Neutron Nuclear Astrophysics at Spallation Neutron Sources

- **What neutron nuclear astrophysics can be done?**
- **How do the various spallation sources compare?**

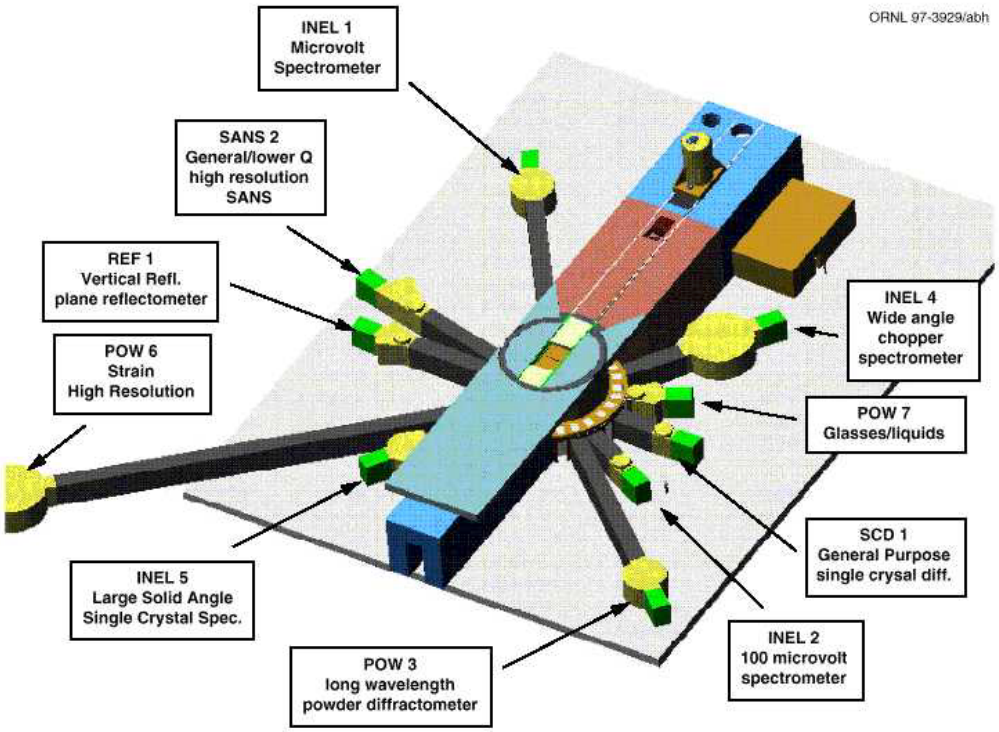
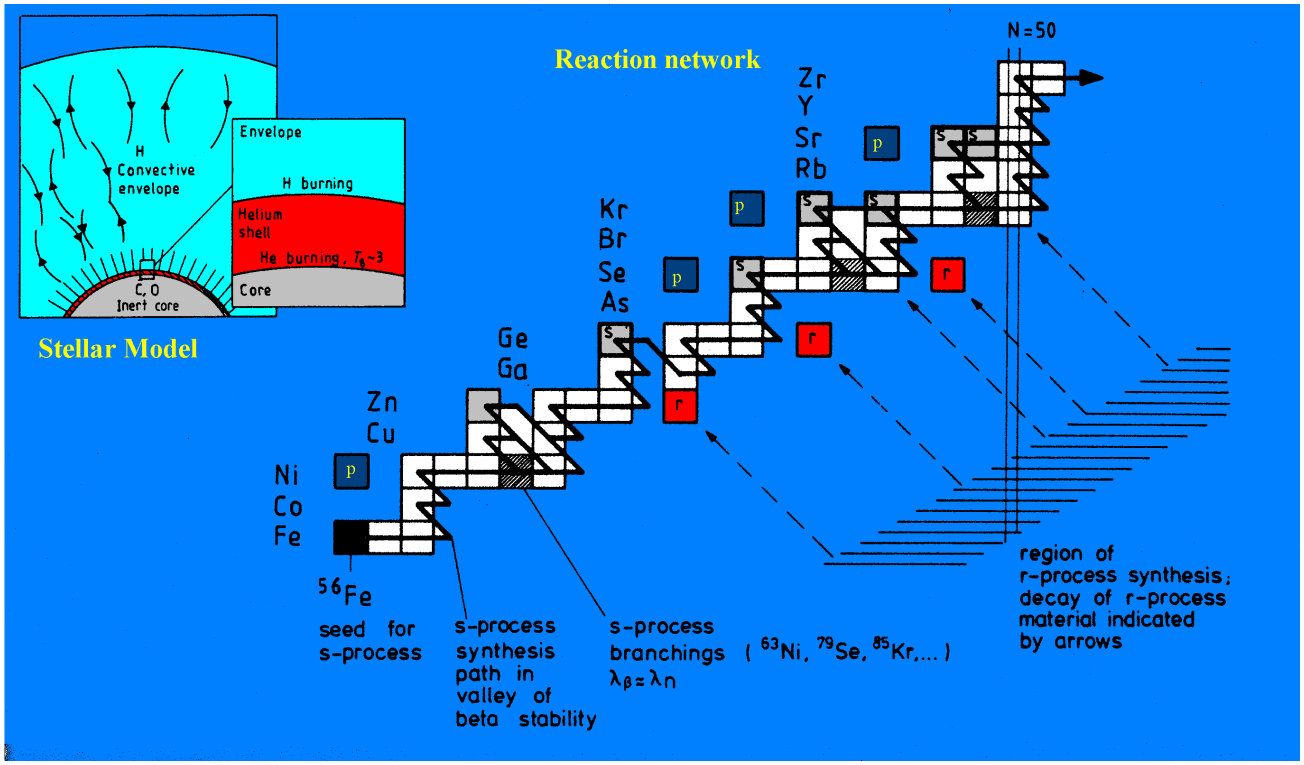


