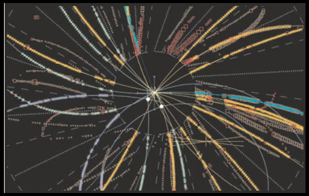
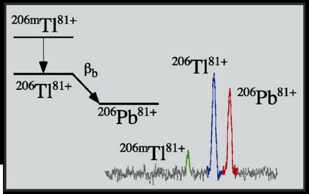
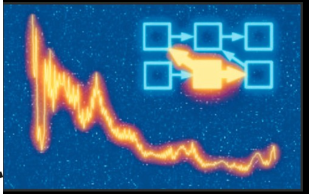
Observation of non-exponential orbital electron-capture decay of H-like ^{140}Pr and ^{142}Pm ions and possible implications for the neutrino masses

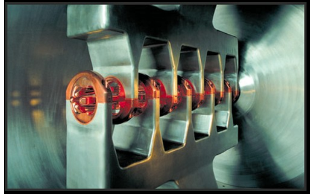
Fritz Bosch, GSI Darmstadt

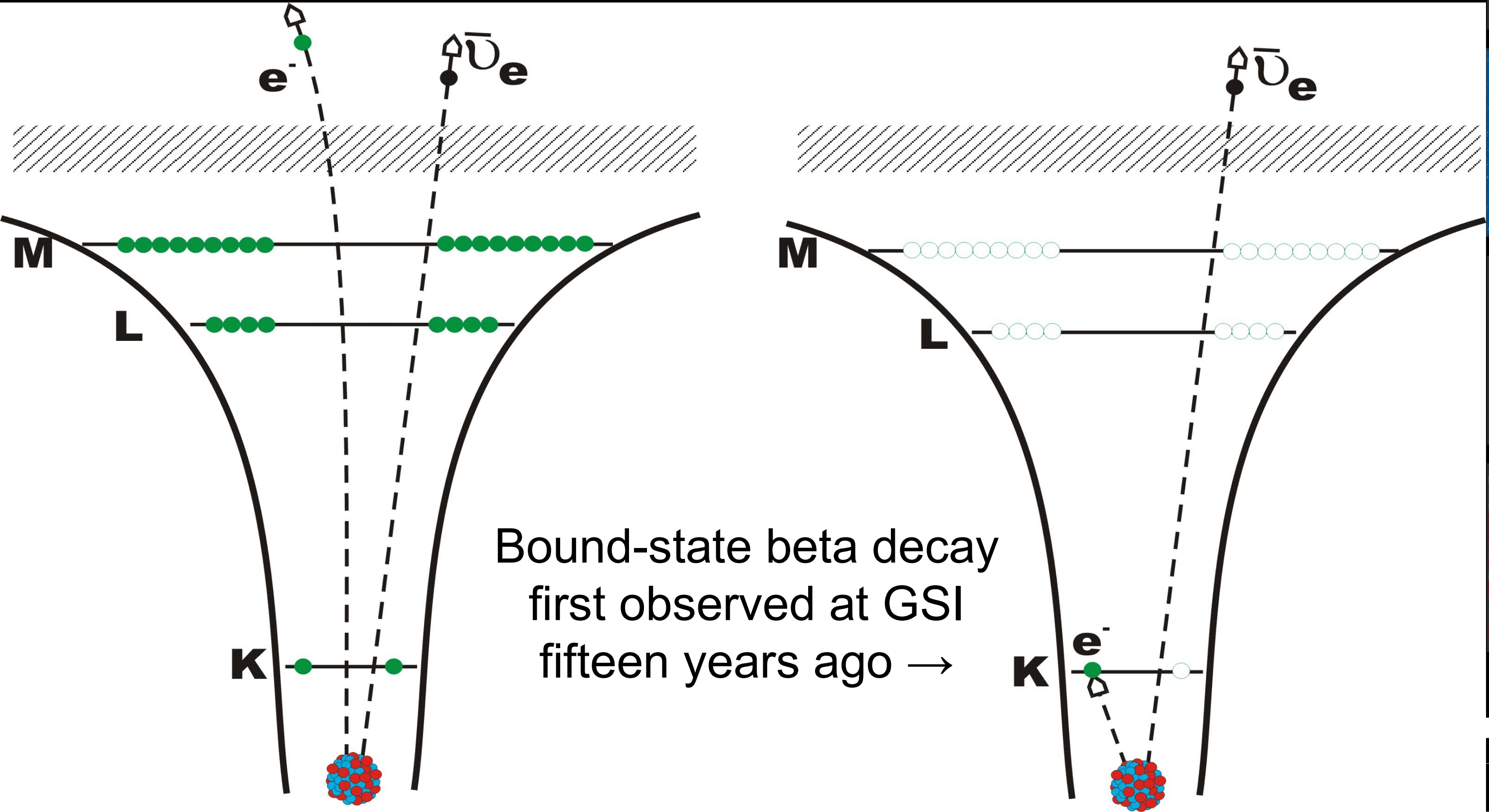
Nuclear physics seminar at Warsaw University, May 14, 2008











Bound-state beta decay
first observed at GSI
fifteen years ago →

Outline

1. Production, storage and cooling of highly-charged ions at GSI
2. Two-body beta decay of stored and cooled highly-charged ions
3. Experimental results for orbital electron capture of H-like ^{140}Pr and ^{142}Pm by means of single-ion decay spectroscopy
4. Tentative explanation(s) of the observed non-exponential decays
5. Summary, questions and outlook

Schottky Mass Spectrometry (SMS) - Collaboration

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E. Haettner, M. Hausmann, M. Hellström, S. Hess, G. Jones, E. Kaza,
Th. Kerscher, P. Kienle, O. Klepper, H.-J. Kluge, Ch. Kozhuharov, K.-L. Kratz,
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Los Alamos
NATIONAL LABORATORY

GSI

MICHIGAN STATE
UNIVERSITY

universität mainz

UniS

RIKEN

LMU

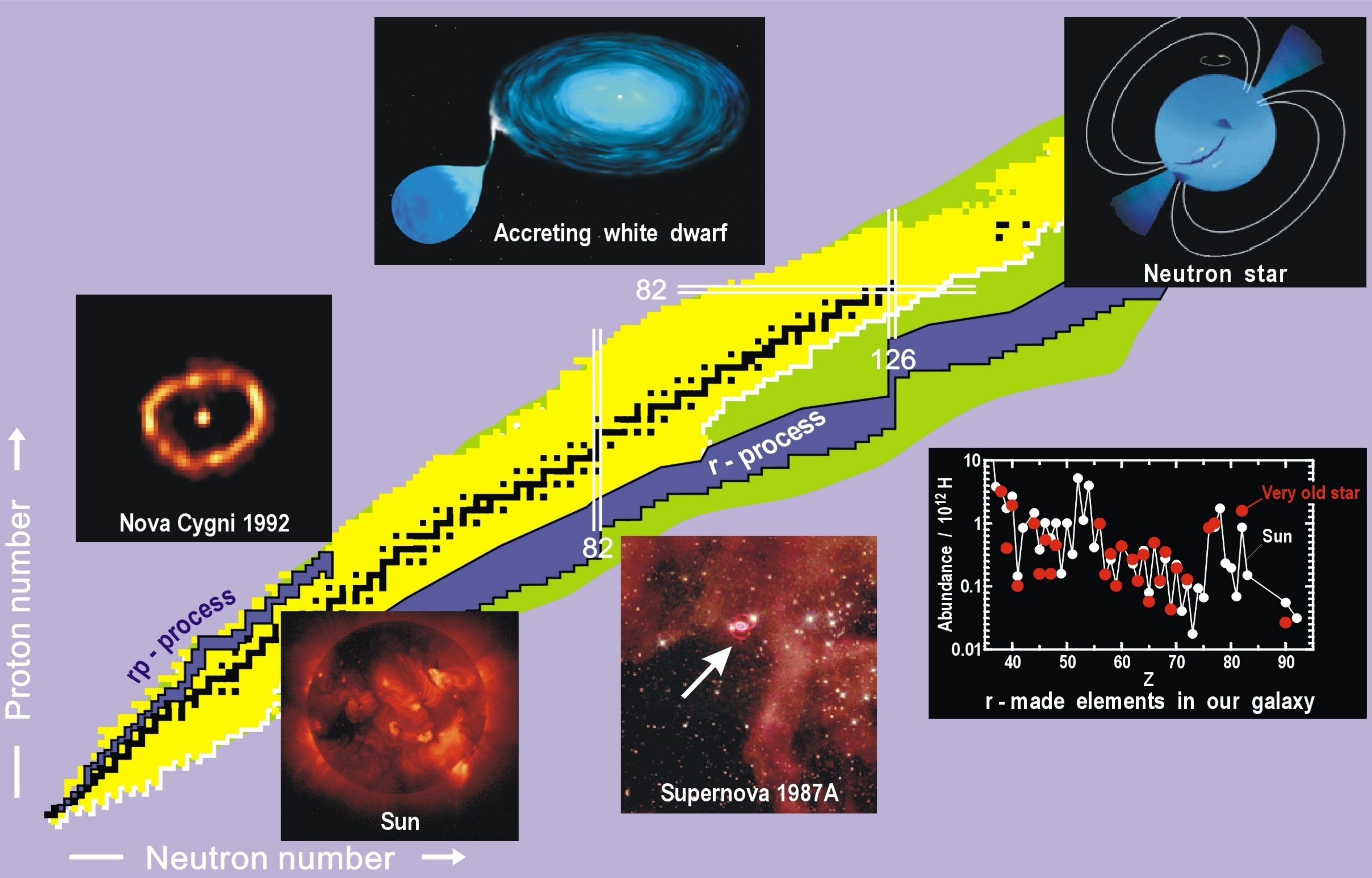
筑波大学

Niigata University

TUM

CSNSM

...back to our roots: stellar nucleosynthesis



Pathways of stellar nucleosynthesis

- Key parameters:

- Masses, beta-lifetimes, n- capture-, n-γ cross-sections

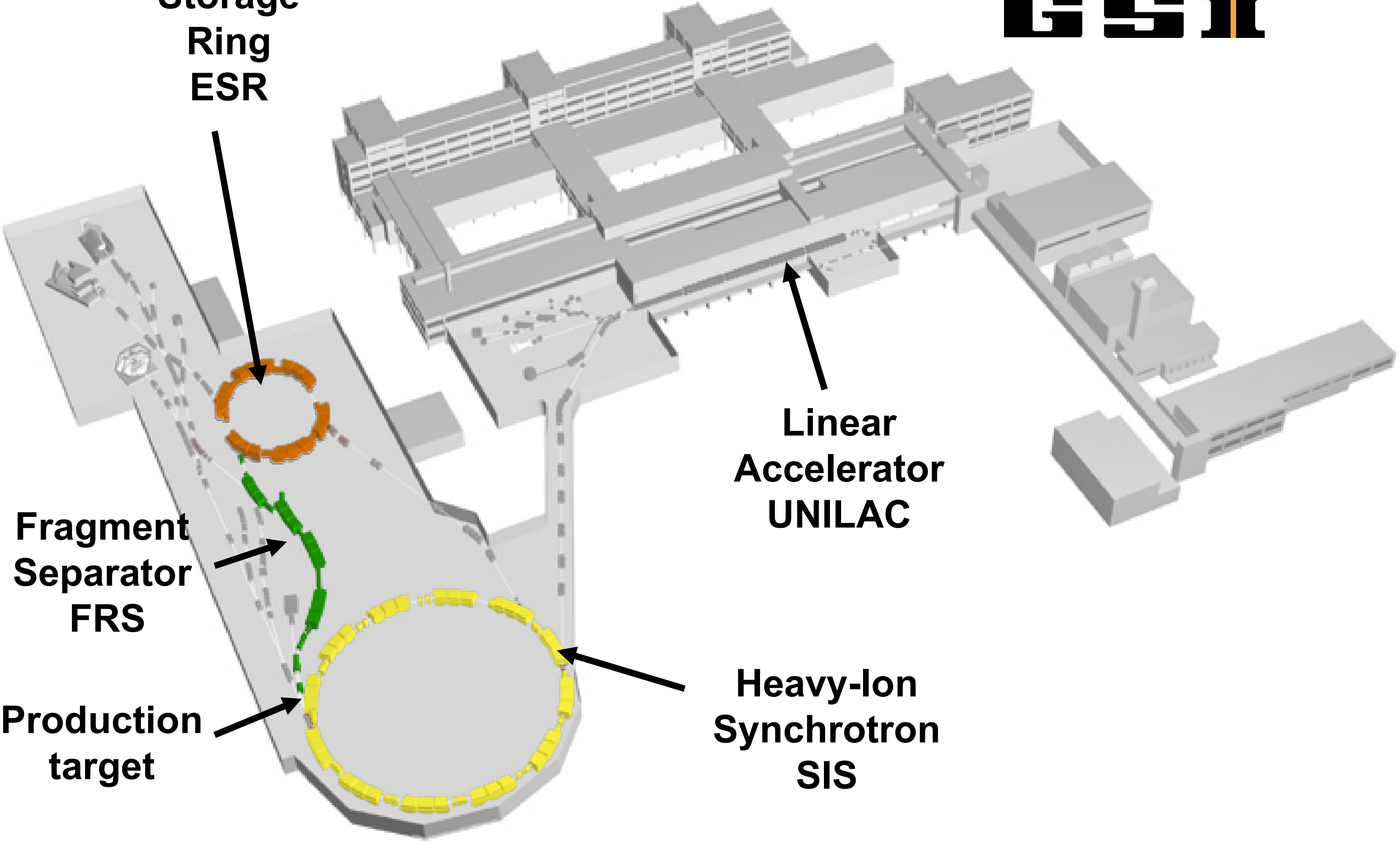
- Masses determine the pathways
- of s-, p-, rp- and r- processes

