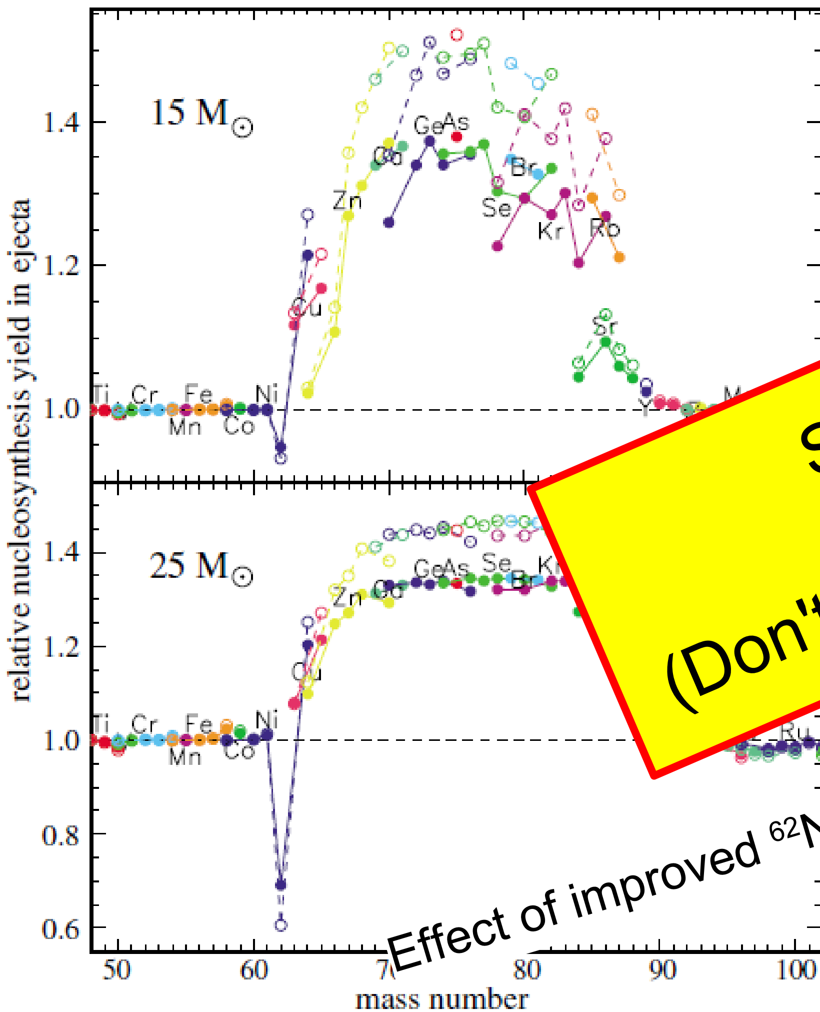
Measurements for the weak *s* process



- New activation measurement on ^{62}Ni adjusted abundances 30 mass units down-stream
- Cross sections for the weak *s* process are
  - small
  - difficult to calculate
  - likely non-statistical
  - Individual resonances and DC likely play a role
  - Impact propogates
- Multiple measurement techniques may be needed to understand the weak *s* process