Fig. 5.0-1. Layout of reference set of instruments.

Astrophysics Motivation:

Heavy Element Nucleosynthesis in the *s*, *r*, and *p* processes



- **Spallation Sources: Can measure (*n*,γ) reaction rates for radioisotopes involved in *s*-process branchings, *r*-process freeze-out, and in the *p* process.**
  Gives direct handle on dynamics of nucleosynthesis processes in stars and in explosive environments.
- **Almost no data.**
  ^{171}Tm(*n*,γ) from LANSCE is the only measurement across range of energies needed.
- **Measurements on about 50 radionuclides needed.**

The Need for New (n,γ), (n,α), and (n,p) Measurements

- **New Observations; isotopic anomalies in stardust, abundance measurements in stars, γ-ray astronomy.**

  Greater number and higher precision "calibration points" with which to test and improve astrophysical models.

- **New Astrophysical Models; AGB stars (lower temperature), galactic chemical evolution, supernovae,…**

  More realistic, more detailed models made possible by bigger and faster computers still have many poorly constrained "knobs".

- **New Applications for Neutron Data; (n,α) measurements to improve reaction rates for explosive nucleosynthesis models.**

  Best means for constraining α-particle reaction rates for models of supernovae and massive stars.

Recent Accomplishments from Neutron Measurements

- **Cracks in the classical *s* process model.**
  Precise new (*n*,γ) rates for isotopes of Nd, Ba and Pt showing inconsistencies in classical *s*-process model and need for more sophisticated model.
- **Cool new stellar *s*-process models.**
  Good agreement with the measured abundances, but extrapolated rates on which it depends are not reliable.
- **Red giant stardust.**
  Precise agreement for Nd, 20% discrepancy at ^{137}Ba, and partial agreement for Sr.
- **Improved rates for explosive nucleosynthesis.**
  (*n*,α) measurements are very useful for constraining largest nuclear physics uncertainty in *p*-process models.
- **First (*n*,γ) measurements on very small and radioactive samples.**
  More data of this type needed to improve *s*-, *r*-, and *p*-process models.

Types of Neutron Measurements Needed

- **(n,γ) to higher precision and lower energies.**
  ***s*-only isotopes, isotopes near s-process branchings, meteoric anomalies.**
- **Small (n,γ) rates.**
  ***s*-process poisons, meteoric anomalies, big bang.**
- **(n,α) and (n,p) across range of masses.**
  Explosive nucleosynthesis, γ-ray astronomy, and *s*-process neutron source.
- **(n,n') for stellar enhancements of (n,γ) rates.**
  Thermal effects in *s*-, *r*-, and *p*-processes.
- **(n,γ) on hot radioactive samples.**
  ***s*-process branchings, *r*-process freeze out, *p*-process.**
- **(n,γ) on warm radioactive and rare stable samples.**
  ***s*-process branchings, *p*-process.**
- **Scattering and transmission.**
  ***s*-process neutron source. Corrections to (n,γ).**

