s-Process Nucleosynthesis Studies with DANCE

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16 March 2009
JINA Lunch Discussion
Michigan State University

Los Alamos
NATIONAL LABORATORY
EST. 1943

NNSA

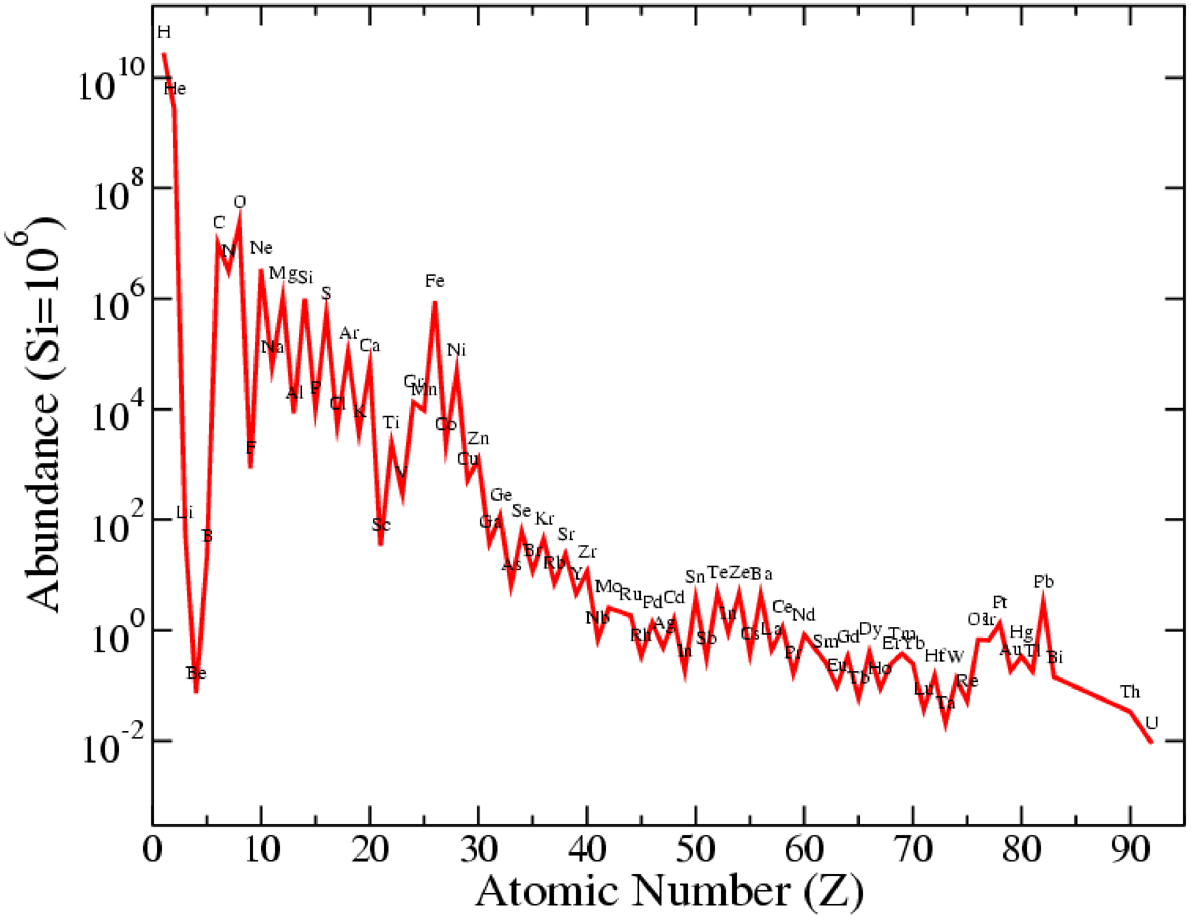
Outline

- The role of neutron capture in nucleosynthesis
- Neutron production at LANSCE
- The DANCE instrument for neutron capture
- Opportunities for new measurements and capabilities
- Conclusions

How do they work?
Why is there not more?

Photo Courtesy of Shannon Scott

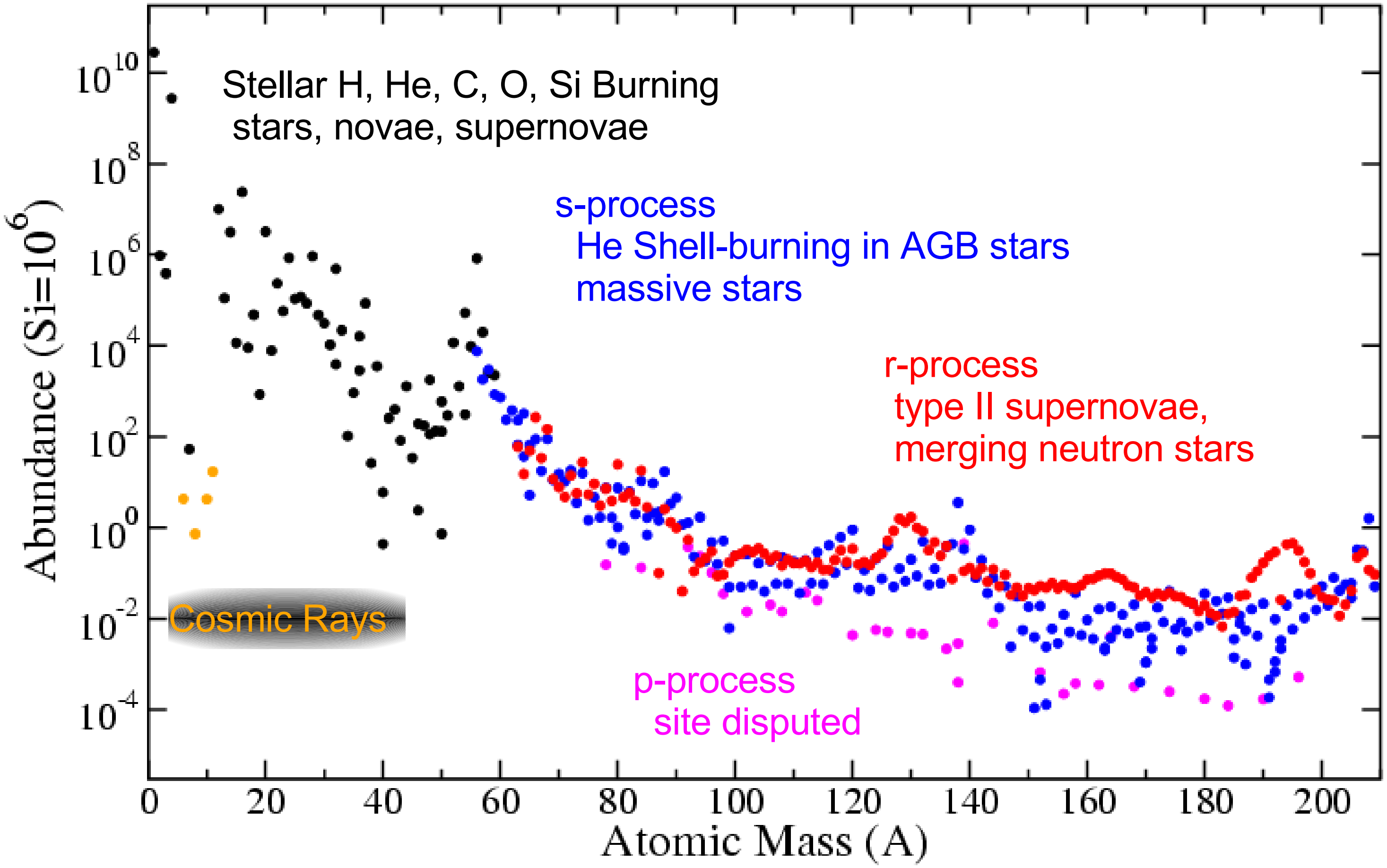
Explaining the Origin of the Elements—the Holy Grail of Nuclear Astrophysics



Anders and Grevesse, 1989

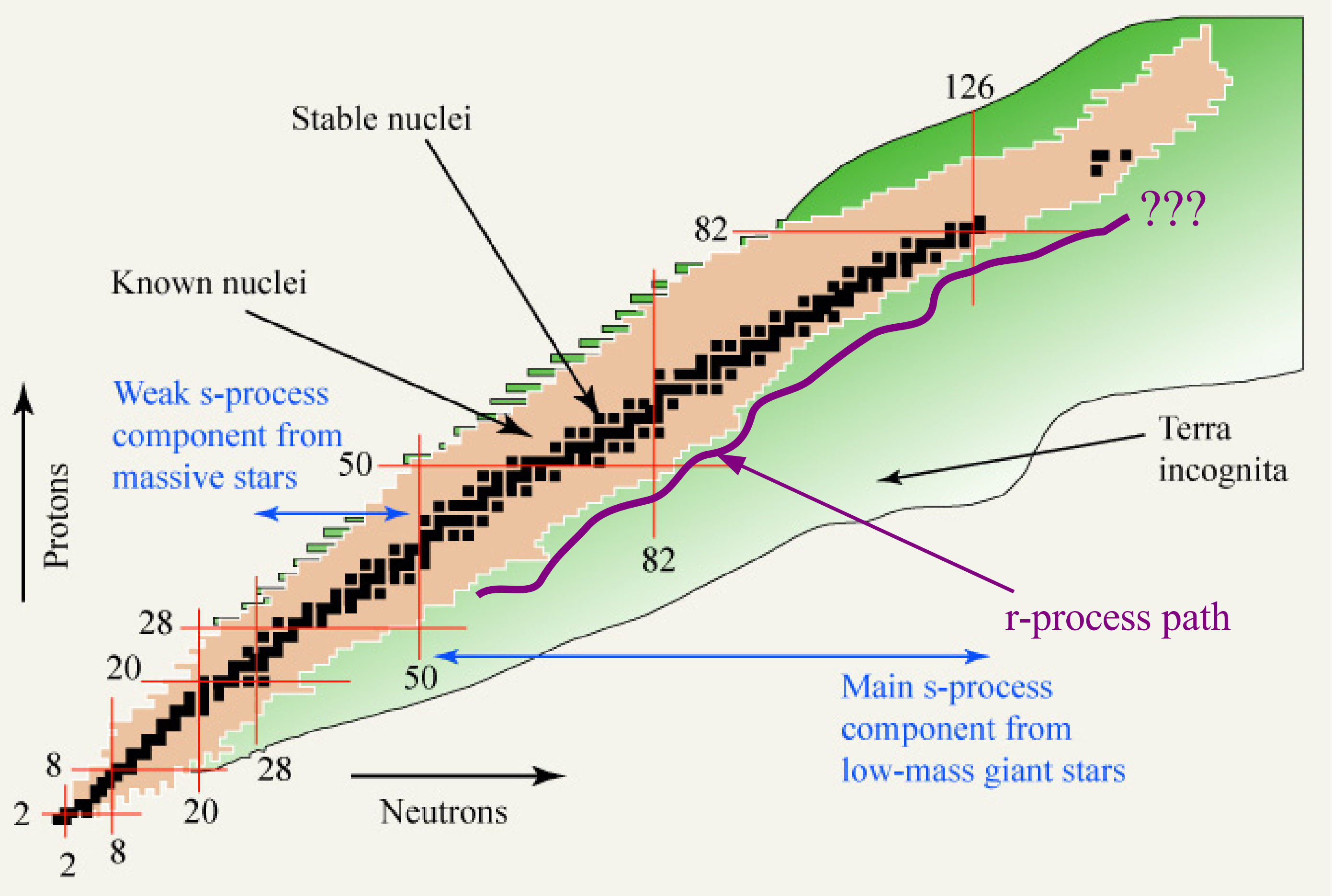
- Solar system abundances from observations and meteorites give an approximate cosmic elemental abundance
- The abundance distribution shows definite nuclear physics effects, indicating the crucial role nuclear physics plays in the production of the elements

