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Title: DANCEing with the Stars: Measuring Neutron Capture on Unstable Isotopes with DANCE

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Los Alamos
NATIONAL LABORATORY
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DANCEing with the Stars: Measuring Neutron Capture on Unstable Isotopes with DANCE

Isotopes heavier than iron are known to be produced in stars through neutron capture processes. Two major processes, the slow (s) and rapid (r) processes are each responsible for 50% of the abundances of the heavy isotopes. While the r process takes place far from stability and has been difficult to investigate both experimentally and theoretically, more progress has been made on the s process, which follows the line of nuclear beta stability. The neutron capture cross sections of the isotopes on the s process path reveal information about the expected abundances of the elements as well as stellar conditions and dynamics. Until recently, however, measurements on unstable isotopes, which are most important for determining stellar temperatures and reaction flow, have not been experimentally feasible.

The Detector for Advance Neutron Capture Experiments (DANCE) located at the Los Alamos Neutron Science Center (LANSCE) was designed specifically to perform time-of-flight neutron capture measurements on unstable isotopes for nuclear astrophysics, stockpile stewardship, and advanced reactor development. DANCE is a 4-pi barium fluoride scintillator array which can perform measurements on sub-milligram samples of isotopes with half-lives of as little as a few hundred days.

I will discuss the nuclear astrophysics campaign for measuring cross sections at DANCE including past measurements and future directions which we plan to pursue.

DANCEing with the Stars: Measuring Neutron Capture on Unstable Isotopes with DANCE