Nassar *et al.* PRL 2005

Measurements for the weak *s* process



Nassar *et al.* PRL 2005

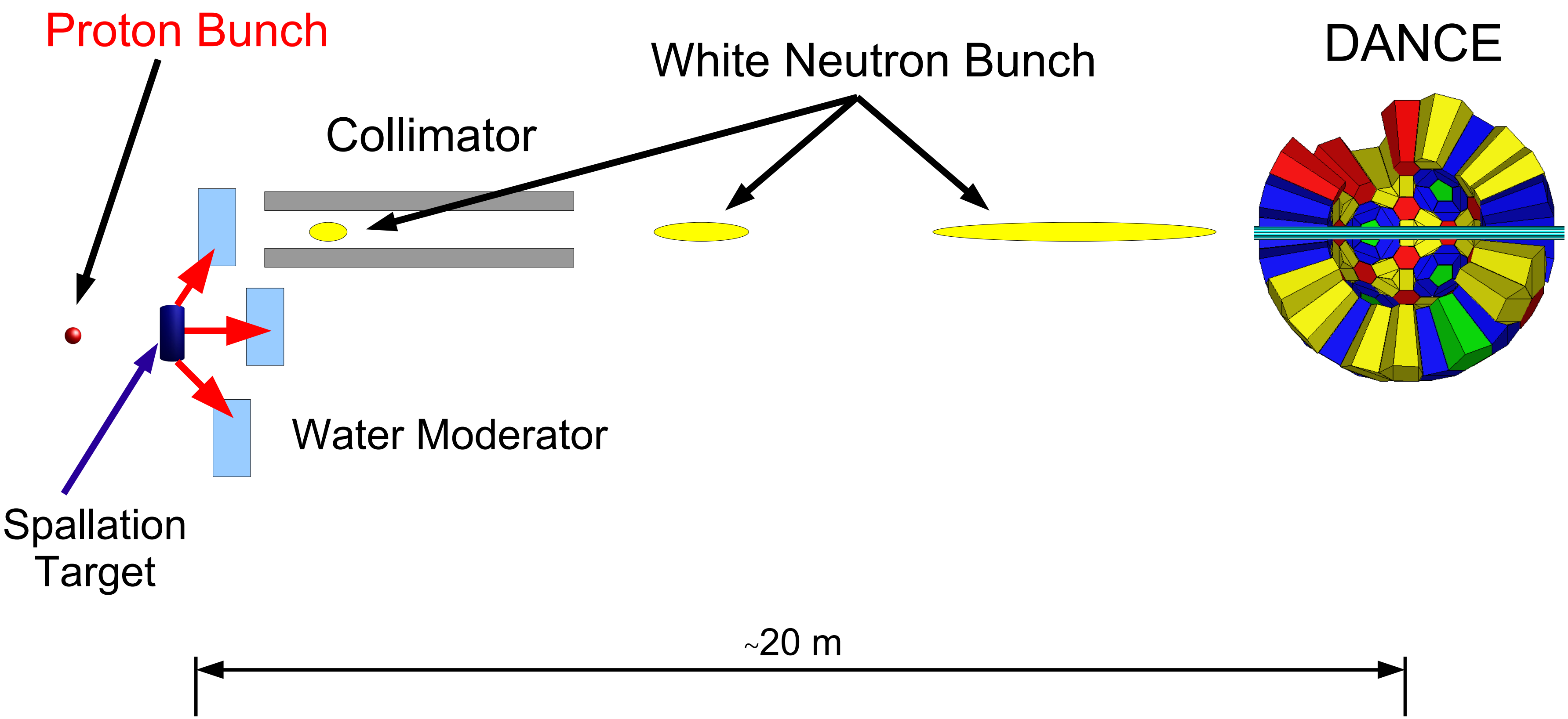
- New activation measurement on ^{62}Ni adjusted abundances 30 mass units down-stream
- Cr… for the weak *s*
  …alculate
  …y non-statistical
  - individual resonances and DC likely play a role
  - Impact propogates
- Multiple measurement techniques may be needed to understand the weak *s* process

See talk by
C. Lederer
(Don't leave after coffee!)

What is needed to measure neutron capture?

