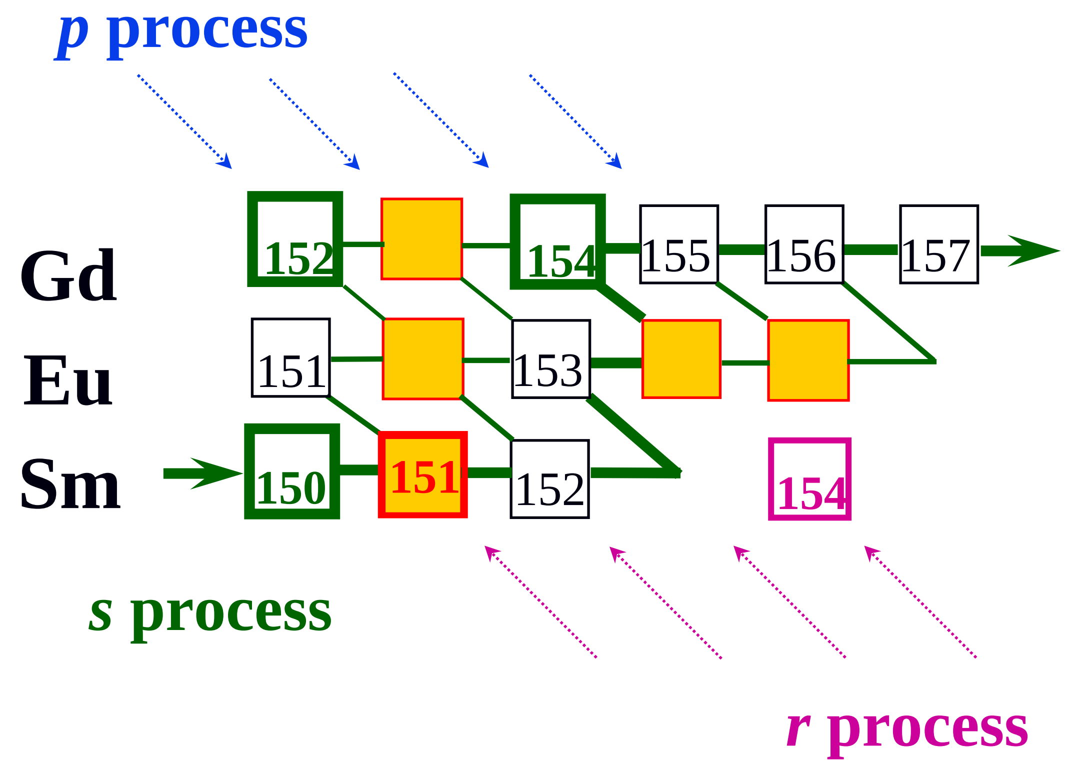
The Origin of the Elements between Iron and the Actinides – Probes for Red Giants and Supernovae

I Outline of scenarios for neutron capture nucleosynthesis (Red Giants, Supernovae) and implications for laboratory studies

II Accelerator neutron sources, experimental techniques based on the time-of-flight method, state-of-the-art detectors, stellar beta decay rates

III Stellar spectra in the lab, activation method, status *s* process, *p*-and *r*-process studies

s-process branchings
MACS and ß-rates for unstable isotopes



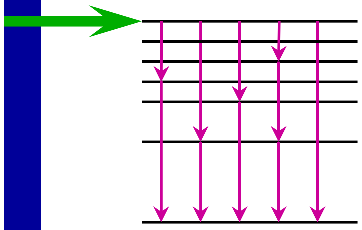
lab half-life of 93 yr
reduced to
$t_{1/2}$ = 3 yr
at *s*-process site

➡ fast decay of
thermally populated
excited states

probing neutron density, temperature, pressure, time scales !

detection of neutron capture events

(n,γ):



prompt γ-rays + TOF-method

single γ´s	* **Moxon-Rae**	ε_γ **~ 1%**
	* **PH-weighting**	~ **20%**
	* **Ge**	**< 1%**
all cascade γ´s	* **4π BaF_2**	**~100%**

milestones in neutron capture studies

1960s	pulsed VdG, eLINACs	MR & C_6D_6 detectors	MCA, computers
1980s	spallation neutrons LAMPF	4π BaF_2, activation	CAMAC, PC, MC simulations
2000…	n_TOF, J-PARC FRANZ	AMS	fast digitizers

what determines quality of (n, γ) data?

- **neutron source** (energy range, flux, resolution)
- **samples** (available mass, purity, activity)
- **detectors** (resolution, efficiency, granularity)
- **data acquisition** (fast digitizers, off-line analyses)
- **data analysis** (simulations, R-matrix codes)
- **methodology** (TOF or activation)

comparison of pulsed neutron sources

Facility	Neutron flux at sample $[\mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{dec}^{-1}]$	Repetition rate [Hz]	Flight path [m]	Pulse width [ns]	Neutron energy range [eV]
Karlsruhe	$1 \cdot 10^4$	250K	0.8	0.7	10^3-$2 \cdot 10^5$
LANSCE at Los Alamos	$5 \cdot 10^5$	20	20	250	th -10^5
n_TOF at CERN	$5 \cdot 10^4$	0.4	185	6	th -10^6
GELINA at Geel	$5 \cdot 10^4$	800	30	1	th -10^6
ORELA at Oak Ridge	$2 \cdot 10^4$	525	40	8	th -10^6

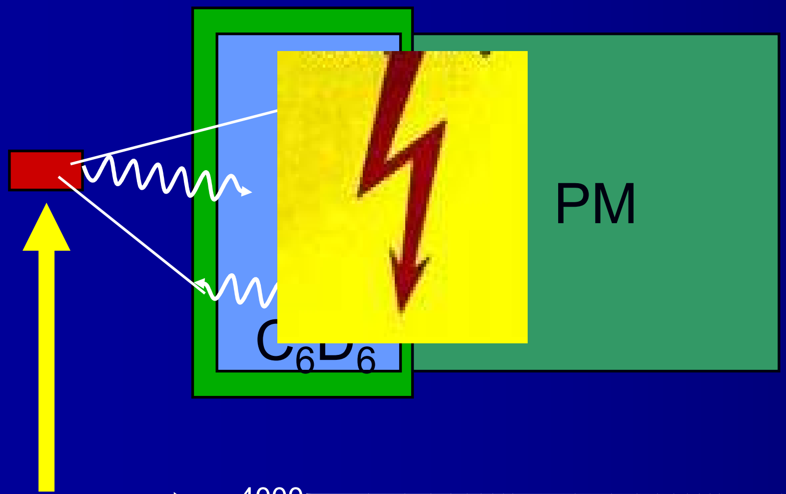
new facilities and upgrades

Frankfurt	$1 \cdot 10^7$	250K	0.8	<1	10^3-$2 \cdot 10^5$
J-PARC	$5 \cdot 10^6$	25	15	100	th -10^5
LANSCE upgrade	$5 \cdot 10^6$	20	20	250	th -10^5
n_TOF at CERN	$3 \cdot 10^6$	0.4	185	6	th -10^6

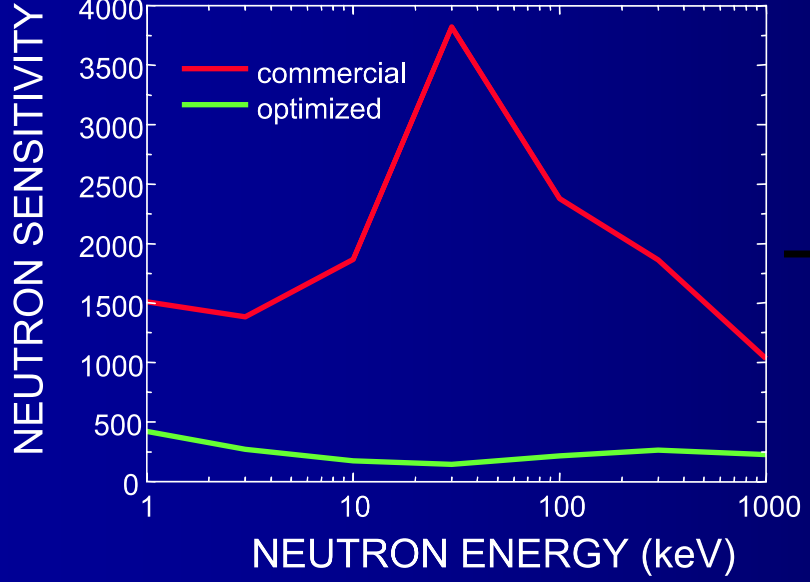
state of the art γ-ray detectors

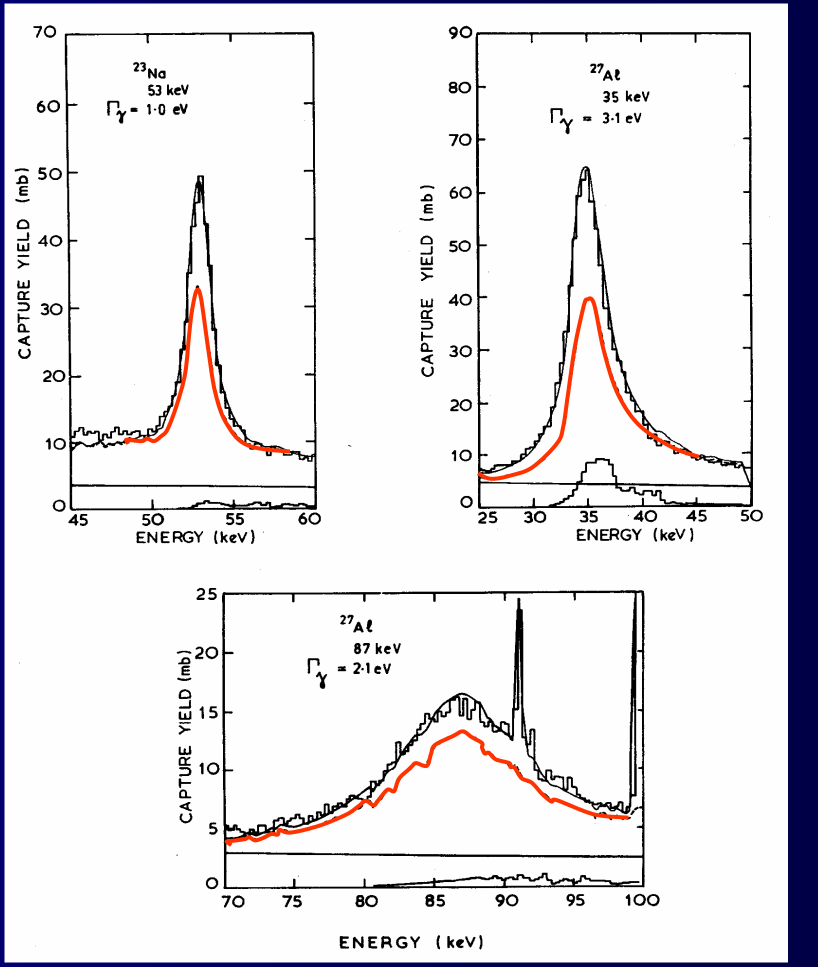
- efficiency: important for measurements of small cross sections and to compensate for sample mass or weak neutron neutron flux
- segmentation: multi-detector arrays for higher efficiency, angular distributions, and background suppression, γ calorimeters (FZK, LANL, n_TOF)
- sensitivity: improved background suppression (C_6D_6 detectors)
- resolution: compromised by efficiency, high resolution **HPGe** detectors crucial for activation measurements