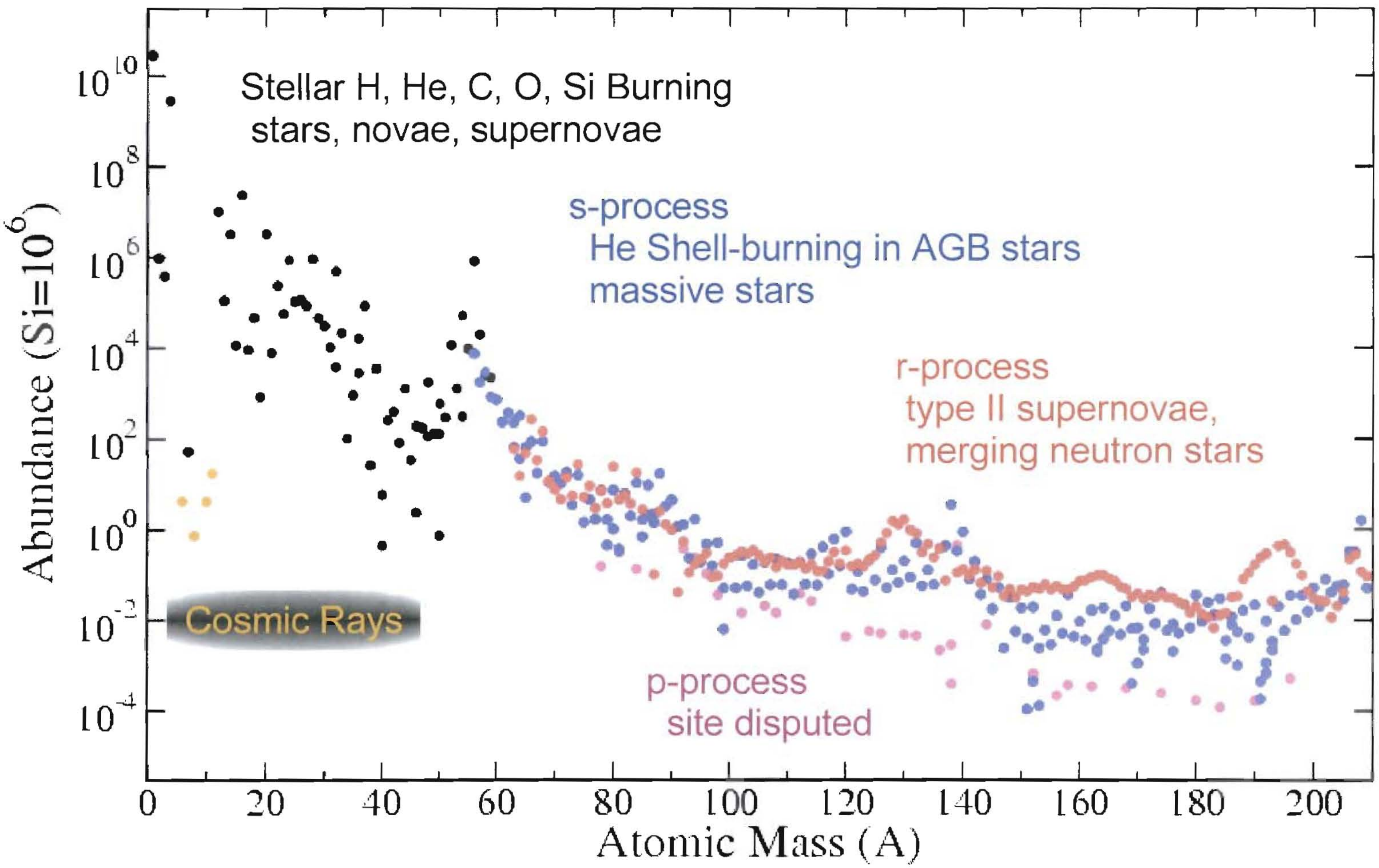
A. Couture

CAARI 2008

12 August 2008

Fort Worth, TX

Observed Solar System Abundances

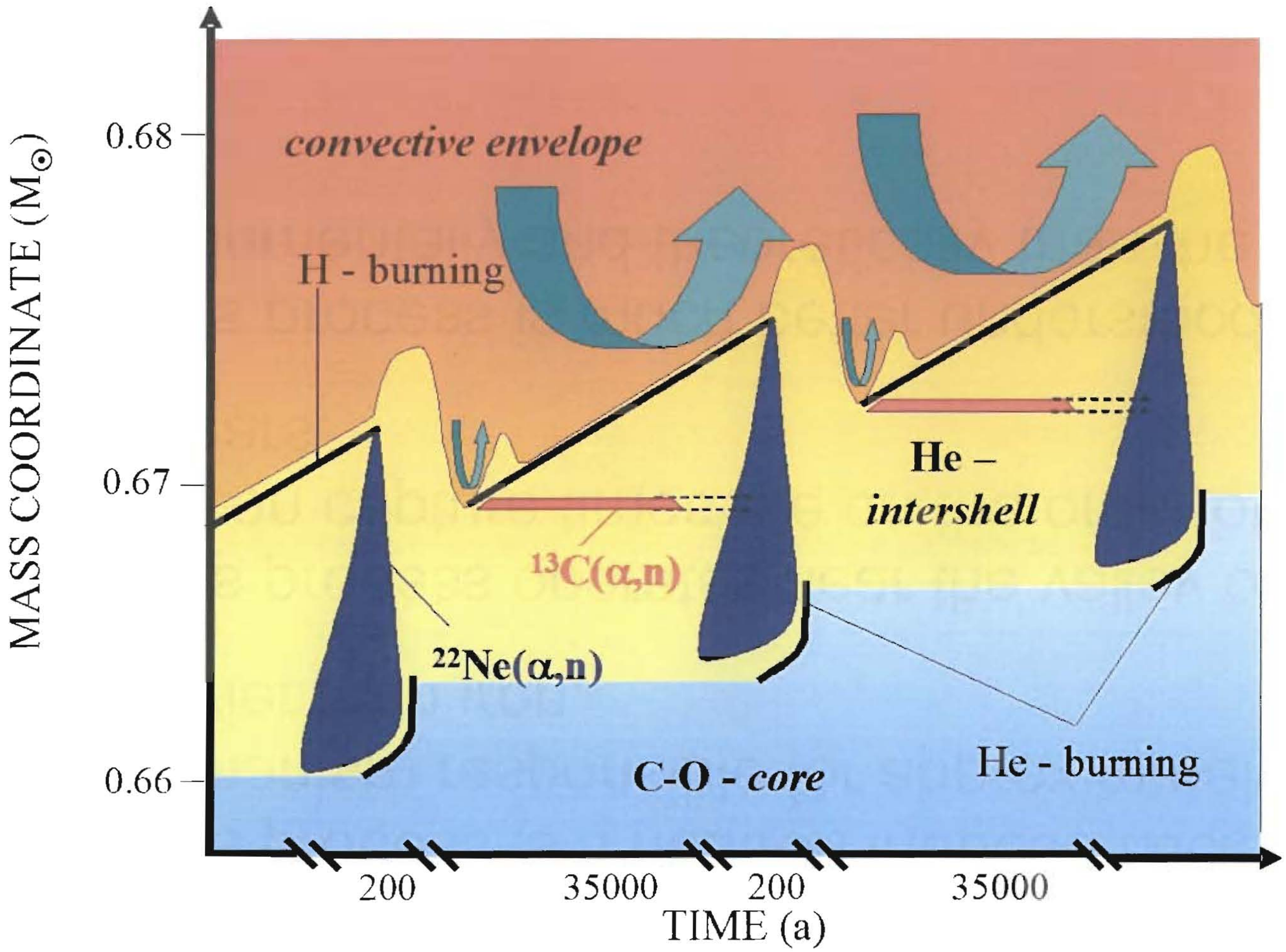


Abundances and Attribution from Anders & Grevesse, 1989
and Käppeler, Beer, and Wisshak, 1989

S-Process Nucleosynthesis

- The s process is a neutron induced nucleosynthesis mechanism responsible for approximately half of the isotopes heavier than iron.
- The s process operates near the valley of stability—typical neutron capture times are on the order of years to hundreds of years.
- The s process is much better understood, both experimentally and theoretically than the r process.

