# Does neutrino flavor mixing cause oscillations in decay rates?


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Collaborators

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# Outline

I am interested in neutrino mixing parameters and oscillations

This paper cropped up on the arxiv …

We quickly realized that IF this paper with its neutrino interpretation were correct, it would change everything…

We reasoned that IF this paper were correct, it should be a very simple test

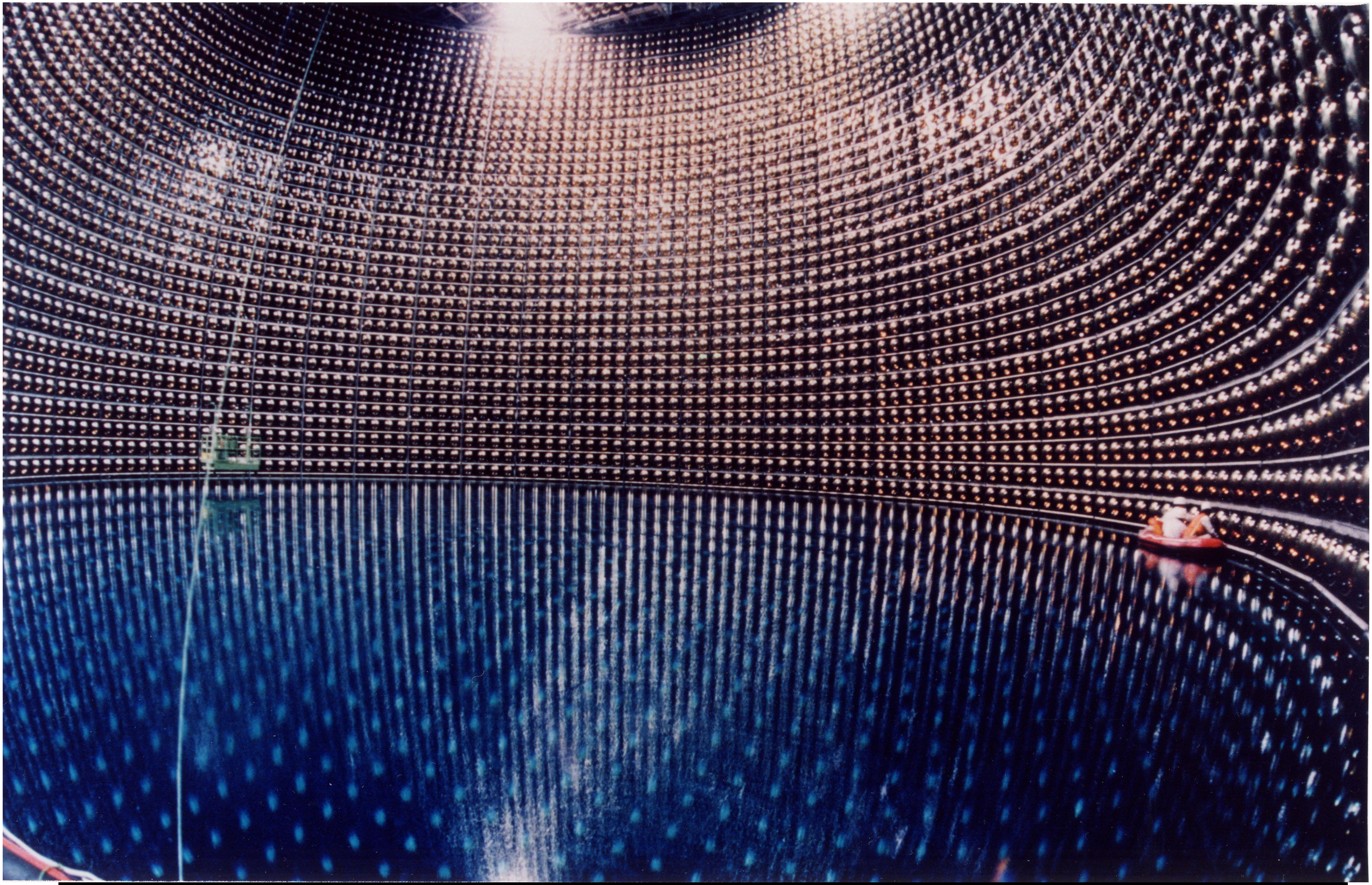
We did a literature search and a simple test.  We find no effect.