Measurements on Short-lived Radioactive Samples: Comparison of Facilities

Comparison* to the ORELA (n,γ) Benchmark

Parameter	Ratio to ORELA Benchmark (8 kW, 8 ns, 40m)				
	ORELA	MLNSC	CERN-TOF		SNS
Flight Path Length	10	20	80	230	20
Power	6.2	8	5.6	5.6	250
Flux @ 30 keV	100	280	85	10	12000
Flux 1 - 300 keV	100	230	75	9.5	10500
FOM 1 - 300 keV	210	12000	12000	520	180000
1/Resolution	0.083	0.032	2.3	6.7	0.011
Sample Size (mg)	0.25	0.10	0.31	2.5	0.0022

- **Resolution with a 20-m flight path at SNS will be comparable to previous experiments at MLNSC.**
  Resolution adequate for many astrophysics experiments.
- **For experiments with short-lived radioactive samples, flux is the most important facility parameter.**
  Flux at the SNS is expected to be over 40 times better than at MLNSC (120 times ORELA, >140 times CERN-TOF).
  Should allow measurements on the widest range of radioactive samples and stable samples having very small natural abundances.

*NIM A 460, 352 (2001).

Background from Radioactive Sample: A Simple Model for the Effect of Sample Size

- **Probability of detecting n pileups in resolution time τ:**

$$P_n = (a\tau)^n e^{-a\tau}/n!$$

$$n = E/E_{decay} \Rightarrow P_n \Rightarrow P_E$$

$$a = N\lambda \text{ (decay rate)}$$

$$\tau = \text{resolution time of detector}$$

- **Total pileup is sum of P_E's above detector threshold.**

Background from Radioactive Sample: Example ^{170}Tm

- $\langle\sigma\rangle_{30}$ = 2300 b => N = 1.8×10^{17} atoms at LANSCE.

- $t_{1/2}$ = 128.6 d, 3.2% of decays yield 84 keV γ ray.
  => 3.6×10^{8} γ/s emitted by sample.

- Assume τ = 50 ns.
  => 2800 bins of 50 ns between 100 keV and 100 eV for a 20 m flight path.
  => 12 counts/pulse above 2.5 MeV bias at LANSCE for 100% efficient detector.

- If sample reduced by 1/2, then counts/pulse above 2.5 MeV bias drops by ~10^{5} (to ~80 per day).

- Get same effect if detector is twice as fast.

Astrophysics Motivation

Need Flux

Need Resolution

- **(n,γ) on hot radioactive samples.**
  ***s*-process branchings, *r*-process freeze out, *p*-process.**
- **(n,γ) on warm radioactive and rare stable samples.**
  ***s*-process branchings, *p*-process.**
- **(n,α) and (n,p) across range of A.**
  Explosive nucleosynthesis, γ-ray astronomy, and *s*-process neutron source.
- **High-precision and low-T (n,γ).**
  ***s*-only isotopes, meteoric anomalies.**
- **(n,n') to get (n,γ) for isomers.**
  Thermal effects in *s*-, *r*-, and *p*-processes.
- **Scattering and transmission.**
  ***s*-process neutron source. Corrections to (n,γ).**
- **Small, but resonance-dominated (n,γ).**
  ***s*-process poisons, meteoric anomalies.**

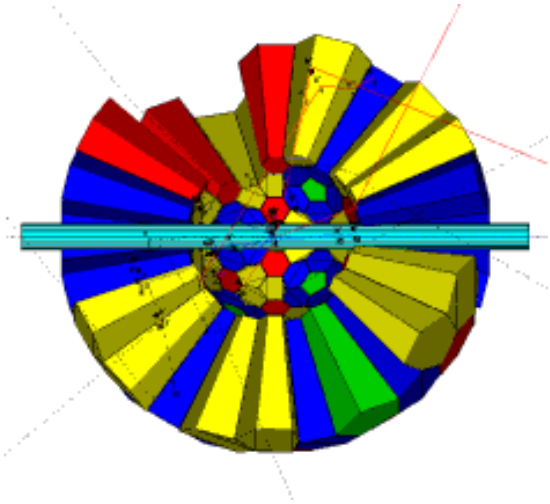
SNS, LANSCE

ORELA, CERN-TOF

Experimental Challenges: (n,γ) measurements

- **Producing and handling the sample.**
- **Background from the radioactive sample.**
- **Background from neutrons scattered from the sample and support material.**
- **Problems associated with the "γ flash" at the start of each pulse.**
- **Backgrounds from other beam lines.**

Substantial R&D is needed.