Isotopic Abundances Allow the Identification of Astrophysical Sites and Processes



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

Neutron Induced Nucleosynthesis



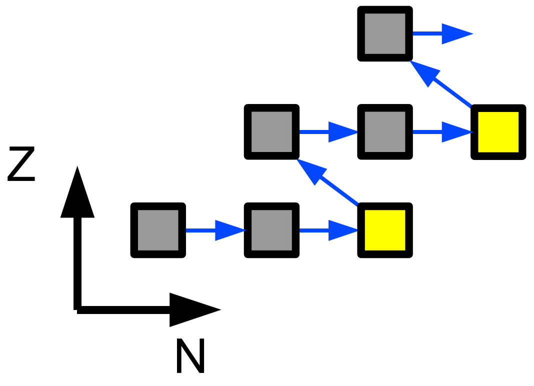
Rapid Neutron Capture (the r process)

- Neutron capture must take place very quickly in order to account for observed structures.
- Time scales are much shorter than typical β^- decay times—capture continues out to the $(n,\gamma)\leftrightarrow(\gamma,n)$ equilibrium.
- At best, nuclear masses and lifetimes are experimentally accessible*.
- Both sites and mechanisms are still contested.
- Nominal physical conditions:
  - 10^{24} n/cm^3 < ρ_n < 10^{28} n/cm^3
  - $T \approx 2$ GK
  - $\Delta t \approx$ seconds

* This is changing with the new facilities and new techniques

The slow neutron capture process (the s process)

- The s-process is one of two main nucleosynthesis mechanisms for isotopes heavier than iron.
- Neutron capture will proceed along an isotopic chain until a short-lived isotope is reached, at which point beta decay will shift it to higher Z.



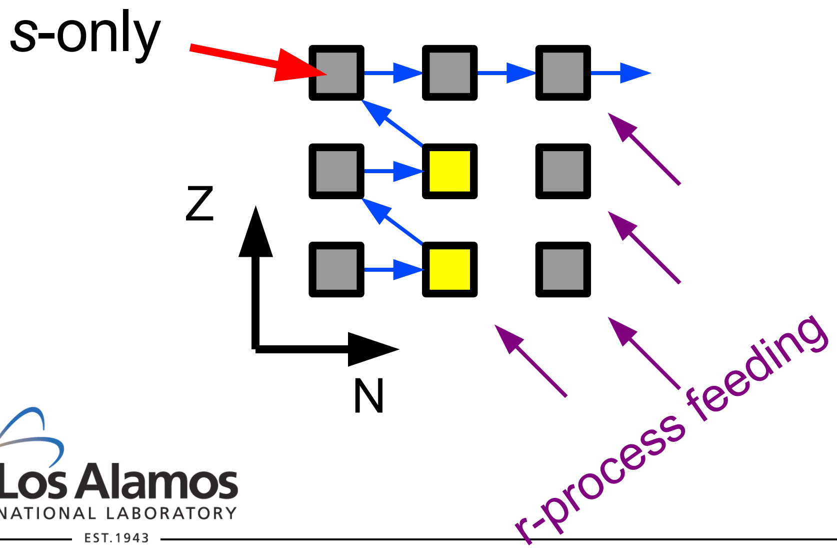
- Typical lifetimes versus neutron capture are on the order of years to tens of years.
- Process time is on the order of tens of thousands of years

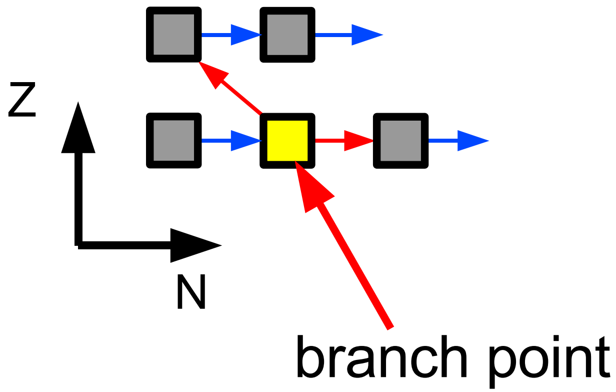
Key Isotopes for Cross Section Measurements

300—400 isotopes lie on the *s*-process path

Branch point and *s*-only isotopes provide sensitive model constraints on temperatures and neutron densities

Measurements are typically needed over a range of energies to account for different stellar scenarios (kT≈ 8, 25 keV, and 90 keV), making extrapolation from activation experiments difficult





Deconvolution of Heavy Element Synthesis

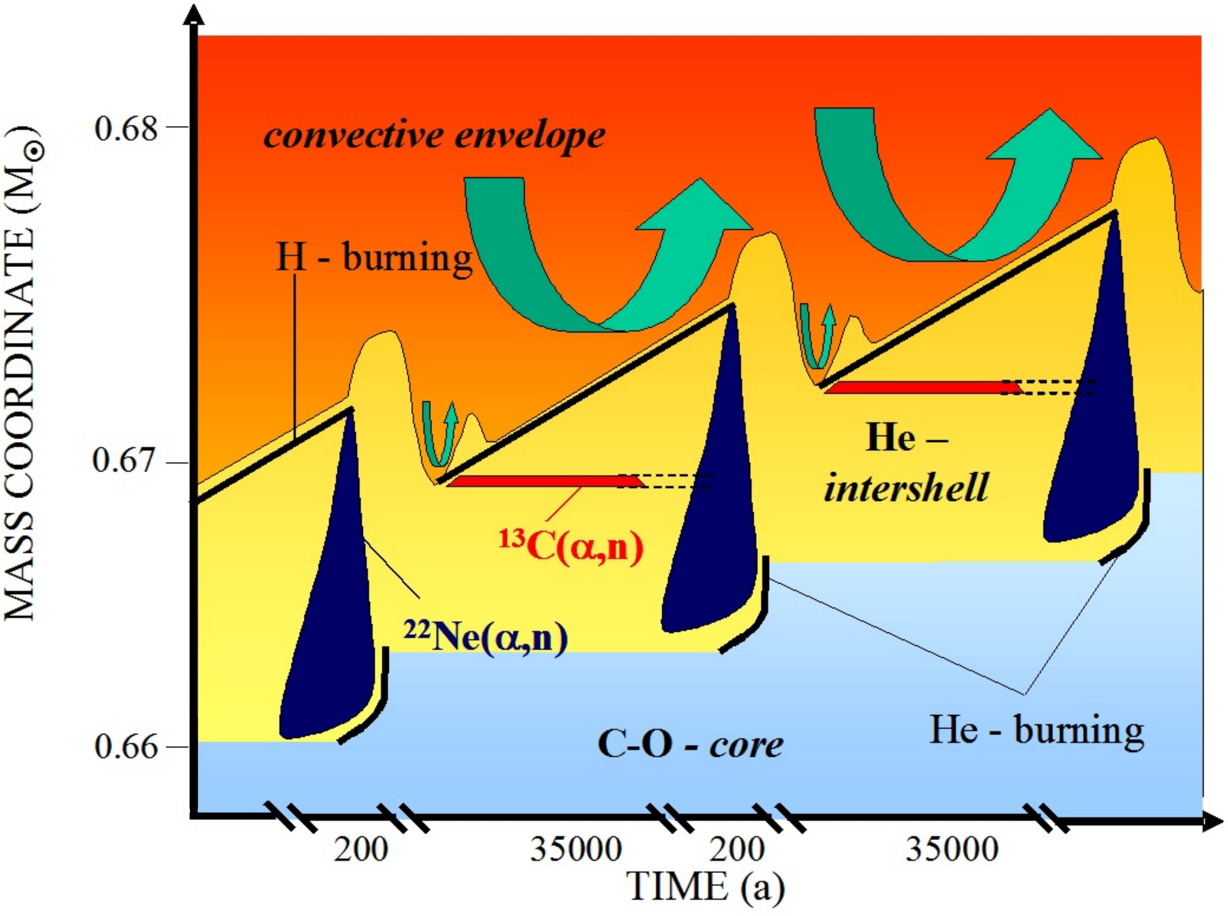
- While there are some s-only or r-only isotopes that allow easy identification of origin, most heavy isotope can be made either through the s or the r process
- Material observed in the cosmos has typically undergone many nucleosynthesis cycles*, mixing contributions from the s and r processes
- Since the understanding of the s process is better, the typical attribution is accomplished by looking at the isotope production from s-process model, scaling it to s-only abundances, and determining the rest to be from r process

* There are now some observations from stars that indicate very little processing

Stellar conditions during s-process nucleosynthesis

- The main s-process operates mainly in low-mass (1-3 $M_\odot$) asymptotic giant branch (AGB) stars.
- The neutron production and capture takes place in the helium burning shell outside of the C-O core.
- The last 10 years have seen rapid advancements in the stellar modeling of the s-process site.
- Temperatures range from 80-300 MK.
- Neutron densities range from 10^6-10^{11} n/cm^3
- Neutrons are produced via the $^{13}C(\alpha,n)$ and $^{22}Ne(\alpha,n)$ reactions.

S-Process Nucleosynthesis in 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 5 keV up to 30 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

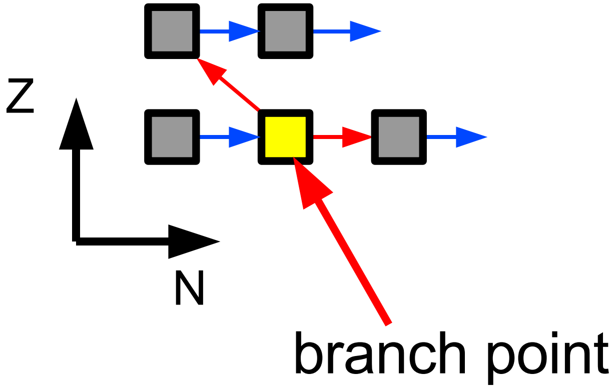
The Origins of the Neutron Sources

- ^{22}Ne can be formed directly in the He shells from the ashes of the CNO cycle
  - A large part of the ashes from the CNO cycle are left as ^{14}N
  - The reactions $^{14}N(\alpha,\gamma)^{18}O(\alpha,\gamma)^{22}Ne$ form sufficient ^{22}Ne
  - $^{22}Ne(\alpha,n)$ is strongly temperature dependent and only operates above T=300MK.

