EMMI-RRTF on
Non-exponential two-body weak decays

organized by the Helmholtz Institute Jena (HIJ), July 06 -10, 2014

Fritz Bosch, GSI Helmholtzzentrum, Darmstadt, for the „Two-body weak decay-collaboration“

Observation of **periodic modulations** of the electron capture (EC) decay of H-like ions

(PL **B664** (2008),162; PL **B726** (2013),638)

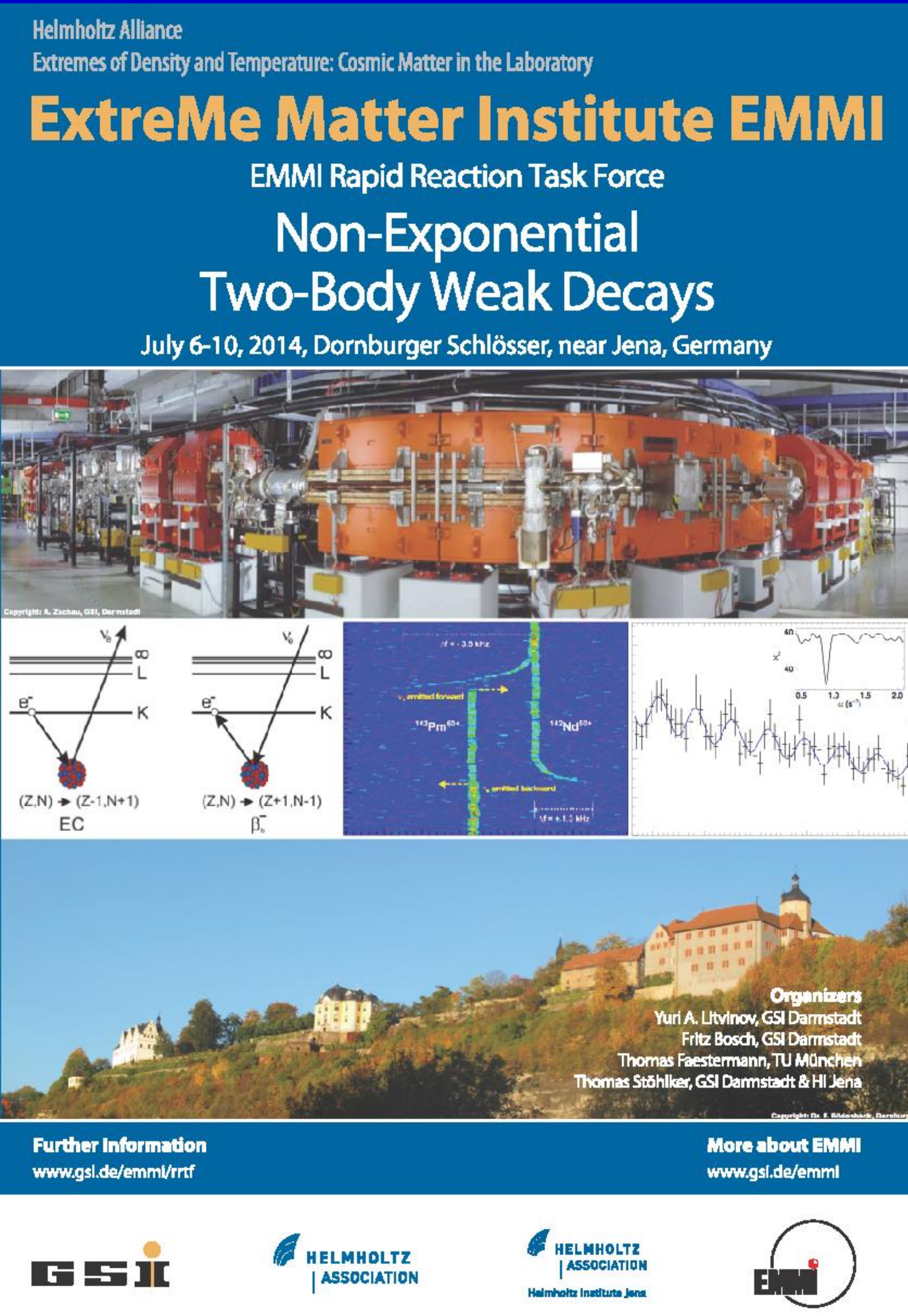
Still under discussion: Are the modulations true? If so, what is their origin?

Tasks of this RRTF:

1. Presentation and discussion of the **actual status of the experiments** on the two-body EC - decay of stored and cooled H-like ions.

2. Discussing **possible origin(s)** of these modulations – supposed they are true

3. Providing a **critical vote** of the participants for the Scientific Directorate of GSI concerning the status and a possible continuation of those experiments in 2014



Entirely sponsored by EMMI. Thank you!

Organizers:
Thomas Stöhlker, HIJ and GSI
Fritz Bosch, GSI
Thomas Faestermann, TU München
Yuri A. Litvinov, GSI

35 invited experts, members of the TBWD coll. and guests

Talks accessible via
www.gsi.de/emmi/rrtf

→ 2014 Non-exponential two-body weak decays
password: **rrtf_jena** → Contributions
→ 24 Talks

"… the fact remains that the exponential decay law, for which we have so much empirical support in radioactive processes, is not a rigorous consequence of quantum mechanics but the result of somewhat delicate assumptions."

E. Merzbacher, *Quantum Mechanics,* p. 484 (1961 edition)
cited by Murray Peshkin at the EMMI-RRTF in Jena

1. Status of the experiments on electron capture -decay of stored H-like atoms

Two-body nuclear β-decays: **$n + \nu_e \leftrightarrow p + e^-_b$**

Orbital electron capture (EC) - and bound beta (β_b) – decay

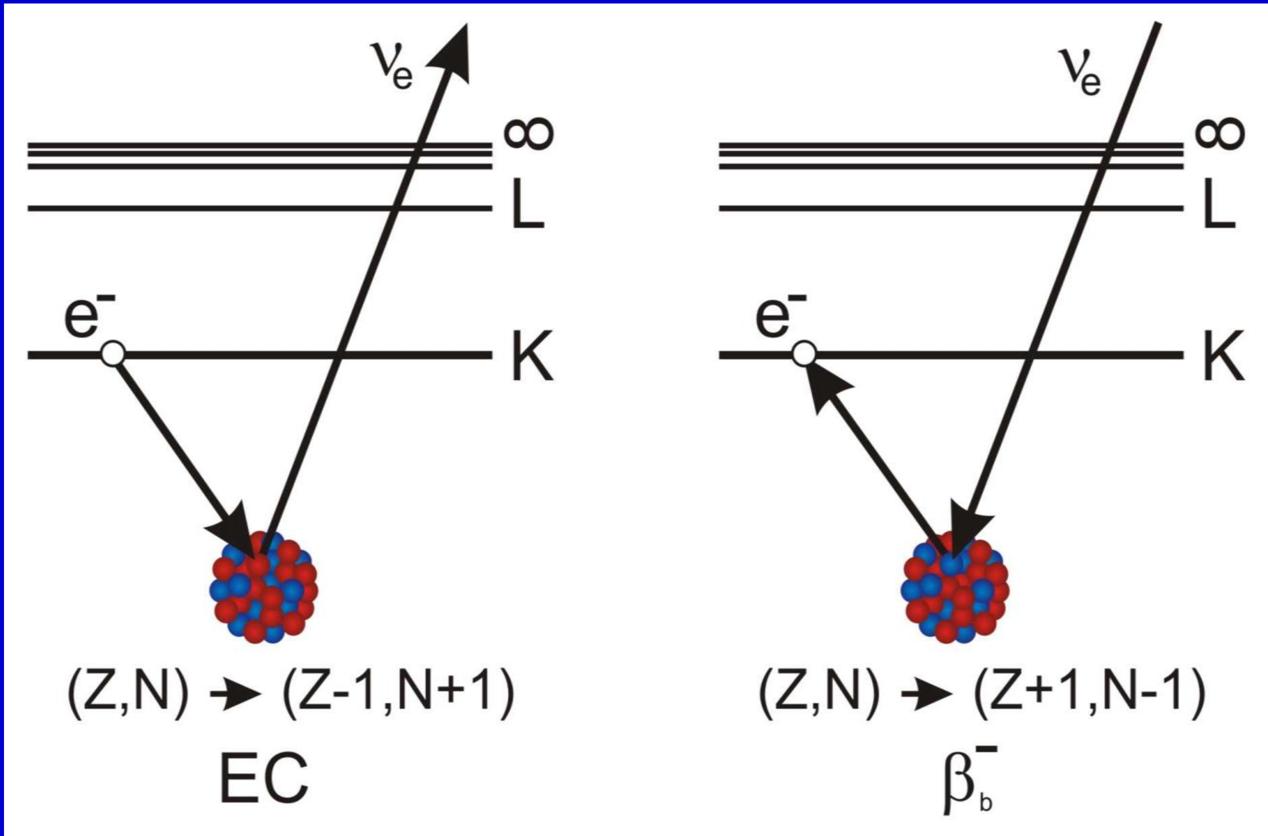
EC

$p + e_b \rightarrow n + \nu_e$

β_b

$n + \nu_e \rightarrow p + e_b$

EC ←Time reversion→ β_b



Two-body β decay of few-electron ions with mono-energetic ν_e

Observing time-resolved the EC- decay of single ions in most simple quantum states (**bare, H-like or He-like ions)**

A storage ring or trap needed

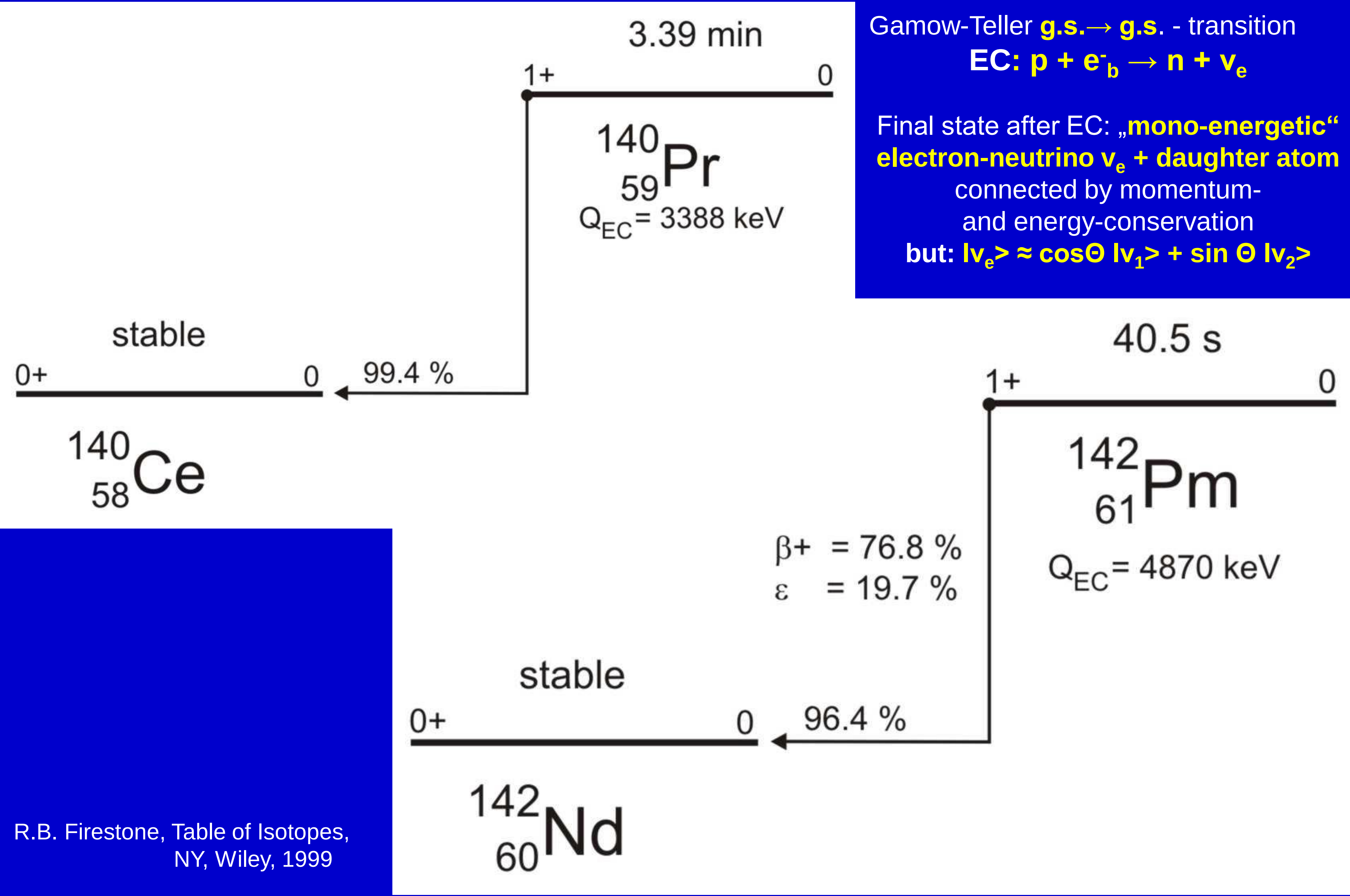
β - decay of H-like ^{140}Pr and of ^{142}Pm (Two-body EC and three-body β^+ decay)