- Beta-lifetimes the accumulated abundances

- Hot stellar environment : atoms are highly-ionized

1. Production, storage and cooling of HCI at GSI

Secondary Beams of Short-Lived Nuclei



Storage Ring ESR

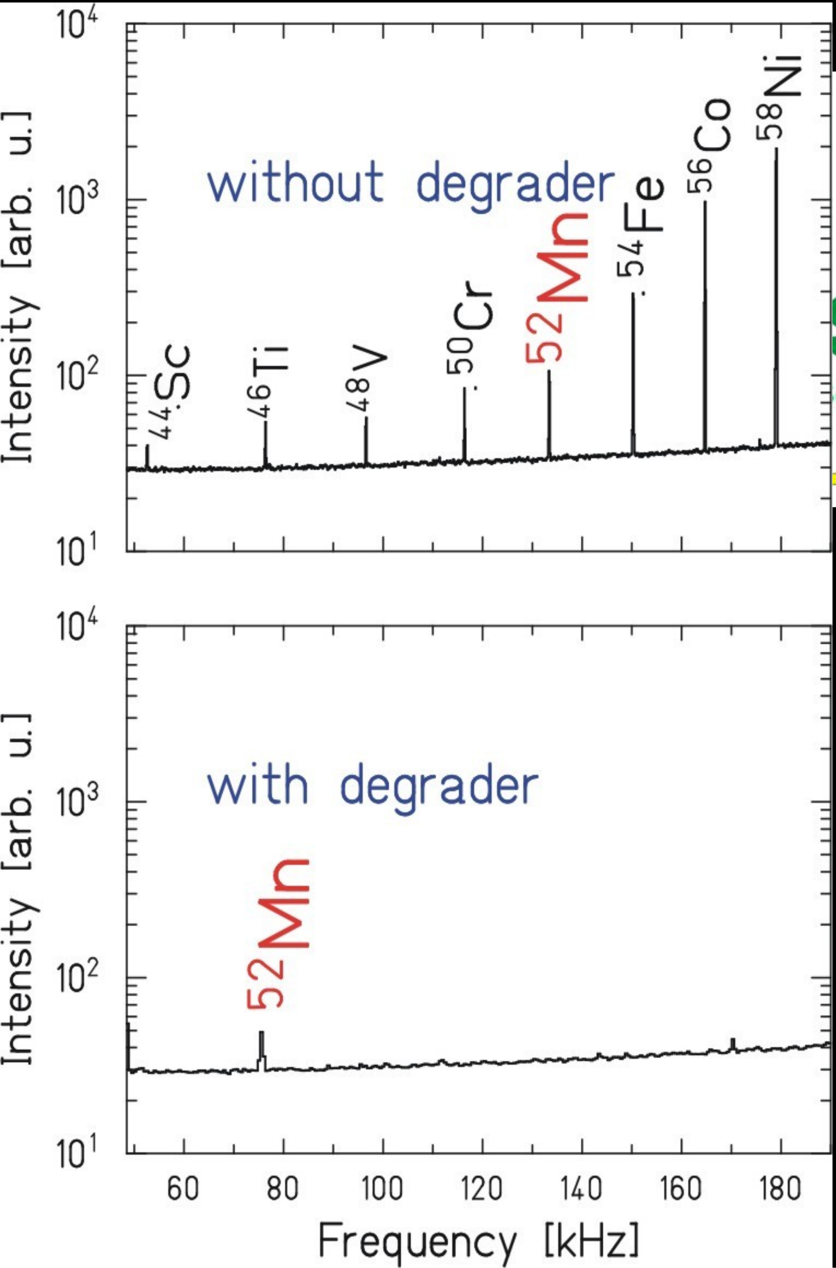
Linear Accelerator UNILAC

Fragment Separator FRS

Production target

Heavy-Ion Synchrotron SIS

Production & Separation of Exotic Nuclei



Highly-Charged Ions

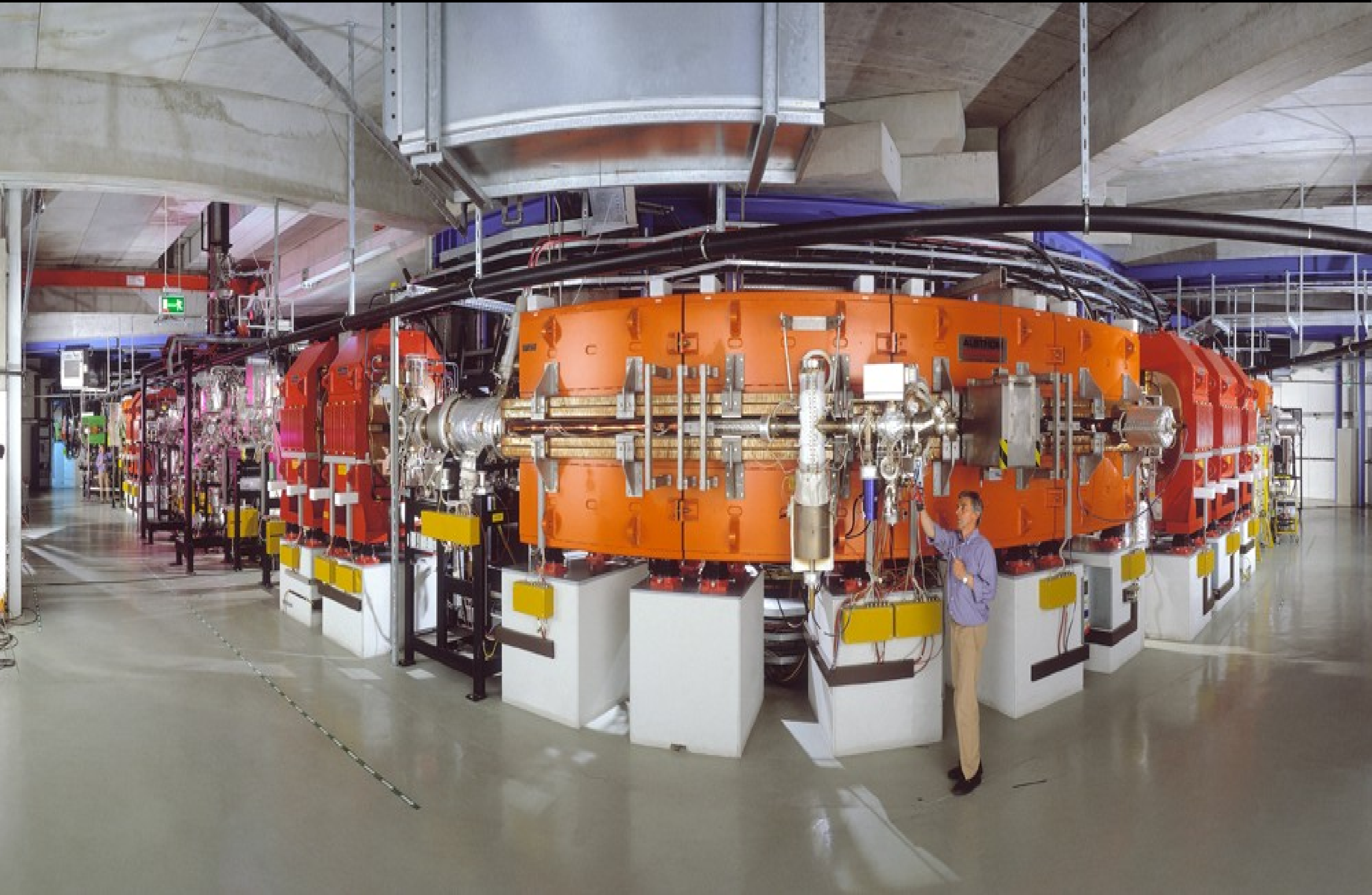
In-Flight separation

Cocktail or mono-isotopic beams

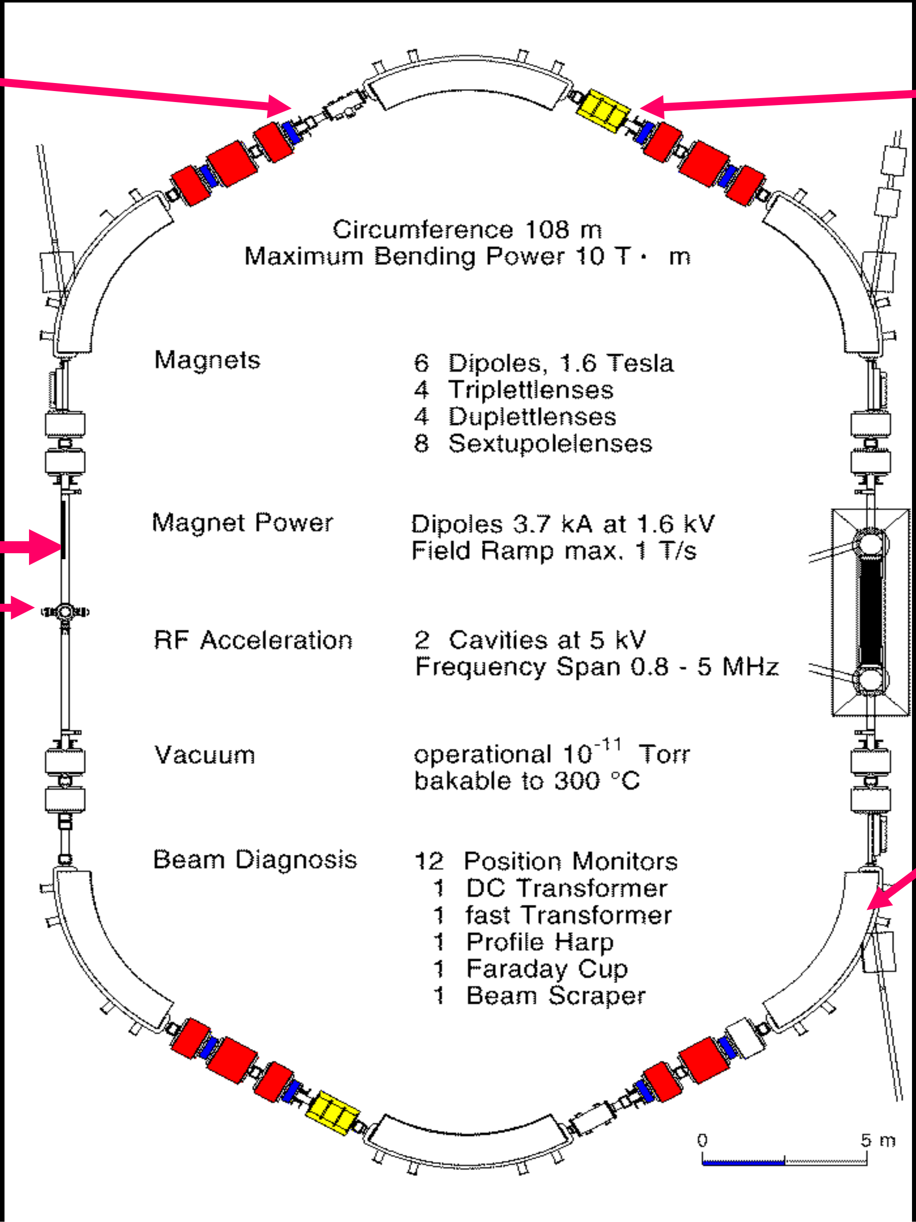
500 MeV/u primary beam ^{152}Sm

400 MeV/u stored beam ^{140}Pr, ^{142}Pm

The ESR : E_{max} = 420 MeV/u, 10 Tm, electron-, stochastic-, and laser cooling



Specifications of the ESR



Circumference 108 m
Maximum Bending Power 10 T · m

Magnets	6 Dipoles, 1.6 Tesla 4 Triplettlenses 4 Duplettlenses 8 Sextupolelenses
Magnet Power	Dipoles 3.7 kA at 1.6 kV Field Ramp max. 1 T/s
RF Acceleration	2 Cavities at 5 kV Frequency Span 0.8 - 5 MHz
Vacuum	operational 10^{-11} Torr bakable to 300 °C
Beam Diagnosis	12 Position Monitors 1 DC Transformer 1 fast Transformer 1 Profile Harp 1 Faraday Cup 1 Beam Scraper

Particle detectors

Two 5 kV rf-cavities

Re-injection to SIS

Fast Injection

Schottky pick-ups

Gas jet

e^- cooler
I = 10...500 mA

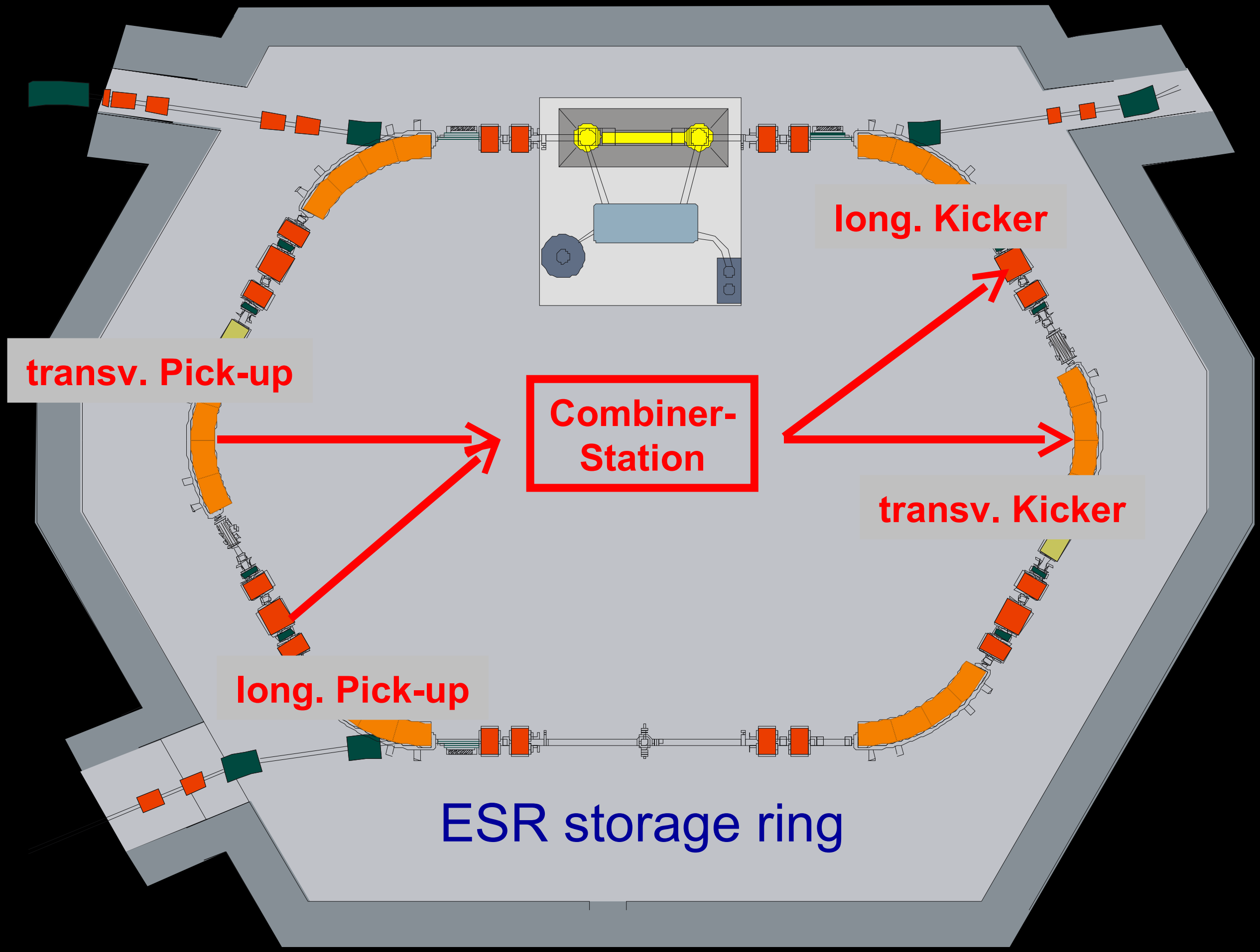
Six 60^0 dipoles
Bρ ≤ 10 T· m

Extraction

L = 108 m =1/2 L_{SIS}

p = $2 \cdot 10^{-11}$ mbar
E = 3...420 MeV/u
f ≈ 1...2 MHz
β = 0.08...0.73
Q ≈ 2.65

Stochastic cooling: Implementation at the ESR

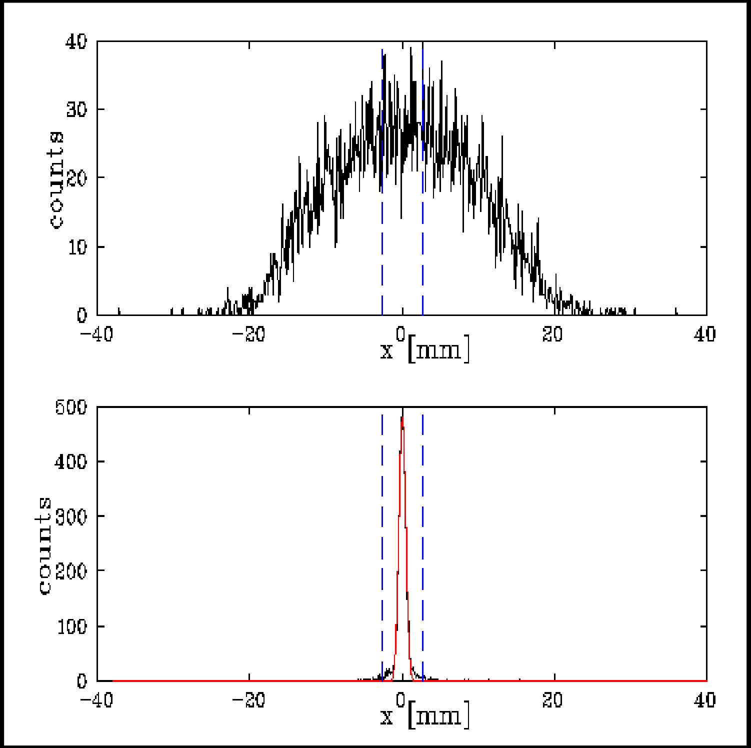


Stochastic cooling is in particular efficient for hot ion beams

"Cooling": enhancing the phase space density

Electron cooling: G. Budker, 1967 Novosibirsk

Momentum exchange
with a cold, collinear e$^-$ beam. The ions get the **sharp velocity** of the electrons, small size and small angular divergence

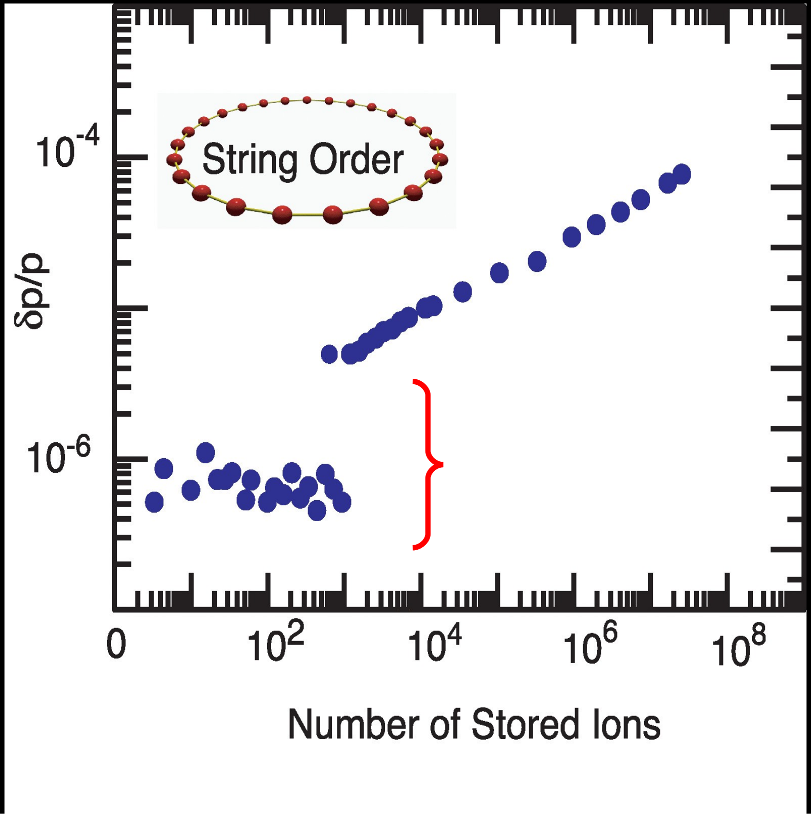


"Phase transition" to a linear ion chain

ESR: circumference ≈ 10^4 cm

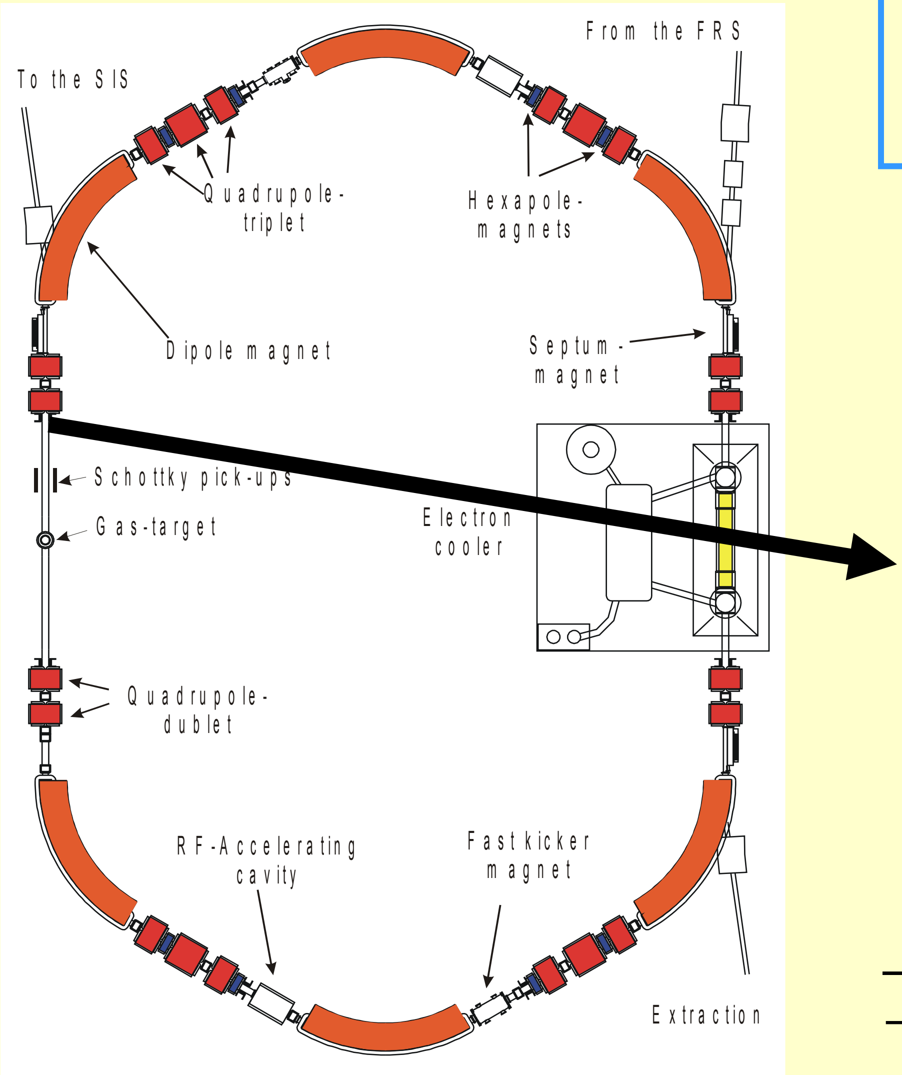
For 1000 stored ions, the mean distance amounts to about 10 cm

At mean distances of about 10 cm and larger
intra-beam-scattering disappeared



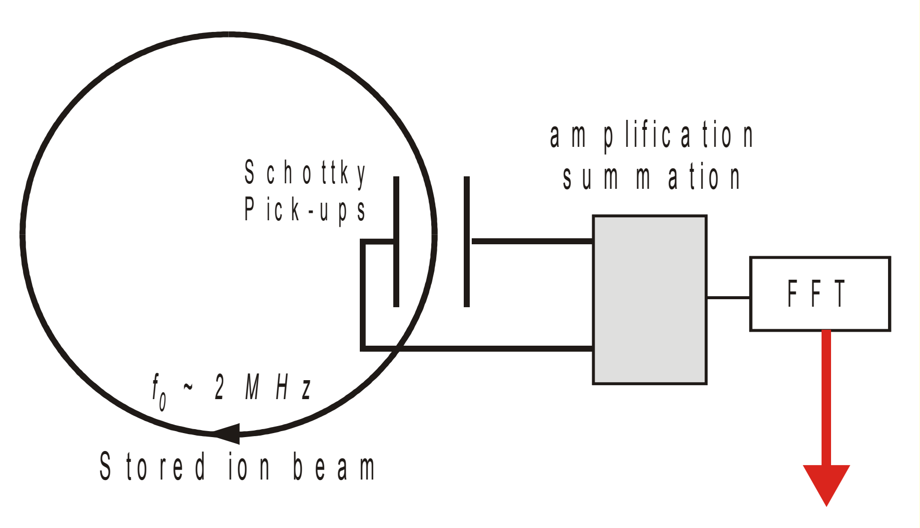
M. Steck et al., PRL **77** (1996) 3803

Recording the Schottky-noise



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

$$\frac{\Delta v}{v} \longrightarrow 0$$



Real time analyzer Sony-Tektronix 3066

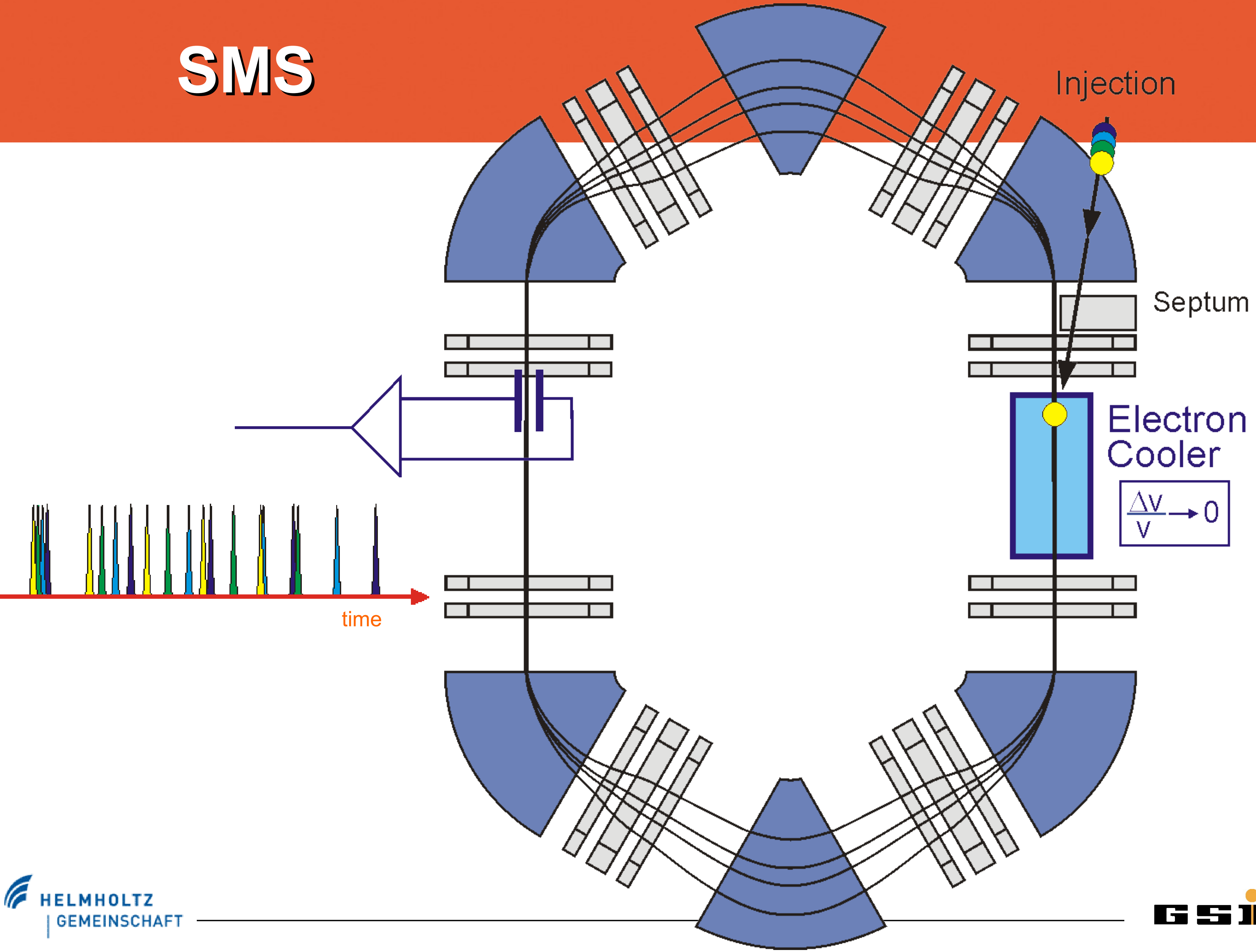
________________________________ 128 msec

