Impact of atomic charge state on stellar nucleosynthesis

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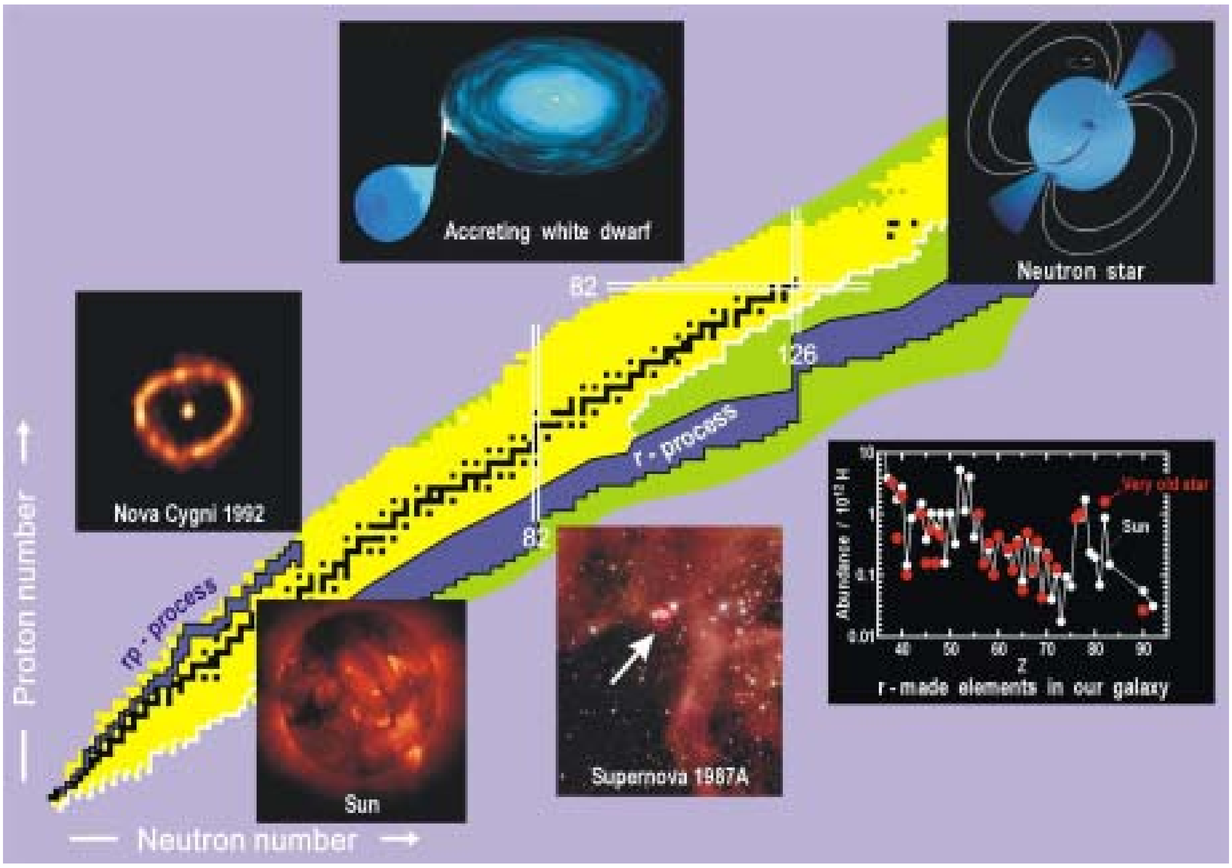


1. **Stellar nucleosynthesis (besides fusion) driven by neutron (proton) capture, β^- and β^+ decay at high temperatures = high atomic charge states**

2. **masses and β lifetimes determine pathway of nucleosynthesis and abundance of elements**

3. **β^-, β^+ lifetimes depend on atomic charge state**

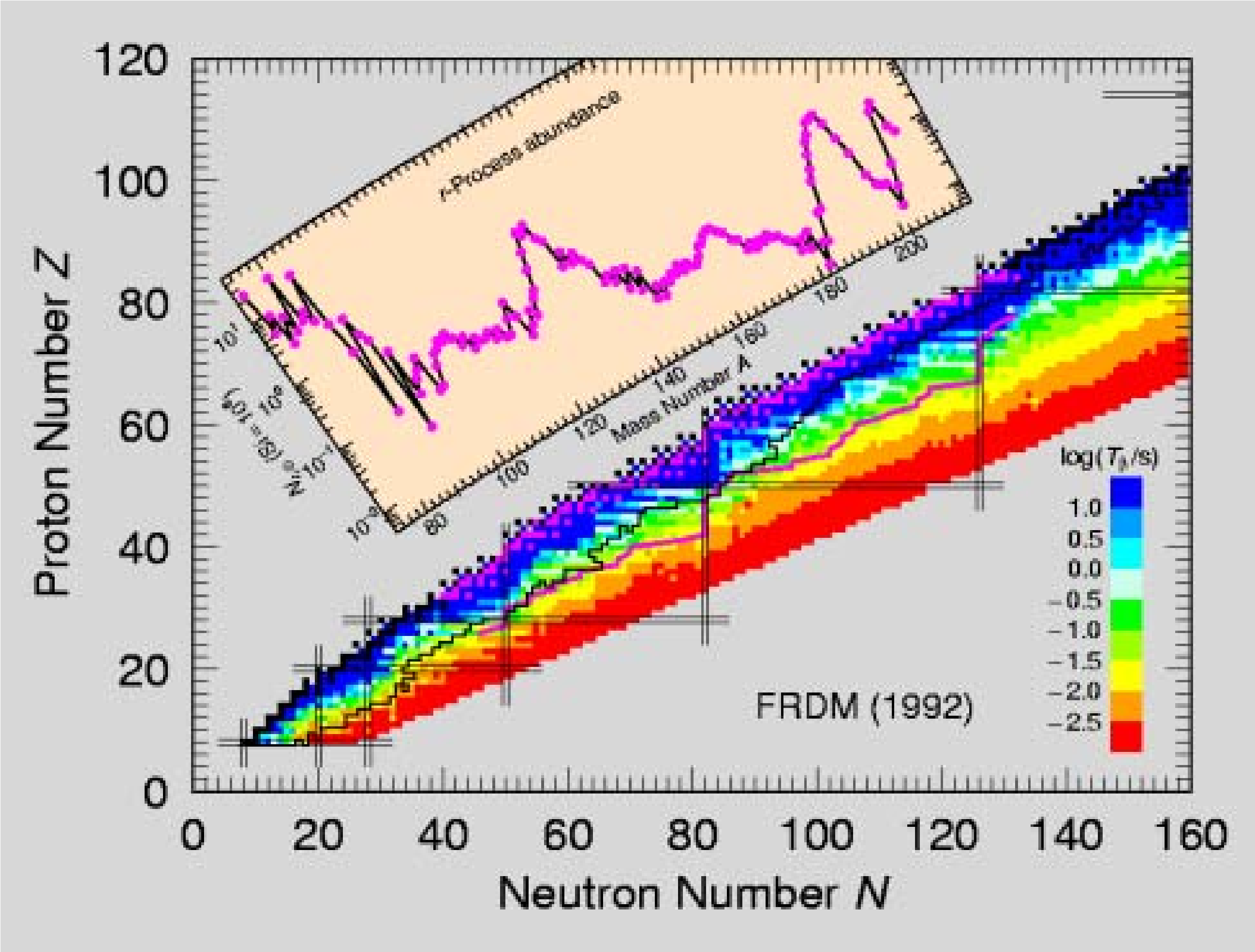
4. **storage rings only tools to measure β decay of HCI**

Explosive nucleosynthesis (r, rp)

