Measurement of the EC Rate and Time Modulation of H- and He-like Ions caused by Spin Statistics and Neutrino Mixing

P. Kienle
SMI Wien and Excellence Cluster “Universe” TU München

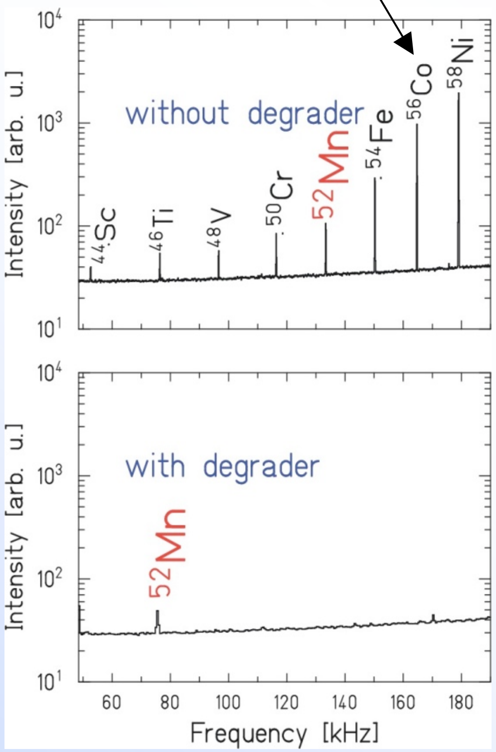
- Single Ion Schottky Mass Spectroscopy for weak decay studies in the Experimental Storage Ring (ESR) of the GSI
- EC/ß+ decay ratios of H-and He-like ^{140} Pr- Spin Statistics
- Study of the EC decays of H-like $^{140}Pr^{58+}$ and $^{142}Pm^{60+}$ ions
- Observation of time modulated non exponential decays
- Decay theory including mixing of massive neutrinos
- Results of Δm^2 and the mixing angle θ of the neutrinos and comparison with KamLAND neutrino oscillation results
- Induced neutrino mass shifts by vacuum polarization effects