Original authors argue that our test didn't count.

Original authors complain about other suggestions -- quantum beats, quantum mechanics, etc.

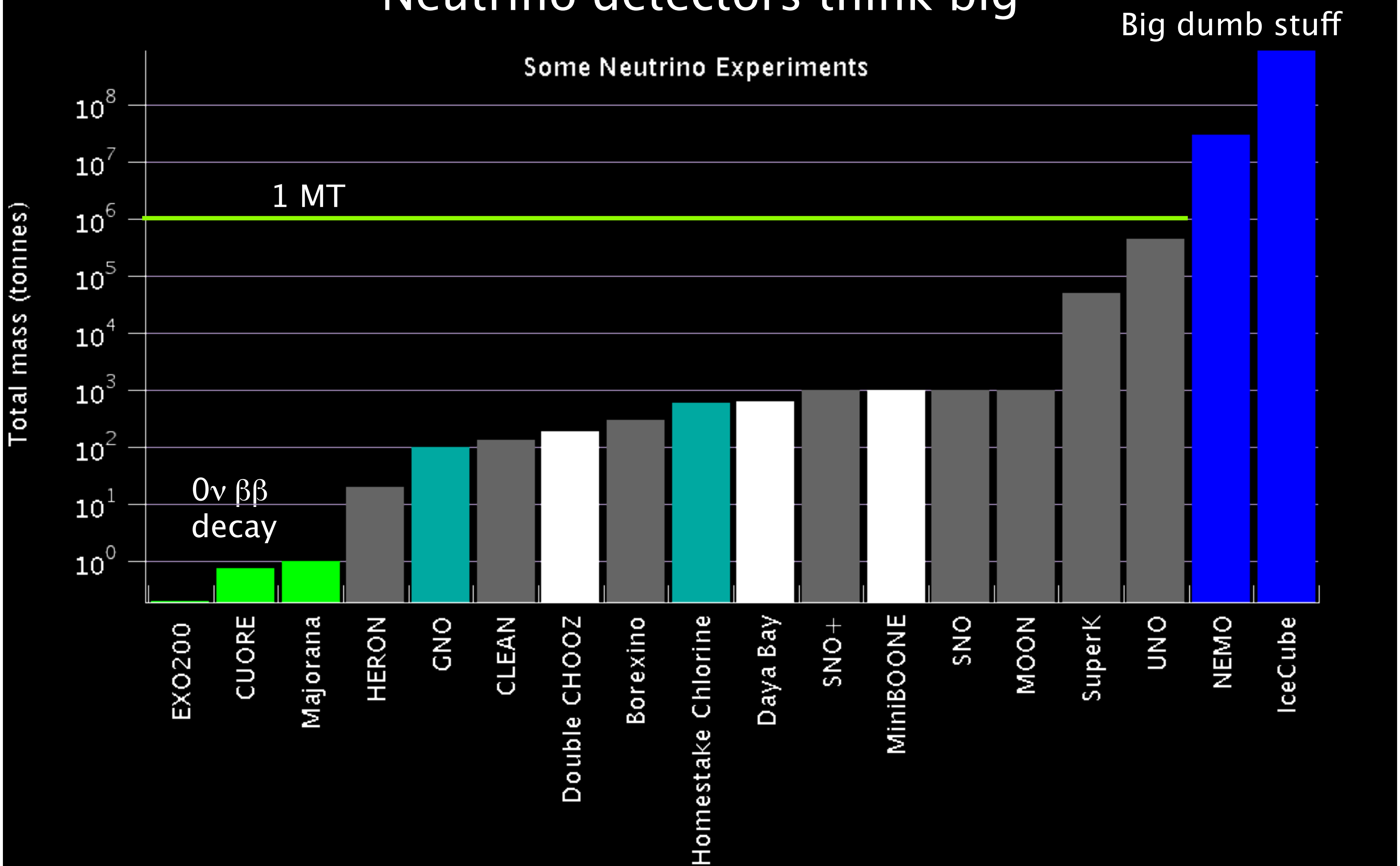
Original authors publish a slew of gibberishy stuff: beta decay rates shouldn't oscillate, new isotope data, new theory