- Neutrons
- Capture Signature
- Sample

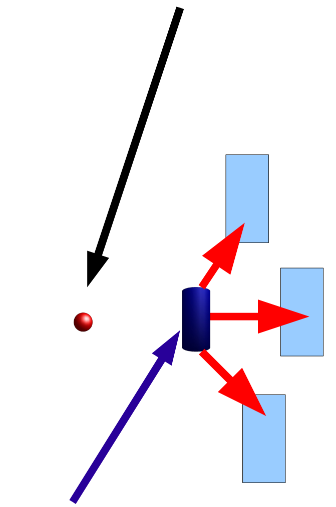
Time of Flight with Spallation Neutrons

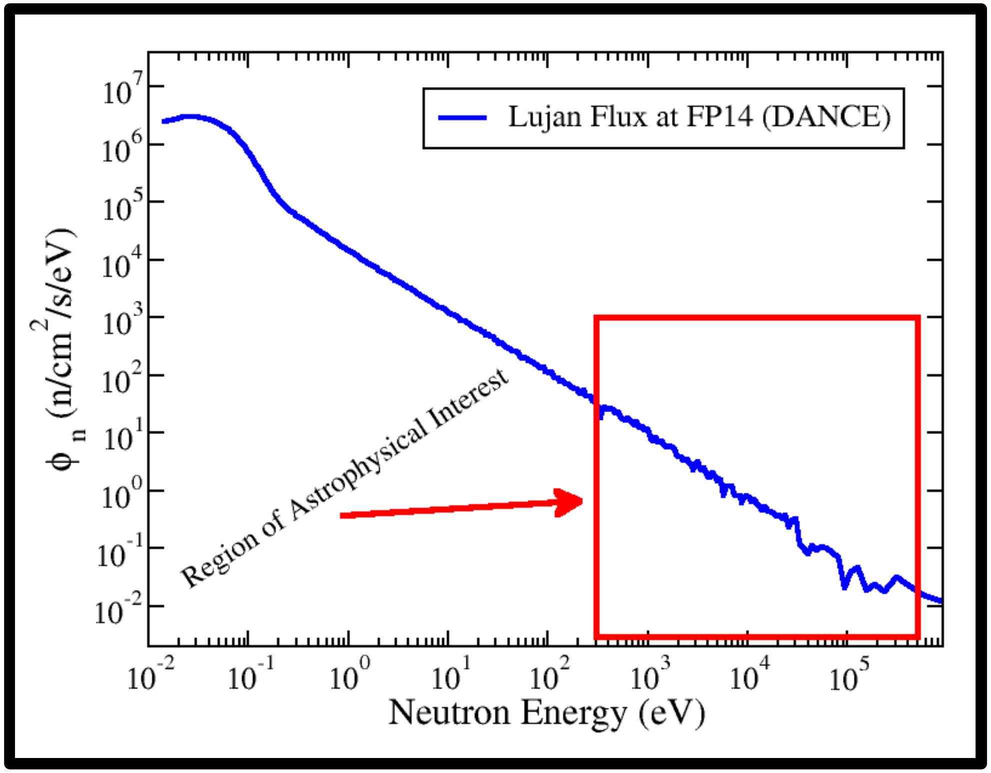


E_p= 800 MeV ν_p=20 Hz 10 meV < E_n < 500 keV

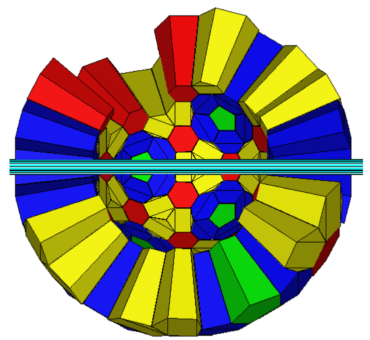