DANCE at LANSCE

4π BaF_2 detector with neutron-absorbing liners.

Astrophysics Motivation

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN/INTC 2000-017
INTC/P124
12 February 2000

PROPOSAL

The *s*-process thermometer ^{151}Sm and the importance of ^{22}Ne(α,n)^{25}Mg as *s*-process neutron source

The n_TOF Collaboration

R.L. Aguiar [27], S. Andriamonje [5], A. Angelopoulos [16], P. Assimakopoulos [17], L. Audouin [8], G. Badurek [2], G. Bakos [19], P. Baumann [11], H. Beer [13], J. Benlliure Anya [34], J.M. Benlloch [36], S. Boffi [24], A. Boiano [23], C. Borcea [38], A. Brusegan [3], F. Calvino [31], C.F. Cambronero [34], D. Cano-Ott [32], P. Cennini [38], G. Charpak [9], V. Chepel [28], N. Colonna [20], G. Cortes [31], F. Corvi [3], J.L. Cura [27], S. Czajkowski [5], C.H. Dasso [35], S. David [8], A. De Blas [31], M. De Poli [22], R. Del Moral [5], J.P. Delaroche [4], G. Della Mea [22], J. Derre [10], S. Diez [32], R. Dolfini [24], I. Duran Escribano [34], C. Eleftheriadis [18], M. Embid Segura [32], F. Farget [8], A. Ferrari [38], R. Ferreira Marques [28], W. Furman [29], A. Gadea [36], J.A. Garzon [34], I. Giomataris [10], C. Giusti [24], E.M. Gonzalez-Romero [32], A. Goverdovski [30], F. Gramegna [22], E. Griesmayer [1], O. Grudzevich [30], K.H. Guber [40], N. Gundrorin [29], F. Gunsing [10], M. Hage-Ali [12], B. Haight [41], S. Harissopoulos [15], M. Heil [13], K.G. Ioannides [17], P.D. Ioannou [16], S. Isaev [30], J. Jastrebski [26], E. Jericha [2], Y. Kadi [38], F. Kaeppeler [13], C. Kalfas [15], D. Karamanis [5], L. Kazakov [30], A. Kelic [11], V. Ketlerov [30], G. Kitis [18], P.E.J. Koehler [40], V. Konovalov [29], I. Kopatch [29], E. Kossionides [15], V. Lacoste [38], B. Lavielle [6], L.C. Leal [40], H. Leeb [2], A. Lepretre [10], M.I. Lopes [28], M. Lozano [35], J.M. Martinez-Val [33], P. Mastinu [22], M.F. Matteucci [25], D. Matveev [29], A. Mengoni [21], R. Meunier [7], P.M. Milazzo [25], E. Minguez Torres [33], V. Mitrofanov [30], A. Molina [35], R. Mordenti [23], O. Morra [20], P. Mutti [3], P.J. Napiorkowski [26], N. Nicolis [17], R. Nolte [14], H. Oberhummer[2], A. Ordine [23], R. Ortega [6], F.D. Pacati [24], A.A. Pakou [17], T. Papaevangelou [18], T. Paradelis [15], V. Paticchio [20], A. Pavlik [2], P. Pavlopoulos [37], J.M. Perlado [33], M. Piera [33], V. Piksaikin [30] A. Plompen [3], A. Poch [31], A. Policarpo [28], A. Popov [29], Y. Popov [29], C. Pretel [31], A. Quaranta [25], J.M. Quesada [35], E. Radermacher [38], M. Radici [24], S. Raman [40], G. Rapp [13], T. Rauscher [37], R. Reifarth [13], V. Rigato [22], J. Robin [11], C. Rubbia [24], B. Rubio [36], G. Rudolf [11], P. Rullhusen [3], B. Rundberg [41], L. Sakelliou [16], F. Saldana [38], D.M. Santos [27], J. Sanz [33], E. Savvidis [18], S. Savvidis [19], H. Schuhmacher [14], P. Sedyshev [29], C. Sergent [6], D. Serov [29], M. Simonoff [8], C. Stephan [8], G. Tagliente [20], J.L. Tain [36], C. Tapia [31], L. Tassan-Got [8], M. Terrani [24], R. Tertychny [30], N. Tsagas [19], A. Tzima [18], A. Valentino [20], E. Vardaci [23], A. Ventura [21], D. Villamarin [32], V. Vlachoudis [38], A.V. Voinov [29], F. Voss [13], H. Weigmann [3], H. Wendler [38], M.C. Wiescher [39], K. Wisshak [13], S. Zeinalov [29]