Gamow-Teller **g.s.→ g.s.** - transition

EC: $p + e^-_b \rightarrow n + \nu_e$

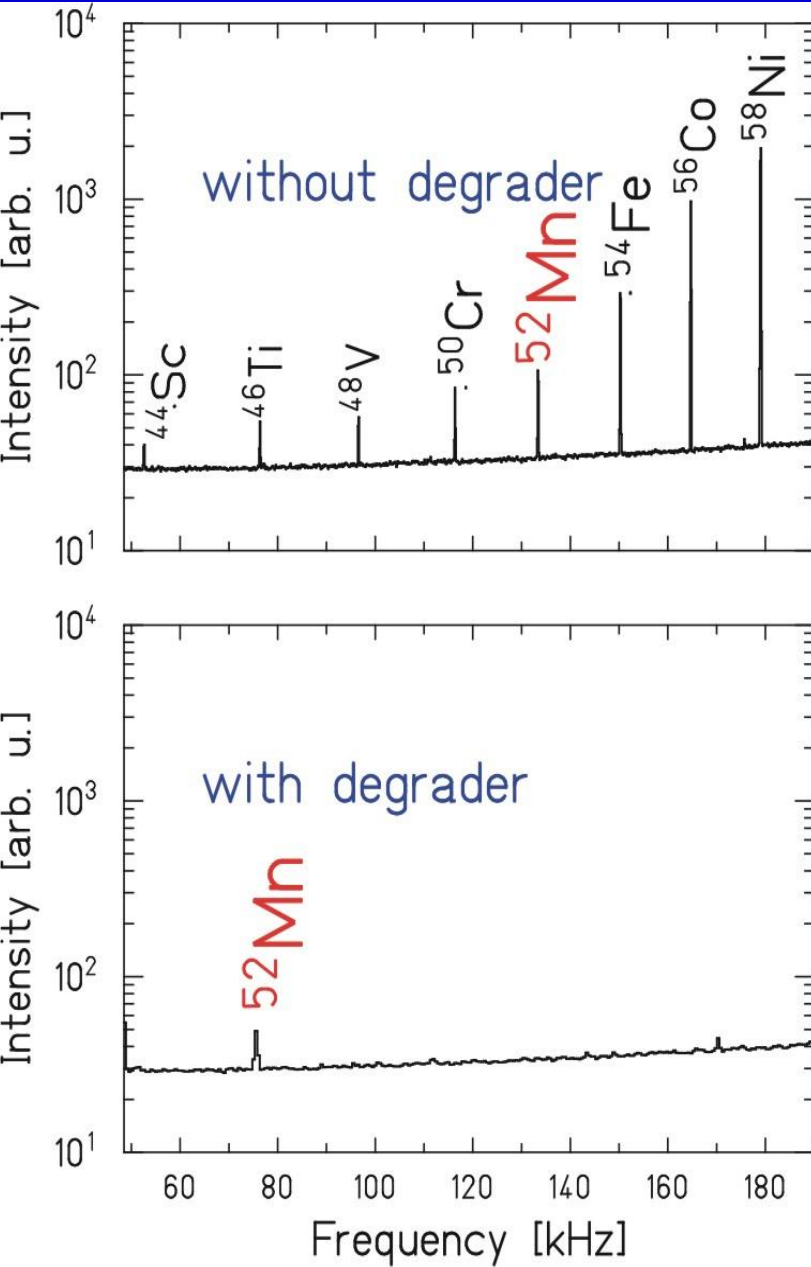
Final state after EC: „**mono-energetic**“ **electron-neutrino ν_e + daughter atom** connected by momentum- and energy-conservation

but: $|\nu_e\rangle \approx \cos\Theta\, |\nu_1\rangle + \sin\Theta\, |\nu_2\rangle$

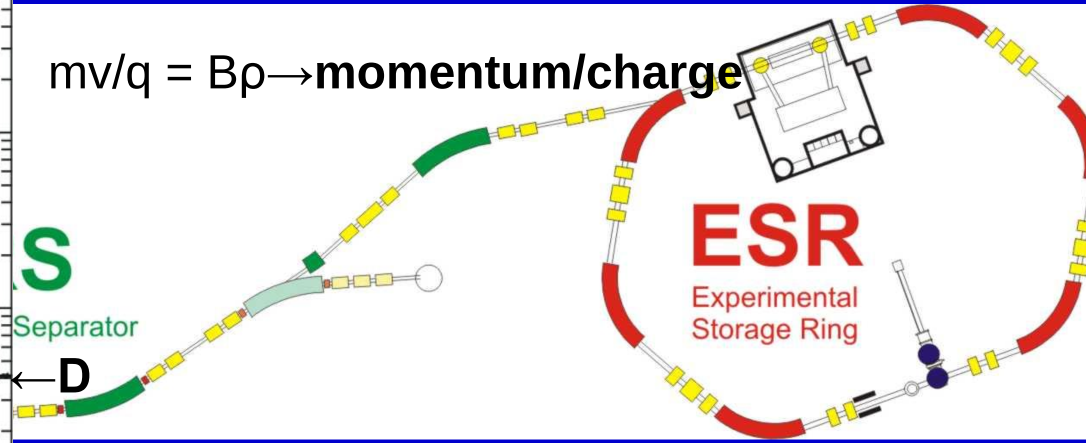


R.B. Firestone, Table of Isotopes, NY, Wiley, 1999

Fragment-Separator and Experimental Storage Ring ESR



mv/q = Bρ→**momentum/charge**



mv/q-separation in-flight at the fragment separator

Many ion species produced; **one** selected by a degrader

Ion-Storage Ring ESR:
400 MeV/u H-like ions at β = 0.71
stochastic and electron cooling → sharp velocity

Revolution frequency depends only on m/q

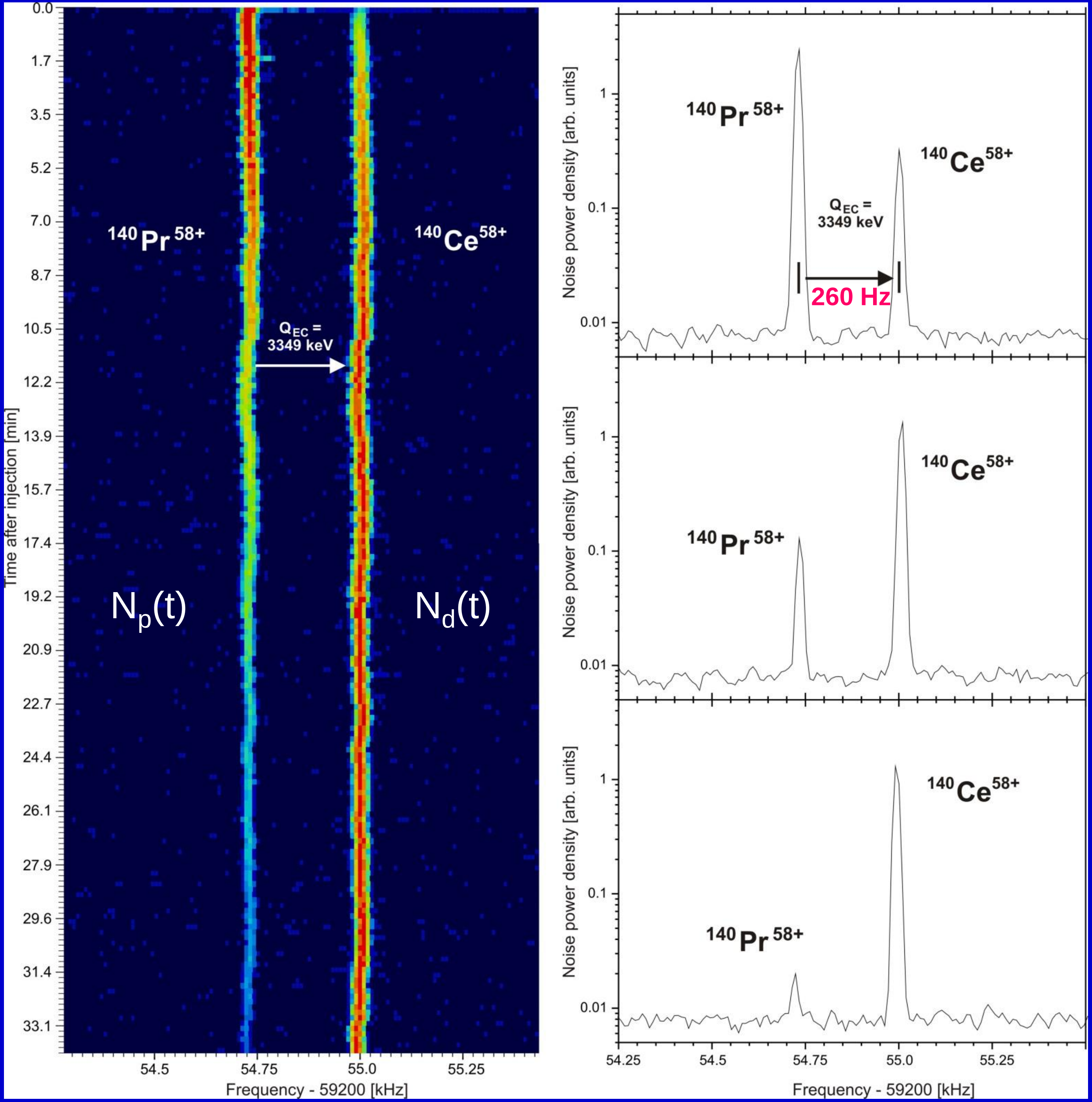
Signals measured at „Schottky pickups“ at each passage

H. Geissel et al., Ann. Rev. Nucl. Part. Sci. **45** (1995) 163
Y. A. Litvinov and F. Bosch, Rep. Progr. Phys. **74** (2011) 016301

Experimental Storage Ring ESR since 1990 operational at GSI

U = 108 m, p ≈ 10^{-11} mbar, E = A•400 MeV (β = 0.71), f ≈ 2 MHz, V_{cool} ≈ 220 kV

B. Franzke et al., NIM Phys.Res.**B24** (1987) 18: M. Steck, F. Nolden, C. Dimopoulou



For cooled beams:
Revolution frequency **f** proportional to **m/q**

Charge state **q** does **not** change in EC-decays

Only change of mass

→ **Δf/f ≈ 4 ppm**

Difference of the **cooled** traces = $E_{\nu 1}$ or $E_{\nu 2}$ or $E_{\nu 3}$

Restricting onto **two** neutrino mass eigenstates: $|\nu_e\rangle = \cos\Theta\, |\nu_1\rangle + \sin\Theta\, |\nu_2\rangle$

EC of H-like atoms demands, for nuclear g.s.→ g.s. transitions : $\mathbf{(p_{recoil\ 1,2})^2 = p^2_{\nu 1,\nu 2}}$

M_p

$M_d + E_{\nu 1} + p^2_{\nu 1} / 2 M_d = M_p$

$\Delta(p_{12}) = p_{\nu 1} - p_{\nu 2}$

$\Delta E_{12} = E_{\nu 1} - E_{\nu 2}$

$M_d + E_{\nu 2} + p^2_{\nu 2} / 2 M_d = M_p$

$E^2_{\nu i} - p^2_{\nu i} = m^2_{\nu i}$

$m^2_{\nu 1} - m^2_{\nu 2} = \Delta m^2_{12}$

$= 7.6 \cdot 10^{-5}$ eV

→ $\mathbf{\Delta E_{12}}$ **(rest frame) =** $\mathbf{\Delta m^2_{12} / 2 M_p = 2.6 \cdot 10^{-16}}$ **eV**

M_d

difference of both, the neutrino -and the recoil energies

← $p^2_{\nu 1} / 2 M_d$ → $E_{\nu 1}$ (channel 1)

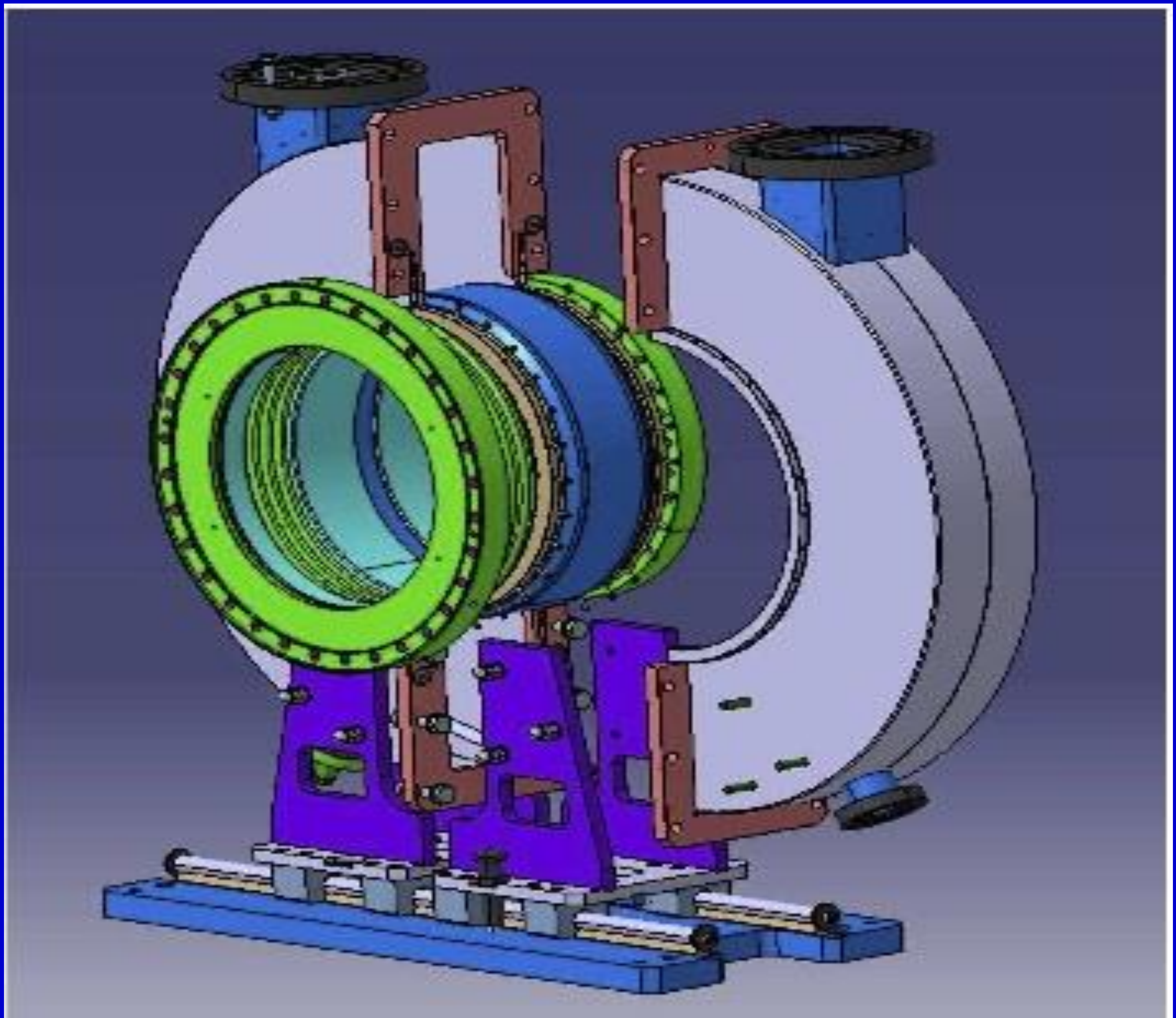
← $p^2_{\nu 2} / 2 M_d$ → $E_{\nu 2}$ (channel 2)