Another example, conclusions…

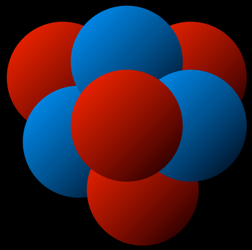


[redacted]

# Neutrino detectors think big

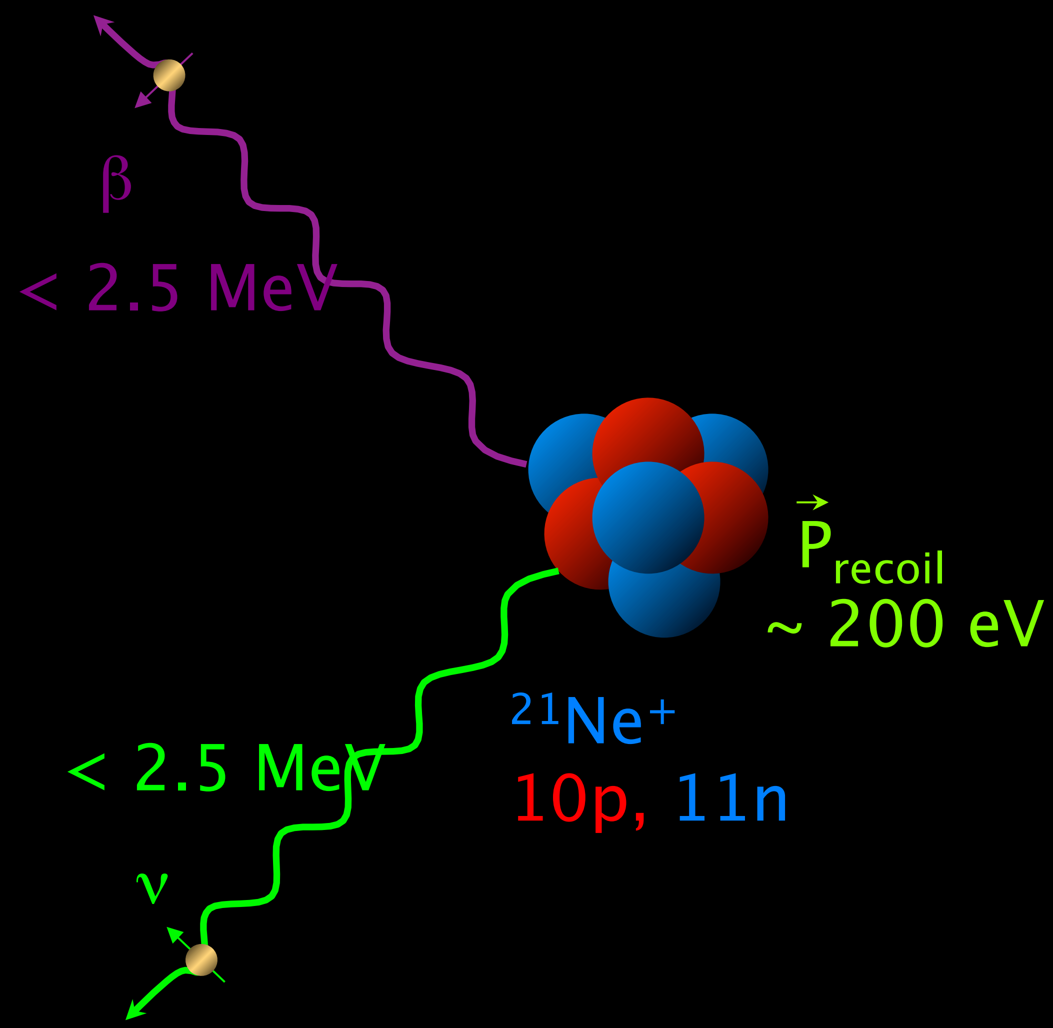


# Neutrinos are emitted in Weak Interactions

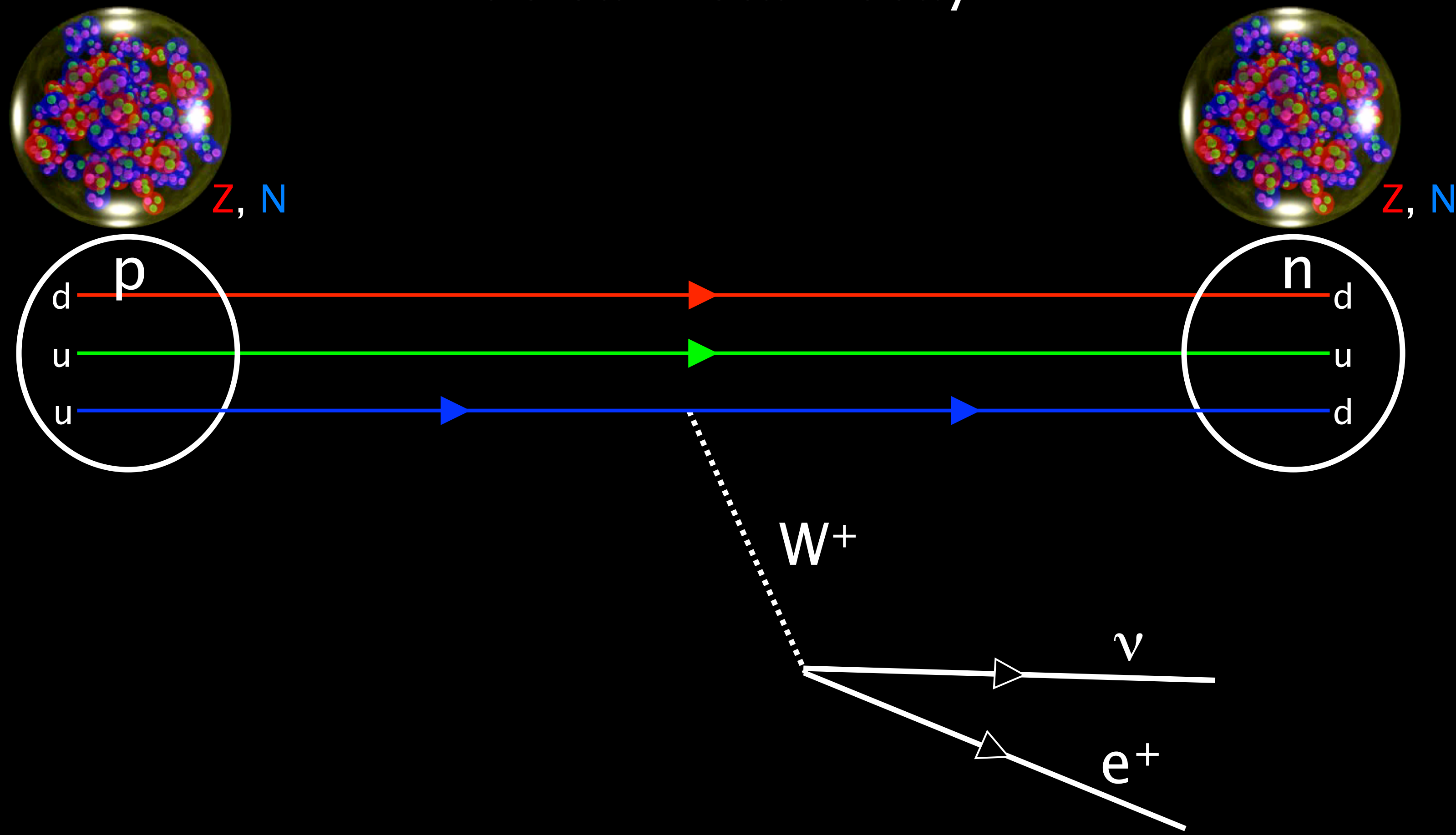