Production & Separation of Exotic Nuclei

In-Flight separation of projectile fragments

400MeV/u bunched ^{140}Pr and ^{142}Pm

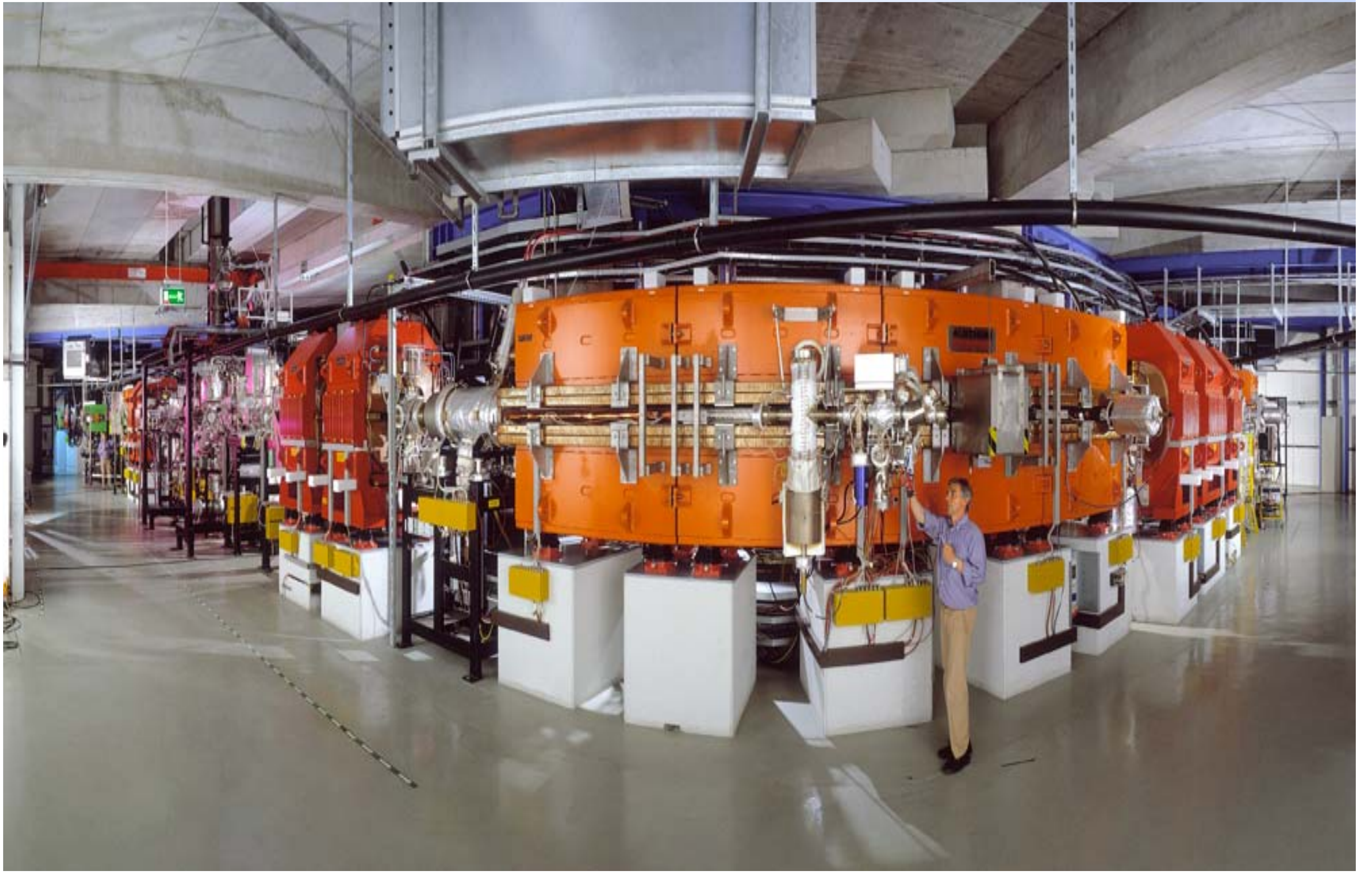
1µs bunched
500 MeV/u
^{152}Sm beam



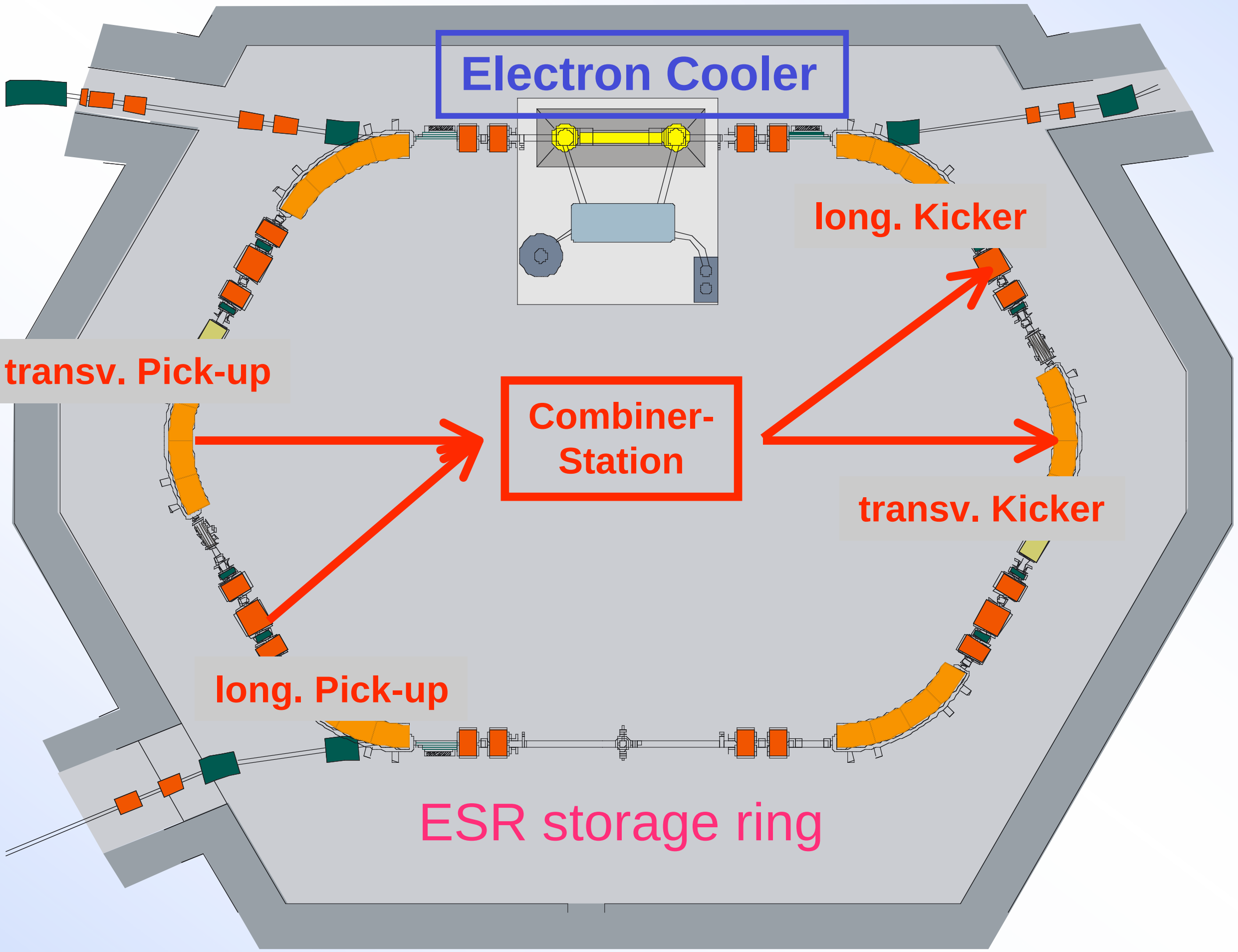
Cocktail of isotopic beams

Mono-isotopic beam ->degrader ($dE/dx \sim Z^2$) followed by magnetic analysis

The Experimental Storage Ring ESR



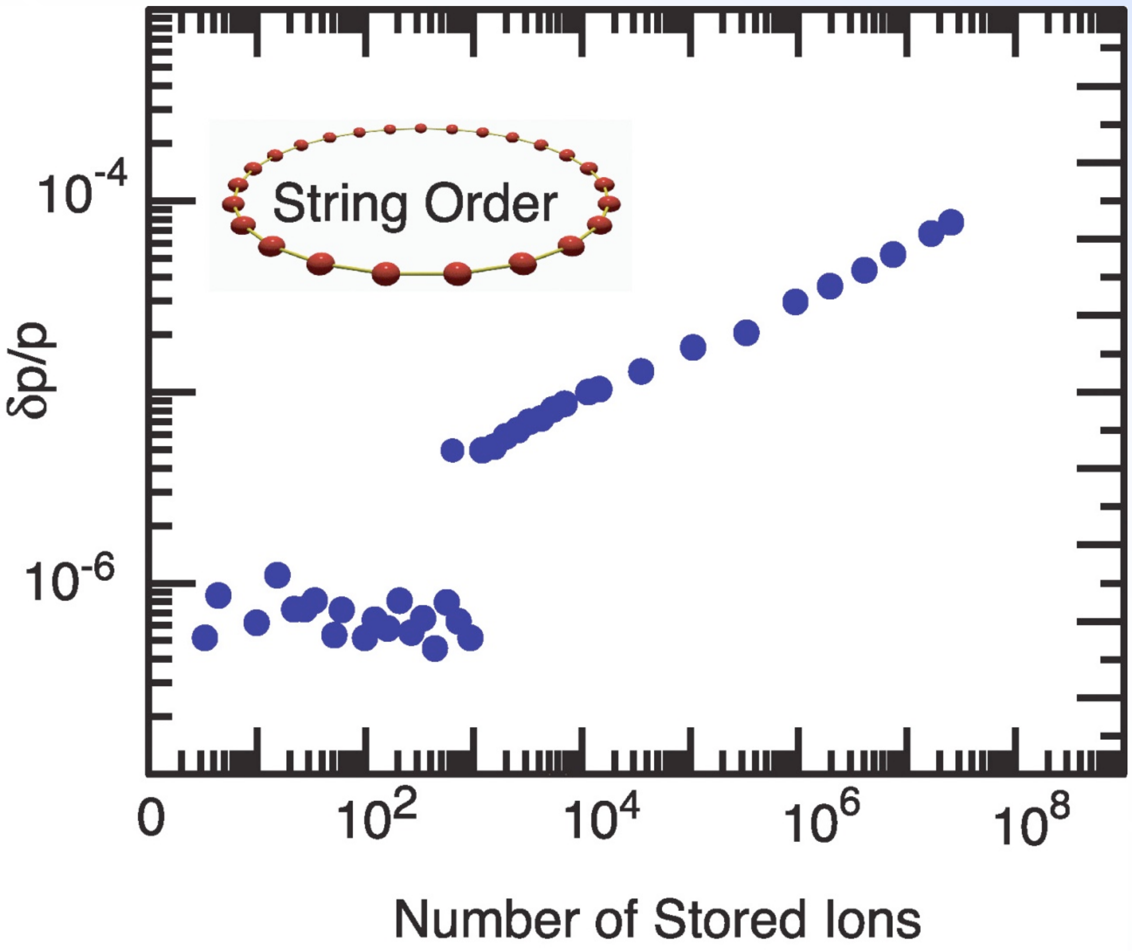
Stochastic and Electron Cooling in the ESR



Fast stochastic cooling @ E = 400 MeV/u for few fragments

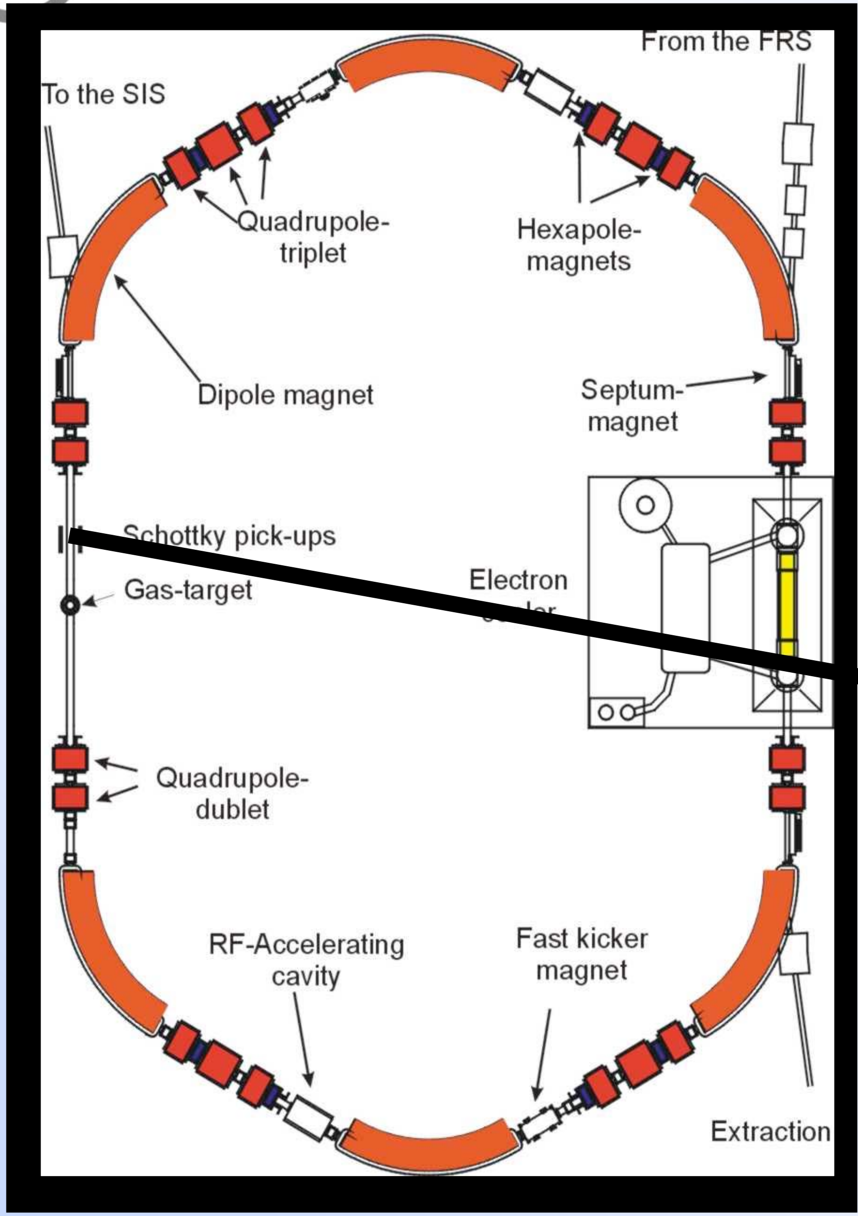
"Phase Transition" to String Order

Allows high mass resolution and single ion detection



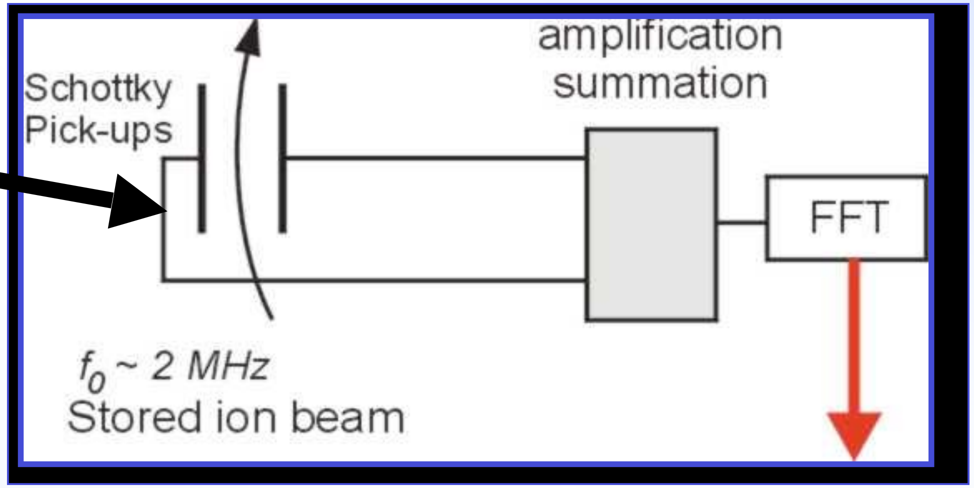
M. Steck et al.,
PRL **77** (1996) 3803

Schottky Mass Spectrometry (SMS)