optimized C_6D_6 detectors

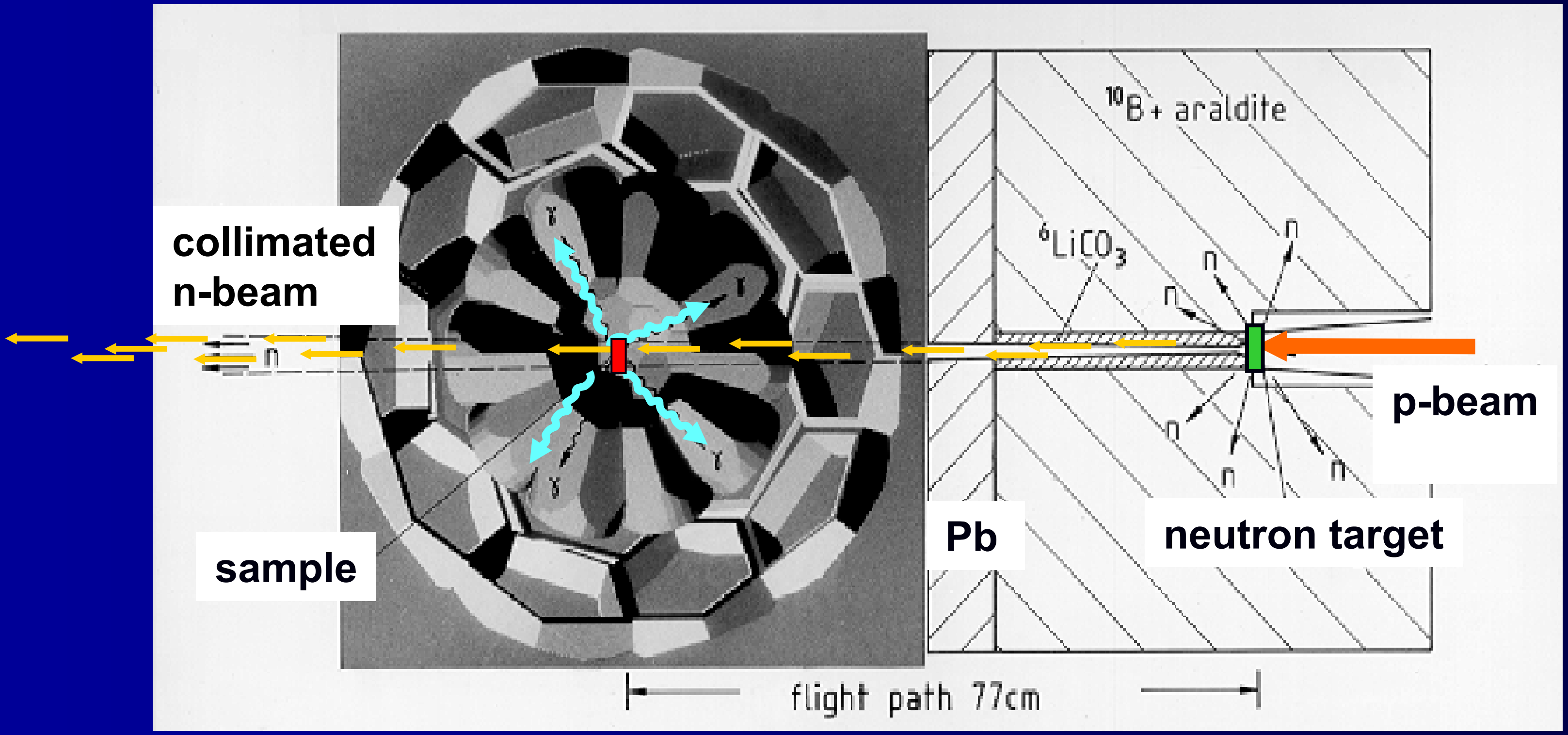


neutron beam





the Karlsruhe 4π BaF_2 array



ε_γ >90% up to 10 MeV

$\Delta E/E$ = 6% at 6 MeV

Δt = 500 ps

ε_{casc} > 98%

clear signatures

good TOF resolution

the Nd cross section measurements with the 4π BaF_2 detector: TOF

sample ladder

^{142}Nd

^{208}Pb

^{143}Nd

^{145}Nd

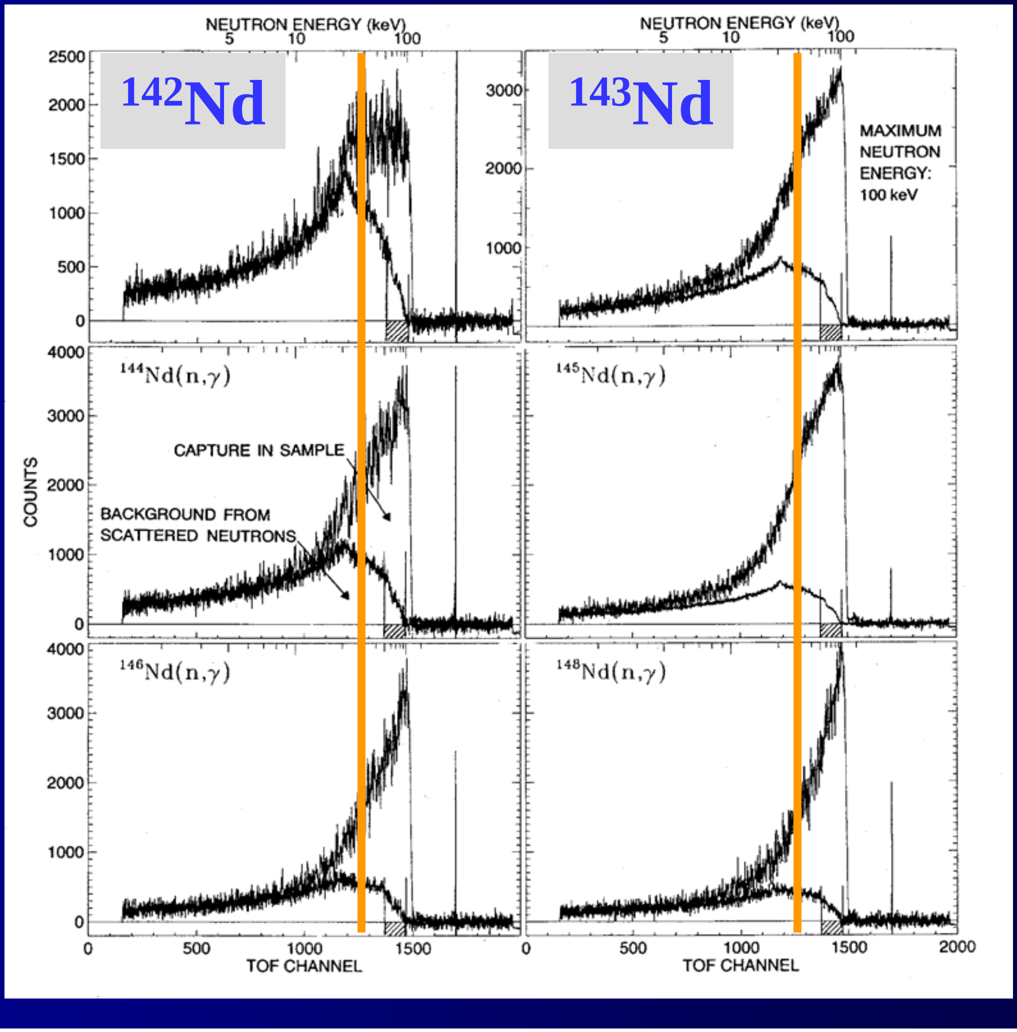
^{197}Au

^{146}Nd

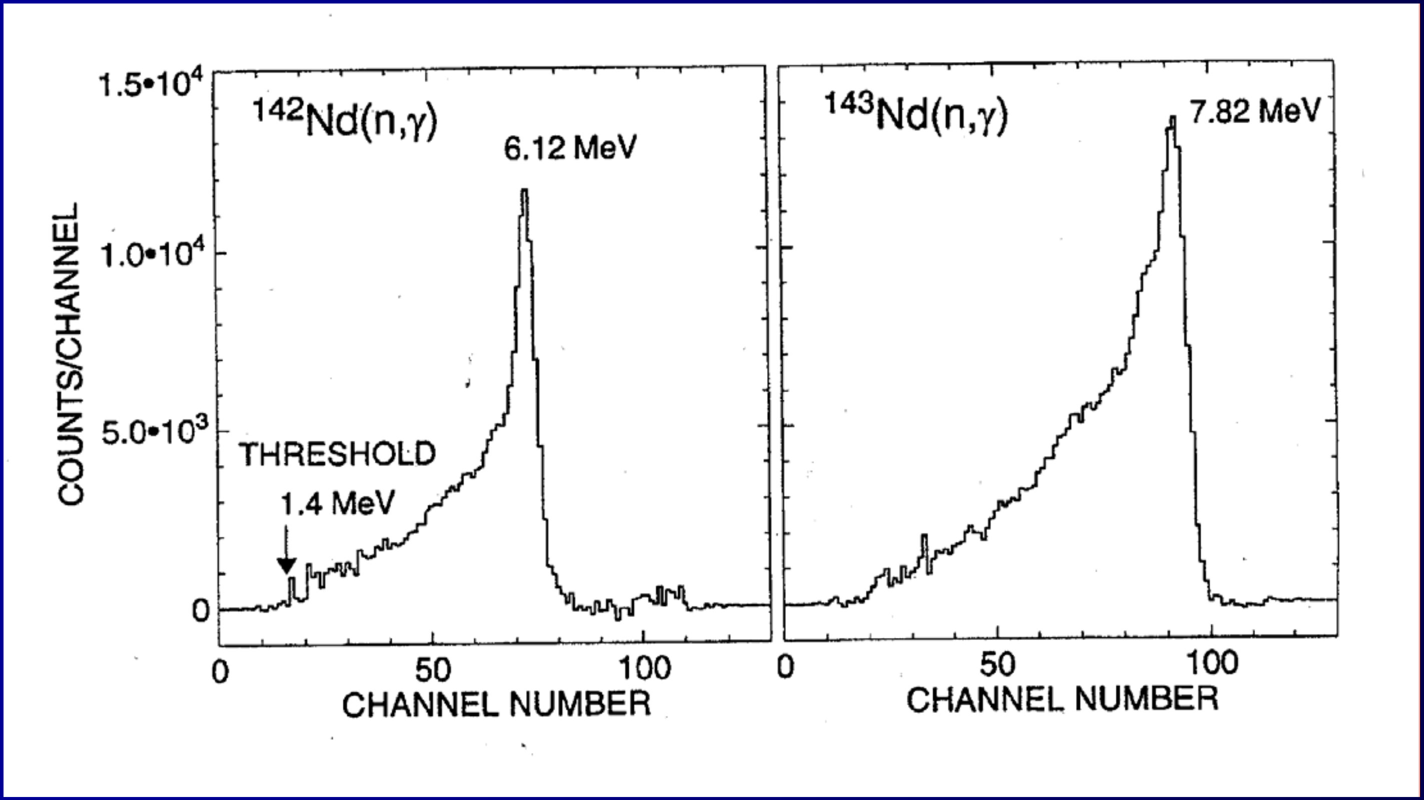
^{148}Nd

Empty

^{144}Nd



the Nd cross section measurements with the 4π BaF_2 detector: N(Eγ)



stellar cross section of ^{142}Nd

previous value	present result
47±7 mb	**35.0±0.7 mb**

$\sigma(E_n)$ measured relative to $^{197}Au(n,\gamma)^{198}Au$

folding with stellar neutron spectrum yields
Maxwellian averaged cross section (MACS)