S-Process Nucleosynthesis in Thermally Pulsing AGB Stars



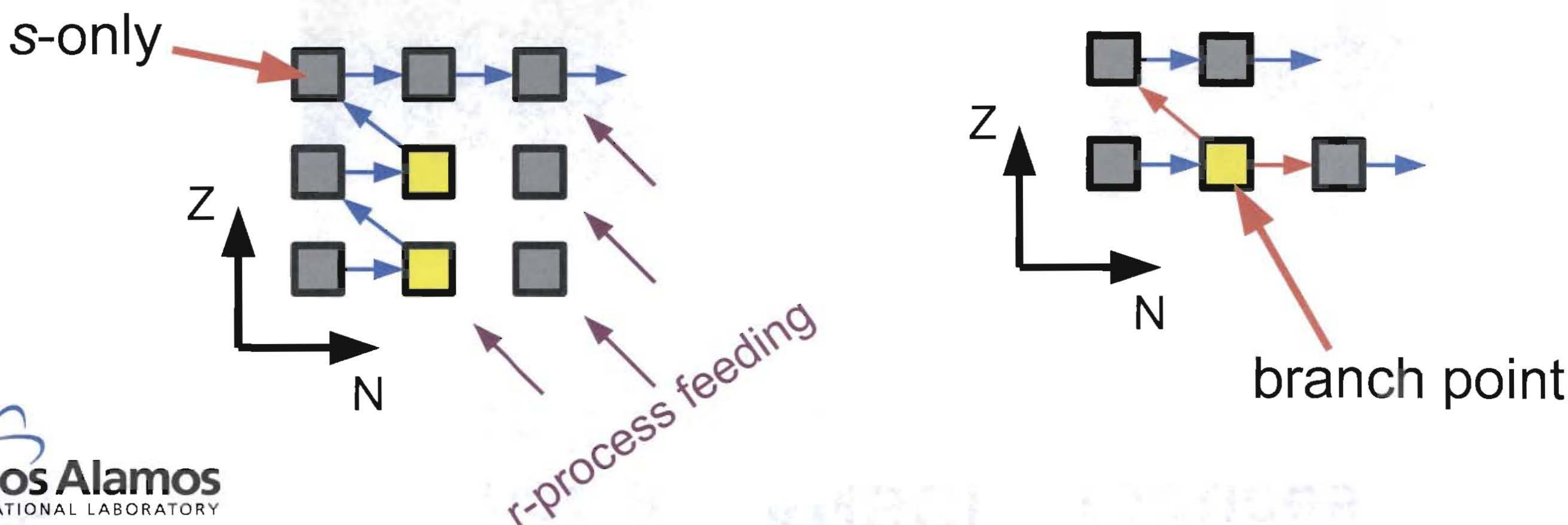
- Neutron exposures of 10^8 n/cm^3 and 10^{11} n/cm^3 are experienced during different phases
- Temperatures range from 5 keV up to 30 keV during the ^{13}C and ^{22}Ne phases
- Neutron capture cross-sections are critical for understanding the stellar sites and differentiating between stellar models
- Convective mixing of H into He shell produces ^{13}C and neutrons

Key Isotopes for Cross Section Measurements

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

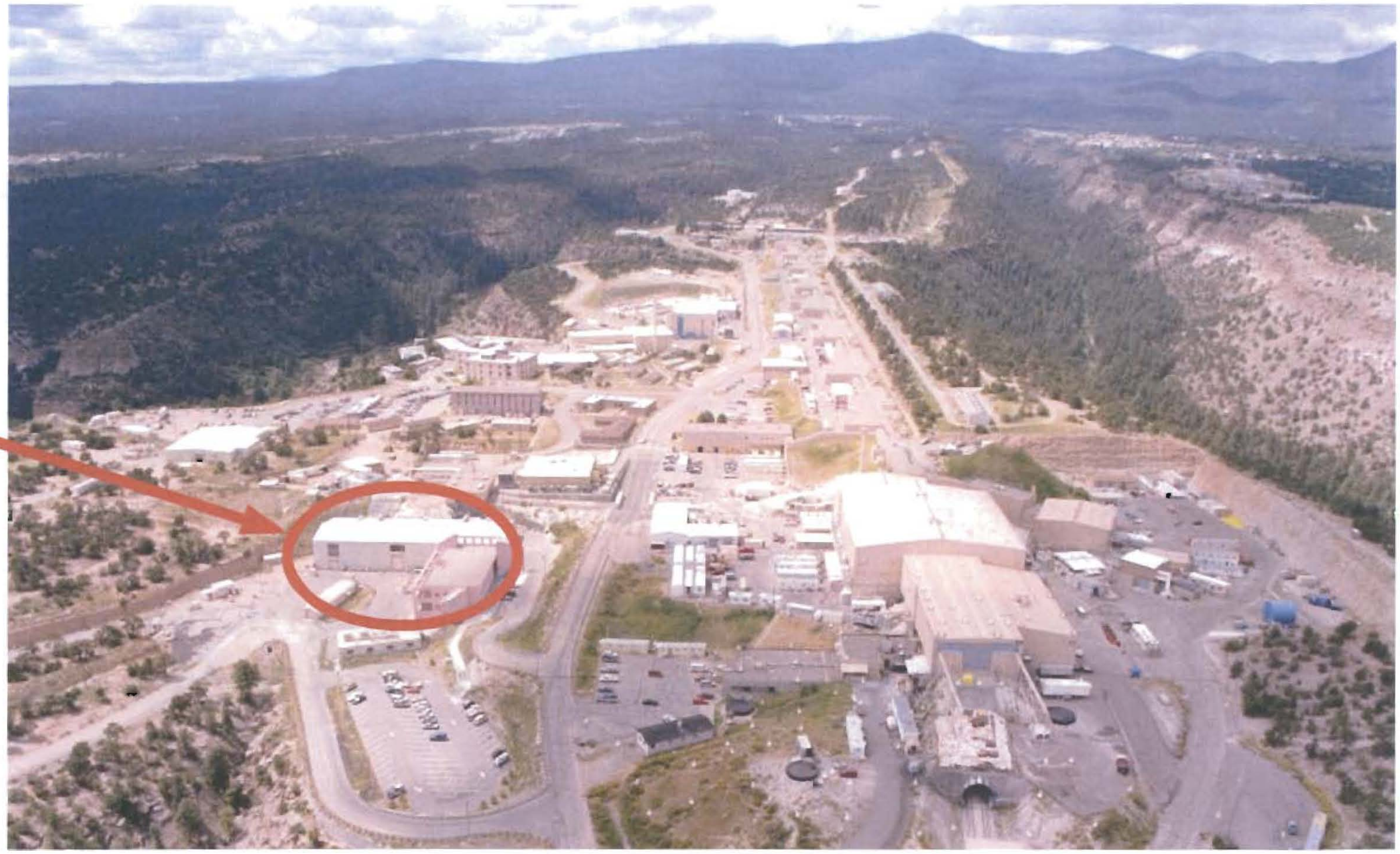
Branch point and *s*-only isotopes provide sensitive model constraints on temperatures and neutron densities