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

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

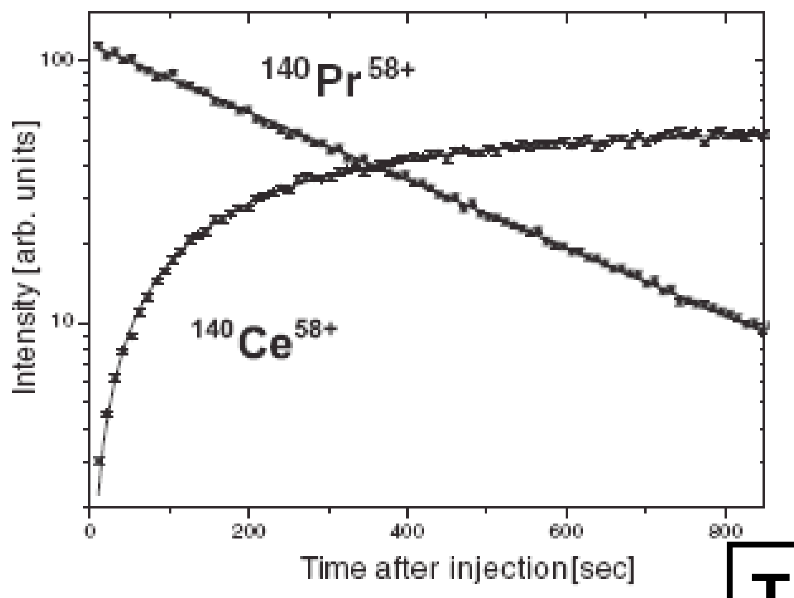


Continuous Digitizing and storage of the FFT data

PRL **99**, 262501 (2007) PHYSICAL REVIEW LETTERS week ending 31 DECEMBER 2007

Measurement of the β^+ and Orbital Electron-Capture Decay Rates in Fully Ionized, Hydrogenlike, and Heliumlike ^{140}Pr Ions

Yu. A. Litvinov,[1,2] F. Bosch,[1] H. Geissel,[1,2] J. Kurcewicz,[3] Z. Patyk,[4] N. Winckler,[1,2] L. Batist,[5] K. Beckert,[1] D. Boutin,[2] C. Brandau,[1] L. Chen,[2] C. Dimopoulou,[1] B. Fabian,[2] T. Faestermann,[6] A. Fragner,[7] L. Grigorenko,[8] E. Haettner,[2] S. Hess,[1] P. Kienle,[6,7] R. Knöbel,[1,2] C. Kozhuharov,[1] S. A. Litvinov,[1,2] L. Maier,[6] M. Mazzocco,[1] F. Montes,[1,9] G. Münzenberg,[1,10] A. Musumarra,[11,12] C. Nociforo,[1] F. Nolden,[1] M. Pfützner,[3] W. R. Plaß,[2] A. Prochazka,[1] R. Reda,[7] R. Reuschl,[1] C. Scheidenberger,[1,2] M. Steck,[1] T. Stöhlker,[1] S. Torilov,[13] M. Trassinelli,[1] B. Sun,[1,14] H. Weick,[1] and M. Winkler[1]

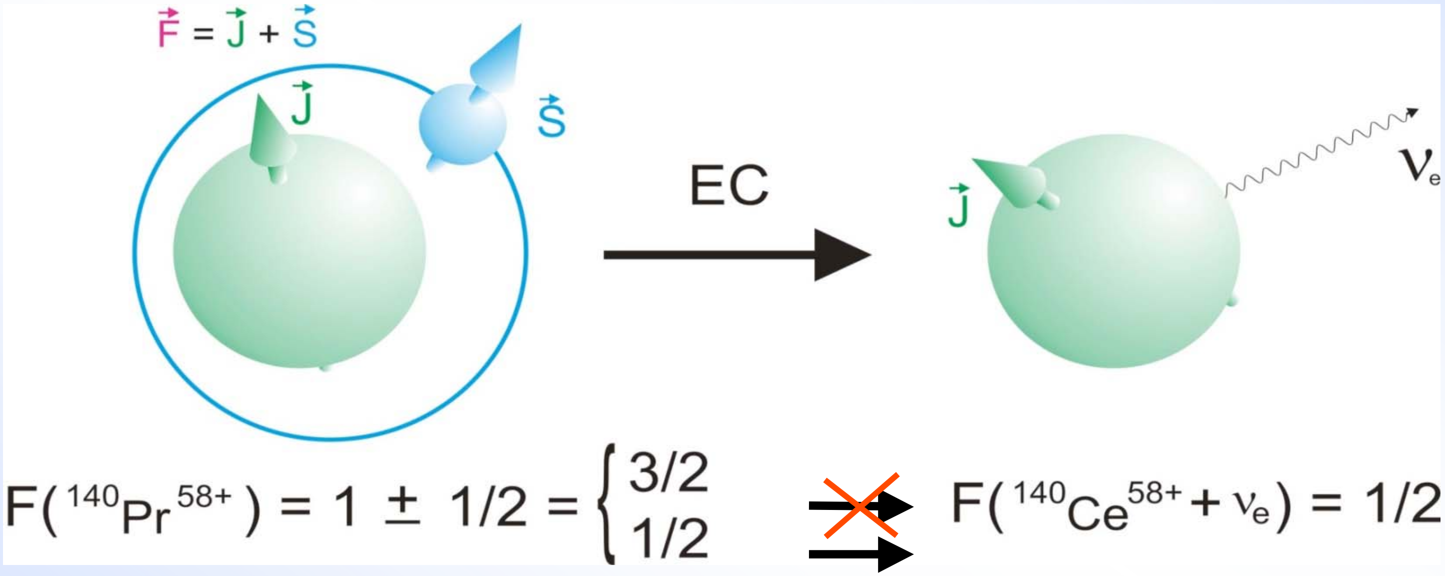


$$R^{(H),exp}_{EC/\beta^+} = 1.36(9),$$
$$R^{(He),exp}_{EC/\beta^+} = 0.96(8),$$
$$R^{(H/He),exp}_{EC/EC} = 1.49(8).$$

The EC decay of H-like ions is ~ 1.5 x faster than for He like ions

The GT-(1^+-0^+) Decay of H-like $^{140}Pr^{58+}$

Coherent production of the 1s hyperfine states F =1/2 , 3/2



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

GT-decay can occur only from the F=1/2 (ground) state
F=3/2 state decays (1.12 eV) by $\gamma \rightarrow$ F=1/2 in τ = 8.5 ms

PHYSICAL REVIEW C 78, 025503 (2008)

Weak decays of H-like $^{140}Pr^{58+}$ and He-like $^{140}Pr^{57+}$ ions

A. N. Ivanov,[1,2,*] M. Faber,[1] R. Reda,[2] and P. Kienle[2,3]

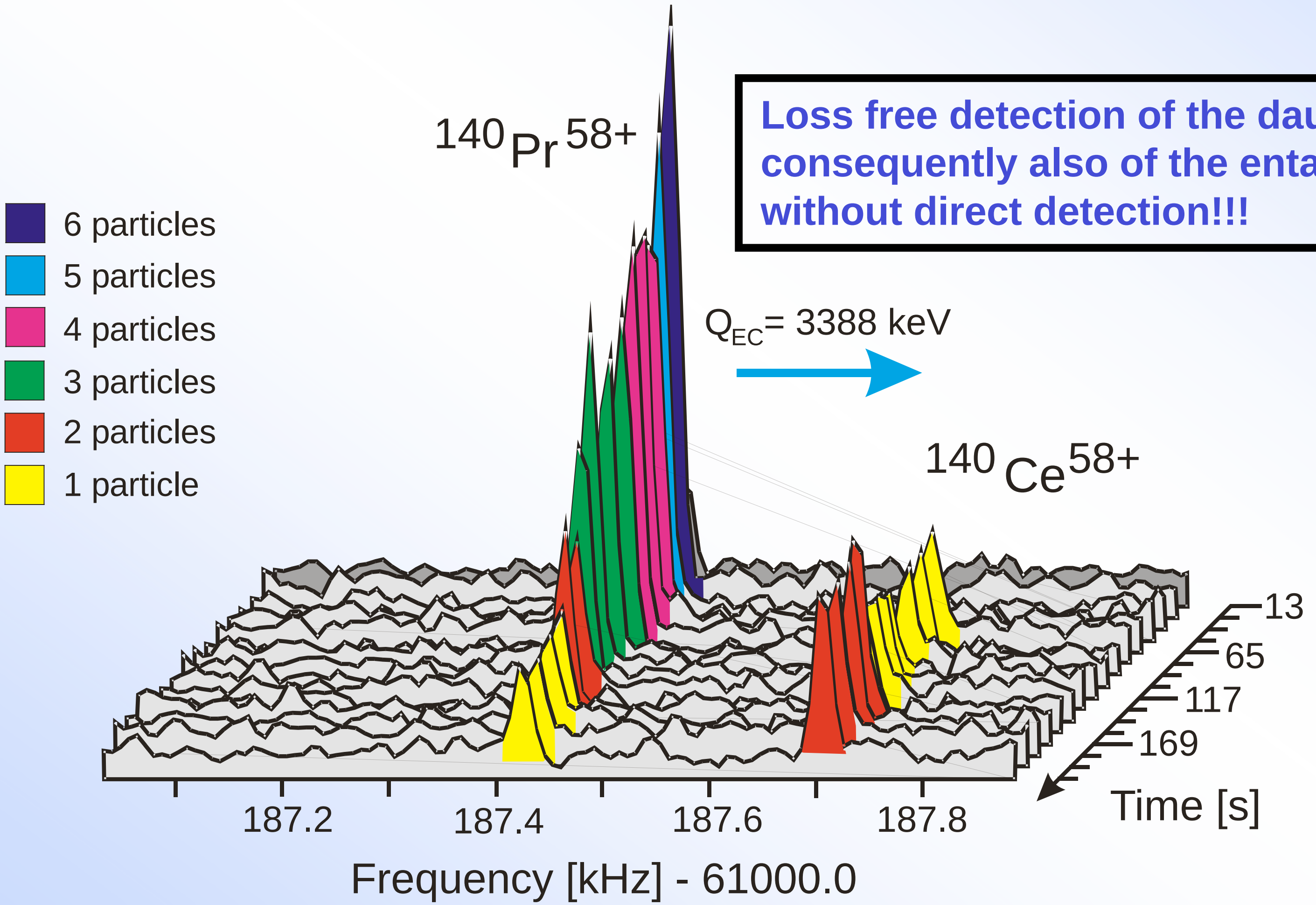
$$R^{(\mathrm{H}),\mathrm{th}}_{EC/\beta^+} = \frac{3\pi^2 Q^2_{\mathrm{H}} |\langle \psi^{(Z)}_{1s} \rangle|^2}{f(Q_{\beta^+}, Z-1)} = 1.40(4)\ \Big[1.36(9)\Big]^{\exp}$$