→ FFT

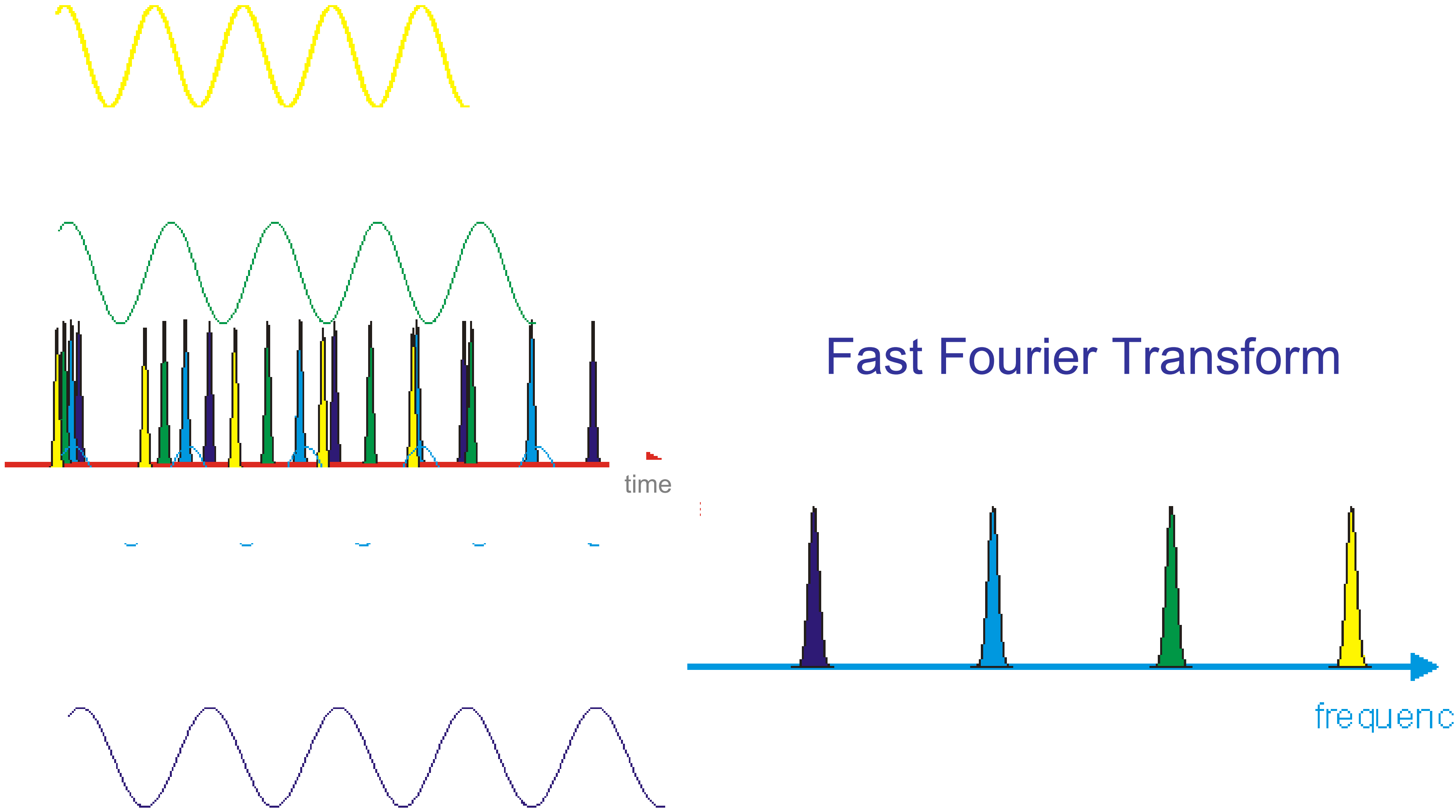
64 msec ________________________

→ FFT

SMS


Injection
Septum
Electron
Cooler
$\frac{\Delta v}{v} \rightarrow 0$
time

SMS



Three-body beta decay, e.g. β^+: $p \rightarrow n + e^+ + v_e$

both, mass (m) **and** charge state (q) change

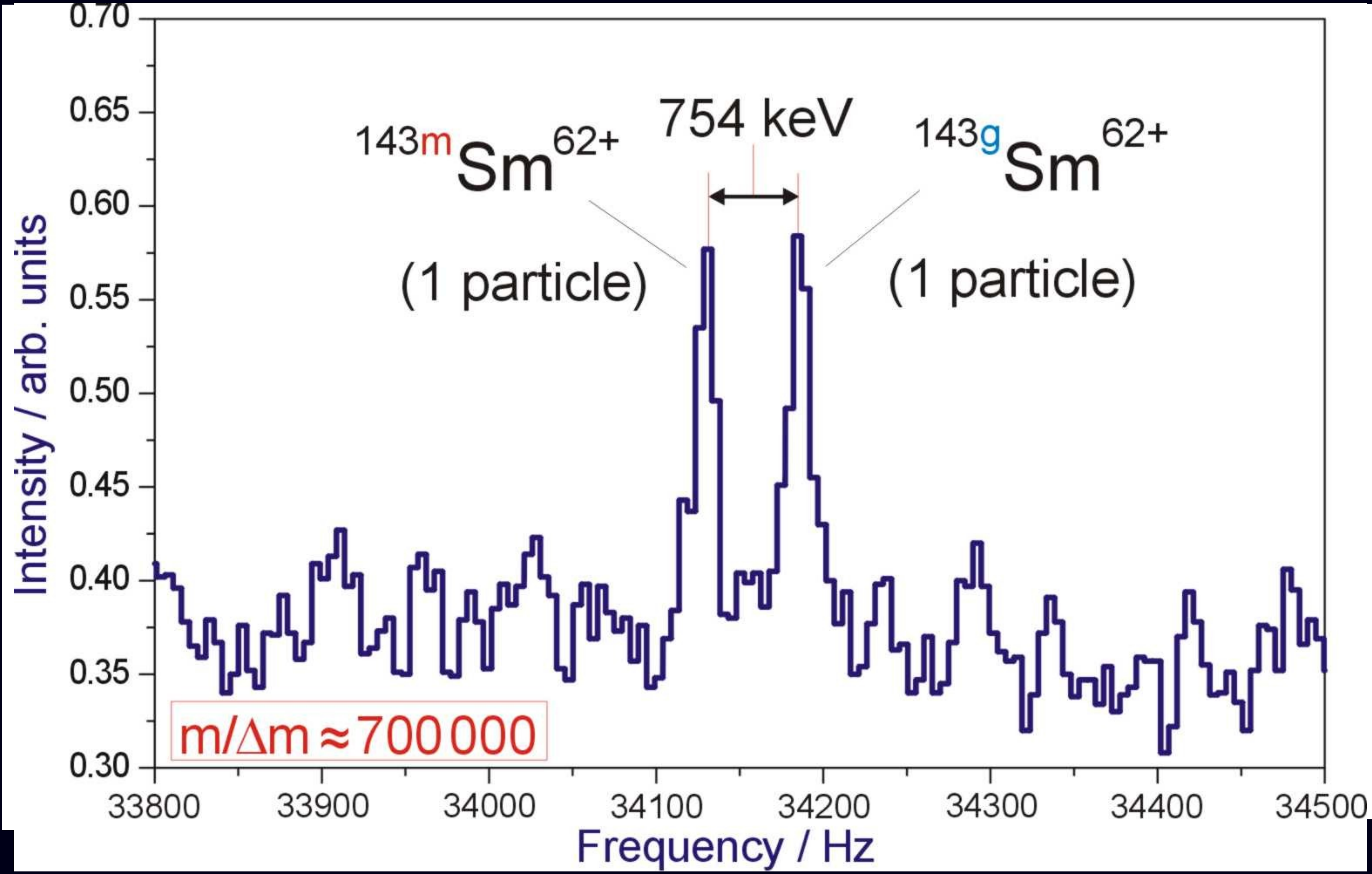
→ quite different revolution frequencies **and** orbits

Two-body beta decay, e.g. EC: $p + e^-_b \rightarrow n + v_e$

only difference of mass, **q** remains the same

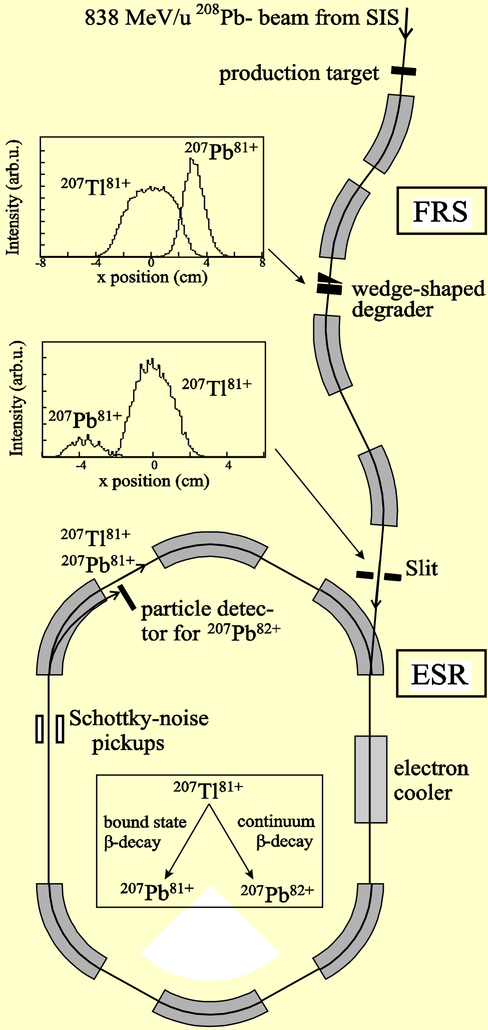
→ small difference in revolution frequency, (almost) **same** orbit

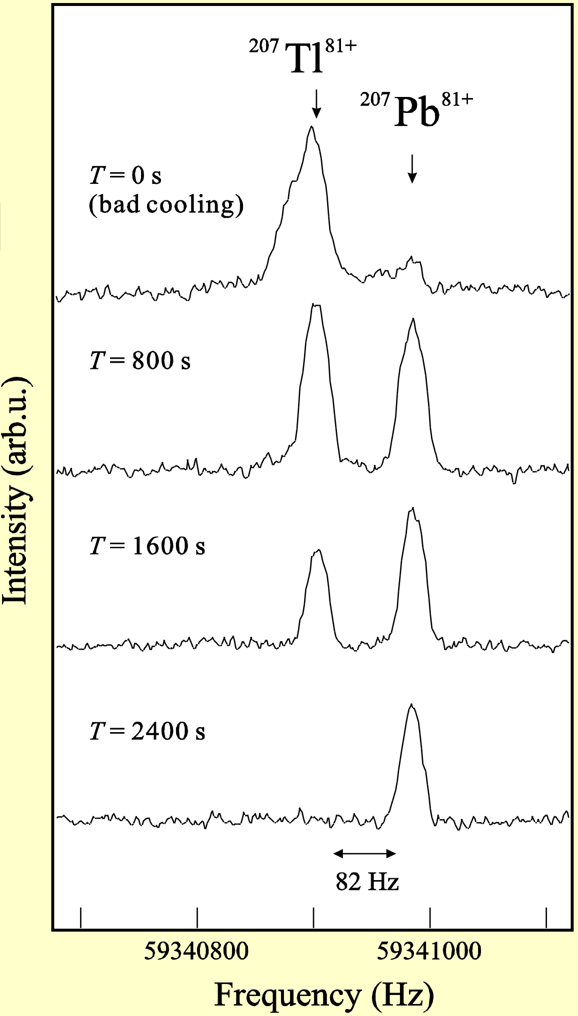
Small-band Schottky frequency spectra

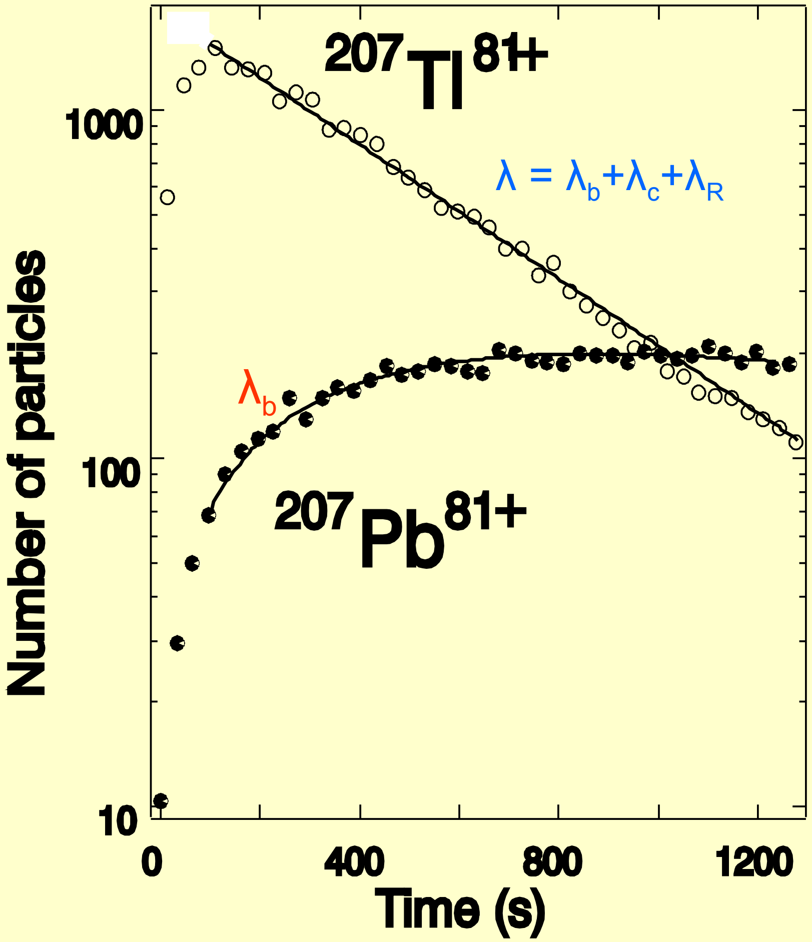


2. Two-body beta decay of stored and cooled HCI

First direct observation of bound-state β decay



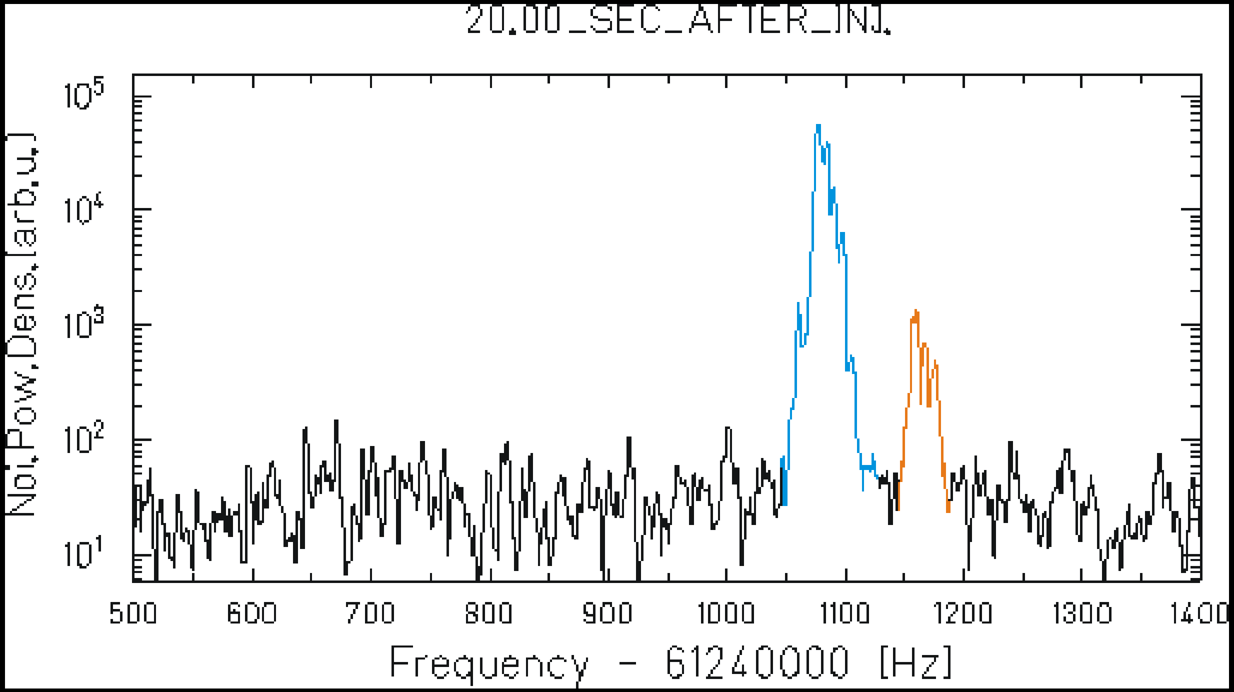




Parent and daughter ions are in the same spectrum

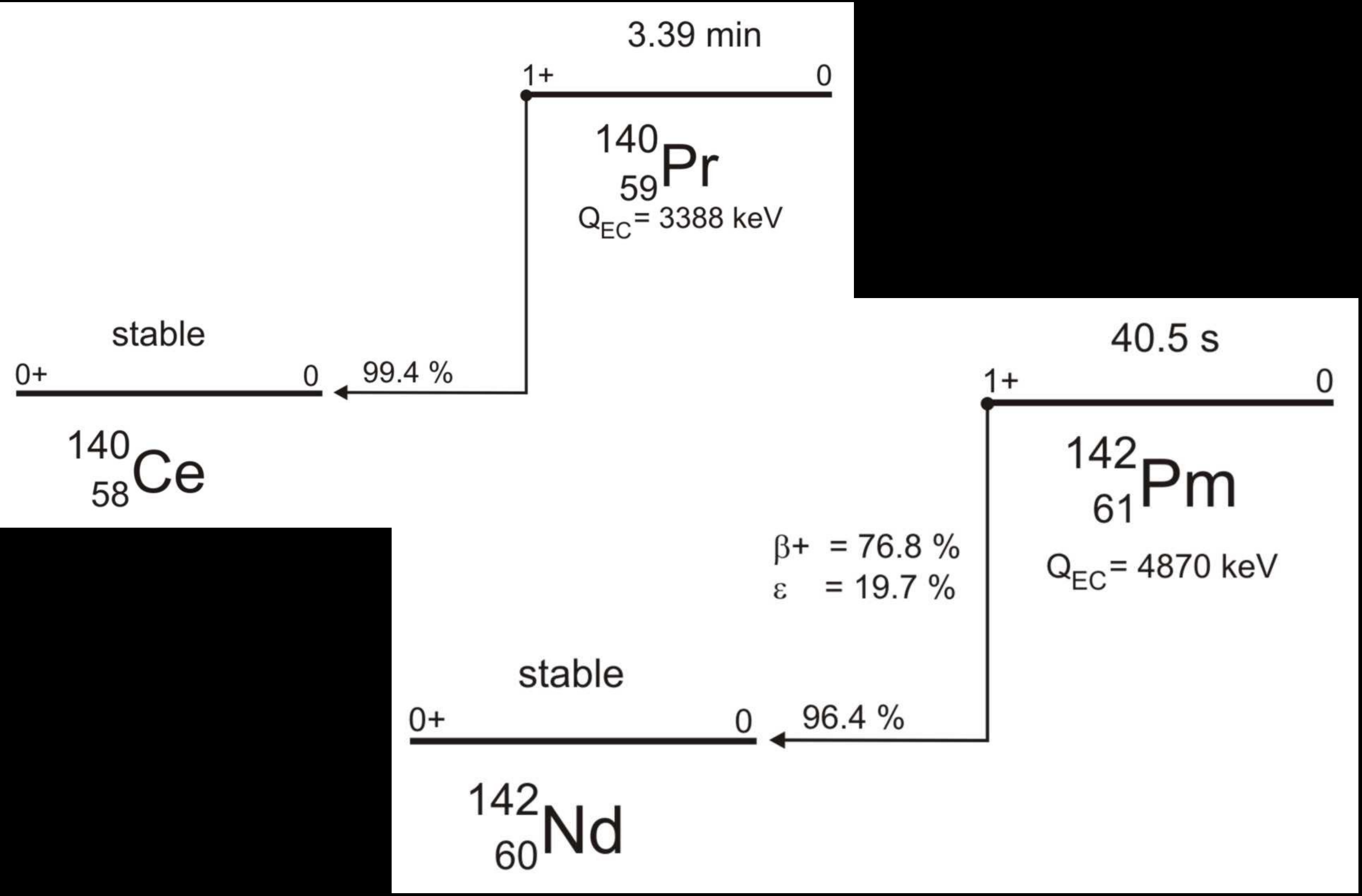
T. Ohtsubo et al., PRL **95** (2005) 052501

