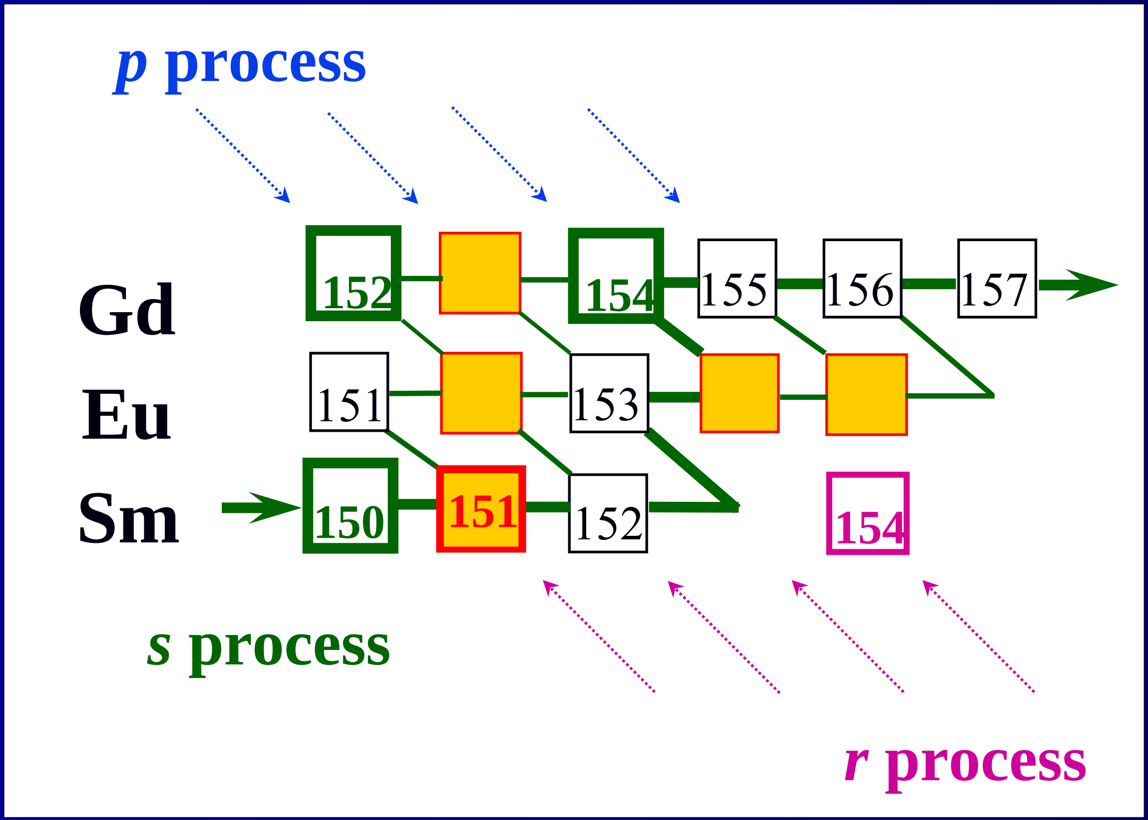
The Origin of the Elements between Iron and the Actinides – Probes for Red Giants and Supernovae

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

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

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

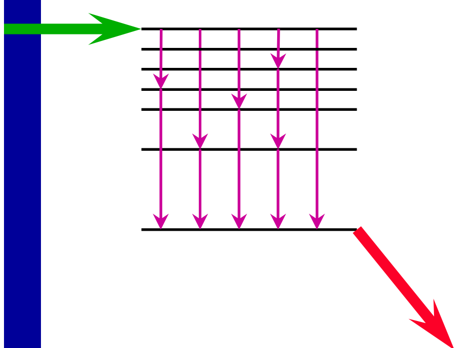
probing neutron density, temperature, pressure, time scales !

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)

detection of neutron capture events

(n,γ):



prompt γ-rays + TOF-method

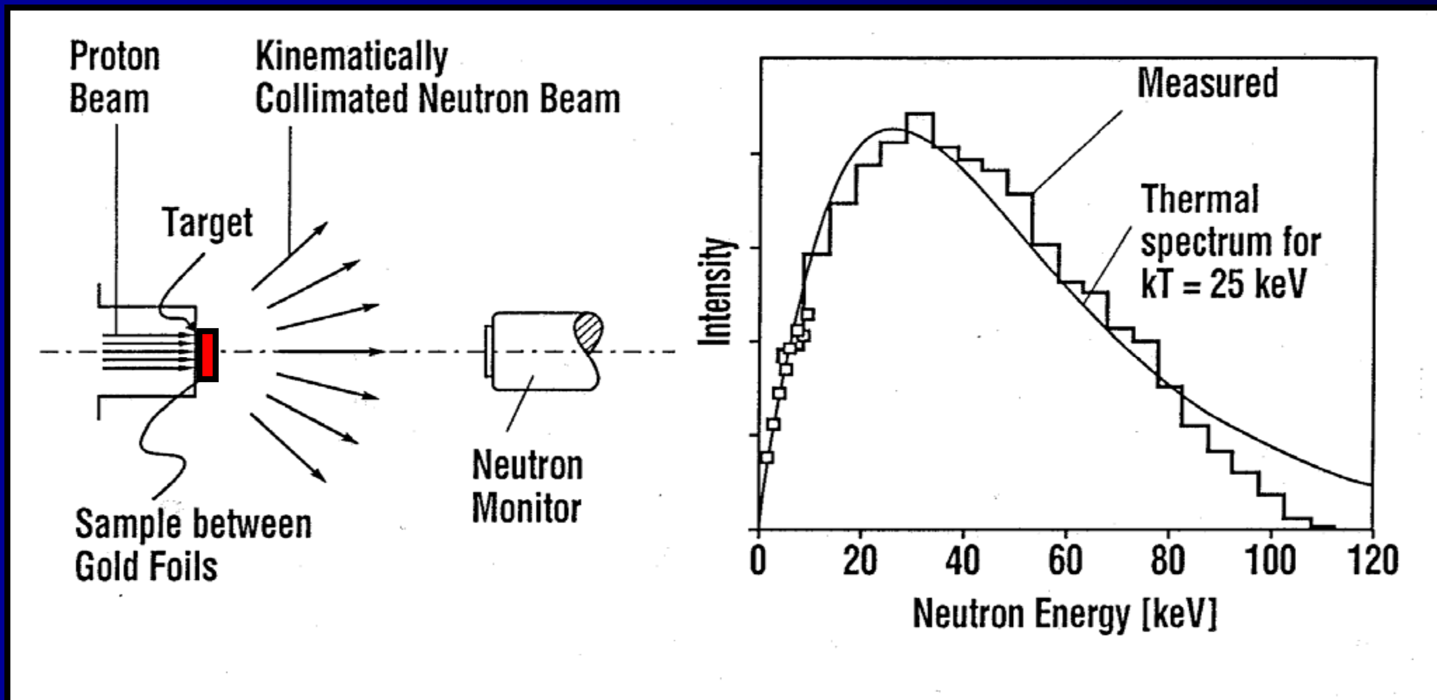
single γ´s	* Moxon-Rae	ε_γ ~ 1%
	* PH-weighting	~ 20%
	* Ge	< 1%
all cascade γ´s	* 4π BaF_2	~100%

activation in quasi-stellar spectrum

most sensitive	* small cross sections, **10^{14}** atoms sufficient
selective	* natural samples or low enrichment

activation technique at kT=25 keV

- neutron production via **$^7Li(p,n)^7Be$** reaction at Van de Graaff
- induced activity measured with HPGe detectors



- **possible when product nucleus is radioactive**

- **very high sensitivity ⟶ small samples & small cross sections**
- **use of natural samples possible, no enriched sample necessary**
- **Direct Capture component included**

flux measurement with gold foils

gold cross section accurately measured via **$^{7}Li(p,n)^{7}Be$** reaction by comparison of gold activity ($E\gamma$ = 412 keV) and ^{7}Be activity of the target ($E\gamma$ = 478 keV)

gamma spectra are practically background free;
Be and Au decay intensities exactly known;

Precise Au cross section
±1.5%

Ge efficiency calibration with a set of standard sources very accurate because lines from ^{7}Be and ^{198}Au very similar in energy

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

induced activity:

$$\mathbf{A} = \varphi_{tot} \cdot N \cdot \sigma \cdot f_b$$

$$f_b = \frac{\int \varphi(t) \cdot \exp(-\lambda (t_a - t))\, dt}{\int \varphi(t)\, dt} \qquad K_\gamma = \frac{1 - \exp(-\mu x)}{\mu x}$$

line strength in γ-spectrum:

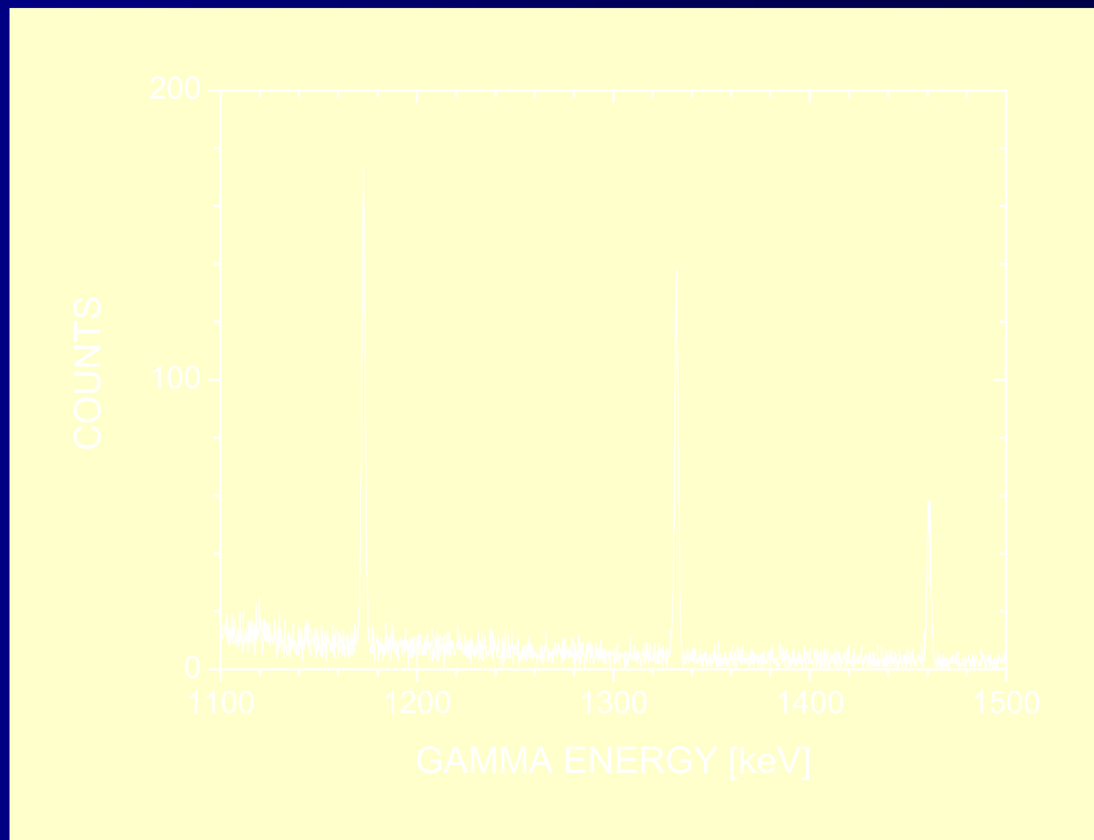
$$\mathbf{C_\gamma} = A \cdot K_\gamma \cdot \varepsilon_\gamma \cdot I_\gamma \cdot (1 - \exp(-\lambda t_m)) \cdot \exp(-\lambda t_w)$$

$$\frac{A_i}{A_{Au}} = \frac{N_i \cdot \boldsymbol{\sigma_i} \cdot f_{bi}}{N_{Au} \cdot \sigma_{Au} \cdot f_{bAu}}$$

induced activity for $^{59}Co(n,\gamma)^{60}Co$

induced gold activity yields strong and almost background-free line at 412 keV

even less favorable cases exhibit good signal/background ratio



activation: unique sensitivity

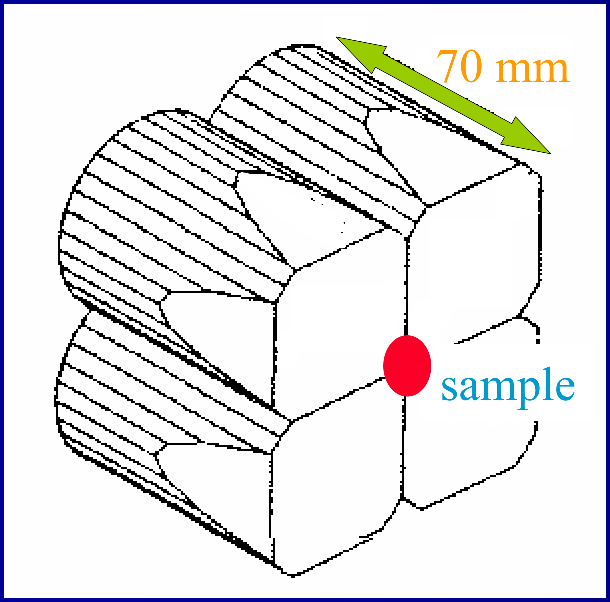
4 - 5 orders of magnitude higher flux than best TOF facilities!

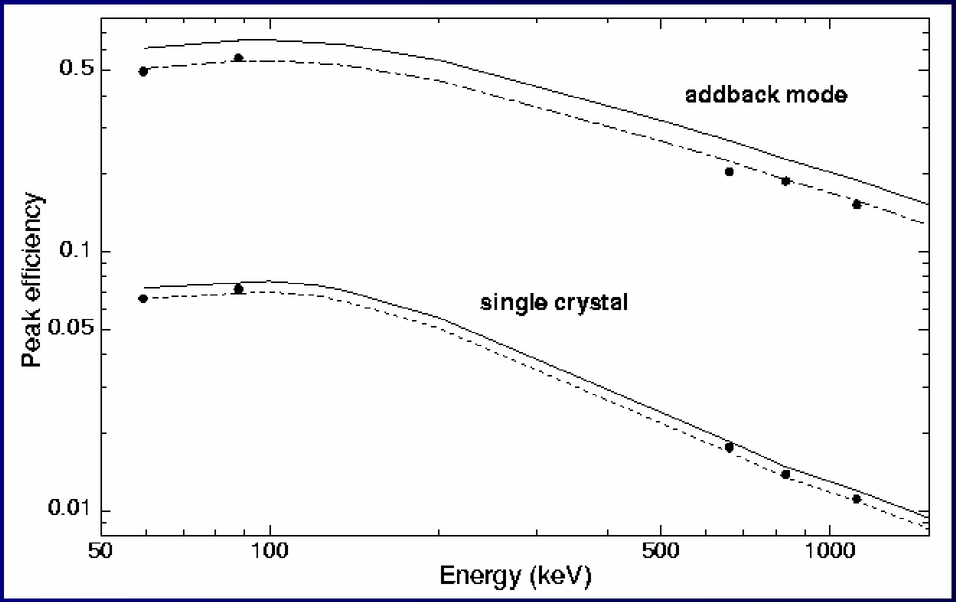
➡ measurement of **μbarn** cross sections

➡ measurements with **ng** samples,
important for cross sections of unstable isotopes