$$R^{(\mathrm{He}),\mathrm{th}}_{EC/\beta^+} = \frac{2\pi^2 Q^2_{\mathrm{He}} |\langle \psi^{(Z-1)}_{1s} \psi^{(Z)}_{(1s)^2} \rangle|^2}{f(Q_{\beta^+}, Z-1)} = 0.94(3)\ \Big[0.96(8)\Big]^{\exp}$$

$$R^{(\mathrm{H/He}),\mathrm{th}}_{EC/EC} = \frac{2I+1}{2F+1} \frac{|\langle \psi^{(Z)}_{1s} \rangle|^2}{|\langle \psi^{(Z-1)}_{1s} \psi^{(Z)}_{(1s)^2} \rangle|^2} \frac{Q^2_{\mathrm{H}}}{Q^2_{\mathrm{He}}} = 1.50(4)\ \Big[1.49(8)\Big]^{\exp}$$

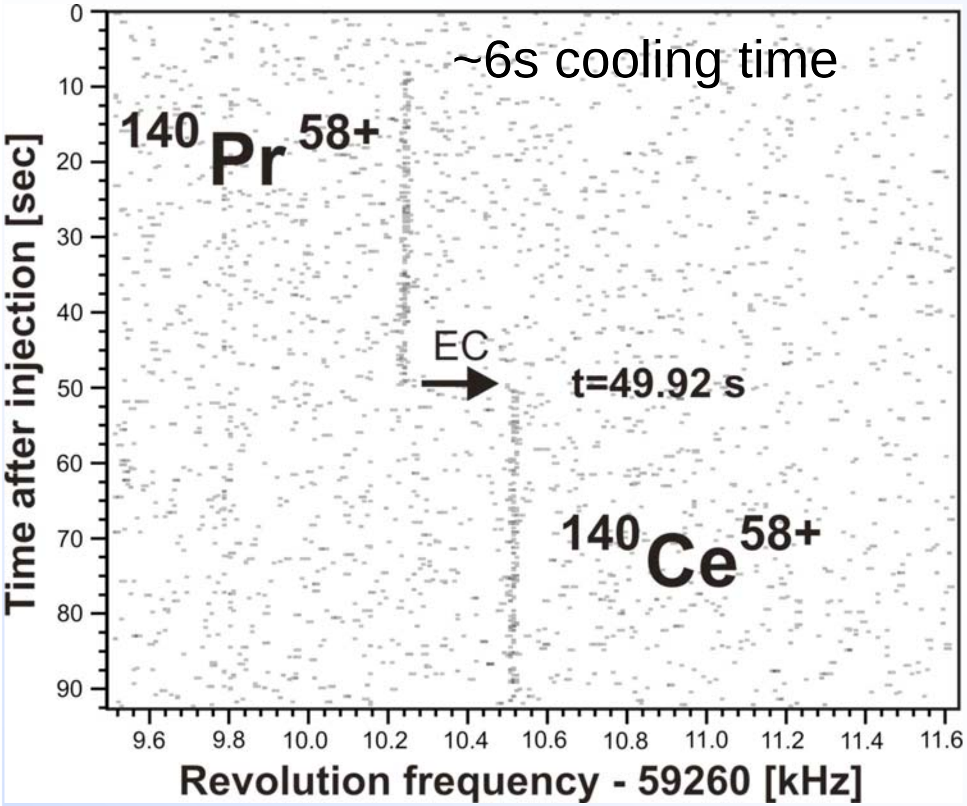
The agreement of $R_{EC/ß+}$ of theory with experiment within 3% **excludes neutrino flavor oscillation** as reason for the time modulation of the EC decays, which would be reduced relative to the $ß^+$ branch

Single-Ion EC-Decay Spectroscopy



Loss free detection of the daughter ion and consequently also of the entangled neutrino without direct detection!!!

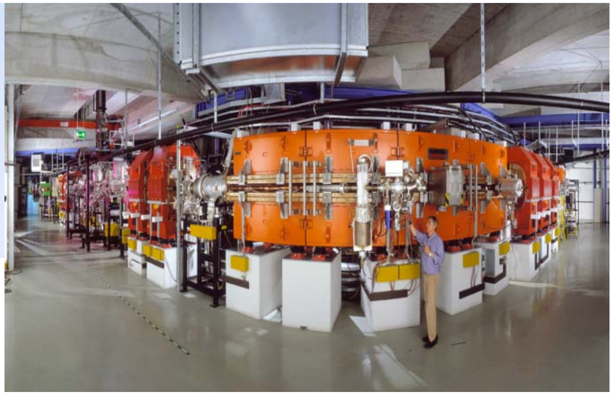
Properties of Measured Time-Frequency Traces



1. Continuous observation
2. Parent/daughter correlation
3. Detection of all EC decays
4. Delay between decay and "appearance" → cooling
5. ^{140}Pr: E_R = 44 eV
   Delay: 900 (300) msec
   ^{142}Pm: E_R = 90 eV
   Delay: 1400 (400) msec

- p transformed to n (hadronic vertex)
- bound e^- annihilated (leptonic vertex)

→ ν in flavour eigenstate ν_e created at t_d ->entangled state with daughter nucleus, which shows all the properties of ν_e



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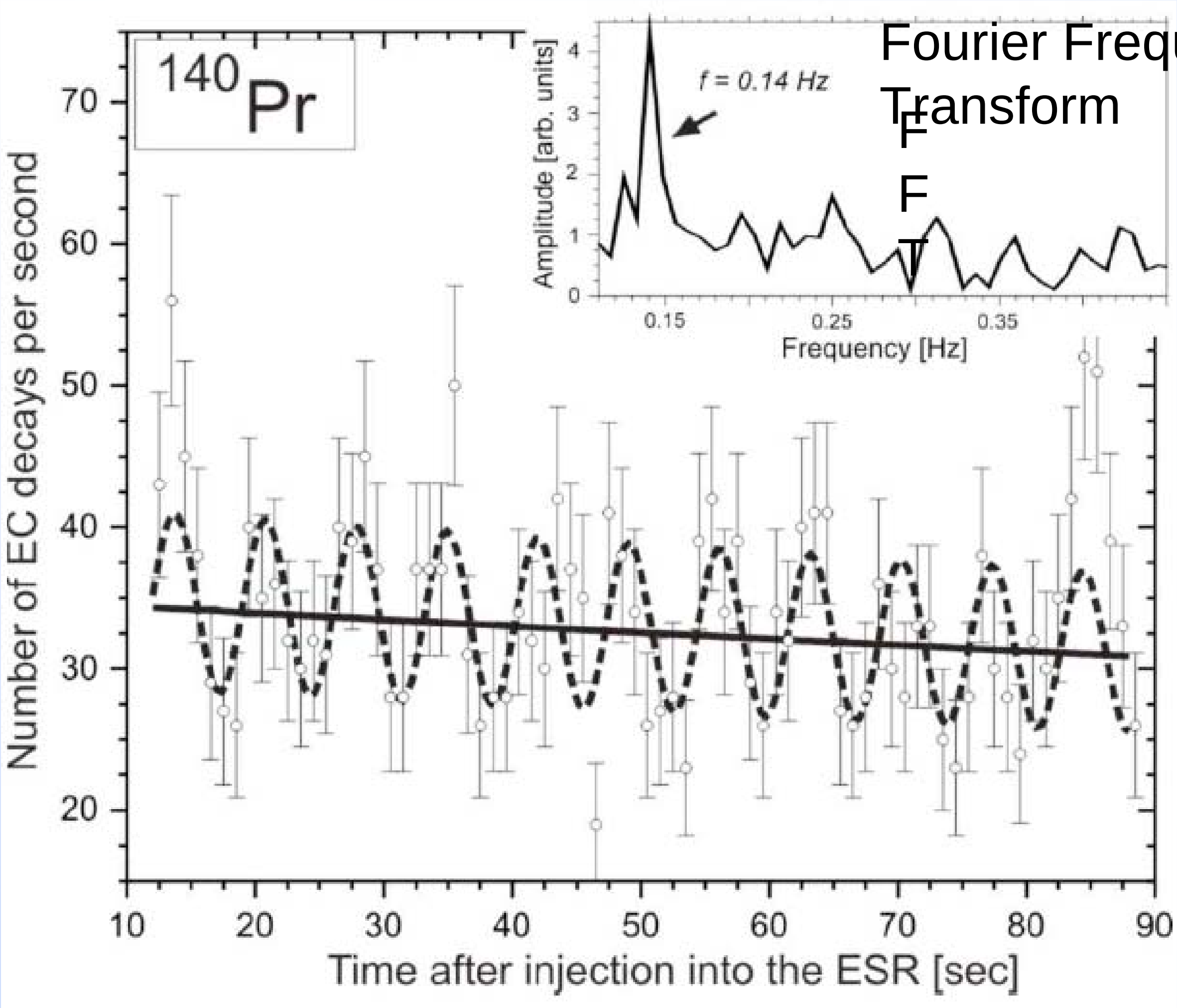
Observation of non-exponential orbital electron capture decays of hydrogen-like ^{140}Pr and ^{142}Pm ions