Cooling



D. Boutin

Present EC-experiments : Decay schemes



3.39 min

1+ 0

$^{140}_{59}\mathrm{Pr}$

Q_{EC} = 3388 keV

stable

0+ 0

99.4 %

$^{140}_{58}\mathrm{Ce}$

40.5 s

1+ 0

$^{142}_{61}\mathrm{Pm}$

Q_{EC} = 4870 keV

β+ = 76.8 %

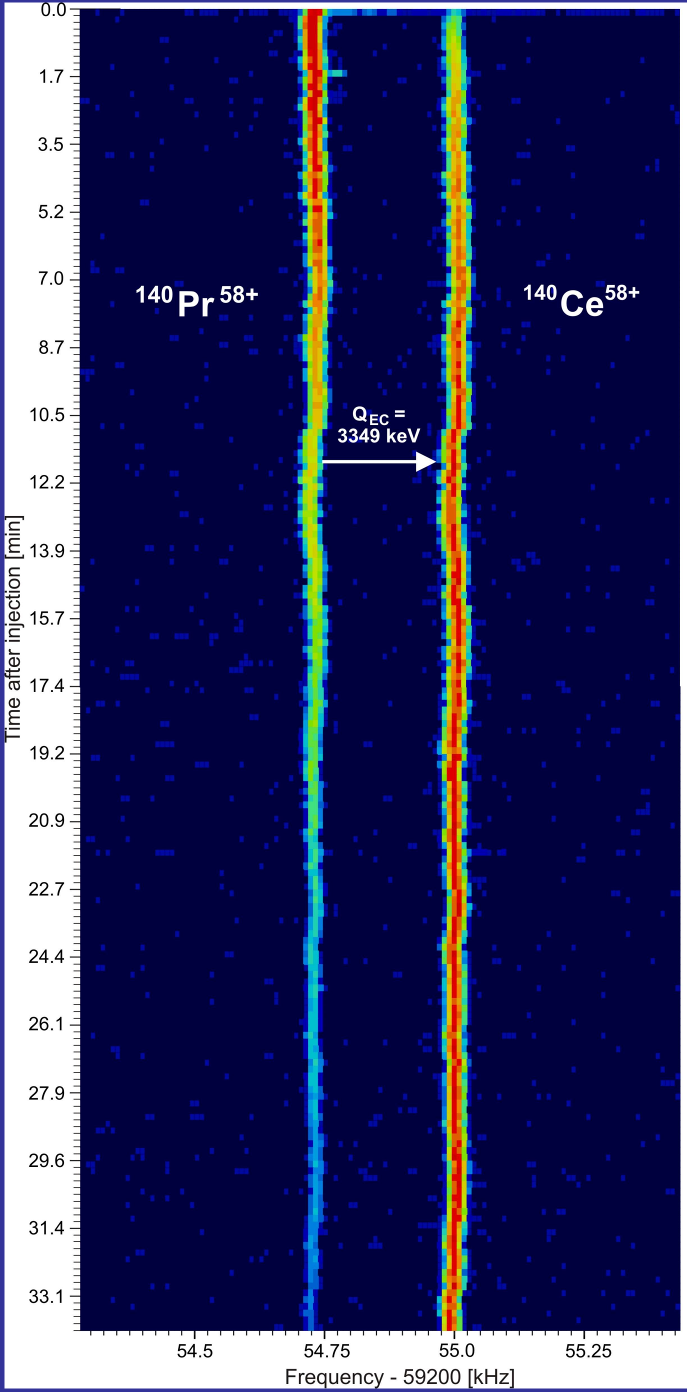
ε = 19.7 %

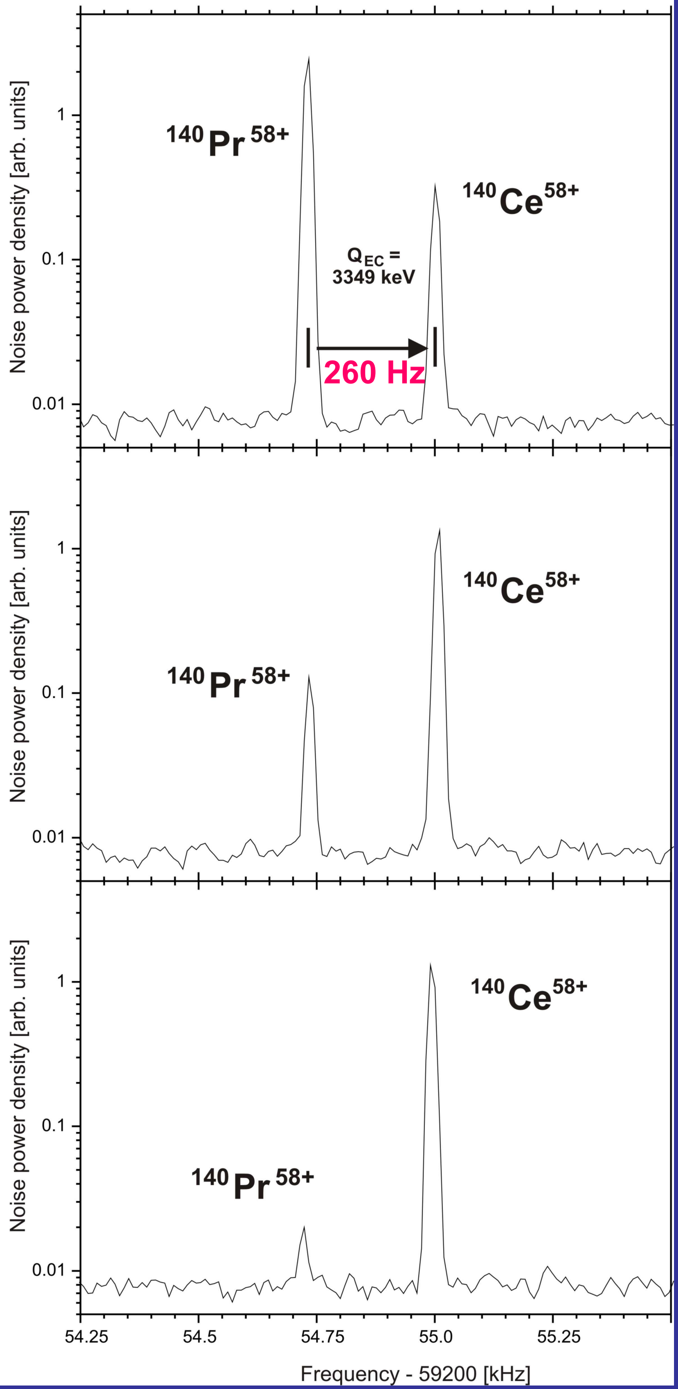
stable

0+ 0

96.4 %

$^{142}_{60}\mathrm{Nd}$





f scales as m/q

Two-body β decay:
q does **not** change

Change of f only due to **change of mass**

EC in Hydrogen-like Ions

Expectations:

$\lambda_{\beta+}/\lambda_{EC}$ (neutral atom) ≈ 1

λ_{EC}(H-like)/λ_{EC}(He-like) ≈ 0.5

FRS-ESR Experiment

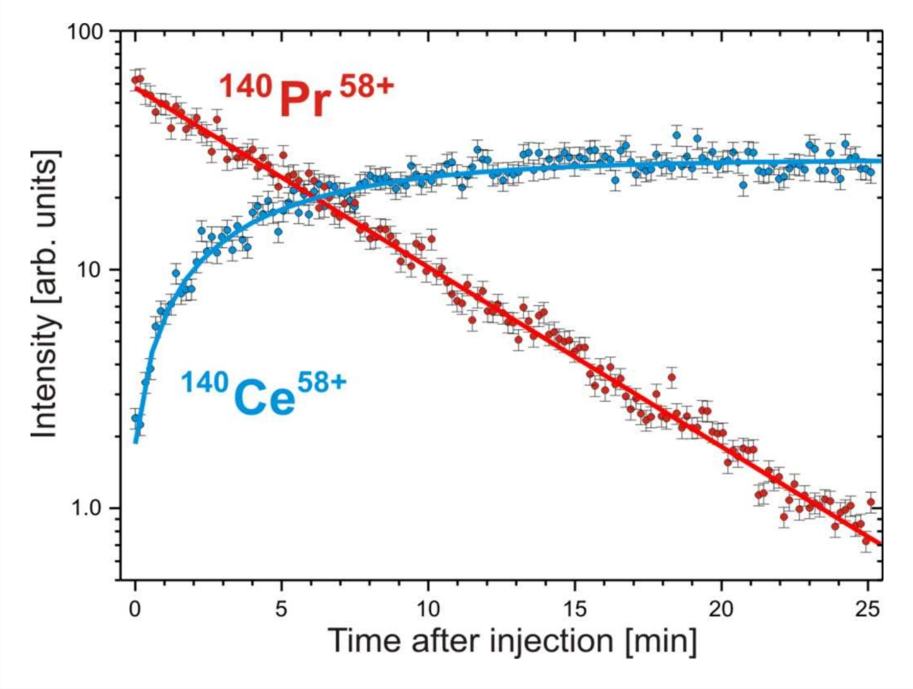
λ(neutral) = 0.00341(1) s^{-1}
G.Audi et al., NPA729 (2003) 3

$\lambda_{\beta+}$(bare) = 0.00158(8) s^{-1} *(decay of $^{140}Pr^{59+}$)*

λ_{EC}(H-like) = 0.00219(6) s^{-1} (decay of $^{140}Pr^{58+}$)

λ_{EC}(He-like) = 0.00147(7) s^{-1} (decay of $^{140}Pr^{57+}$)

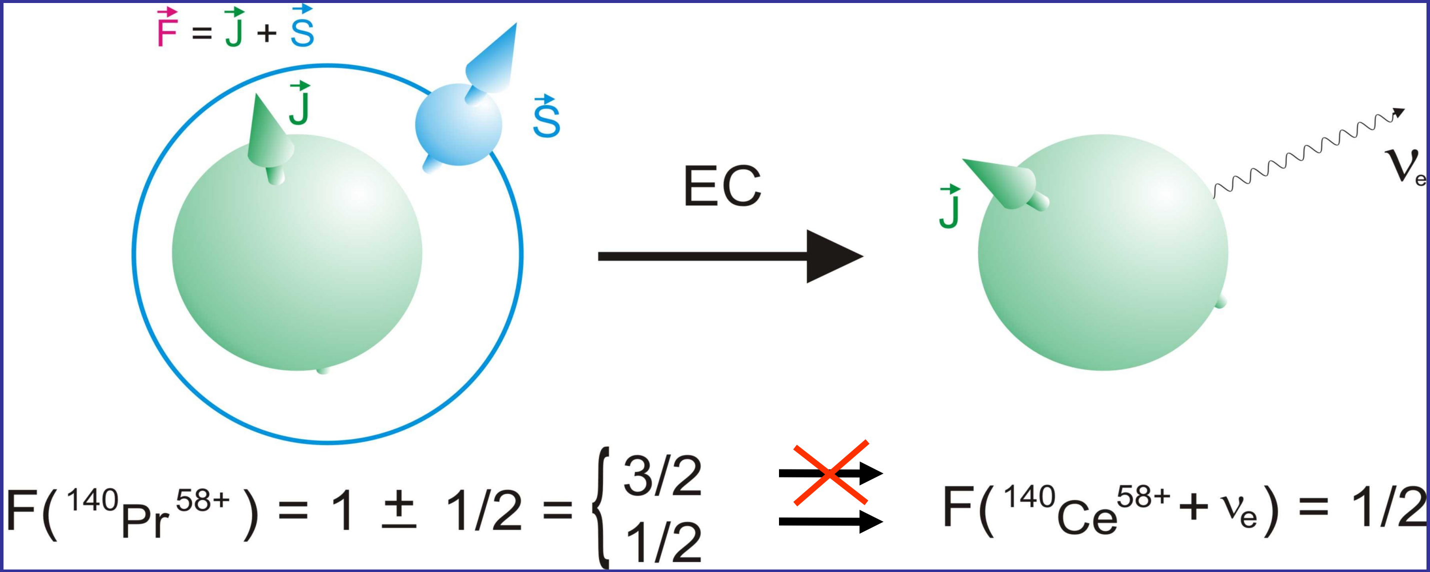
λ_{EC}(H-like)/λ_{EC}(He-like) = 1.49(8)



Yu. Litvinov et al., PRL **99** (2007) 262501

Electron Capture in Hydrogen-like Ions

Gamow-Teller transition $1^+ \rightarrow 0^+$



$$F(^{140}Pr^{58+}) = 1 \pm 1/2 = \begin{cases} 3/2 \\ 1/2 \end{cases} \quad \xrightarrow{} \quad F(^{140}Ce^{58+} + \nu_e) = 1/2$$

S. Typel and L. Grigorenko

$\mu = +2.7812\ \mu_N$ (calc.)

Probability of EC Decay

Neutral ^{140}Pr:	**P = 2.381**
He-like ^{140}Pr:	**P = 2**
H-like ^{140}Pr:	**P = 3**

Theory: Z. Patyk et al., PR **C77** (2008) 014306

The H-like ion really decays by 20% faster than the neutral atom!

$\lambda(H)/\lambda(He) = (2I+1)/(2F+1)$

Single-Particle Decay Spectroscopy

Sensitivity to single stored ions

Well-defined creation time t_0

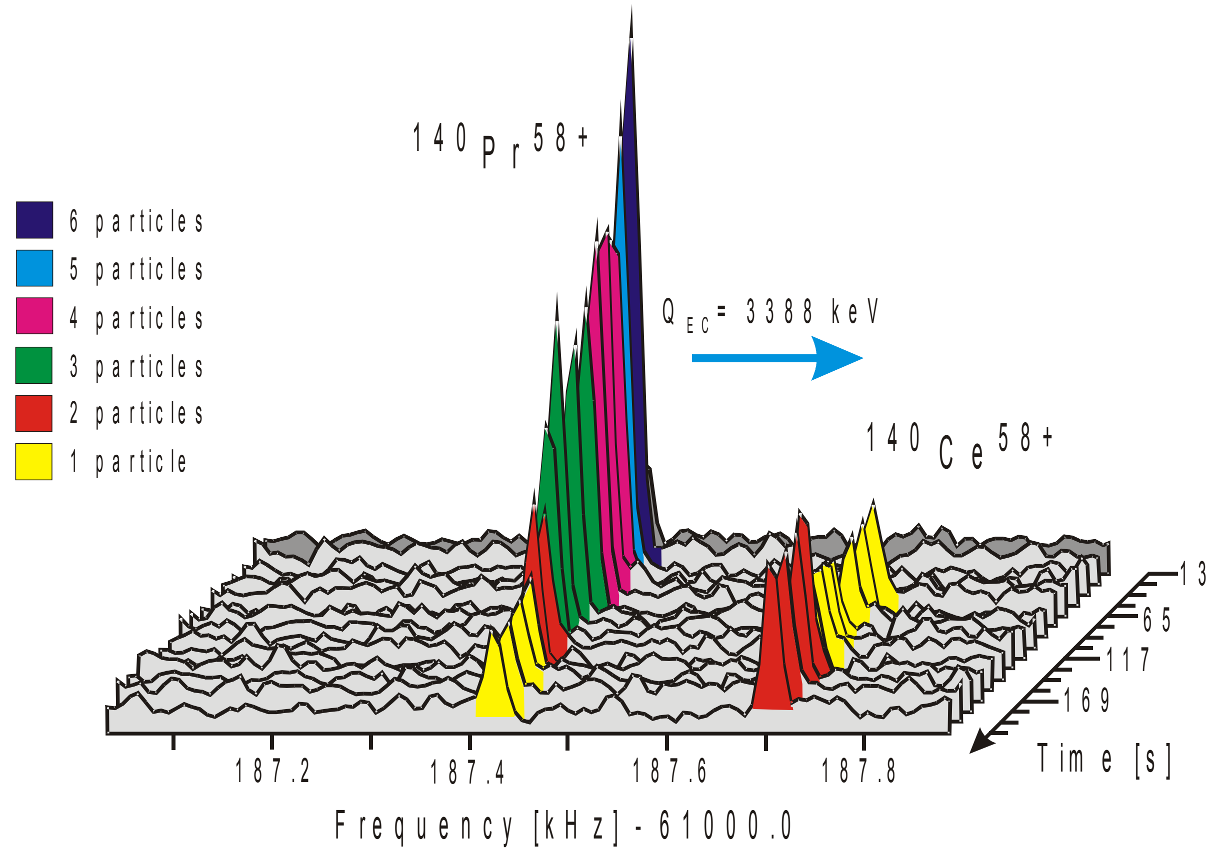
Well-defined quantum states

Two-body β-decay (g.s. → g.s.)
emission of flavour eigenstate ν_e
Entanglement of ν_e and daughter atom by momentum and energy

Recording the correlated changes of peak intensities of mother- and daughter ions defines the decay

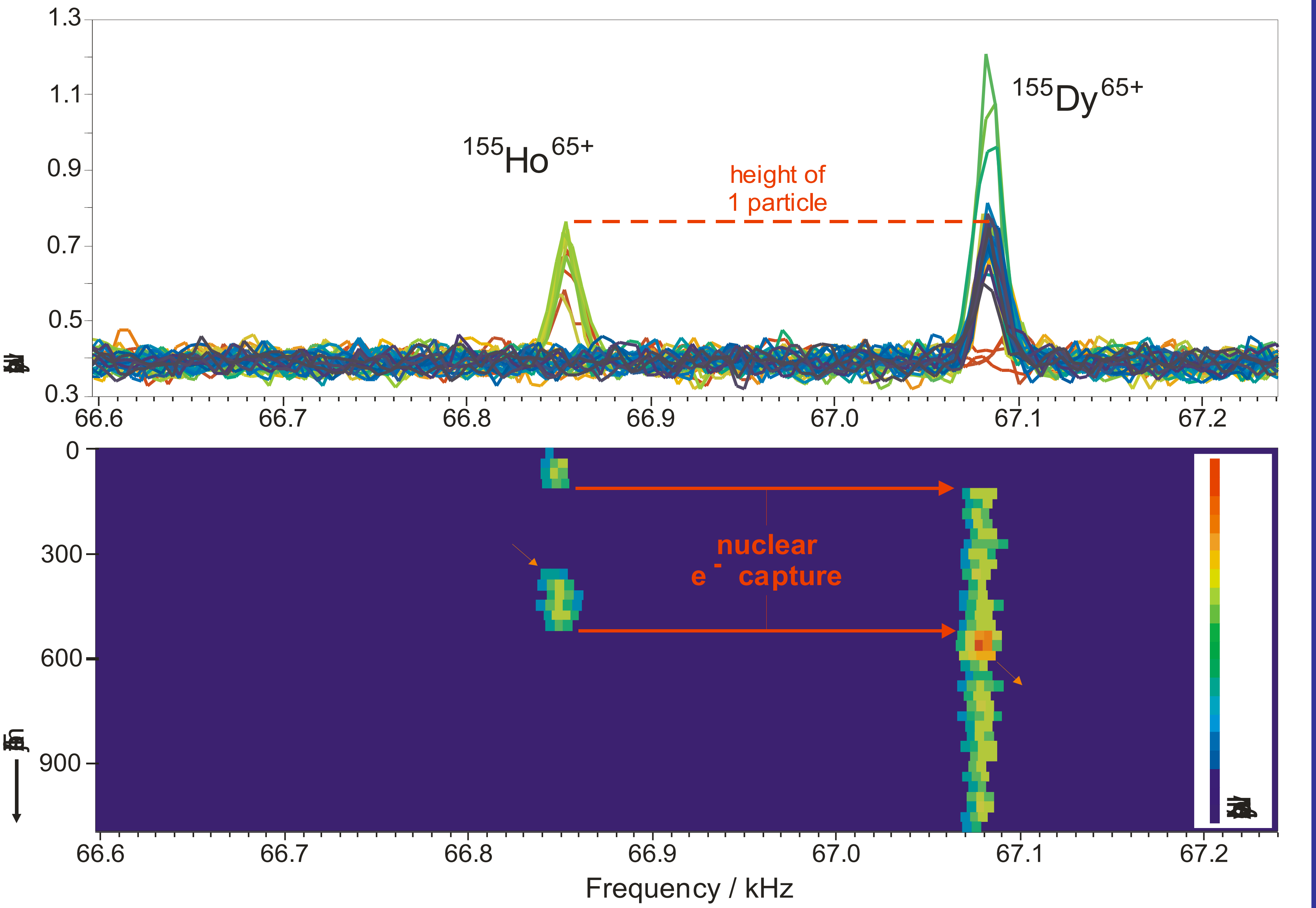
Time-dependence of detection efficiency and other systematical errors are nearly excluded