$$\langle\sigma\rangle = \frac{\langle\sigma v\rangle}{v_T} = \frac{2}{\sqrt{\pi}} \frac{\int \sigma(E_n)\, E_n \exp(-E_n/kT)\, dE_n}{\int E_n \exp(-E_n/kT)\, dE_n}$$

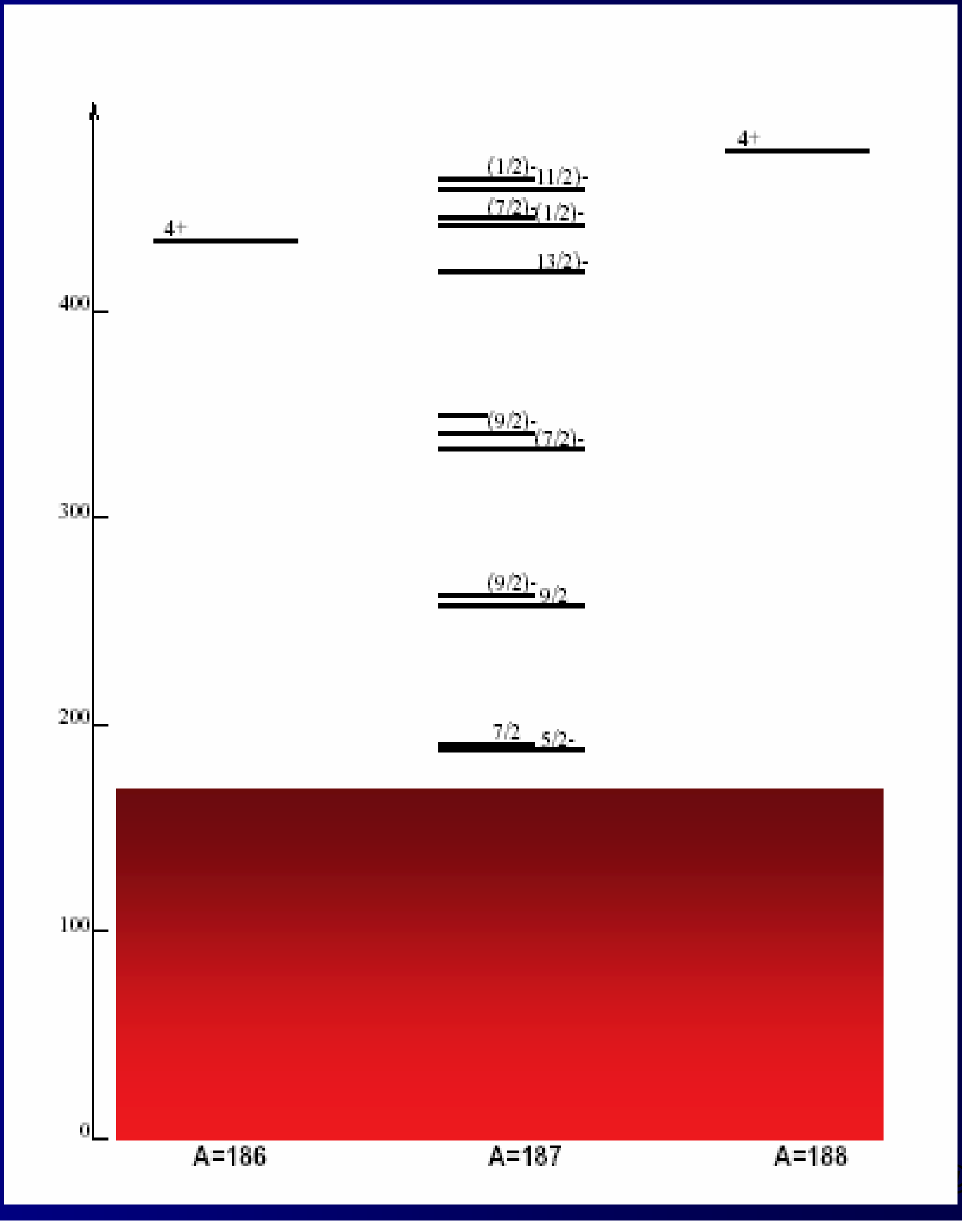
SEF: thermal population of nuclear states

$$P(E_k) = \frac{(2J_k+1)e^{-E_k/kT}}{\sum\limits_m (2J_m+1)e^{-E_m/kT}}$$

in ^{187}Os at *kT* = 30 keV:

P(gs) = 33%
P(1st) = 47%
P(all others) = 20%

stellar enhancement factor
= SEF = stellar σ / lab. σ



stellar ^{187}Os(n,γ) cross section: theory

Hauser-Feshbach statistical model:

$$\sigma_{n,\gamma}(E_n) = \frac{\pi}{k_n^2} \sum_{J\pi} g_J \frac{\sum_{ls} T_{n,ls} T_{\gamma,J}}{\sum_{ls} T_{n,ls} + \sum_{ls} T_{n',ls} + T_{\gamma,J}} W_{\gamma,J}$$

- neutron transmission coefficients, T_n: from OMP calculations

- γ-ray transmission coefficients, T_γ : from GDR (experimental parameters)

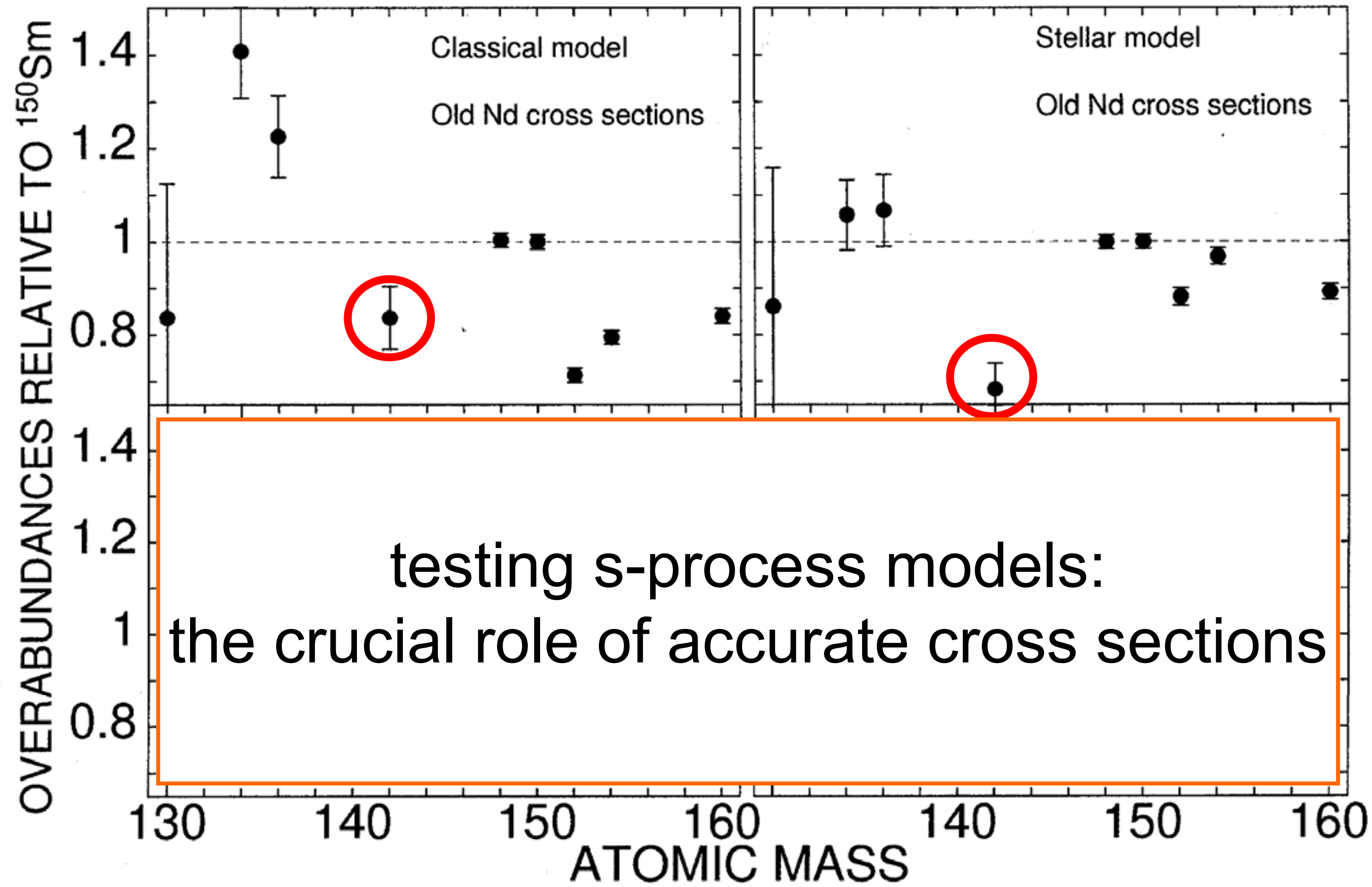
- nuclear level densities: fixed at the neutron binding from $<D>_{exp}$