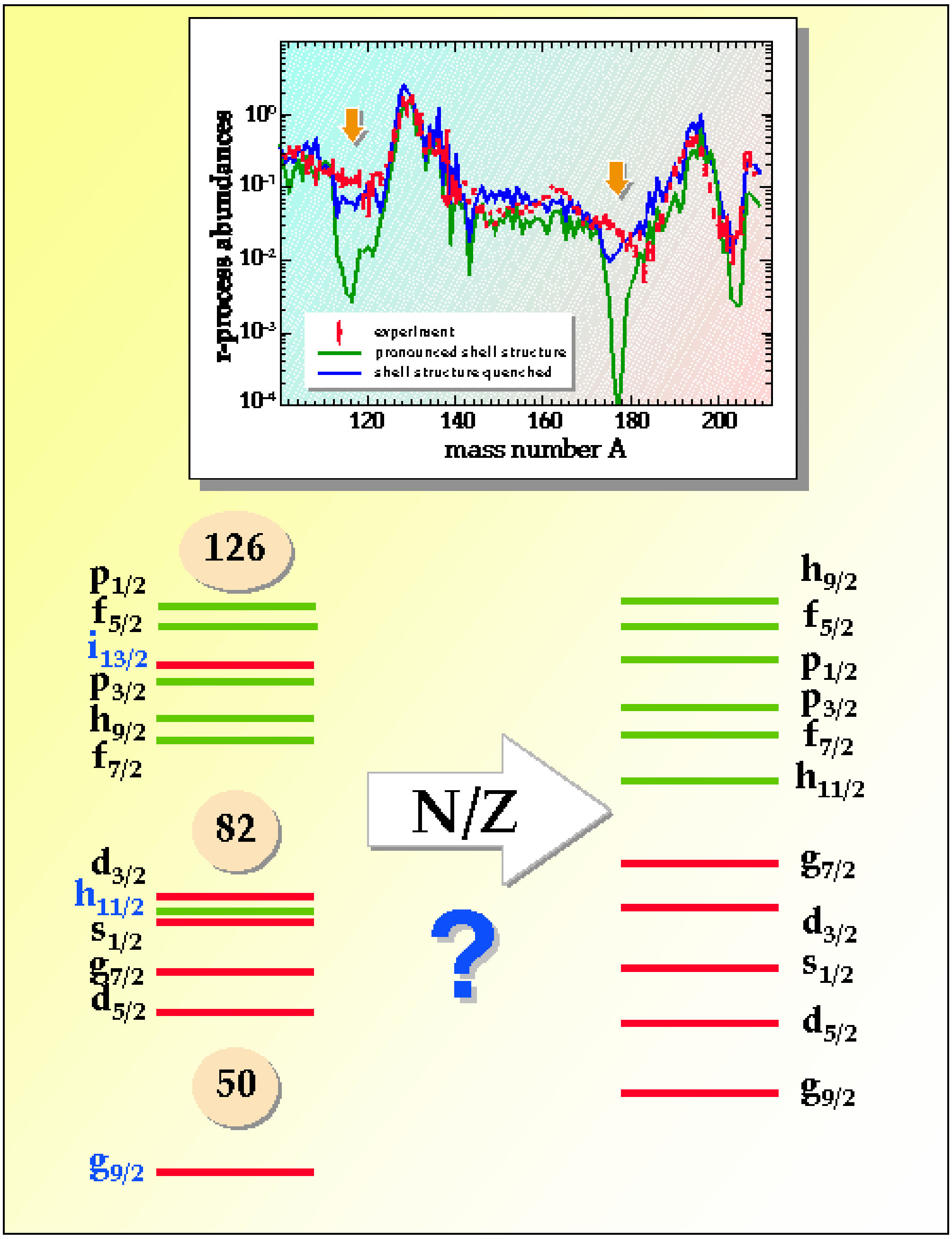
not yet understood

r-process(es): rapid neutron capture

one or several, site, pathway?



→ **abundance of heavy elements in our solar system**

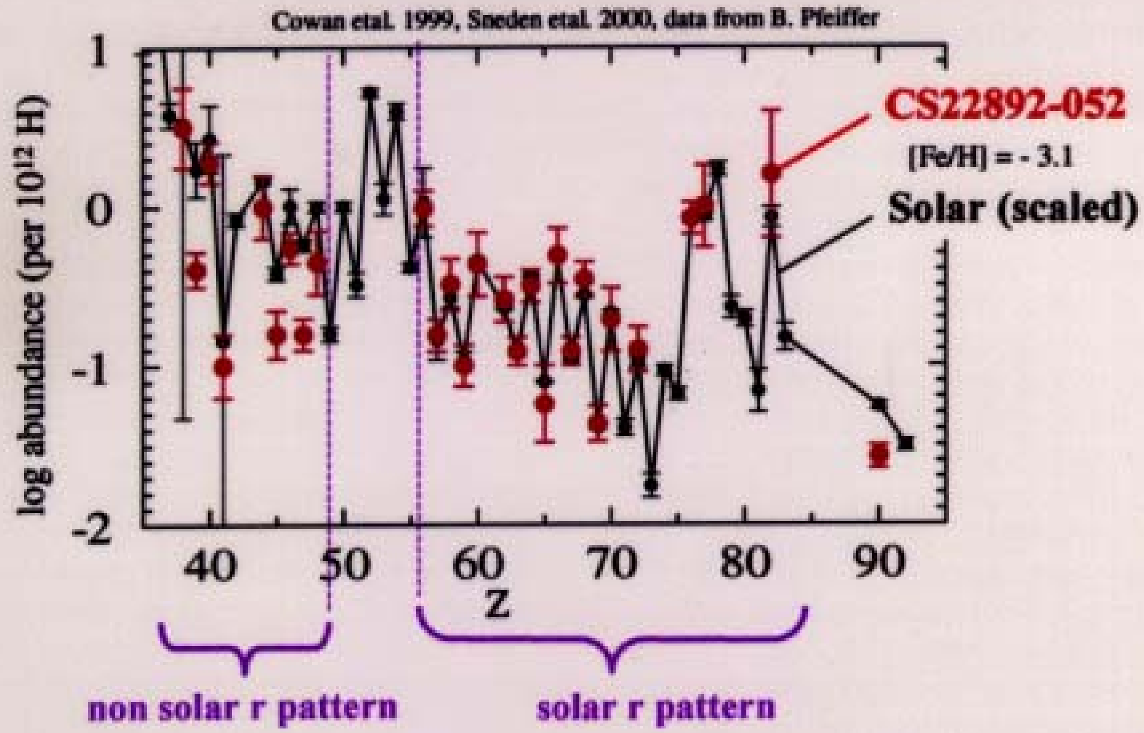


Entanglement of nuclear structure and nucleosynthesis in the r-process
Quenching of shell gaps?

→ produce neutron-rich, highly charged atoms and measure their ground state properties: masses and β^- lifetimes

Ultra metal poor halo stars

A window into the composition of the galaxy at age 0.1-0.7 Gyrs

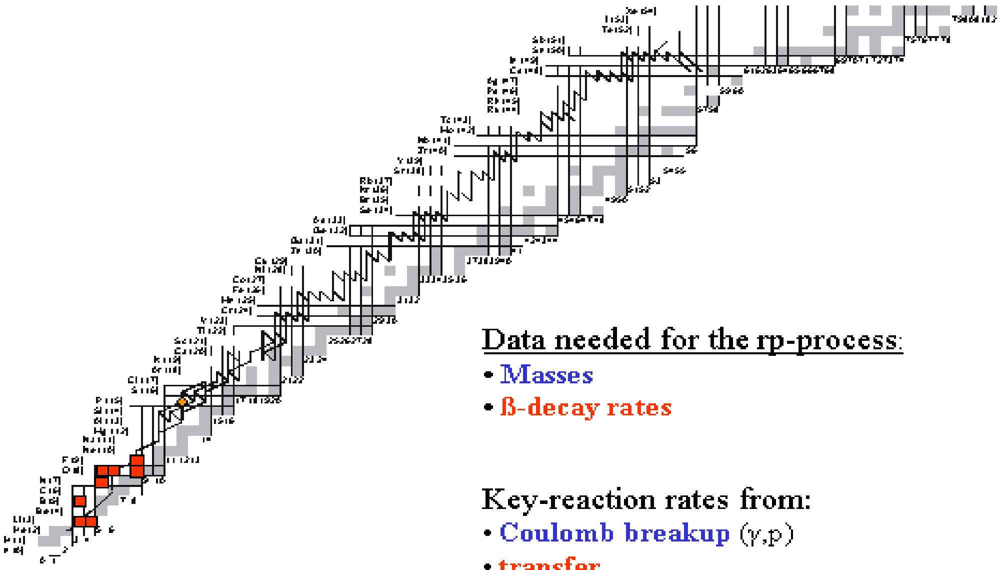


Open questions:

? What are these r process events ?

Two r processes ?