ϕ_n = 3 • 10^5 n/s/cm^2/decade

Time of Flight with Spallation Neutrons





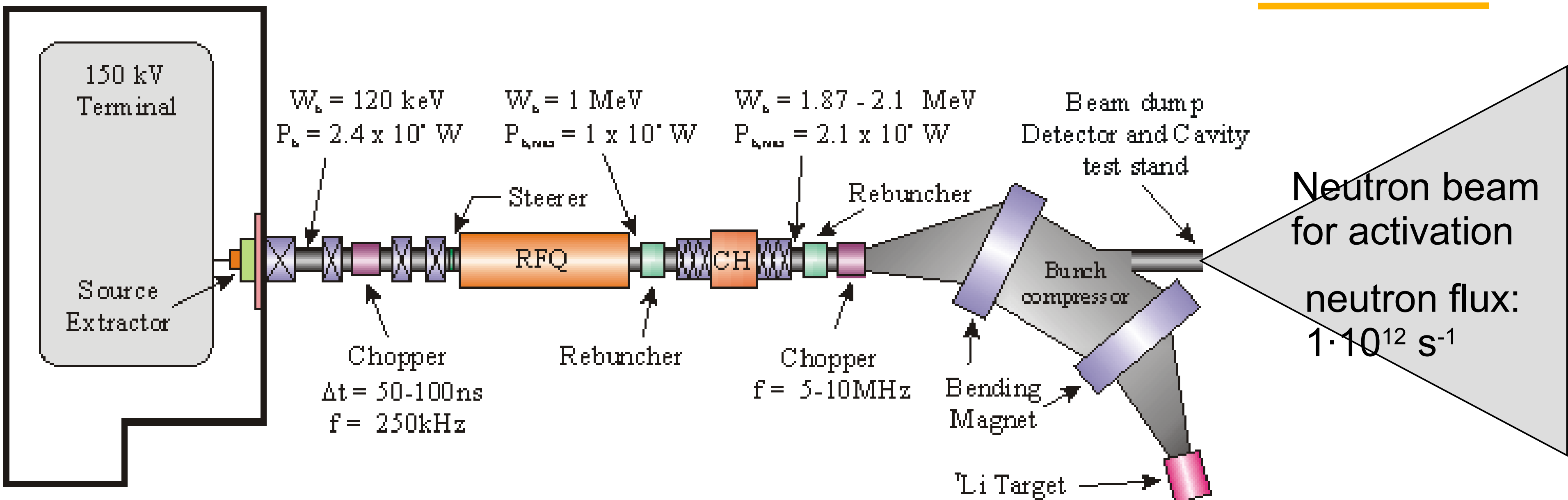
DANCE



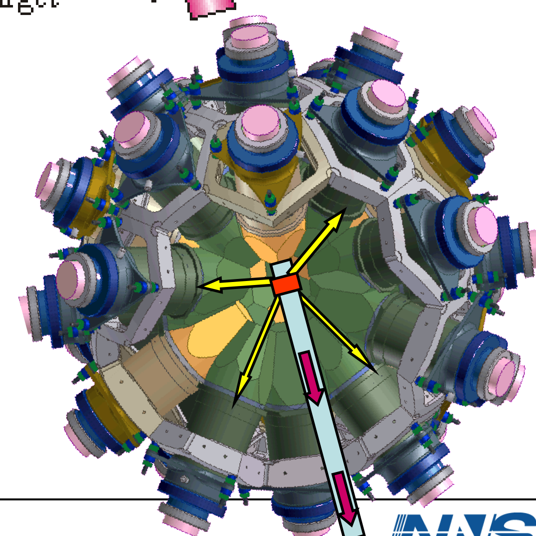
E_p = 800 MeV $\quad \nu_p$=20 Hz $\quad$ 10 meV < E_n < 500 keV