all these parameters can be derived and fixed from the analysis of experimental data at low-energy

stellar correction factor $F_\sigma = SEF_{186} / SEF_{187}$

kT (keV)	$\langle\sigma_{187}\rangle^{lab}$ (mbarn)	$\langle\sigma_{187}\rangle^{calc}$ (mbarn)	$\langle\sigma_{187}\rangle^{*}$ (mbarn)	SEF_{187}	F_σ
10	1988	2111	2324	**1.10**	0.91
20	1171	1193	1402	**1.18**	0.85
30	874	876	1059	**1.21**	0.86
40	715	712	877	**1.23**	0.89
50	614	610	766	**1.26**	0.93

the *s* process in AGB stars:
the search for an abundance signature



testing s-process models:
the crucial role of accurate cross sections

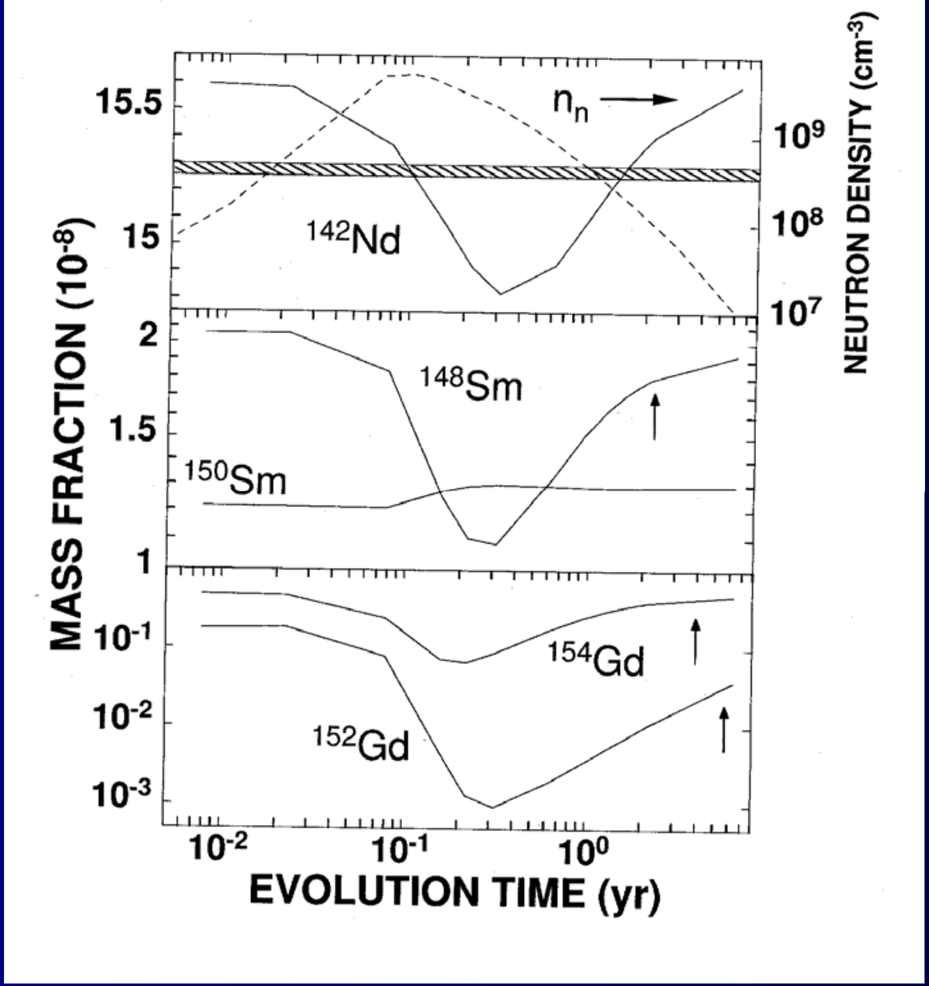
freeze-out of final abundance patterns

large freeze-out effects in *s*-process branchings:

sensitive tests for stellar model with respect to

- **neutron flux**
- **temperature**
- **density**

^{142}Nd ± 5%
^{148}Sm factor ± 2
^{152}Gd factor ± 100



n_TOF - the CERN spallation neutron source

PS213

The TOF Collaboration

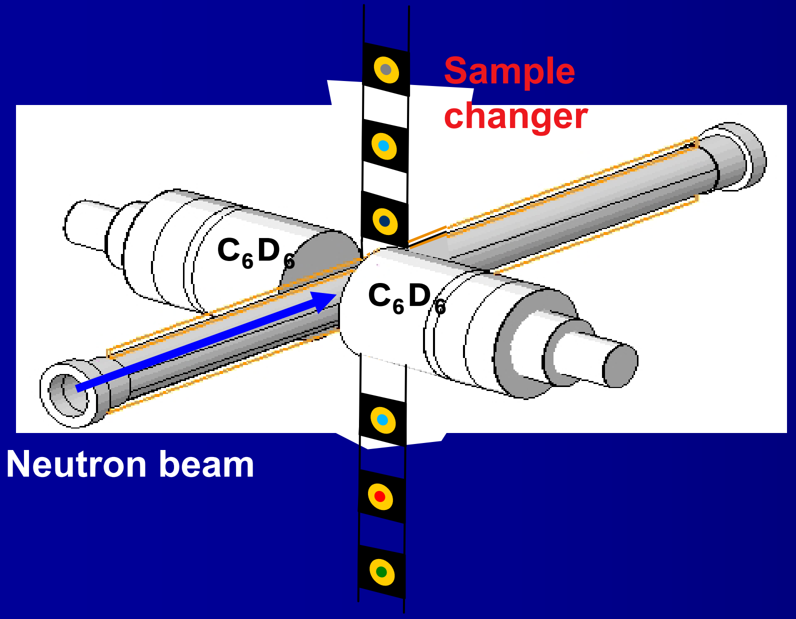
20 GeV protons on lead block

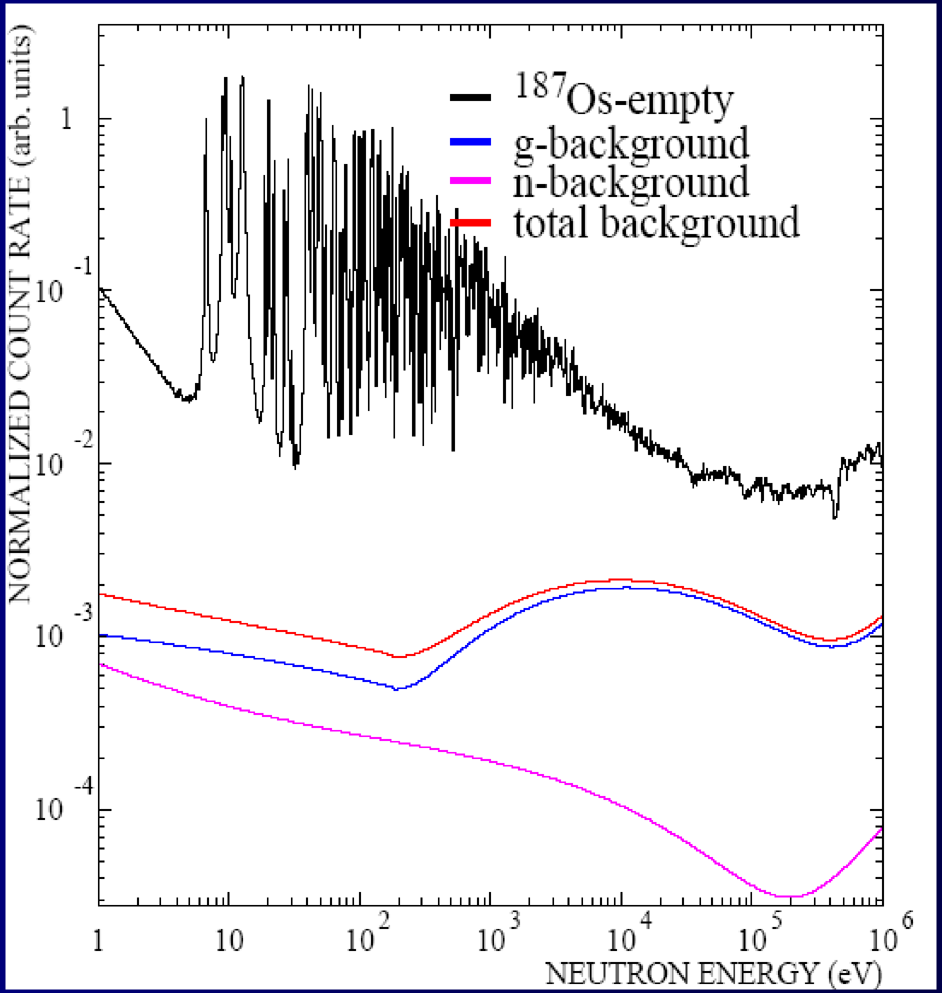
- 300 neutrons per proton
- most luminous n-source worldwide
- high resolution TOF facility