If the two channels can be summed up **coherently (?)**

→ **Period T(rest frame)** = $h/\Delta E_{12}$ = $2hM_p/\Delta m^2_{12}$ **= 14.4 s**

→ **Period T(lab. frame)** = $\gamma \cdot h/\Delta E_{12}$ = $1.43 \cdot 14.4$ s **= 20.6 s**

245 MHz resonator serves as Schottky detector since 2010
(U. Hülsmann, F. Nolden, P. Petri, S. Sanjari...)



If $\Gamma = (E_{coul} = q^2 / R) / (E_{therm} = 3/2\ kT) \approx 1$,

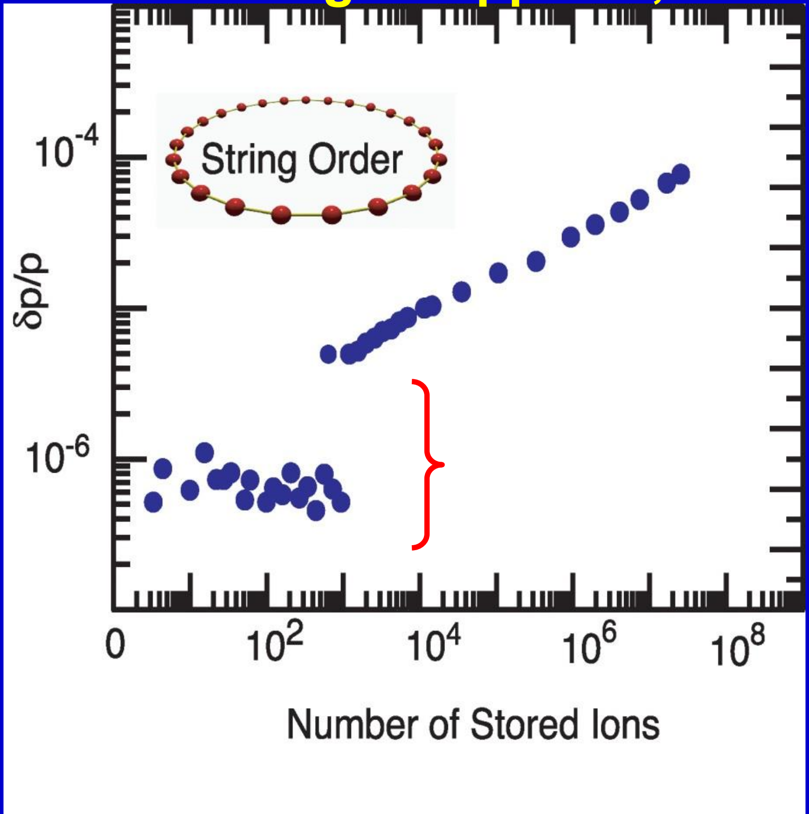
→ **Phase transition** of pre-cooled ions to an **orderly linear chain**

ESR: circumference ≈ 10^4 cm

For ≈ 1000 ions the mean distance < d > ≈ 10 cm ($E_{coul} \approx 10^{-4}$ eV, T ≈ 1 K)

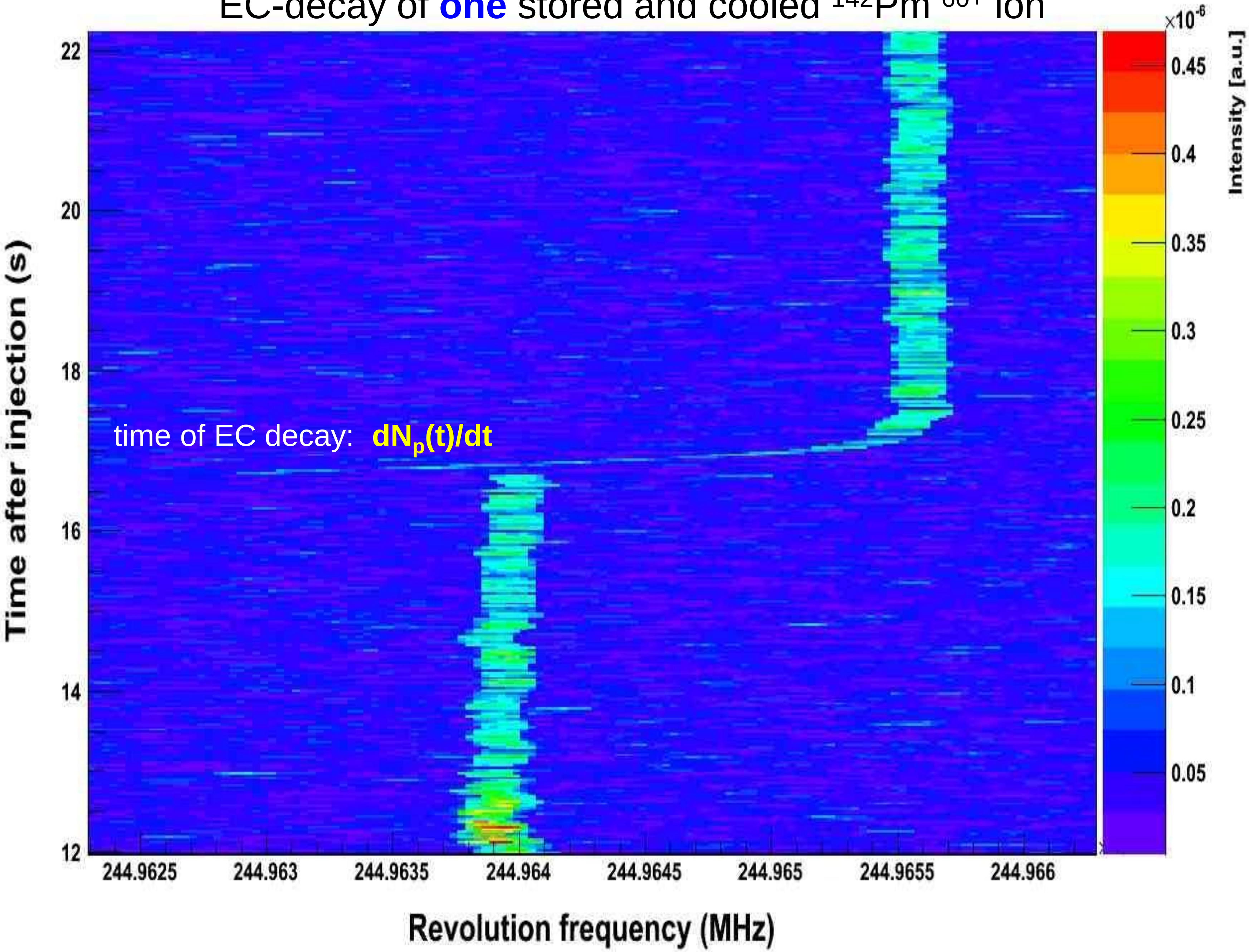
At those mean distances

the intra-beam scattering disappears, momentum spread → 0



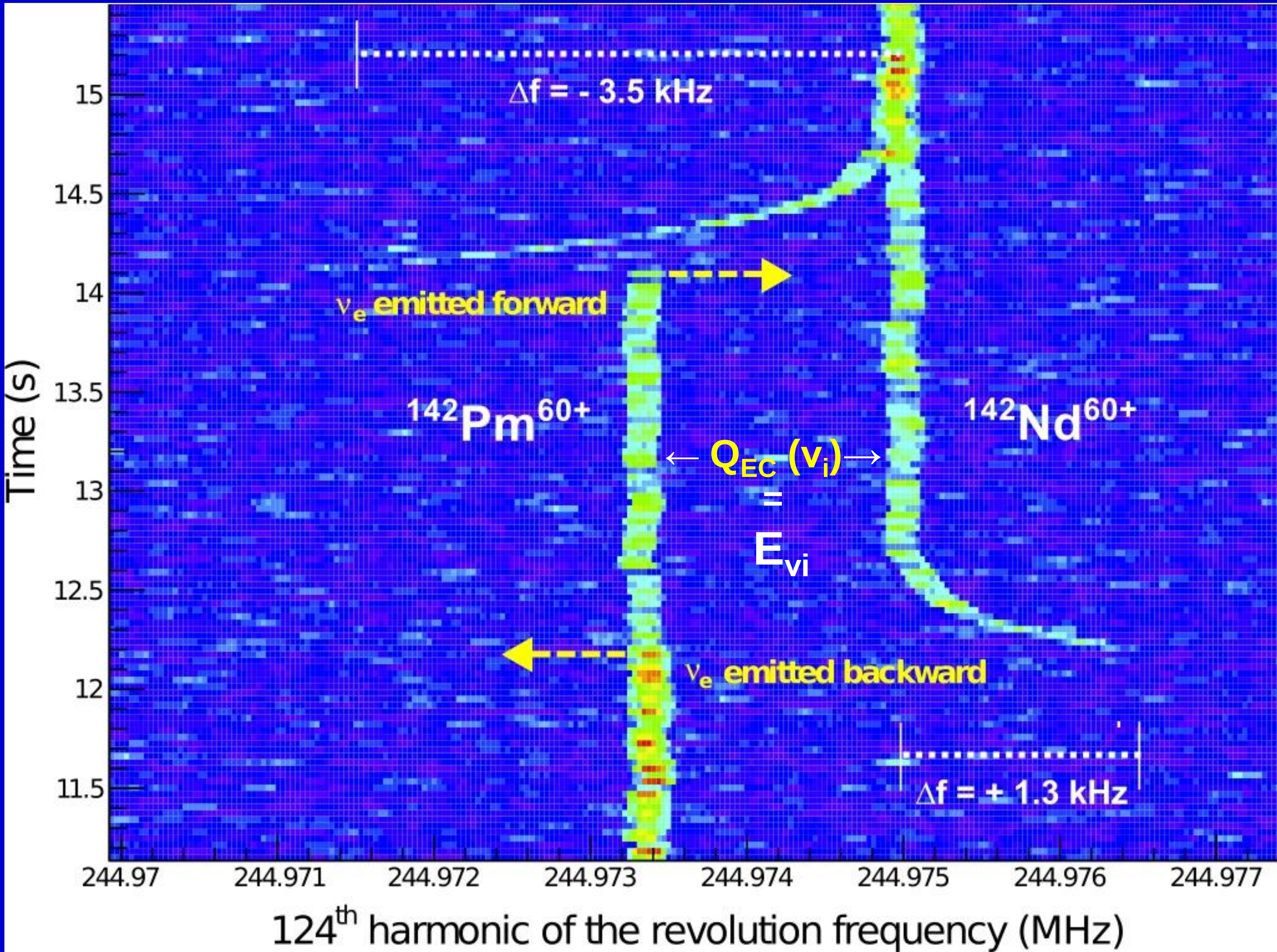
M. Steck et al.,
PRL **77**, 3803 (1996)