$^{21}$Na
11p, 10n

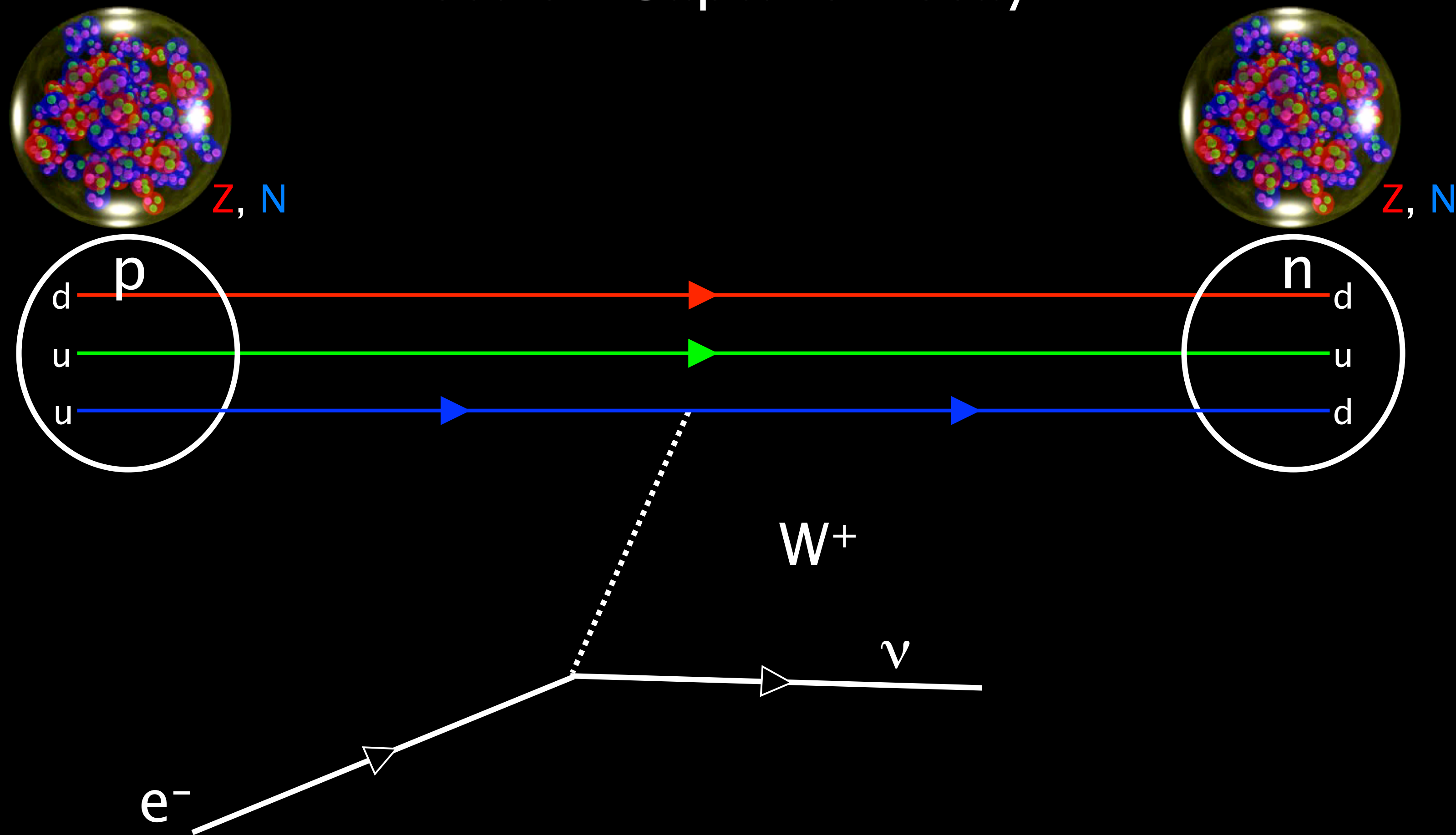
# Neutrinos are emitted in Weak Interactions