the n_TOF tunnel

Os(n, γ) cross sections measured at n_TOF/CERN

γ-ray detection: C_6D_6 scintillators



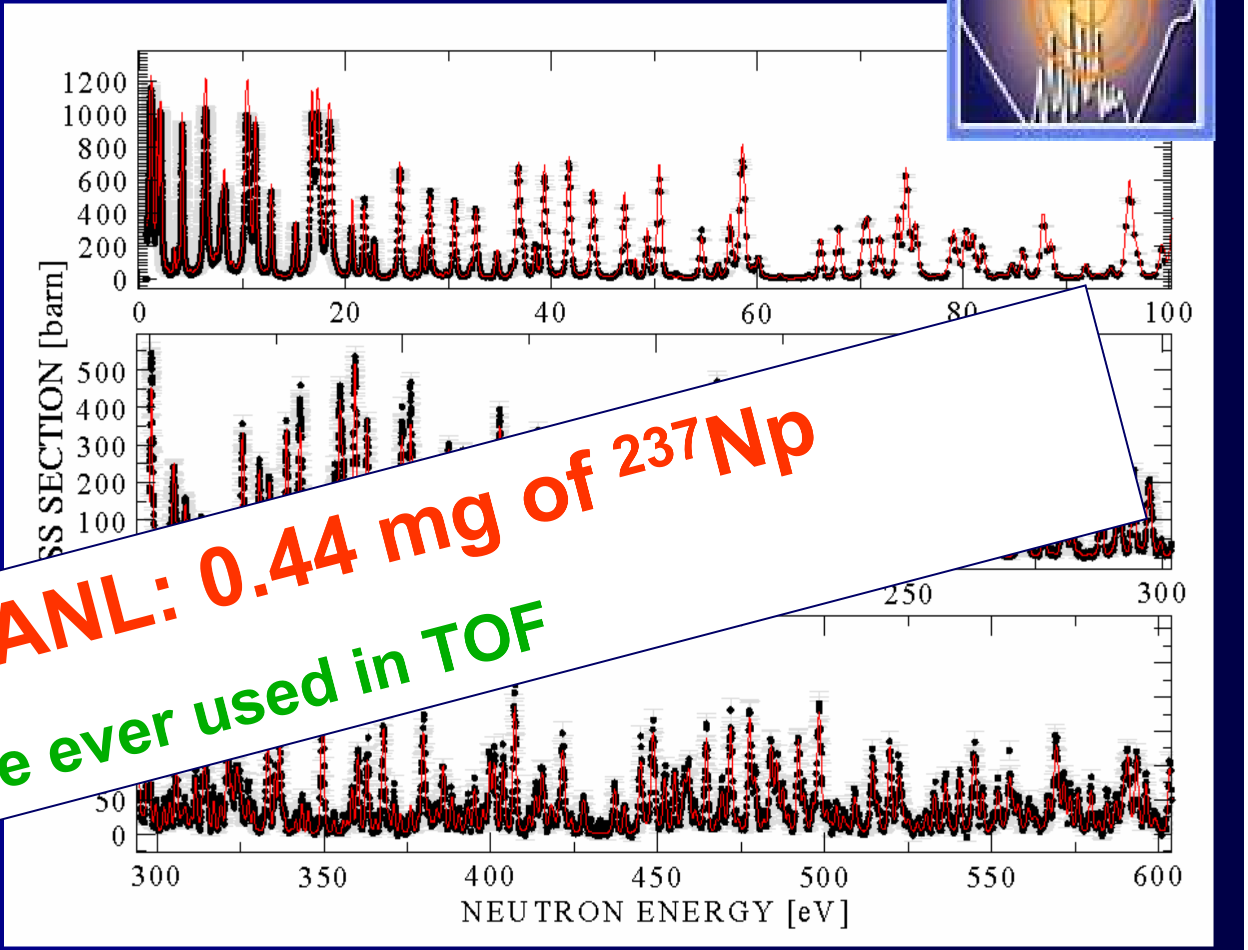


resolution & sensitivity

^{151}Sm(n, γ)

→ more than 200 „new“ resonances

important for obtaining level densities & strength functions for improved Hauser-Feshbach calculations



recently at LANL: 0.44 mg of ^{237}Np

smallest sample ever used in TOF

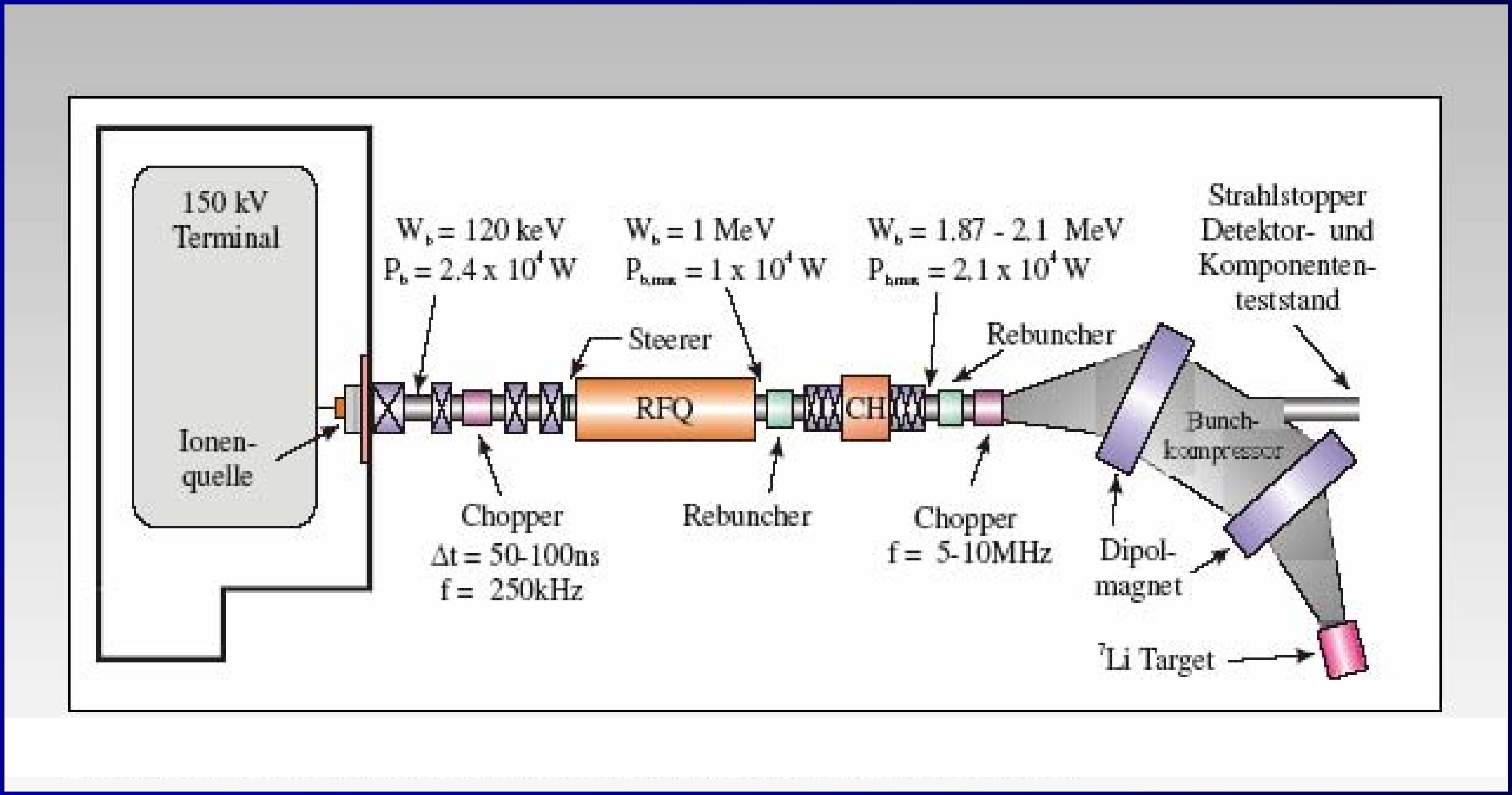
spallation sources for TOF measurements of stellar (n,γ) rates