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

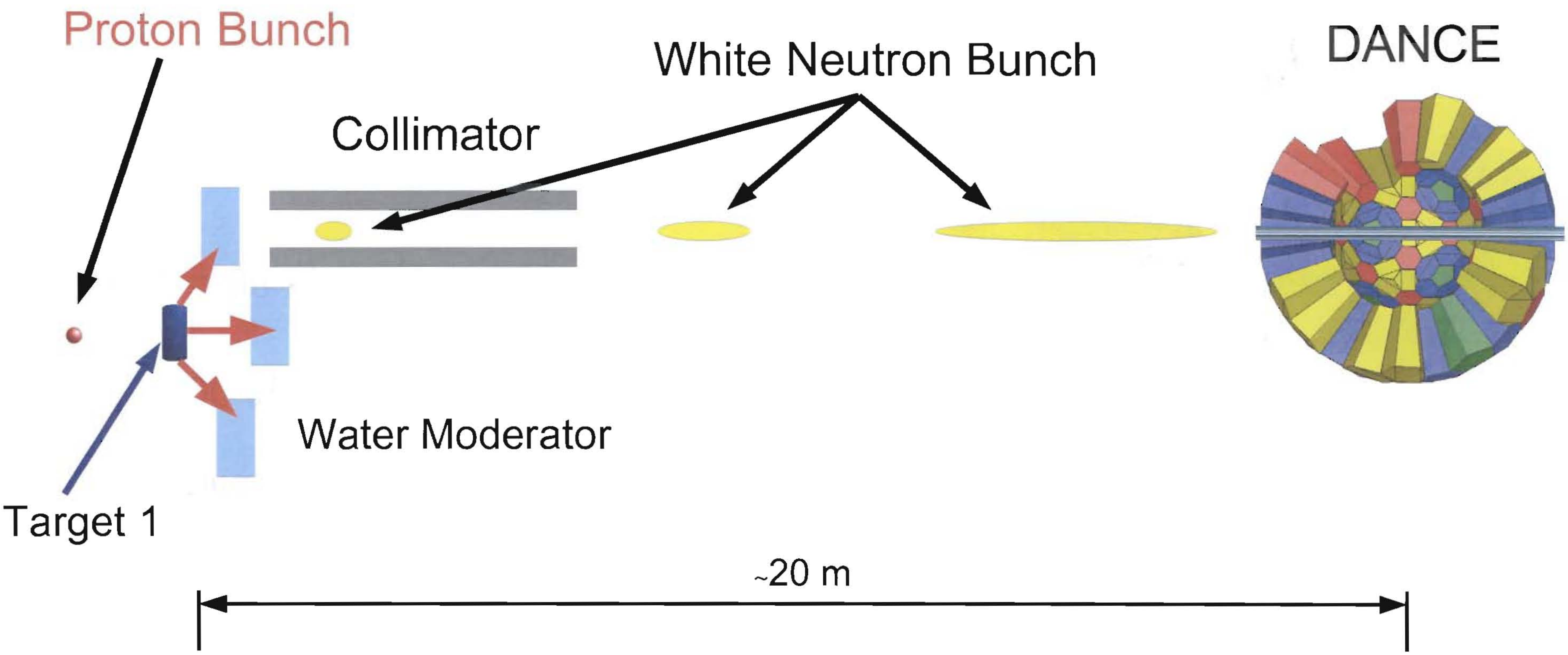


The 800 MeV linac at LANSCE produces neutrons via spallation on Tungsten

Lujan Center



Time of Flight with DANCE at the Lujan Center



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

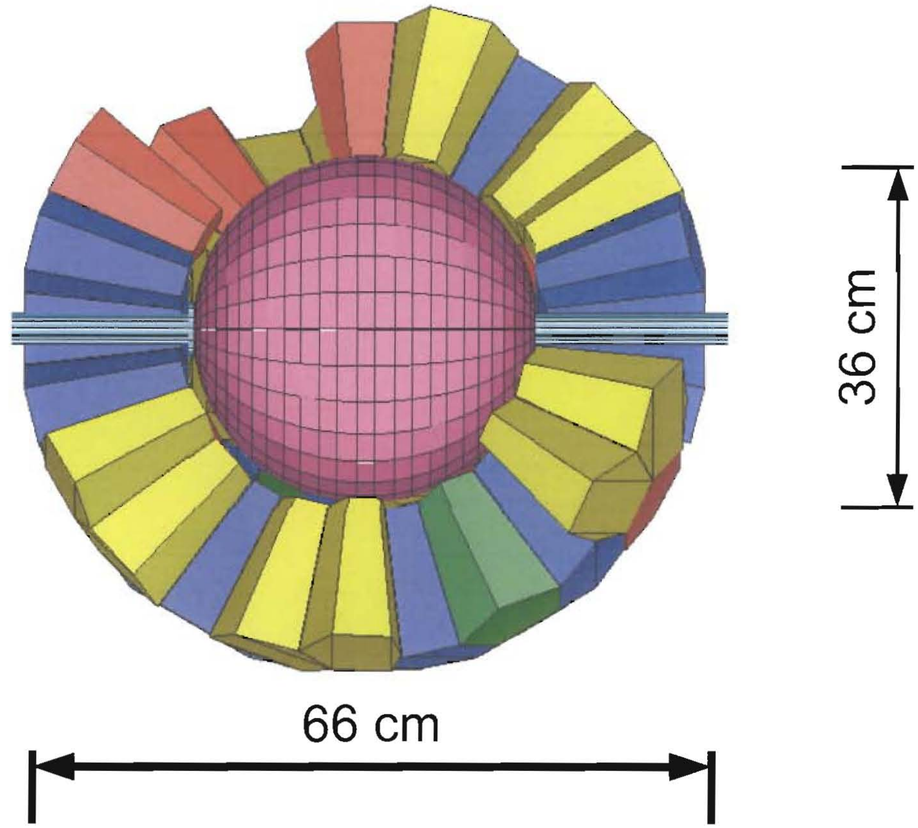
The Detector for Advanced Neutron Capture Experiments (DANCE)