28 ng ^{147}Pm

efficient γ-counting:
2 Ge Clovers face to face



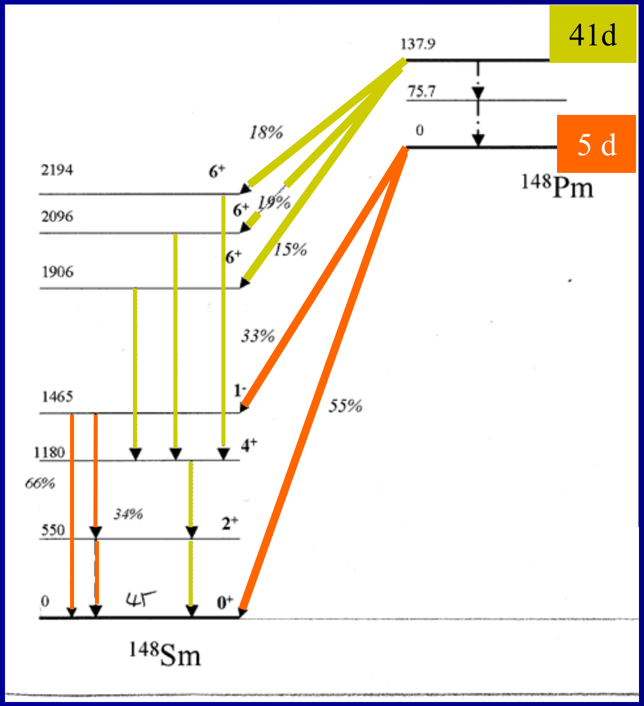


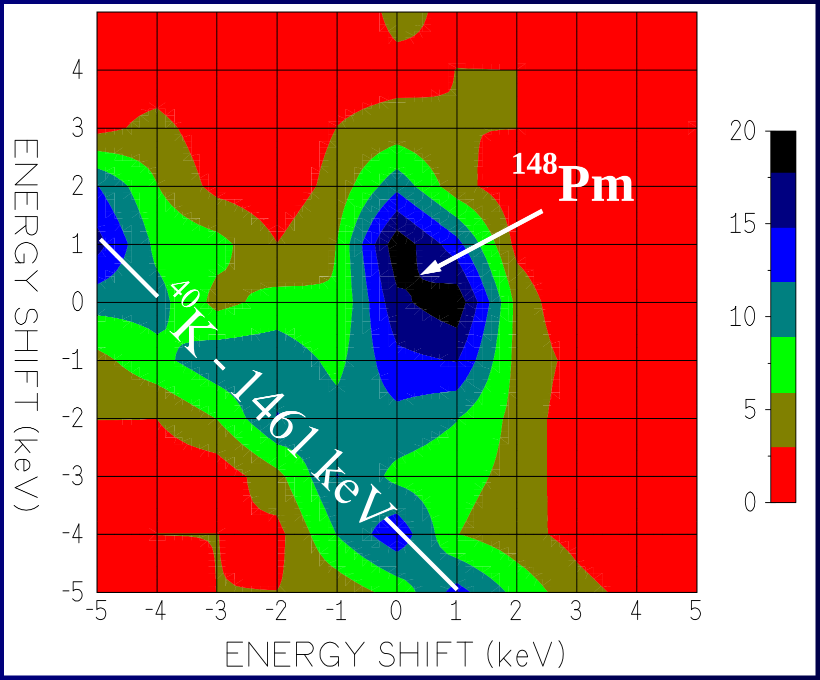
^{147}Pm sample irradiated for 12 d, induced activity counted for 20 d

⬇

individual γ-transitions from ^{148}Pm decay

coincident detection of γ-cascades



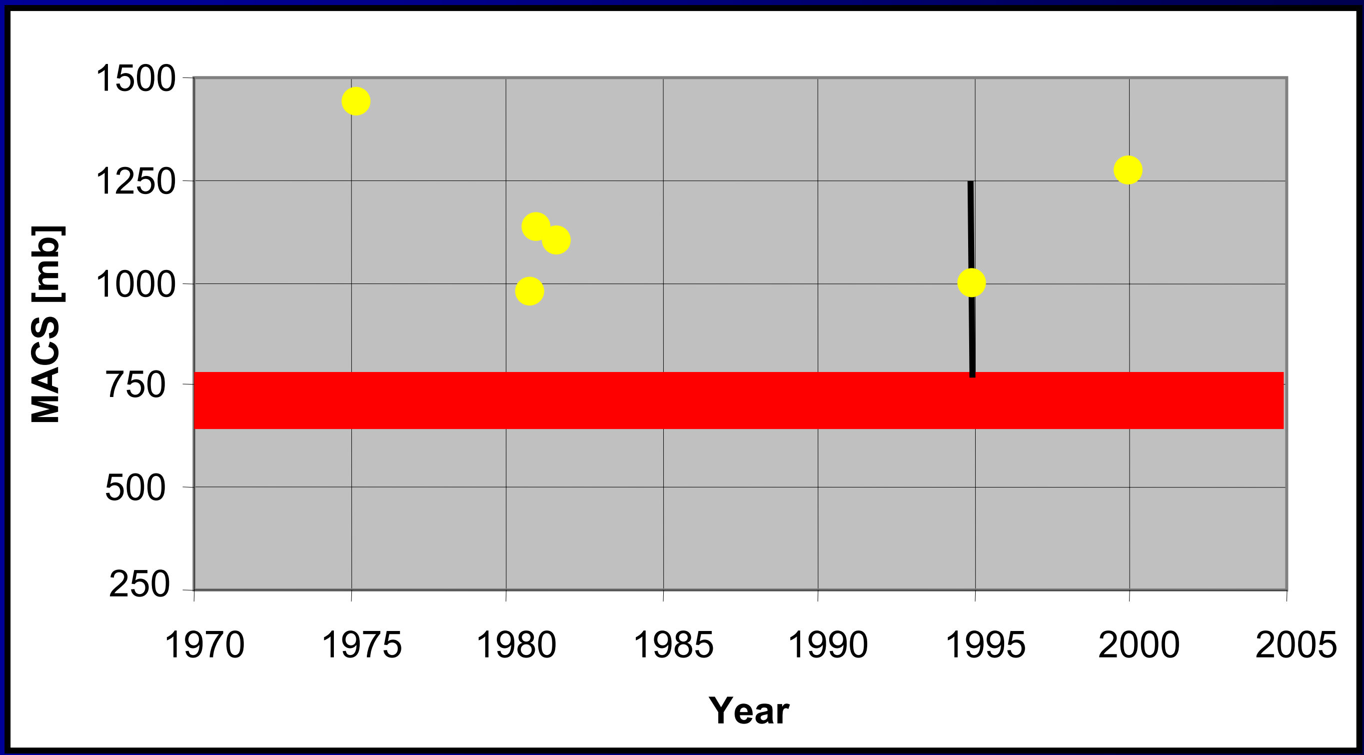


experimental results: $\sigma^g = 313 \pm 60$ mbarn, $\sigma^m = 395 \pm 55$ mbarn

$$\sigma^{tot} = 709 \pm 100 \text{ mbarn}$$

theoretical predictions (1976-2000): 938 - 2000 mbarn

^{147}Pm: comparison with calculations



- calculations (no previous measurements!)
- activation FZK 2003

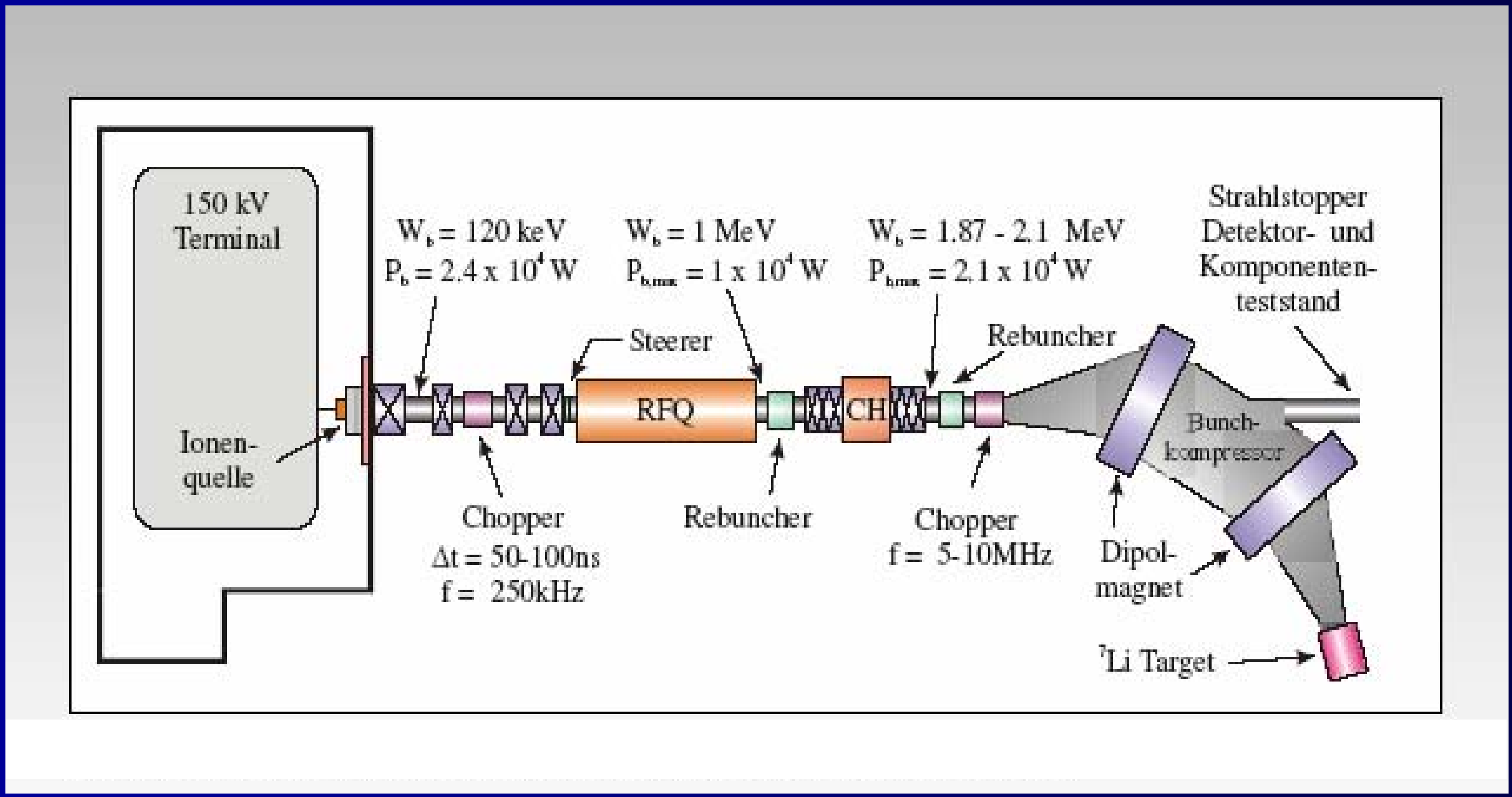
branching analysis: average neutron density $4x10^8$ cm^{-3}