The rp-process



■ Previous Coulomb-breakup experiments

Data needed for the rp-process:

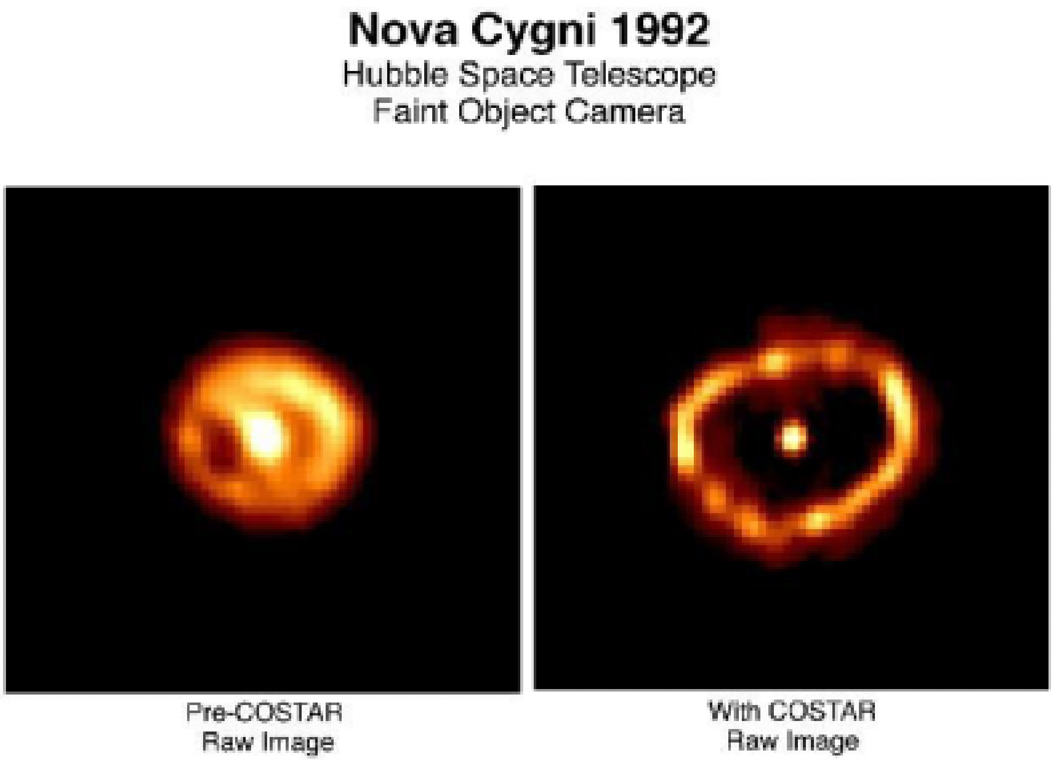
- Masses
- ß-decay rates

Key-reaction rates from:

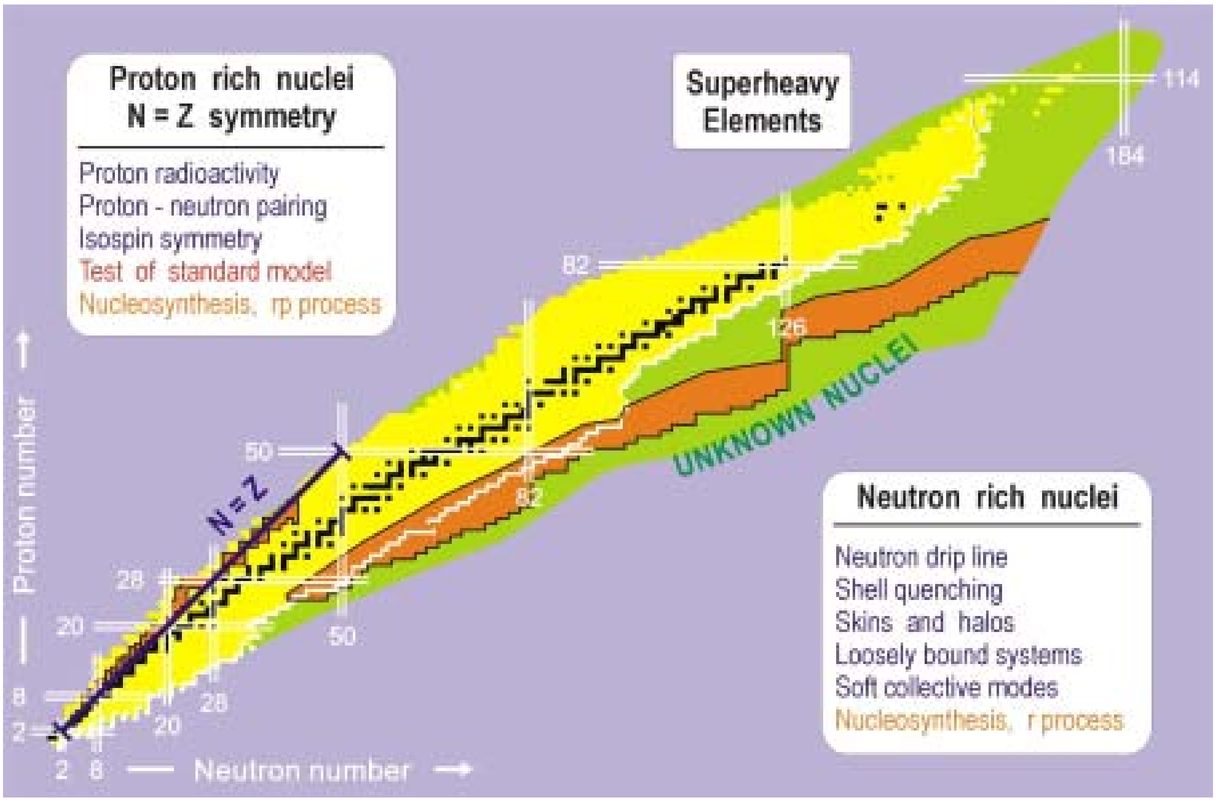
- Coulomb breakup (γ,p)
- transfer
- 2p-captures

rp (rapid proton capture) -process:
explosive H-burning on the surface of mass accreting white dwarfs at high T

ground state properties of p-rich, highly-charged atoms:
masses and β^+ lifetimes



Nova outburst signals explosive H burning up to tin along the proton dripline via p-capture, p-decay, β^+ decay



Why and how ß lifetimes depend on atomic charge state

a) orbital electron capture EC: $\lambda_{EC} = f(n_{eb})$

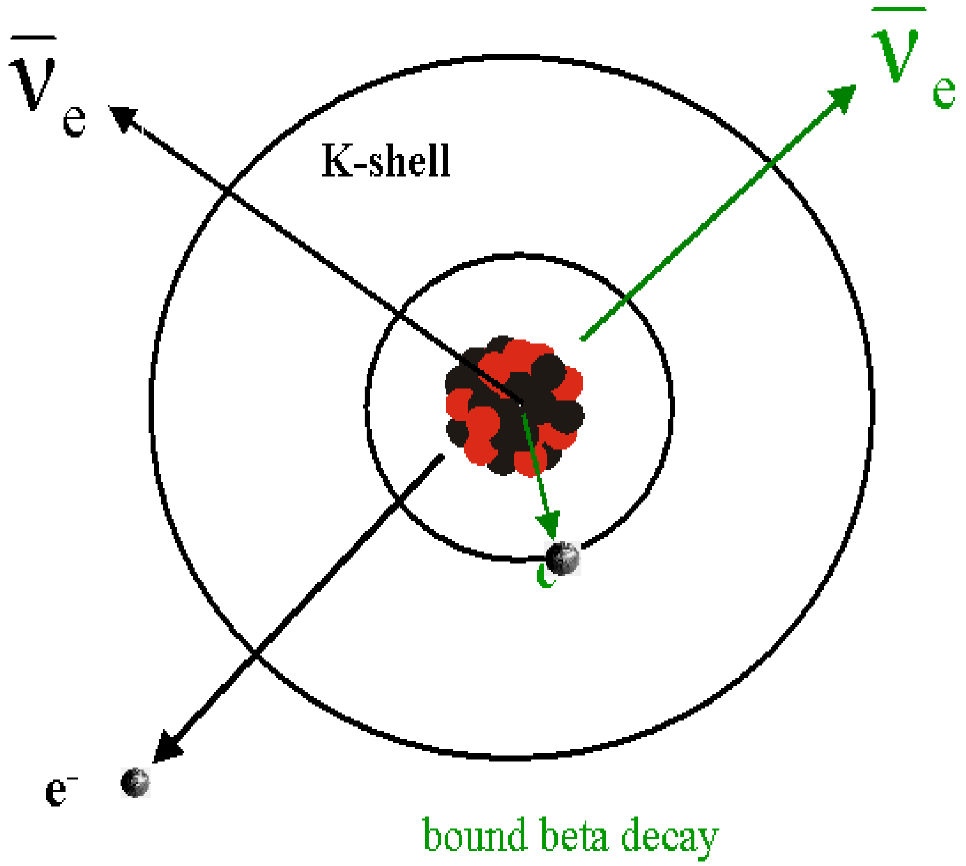
$$p + e_b \rightarrow n + \nu_e$$

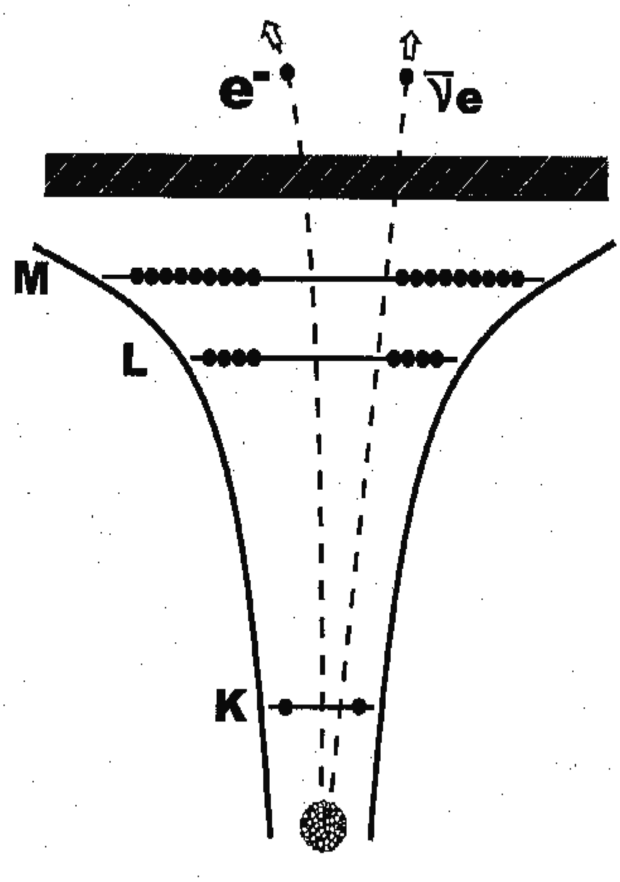
if $Q_{EC} < 2\ m_e c^2$ atom gets stable for $n_{eb} = 0$