Yu.A. Litvinov[a,b,*], F. Bosch[a], N. Winckler[a,b], D. Boutin[b], H.G. Essel[a], T. Faestermann[c], H. Geissel[a,b], S. Hess[a], P. Kienle[c,d], R. Knöbel[a,b], C. Kozhuharov[a], J. Kurcewicz[a], L. Maier[c], K. Beckert[a], P. Beller[†], C. Brandau[a], L. Chen[b], C. Dimopoulou[a], B. Fabian[b], A. Fragner[d], E. Haettner[b], M. Hausmann[e], S.A. Litvinov[a,b], M. Mazzocco[a,f], F. Montes[e], A. Musumarra[g,h], C. Nociforo[a], F. Nolden[a], W. Plaß[b], A. Prochazka[a], R. Reda[d], R. Reuschl[a], C. Scheidenberger[a,b], M. Steck[a], T. Stöhlker[a,i], S. Torilov[j], M. Trassinelli[a], B. Sun[a,k], H. Weick[a], M. Winkler[a]

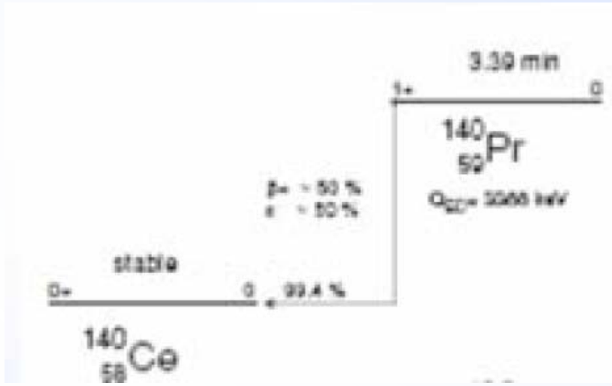
Modulation of the $^{140}Pr^{58+}$ EC Decay



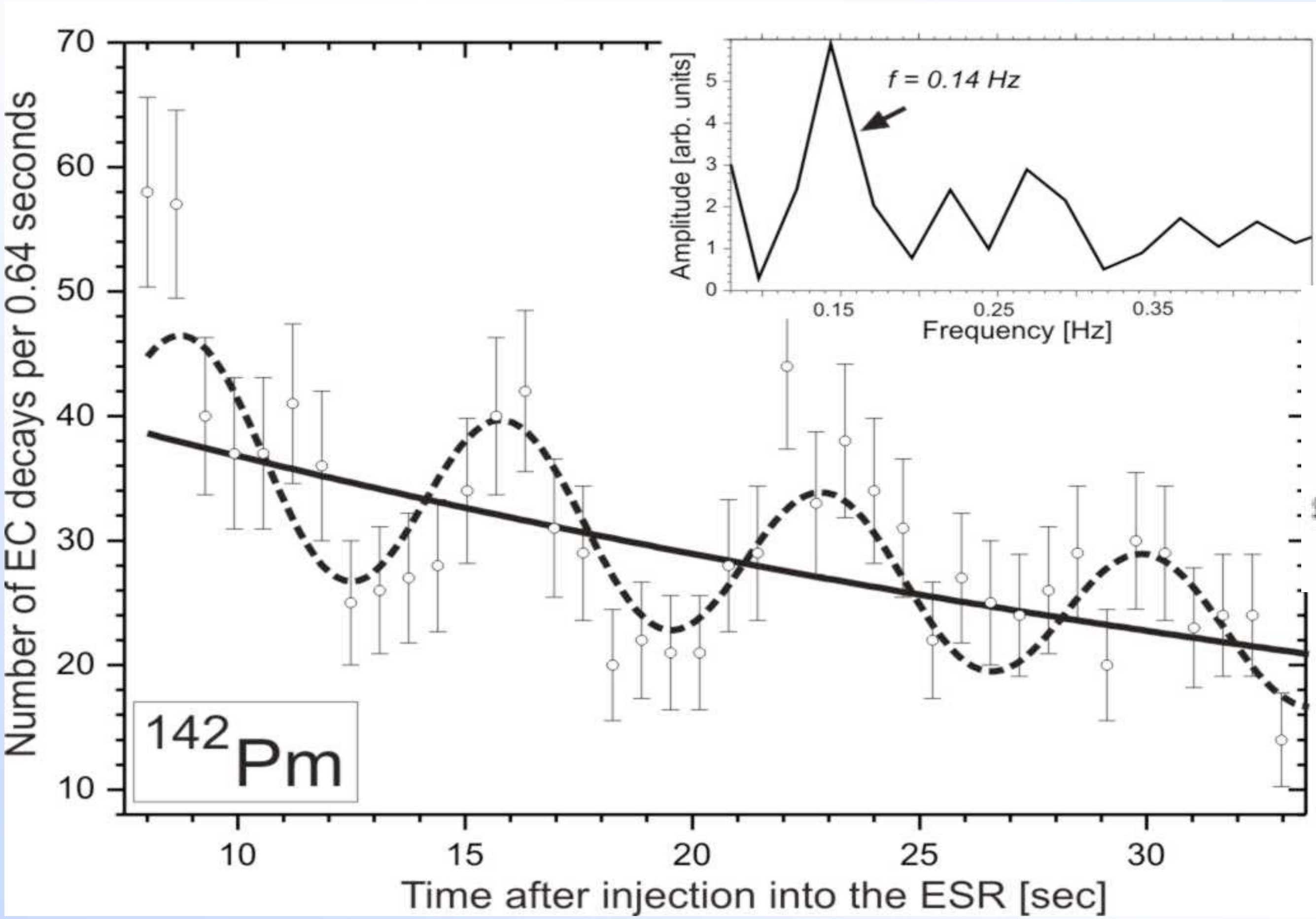
Fourier Frequency Transform

F
F
T

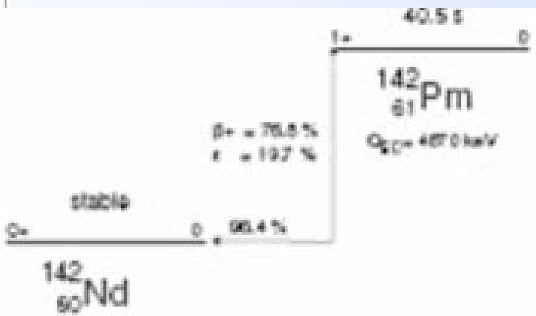
T= (7.06± 0.08)s
a= (0.18± 0.03)



Modulation of the ^{142} Pm^{60+} EC Decay



***T*= (7.10 ± 0.22)s**
a= (0.22 ± 0.03)



Decay Parameters for the ^{140}Pr and ^{142}Pm Time-Modulated Decays

$$\frac{dN_{EC}(t)}{dt} = N(0) \cdot \lambda_{EC} \cdot e^{-\lambda t},$$

$$\frac{dN_{EC}(t)}{dt} = N(0) \cdot e^{-\lambda t} \cdot \widetilde{\lambda_{EC}}(t),$$

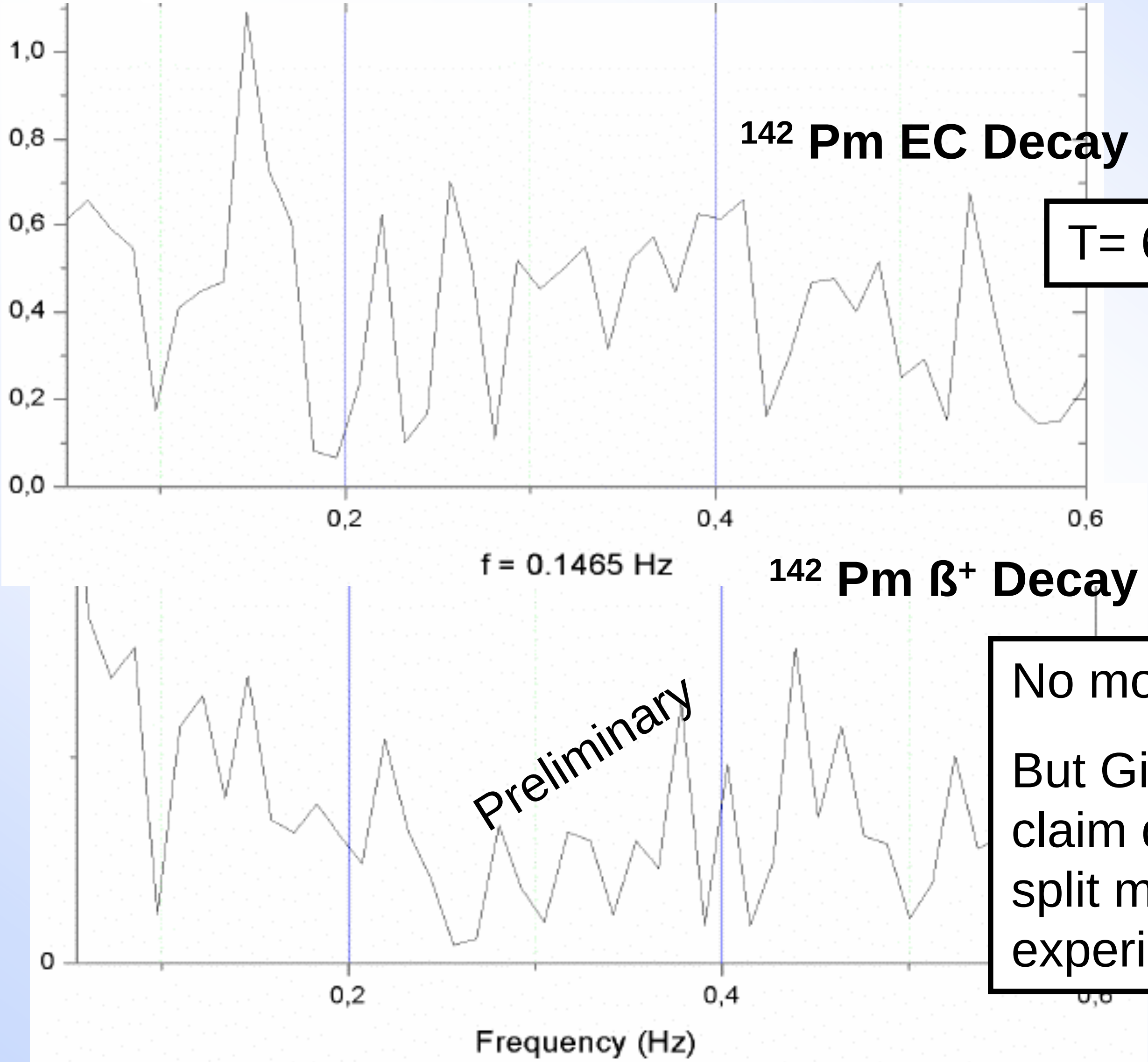
$$\widetilde{\lambda_{EC}}(t) = \lambda_{EC} \cdot [1 + a \cdot cos(\omega t + \phi)]$$