EC-decay of **one** stored and cooled $^{142}Pm^{60+}$ ion

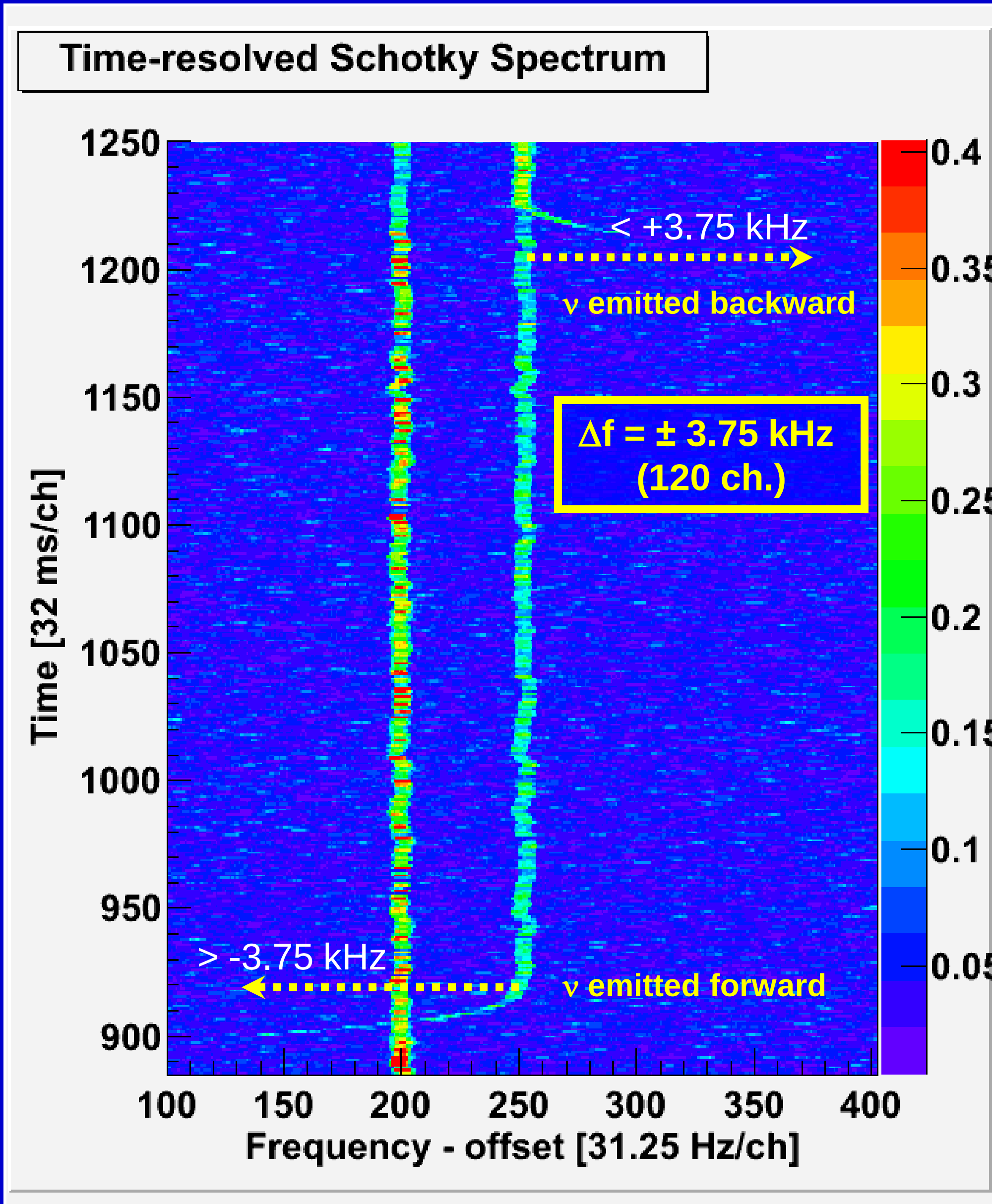


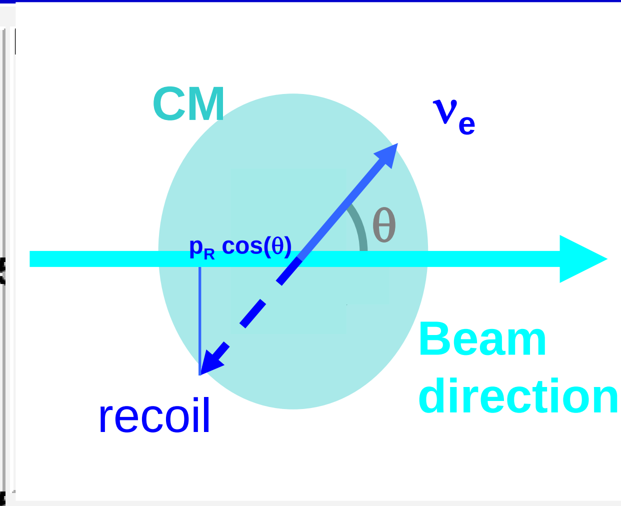
Δf: Projection of the velocity of the recoiling daughter nucleus onto the beam direction = **v cosθ**

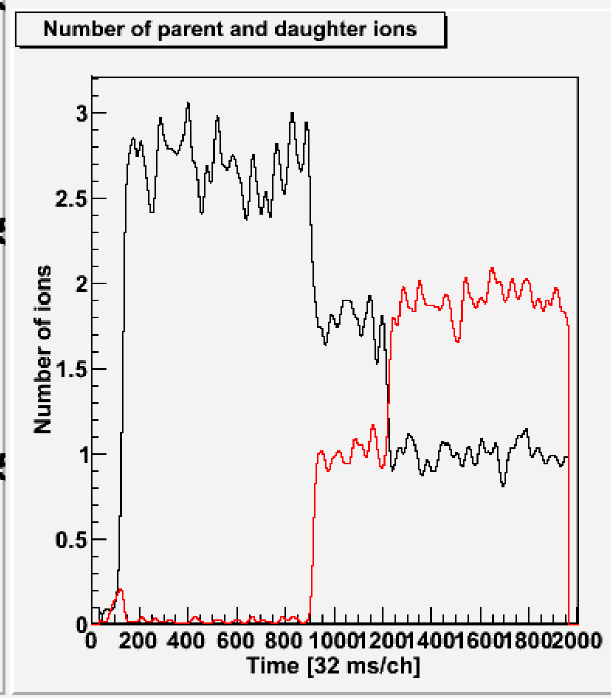
→ **momentum $M_d \cdot |v_i|$ cosΘ** of daughter nucleus = **p_{vi} cos(π – Θ) of v_i** = $[E^2_{vi} - m^2_{vi}]^{1/2}$ cosθ

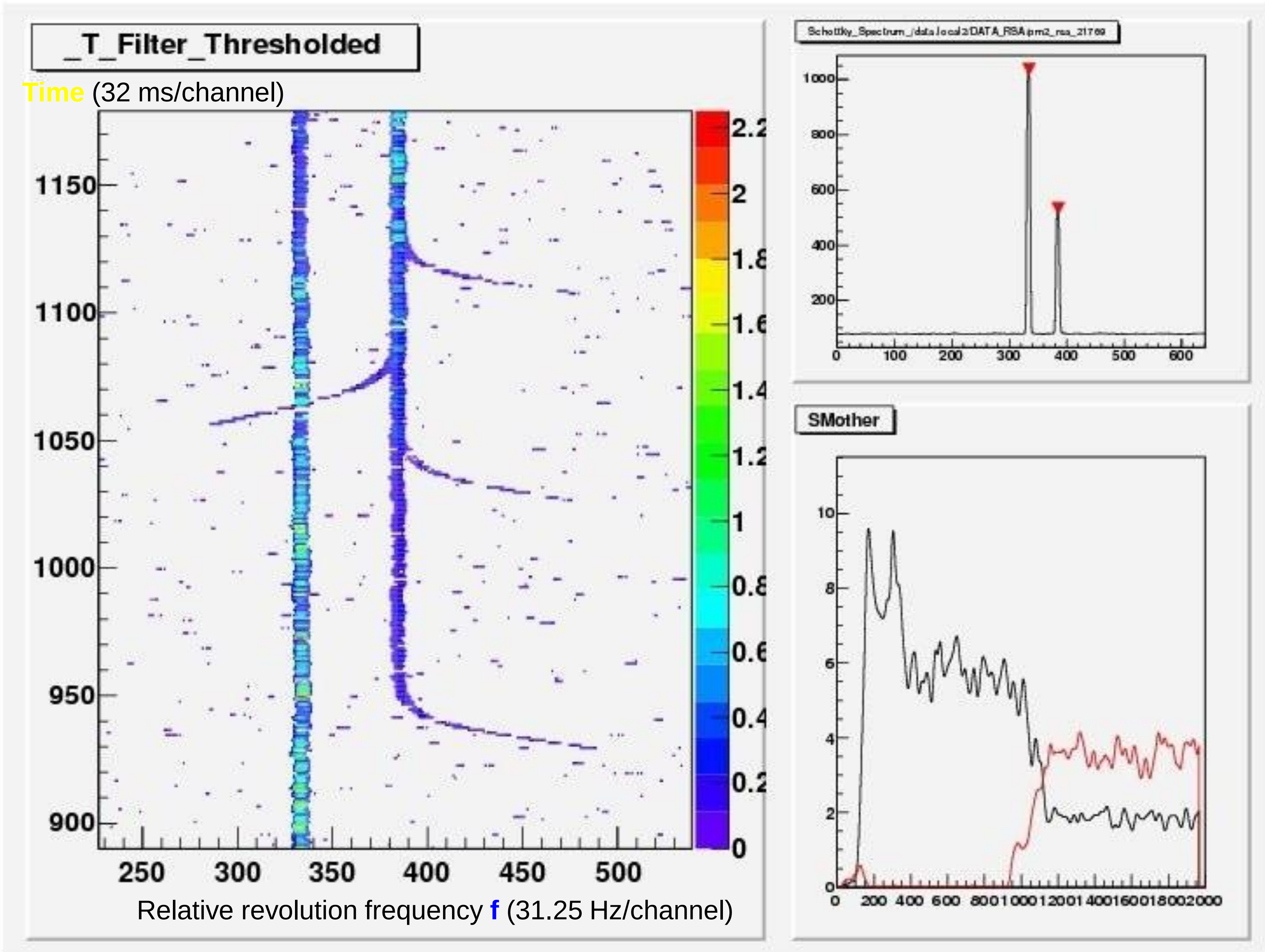


Three parent ions and two EC- decays (N. Winckler)

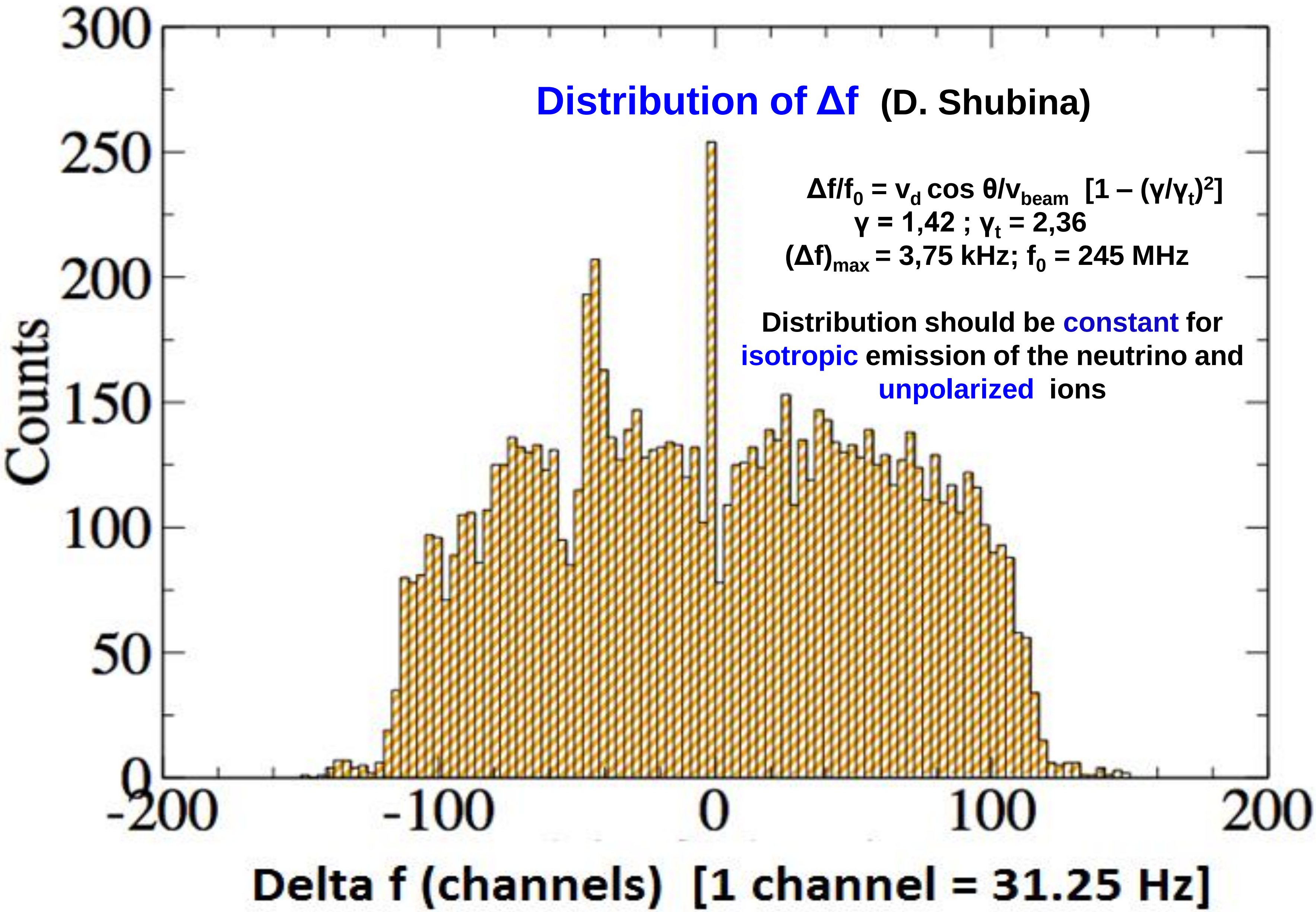


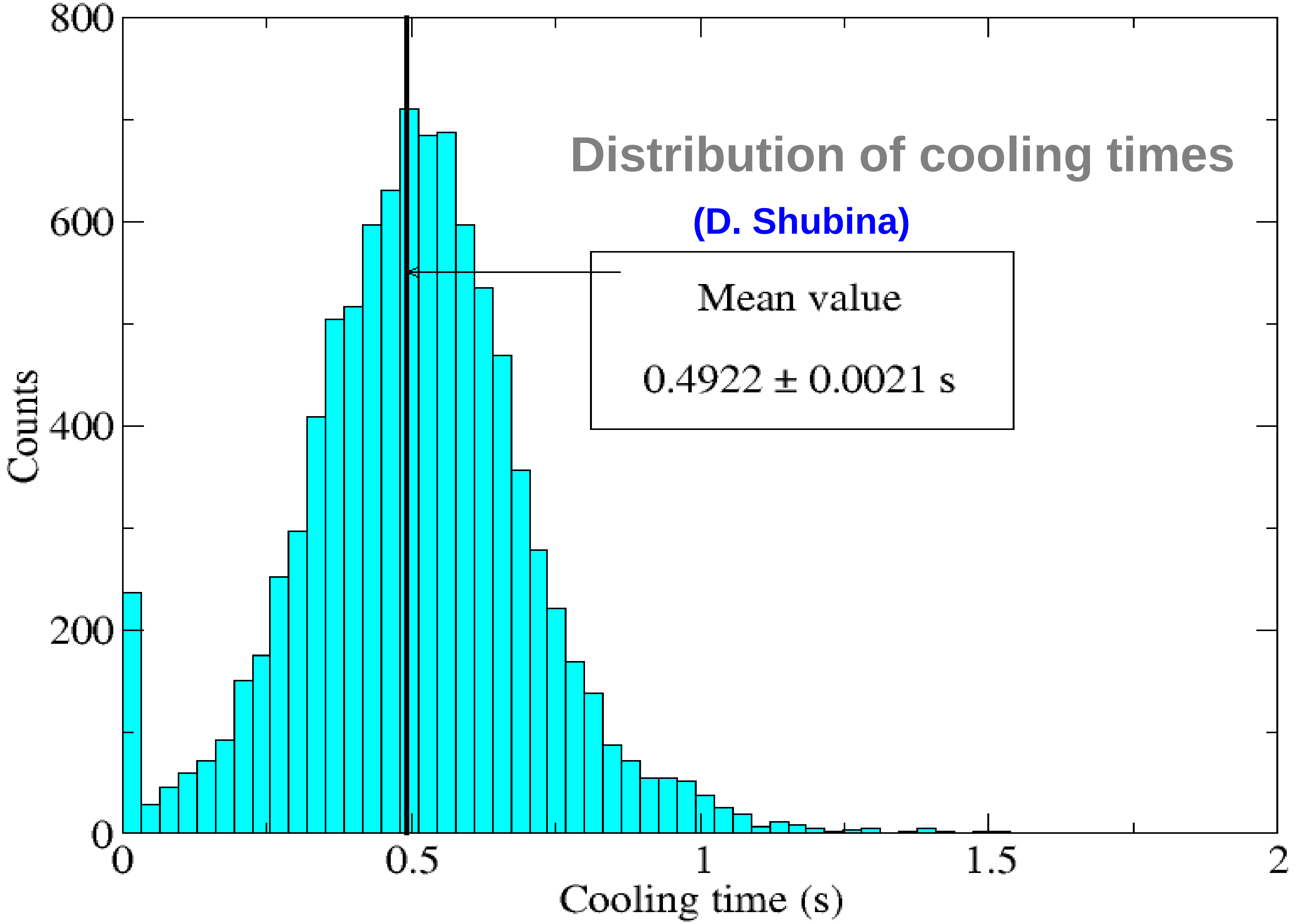





_T_Filter_Thresholded
Time (32 ms/channel)
1150
1100
1050
1000
950
900
250
300
350
400
450
500
Relative revolution frequency f (31.25 Hz/channel)
SMother
N. Winckler, GSI