Restricted counting statistics

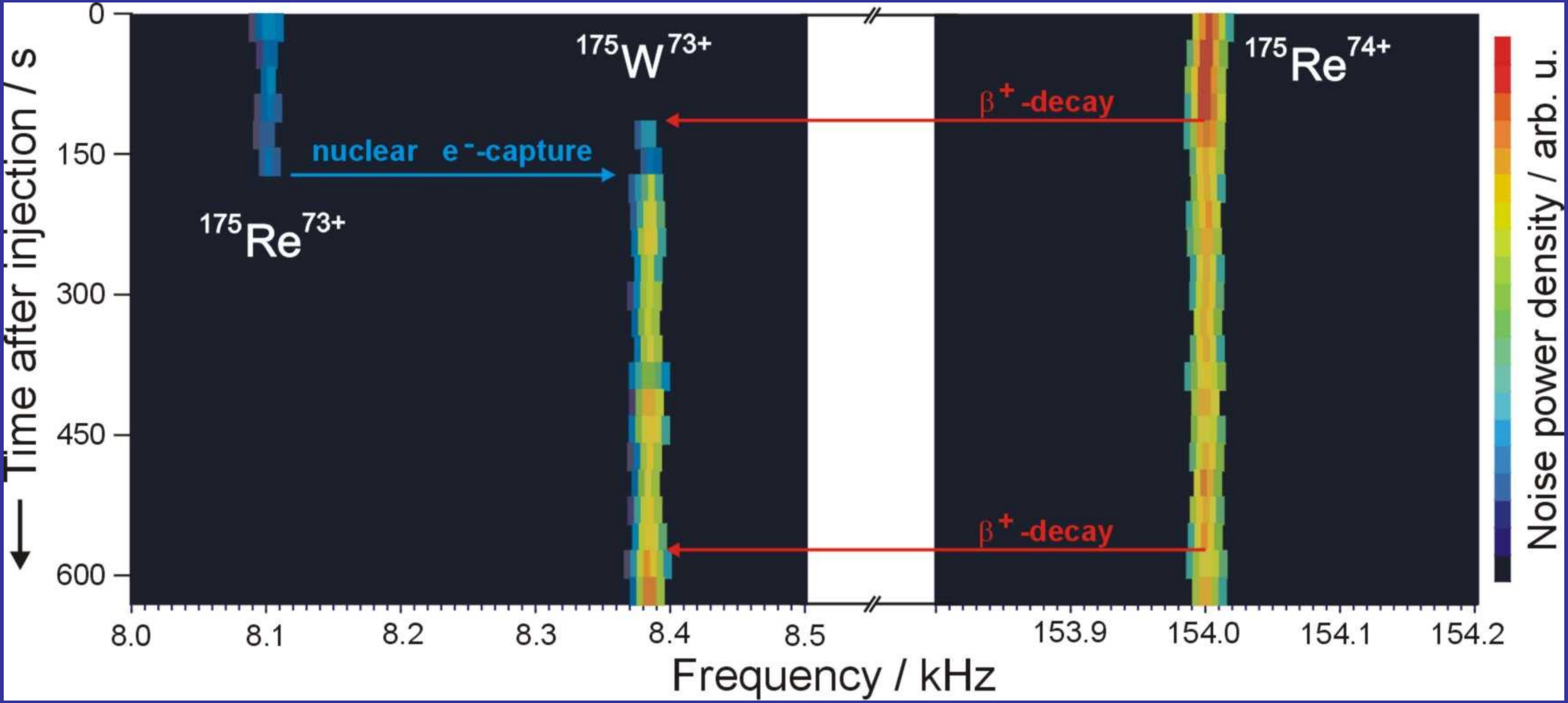


F. Bosch et al., Int. J. Mass Spectr. **251** (2006) 212

Nuclear Decay of Stored Single Ions

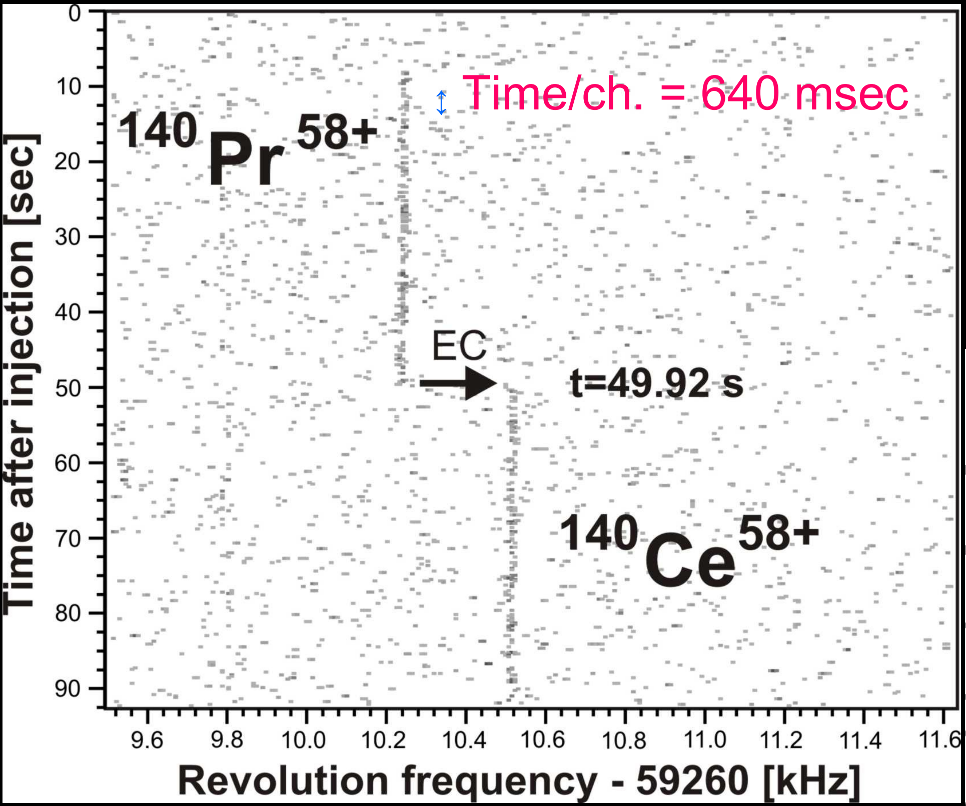


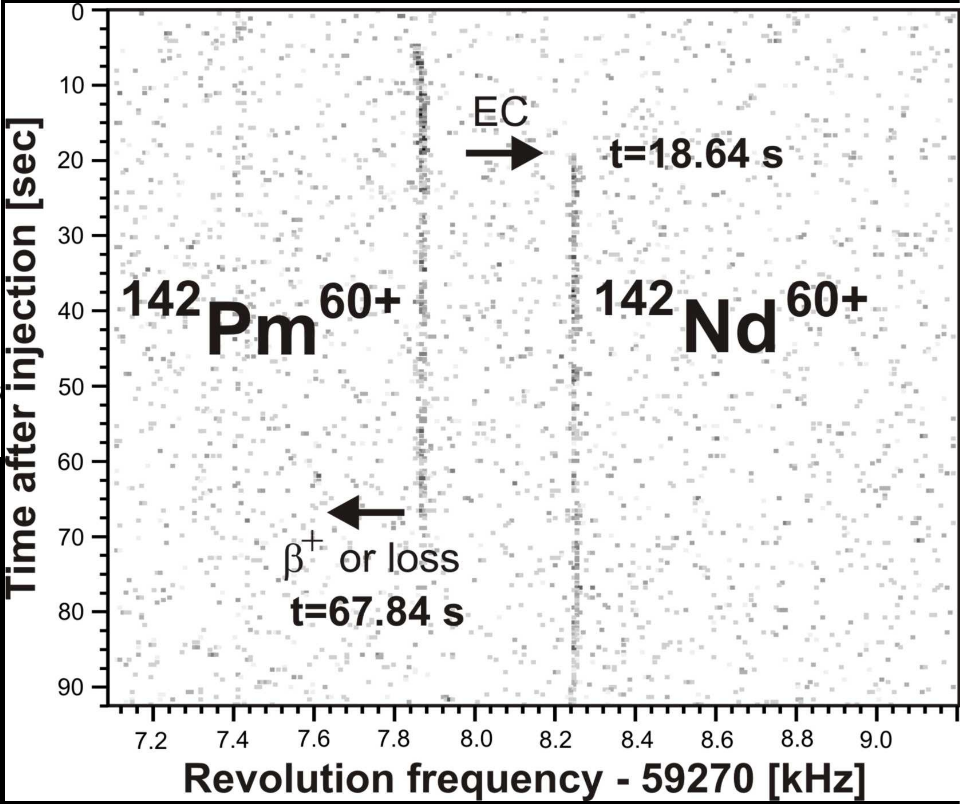
Nuclear Decay of Stored Single Ions

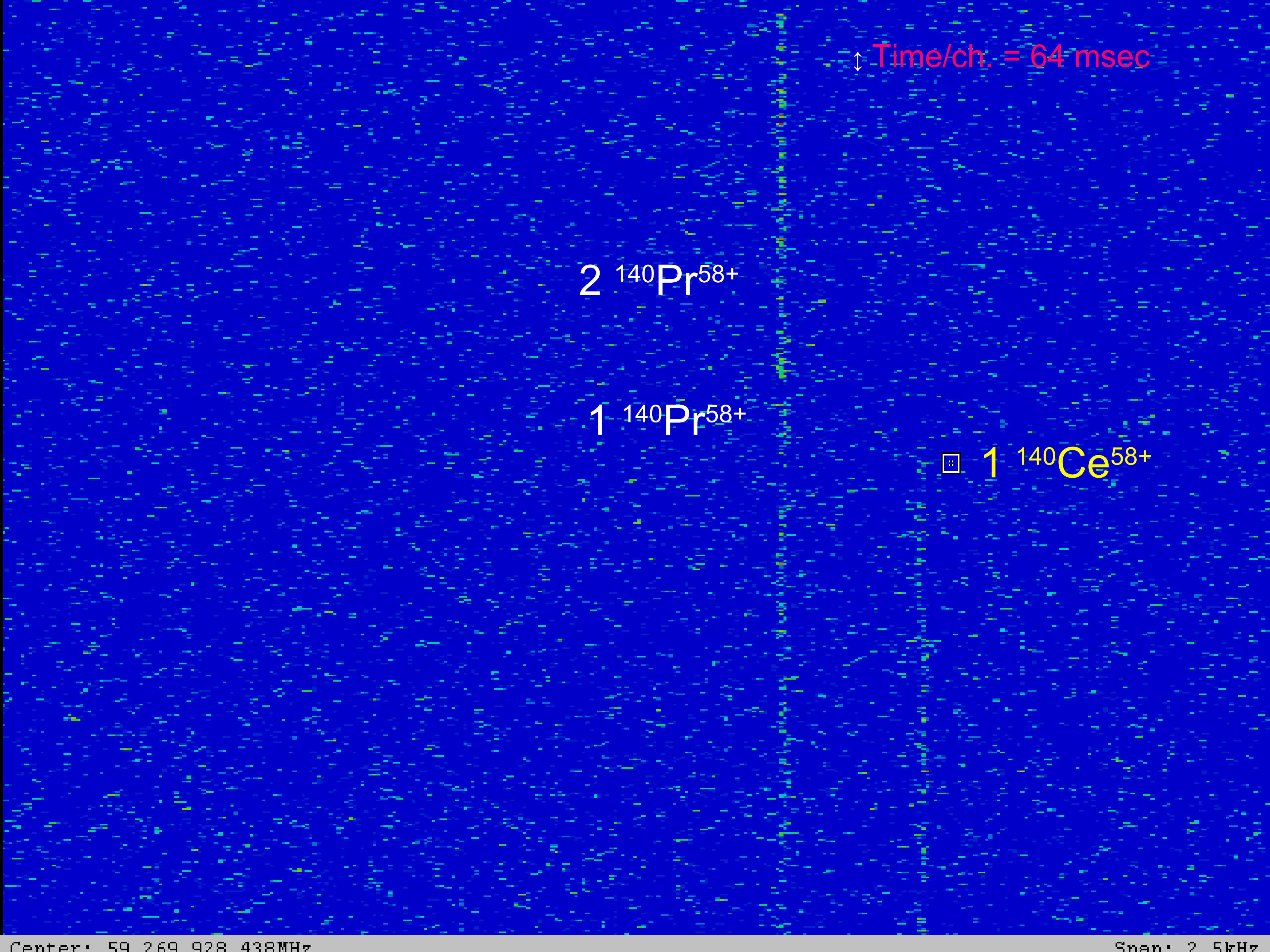


Time/channel = 30 sec.

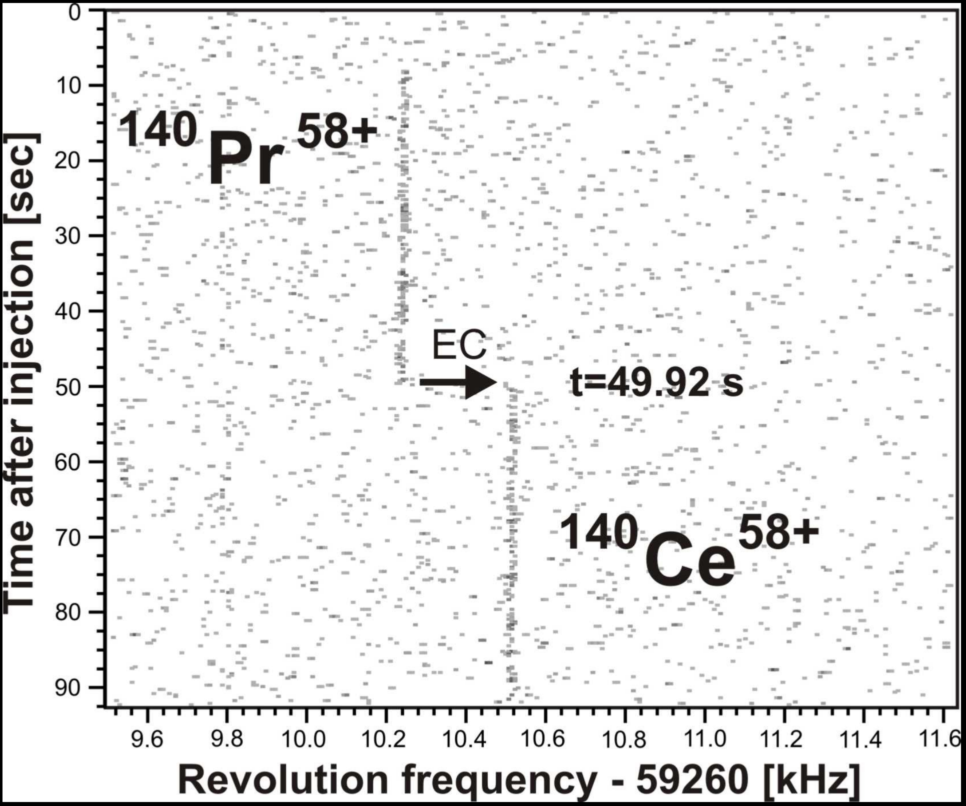
Examples of measured time-frequency traces






↕ Time/ch. = 64 msec
2 140Pr58+
1 140Pr58+
1 140Ce58+
Center: 59.269 928 438MHz
Span: 2.5kHz

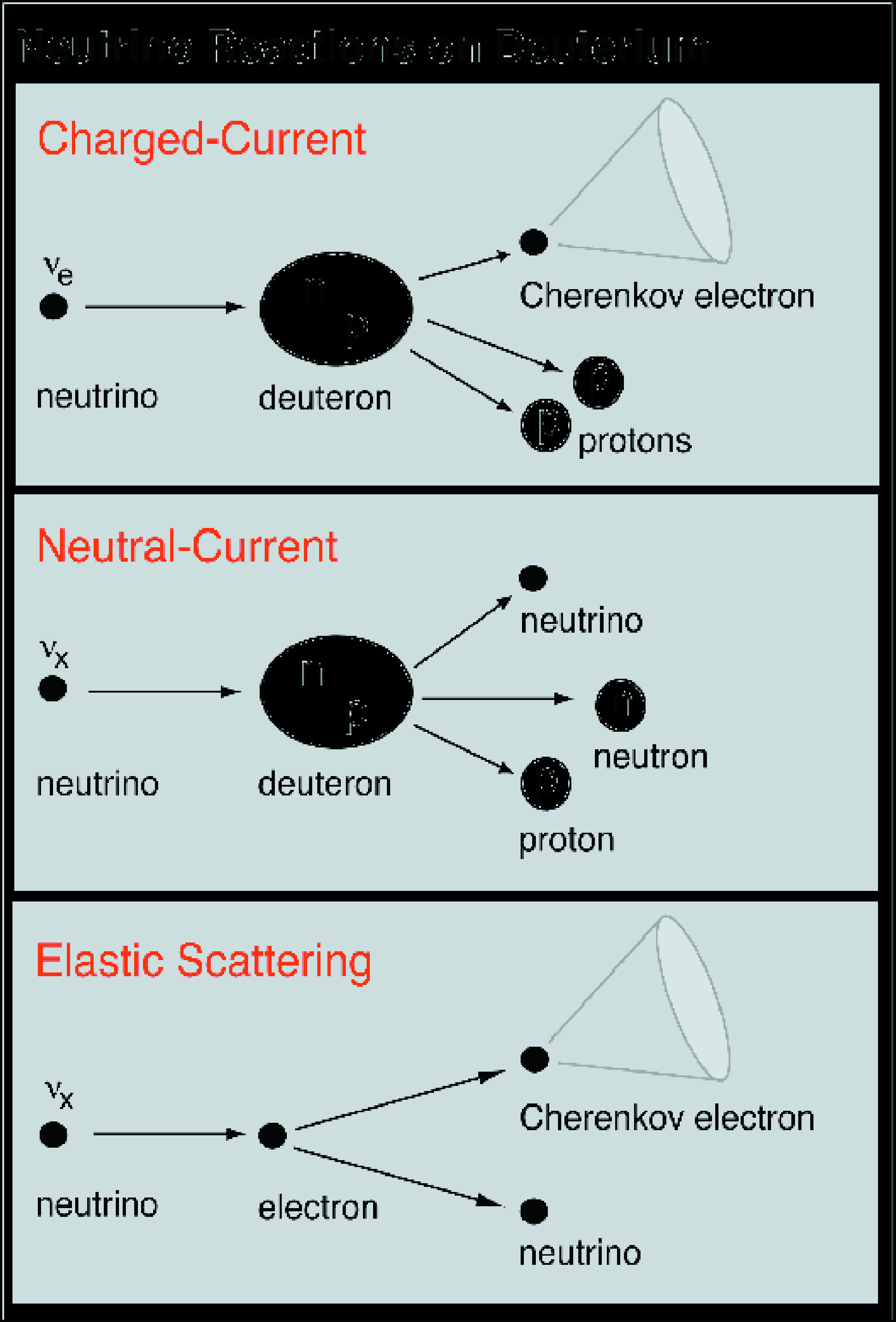
Properties of measured time-frequency traces



1. Continuous observation
2. Parent/daughter correlation
3. Detection of all EC decays
4. Delay between decay and "appearance" due to cooling
5. ^{140}Pr: E_R = 44 eV
   Delay: 900 (300) msec

   ^{142}Pm: E_R = 90 eV
   Delay: 1400 (400) msec

Measured frequency: p transformed to n (hadronic vertex)
bound e^- annihilated (leptonic vertex)
→ ν in flavour eigenstate ν_e created at t_d
if lepton number conservation holds



Charged-Current event at SNO

Appearance of **two protons and of a fast electron:**

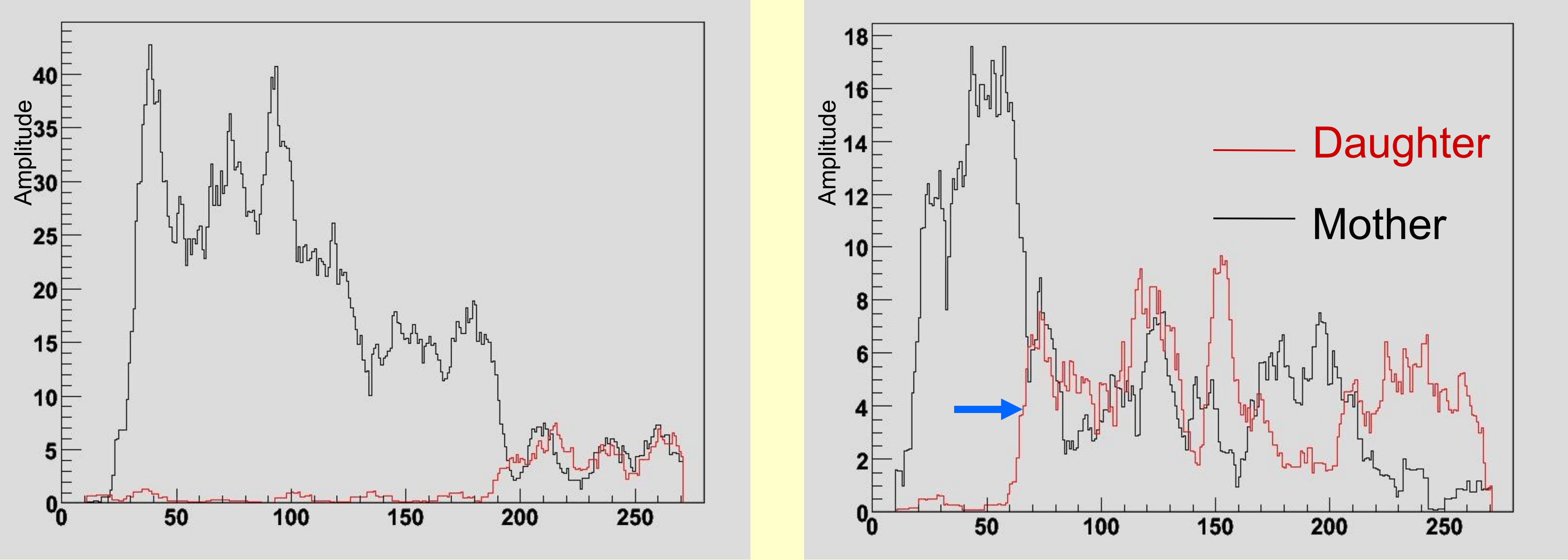
ν_e- component picked-up from incoming neutrino :

$$\nu_e + n \rightarrow p + e^-$$

$$\nu_e = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$$

Why we have to restrict onto 3 injected ions at maximum ?