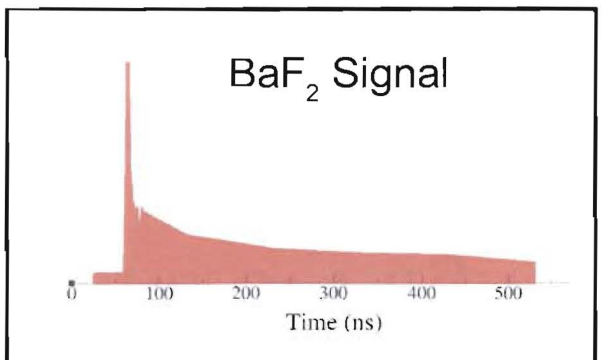
160 BaF_2 Scintillators

4 Detector Shapes each covering the same solid angle

$\varepsilon_\gamma \approx 90$ %

$\varepsilon_{casc} \approx 98$ %

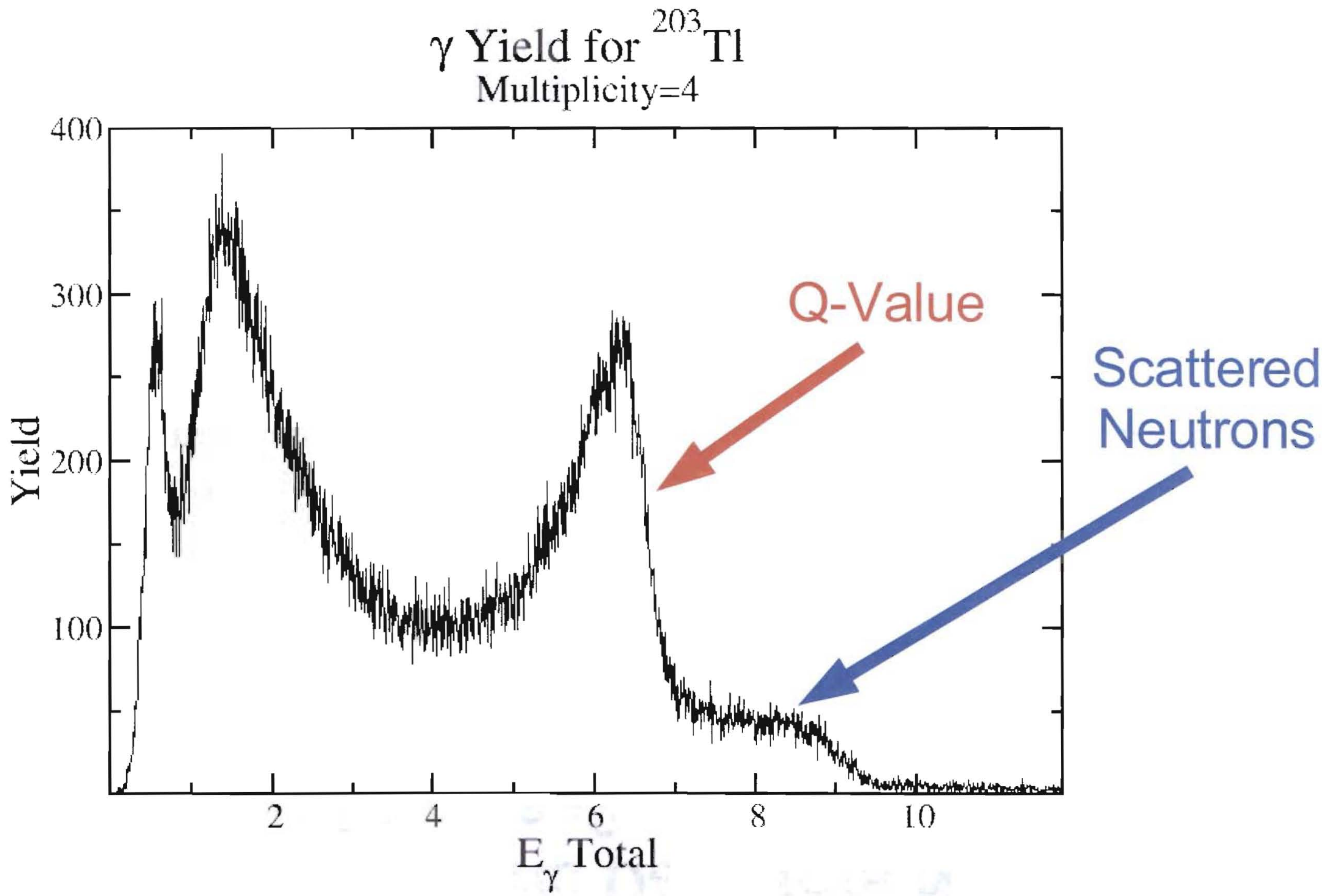




^{6}LiH Shell Surrounds Sample (6 cm)

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

DANCE Capture Response



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.