- ^{13}C is more difficult to produce. It is not an ash of the CNO cycle or He burning.
  - It can only be produced by the introduction of hydrogen below the hydrogen burning shell
  - A small mixture of hydrogen allows the ^{12}C ashes to undergo the reactions $^{12}C(p,\gamma)^{13}N(\beta^-)^{13}C$
  - $^{13}C(\alpha,n)$ operates at lower temperatures and will burn to exhaustion

Folding Cross Sections into Stellar Models

- The neutron exposure from $^{13}C(\alpha,n)$ is determined by the amount of hydrogen mixed into the helium shell.
  - Detailed neutron capture cross sections give information about the neutron density and thus, the convection in the shell.
- The $^{22}Ne(\alpha,n)$ reaction is marginally activated at $T_8=3$ so that the neutron exposure from this reaction is a sensitive thermometer for the thermal pulse.



Caveats and Complications

- The s process is not a unique process
  - Nucleosynthesis yields will be different for different masses and starting seed compositions (metallicity).
  - Different branch points play a critical role for different stars
  - Many measurements are needed!
- The s process is *very* different in massive stars
  - Temperatures in the He burning core are sufficient to drive the ^{22}Ne(α,n) reaction, but with sufficiently low neutron densities that nucleosynthesis is limited to A<90.
- Reactions on light isotopes (A<60) modify the expected abundances
  - While capture cross sections on O-Na-Ne isotopes are small, due to their large abundances, they can significantly affect the neutron densities

Outline

- The role of neutron capture in nucleosynthesis
- **Neutron production at LANSCE**
- The DANCE instrument for neutron capture
- Opportunities for new measurements and capabilities
- Conclusions

LANSCE presently provides a unique and diverse set of premier research facilities

Lujan Center

- *Materials science and condensed matter research*
- *Bio-science, nuclear science*
- *National security research*

WNR

- *Nuclear national security research*
- *Semiconductor irradiation*

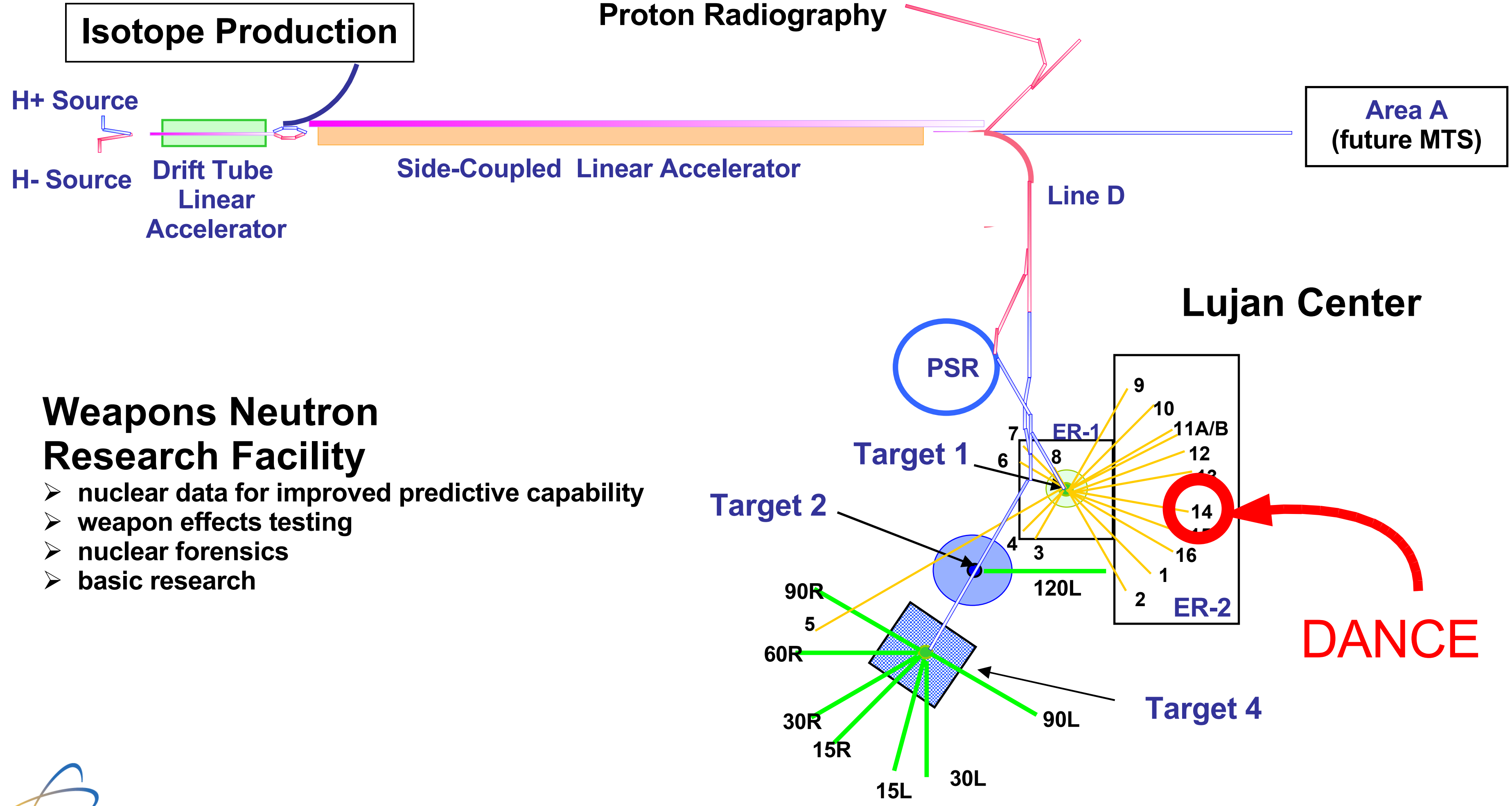
Ultra-cold Neutron Facility

- *Fundamental Nuclear Physics*

Isotope Production Facility

- *Nuclear Medicine*
- *Research isotope production*

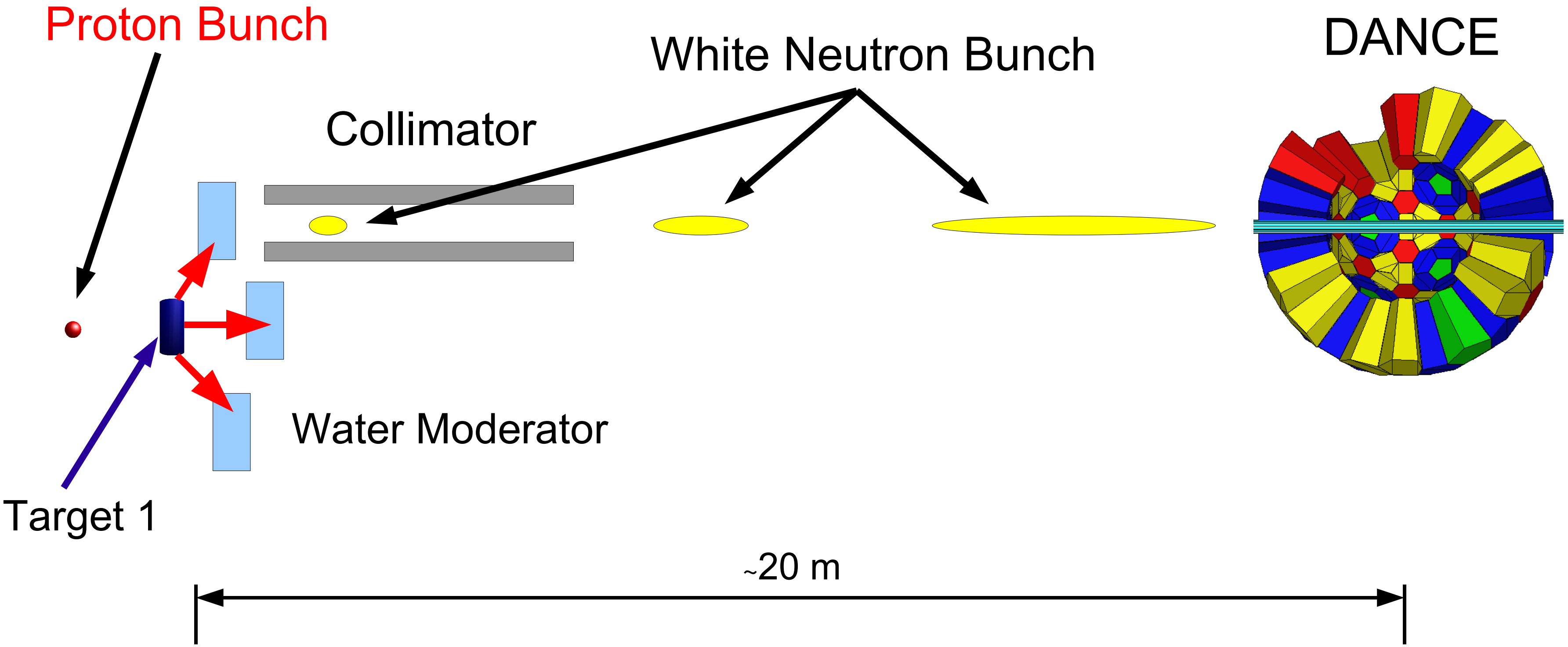
LANSCE proton beams are delivered to experimental facilities in a variety of beam structures and intensities



Weapons Neutron Research Facility

- nuclear data for improved predictive capability
- weapon effects testing
- nuclear forensics
- basic research