activation versus TOF

Facility	Neutron flux at sample [cm^{-2} s^{-1} dec^{-1}]	Repetition rate [Hz]	Flight path [m]	Pulse width [ns]	Neutron energy range [eV]
Karlsruhe, TOF	$1 \cdot 10^4$	250K	0.8	0.7	10^3-$2 \cdot 10^5$
LANSCE	$5 \cdot 10^5$	20	20	250	th -10^5
Karlsruhe, activation	**$3 \cdot 10^9$**				10^3-$2 \cdot 10^5$

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
Frankfurt, activation	**$3 \cdot 10^{12}$**				10^3-$2 \cdot 10^5$

the Frankfurt Neutron source at the SGZ

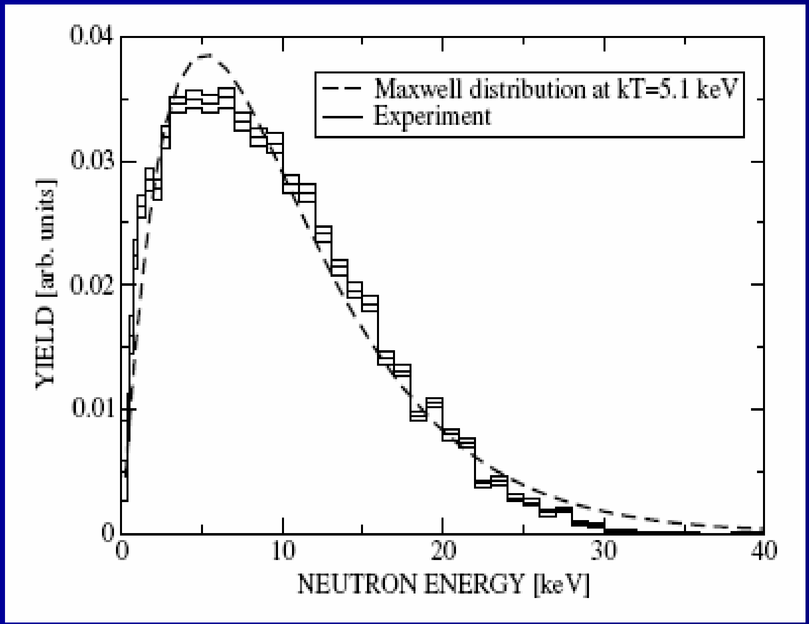


E_p = 1.9 – 2.4 MeV, Δt = 1 ns

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

more stellar spectra

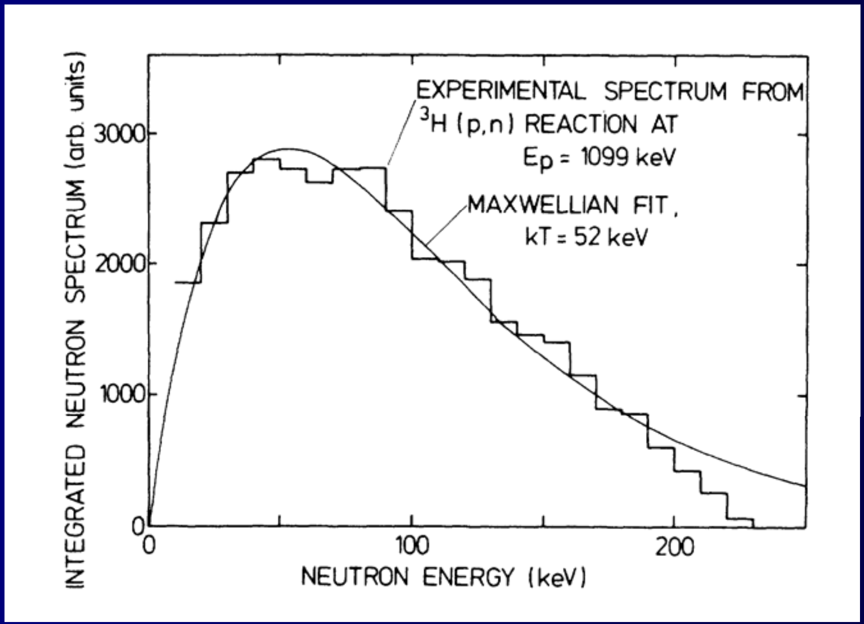
$^{18}O(p,n)^{18}F$



kT = 5.1 keV

$2 \cdot 10^5$ s^{-1} @ 100 μA

$^3H(p,n)^3He$



kT = 52 keV

$2 \cdot 10^8$ s^{-1} @ 100 μA

sample requirements

VdG and eLINAC:

TOF 50 - 1000 mg, separated isotopes

activation 10 - 100 **ng** **"natural" s**amples

spallation neutron source:

TOF/10-200m 0.5 - 5 **mg** separated isotopes

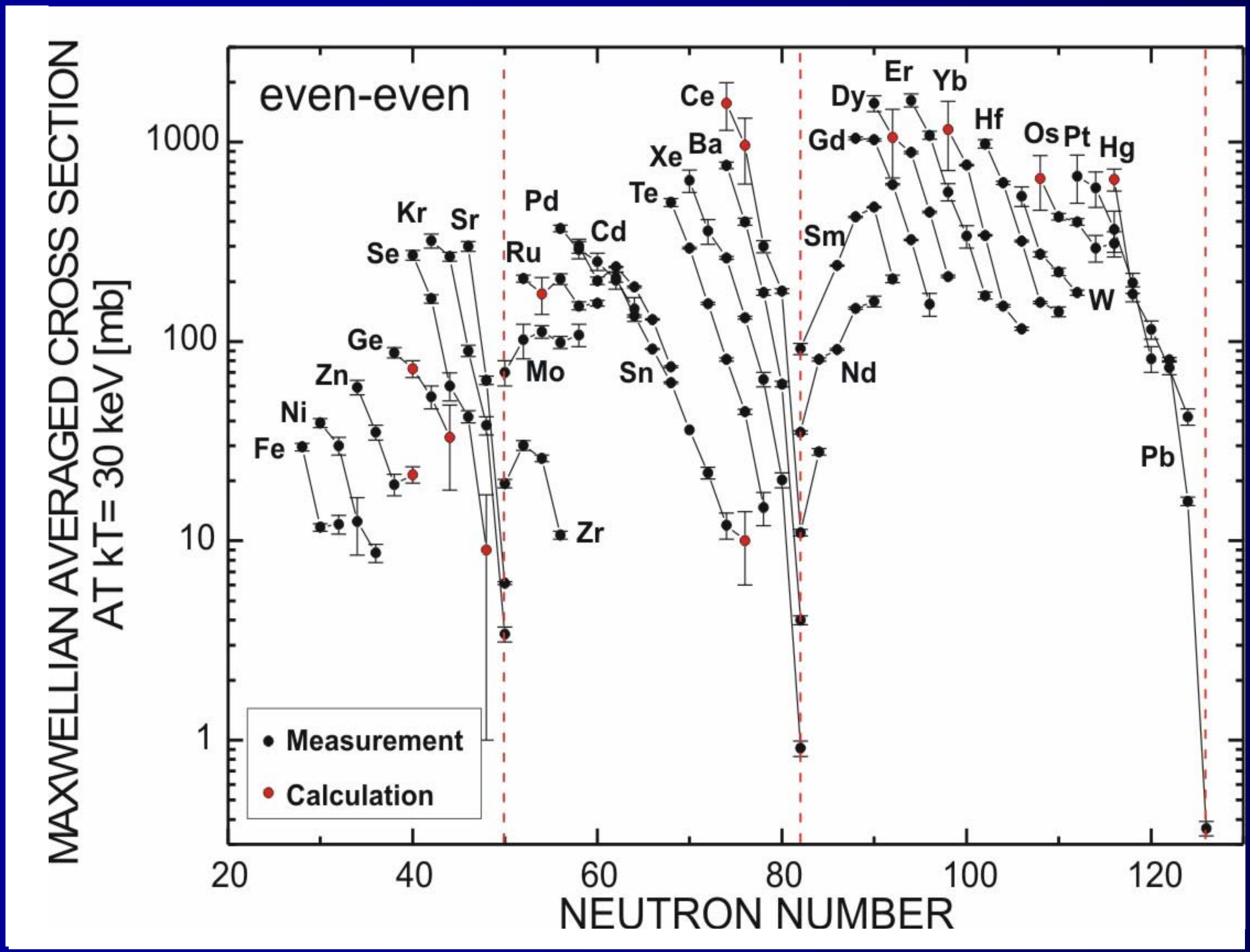
→ measurements on radioactive samples

Frankfurt:

Activation 50 – 5000 **pg** **"natural"** samples

→ measurements on short-lived samples

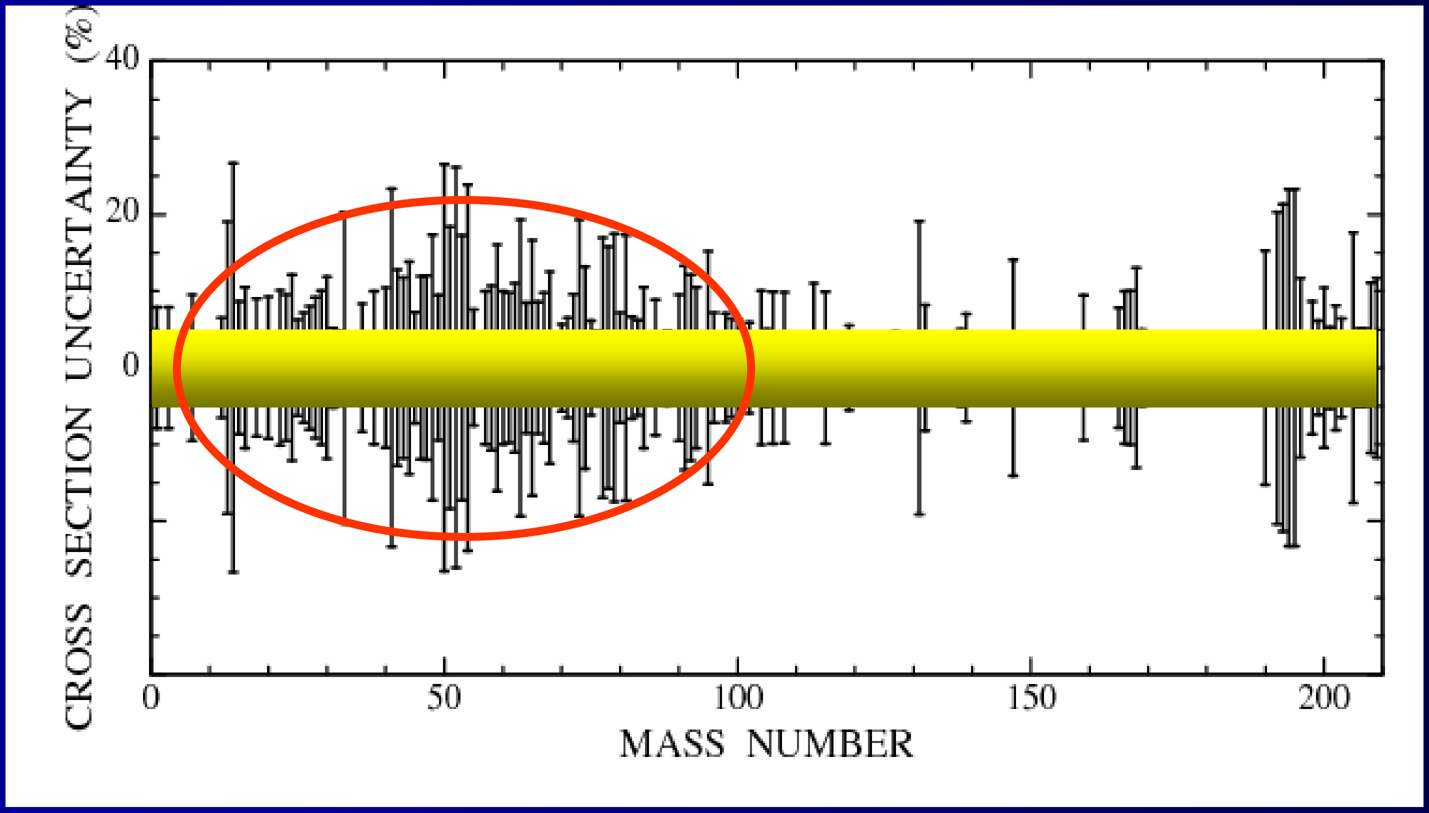
MACS data @ kT=30 keV



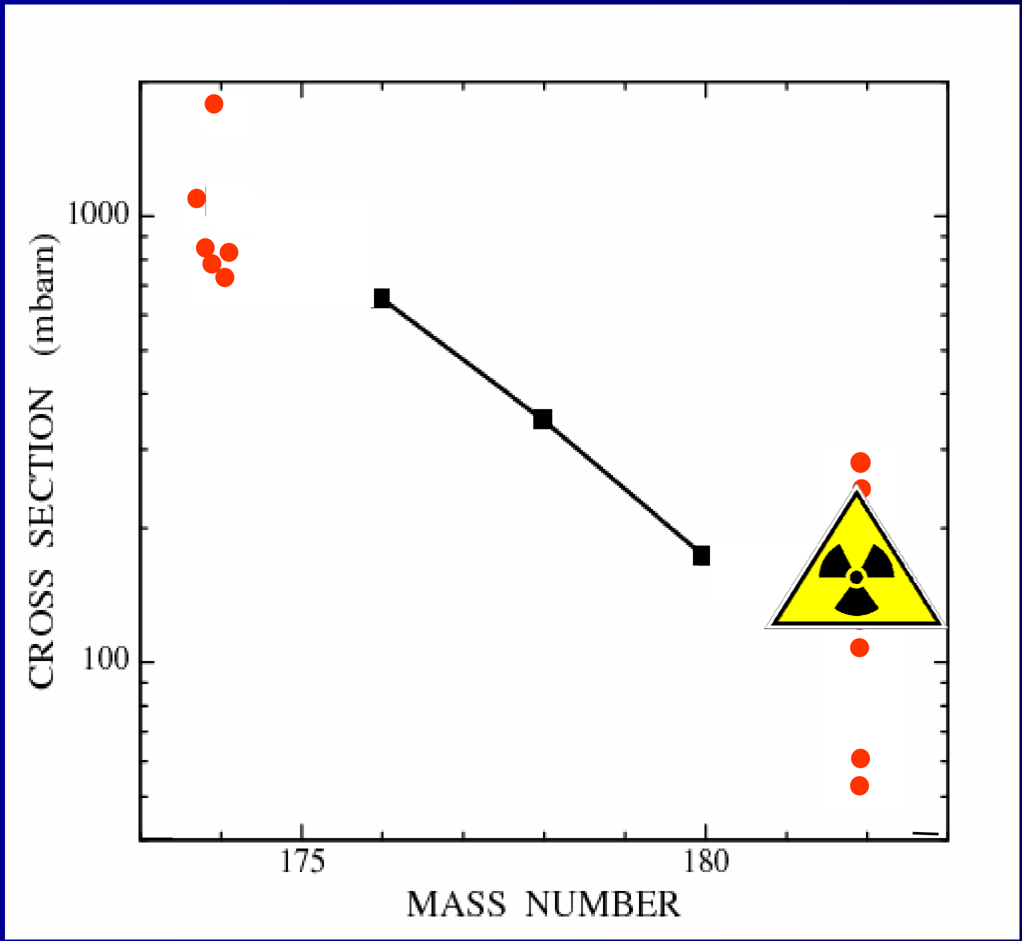
Brookhaven
CERN
Dubna
Geel
Gent
Harwell
Karlsruhe
Livermore
Los Alamos
Notre Dame
Oak Ridge
Obninsk
Rensselaer
Tokyo

status and requests

needed: cross sections with uncertainties between **1** and **5%**



what about theory?