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

Measurements with $^{7}Li(p,n)$

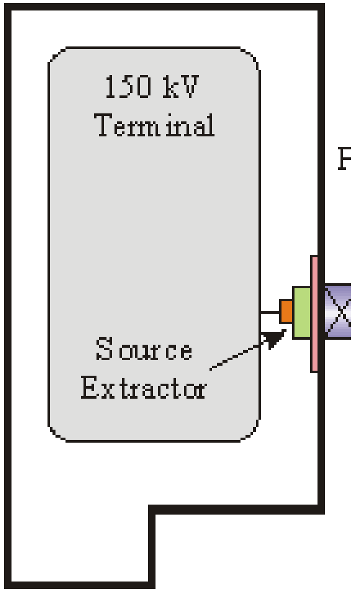


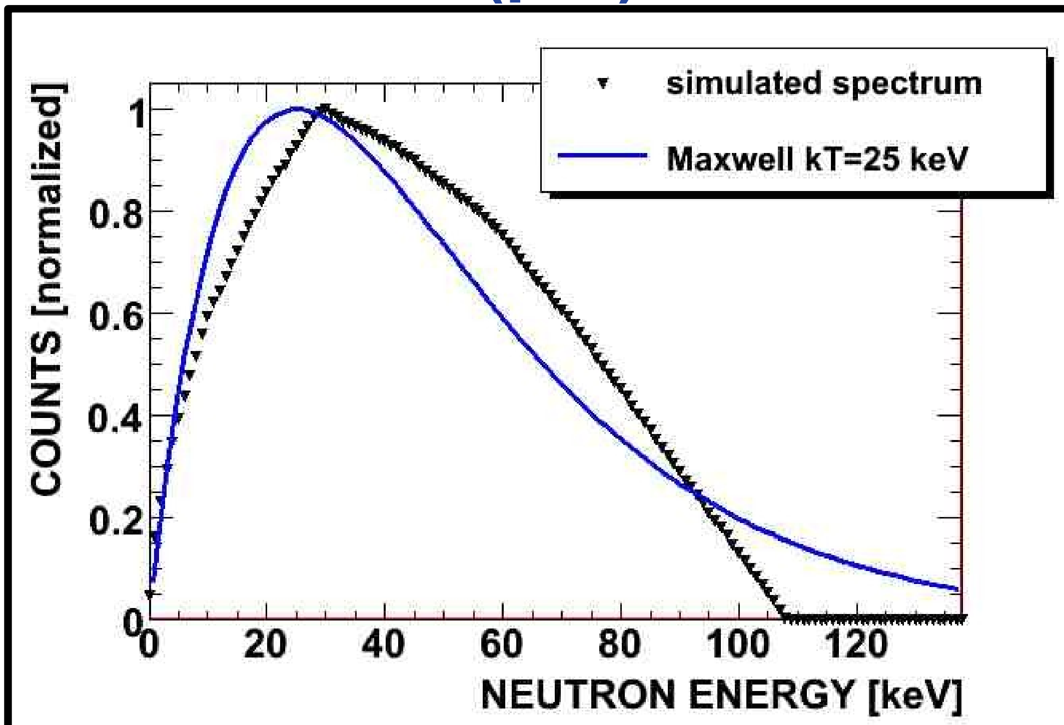
2 mA proton beam
250 kHz
< 1ns pulse width
neutron flux: $4 \cdot 10^{7}\ s^{-1}\ cm^{-2}$



Layout of the FRANZ Facility
R. Reifarth, PASA 2009

Measurements with ^{7}Li(p,n)

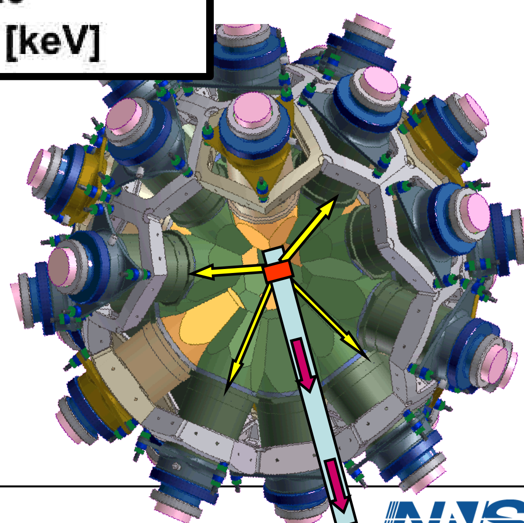




Neutron beam for activation

neutron flux: $1 \cdot 10^{12}$ s^{-1}

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

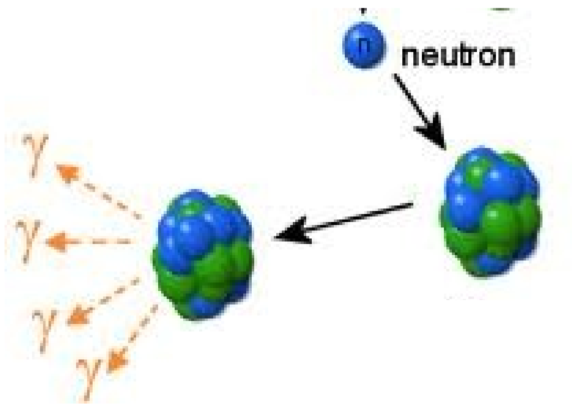


Layout of the FRANZ Facility
R. Reifarth, PASA 2009

Neutron source properties

- Neutron spallation sources
  - Cover a very wide energy range
  - Excellent energy resolution
  - High resolution differential data can be adapted to the burning regime of interest
  - May have difficulties with non-resonant components
  - Cannot be used for activation
- $^{7}Li(p,n)$ sources
  - Provide “ideal” spectrum
  - Relatively small
  - Miss the high and low energy parts of the spectrum
  - Can be used for high intensity activation