Time of Flight with DANCE at the Lujan Center



Proton Bunch

White Neutron Bunch

DANCE

Collimator

Water Moderator

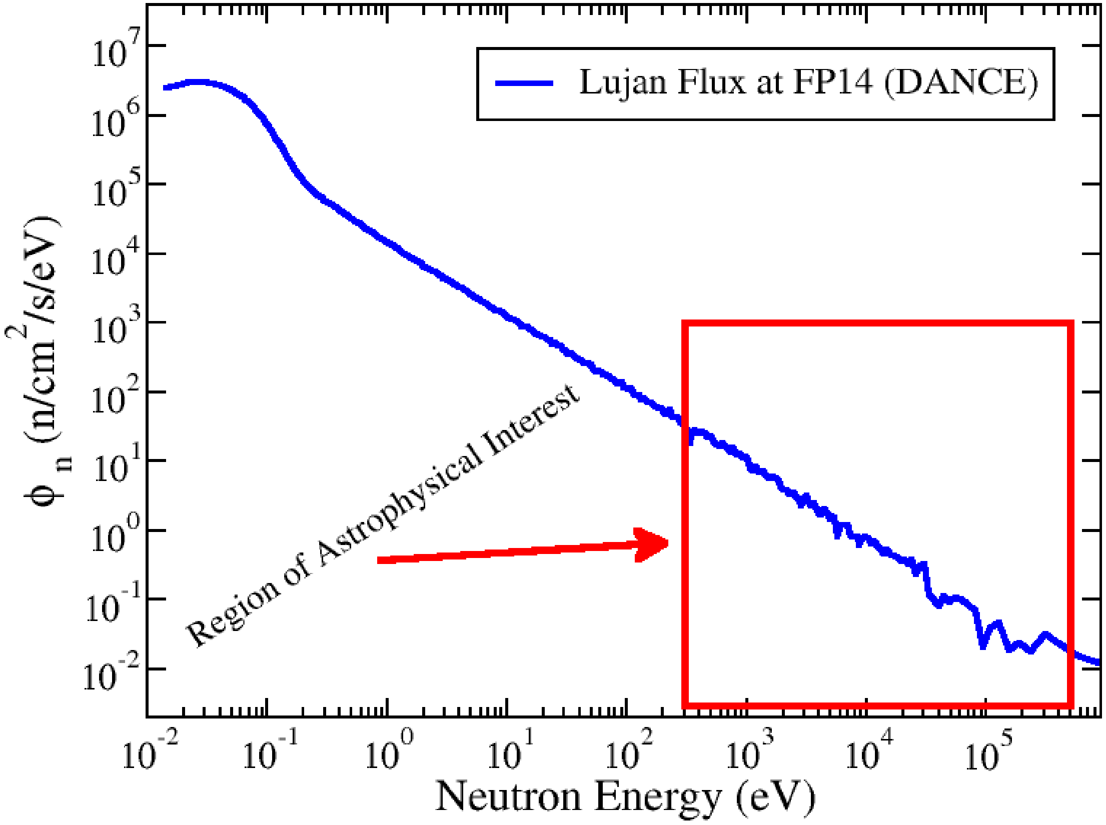
Target 1

~20 m

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

Neutron Flux at DANCE



- DANCE can perform measurements over several orders of magnitude.
- Unfortunately, the flux is lowest in the region of highest interest and lowest cross section.

Facilities for Neutron Reaction Measurements

Facility	Neutron Spectrum	Detection
DANCE/LANSCE	Spallation TOF white	BaF_2 (E sum)
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

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

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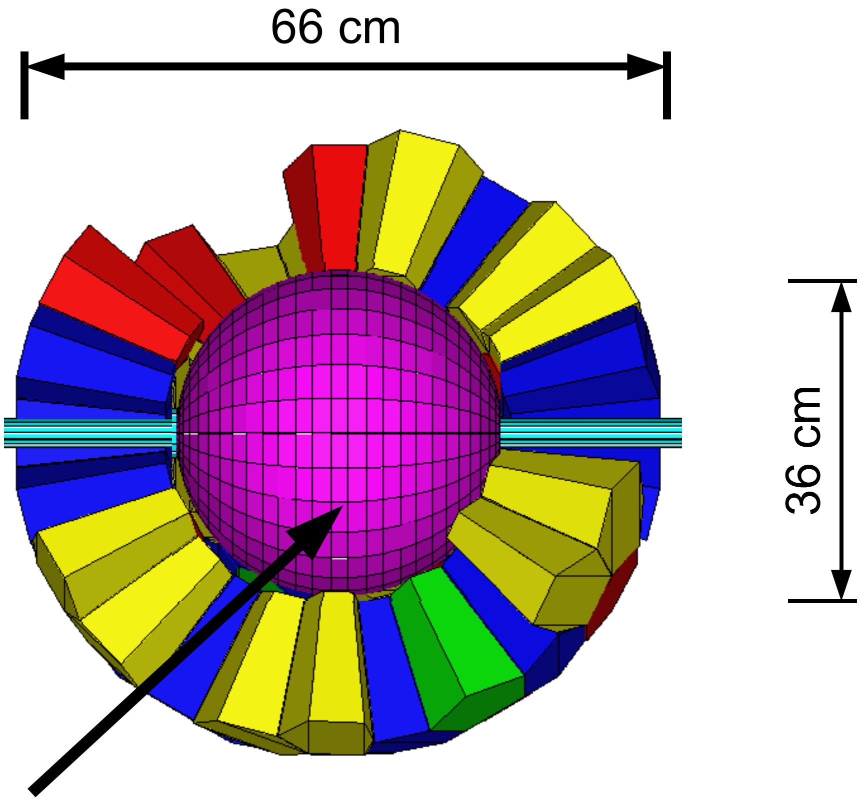
The Detector for Advanced Neutron Capture Experiments (DANCE)

160 BaF_2 Scintillators

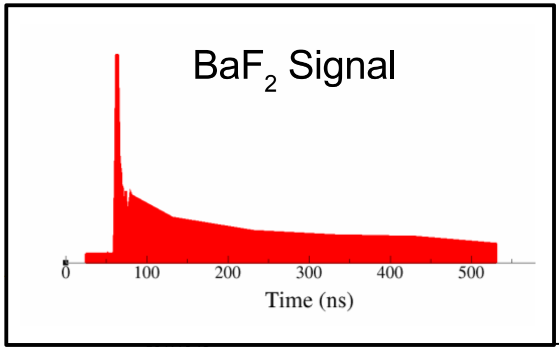
4 Detector Shapes each covering the same solid angle

$\varepsilon_{\gamma} \approx 90$ %

$\varepsilon_{casc} \approx 98$ %



^{6}LiH Shell Surrounds Sample
(6 cm)

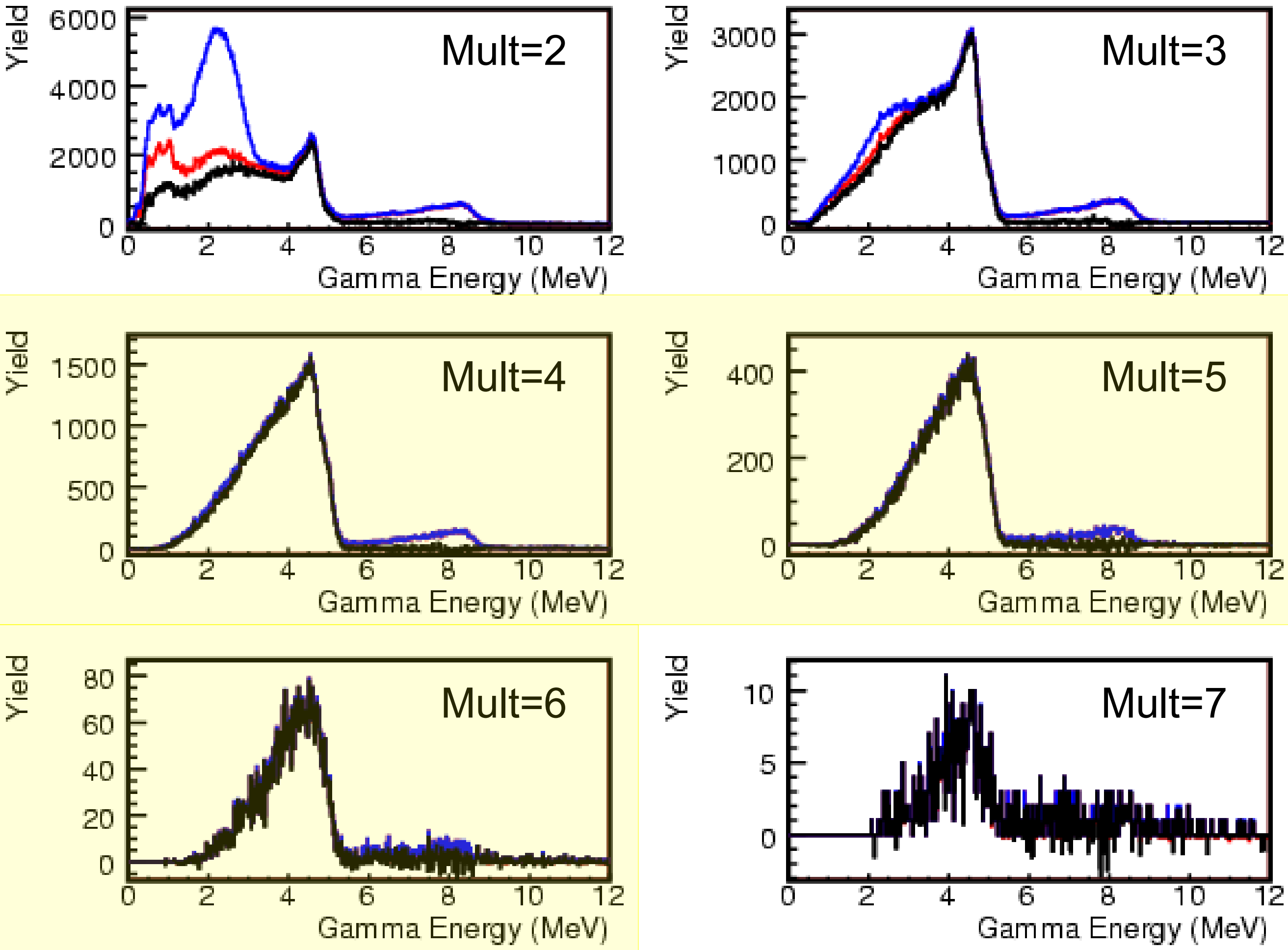


For details see: Heil *et al,* NIM A 459 (2001) 229-246

Total Gamma Energy vs. Multiplicity
(E_n = 1-10 eV, Q = 5.03 MeV)