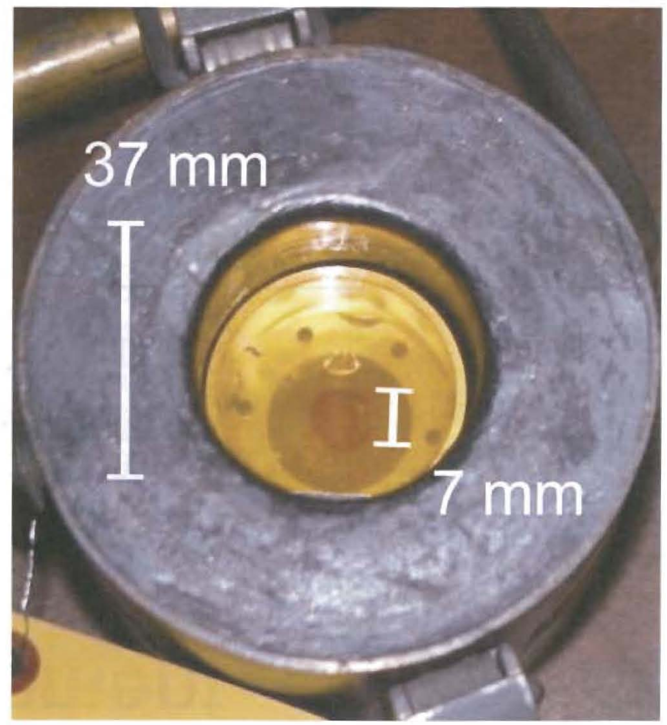
Potential Isotopes for Measurement

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	2×10^6 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	9.0×10^{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	2.6×10^{16}	s-process	yes
^{154}Eu	^{151}Eu ^{153}Eu	8.8 a	β^-, γ	8.2 MeV 6.3 MeV 6.4 MeV	5.0×10^{15}	s-process	
^{204}Tl	^{203}Tl ^{205}Tl	3.8 a	β^-, EC	7.5 MeV 6.7 MeV 6.5 MeV	9.2×10^{18}	s process	yes

The ^{152}Eu sample

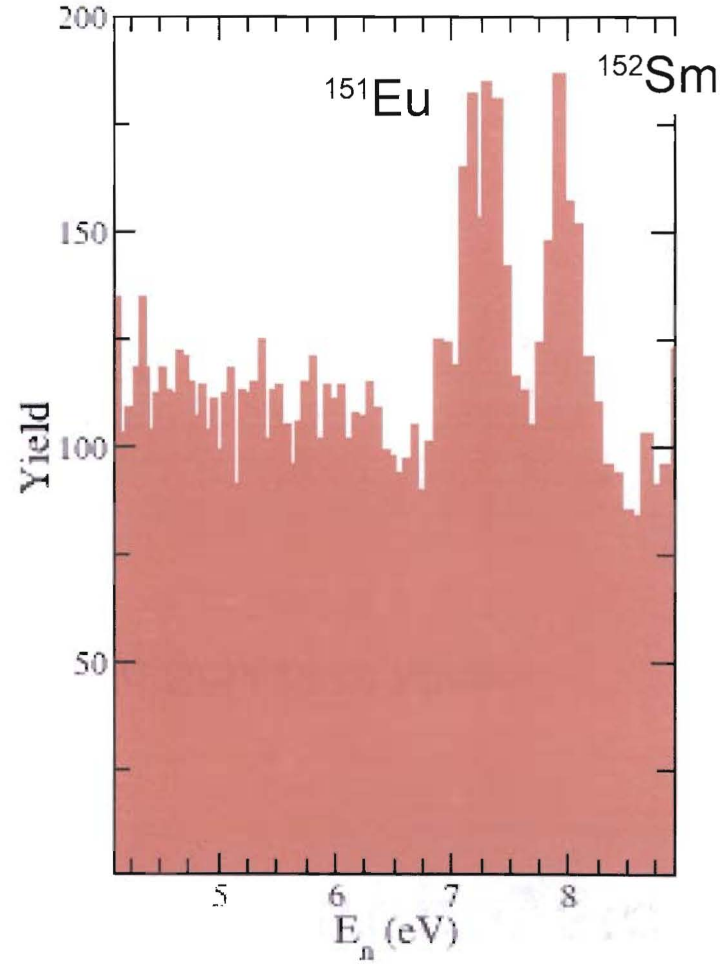
- ^{152}Eu decay exhibits complicated, high energy gammas ($Q_{EC/\beta} \approx 1.8$ MeV).
- $T_{1/2}$=13.5 years
- Produced by irradiation of a natural sample
  - ~ 50μg ^{151}Eu
  - ~ 50μg ^{153}Eu
  - ~ 6 μg ^{152}Eu
- This corresponded to 3×10^7 decays/s

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



(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.