Fit parameters of ^{140}Pr data						
Eq.	$N_0\lambda_{EC}$ [sec^{-1}]	λ [sec^{-1}]	a	ω [sec^{-1}]	ϕ	χ^2/DoF
1	34.9(18)	0.0014(10)	-	-	-	107.2/73
2	35.4(18)	0.0015(10)	0.18(3)	0.890(11)	0.4(4)	67.18/70
Fit parameters of ^{142}Pm data						
Eq.	$N_0\lambda_{EC}$ [sec^{-1}]	λ [sec^{-1}]	a	ω [sec^{-1}]	ϕ	χ^2/DoF
1	41.5(17)	0.0170(9)	-	-	-	173/124
1	46.8(40)*	0.0240(42)*	-	-	-	63.77/38*
2	46.0(39)*	0.0224(42)*	0.23(4)*	0.885(31)*	-1.6(5)*	31.82/35*

On the Time–Modulation of the β^+–Decay Rate of H–like $^{140}Pr^{58+}$ Ion

A. N. Ivanov[a,b], E. L. Kryshen[c], M. Pitschmann[a], P. Kienle[b,d]

arXiv:0806.2543v1 [nucl-th]; accepted in Physical Review Letters



T= 6.83 s as expected

No modulation as expected,

But Giunti, Lindner et al claim quantum beats from split mother state, which is experimentally disproved

Towards Understanding the EC Decay Time Modulation

- **Preliminary tests using the β^+ decay branch of ^{142}Pm show no modulation in contrast to the EC branch**

- **This excludes various experimental sources, so we assume lepton entanglement of the weak decay with massive neutrinos and quantum beats from split mother state.**

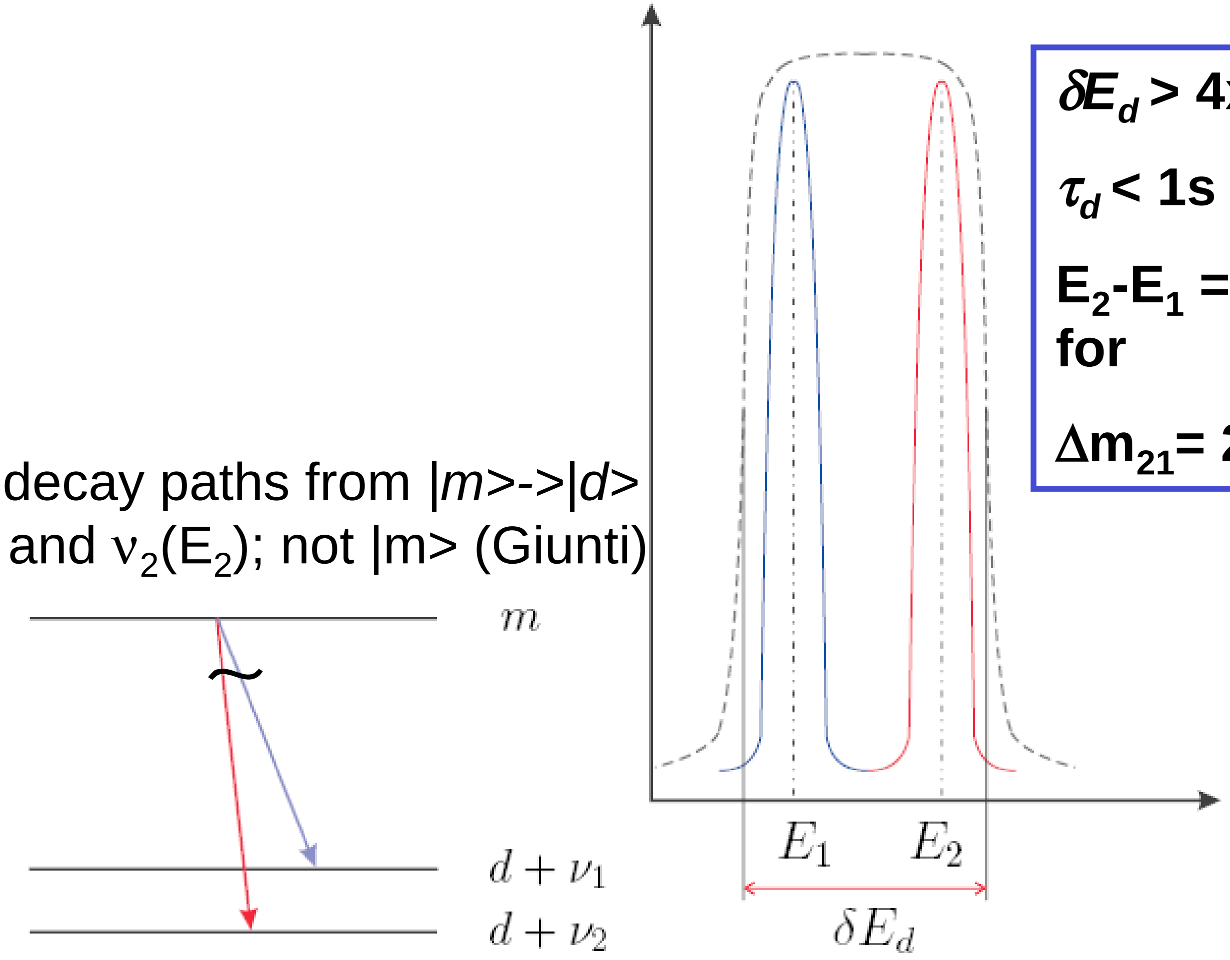
- **Time dependent perturbation theory of the decay with superimposed massive neutrinos, Ivanov, Reda, PK, nucl-th/ 0801.2121 v3 and PLB**

- **Interpretation of the difference of Δm^2(KamLAND) and (EC decay) with neutrino mass shifts, Ivanov, Kryshen, Pitschmann, PK nucl-th/0804.1311 and PLB**

Neutrino Quantum Beats (schematic)

Observation of interference if $\delta E_d > (E_2 - E_1)$

Note: Two decay paths from |*m*>->|*d*> with $\nu_1(E_1)$ and $\nu_2(E_2)$; not |m> (Giunti)



$\delta E_d > 4x10^{-15}$ eV for

$\tau_d < 1$s

E_2-E_1 = $0.86x10^{-15}$ eV for

Δm_{21}= $2.22x10^{-4}$ eV²

On the time–modulation of the K–shell electron capture decay of H-like $^{140}Pr^{58+}$ ions produced by neutrino mass differences

A. N. Ivanov [a*], R. Reda[b], P. Kienle[b,c†], nucl-th/ 0801.2121 v3 and PLB

Weak interaction with **mixed neutrino wave functions** $U_{ej}\psi_{\nu_j}$ with masses m_1, m_2, m_3

$$U_{e1} = \cos\vartheta_{12}\cos\vartheta_{13} \quad U_{e2} = \sin\vartheta_{12}\cos\vartheta_{13} \quad U_{e3} = \sin\vartheta_{13}\, e^{-i\delta_{CP}}$$

The phase δ_{CP} is a CP violating phase, assumed as $e^{i\delta_{CP}}=1$

The transition matrix element is taken as **coherent sum** of the amplitudes to the states $I_f + \nu_j$ given by the expression

$$M(I_i \to I_f + \nu)(t) = \sum_j M(I_i \to I_f + \nu_j) = \sum_j U_{ej}\mathcal{M}_j(t)$$

The matrix element $M_j(t)$ is integrated from t=-∞ using the ε->0 regularisation

$$\mathcal{M}_j(t) = -i\frac{G_F}{\sqrt{2}}V_{ud}\int_{-\infty}^{t} d\tau\, \langle \nu_j, I_f|H_W(\tau)|I_i\rangle,$$

$$\mathcal{M}_j(t) = -\frac{e^{i\,(\Delta E_j(\vec{k}_j) - i\,\varepsilon)t}}{\Delta E_j(\vec{k}_j) - i\,\varepsilon}\mathcal{M}_j(0),$$

Neutrino Wave Packets

The neutrino components with different momentum k_j and $k_{j'}$ require wave packets as wave functions with spatial spread δ for their presentation.