^{242}Pu Raw
^{242}Pu less Ambient
^{242}Pu Final

Multiplicities used in cross-section determination



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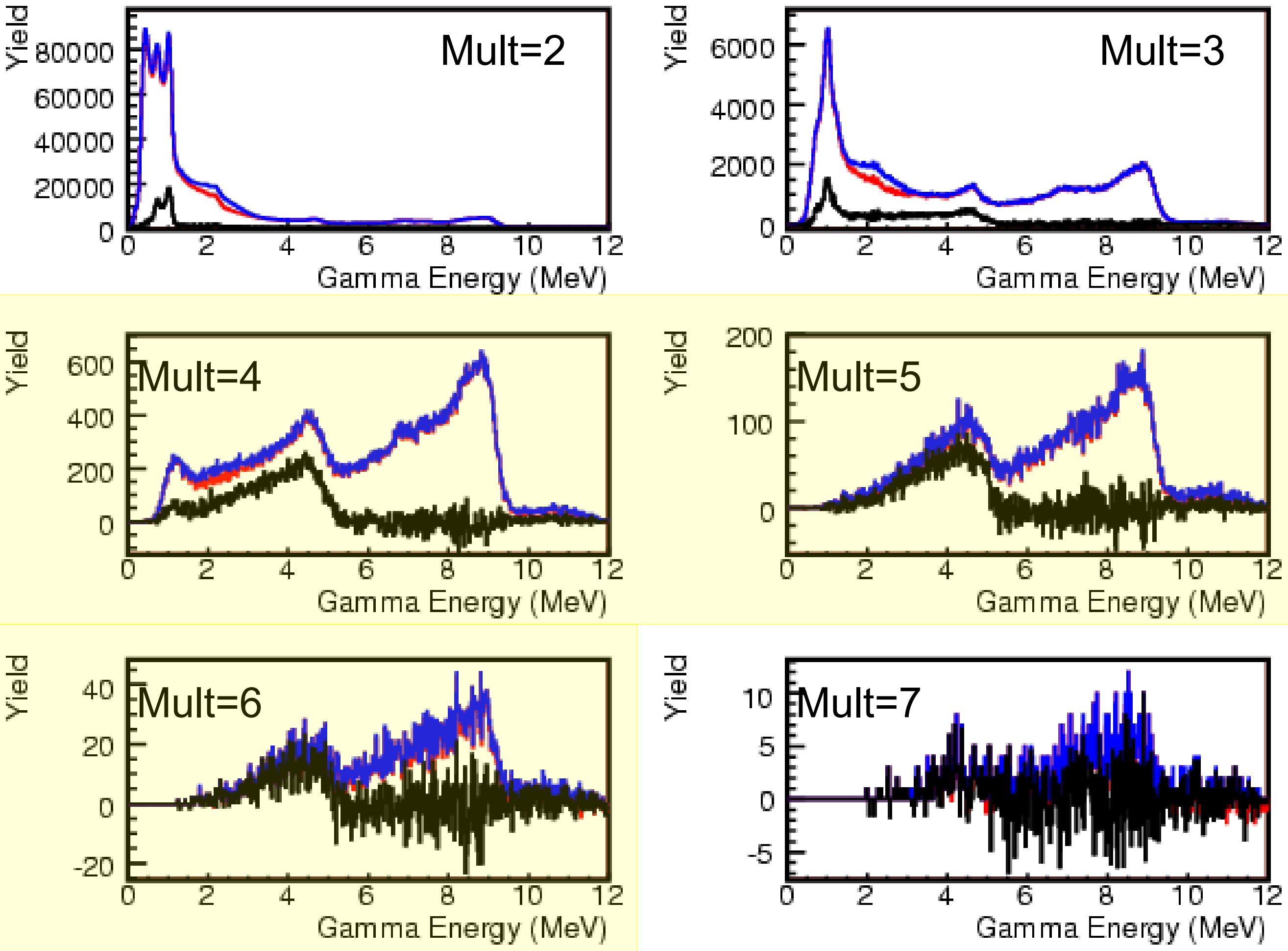
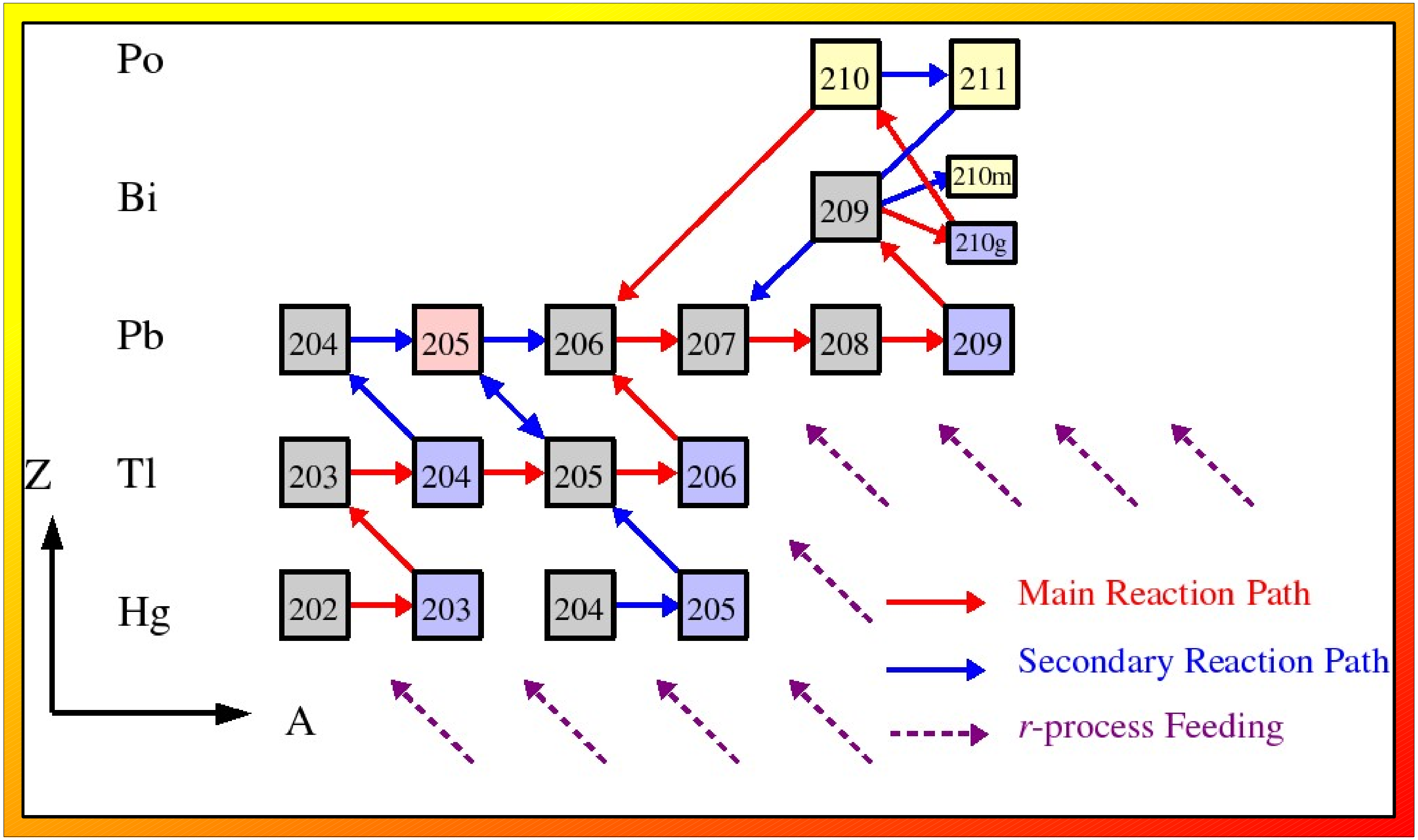
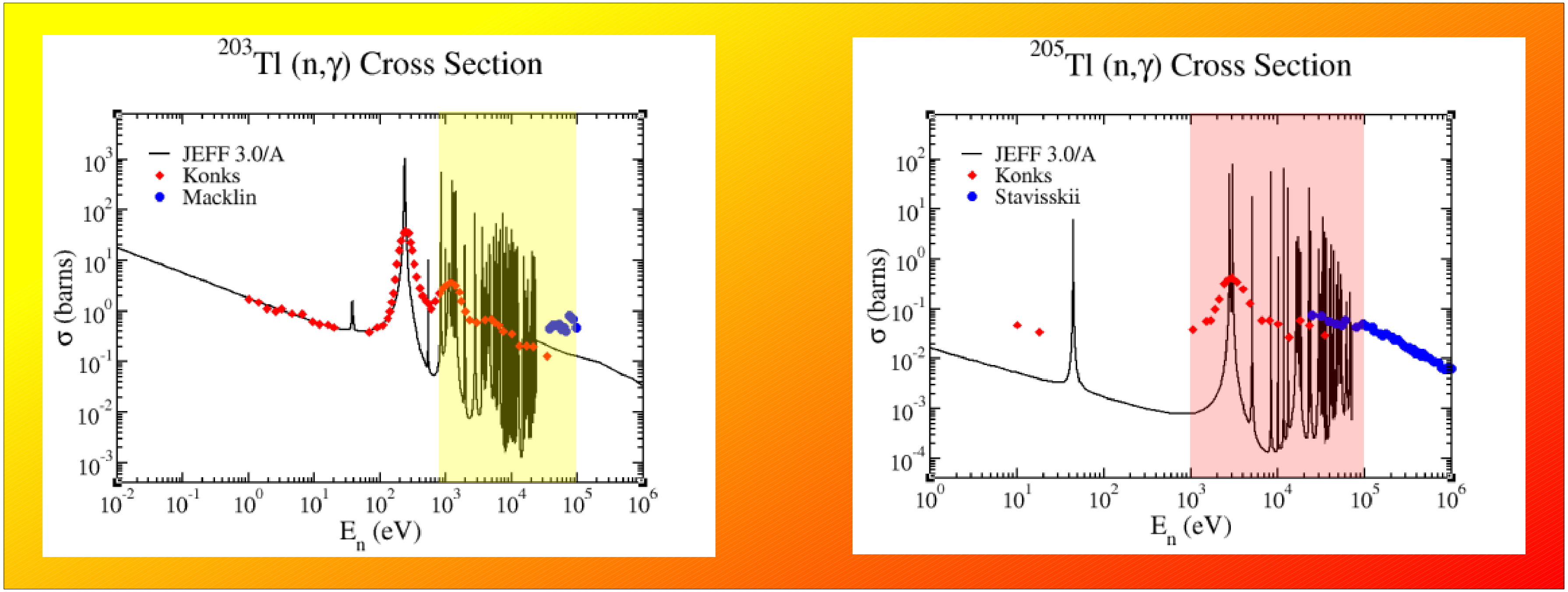