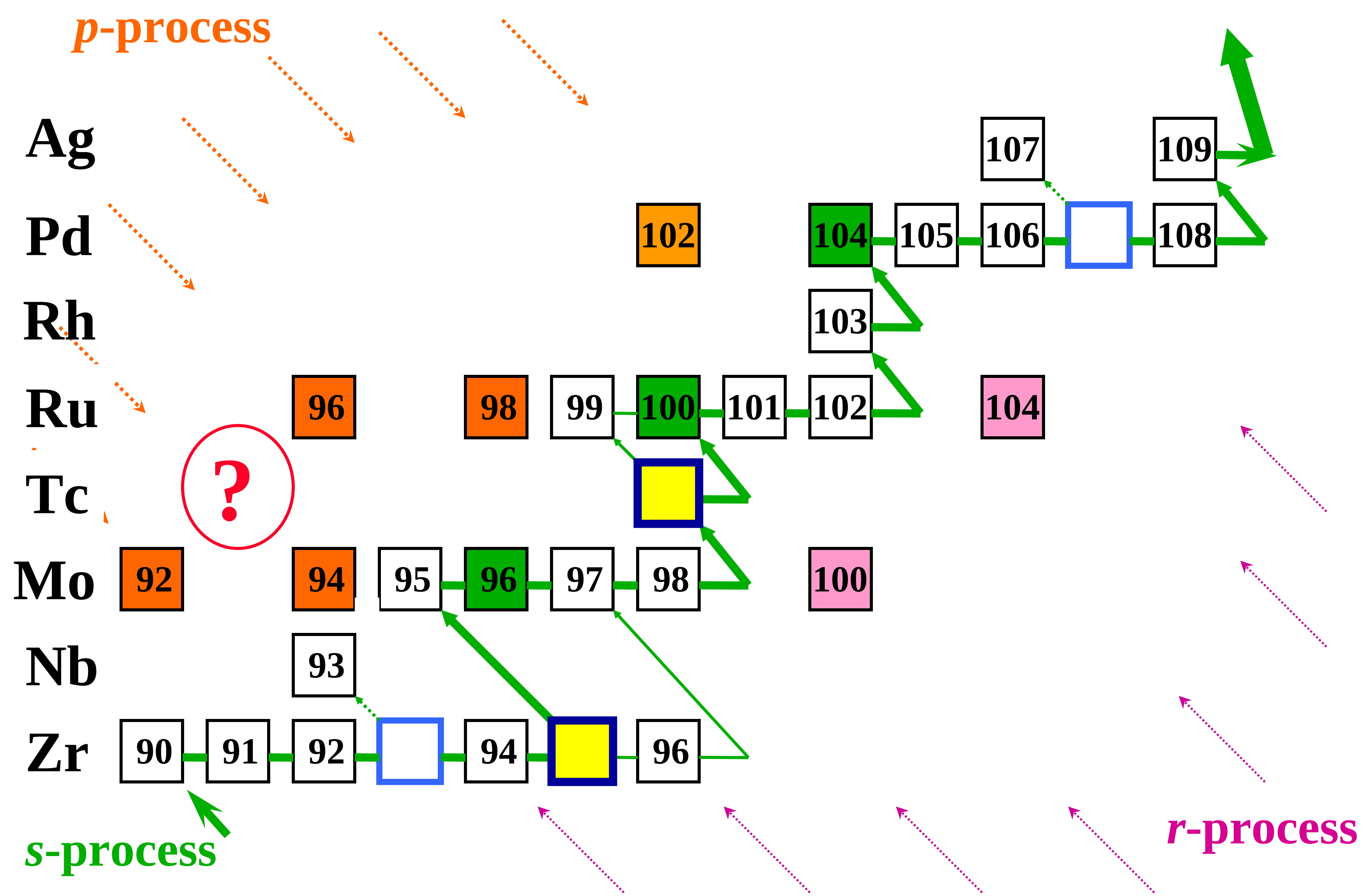


^{176}Hf, ^{178}Hf, ^{180}Hf:

MACS uncertainties

1 - 2%

exercise joined by 6 leading groups: **calculate MACS of ^{174}Hf and ^{182}Hf prior to measurement**

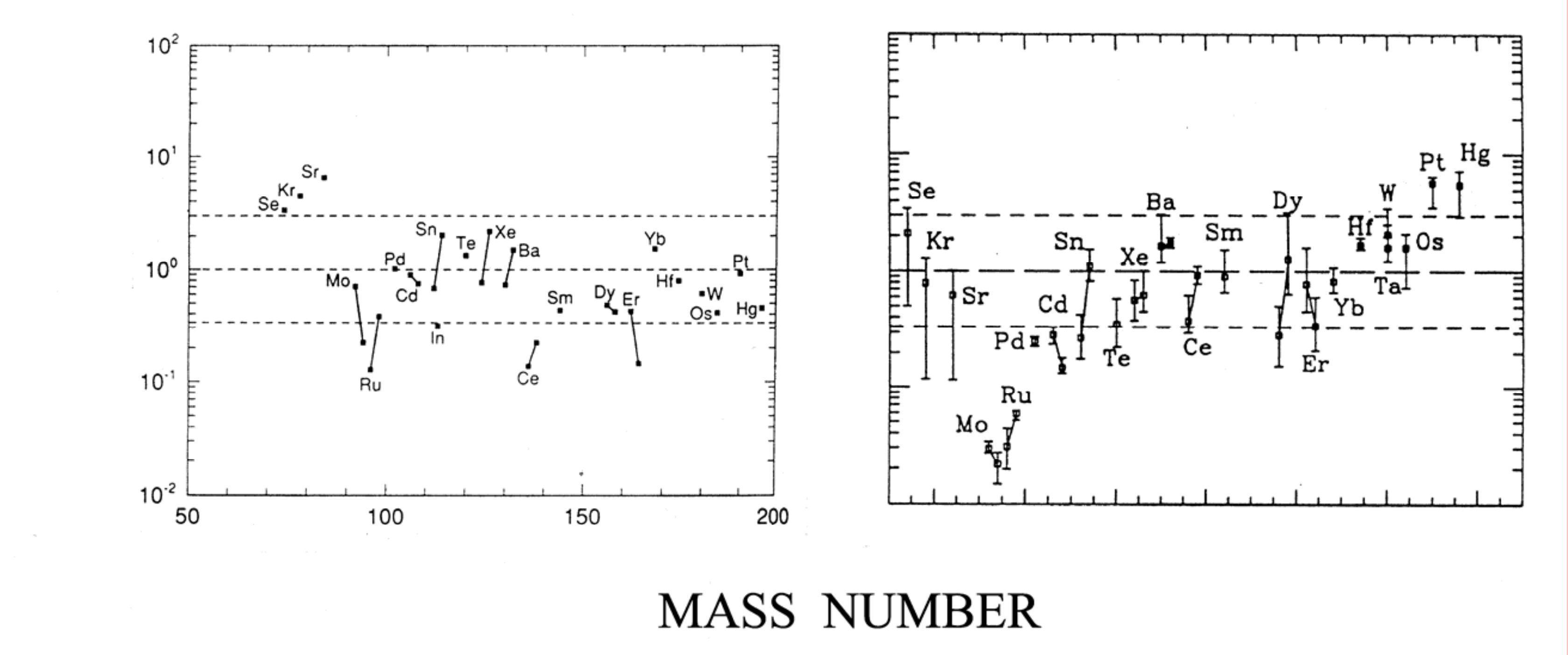


p-process
Ag
Pd
Rh
Ru
Tc
Mo
Nb
Zr
?
107
109
102
104
105
106
108
103
96
98
99
100
101
102
104
92
94
95
96
97
98
100
93
90
91
92
94
96
s-process
r-process