b) bound beta decay β_b = time-mirrored EC

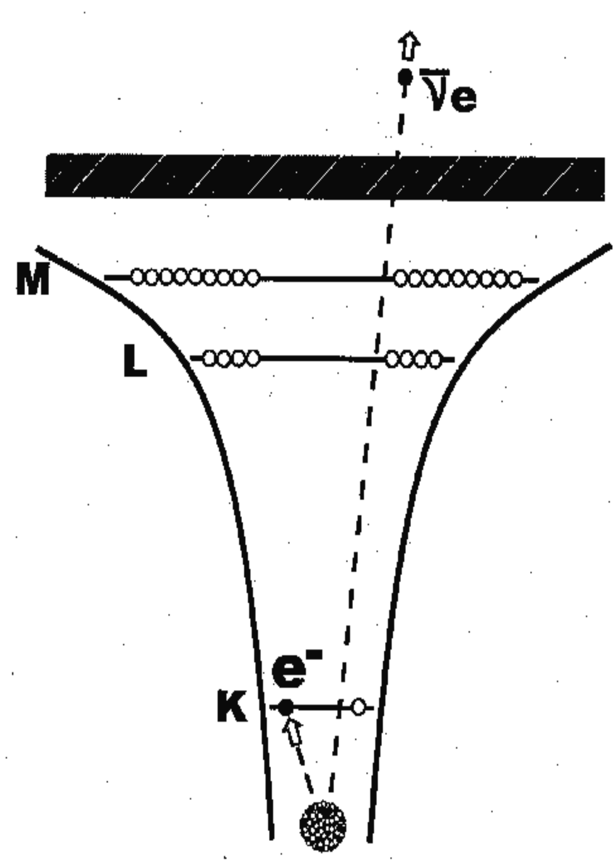
$$n + \nu_e(\text{bar}) \rightarrow p + e_b$$

if inner shell vacancies available





β_c



β_b

Q value larger
by e^- binding energy

decay probability $\lambda_{\beta b} > \lambda_{\beta c}$

stable neutral atoms get unstable

if $Q(\text{neutral}) < |E_b(K)|$

The couple $^{163}Dy/^{163}Ho$ ($^{205}Tl/^{205}Pb$, $^{193}Ir/^{193}Pt$,...)

a) neutral atoms (on earth)

$^{163}Ho^{0+}$

$T_{1/2} = 4570$ y

$Q_{EC} = +\,2.6$ keV

$^{163}Dy^{0+}$

$T_{1/2} = \infty$

b) bare nuclei in stellar plasma

Cont.

$^{163}Dy^{66+}$

$T_{1/2} = 47$ d

L

$Q^{K}_{\beta b} = +\,50$ keV

$^{163}Ho^{66+}$ K

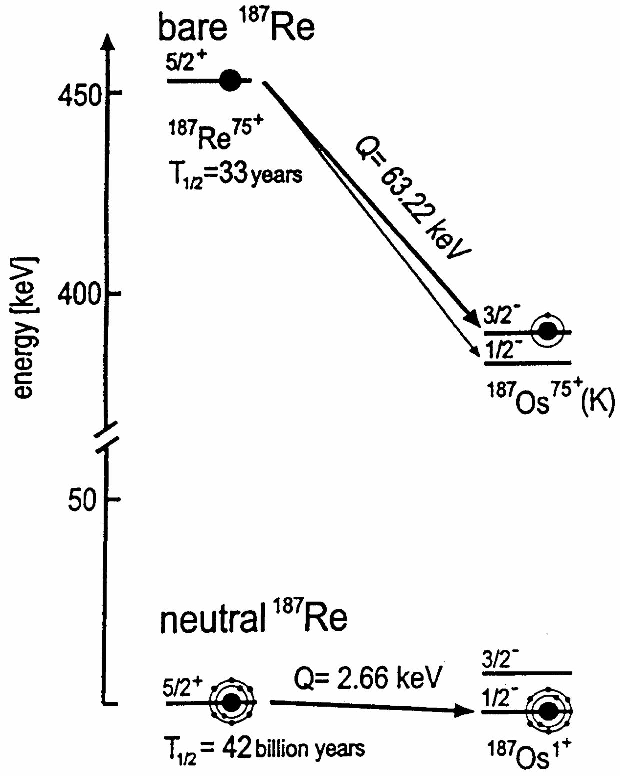
$T_{1/2} = \infty$

$$Q^{K,L}_{\beta b} = -\,Q_{EC} - \Delta B_e + B_{K,L}$$

$-\,2.6$	$-\,12.5$	$+\,65.1$	$= +\,50$ keV (K)
		$+\,16.3$	$\approx +\,1$ keV (L)

The couple $^{187}Re/^{187}Os$ ($^{205}Tl/^{205}Pb$,...)

β_b decay goes to an excited state, forbidden in β_c



β_b decay provides

first possibility to measure the

branching ratio $\lambda_{\beta b}$ / $\lambda_{\beta c}$

for the *same* nuclear transition

$$\lambda_{\beta b} / \lambda_{\beta c} = [Q_{\beta b}/Q_{\beta c}]^2 \; \psi(0)^{2} / f(Z, W_0)$$

$\Rightarrow$ ***Fermi function $f(Z,W_0)$***
for β^- decay

still missing complement to the well known
Fermi function for β^+ decay from
$\lambda_{\beta+} / \lambda_{EC}$

c) internal conversion IC (isomers)

for high multipolarities (E4, M4...) IC large

lifetime much longer (10,...10^6) without e_b

neutral $^{193}Ir^{0+}$

$T_{1/2}$ = 10 d ______________________ $^{193}Ir^{*0+}$ $11/2^-$ E = 80 keV

M4

______________________ $^{193}Ir^{0+}$ $3/2^+$

bare $^{193}Ir^{77+}$

$T_{1/2} > 10^3$ y ______________________ $^{193}Ir^{*77+}$

M4 (no e_b)

______________________ $^{193}Ir^{77+}$

s (slow neutron capture)- process:

Z |→|→|→|
|→|→|
|→|→| N

near the valley of stability: n-capt. / β^- decay

β^- decay for $T_{1/2}(\beta) \leq$ 1 year

neutron density $\approx 10^8$ cm^{-3}

electron density $\approx 10^{27}$ cm^{-3}

temperature $T_S \approx 3 \cdot 10^8$ K, kT $\approx$ 30 keV

(n, γ)- (γ,n) equilibrium

$$\Rightarrow \quad N_{(A)} * \sigma_n(A) = N_{(A+1)} * \sigma_n(A+1)$$

branching points induced by $\beta_b = f(T_S)$

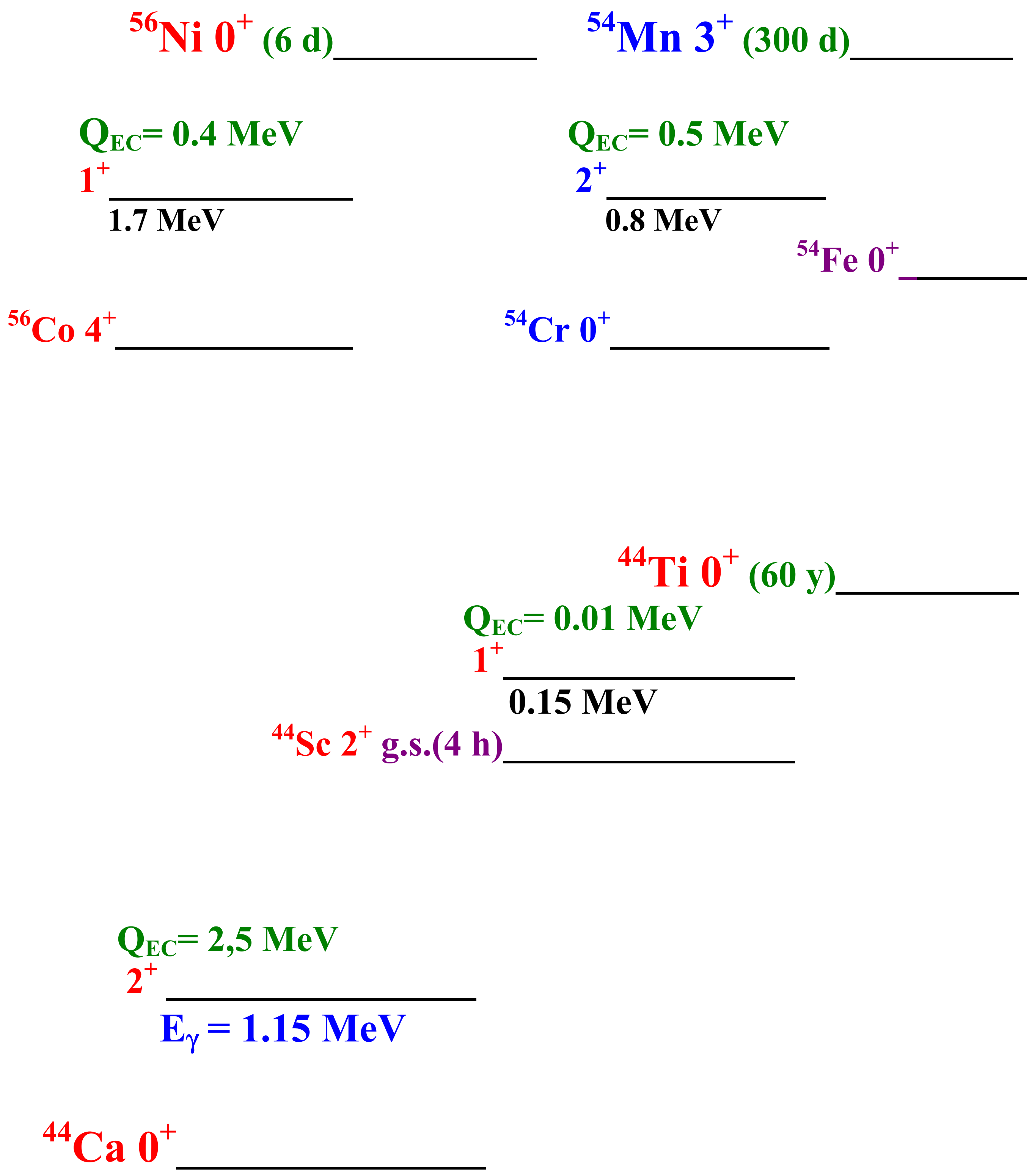
$$\lambda^* / \lambda^0 > 1 \quad \Rightarrow \quad T_S$$

$_{68}$Er 164→ →
$_{67}$Ho 163→ • → →
$_{66}$Dy 162→ • → →

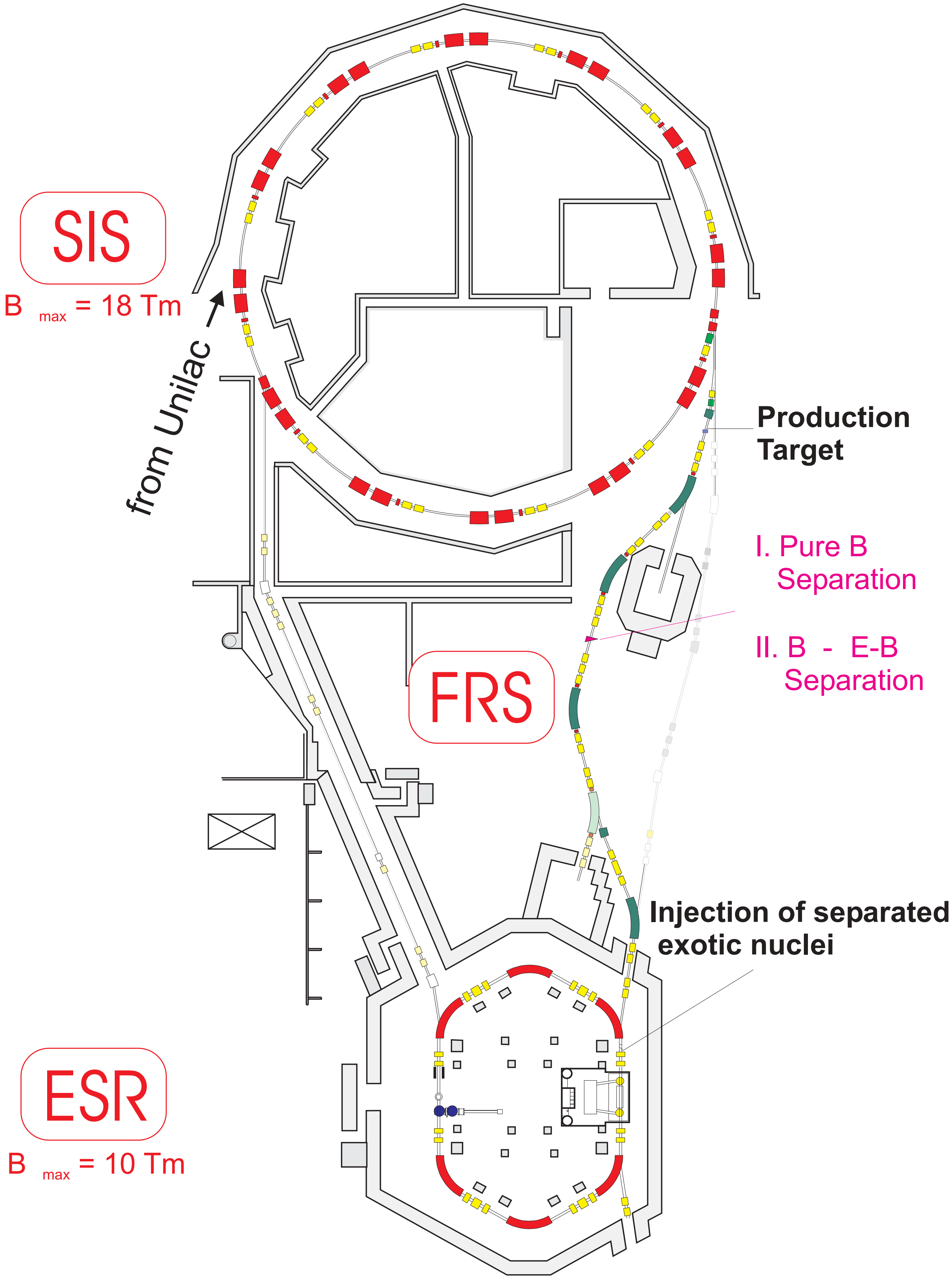
other example: ^{205}Tl (stable); $^{205}Tl^{81+} \rightarrow (\beta_b)$ $^{205}Pb^{81+*}$ ($T_{1/2}$ = 1 y?)

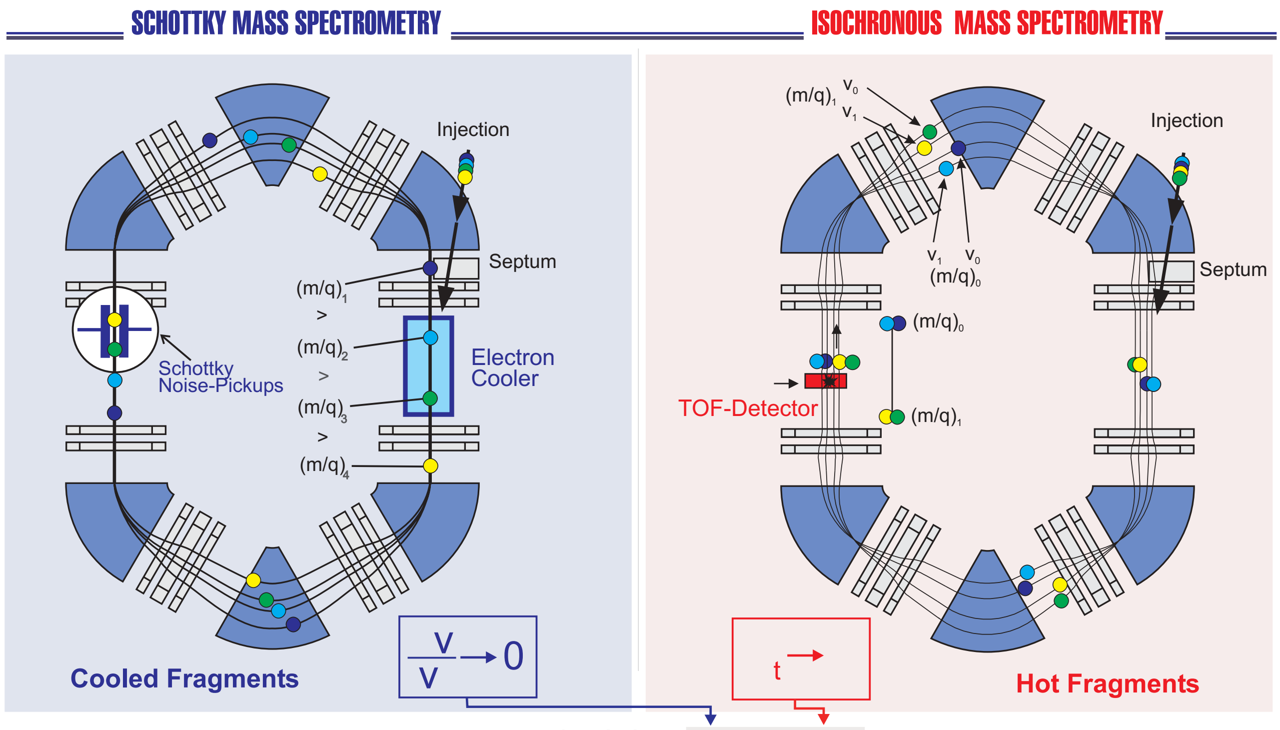
key-nuclei: Supernova outbursts, galactic cosmic rays