Multiplicities used in cross-section determination

The Role of Tl in the Stellar s-process



Previous Measurements on Tl isotopes

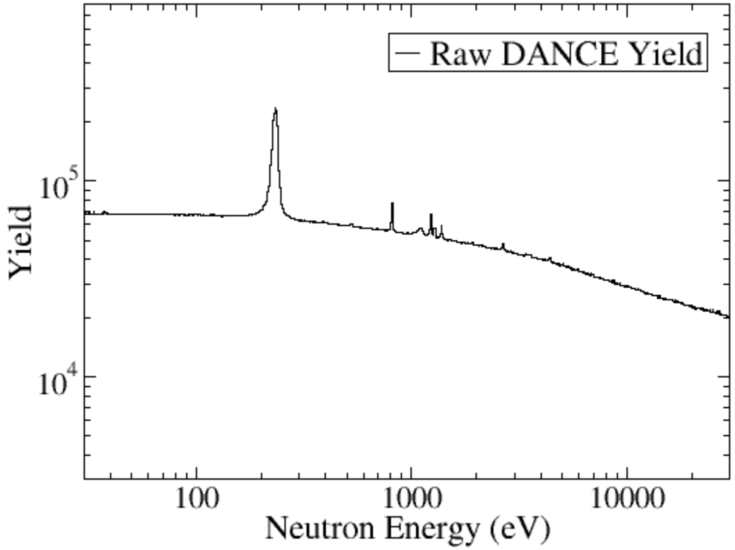


Resolution generally insufficient

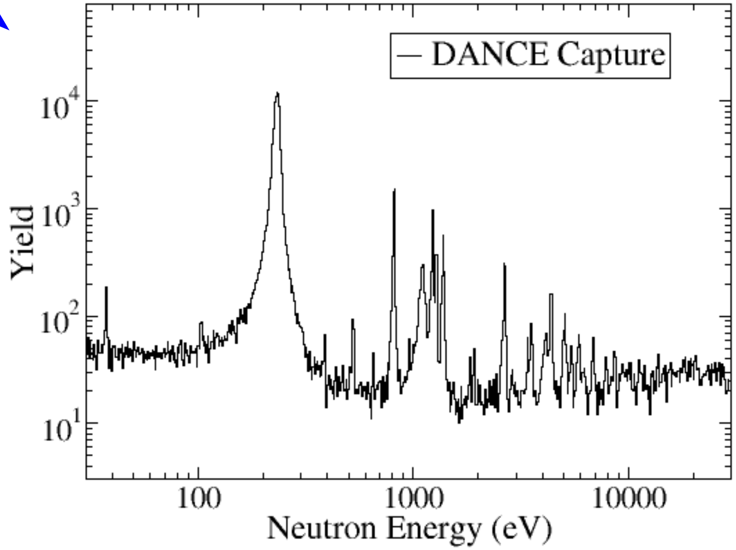
Significant discrepancies between evaluation and measurements

Only one evaluation has isotopic information

Effect of DANCE Selection on Q-Value and Multiplicity

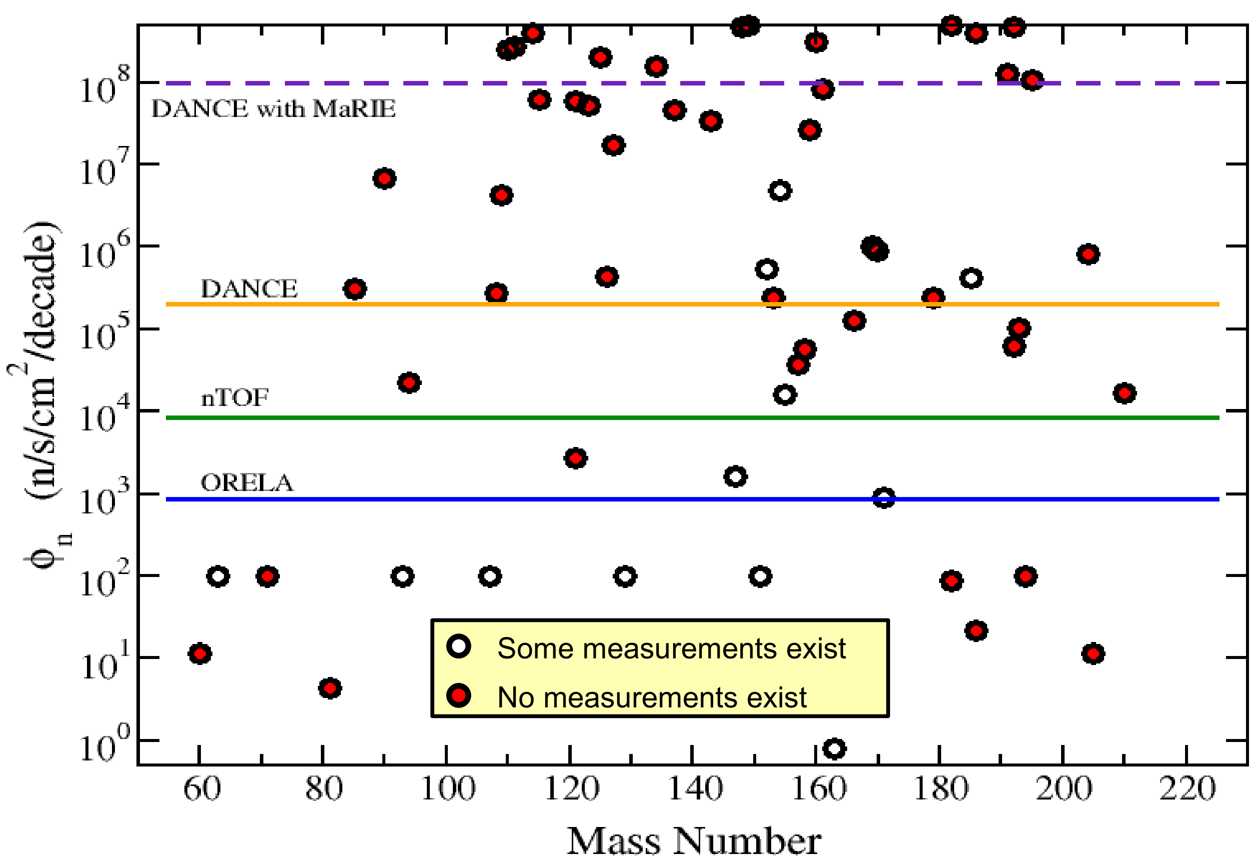


Mult and Q Cuts



- All measurements are from a 50 mg sample of ^{203}Tl.
- No subtraction of elastic background has been done.
- While the losses in efficiency are large, the enhanced S/N is worth it.

Estimated Neutron Fluxes Required for Measurements on Branch Point Isotopes



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

A. Couture and R. Reifarth, “Direct Measurements of Neutron Capture on Radioactive Isotopes”, At. Data and Nucl. Data Tables, **93** (2007) 803.

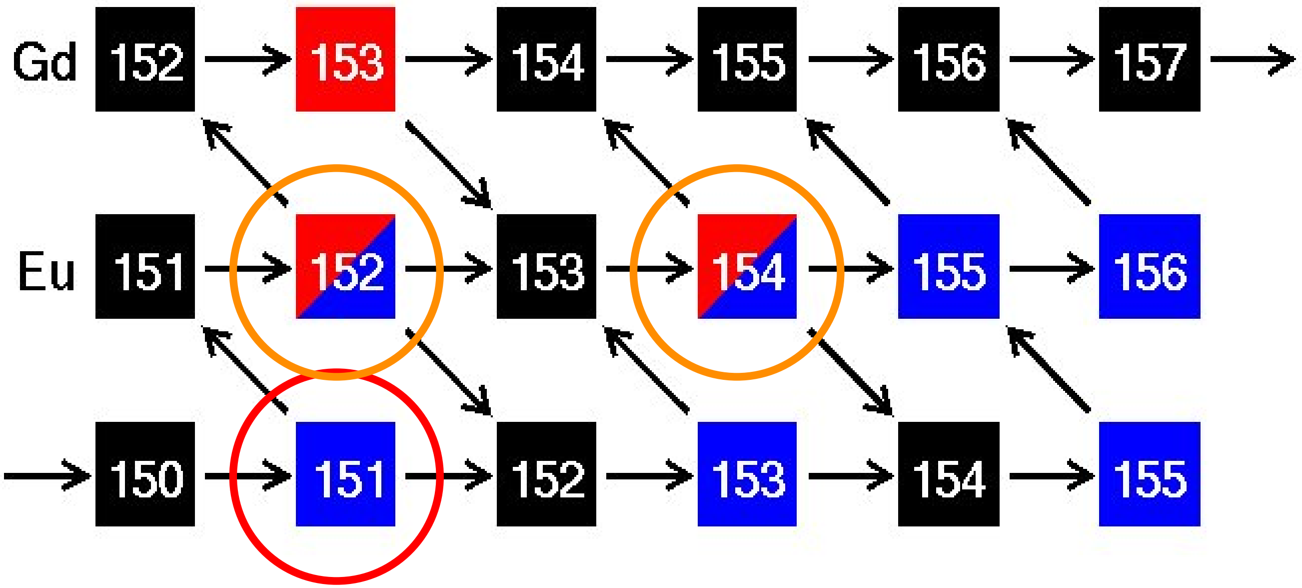
Why are Calorimetric Detectors Needed for Radioactive Samples?

- Traditional neutron capture measurements were done 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.

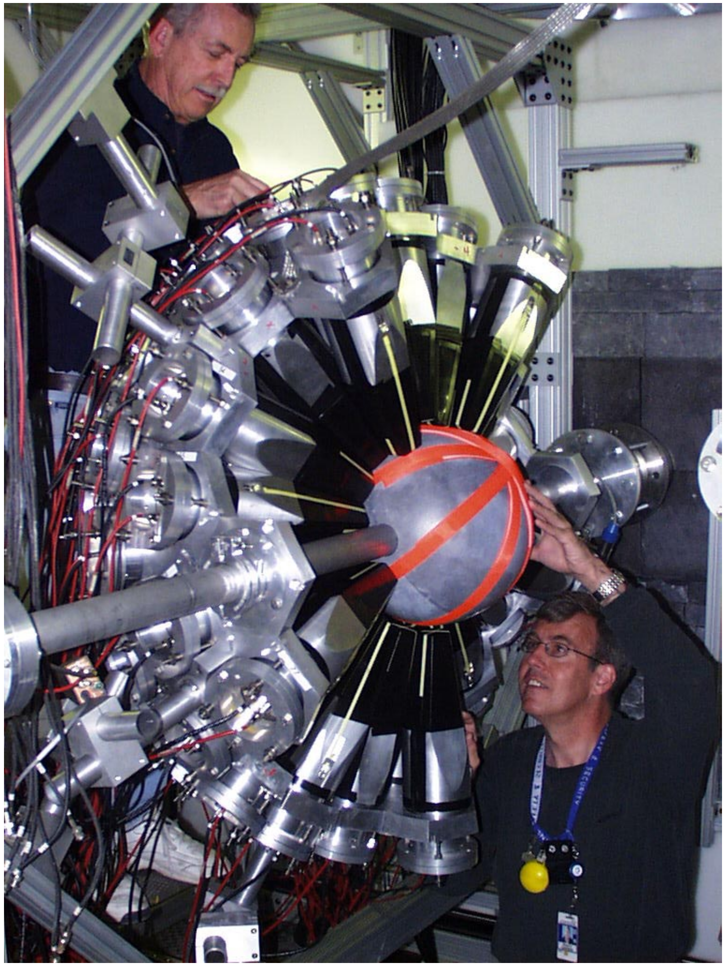
Potential Isotopes for Measurement

Isotope	Contaminants	$t_{1/2}$	Decay Mode	Q-Value	Max Atoms	Process	Now?
^{63}Ni	^{62}Ni ^{64}Ni	100 a	β^- (63 keV)	9.7 MeV 6.8 MeV 6.1 MeV	N/A	s-process	yes
^{135}Cs	^{133}Cs	2 x 10^6 a	β^- (200 keV)	6.8 MeV 6.9 MeV	N/A	s, r process	yes
^{137}Cs	^{133}Cs	30.2 a	β^-, γ	4.4 MeV 6.9 MeV	9.0 x 10^{15}	s, r process	
^{152}Eu	^{151}Eu ^{153}Eu	13.3 a	β^-, EC, γ	8.6 MeV 6.3 MeV 6.4 MeV	2.6 x 10^{16}	s-process	yes
^{154}Eu	^{151}Eu ^{153}Eu	8.8 a	β^-, γ	8.2 MeV 6.3 MeV 6.4 MeV	5.0 x 10^{15}	s-process	
^{204}Tl	^{203}Tl ^{205}Tl	3.8 a	β^-, EC	7.5 MeV 6.7 MeV 6.5 MeV	9.2 x 10^{18}	s process	yes