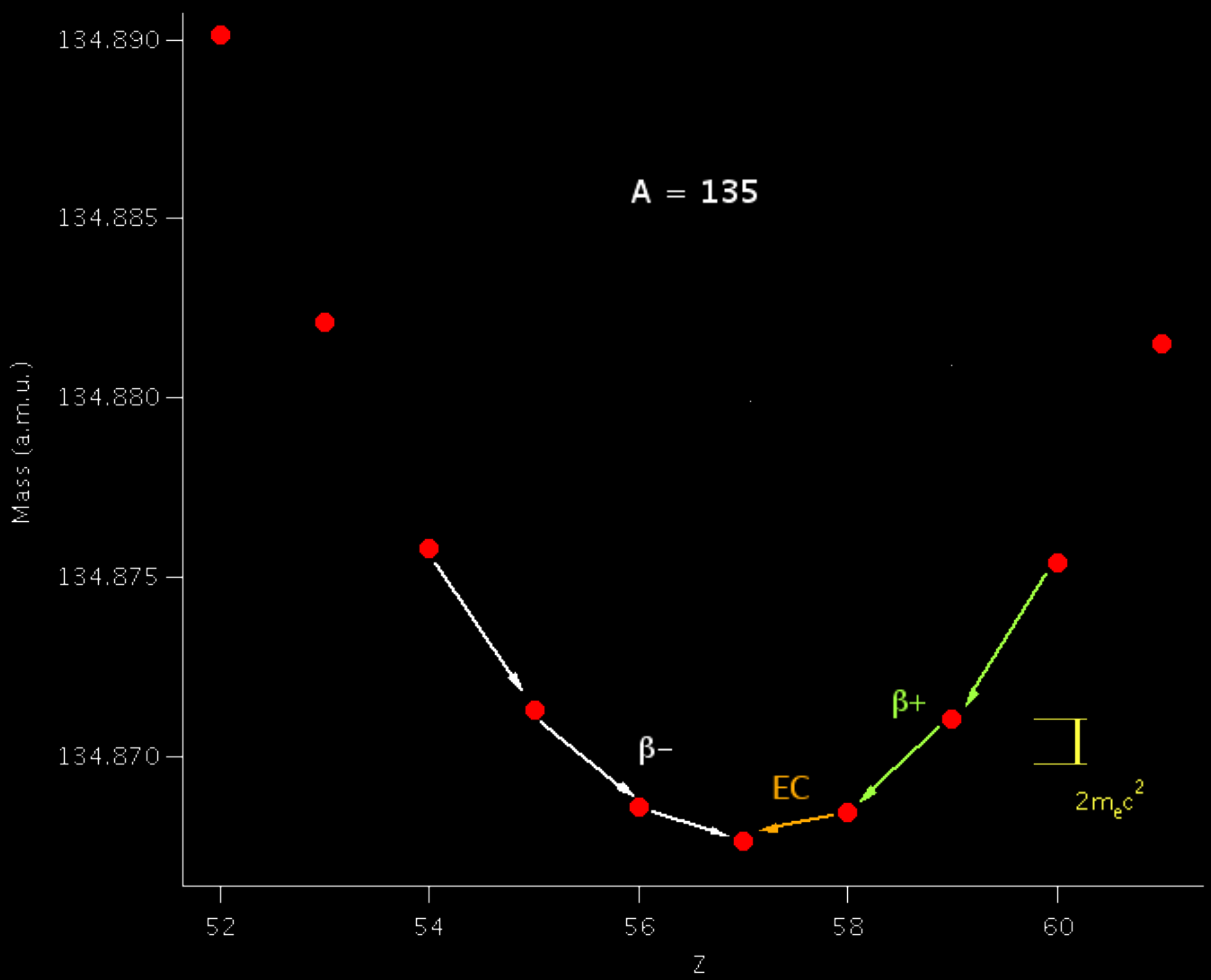
# Nuclear Beta Decay



# Electron Capture Decay



# Positron Decay/Electron Capture



# Neutrino Oscillation Primer

The SU(2) doublets in the Electroweak Standard Model are:

leptons $\psi_i = \begin{pmatrix} \nu_i \\ \ell_i^- \end{pmatrix}$ $\psi_i = \begin{pmatrix} u_i \\ d_i' \end{pmatrix}$ quarks

i = mass eigenstates $\alpha$ = flavor eigenstates

$$|\nu_i\rangle = \sum_\alpha U_{\alpha i} |\nu_\alpha\rangle \qquad |\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

Neutrino flavors have a mixing matrix to the mass eigenstates
Similar to the CKM matrix for quarks. Why? We don't know yet.

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

# Unusual Result from GSI

arXiv:nucl-ex/0801.2079 14 Jan 2008

## Observation of Non-Exponential Orbital Electron Capture Decays of Hydrogen-Like $^{140}$Pr and $^{142}$Pm Ions

Yu.A. Litvinov[ab*], F. Bosch[a], N. Winckler[ab], D. Boutin[b], H.G. Essel[a], T. Faestermann[c], H. Geissel[ab], S. Hess[a], P. Kienle[cd], R. Knöbel[ab], 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[ab], M. Mazzocco[af], F. Montes[e], A. Musumarra[gh], C. Nociforo[a], F. Nolden[a], W. Plaß[b], A. Prochazka[a], R. Reda[d], R. Reuschl[a], C. Scheidenberger[ab], M. Steck[a], T. Stöhlker[ai], S. Torilov[j], M. Trassinelli[a], B. Sun[ak], H. Weick[a], M. Winkler[a]