^{56}Ni, ^{54}Mn, $^{44}Ti/^{44}Ca$

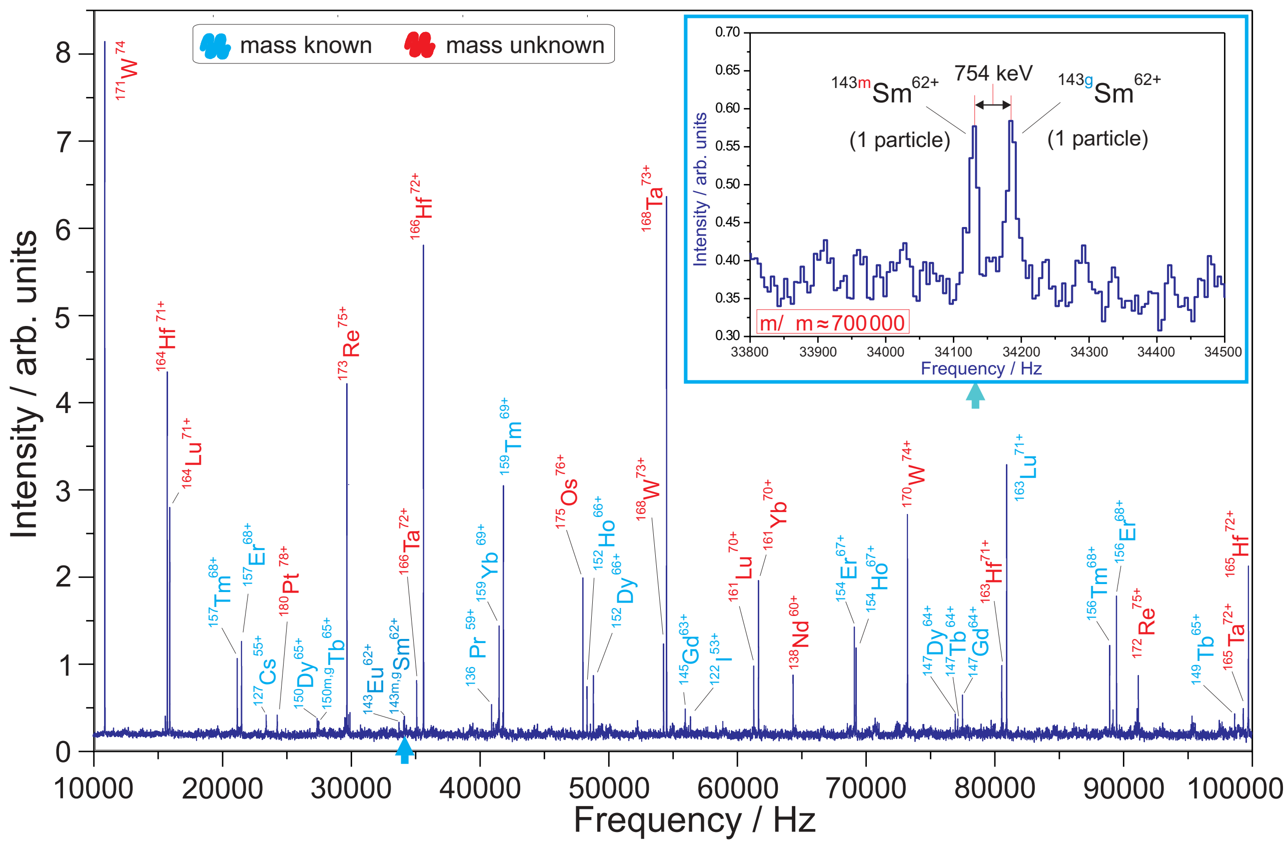


Mass and Lifetime Measurements of Stored Exotic Nuclei





$$\frac{\Delta f}{f} = -\frac{1}{\gamma_t^2}\frac{\Delta (m/q)}{m/q} + \frac{\Delta v}{v}\left(1-\frac{\gamma^2}{\gamma_t^2}\right)$$



Principle of Lifetime Measurements for Cooled Fragments

$\xrightarrow{\text{projectiles}}$ **FRS** $\xrightarrow{\text{fragments}}$ **ESR** $\longrightarrow$ Schottky Sp.

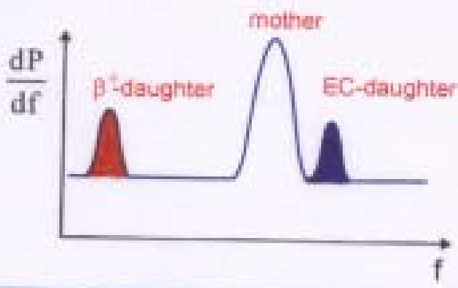
$$\beta_c^-: \quad \frac{A}{q} \rightarrow \frac{A-Q}{q+1}$$

$Q \gtrsim 1$ MeV

For $Z \geq 28$ both are circulating within the acceptance of the ESR

$$\beta^+: \quad \frac{A}{q} \rightarrow \frac{A-Q}{q-1}$$

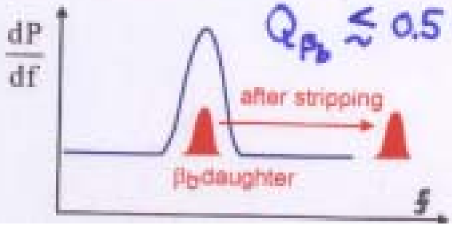
$$EC: \quad \frac{A}{q} \rightarrow \frac{A-Q}{q} \qquad q < Z$$



$$\beta_b^-: \quad \frac{A}{q} \rightarrow \frac{A-Q}{q}$$

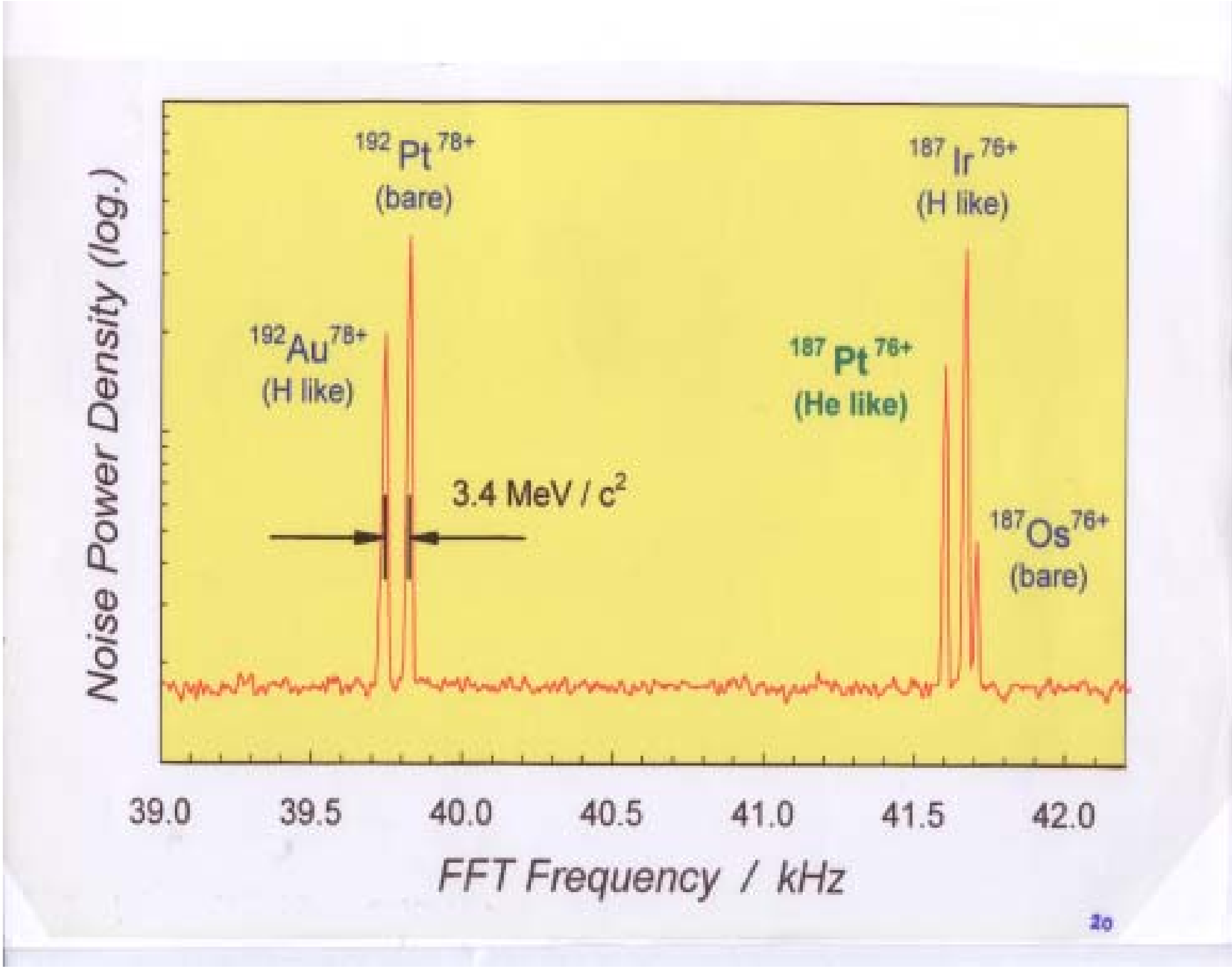
$Q_{\beta^+} >> Q_{EC}$ [redacted]