Signatures of Capture: Why detectors matter



- Typical capture releases 6-10 MeV in gamma ray energy
- Neutron energies do not significantly impact emitted energy

- Neutron capture measurements were often performed with C_6D_6 liquid scintillators
  – C_6D_6 has very low neutron sensitivity, but no energy information.
  – High purity samples are always required.
  – Gamma rays from a radioactive sample could not be distinguished from neutron capture.
  – C_6D_6 has very low efficiency, typically requiring gram samples.
- Calorimetric detectors can distinguish capture from decay based on total energy.
  – High efficiency allows small samples.
  – Isotopically mixed samples can be used if the isotopes have sufficiently different Q-value
  – High segmentation limits individual crystal count rates.

Alternatives to direct gamma-detection

- Activation/AMS
  - Offers measurement on small samples
  - Naturally measures DC and resonant components
  - Requires an appropriate lifetime product
  - Different systematics than “traditional” measurements
  - Integral measurements valuable, but may be difficult to generalize

- Photodissociation *(γ,n)*
  - Deduces rate from detailed balance
  - Can offer alternative way to reach unstable nuclei

Alternatives to direct gamma-dete

- Activation/AMS
  - Offers measurement on smal
  - Naturally measures DC and re   ents
  - Requires an appropriate lifetime   ct
  - Different systematics than "traditional" measurements
  - Integral measurements valuable, but may be difficult to generalize

See poster by
A. Wallner
NIC_XI_375

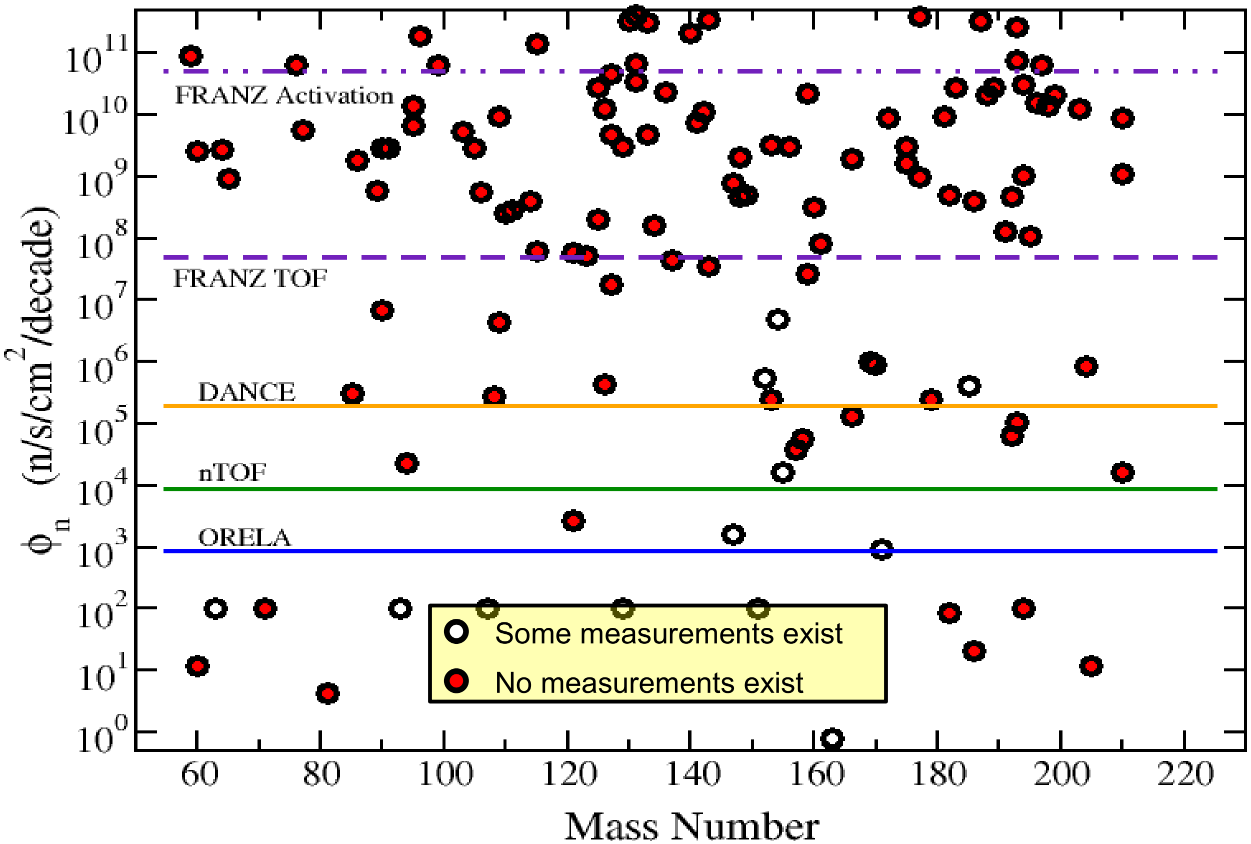
- Photodissociation *(γ,n)*
  - Deduces rate from detailed b
  - Can offer a