Los Alamos
NATIONAL LABORATORY
LANSCE
Los Alamos Neutron Science Center

PS213
n_TOF Collaboration

0.8	proton energy (GeV)	24
20	repetition rate (Hz)	0.4
250	pulse width (ns)	5
20	flight path (m)	185
200	average proton current (μA)	2
20	neutrons per proton	760

the Frankfurt Neutron source at the SGZ



E_p = 1.9 – 2.4 MeV, Δt = 1 ns

TOF mode: 250 kHz, 2 mA **or** CW mode: 175 MHz, 200 mA

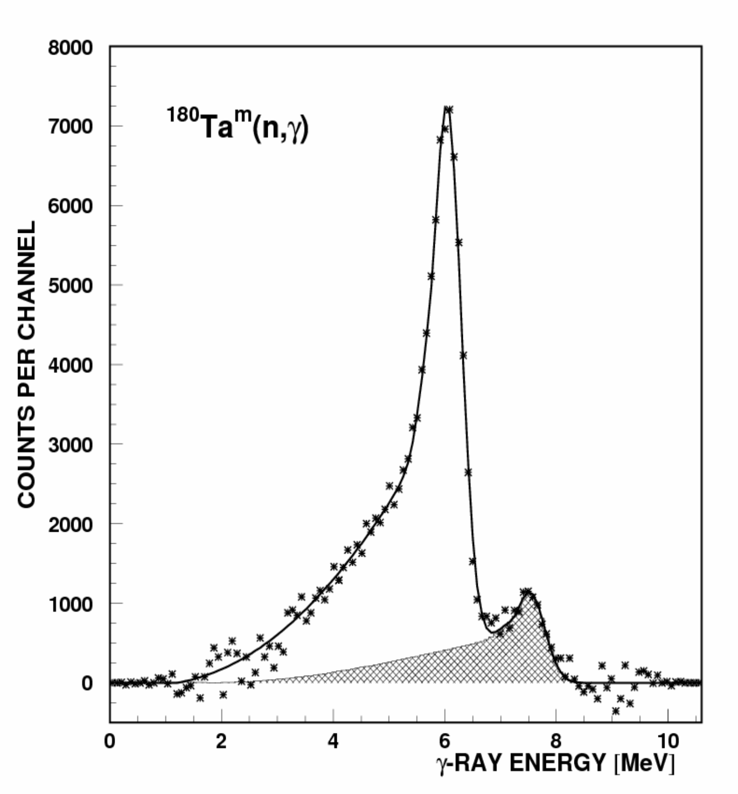
data acquisition and analysis

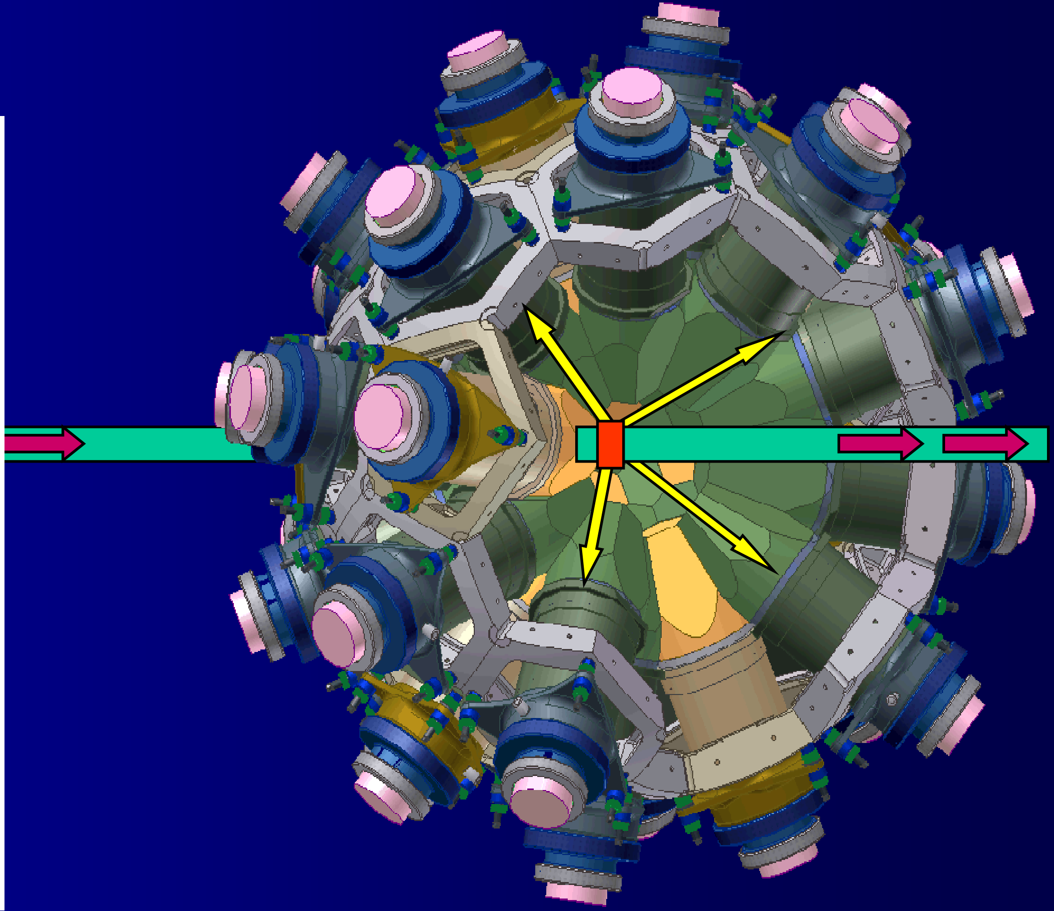
- flash-ADC: for flexible and comprehensive off-line analysis (fast digitizers for recording full detector response, e.g. @ n_TOF over 16 ms with 500 MS/s)

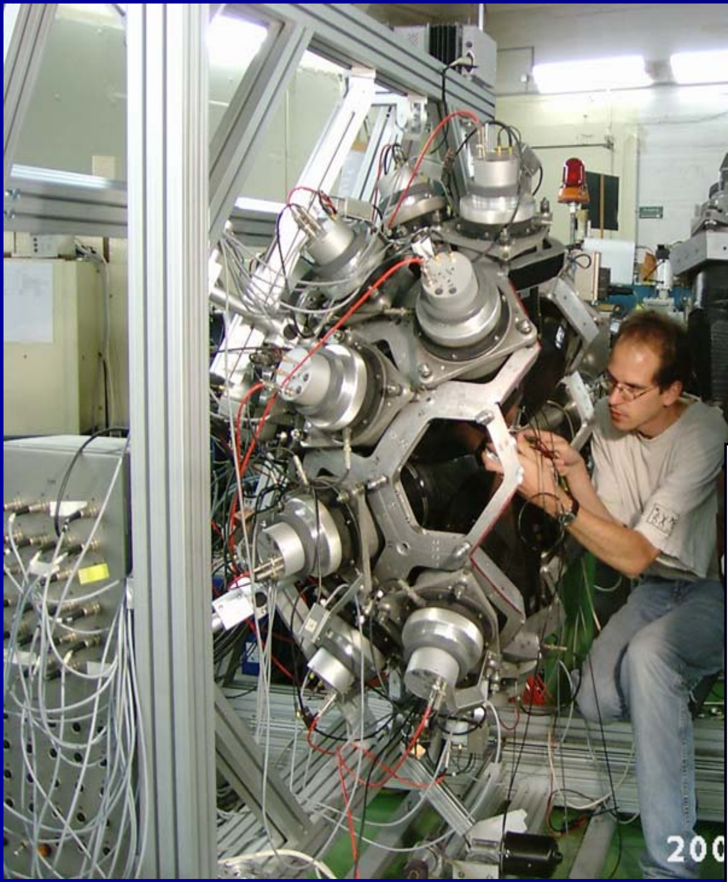
- simulations: MCNP and GEANT are becoming standard tools for planning of experiments and – necessarily - for the analysis of cross section measurements with complex detector arrays

computer simulations

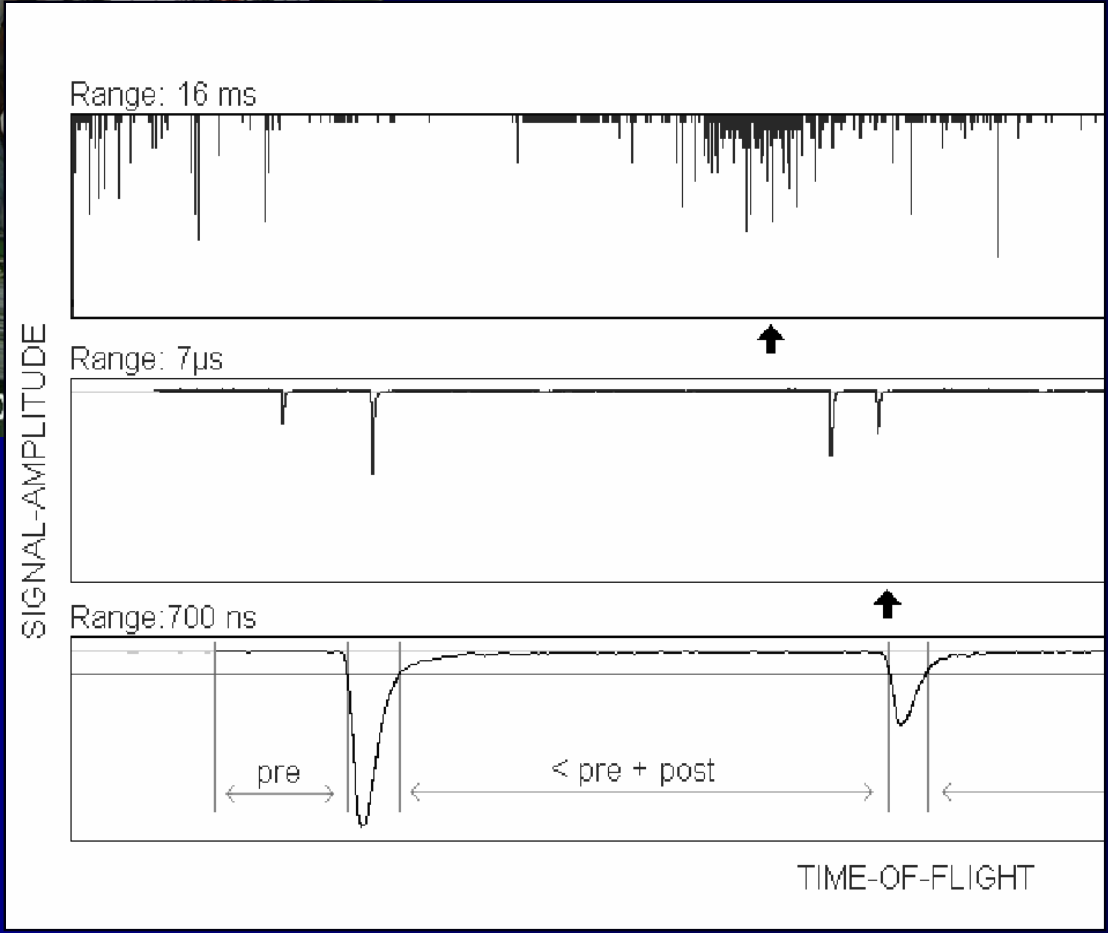
42 independent modules
in total 60 l of BaF_2







signals from a single n_TOF neutron burst recorded with fast digitizer



sample requirements

VdG and e-linac:

TOF	0.05 - 5 g	separated isotopes
	→	too much for short-lived samples
activation	100 **ng**	**"natural"** samples
	→	limited to special cases

spallation neutron source:

TOF/1-200m 10 – 500 **µg** separated isotopes

(if scaled with neutron flux)

→ measurements on radioactive samples

unstable samples: now and soon

s process

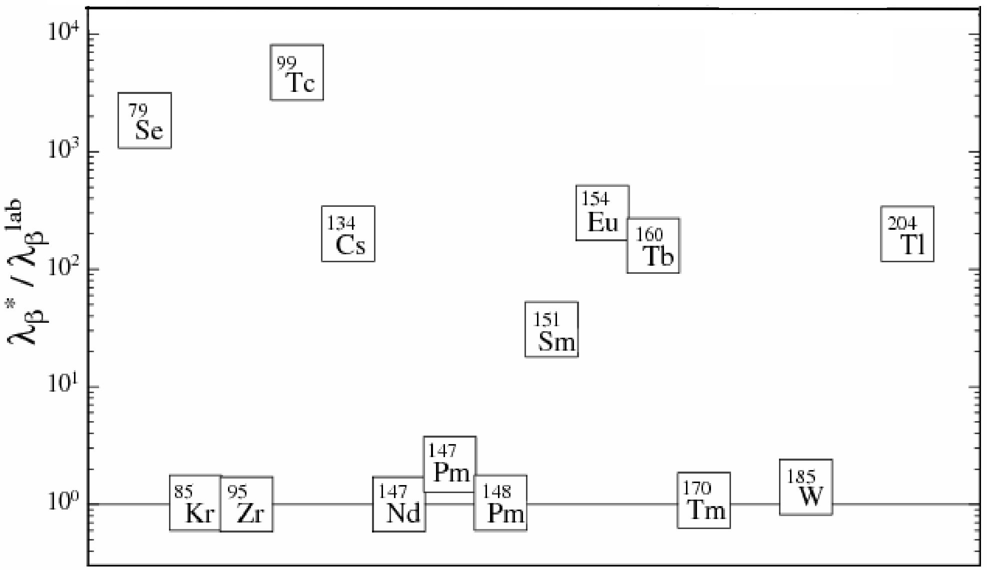
branch point	status	future
^{63}Ni	🔴	🟢
^{79}Se	🔴	🟢
^{81}Kr	🔴	🟢
^{85}Kr	🔴	🟢
^{147}Nd	🔴	🟢
^{147}Pm	🟡	🟢
^{148}Pm	🔴	🔴
^{151}Sm	🟢	🟢
^{154}Eu	🔴	🟢
^{155}Eu	🟡	🟢
^{153}Gd	🔴	🟢
^{160}Tb	🔴	🔴
^{163}Ho	🟡	🟢
^{170}Tm	🔴	🟢
^{171}Tm	🟡	🟢
^{179}Ta	🔴	🟢
^{185}W	🔴	🟢
^{204}Tl	🔴	🟢

r and *p* process

(n,γ) cross sections for a variety of
unstable isotopes
(*r* : ^{60}Fe, ^{106}Ru, ^{126}Sn, ^{182}Hf...,
+ double neutron capture !
(*p* : ^{91,92}Nb, ^{97,98}Tc...)

- ✓ for direct use in reaction networks
- ✓ to derive rates of inverse reactions
- ✓ to test and assist statistical models

stellar enhancement of ß-rates



ß- rates: - decay of thermally populated excited states

- bound beta decay

EC: - ionization versus capture from continuum

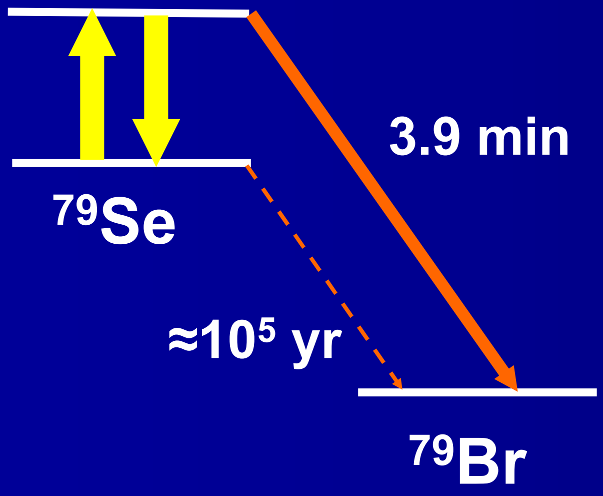
ß-rates of unstable isotopes

- ➡ decay of thermally populated excited states
  - A>60: Takahashi and Yokoi (1987)
  - experiments: 1 direct case (^{79}Se) and 1 indirect (^{176}Lu))
- ➡ bound beta decay
  - experimentally verified at GSI in 3 cases

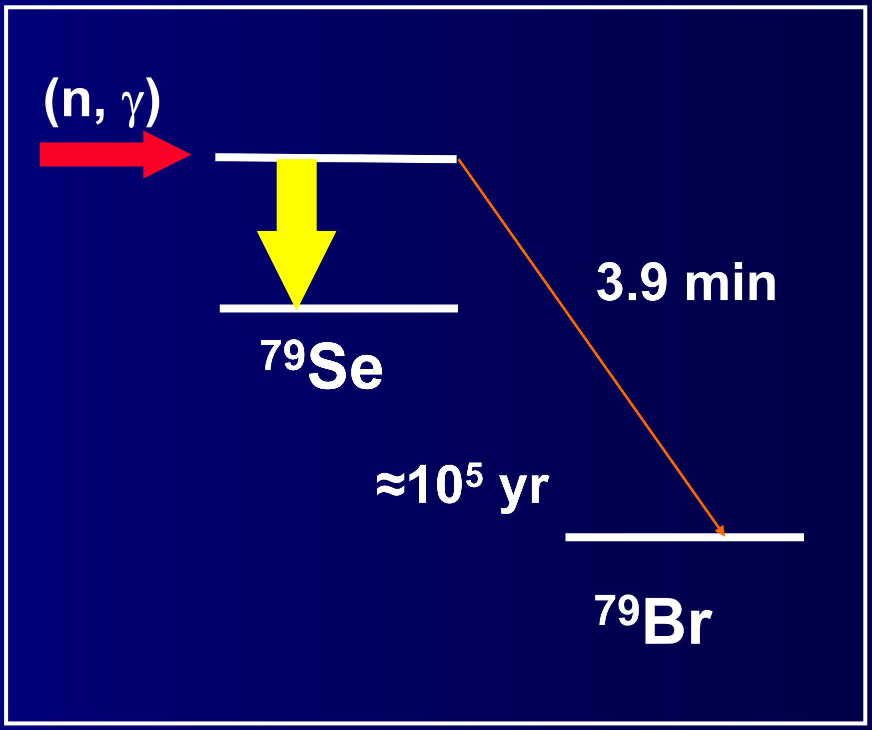
    (^{163}Dy, ^{187}Re, ^{207}Tl)