From $(\Delta f)_{max}$ ≈ **3.75 kHz**→ **$|v_d|_i$** → M_d **$|v_d|_i$** → **momentum of (daughter)$_i$ = p_{vi}**

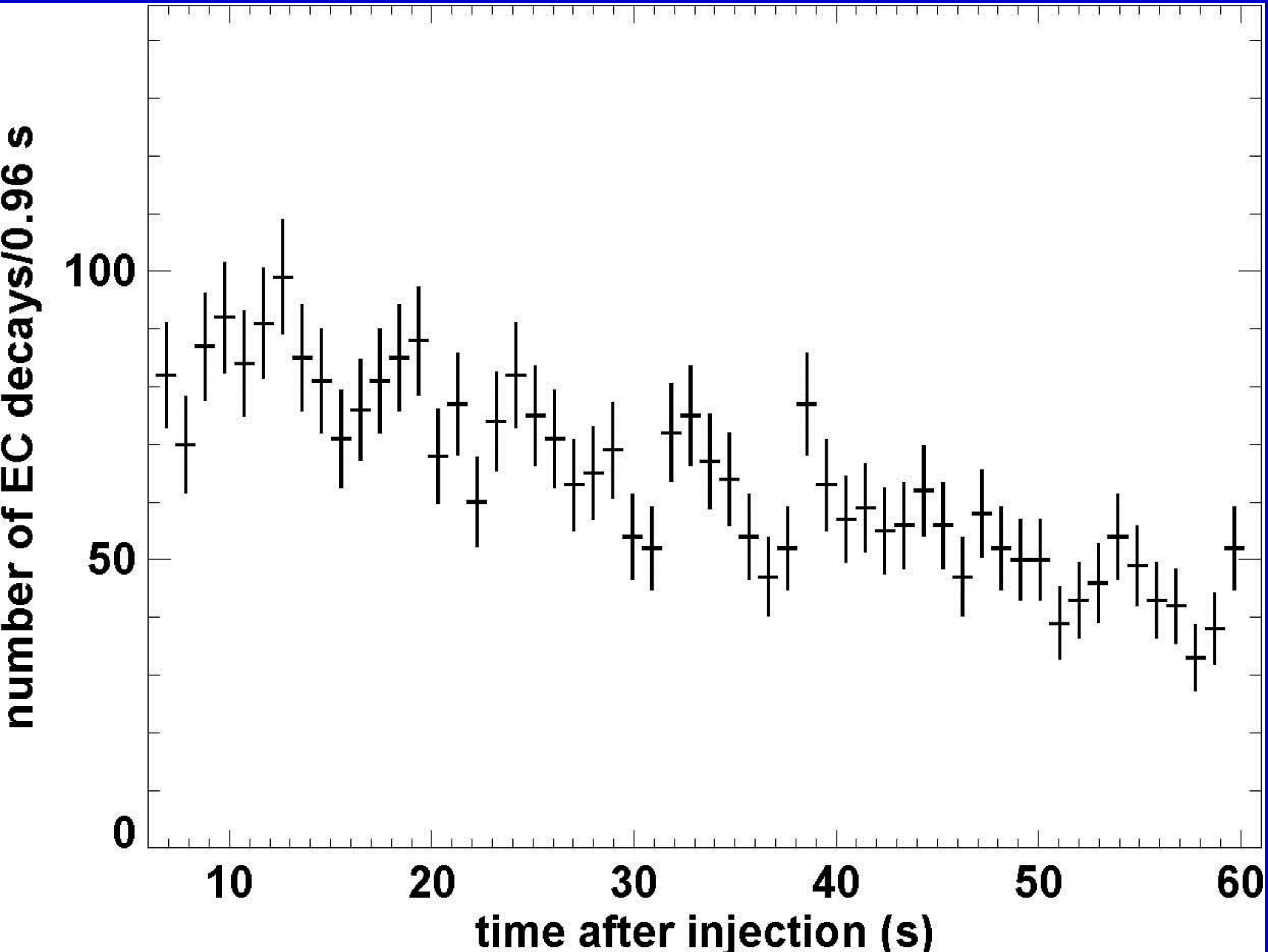


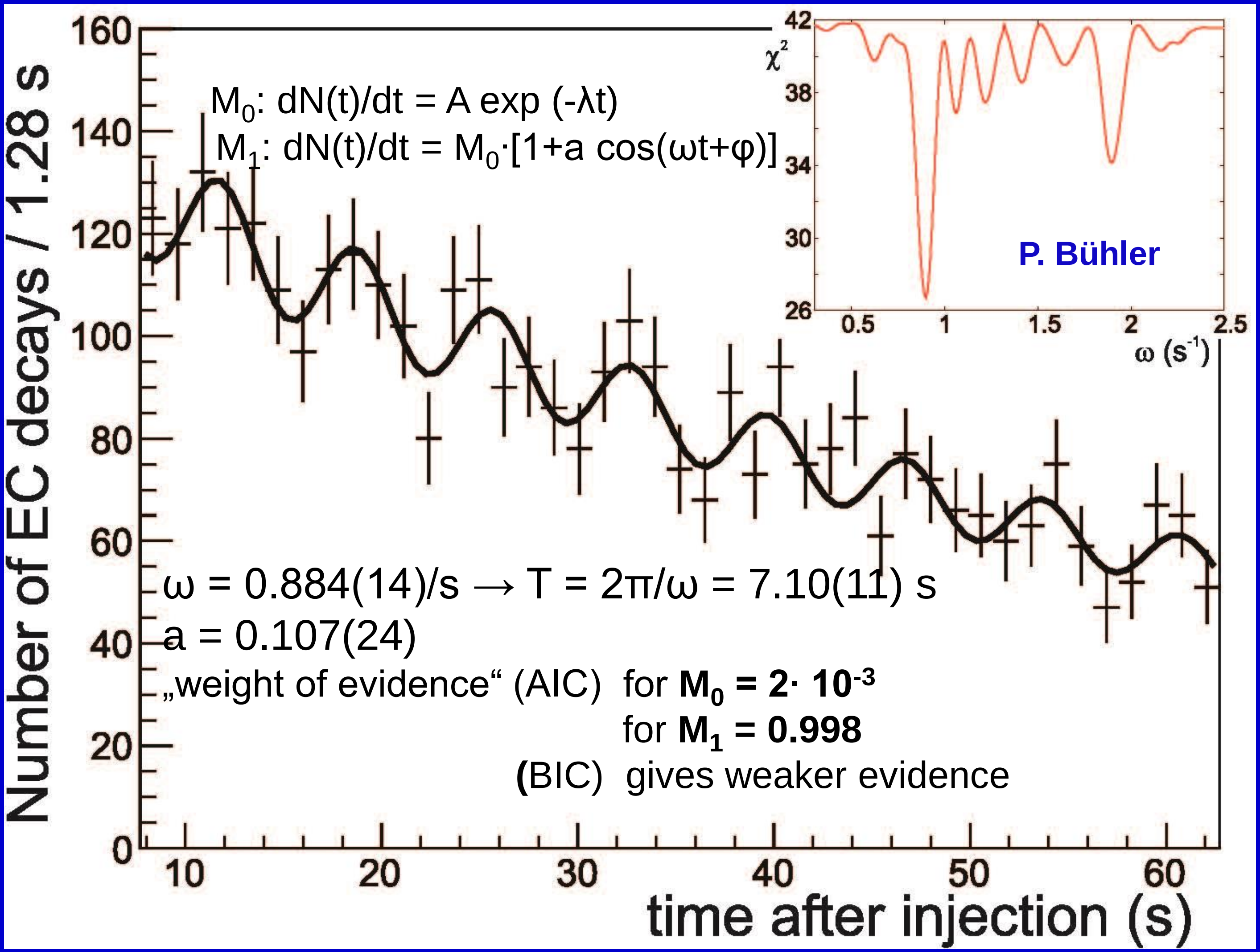


Distribution of cooling times
(D. Shubina)
Mean value
0.4922 ± 0.0021 s
800
600
400
200
0
Counts
0
0.5
1
1.5
2
Cooling time (s)

245 MHz resonator: **≈ 3600 EC-decays** of H- like $^{142}Pm^{60+}$

P. Kienle et al., PL **B726** (2013) 638; first data: Y.A.Litvinov et al., PL **B664** (2008), 162 (without the 245 MHz resonator)



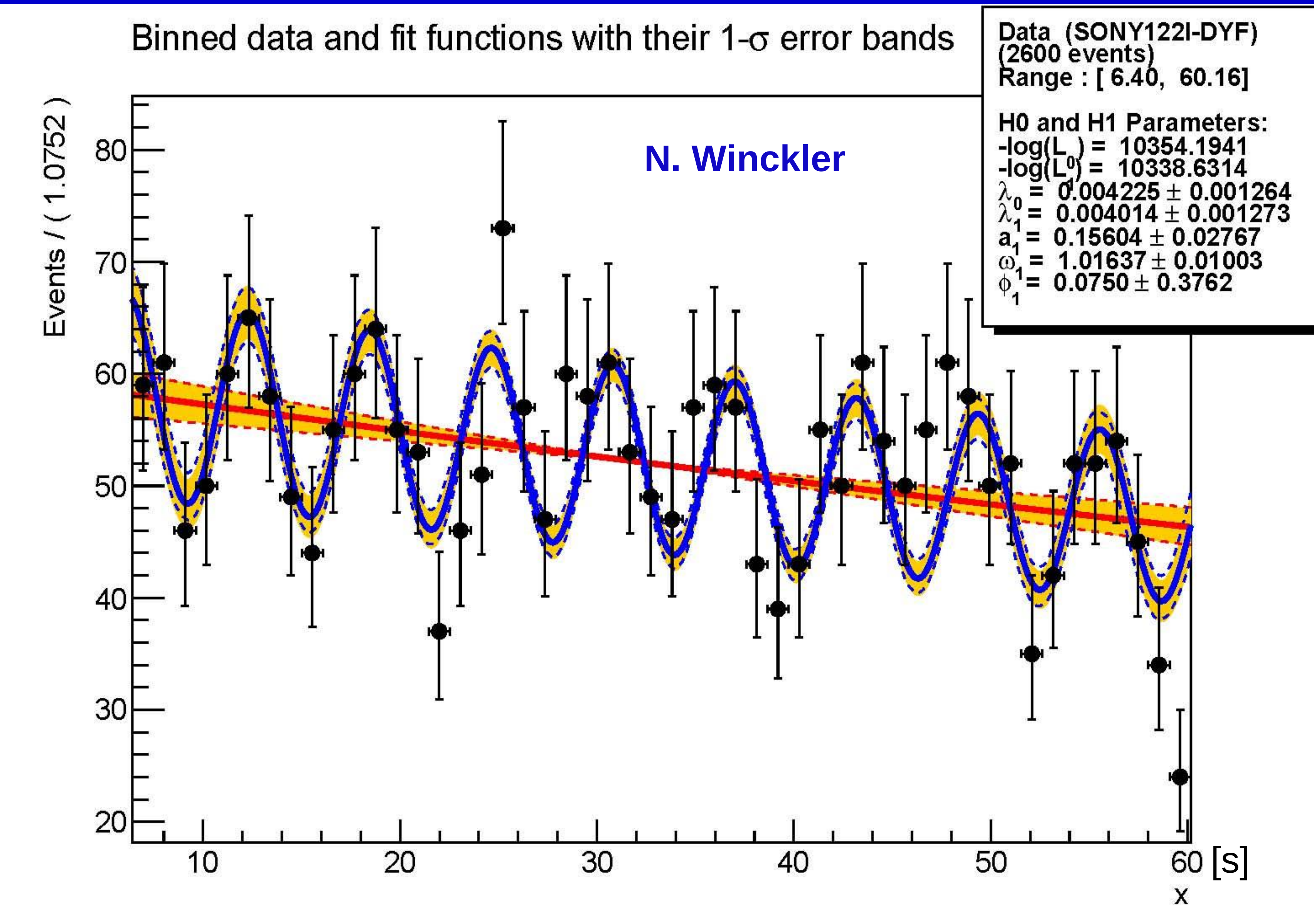


M0: dN(t)/dt = A exp (-λt)
M1: dN(t)/dt = M0·[1+a cos(ωt+φ)]
ω = 0.884(14)/s → T = 2π/ω = 7.10(11) s
a = 0.107(24)
„weight of evidence" (AIC) for M0 = 2· 10-3
for M1 = 0.998
(BIC) gives weaker evidence
P. Bühler
χ2
ω (s-1)
Number of EC decays / 1.28 s
time after injection (s)

ECof H-like $^{122}I^{52+} \rightarrow {}^{122}T^{52+}$ recorded by the „old“ Schottky detector, all files with **one EC- decay**:

ω = 1.106(10)/s $\rightarrow$**T = 6.18(6) s**; **a = 0.156(28)**

still preliminary, P. Kienle et al., Progr. Part. Nucl. Phys. **64** (2010, 439)



Summary of the present status of the EC-decay analysis of stored H-like ions

1. **Periodic modulations** in the two-body EC of H-like atoms have been **found again** with the same period T = 7.1 s for A = 142(Pm) [and 140(Pr) and T = 6.2 s for A = 122 (Iodine)] The modulation **does not appear** in the **three-body β^+ decay** of H-like $^{142}Pm^{60+}$ ions, nor for EC-decays of atoms implanted in a matrix.