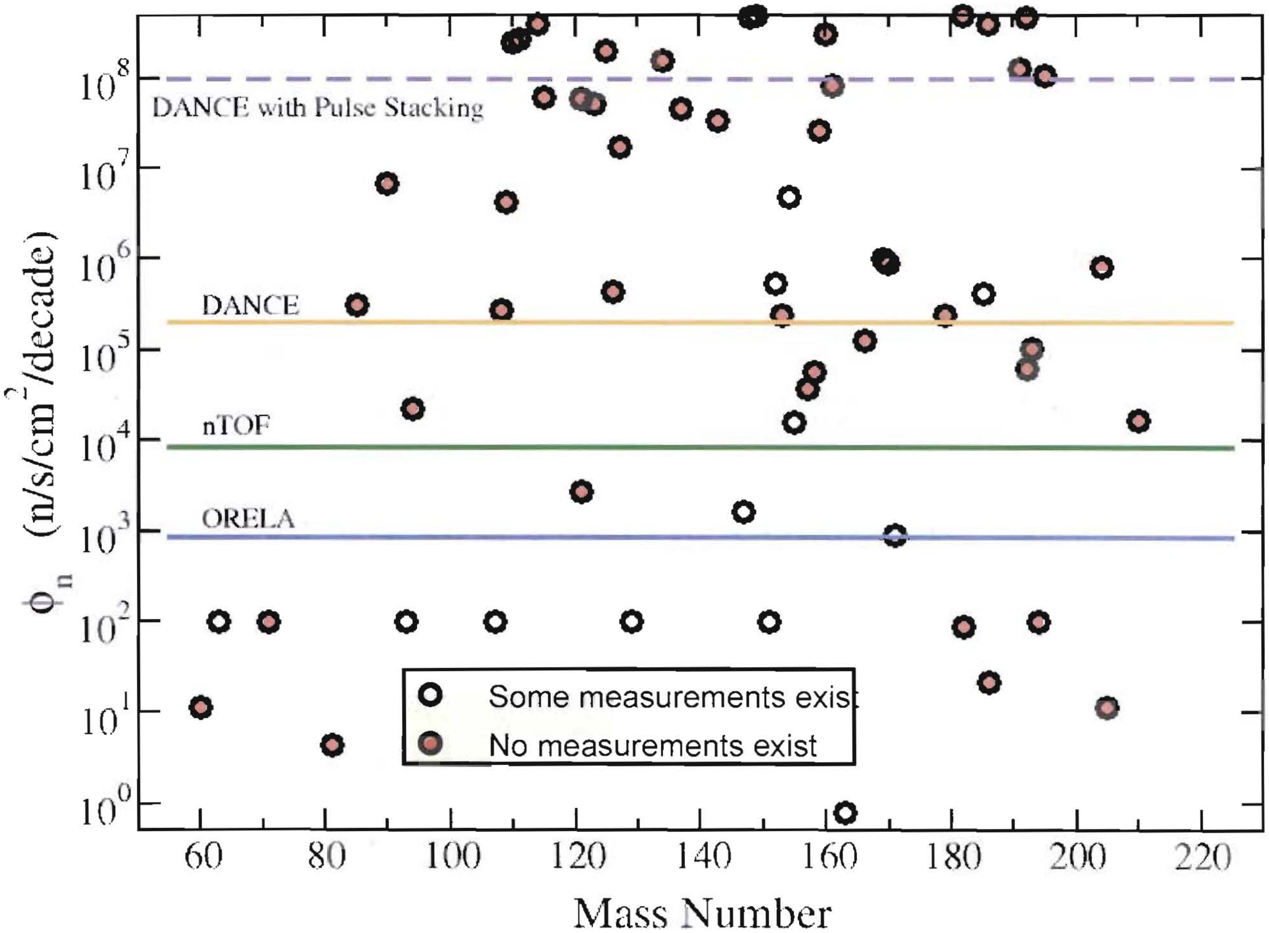


Other Measurements for Nuclear Astrophysics

- $^{62}Ni(n,\gamma)$
  - Master's Thesis, A. Alpizar-Vicente, Colorado School of Mines
  - Published, Phys. Rev. C regular article
- $^{151}Sm(n,\gamma)$
  - Measurement completed, analysis ongoing
  - Important for understanding Gd-Eu-Sm region
- $^{203,205}Tl(n,\gamma)$
  - Measurement completed, analysis ongoing
  - Important for understanding s-process endpoint
  - Prepares way for ^{204}Tl measurement
- $^{63}Ni(n,\gamma)$
  - Scheduled for 2008 beam cycle
  - Measurement in collaboration with FZK, Univ. of Munich, Univ. of Notre Dame

Possibilities for Other Branch Point Measurements

- For many branch points there are no experimental measurements to date.
- While some of these are still well outside of the experimental reach, many are accessible with present facilities.
- Measurements are needed on many isotopes to study varied s-process conditions.



A. Couture and R. Reifarth ADNDT 2007
P. Koehler, NIMA 2001

Conclusions

- Neutron capture cross sections on branch-point isotopes offer critical nuclear physics input to s process nucleosynthesis studies.
- DANCE is a unique instrument in the world for investigating neutron capture cross sections on radioactive samples.
- While pure samples are not needed, the availability of sufficient quantities of radioisotopes for measurements is still a problem.
- We continue to perform measurements on stable isotopes which are of interest to the community (^{62}Ni, ^{102}Pd, ^{175,176}Lu, ^{203,205}Tl)