stellar ß-rate of ^{79}Se

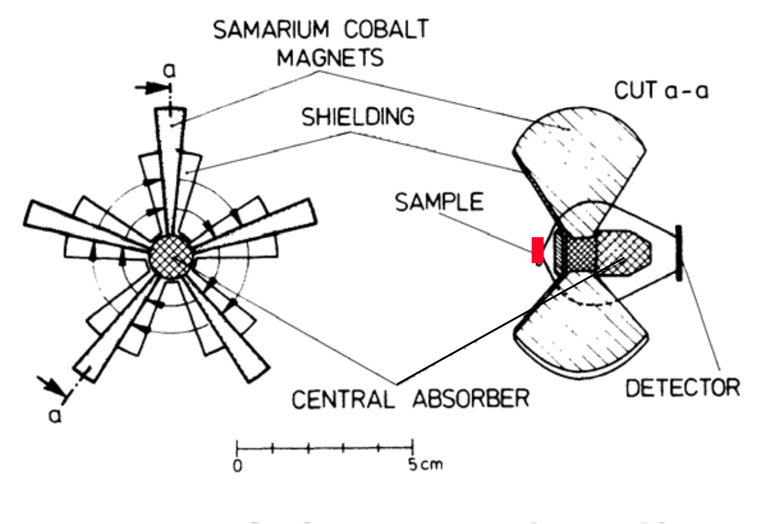
stellar

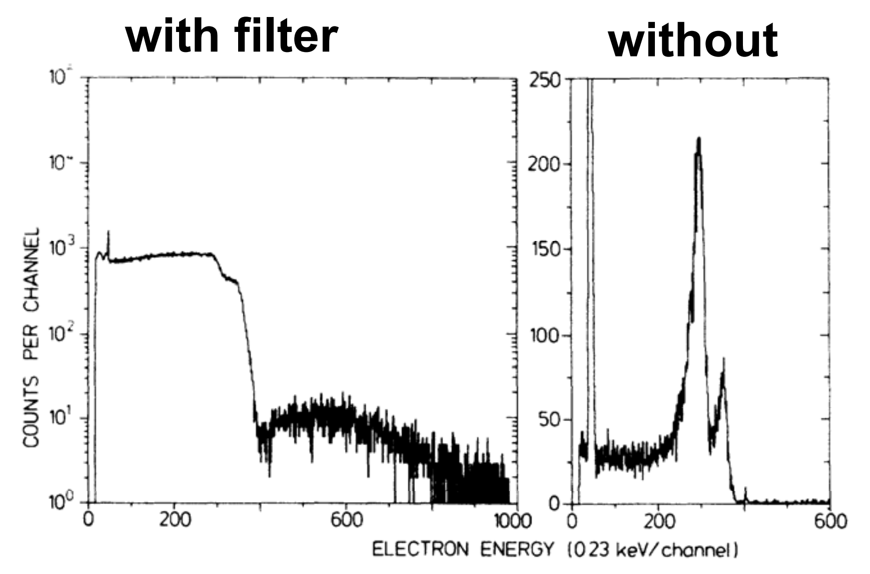


experimental



ß-decay of $^{79}Se^{m}$



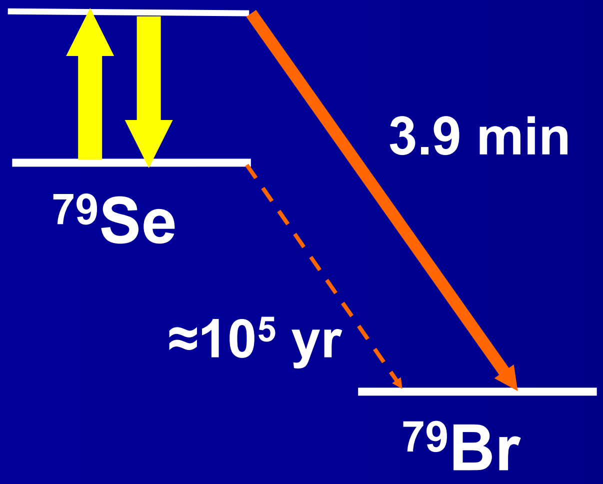


mini-orange spectrometer for suppression of conversion electrons

$$\frac{\lambda_\gamma}{\lambda_\beta} = 1780^{+560}_{-310}$$

$$\log ft = 4.70^{+0.10}_{-0.09}$$

stellar

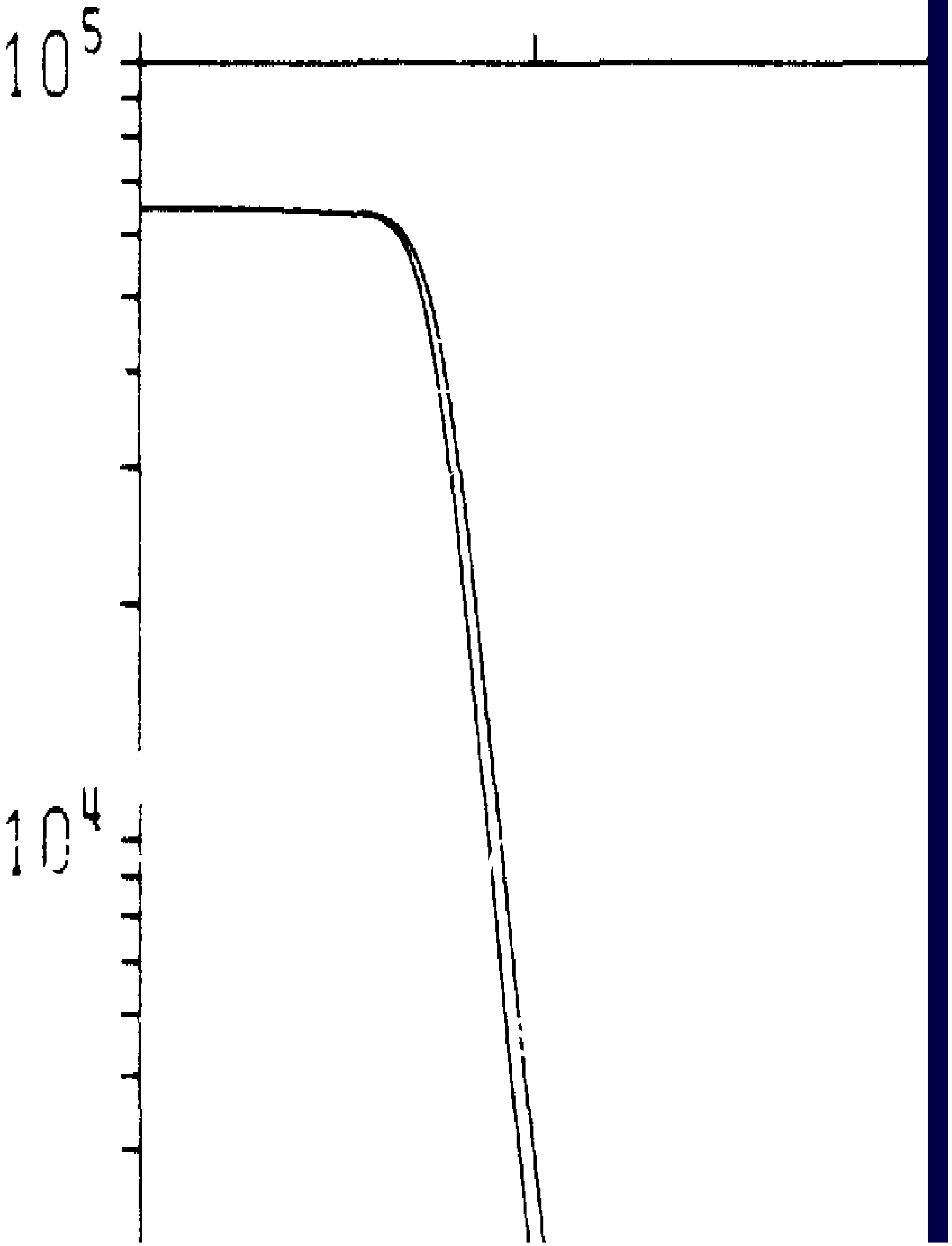


3.9 min

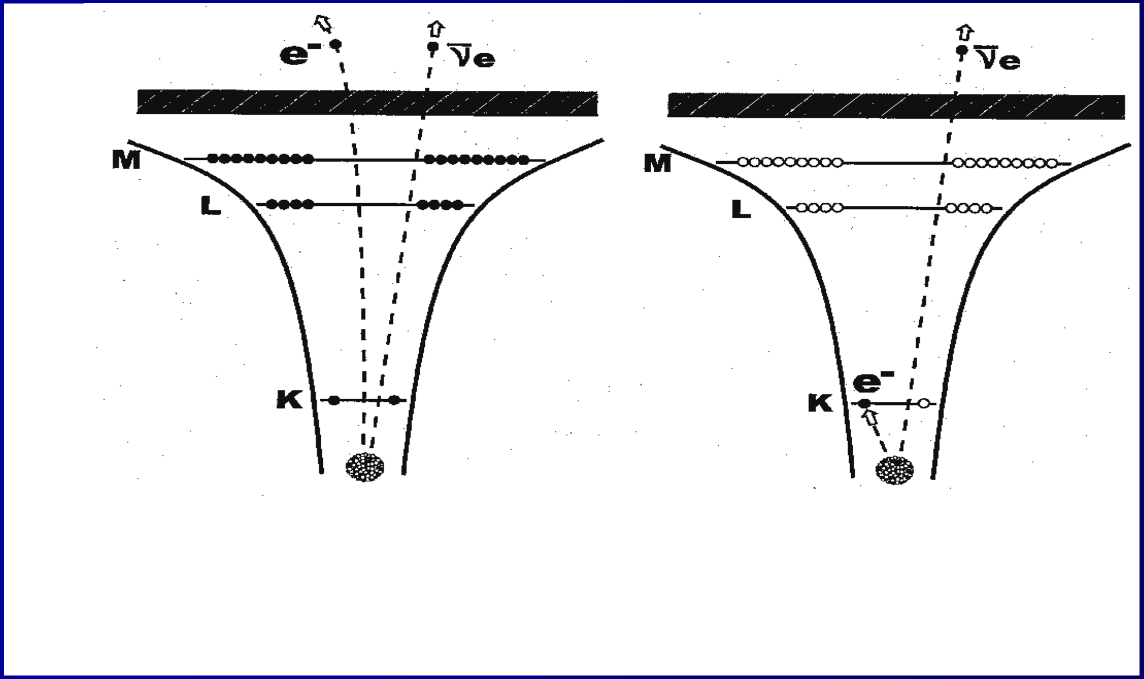
^{79}Se

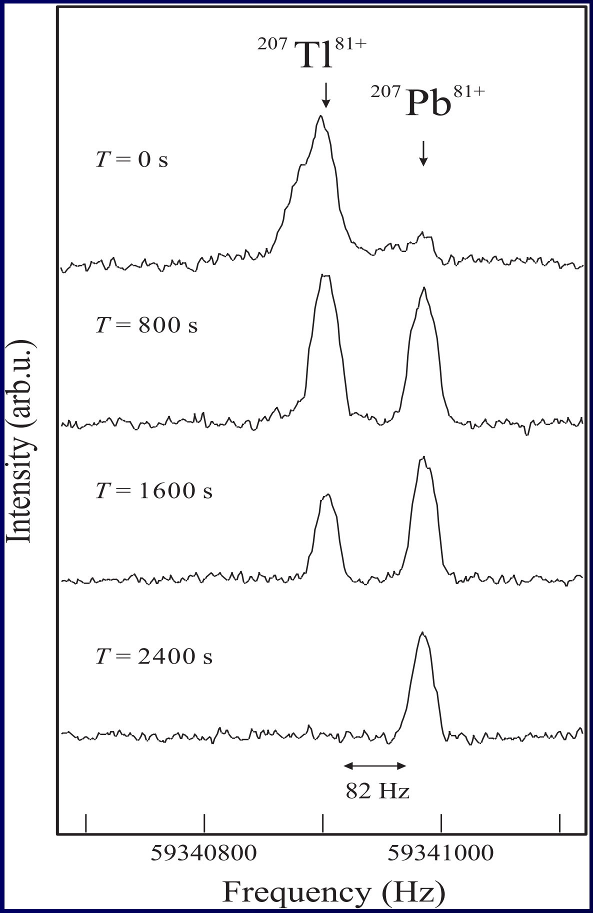
≈10^5 yr

^{79}Br



bound ß-decay





fully stripped ^{207}Tl injected in ESR@GSI

→ **β_b decay of bare ^{207}Tl^{81+} $\rightarrow$ ^{207}Pb^{81+}**

summary of lecture II

- (n,γ) cross sections are crucial for abundances: *s*-process branchings and freeze-out phases
- existing experimental possibilities in some cases suited even for measurements on unstable isotopes, but branching points and *p*- and *r*-process regions represent big challenge
- high flux at spallation sources: new possibilities for a variety of measurements on important unstable isotopes