$Q_{\beta_b} \lesssim 0.5$ MeV

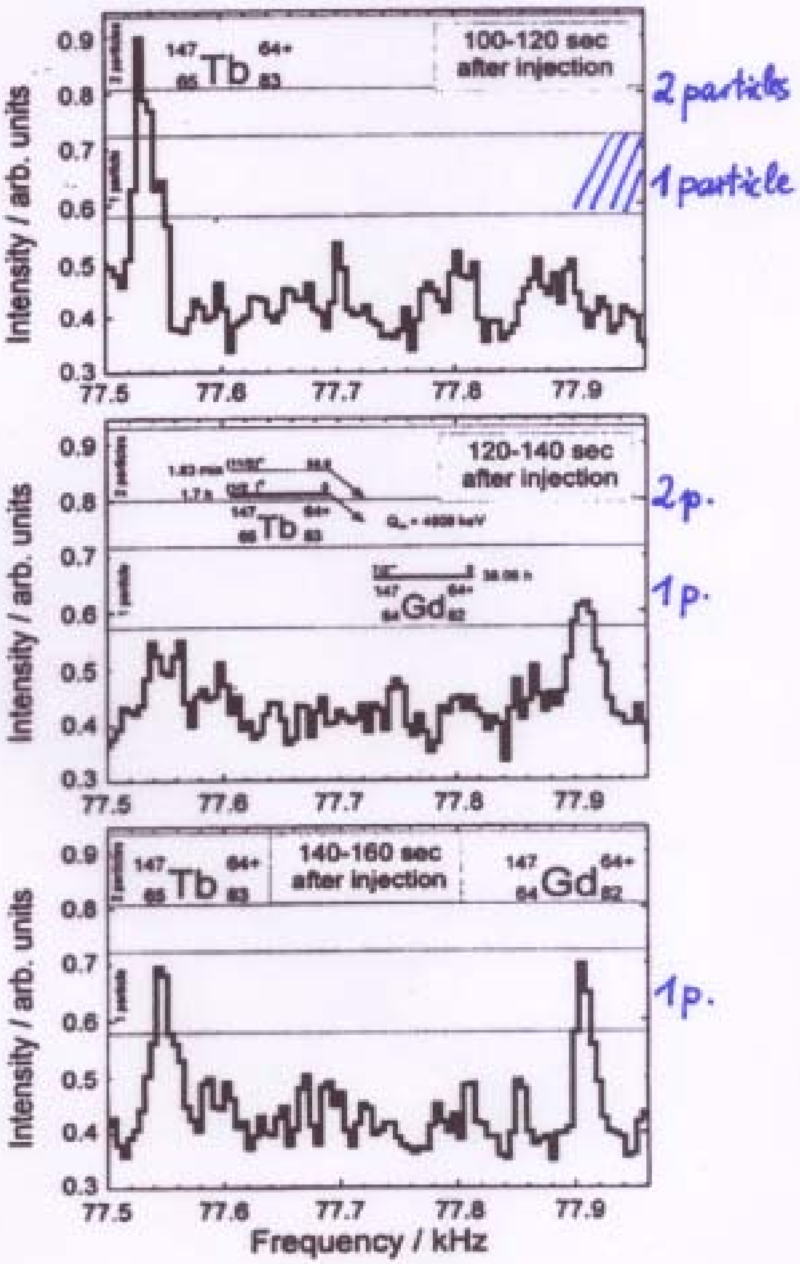


Unique:

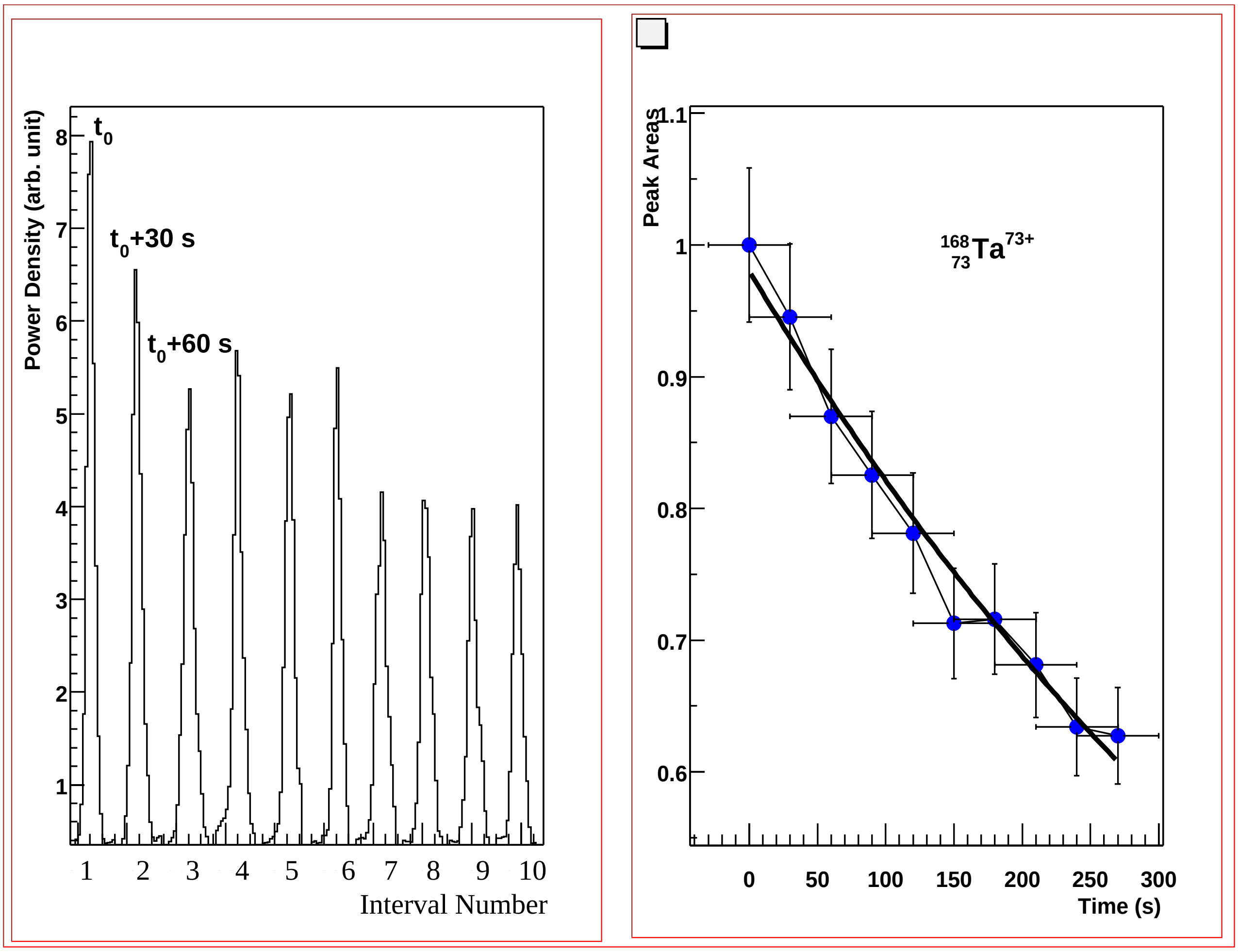
1) Both mother and daughter nuclei can be measured simultaneously
2) $T_{1/2}$ can be studied for different atomic charge states