For more on photodissociation, see
I. Dillmann (After Coffee)
K. Sonnabend (NIC_XI_272)

Los Alamos
NATIONAL LABORATORY
EST. 1943

NNSA

Estimated Neutron Fluxes Required for Measurements on Branch Point Isotopes



Couture and Reifarth, ADNDT(2007)

Each branch-point illustrates how the s-process operates in stars of different mass, age and metallicity

Only with measurements on many isotopes will we understand the temperature and densities in the many different s-process scenarios

There remains much to do, but many of the tools are available today

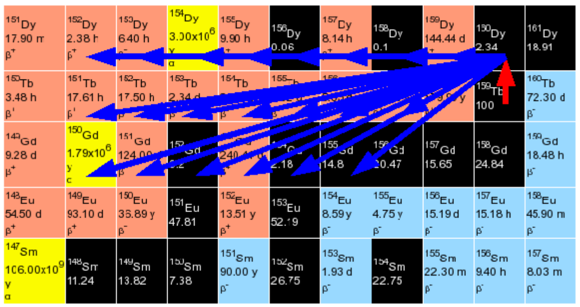
Los Alamos NATIONAL LABORATORY EST.1943

NNSA

Where, oh where, can my sample be?

Should I make it?

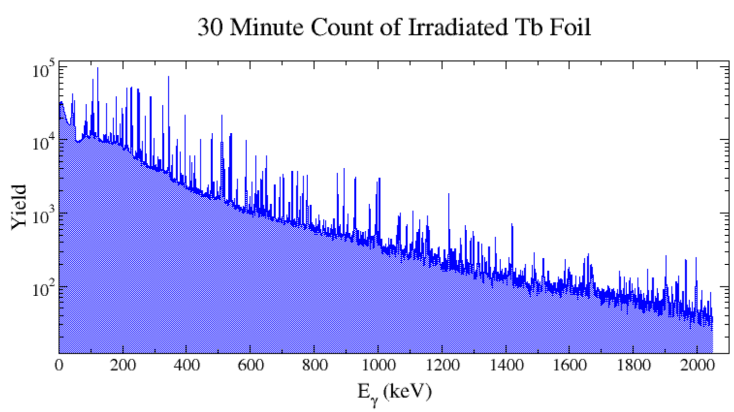
- For modern facilities, we need 100 µg- 10 mg size samples