2. The **decay statistics is still very modest** (2700 – 3600 EC- and 2700 β^+ - decays), and the **difference** of the amplitude a = 0.11(2.5) to the previously measured a = 0.23(4) is large.

3. The new 245 MHz resonator provides **unambiguous** EC **decay-times.** But serious problems **(„injection kicker“)** prevented us utilizing the full set of recorded EC-decays (≈ 9000) and forced us to restrict ourselves on **7200 consecutive injections with** ≈ 3600 EC-decays. There was, however, **no file-by-file proof** of a correct kicker operation possible.

→ irrevocable necessity for improving the statistics and eliminating all shortcomings

2. Condensed summary of the discussions in Jena on the origin of the modulation (supposed they are true)

Quantum Mechanical Incoherence (Boris Kayser in his talk)

The rates to produce ***different final states*** that differ from one another in any way (particle content, kinematical properties, etc.) contribute to the total event rate ***incoherently.***

This is true whether or not we can actually distinguish between the different final states in practice. What matters is that we can ***in principle distinguish*** between the different final states ***without affecting the experiment.***

The total event rate is then obviously the ***incoherent sum of the rates of the events*** in the different bins.

[in agreement with M. Peshkin, A. Gal, H. Feldmeier, M. Lindner, C. Giunti...
but in disagreement with A. Ivanov, M. Faber, and previously H. Lipkin, P. Kienle...]

In quantum mechanics, this rule has the consequence that ***the amplitudes to produce different final states can never coherently interfere*** with each other.

Is the Observed Period a Clue? (Boris Kayser)

ν_e is approximately a superposition of just two mass eigenstates,
$|\nu_e\rangle \approx \cos\Theta\, |\nu_1\rangle + \sin\Theta\, |\nu_2\rangle$ with $\Delta m^2 \equiv m_2^2 - m_1^2 \cong 7.5 \cdot 10^{-5}\,\mathrm{eV}^2$

In $P \rightarrow D + \nu$, in the P rest frame, the mass eigenstates ν_1 and ν_2 are produced with energies differing by $\boldsymbol{\Delta E \equiv E_2 - E_1 = \Delta m^2 / 2M_P}$

If the ν were present in the ***initial*** state, before the decay, ν_1 and ν_2 could contribute ***coherently***, e^{-iE1t} - e^{-iE2t} ***→** discussion:

[Project the ν_i-amplitudes at origin **onto ν_e** : → $\{\langle \nu_e|(\cos\Theta\, e^{-iE1t}|\nu_1\rangle + \sin\Theta e^{-iE2t}|\nu_2\rangle\}\cdot e^{-\lambda/2\, t}$

- → $|\{\langle \nu_e\, |(\cos\Theta\, e^{-iE1t}|\nu_1\rangle + \sin\Theta e^{-iE2t}|\nu_2\rangle\}|^2 = e^{-\lambda t}\, \{\mathbf{1 + 2 \cos\Theta \sin\Theta \cos(\Delta E t)}\}$]

Interference could lead to oscillation of the EC decay rate with period:
$\boldsymbol{T = h/\Delta E = h\, (2m_P/\Delta m^2) \approx 15}$ **sec.**

At GSI, the parent ions are moving with $\gamma = 1.43$, so in the lab. the time-dilated oscillation period would be :$\boldsymbol{T \approx 21}$ **sec**. Observed period:$\boldsymbol{T \approx 7}$ **sec**
(P. Kienle et al., PL **B726** (2013), 638

BUT: If the neutrino is the one in the **final** state
O The neutrino is **not** present before the decay
O Different *ν* mass eigenstates do **not** contribute **coherently**

Summary of the talk of Boris Kayser

Amp (P → D + v1) and Amp (P → D + v1)

contribute ***incoherently*** to the total EC decay rate of *P.*

The oscillations seen at GSI **cannot be due** to interferences between the amplitudes to produce ***different final states.***

However, this does **not** prove that Amp $P \to D + v_1$ cannot depend on the properties (such as the mass) of ***both*** v_1 and v_2.

The next talk, by Murray Peshkin will address this question

Summary of Murray Peshkin's talk

1. Quantum mechanics alone **does not forbid oscillations** due to interference between parts of the wave function dependent upon different masses. That is because the **mass channels are coupled through their interaction with the parent-state channel.**

2. The interference must be strong but **not necessarily strongly dependent on the masses**. That depends upon dynamical details.

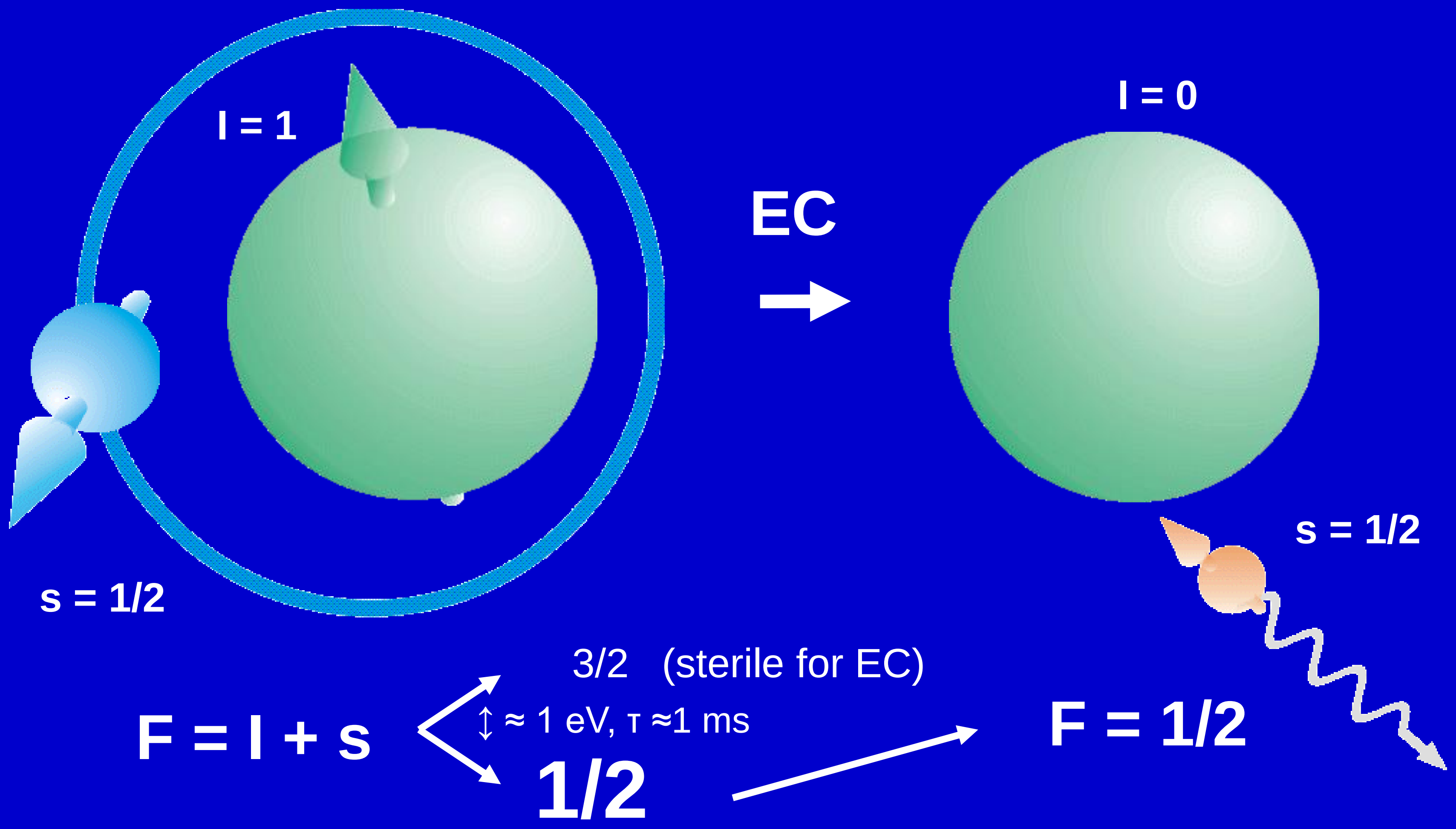
3. Even if the interference between the masses is strong in the wave function, **the decay rate does not necessarily oscillate**. That again depends upon the dynamics.

4. Even if the electron-capture decay rate oscillates strongly, **the positron-emission (β^+) rate may not** (probably does not).

Some (conspicious!?) analogies between GSI-oscillations and **quantum beats**

Ernst Otten, EMMI-RRTF in Jena/Dornburg

Are there two ***coherently*** excited ***initial states*** with a tiny energy difference $\Delta E = h/T =$ **$6 \cdot 10^{-16}$ eV**?



Y. A. Litvinov et al., PRL **99** (2007) 261501
Z. Patyk et al., Phys. Rev. **C77** (2008) 014306
N. Winckler et al., PL **B679** (2009) 36

Quantum beats

"Quantum beats"* - decay of two coherently excited states with $\Delta E = h/T$

Coherent excitation of an electron in two quantum states, separated by $\Delta E = h/T \approx 3\cdot10^{-6}$ eV for $^3P_1$ and $^3P_2$ in He.

The exponential decay is modulated by **$\cos[\Delta\omega(t-t_0)]$**

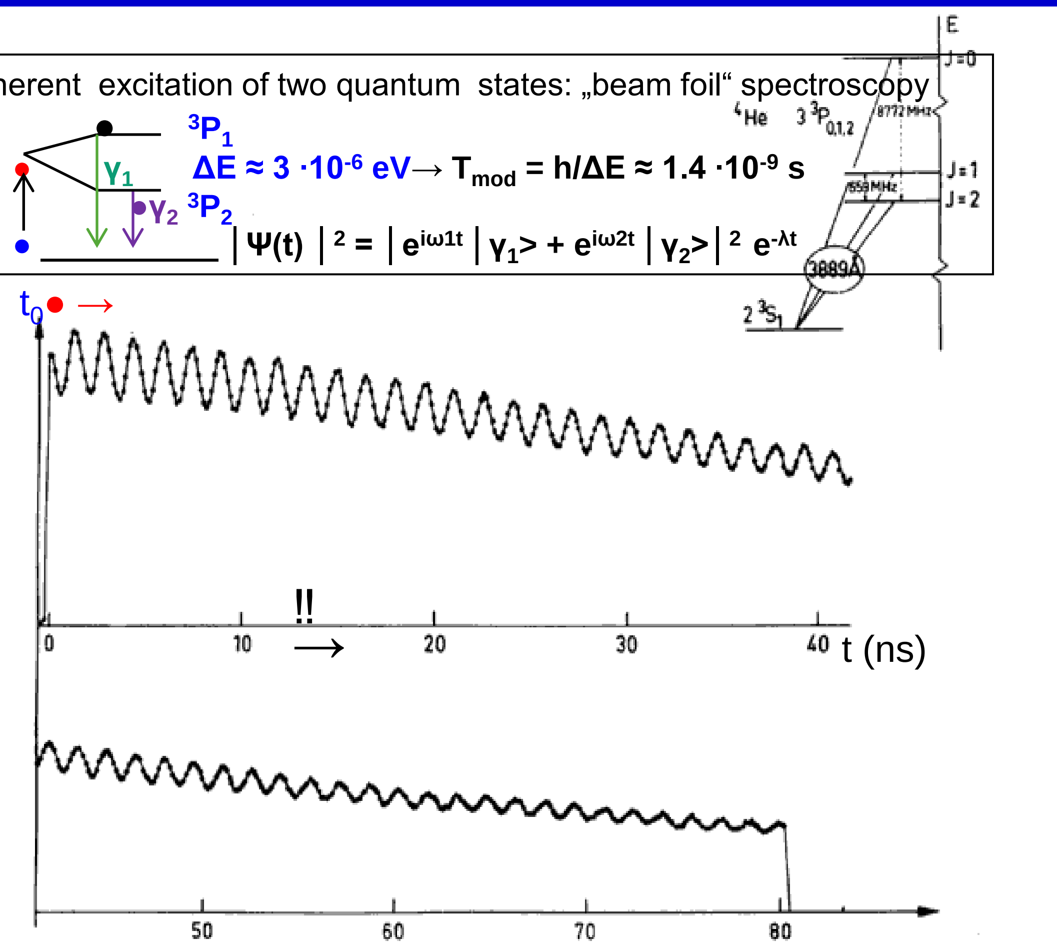


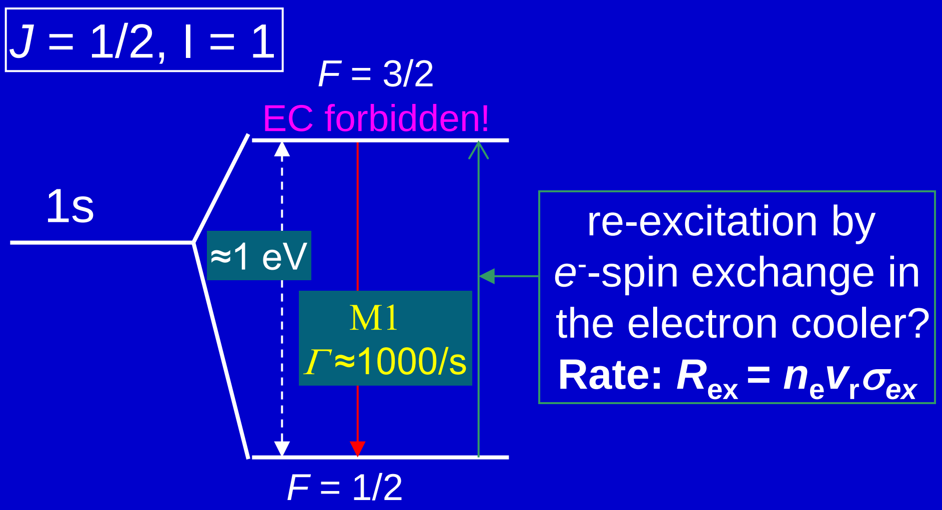
Fig. 24. Zero-field oscillations between the 1s 3p $^3P_1$ and 1s 3p $^3P_2$ states in He I (659 MHz), Wittmann [248]. The oscillations are superimposed on the exponential decay of the 1s 3p ^3P term (96 ns). To record this decay curve about 10 hours beam time (a few μA) and more than 20 carbon foils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

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

External interactions:Spin exchange with cooler electrons

Does the electron cooler generate the oscillations by periodic re-excitation of F = 3/2?