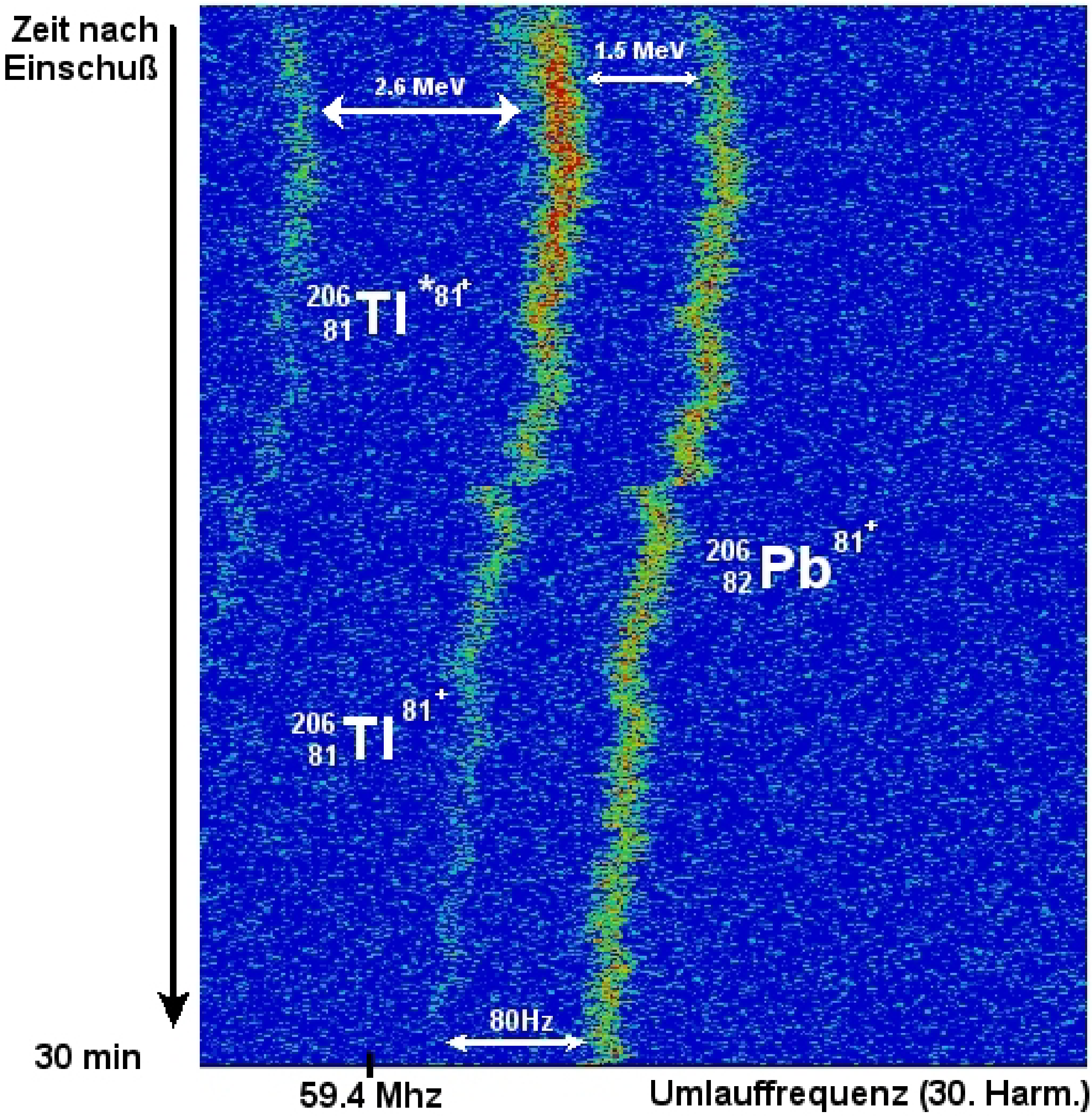
$^{192}Pt^{78+}$
(bare)
$^{192}Au^{78+}$
(H like)
3.4 MeV / c²
$^{187}Ir^{76+}$
(H like)
$^{187}Pt^{76+}$
(He like)
$^{187}Os^{76+}$
(bare)
Noise Power Density (log.)
39.0
39.5
40.0
40.5
41.0
41.5
42.0
FFT Frequency / kHz
2o



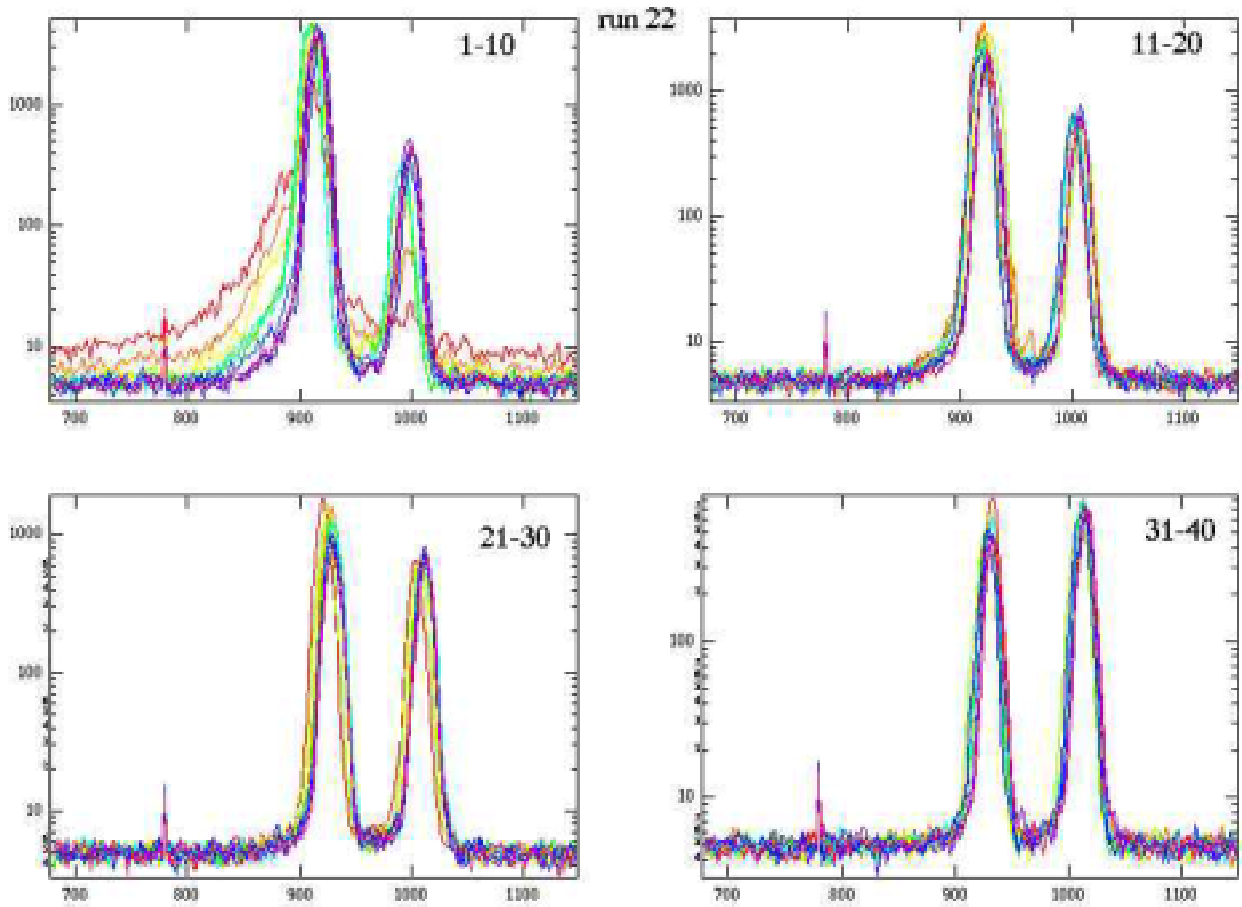
100-120 sec
after injection
2 particles
1 particle
120-140 sec
after injection
2p.
1p.
140-160 sec
after injection
1p.
Intensity / arb. units
Frequency / kHz



t0
t0+30 s
t0+60 s
Power Density (arb. unit)
Interval Number
Peak Areas
$^{168}_{73}Ta^{73+}$
Time (s)



Zeit nach Einschuß
30 min
2.6 MeV
1.5 MeV
$^{206}_{81}Tl^{*81+}$
$^{206}_{82}Pb^{81+}$
$^{206}_{81}Tl^{81+}$
80Hz
59.4 Mhz
Umlauffrequenz (30. Harm.)



rev. frequency (a.u.)

$^{207}Tl^{81+} \rightarrow (\beta_b) \quad ^{207}Pb^{81+}$

$Q_{\beta b}$ = 1.5 MeV

1 cycle = 32.4 s (starting at injection)

separation of $^{207}Tl/^{207}Pb$-lines ≈ 80 Hz / 60 Mhz

At new storage rings same techniques:

stochastic pre-cooling, electron cooling

detection of β^-, β^+, β_b and EC by

Schottky spectrometry / particle detectors

but:

≈ 10^2 more primary, ≈ 10^4 more secondary beams