Sample

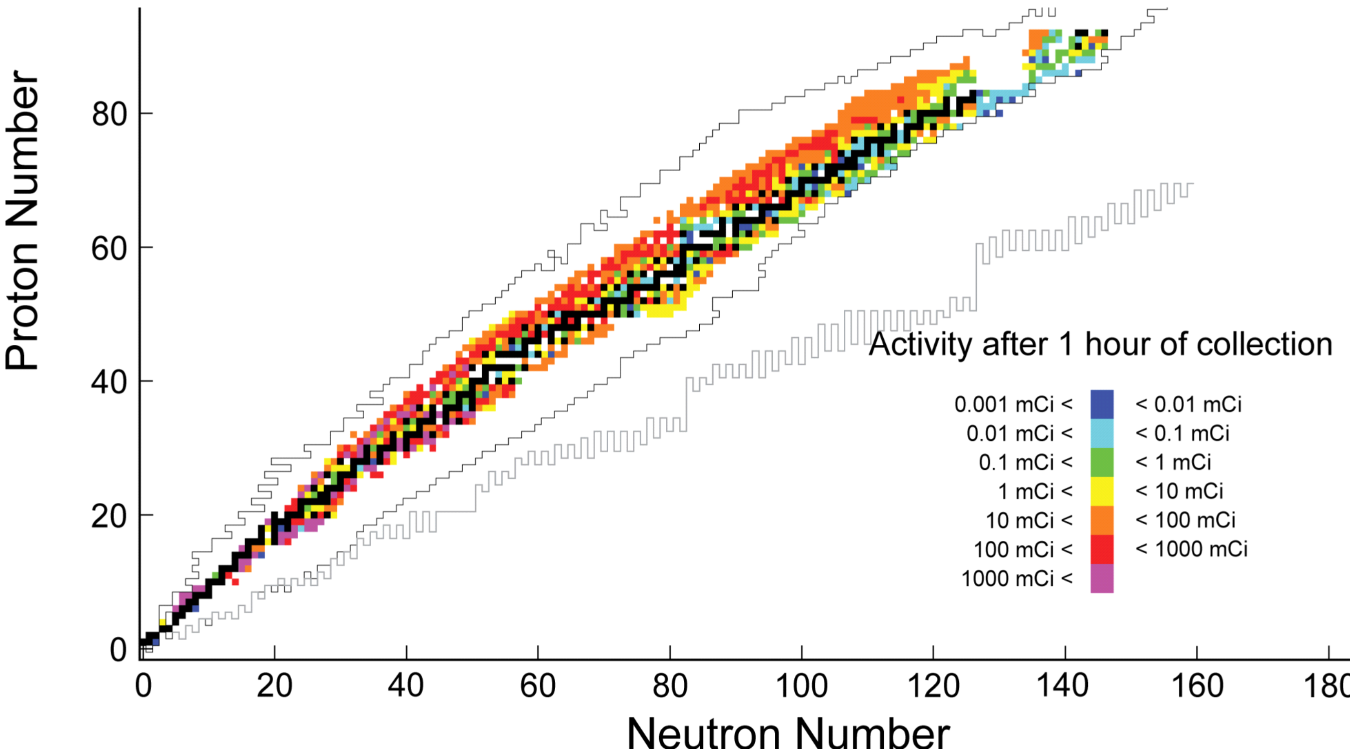
Isotope Separation?

Radiochemistry



- Very expensive
- Each isotope is a research project
- Time consuming

Or should I look in the trash?



Estimated FRIB Activities
B. Sherrill, *private comm.*

- In addition to "science" beams, new RIB facilities will make lots of valuable "trash"
- If it can be salvaged, it may offer useful samples for *s* process studies
- Planning should be done early

Conclusions

- A very diverse set of experiments are needed to support *s* process nucleosynthesis studies
- Charged particle studies are challenging and exhibit many similar properties as measurements that have been discussed for He burning and measurements at underground labs
- To understand neutron capture, a diverse set of tools are needed
  - Because the stellar sites have changed, it is necessary to revisit some measurements and predictions
- Measurements on radioactive isotopes are often possible, but we lack samples
  - We must be creative in trying to find ways to get them