- **First proposal for astrophysics measurement at new CERN-TOF facility.**
- **165 people from 41 institutions.**

s-process Wish List

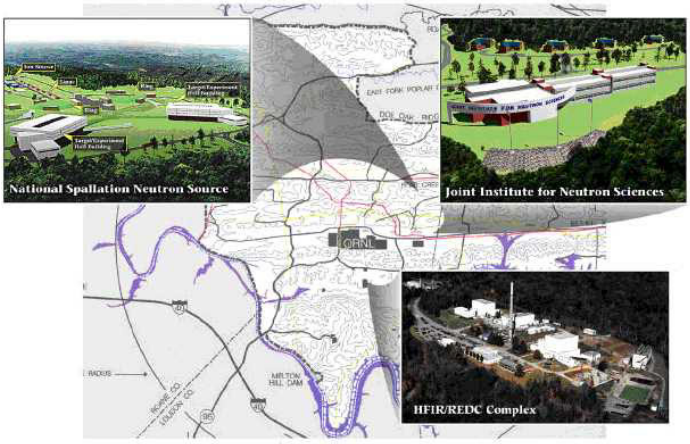
Radionuclides involved in *s*-process branchings

Isotope	Priority	$\langle\sigma\rangle_{30}$ (mb)	$t_{1/2}$	Atoms at the SNS
^{79}Se	1	220	$<6.5\times10^{4}$ yr	4.5×10^{16}
^{85}Kr	1	70	10.7 yr	1.5×10^{17}
^{94}Nb	2	500	2×10^{4} yr	2.0×10^{16}
^{106}Ru	2/3	140	367 d	7.1×10^{16}
^{135}Cs	2	200	2×10^{6} yr	5×10^{16}
^{147}Pm	1	1200	2.62 yr	8.6×10^{15}
^{155}Eu	1	1900	4.9 yr	5.3×10^{15}
^{153}Gd	1	2800	241.6 d	3.6×10^{15}
^{163}Ho	1	2600	4570 yr	3.8×10^{15}
^{169}Er	1/2	610	9.40 d	1.6×10^{16}
^{170}Tm	1	2300	128.6 d	4.4×10^{15}
^{171}Tm	1	990	1.92 yr	1.0×10^{16}
^{179}Ta	1	1200	1.7 yr	8.3×10^{15}
^{182}Hf	2/3	240	9×10^{6} yr	4.2×10^{16}
^{185}W	1	620	75.1 d	1.6×10^{16}
^{193}Pt	1/2	1500	50 yr	6.7×10^{15}
^{204}Tl	1	130	3.77 yr	7.7×10^{16}

- **Some branchings sensitive to temperature, neutron pulse duration or density.**
- **Need (n,γ) cross section measured from 100 eV to 300 keV.**
- **Need reaction rate to ~5%.**
- **Similar wish lists for *p*-process and *r*-process freeze-out.**

Conclusions

- **Spallation sources could play a very important role in nuclear astrophysics.**
  They excel at measurements on radioactive and very small stable samples.
- **The SNS would have a factor of 40 advantage (in flux) for these types of measurements.**
  Astrophysics programs would require very little from the SNS - 1 beam line.
- **Complementary facilities will still be needed to cover the range of experiments of interest to nuclear astrophysics.**



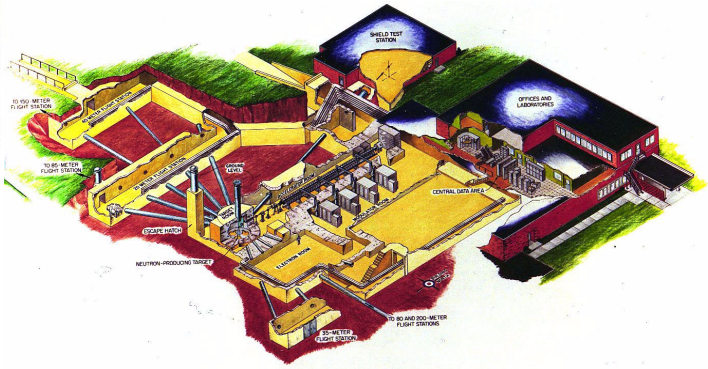


Fig. 1.0-1. The proposed site at ORNL for NSNS and JINS.