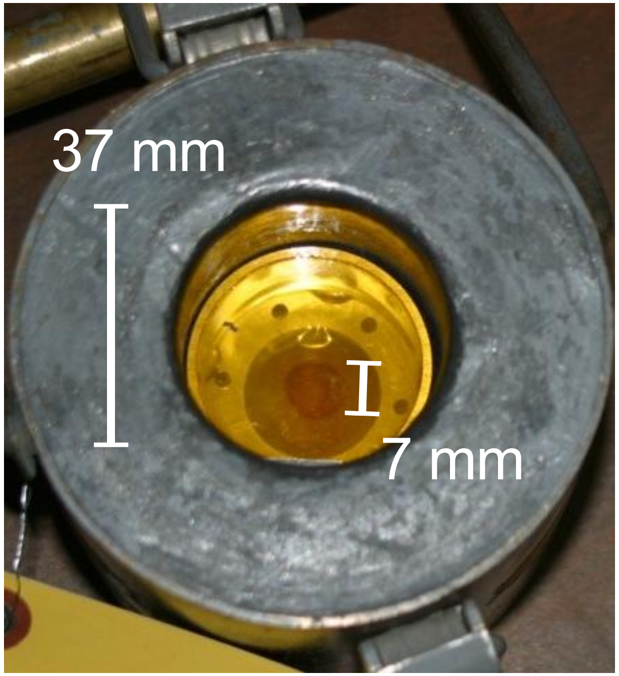
s-Process between Nd and Gd



Running ^{152}Eu at DANCE



Sample Prepared at INL
Mounted on Mylar
Kapton windows provide secondary containment

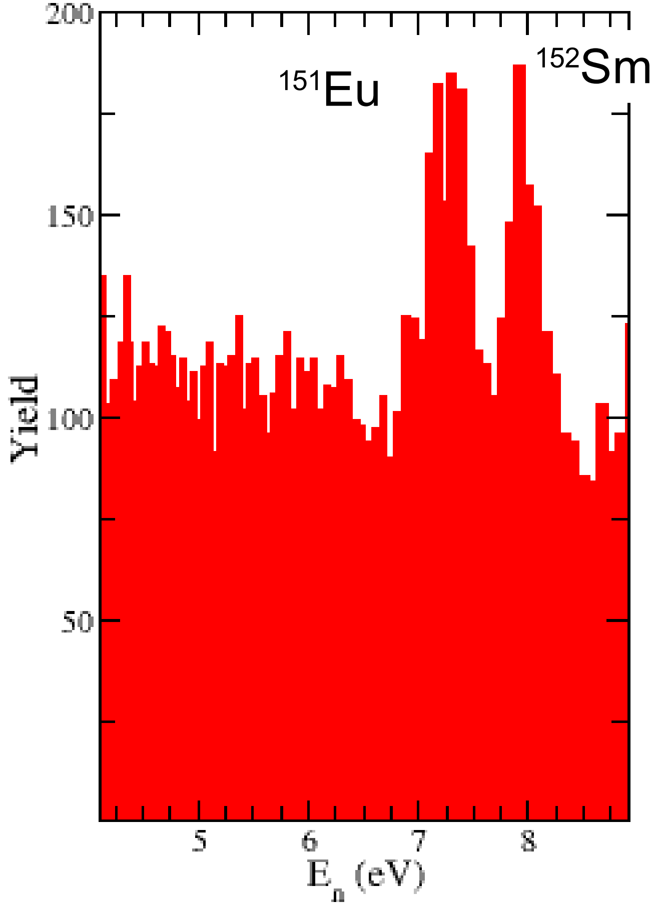


Status of ^{152}Eu

- Measurement was performed over 3 weeks.
- A 6 μg sample of ^{152}Eu in ~100 μg of natural Eu was used.
- The 6 μg sample corresponds to an activity of 30 MBq, or one event/30 ns.
- There is a ~2 MeV difference in Q-value between ^{152}Eu(n,γ) and ^{nat}Eu(n,γ) which would normally allow a clean separation, even with 10x the sample material.
- Due to the high background, effort was focused on the resolved resonance region (< 100 eV)

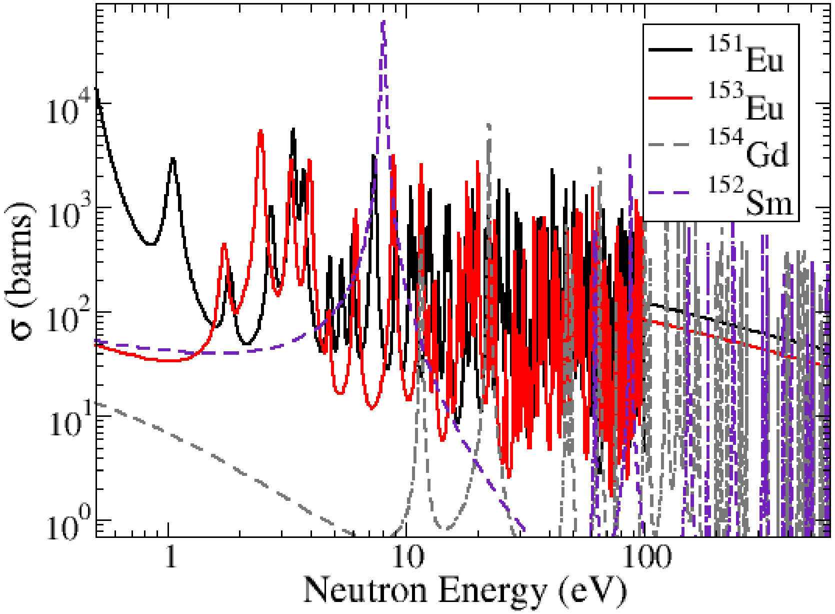
(Early) ^{152}Eu Results

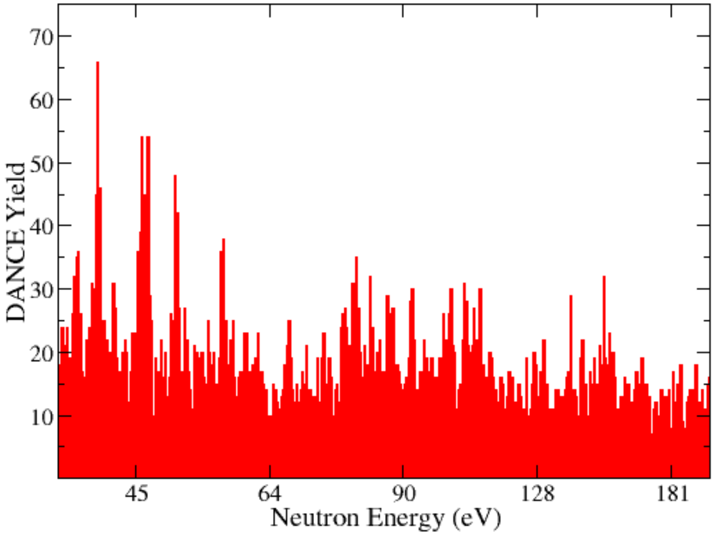
- We can clearly identify neutron capture resonances in the stable Eu isotopes.
- Improved signal to noise can still be achieved by improved energy and timing calibrations.
- The expectation is that this experiment will extract resonance parameters at low energy to constrain the evaluated cross section and theoretical reaction rate.



The resonances are there—but are there too many?

- The sample was made by activation of natural Eu
    - After several halflives, ^{151}Eu, ^{153}Eu, ^{152}Sm, and ^{154}Gd are all present





What is the future for Eu?

- The Good:
  - The radiogenic background is not insurmountable.
  - It has allowed us to probe the limits of high rate experiments with DANCE
- The Bad:
  - The DANCE gamma-ray energy resolution is not as good in a strong gamma field
  - The target made from natural Eu irradiated 30 years ago is probably not good enough--there are too many resonances from too many sources
- The Next Step:
  - Production of a new sample via activation or collection at a rare isotope facility

What is Still Needed?

- Samples
  - Radioactive sample material for measurements is difficult to make.
  - Chemical and isotopic purity are helpful, but not always needed.
  - 10% enrichment is a nominal requirement.
  - IPF and MTS offer new possibilities for sample production.
  - Outside collaborations are often effective in helping make material.
  - The high sensitivity of DANCE together with the enhanced fluxes at next generation rare isotope facilities make this an interesting new possible source of samples.
- Stellar Models
  - Stellar models aid in identifying important cross-sections and folding measurements into predictions
  - Even further, Galactic Chemical Evolution (GCE) calculations would be helpful

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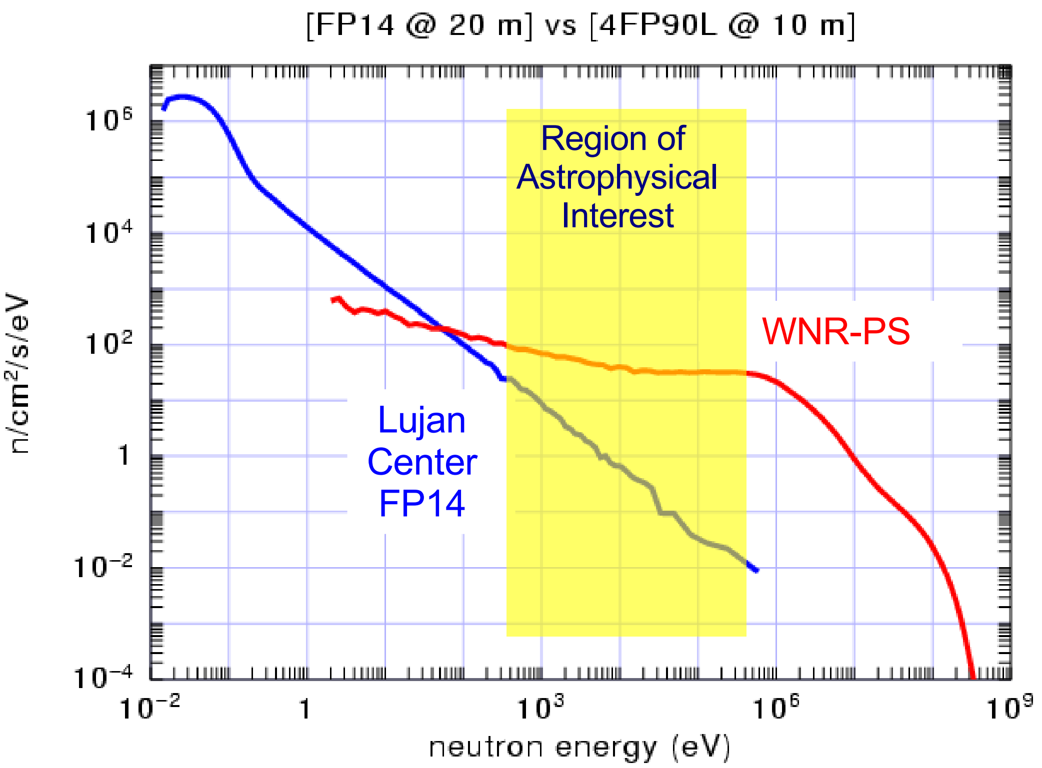
Improved Neutron Flux for Capture at LANL