$$\psi_{\nu_j}(\vec{r},t) = (2\pi\delta^2)^{3/2} \int \frac{d^3k}{(2\pi)^3}\, e^{-\frac{1}{2}\delta^2(\vec{k}-\vec{k}_j)^2}\, e^{i\vec{k}\cdot\vec{r} - iE_j(\vec{k})t} u_{\nu_j}(\vec{k},\sigma_{\nu_j})$$

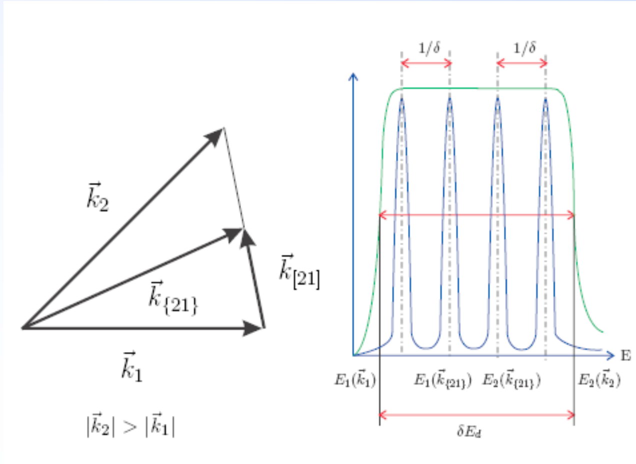
$$W_{I_i \to I_f+\nu}(t) = \sum_j e^{\varepsilon t} \frac{2\varepsilon}{(\Delta E_j(\vec{k}_j))^2 + \varepsilon^2} |U_{ej}|^2 |\mathcal{M}_j(0)|^2 + \sum_{j>j'} U^*_{ej} U_{ej'} \mathrm{Re}[\mathcal{M}^*_j(0)\mathcal{M}_{j'}(0)]$$
$$\times e^{\varepsilon t}\left[\frac{2\varepsilon}{(\Delta E_j(\vec{k}_j))^2 + \varepsilon^2} + \frac{2\varepsilon}{(\Delta E_{j'}(\vec{k}_{j'}))^2 + \varepsilon^2}\right] \cos\left[\Big(E_j(\vec{k}_j) - E_{j'}(\vec{k}_{j'})\Big)t\right]. \quad (30)$$

Eq.(30) was obtained by tuning the decay energy region ***I_i->I_f+ν_j*** to ***I_i->I_f+$\nu_{j'}$*** by means of the width δ of the wave packet with ***(k_j-$k_{j'}$)*** and energy conservation ***$\Delta E_j(k_j)$= $\Delta E_j(k_{j'})$***

Energy and Momentum Conservation

Case 1:Energy conservation and neutrino momentum non conservation

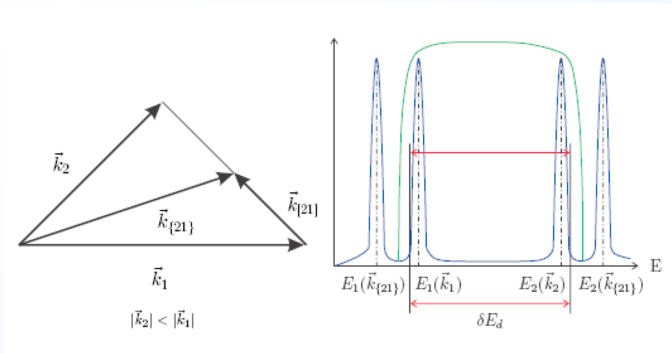
$$E_2 - E_1 = (m^2_2 - m^2_1)/2\,M_m = \omega_{21}$$



Case 2: Neutrino momentum conservation

$$E_2 - E_1 = (m^2_2 - m^2_1)/2Q = \Omega_{21}$$

Not observable with
present time resolution



Time Modulated Decay Constant

$$\frac{\lambda_{EC}^{(\mathrm{H})}(t)}{\lambda_{EC}^{(\mathrm{H})}} = 1 + a_{EC}\cos(\omega_{21}t) + \tilde{a}_{EC}\cos(\Omega_{21}t)$$

$$\lambda_{EC}^{(\mathrm{H})} = \frac{1}{2F+1}\frac{3}{2}|\mathcal{M}_{\mathrm{GT}}|^2|\langle\psi_{1s}^{(Z)}\rangle|^2\frac{Q_{\mathrm{H}}^2}{\pi},$$

$$\omega_{21} = \Delta m_{21}^2/2M_m$$

$$\Omega_{21} = \Delta m_{21}^2/2Q_{\mathrm{H}}$$

$$a_{EC} = p\,\sin 2\vartheta_{12}\ ,\ \tilde{a}_{EC} = (1-p)\,\sin 2\vartheta_{12}$$

Δm^2_{21} and θ_{21} from the Modulation Period *T* and the Amplitude *a*

- **The modulation period of ^{140}Pr is T= 7.06(8) s and of ^{142}Pm T= 7.10(22) s with γ= 1.43 gives Δm^2_{21}= 2.22(3)x10^{-4} eV²**

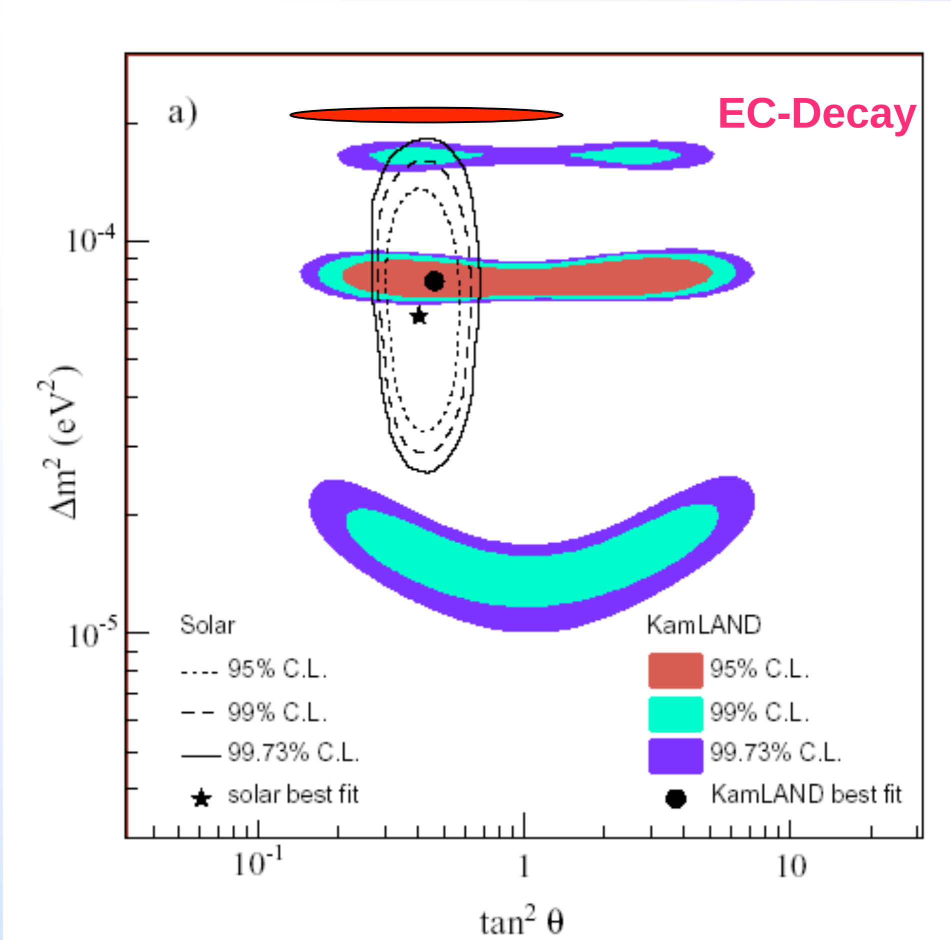
- **The agreement of *T* for both systems with *different Q* values and life times indicates M_d scaling of the period *T* as expected by theory**

- **Δm^2_{21}= 2.22(3)x10^{-4} eV² is in agreement with the values derived by Lipkin's oscillation model and Kleinert and Kienle's pulsating neutrino vacuum method**

- **It is by a factor 2.75 larger than the value Δm^2_{21}= o.80(6)x10^{-4} eV² from KamLAND data**

- **With a modulation amplitude of a=0.20(2) from the ^{140}Pr and ^{142} Pm decay and assuming p~ 0.2 , one gets the neutrino mixing angle comparable to the combined KamLAND and sun neutrino results**