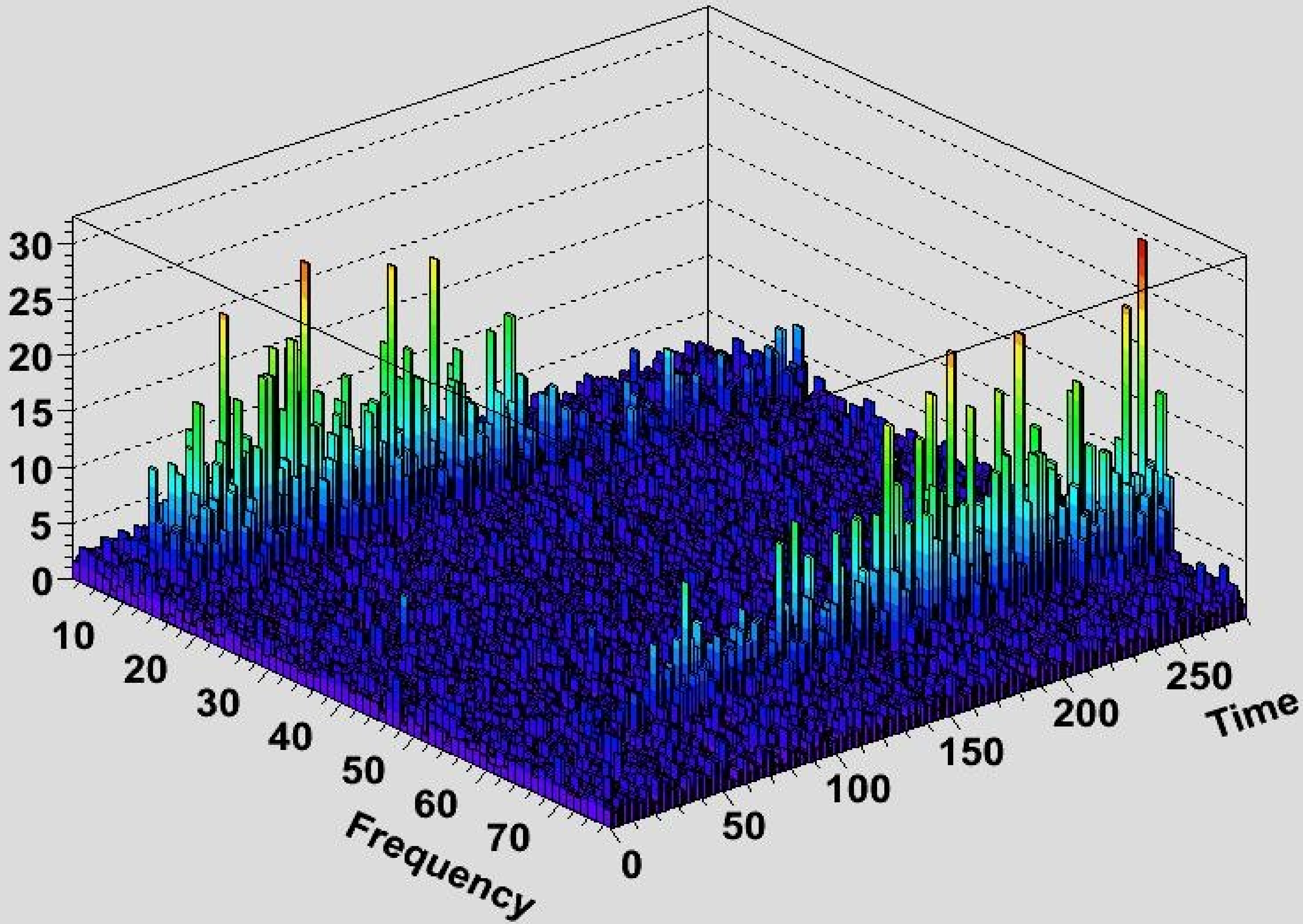
The variance of the amplitudes gets larger than the step 3→4 ions



Amplitude distributions corresponding to **1,2,3-particles**; 1 frame = 64 msec.

The presented final data suppose **agreement within +- 320 msec.** between computer- and "manual" evaluation; always the **"appearance"** time has been taken

Frequency-time characteristics of an EC decay



EC in H-like ions for nuclear g.s.→ g.s. transitions

Decay identified by a **change of atomic mass at time t_d**

→ Appearance of the recoiling daughter ion shortly **later** (cooling)

Distribution of delays due to **emission characteristics** of the neutrino

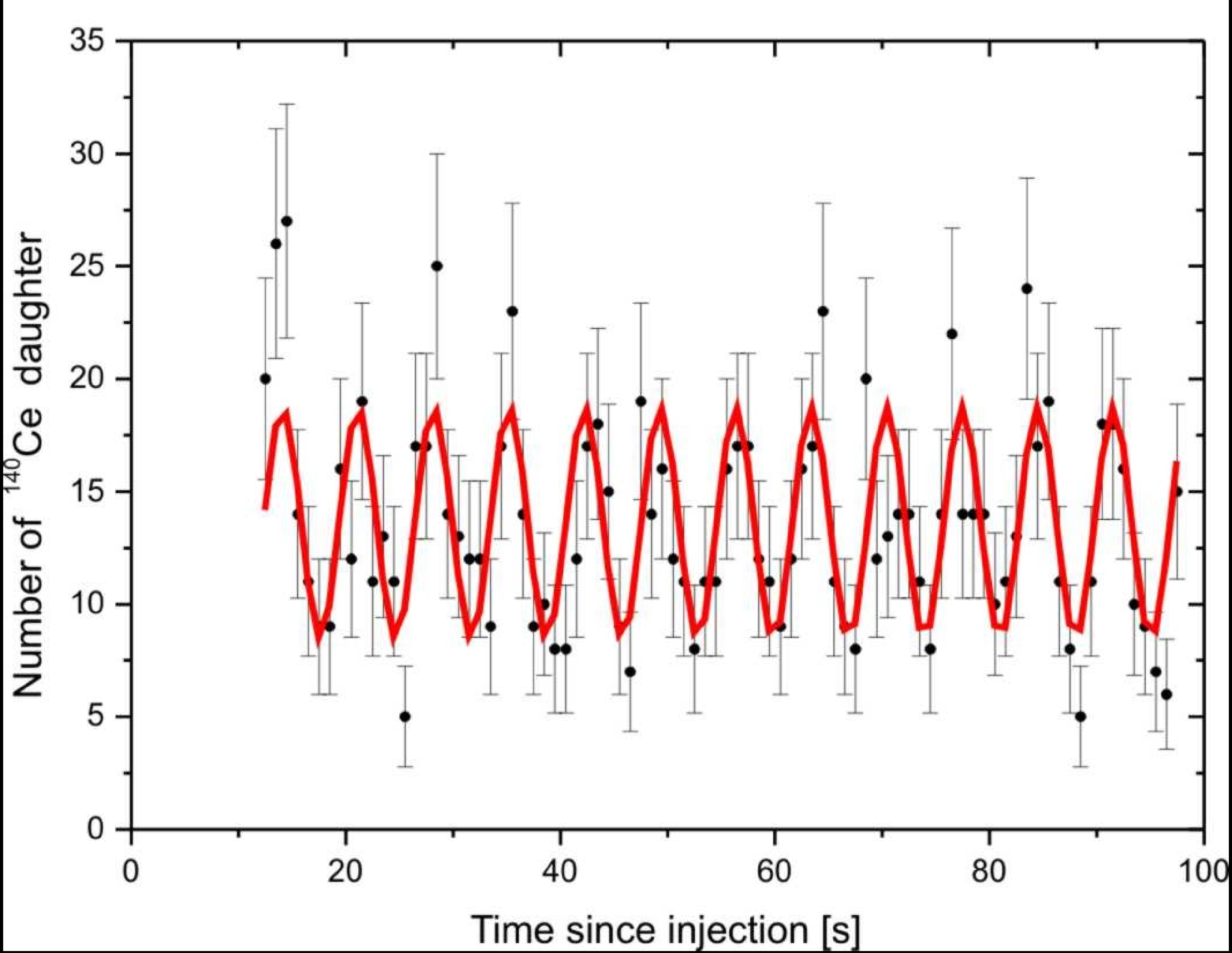
No third particle involved

→ **daughter nucleus and neutrino entangled** by momentum- and energy conservation → **EPR scenario**

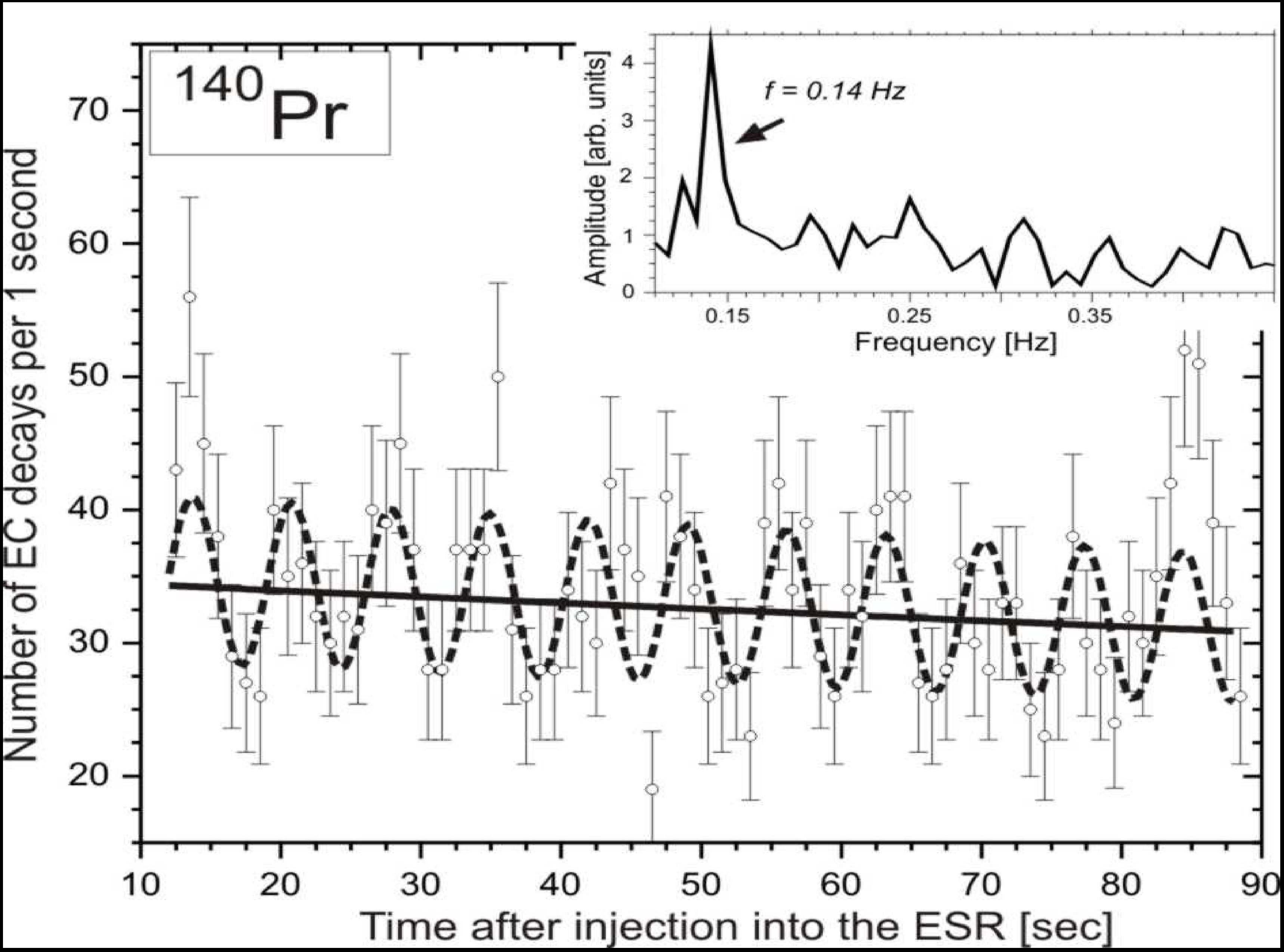
3. Experimental results of EC of H-like ^{140}Pr and ^{142}Pm

Yu. Litvinov, F. Bosch et al., arXiv: 0801.2079, Phys. Lett. B in press

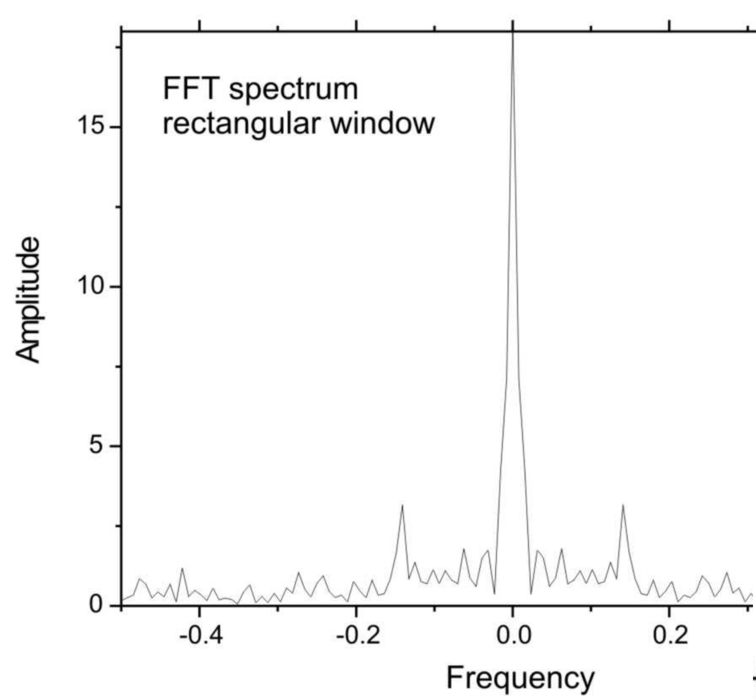
Decay statistics of $^{140}Pr^{58+}$ EC-decays