→ **perform a measurement with the e- cooler turned off**



At Z = 80, E_{rel} = 13.6 eV:

$\sigma_{ex} = 0.23(a_0)^2$

(Mukherjee et al., Z.Physik D9,167(1988))

Steeply rising towards lower E_{rel}!

How large is E_{rel} in the cooler?
If E_{rel} << 1 eV → little re-excitation

$\boldsymbol{R_{ex}}$ should be checked!
If considerable, EC-rate slows down!

Together with periodic misalignment between ion track and e-beam EC-oscillations could be produced!

Francesco Giacosa

GSI-Anomaly: **Modified Breit-Wigner** distribution:

Non-exponential decay due to **deviations from the Breit-Wigner limit** .

Reasons: There must be a minumum energy as well as a finite mean energy

Cutoff needed

A cutoff at $\boldsymbol{\Lambda = 32\,\Gamma}$ yields a modulation with T ≈ 7s but **strongly damped amplitude.**

How could a reasonable cutoff value be provided?

A few out of many further questions addressed:

1) Are our alternatives – either purely exponential (M_0) or modulation with **one** frequency and with a **not** damped amplitude (M_1) – sufficient at all?

2) Is there any effect due to our **continuous observation** (Quantum Zeno)?

3) Is there any effect of the **number of the stored parent ions** and/or of the **number of EC decays**
(„induced“ or „delayed“ emission, Hanbury Brown Twiss effects?)

3. Providing a critical vote of the participants: Recommendations of the RRTF

"On the basis of the currently available experimental data, the explanation of the observed modulated EC decay phenomenon **remains an unsolved puzzle**. The latter may be due to an **instrumental or a limited-statistics effect**. However, it could lead to insights into new physics.

It was unanimously agreed that an **urgent clarification of this effect is mandatory**. Possibilities to perform independent experiments at other facilities in the world were considered. It was It was concluded that **in the next few years such experiments can be conducted only at the present GSI facility.**

GSI has the responsibility to **demonstrate conclusively whether or not modulations in the EC decay exist**. The participants of the EMMI RRTF, in particular the invited experts, ask the directorate of GSI to **provide the beam time necessary** to carry out this responsibility.

1) The **experiment must be repeated** with greatly increased statistics (≈ 15 000 decays), running **under the same conditions as before** while avoiding previously undiscovered technical malfunctions. One should then modify the experimental running conditions.

Comment: The error bars shut be cut in half (15 000 decays), for getting a conclusive result for an assumed 10% amplitude. Measurement for 64 s with 1 EC decay at average per injection. The survival of any ion in the ring from previous runs should be excluded in controlled way. An additional kicker has to be applied still during data taking.

2) Measurement at **another magnetic field / velocity**

Comment: To Investigate the influence of the magnetic field as well as of the Lorentz factor **γ**

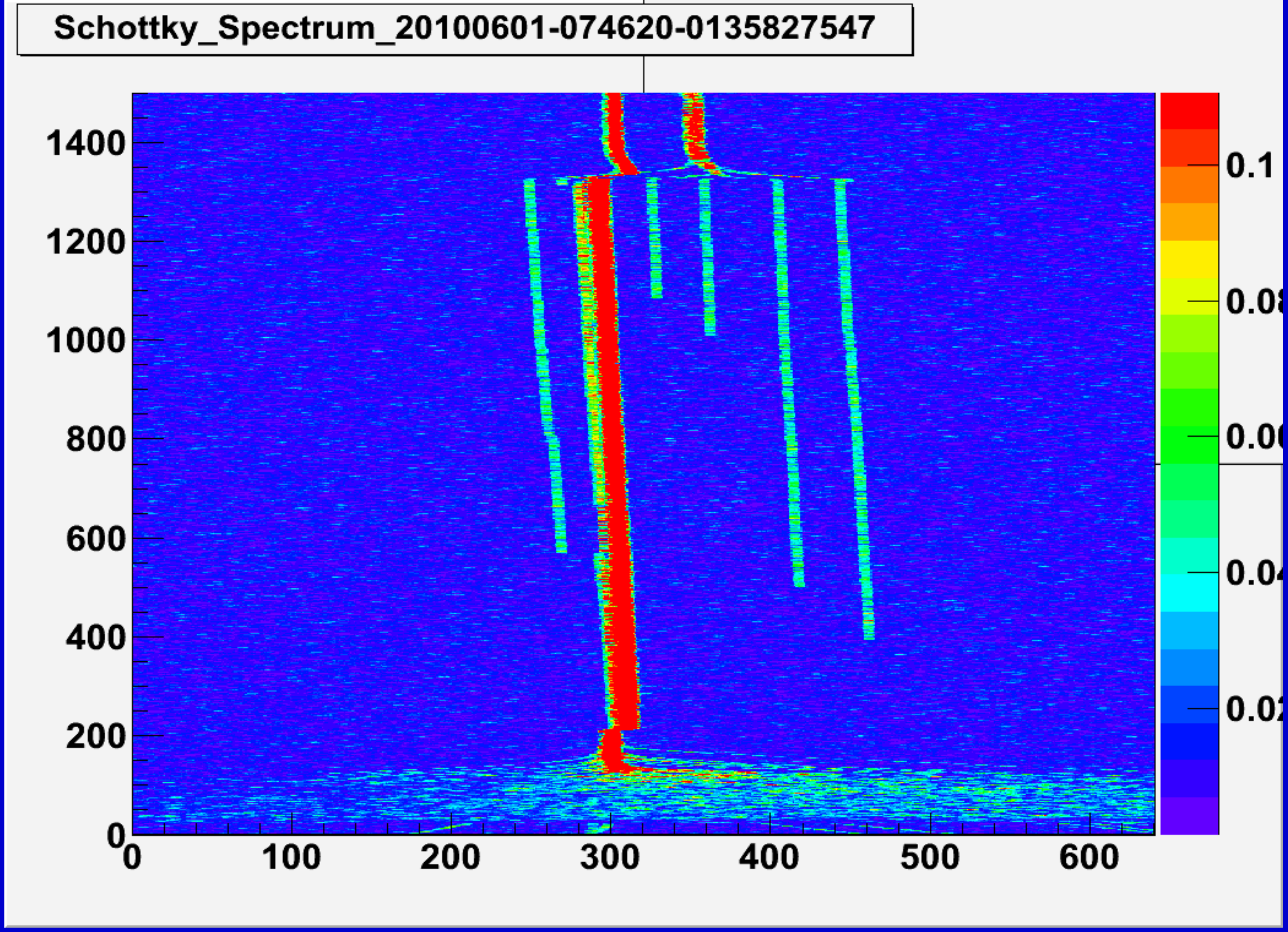
3) Measurement with **the electron cooler switched off**

Comment: Switching off the cooler could answer (at least) two basic questions:

a) does the cooler **generate** the oscillatons e.g. by periodic repopulation of F = 3/2?

b) or, vice versa, is the **coherence weakend** by the steady interaction with the cooler electrons

4) The EMMI RRTF recommends a minimum of **4 weeks beam-time.**



EC-decay with electron cooler switched off. The daughters save their initial velocity in beam direction (smoothly decreasing by interaction with the rest gas). This corresponds to to the motion of the **muon after the two-body decay of a pion**, except that here the motion is spatially confined by the storage ring. The vigorously and since a long time discussed question, whether or not there is a time-oscillation of the muons could by adressed in such experiments at the ESR (Avraham Gal)

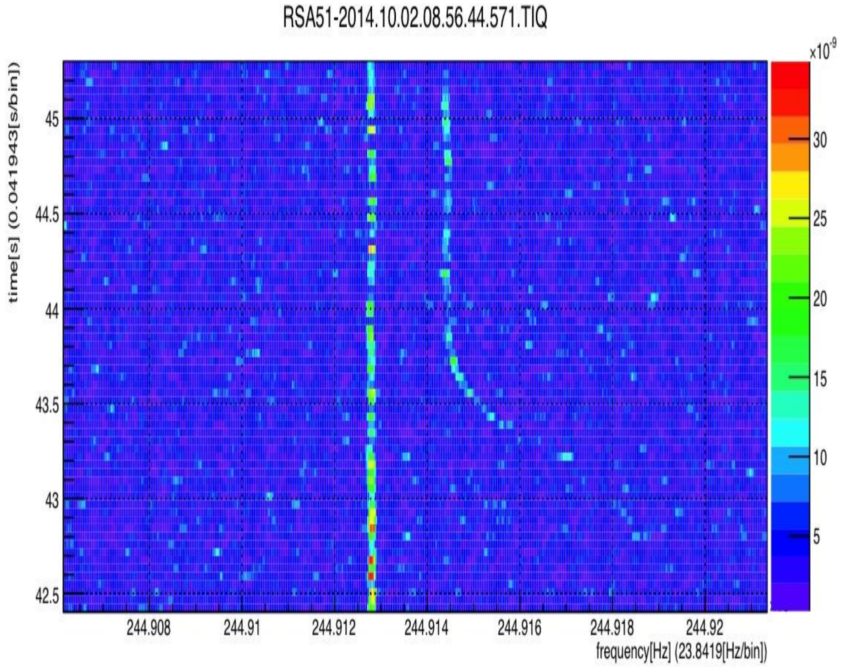
The Scientific Directorate of GSI provided us **19 days** of beamtime, 24.9. -13.10., 2014. Unfortunately the first 6 days were lost by a serious vacuum leak in the SIS 18.

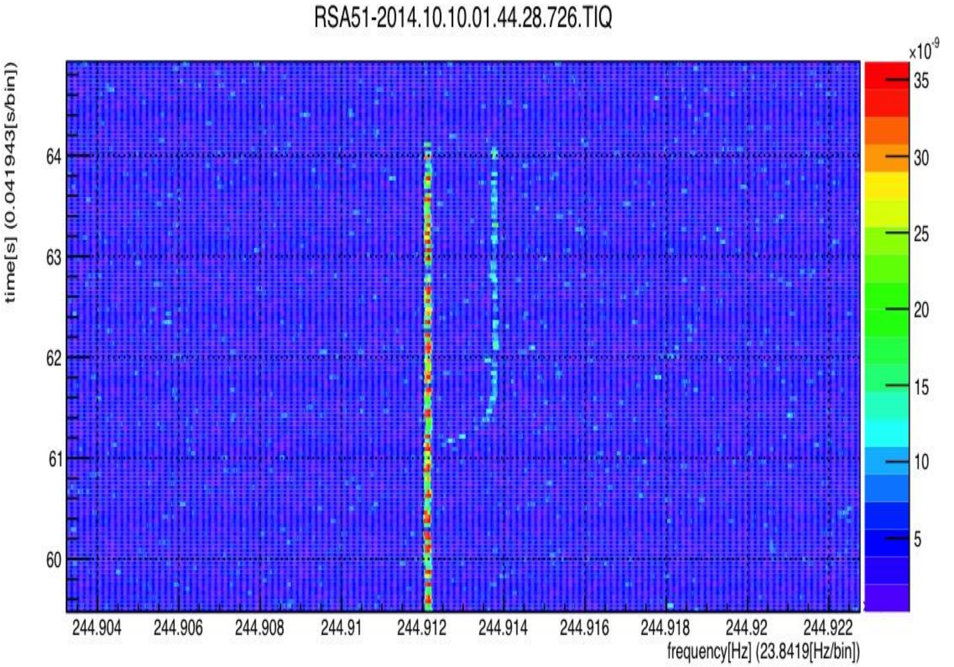
Within the **remaining 12 days** we could record more than **10 500 EC decays** with an excellent quality, efficiency and an optimal performance of all devices.

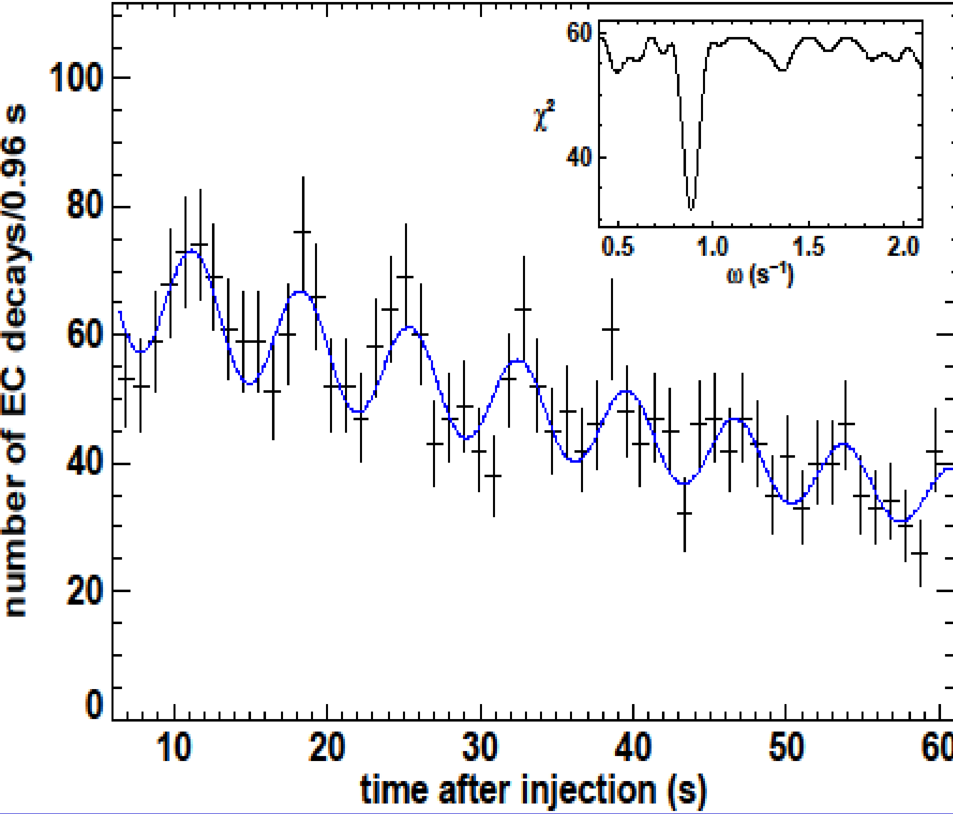
The data were analyzed online **visually** and also by an **automatic code.**

The total number of detected EC decays still differed significantly for the two methods.