The DANCE Collaboration

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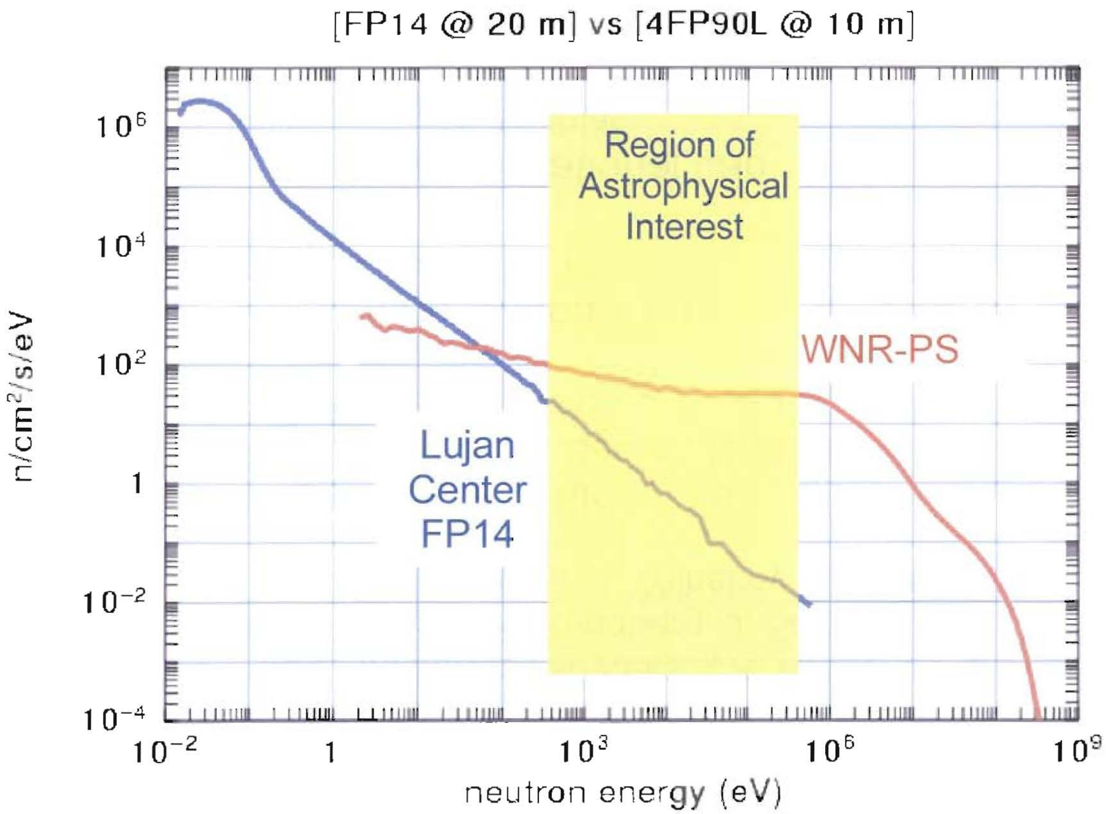
Improved Neutron Flux for Capture at LANL



Proof-of-Principle experiment performed last week.

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**

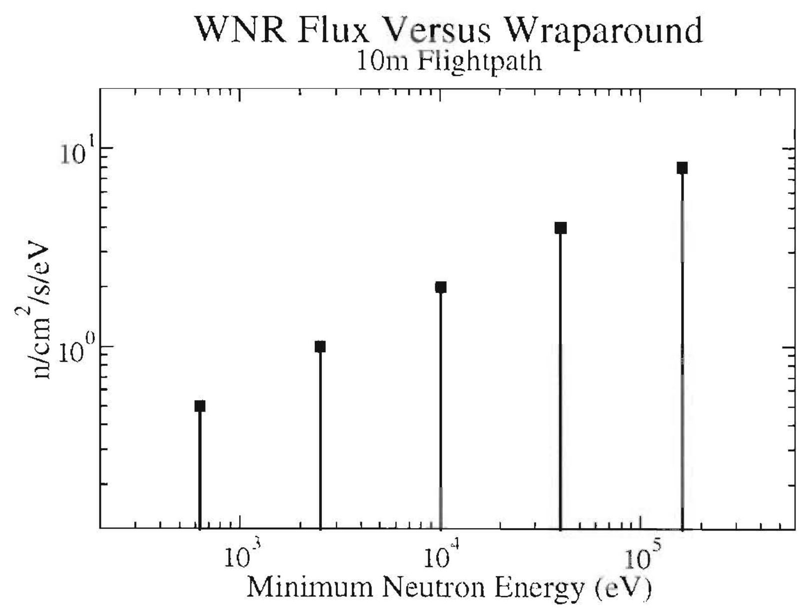
This will enable measurements on smaller, short-lived isotopes.

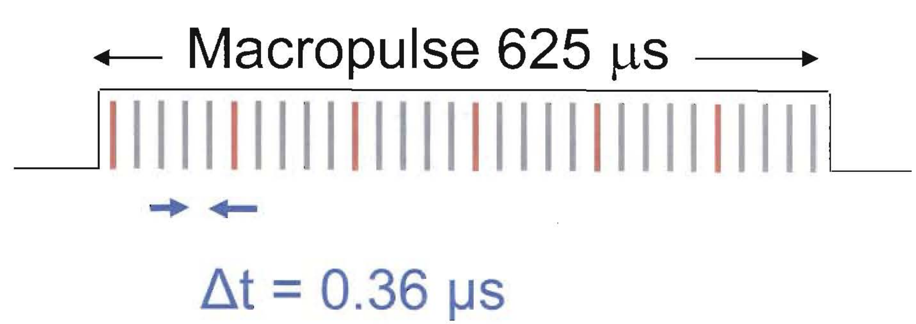
Los Alamos NATIONAL LABORATORY EST. 1943

NNSA

Potential Capture Measurements at WNR

- Capture measurements at WNR are hindered by present proton pulse delivery structure
- Extending to cover the full region of astrophysical interest comes at a significant cost in flux
- Capturing full macropulse would have major advantages





The LANSCE PSR pulse stacking upgrade consists of three major elements