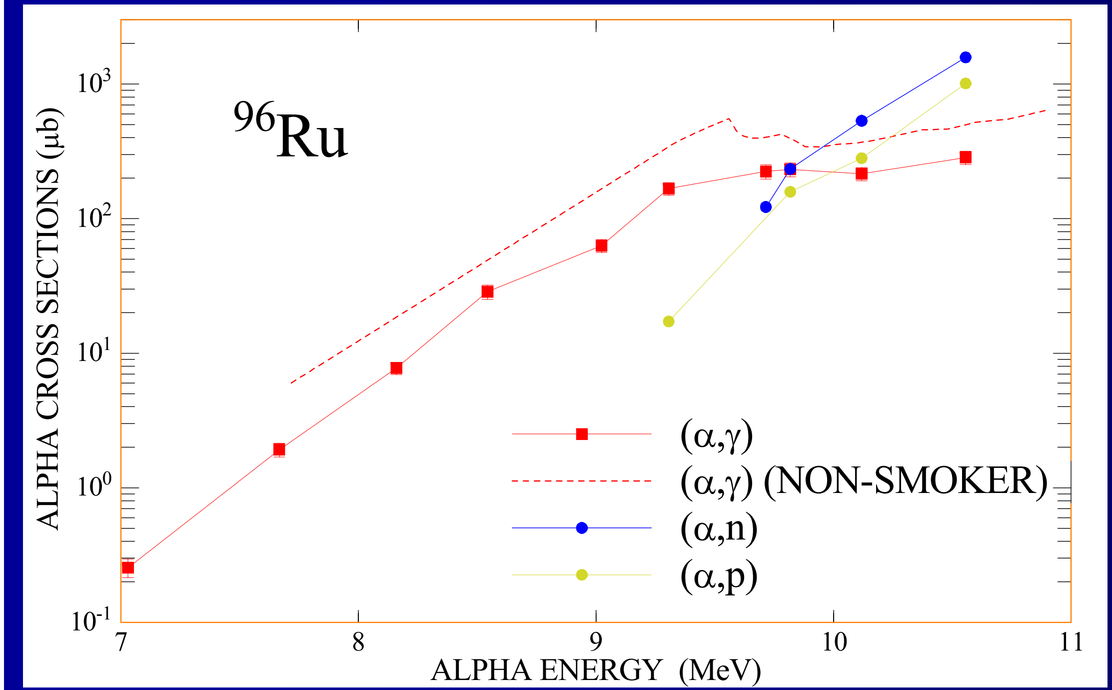
the *p*-process problem with the Mo and Ru isotopes

Howard et al., Ap. J. 309 (1991) L5

Rayet et al., A&A 298 (1995) 517



results compared to Hauser-Feshbach predictions for α-induced reactions on Ru



	EXPERIMENT / NON-SMOKER
^{96}Ru(α,γ)^{100}Pd	**0.4**
^{96}Ru(α,n)^{99}Pd	**0.3**
^{96}Ru(α,p)^{99m}Rh	(~1)
^{98}Ru(α,n)^{101}Pd	**0.4**

Hauser-Feshbach predictions for Ru much better than for ^{144}Sm:

➡ **need for data over wider mass range**

Hauser-Feshbach predictions for p- induced reactions on Ru and Mo

	EXPERIMENT / NON-SMOKER
$^{96}Ru(p,\gamma)^{97}Rh$	0.6
$^{98}Ru(p,\gamma)^{99}Rh$	2.1
$^{99}Ru(p,\gamma)^{100}Rh$	1.1
$^{104}Ru(p,\gamma)^{105}Rh$	1.4

Bork et al., PRC 58 (1998) 524

	EXPERIMENT / NON-SMOKER
$^{92}Mo(p,\gamma)^{93}Tc$	0.9
$^{94}Mo(p,\gamma)^{95}Tc$	1.6
$^{95}Mo(p,\gamma)^{96}Tc$	2.2
$^{98}Mo(p,\gamma)^{99}Tc$	0.5

Sauter and F.K., PRC 55 (1997) 3127

Hauser-Feshbach predictions for n- induced reactions on Ru and Mo

	EXPERIMENT / NON-SMOKER
$^{96}Ru(n,\gamma)^{97}Ru$	0.7
$^{100}Ru(n,\gamma)^{101}Ru$	1.0#
$^{102}Ru(n,\gamma)^{103}Ru$	1.0
$^{104}Ru(n,\gamma)^{105}Ru$	1.5

Bao et al., ADNDT (2000)

	EXPERIMENT / NON-SMOKER
$^{92}Mo(n,\gamma)^{93}Mo$	0.5
$^{94}Mo(n,\gamma)^{95}Mo$	0.7
$^{95}Mo(n,\gamma)^{96}Mo$	0.6
$^{98}Mo(n,\gamma)^{99}Mo$	1.1

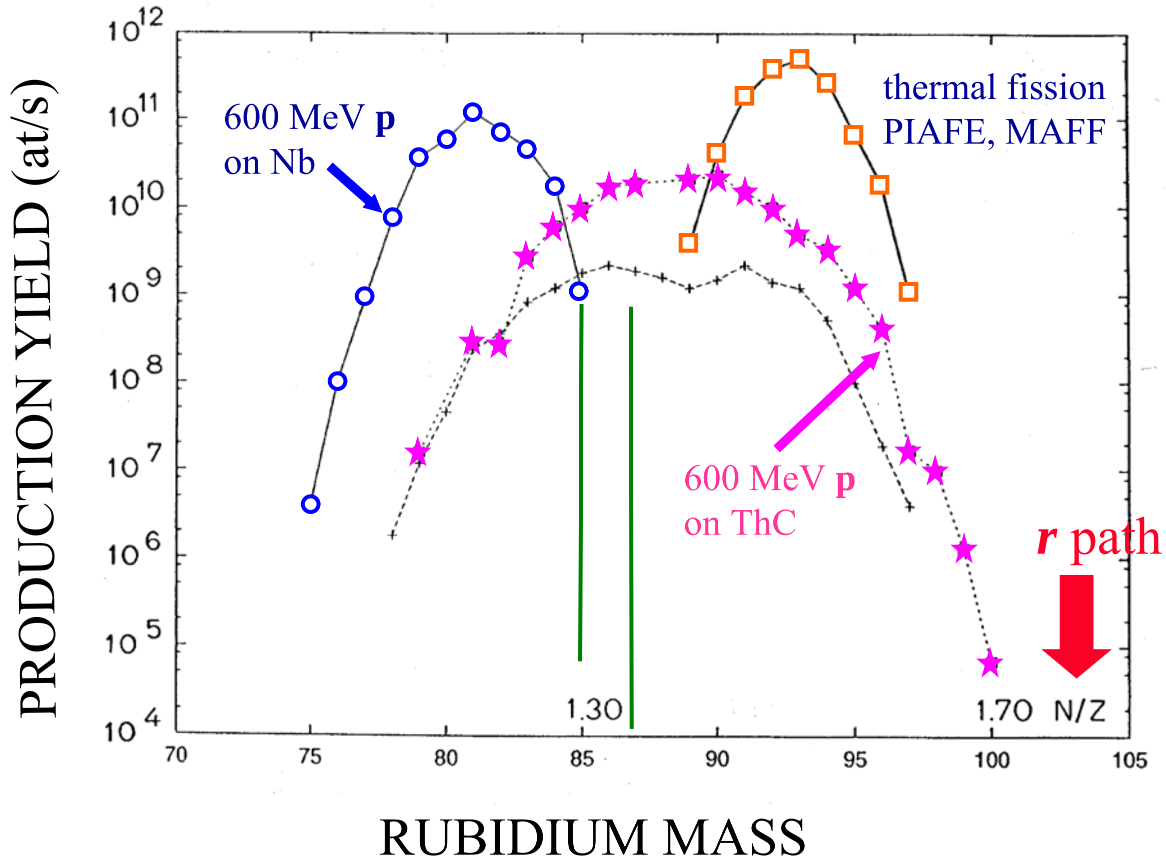
Bao et al., ADNDT (2000)