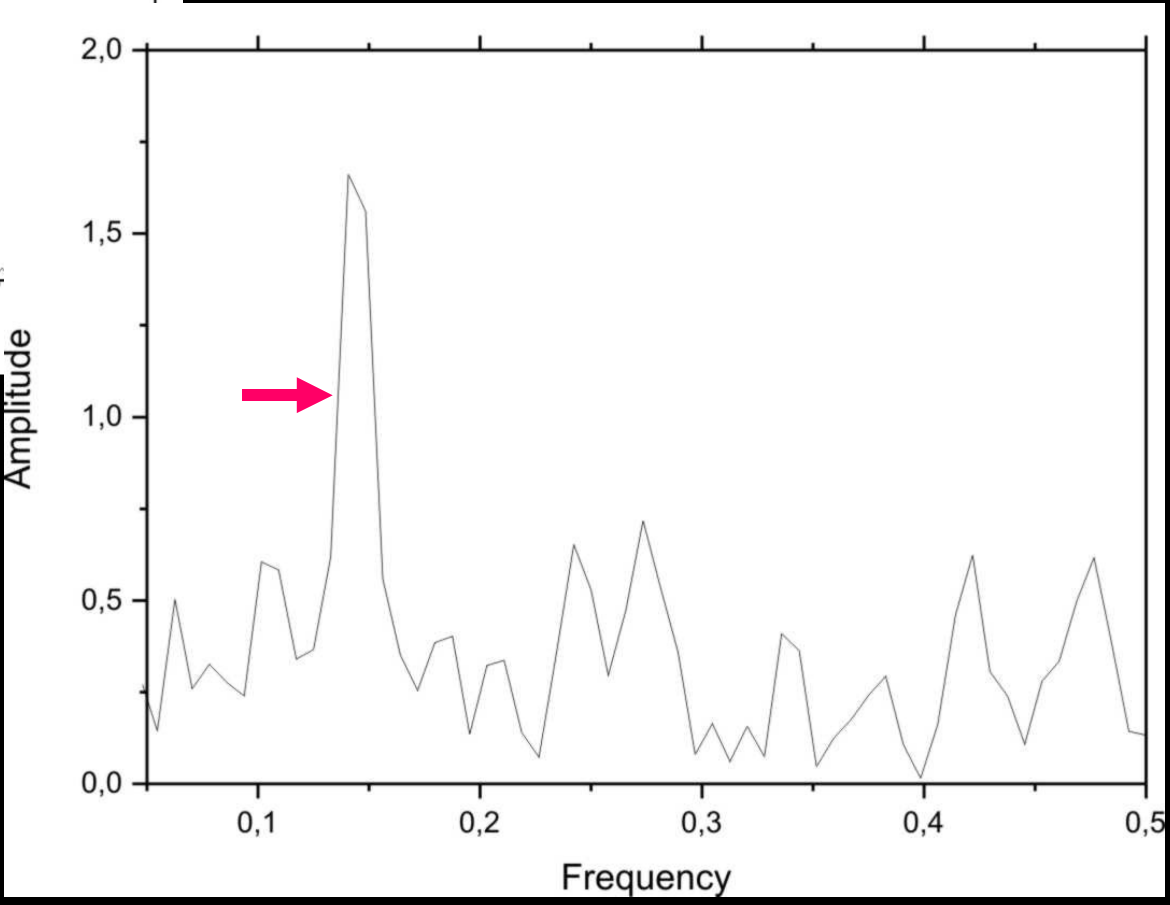


^{140}Pr all runs: 2650 EC decays from 7102 injections



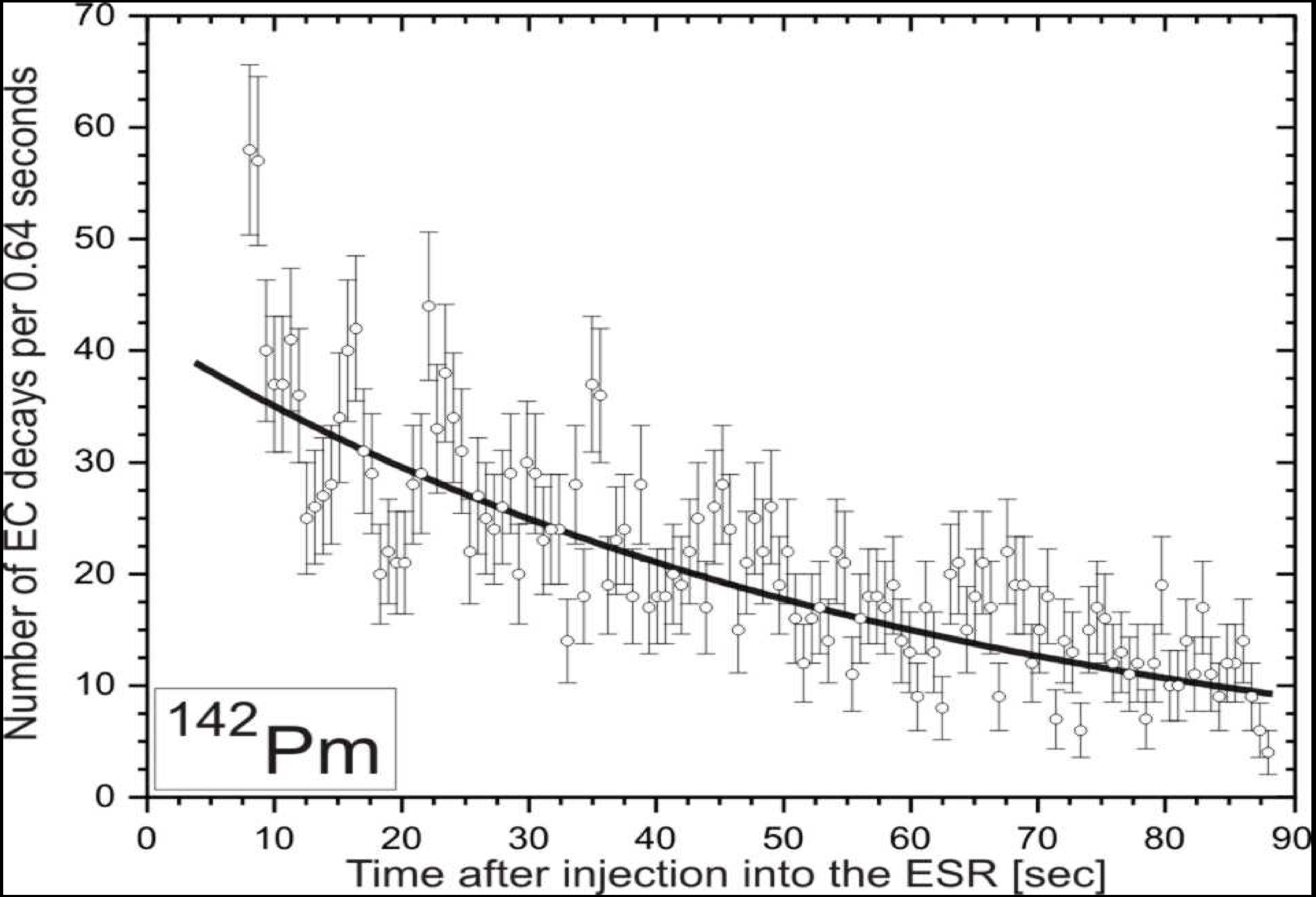
Fast Fourier Transform of the data



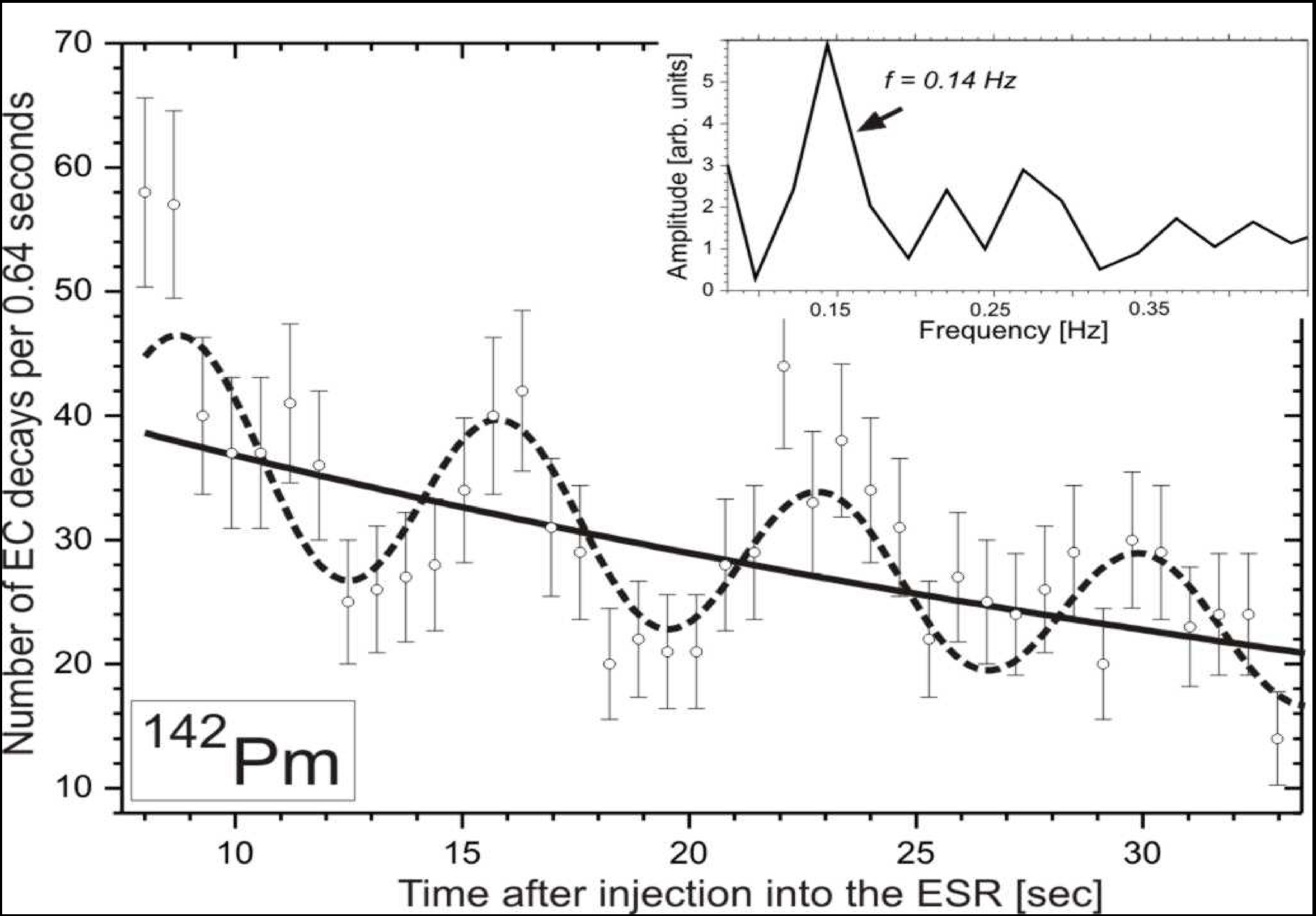


Frequency peak at f = 0.142 Hz

^{142}Pm: 2740 EC decays from 7011 injections



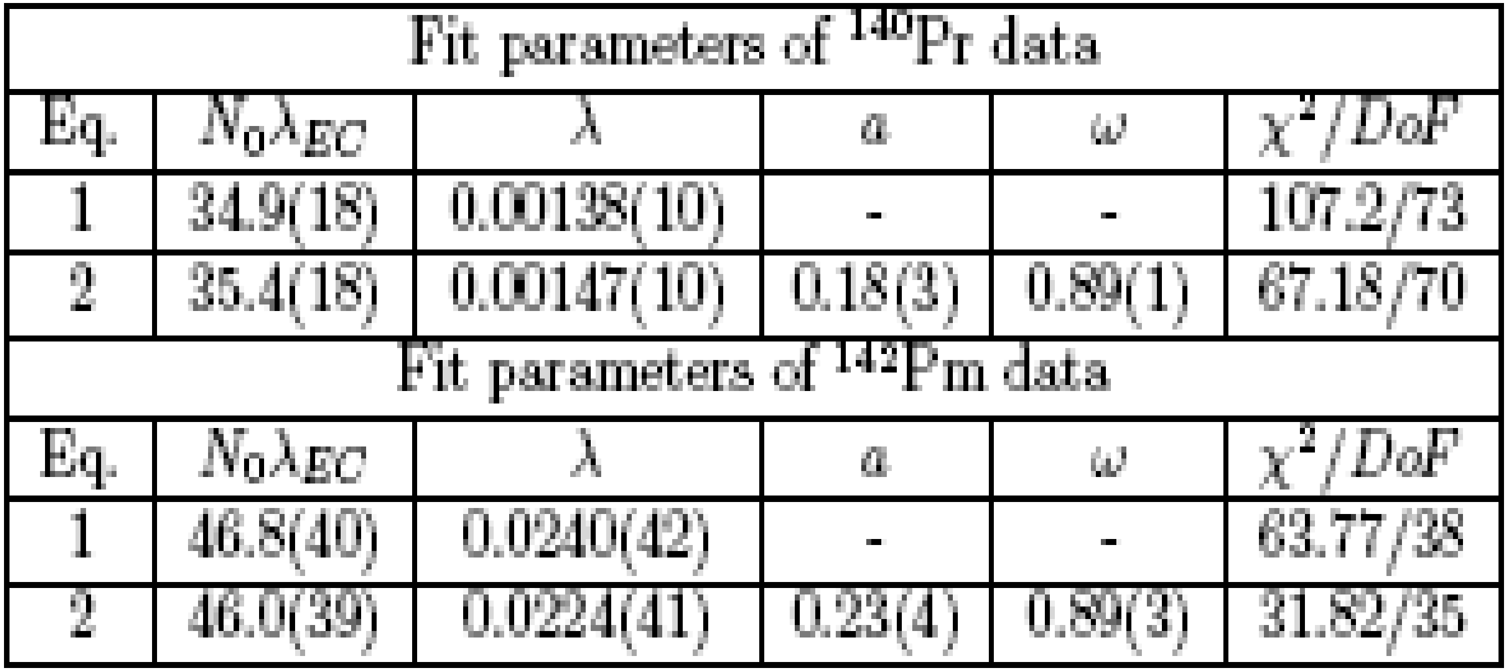
^{142}Pm: zoom on the first 33 s after injection



Fits with pure exponential (1) and superimposed oscillation (2)

$dN_{EC}(t)/dt = N_0 \exp\{-\lambda t\} \lambda_{EC}$; $\lambda = \lambda_{\beta+} + \lambda_{EC} + \lambda_{loss}$ (1)

$dN_{EC}(t)/dt = N_0 \exp\{-\lambda t\} \lambda_{EC}(t)$; $\lambda_{EC}(t) = \lambda_{EC}[1 + a \cos(\omega t + \varphi)]$ (2)



Fit parameters of ^{140}Pr data

Eq.	$N_0 \lambda_{EC}$	λ	a	ω	χ^2/DoF
1	34.9(18)	0.00138(10)	-	-	107.2/73
2	35.4(18)	0.00147(10)	0.18(3)	0.89(1)	67.18/70

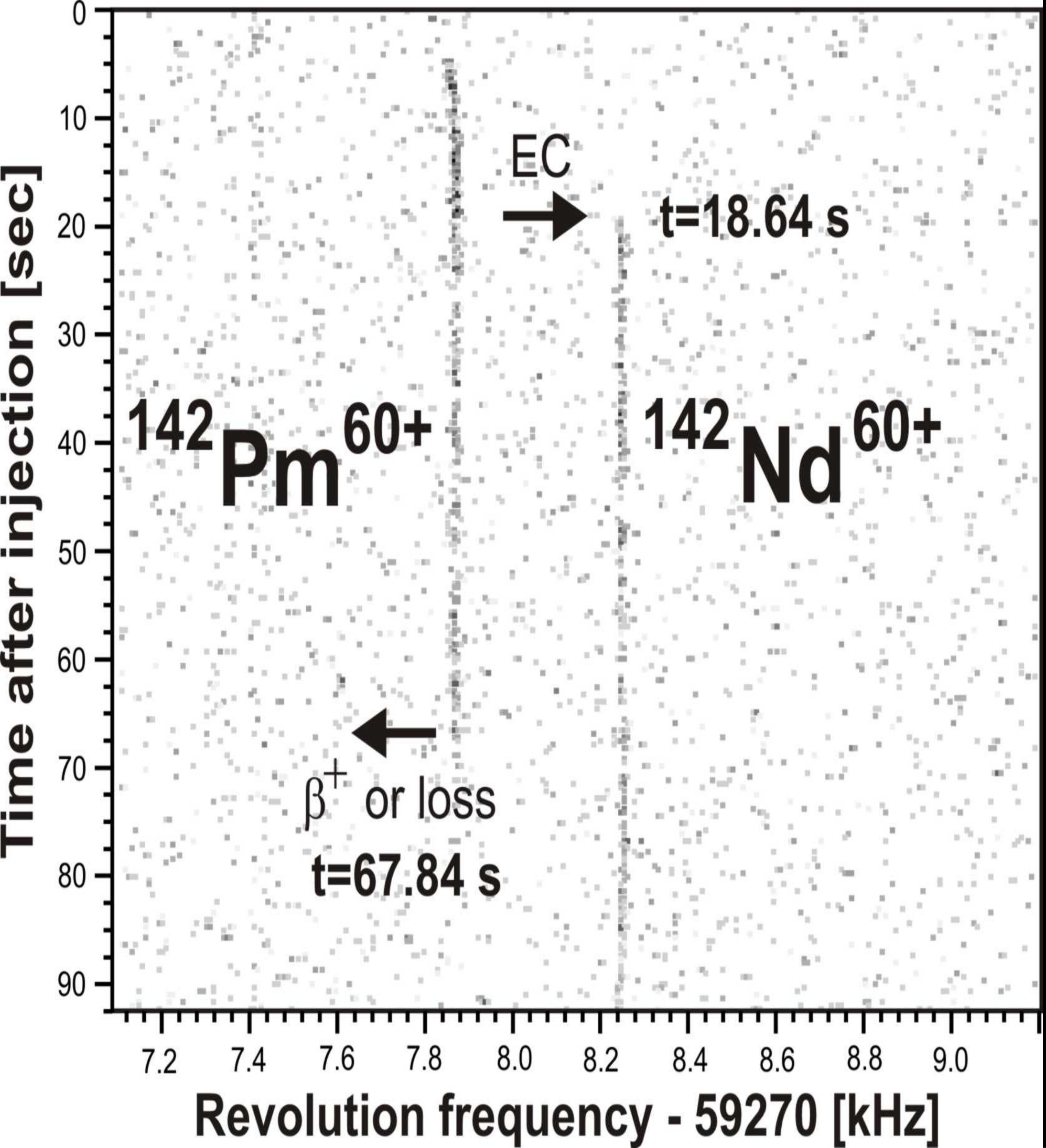
Fit parameters of ^{142}Pm data

Eq.	$N_0 \lambda_{EC}$	λ	a	ω	χ^2/DoF
1	46.8(40)	0.0240(42)	-	-	63.77/38
2	46.0(39)	0.0224(41)	0.23(4)	0.89(3)	31.82/35

T = 7.06 (8) s
φ = - 0.3 (3)

T = 7.10 (22) s
φ = - 1.3 (4)

4. Tentative explanation(s)



periodic "holes" ?

no

1. Are the periodic modulations real ?

   → artefacts nearly **excluded**, but

   statistical significance only 3.5 σ at present

2. Can **periodic beats** be preserved over macroscopic times for a motion **confined in an electromagnetic potential** and at **continuous observation** ?

→ C. Giunti: **"no"** in arXiv: 0801.4639v2, March 4, 2008

Addendum 2: Quantum effects in GSI nuclear decay

C. Giunti in arXiv: 0801.4639v3, April 17, 2008

"In the first version of this addendum **I incorrectly claimed** that the GSI anomaly **cannot be due to a quantum effect** in nuclear decay. I would like to thank Yu.A. Litvinov for an enlightening discussion on this point...

...The GSI anomaly could be due to the **quantum interference between two coherent states** of the decaying ion if the interaction with the measuring apparatus does **not distinguish** between the two states. In order to produce quantum beats with the observed period of about 7 s, the **energy splitting** between the two states must be of the **order of 10^{-16} eV**...

The problem is to **find the origin of such a small energy splitting**....

It is difficult to find a [corresponding] energy splitting."

"Classical" quantum beats

Coherent excitation of an electron in two quantum states, separated by ΔE at time t_0, e.g. $^3P_0$ and $^3P_2$

Observation of the decay photon(s) as a function of $(t-t_0)$

Exponential decay modulated by

$\cos(\Delta E/h\ 2\pi\ (t-t_0))$

if **$\Delta T \ll \Delta t = h/(2\pi\Delta E)$**

→ no information whether E_1 or E_2

"which path"? addition of **amplitudes**

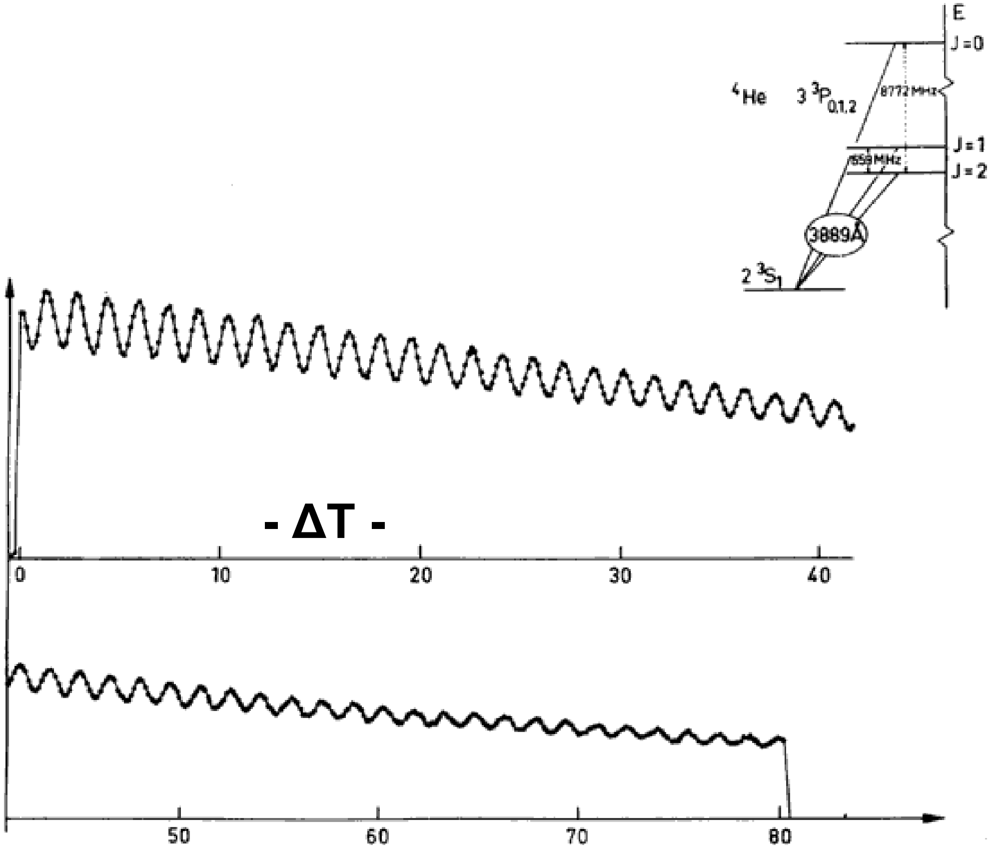


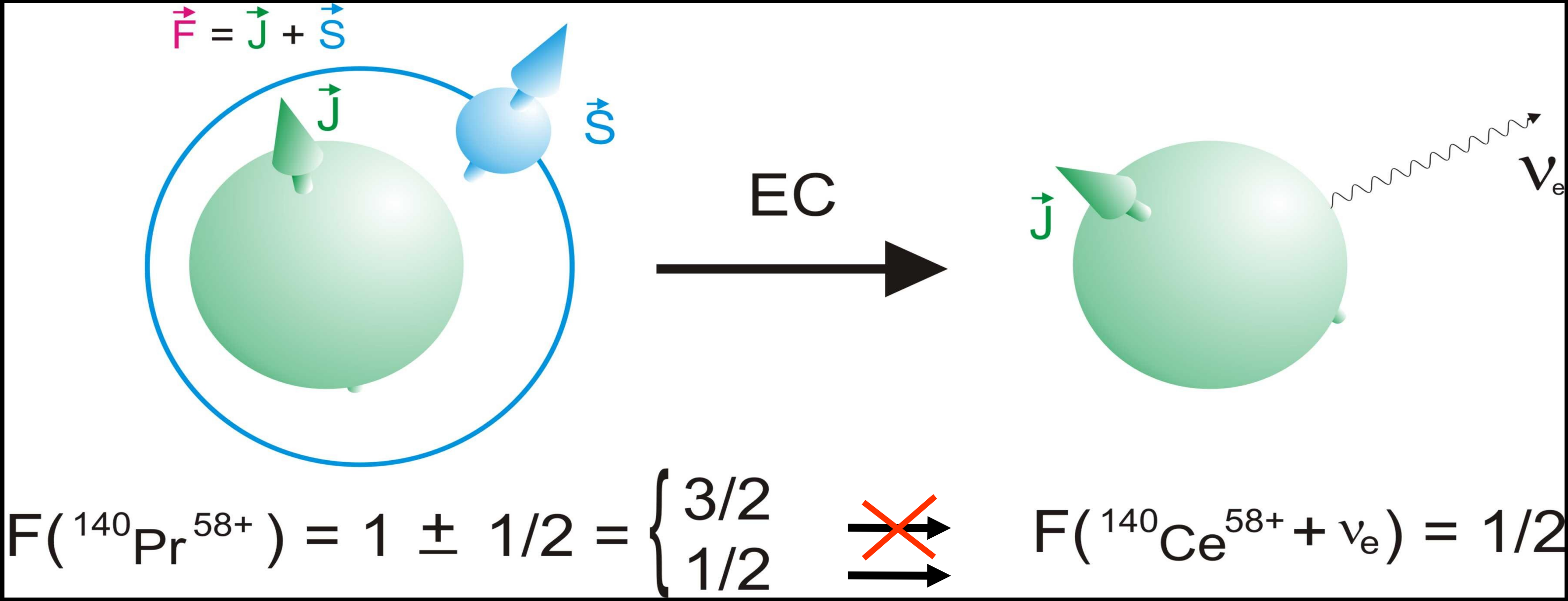
Fig. 24. Zero-field oscillations between the 1s 3p $^3P_1$ and 1s 3p $^3P_2$ states in He I (659 MHz), Wittmann [248]. The oscillations are superimposed on the exponential decay of the 1s 3p ^3P term (96 ns). To record this decay curve about 10 hours beam time (a few μA) and more than 20 carbon foils were needed.