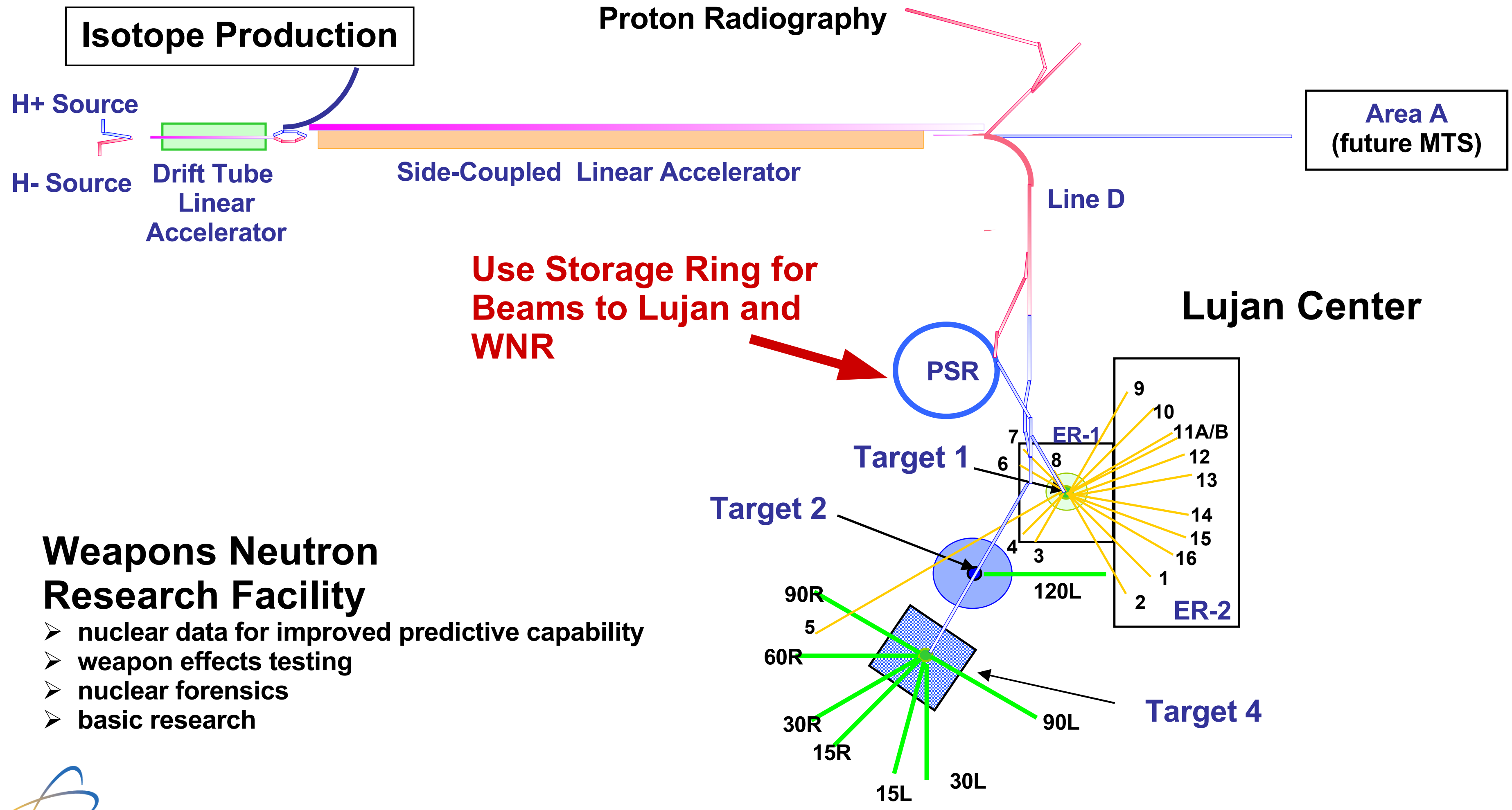
Successful proof-of principle experiment performed in August 2008.

Neutron capture cross-sections are needed from
300 eV – 500 keV

Pulse stacking will enhance the neutron flux over present capabilities by **factors of 50-1000**

This will enable measurements on smaller, short-lived isotopes.

The use of the storage ring to deliver nuclear physics beams increases the energy range and intensity



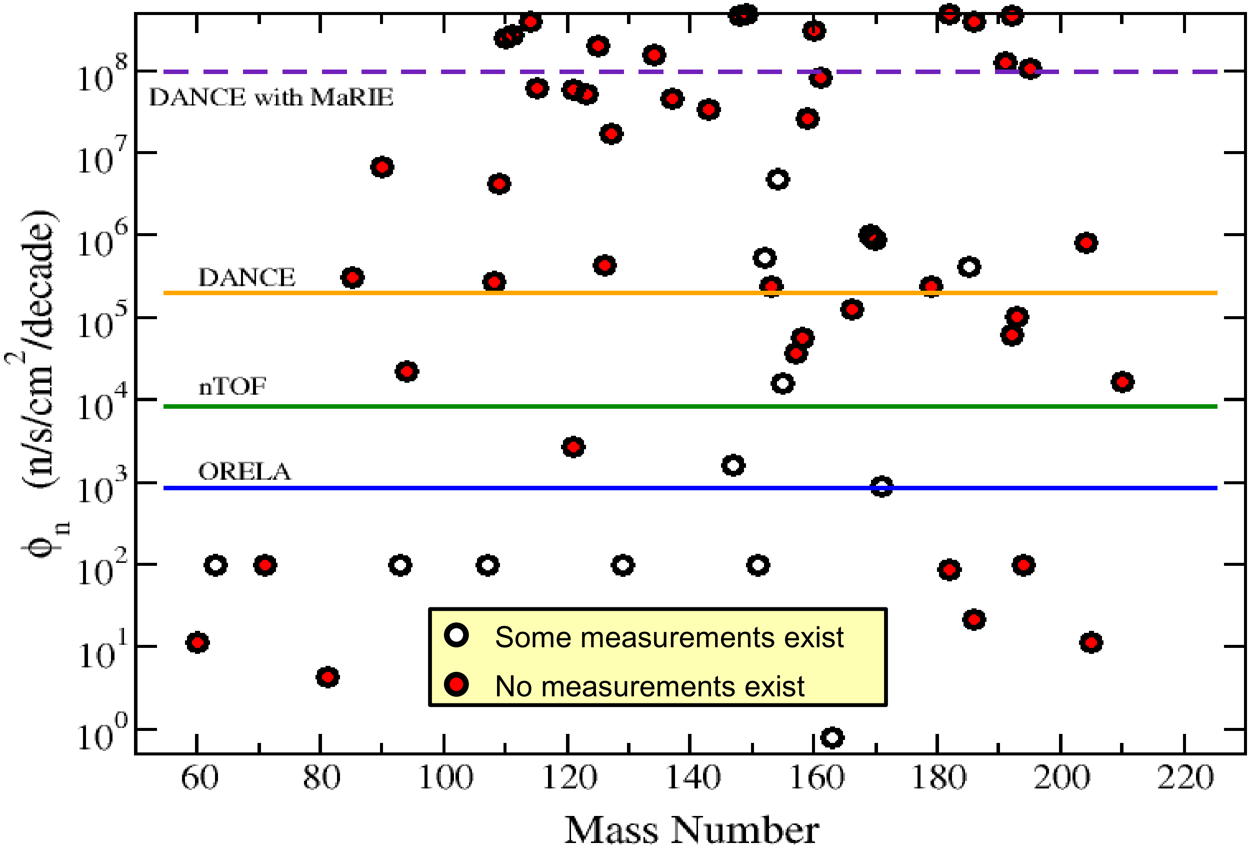
Weapons Neutron Research Facility

- nuclear data for improved predictive capability
- weapon effects testing
- nuclear forensics
- basic research

WNR Pulse Stacking—The Next Step

- Because Lujan Center is designed primarily as a neutron scattering facility, the neutron flux and time distribution is not optimized for neutron capture.
- The present WNR pulse structure limits measurements to above ~500 keV.
- Pulse Stacking will allow measurements all the way to thermal and enhance flux by a minimum of a factor of 5
- Capture measurements will
  see enhancements of 50-1000
  over what is available at Lujan

Estimated Neutron Fluxes Required for Measurements on Branch Point Isotopes



Pulse stacking will increase the available flux at 100 keV by a factor of 1000, drastically increasing the reach and quality of measurements

Increased flux allows us to choose highest impact measurements rather than only measuring those few isotopes we can reach

A. Couture and R. Reifarth, “Direct Measurements of Neutron Capture on Radioactive Isotopes”, At. Data and Nucl. Data Tables, **93** (2007) 803.

Conclusions

- Neutron induced reactions play an important role in a range of astrophysical environments
- LANSCE at Los Alamos produces high intensity Time-of-Flight neutron beams appropriate for nuclear astrophysics
  - These beams open the door to measurements on unstable isotopes which have previously been unachievable
- Samples of sufficient size and purity are a continuing challenge, but new resources are making them more available.
- LANSCE is a User Facility with an annual proposal call for beam requests
  - External Basic Science proposals are typically well received

Conclusions (II)

- Neutron capture measurements on a wide variety of isotopes are essential for understanding stellar element production as well as discriminating between theoretical stellar models
- DANCE is a unique instrument in the world, capable of making measurements on small samples and radioactive isotopes, a regime of significant interest
- These cross sections offer the opportunity to significantly improve the underlying nuclear physics theory
- There are opportunities to drastically increase the neutron flux for neutron capture as well as the range of experiments which can be done at LANL for Nuclear Astrophysics

Acknowledgments

LANSCE-NS
J. M. O'Donnell, J. L. Ullmann S. A. Wender

C-NR
T. A. Bredeweg, M. Jandel, A. L. Keksis, R. S. Rundberg, D. J. Vieira

NC State
B. Baramsai, A. Chyzh, G. Mitchell, C. Walker

GSI
R. Reifarth

The DANCE Collaboration

Thank You!

Orion's Belt seen from Los Alamos

Photo Courtesy of Shannon Scott