Solar, KamLAND, EC Results on Δm^2-$\tan^2\theta$



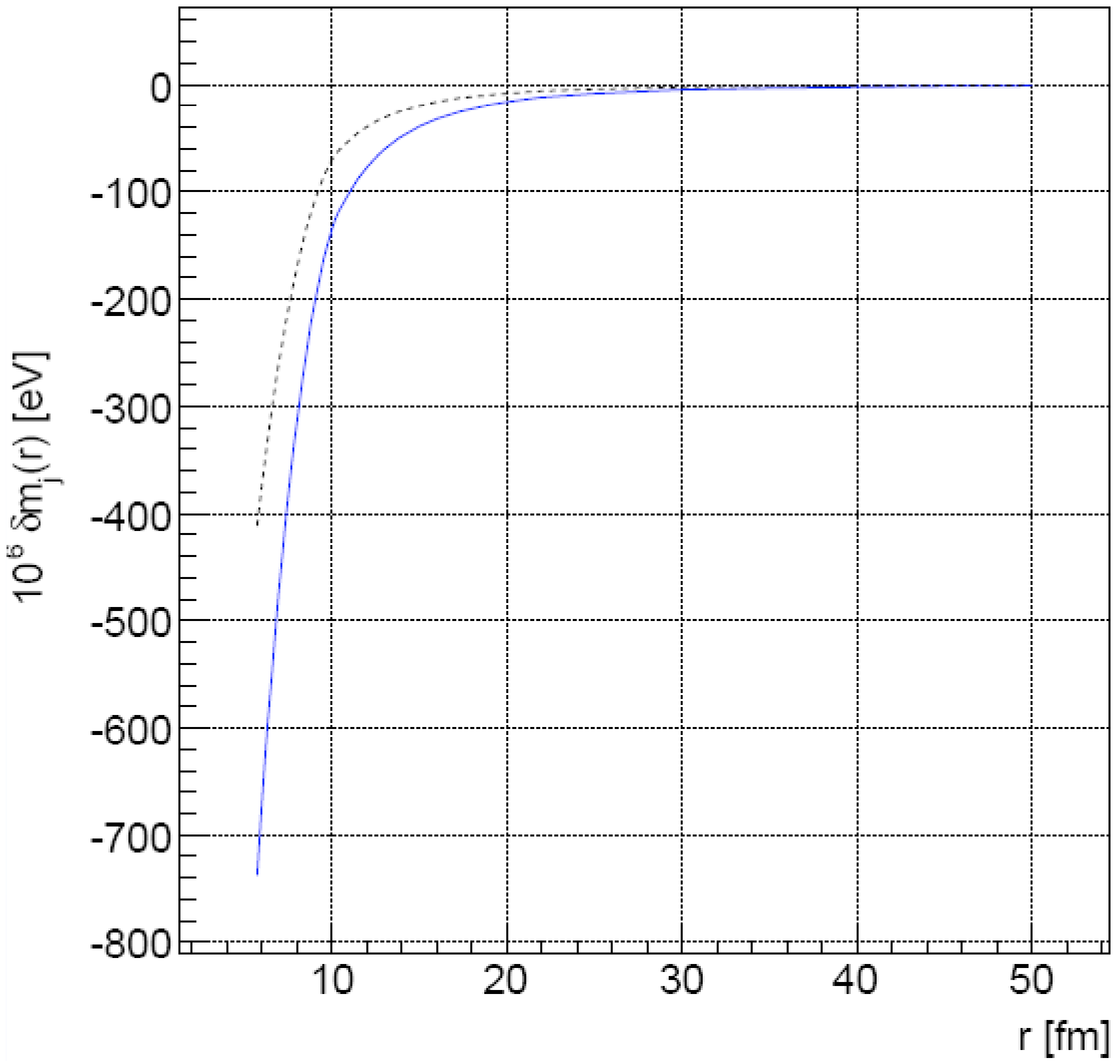
Origin of the Difference of EC and KamLAND results?

- What is the origin of the difference Δm^2 of the decay and the KamLAND neutrino oscillation results?
- Instrumental effects, such as confinement in a storage ring ($p^* = (p_k - qeA/c$ and broken Lorentz invariance). Most likely not
- Polarisation of virtual lepton-W boson pairs in the high Coulomb field of a high Z nucleus (Ivanov et al)

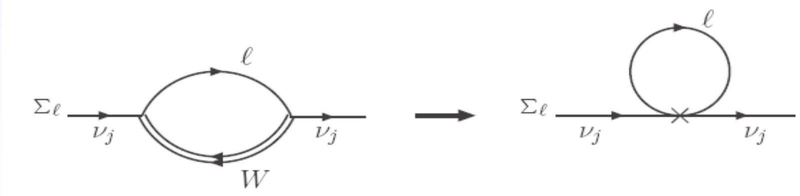
Neutrino masses from the Darmstadt oscillations

A. N. Ivanov [a,b*], E. L. Kryshen [c†], M. Pitschmann [a‡], and P. Kienle [b,d§],

(arXiv:0804.1311)



Vacuum polarisation by L-W loop



$$\delta m_1(R) = -7.37 \times 10^{-4}\,\mathrm{eV},$$
$$\delta m_2(R) = -4.11 \times 10^{-4}\,\mathrm{eV}.$$

The period of modulation is thus redefined as

$$T_d = \frac{4\pi\gamma M_d}{(m_2 + \delta m_2(R))^2 - (m_1 + \delta m_1(R))^2}. \qquad (10)$$

$$\delta m_2^2(R) - \delta m_1^2(R) = (\Delta m_{21}^2)_{\rm GSI} - (\Delta m_{21}^2)_{\rm exp}, \qquad (11)$$

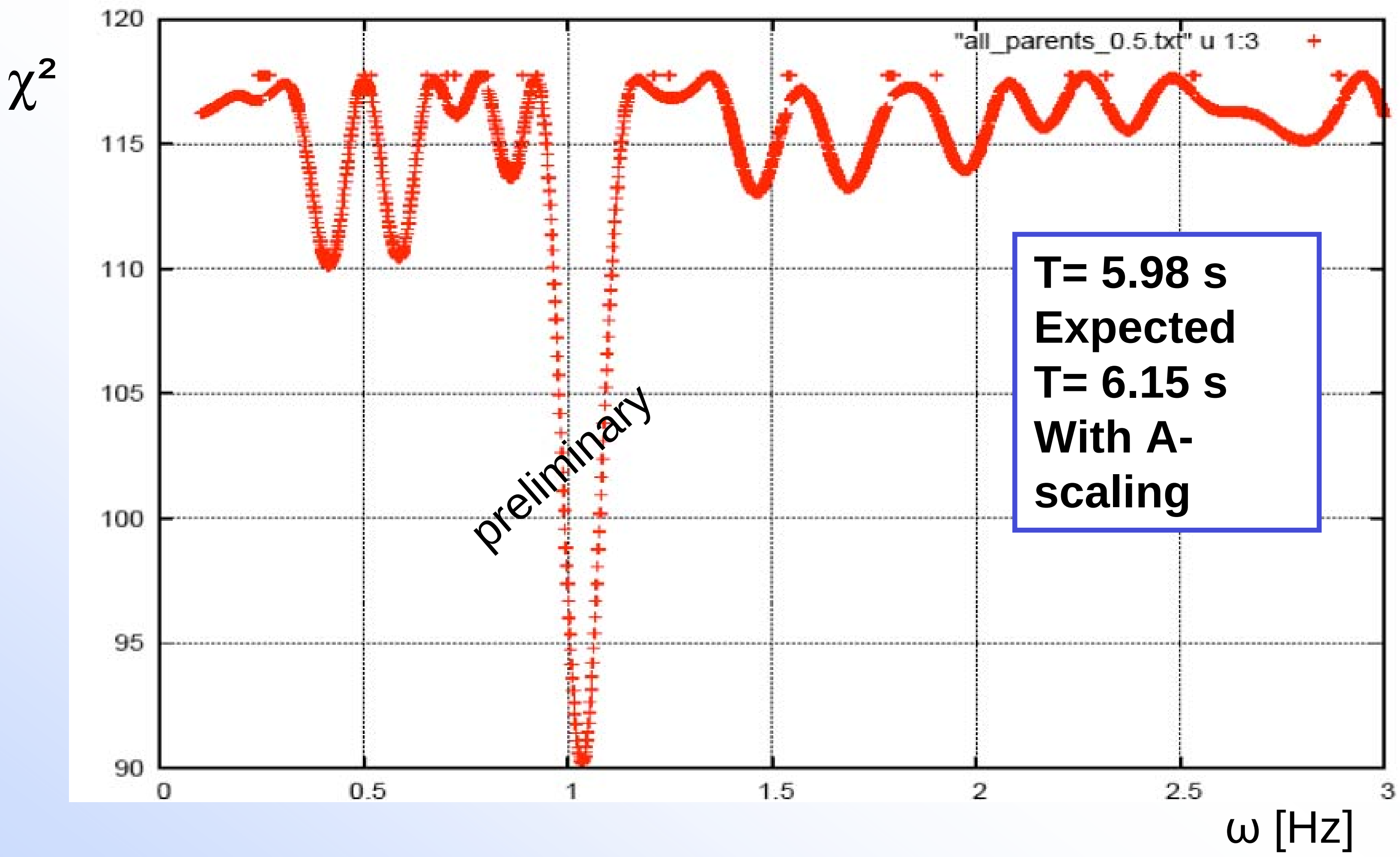
Question: $(\Delta m^2_{21})_{exp}$?

Further Questions

- How does the modulation frequency scale with M and Z of the nuclei involved?

- What is the prediction for the EC decay of H-like ^{122}I our recent experiment?

χ^2 of Modulation Frequency ω of ^{122}I



Conclusion

- We have developed an **efficient, new method** for the study of **neutrino properties** by making use of **lepton entanglement** in detecting **two body weak decays**, thus avoiding the inefficient direct detection of the neutrinos

- Time modulation of various EC decays of H- like ions were studied in the ESR storage ring at GSI Darmstadt

- Using time dependent perturbation theory with wave functions of massive neutrinos, their properties, such as mass, mixing, and vacuum polarisation are tentatively derived

Thank you !

Modulation of EC Decays (SMS) - Collaboration

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Th. Bürvenich, L. Chen, I. Cullen, Ch. Dimopoulou, H. Essel, B. Fabian,
Th. Faestermann, M. Falch, A. Fragner, B. Franczak, B. Franzke, H. Geissel,
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,
R. Knöbel, J. Kurcewicz, S.A. Litvinov, Yu.A. Litvinov, Z. Liu, K.E.G. Löbner†, L. Maier,
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H. Schatz, Ch. Scheidenberger, M. Shindo, V. Shishkin, J. Stadlmann, M. Steck,
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