Presently, we are performing again visual analyses of all data by two groups and are also improving the computer code.


RSA51-2014.10.02.08.56.44.571.TIQ
time[s] (0.041943[s/bin])
frequency[Hz] (23.8419[Hz/bin])
x10^-9


RSA51-2014.10.10.01.44.28.726.TIQ
time[s] (0.041943[s/bin])
frequency[Hz] (23.8419[Hz/bin])
x10^-9



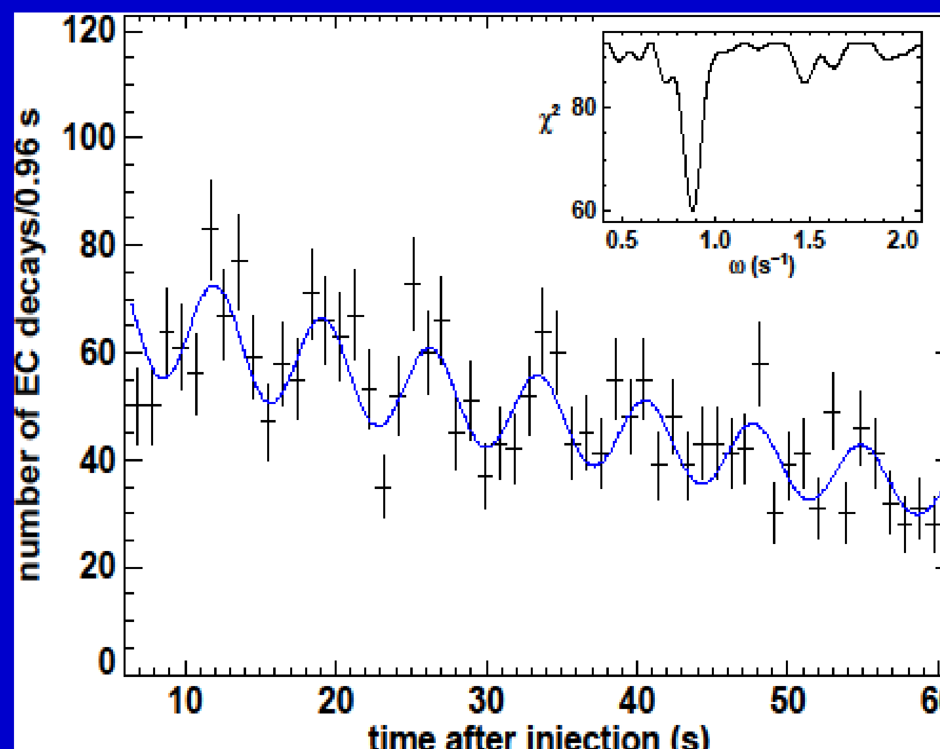
2940 Correlated EC- decays

← **245 MHZ resonator**

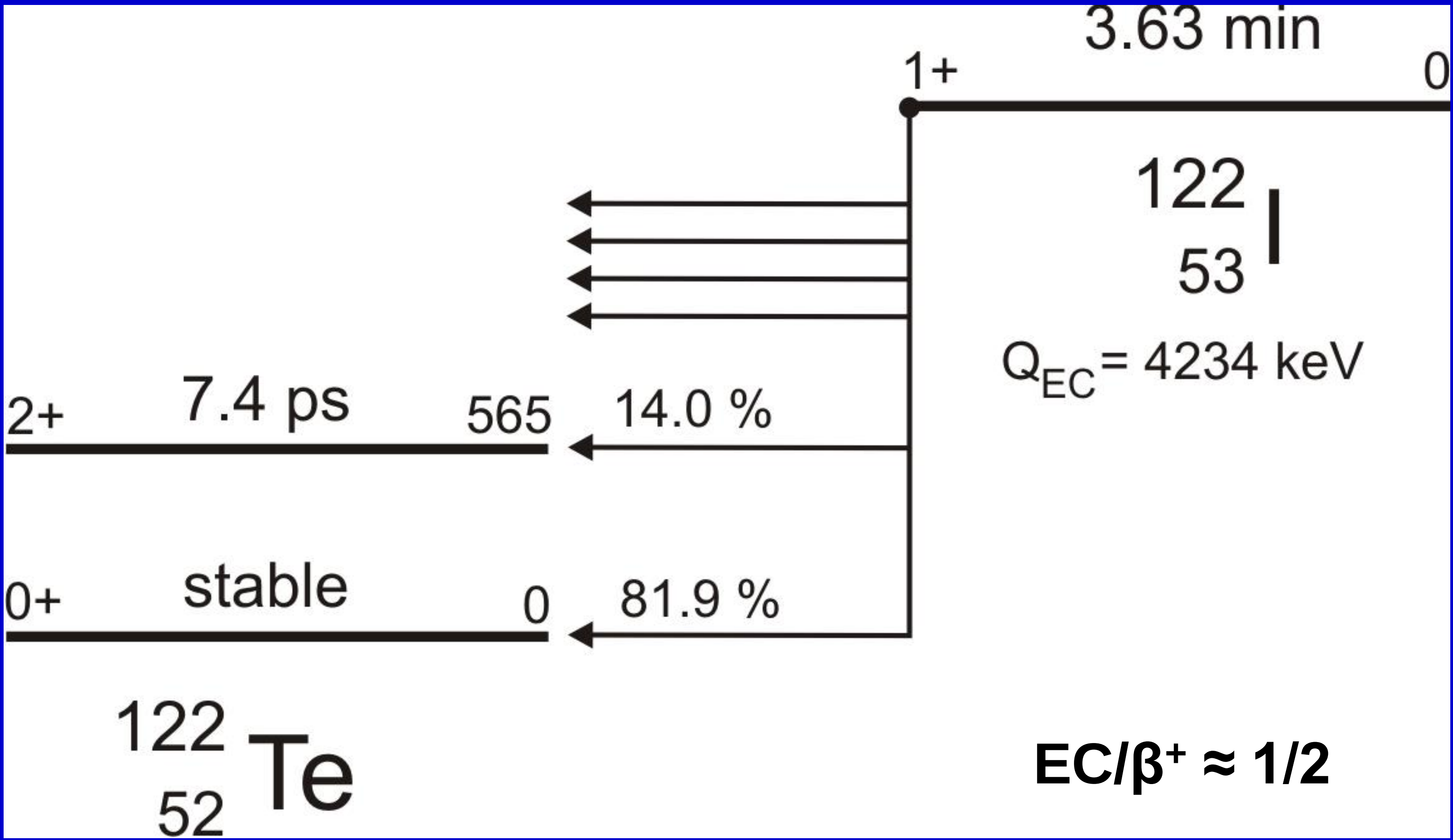
period T = 7.08(9) s
amplitude a = 0.147(28)
χ^2/dof = 33.9/51

capacitive pick-up →

period T = 2π/ω = 7.15(9)s
amplitude a = 0.161(28)
χ^2/dof = 65.5/51

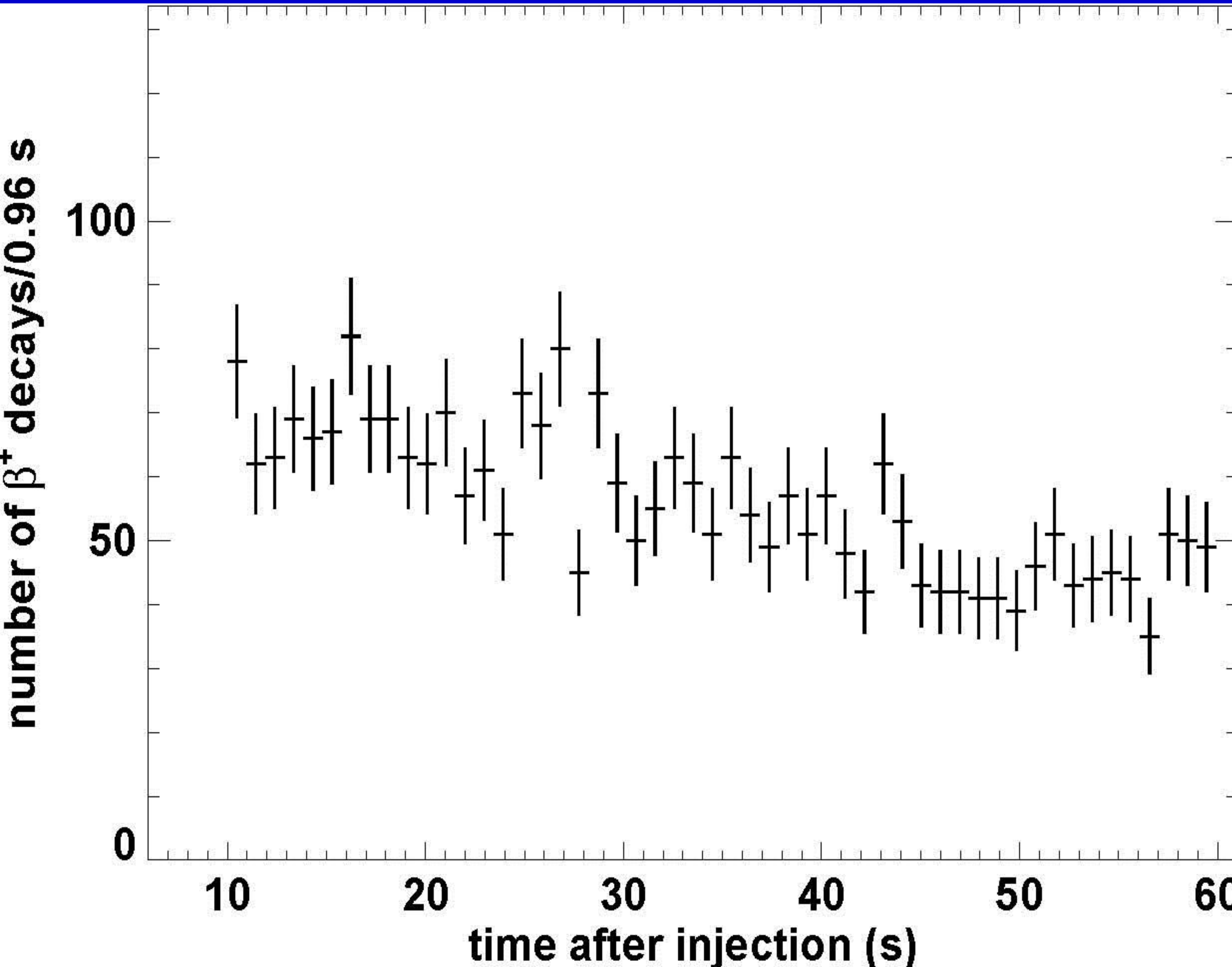


β - decay of $^{122}I^{52+}$



EC/β⁺ ≈ 1/2

β⁺ - decay of H-like $^{142}Pm^{60+}$ (245 MHz resonator)



EC in Hydrogen-like Ions

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

Expectations:

λ_{EC}(H-like)/λ_{EC}(He-like) ≈ 0.5

FRS-ESR Experiment

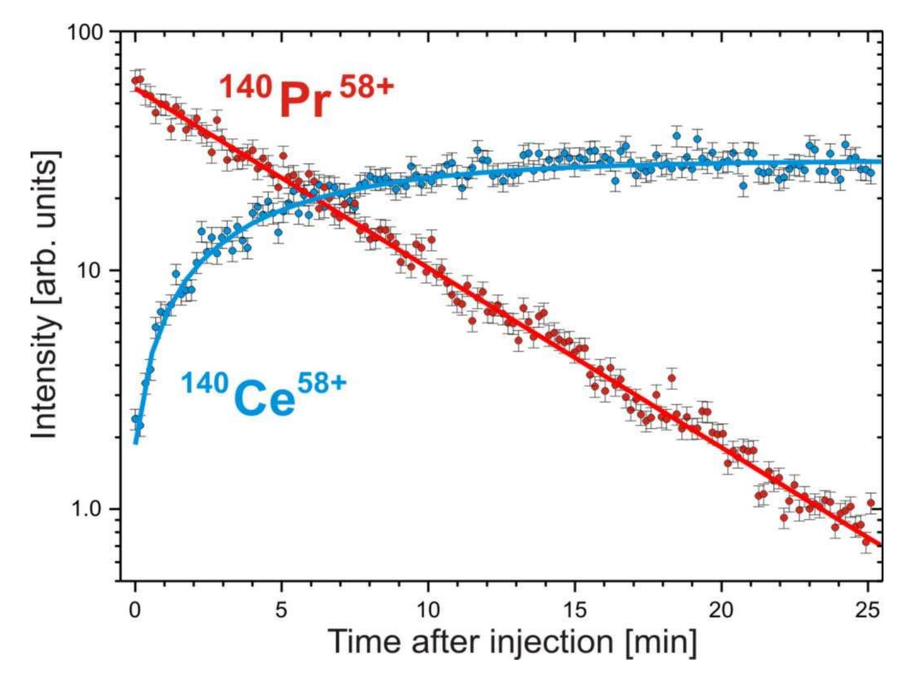
λ(neutral) = 0.00341(1) s^{-1}
G.Audi et al., NPA729 (2003) 3

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

λ_{EC}(H-like) = 0.00219(6) s^{-1} (d*ecay 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)



Capacitive pick-up: $\omega = 2\pi/T = 0.882(14)/s$, **$T = 7.12(11)$ s**, $a = 0.134(27)$