experiments on the *r*-process path

needed: half-lives, binding energies

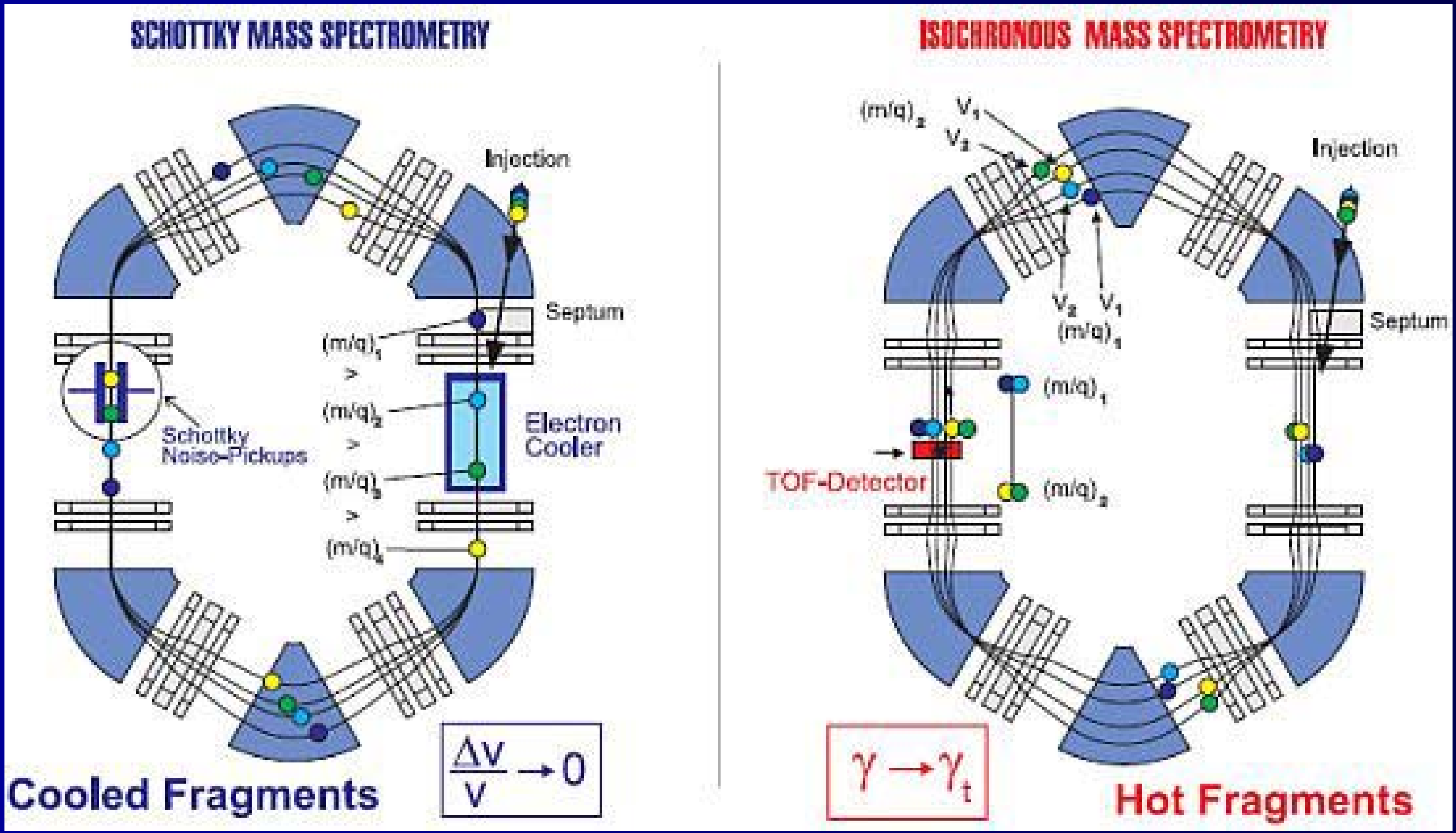
difficulties:
- production yields extremely low
- backgrounds due to isobars (mass select.), isotones (charge sel.), daughter decays

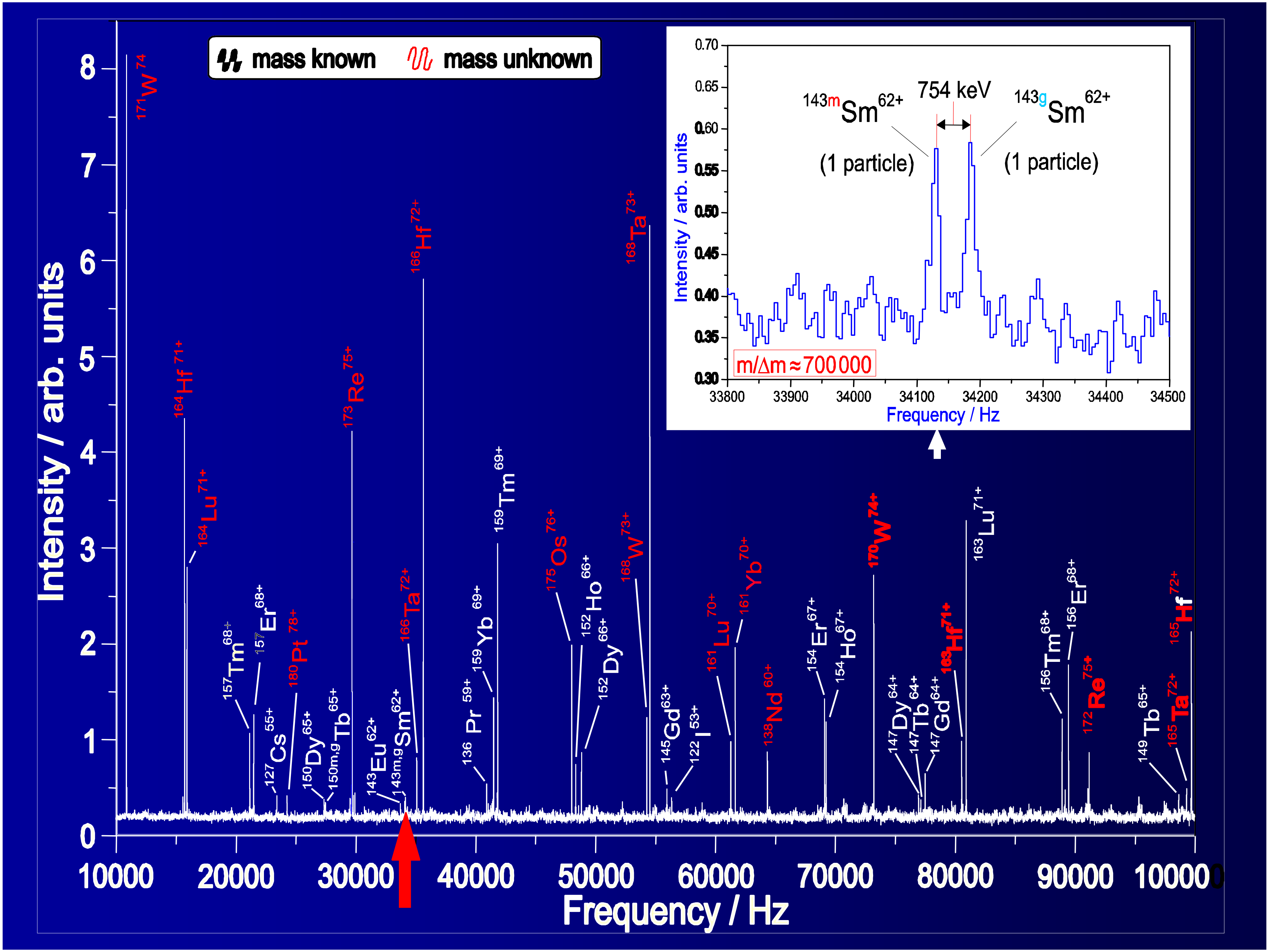
solution:
laser ion sources



the ESR @ GSI Darmstadt

needed: half-lives, binding energies





mass known
mass unknown
Intensity / arb. units
Frequency / Hz
143m Sm 62+
754 keV
143g Sm 62+
(1 particle)
(1 particle)
m/Δm≈700000
Intensity / arb. units
Frequency / Hz

waiting point half-lives

first measurements:

^{80}Zn (BNL 1986) — thermal fission, mass separator
Gill et al. PRL 56, 1874
$t_{1/2}$ = 550 ± 20 ms

^{130}Cd (CERN 1986) — 600 MeV protons on U, ISOL
Kratz et al. Z. Phys. A 325, 489
$t_{1/2}$ = 195 ± 35 ms

the struggle for **^{129}Ag**:

early predictions — $t_{1/2}$ = 172 ms (RPA calculations)
160 ms β-flow

CERN 1999 - **46 ± 10 ms**

further projects:

→ going beyond the ***r*** process path - **^{132}Cd**

→ mass measurements out to ***r*** path

summary of lecture III

- activation technique represents important complement to time-of-flight measurements
- even (n, γ) cross sections of short-lived nuclei are accessible: *s*-process branchings, freeze-out phase in explosive scenarios
- status by far not satisfactory, unceretainties too large, most branching points and vast majority of *p*- and *r*- process regions not covered
- significant progress to be expected from high flux at new facilities and improved detection techniques