Chow et al., PR **A11**(1975) 1380

Quantum beats from the hyperfine states

Coherent excitation of the 1s hyperfine states F =1/2 & F=3/2

Beat period $T = h/\Delta E \approx 10^{-15}$ s



$$F(^{140}\text{Pr}^{58+}) = 1 \pm 1/2 = \begin{cases} 3/2 & \cancel{\longrightarrow} \\ 1/2 & \longrightarrow \end{cases} \quad F(^{140}\text{Ce}^{58+} + \nu_e) = 1/2$$

$\mu = +2.7812\ \mu_N$ (calc.)

Decay can occur only from the F=1/2 (ground) state

Periodic spin flip to "sterile" F=3/2 ? → λ_{EC} reduced

Periodic transfer from F = 1/2 to "sterile" F = 3/2 ?

1. Decay constants for H-like ^{140}Pr and ^{142}Pm should get smaller than expected. ⟶ NO

2. Statistical population in these states after $t \approx \max\,[1/\lambda_{flip}, 1/\lambda_{dec.}]$

3. Phase matching over many days of beam time?

Classical quantum beats vs.EC-decay in the ESR

Quantum beats

- **two well-defined initial states**
- **excited atom moves free in space**
- **observation time nanoseconds - microseconds**

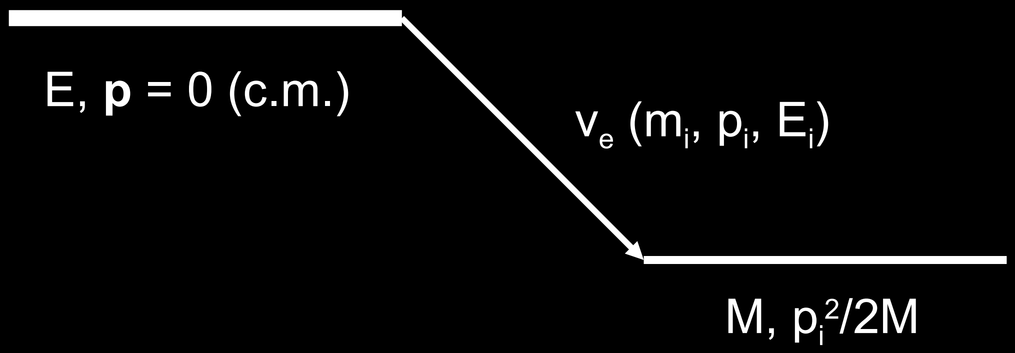
EC - decay of H-like ions stored in a ring

- **parent atom created by nuclear reaction**
- **moves confined by electromagnetic forces**
- **interacts with e^- of the cooler, atoms, beam pipe..**
- **observation time some 10 seconds**

Beats due to neutrino being not a mass eigenstate?

The electron neutrino appears as coherent superposition of mass eigenstates

The recoils appear as coherent superpositions of states entangled with the electron neutrino mass eigenstates by momentum- and energy conservation



E, $\mathbf{p} = 0$ (c.m.)

ν_e (m_i, p_i, E_i)

M, $p_i^2/2M$

$M + p_1^2/2M + E_1 = E$

$M + p_2^2/2M + E_2 = E$

"Asymptotic" conservation of E, $\mathbf{p}$

$m_1^2 - m_2^2 = \Delta^2 m = 8 \cdot 10^{-5}\,\mathrm{eV}^2$

$E_1 - E_2 = \Delta E_\nu$

$$\boldsymbol{\Delta E_\nu \approx \Delta^2 m/2M = 3.1 \cdot 10^{-16}\ \mathrm{eV}}$$

$$\boldsymbol{\Delta p_\nu \approx -\Delta^2 m/\ 2 \langle p_\nu \rangle = 2 \cdot 10^{-11}\ \mathrm{eV}}$$

$\cos(\Delta E/\hbar\, t)$ with $T_{lab} = h\,\gamma\,/\,\Delta E \approx 7\mathrm{s}$

a) $M = 140$ amu, $E_{\nu} = 3.39$ MeV (Pr)

b) $M = 142$ amu, $E_{\nu} = 4.87$ MeV (Pm)

$M = 141$ amu, $\gamma = 1.43$, $\Delta^2 m_{12} = 8 \cdot 10^{-5}\ \mathrm{eV}^2$

$$\Delta E = h\gamma\,/\,T_{lab} = 8.4 \cdot 10^{-16}\ \mathrm{eV}$$

$$\Delta E_{\nu} = \Delta^2 m\,/2\,M = 3.1 \cdot 10^{-16}\ \mathrm{eV}$$

H.J. Lipkin

New method for studying neutrino mixing and mass differences

arχiv: 0801.1465v1 [hep-ph]

"The initial nuclear state has a **momentum spread** required by Heisenberg. The wave packet contains pairs of components with different momenta which can produce neutrinos in two mass eigenstates with exactly the same energy and different momenta.

These neutrino amplitudes mix to produce a single electron-neutrino state with the same energy. Since there is no information on which mass eigenstates produced the neutrino this is a typical quantum mechanics 'two-slit' or 'which path' experiment. A transition between the same initial and a final states can go via two paths with a phase difference producing interference and oscillations."

(Abstract)

"The final 'electron-neutrino' state is a linear combination of mass eigenstates with the same energy, different momenta and a well defined phase. During the passage of the radioactive nucleus between the point where it enters the apparatus and the point where the decay transition takes place the relative phases between the momentum eigenstate components of the initial wave function change linearly with the distance.

Thus the probability that the decay will take place to the final electron neutrino state oscillates with the distance [X] travelled by the nucleus along its trajectory in space. The wave length of the oscillation depends upon the momentum difference which in turn depends upon the mass differences between the mass eigenstates. " [$P_1 - P_2 = f\,(p_1 - p_2, p_v, m(\text{recoil}))$]

(page 4)

X

$\mathbf{P_i} = \mathbf{p_i}(v_i) + \mathbf{p_i}\,(\text{recoil})$

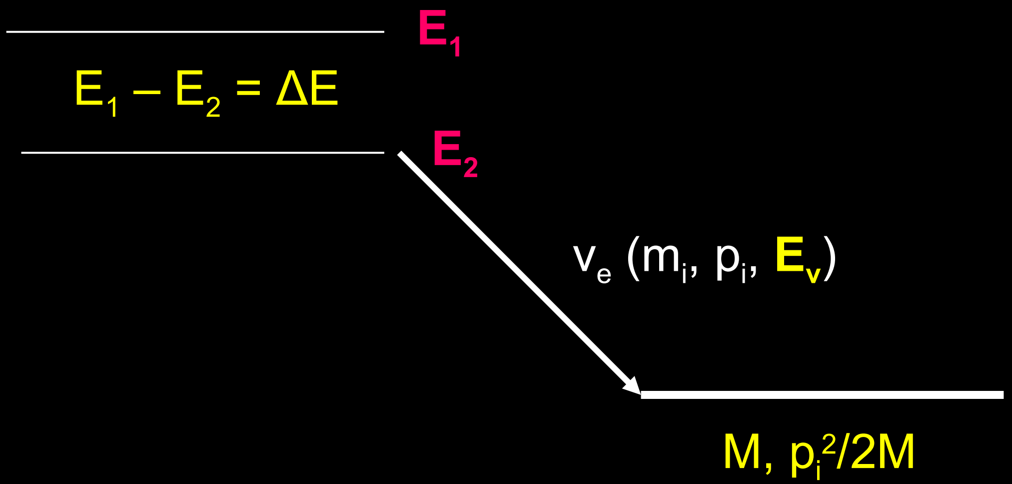
$P_1 \rightarrow\rightarrow\rightarrow\rightarrow E_v, p_1(v_1), m_1, p_1\,(\text{recoil}) \quad \exp\,(i\,P_1X)$

{ } $|v_e> @ |\text{rec.}>$

$P_2 \rightarrow\rightarrow\rightarrow\rightarrow E_v, p_2(v_2), m_2, p_2\,(\text{recoil}) \quad \exp\,(i\,P_2X)$

* **Same** energy of the ν mass eigenstates (Lipkin)

$E_\nu(1) = E_\nu(2) = E_\nu$ → **two** different **initial** energies **E_1, E_2**



$M + p_1^2/2M + E_\nu = E_1$

$M + p_2^2/2M + E_\nu = E_2$

ΔE $= (E_\nu^2 - m_1^2 - E_\nu^2 + m_2^2) / 2M$ **$= - \Delta^2 m / 2M$** $\approx -3 \cdot 10^{-16}$ eV

$\Delta p_\nu = - \Delta^2 m / 2\langle p_\nu \rangle \approx -2 \cdot 10^{-11}$ eV

???

H. Lipkin	arXiv: 0801.1465v1,2 [hep-ph]
A. Ivanov, P. Kienle et al.,	arXiv: 0801.2121 [nucl-th]
M. Faber	arXiv: 0801.3262 [nucl-th]

Beats due to emitted neutrino being not a mass eigenstate

C. Giunti (and many others) arXiv: 0801.4639v1,2,3 [hep-ph]

Could only happen
if there would be two different initial states, separated by $\approx 10^{-16}$ eV...

Beats due to neutrino being not a mass eigenstate?

A few out of many objections :

1. No coherence due to the orthogonality of mass eigenstates

C. Giunti, arXiv: 0801.4639v1 [hep-ph], January 30, 2008

$$|\nu_e(t)\rangle = \Sigma A_k(t)\,|\nu_k\rangle \quad \text{(eq. 9)}$$

→ decay amplitude **$A(t) = (\Sigma\,|\alpha_k A_k(t)|^2)^{1/2}$**

At t_d one has to project $|\nu(t)\rangle$ onto the flavour eigenstate $|\nu_e\rangle$

$$|\nu(t_d)\rangle = \Sigma A_k(t_d)\,|\nu_e\rangle\langle\nu_e|\nu_k\rangle$$

→ decay amplitude **$A(t_d) = (|\Sigma\,\beta_k A_k(t_d)|^2)^{1/2}$**

Beats due to neutrino being not a mass eigenstate?

2. One does **not** observe the neutrino: → **no** interference **(EPR?)**

3. Beats are only possible if the **flavour** is determined at both the **generation and the decay** (M. Lindner)

4. One observes the quantum state of the system **continuously** :
→ **no beats** (Giunti V2),
except the two states **cannot** be distinguished (Giunti V3)

Beats due to neutrino being not a mass eigenstate ?

We have no information on which neutrino mass eigenstate was created

$$\alpha_1\ [\,|\,v_1> (E_{v1},\ p_{v1},\ m_1,\ p_1,)\ \ @\ \ \mathrm{Rec.}_1>]$$

$$\}\ \mathrm{I}v_e>\ @\ |\,\mathrm{Rec}_e>$$

$$\alpha_2\ [\,|\,v_2> (E_{v2},\ p_{v2},\ m_2,\ p_2,)\ \ @\ \ \mathrm{Rec.}_2>]$$

"which path" experiment → addition of the amplitudes

if there would be two different initial (parent) states

5. Summary, questions and outlook

For the two-body EC decays of H-like ^{140}Pr and ^{142}Pm periodic modulations according to $e^{-\lambda t}\,[1+a\cos(\omega t+\varphi)]$ with $T_{lab} = 2\pi/\omega = 7s$, $a \approx 0.20\ (4)$ were found

Statistical fluctuations are not excluded on a c.l. > 3.5 σ

Supposing $\Delta E = h\,\gamma/T_{lab} = \Delta^2 m_{12} / 2M$ $(\gamma = 1.43)$

$\rightarrow$ **$\Delta^2 m_{12} = (2M\,h\,\gamma) / T_{lab} = 2.20 \cdot 10^{-4}\ eV^2$**

Things get **really** interesting only if

1. Oscillations would be observed for other two-body beta decays at **other periods** (proportional to **nuclear mass** ??)
2. A reasonable argument for **two initial states** separated by about **10^{-16} eV** could be found

Outlook

1. Other two-body beta decays (EC, bound beta (β_b) decay):

- bare ^{205}Hg (1/2$^-$) $\beta_b \rightarrow$ ^{205}Tl (1/2$^+$) , β_b - branch ≈ 12% ; ≈ 80% into K shell

- H-like ^{118}Sb (1$^+$) EC → ^{118}Sn (0$^+$) accepted proposal

2. Improving detection (signal-to-noise) → more statistics

3. Evaluation of three-body β^+ decays

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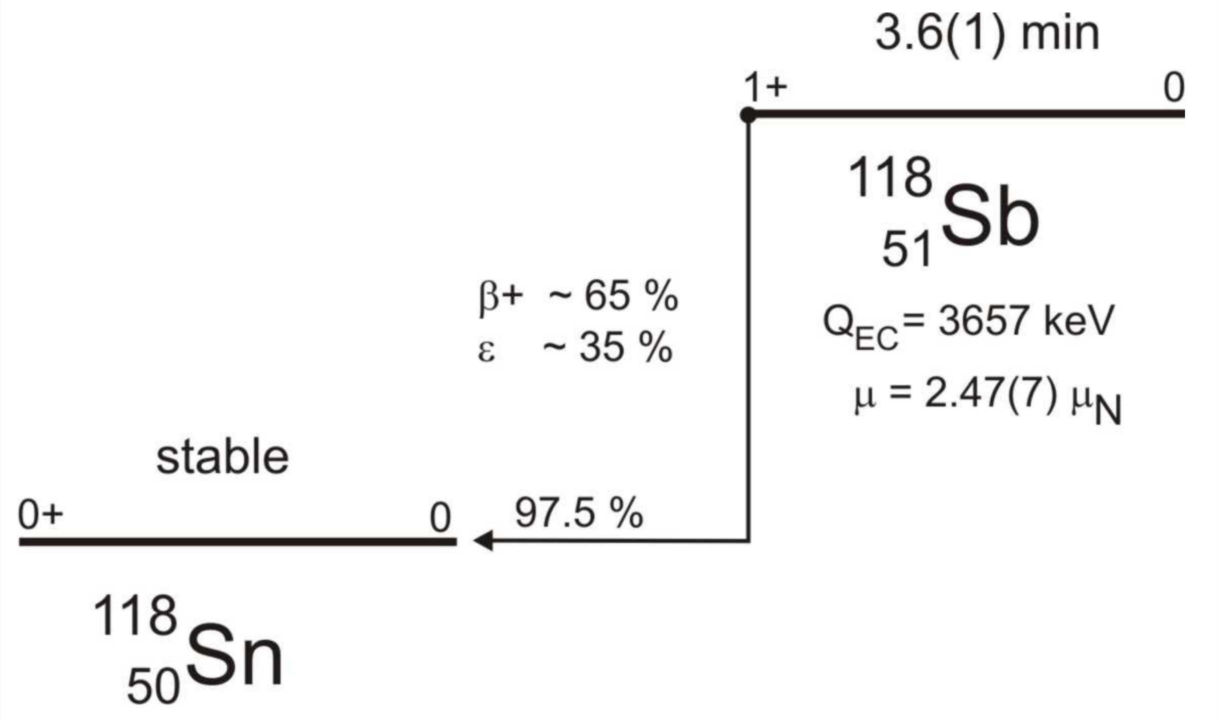
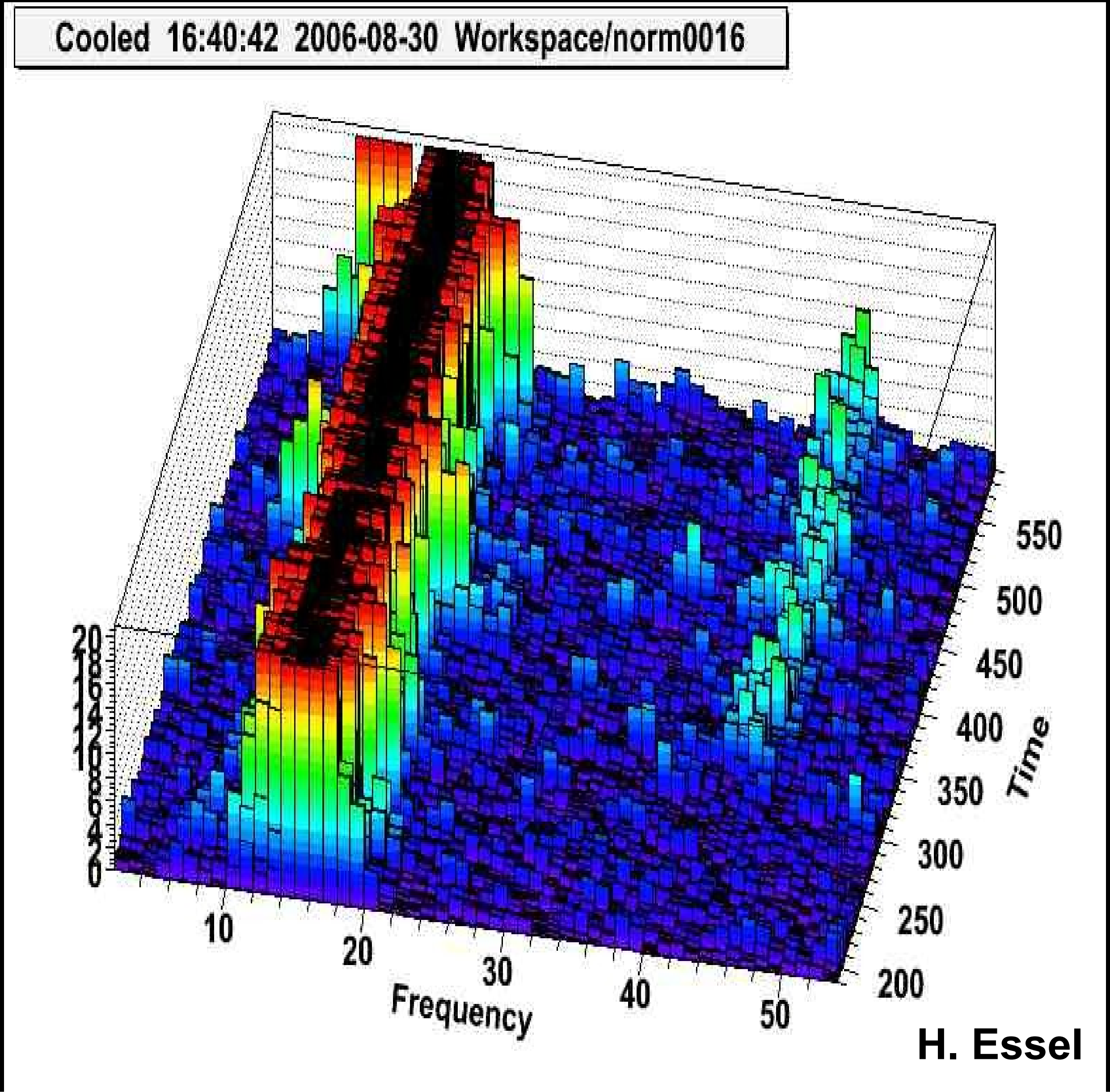
4. Two-body decays to excited states

Decay scheme of ^{118}Sb



Time-frequency relation

β_b -decay of bare $^{205}Hg^{80+} \rightarrow$ H-like $^{205}Tl^{80+}$



test in 2006