We report on time-modulated two-body weak decays observed in the orbital electron capture of hydrogen-like $^{140}\mathrm{Pr}^{59+}$ and $^{142}\mathrm{Pm}^{60+}$ ions coasting in an ion storage ring. Using non-destructive single ion, time-resolved Schottky mass spectrometry we found that the expected exponential decay is modulated in time with a modulation period of about 7 seconds for both systems. Tentatively this observation is attributed to the coherent superposition of finite mass eigenstates of the electron neutrinos from the weak decay into a two-body final state.

Later published as Phys. Lett. B **664**, 162 (2008)

# Exponential Decay

The exponential decay law is a statement of Maximum Ignorance

**Assume we know only that:**

- Collection of N identical "things" which ultimately must vanish to zero
- The decay of each thing is independent of the other ones (no dependence on initial conditions)
- Each thing decays at an unknowably random time
- A thing is equally likely to decay at any time

You can show (quite rigorously) that this dictates

$$\frac{dN}{dt}(t) = -\frac{N(0)}{\tau}\exp^{-t/\tau}$$

# Exponential Decay

Why is it a surprise to violate the exponential decay law? Because it's a law of maximum ignorance

Please note the utter absence of quantum mechanics or spookiness or coherence in this discussion.

There are plenty of examples of "classical systems" which obey an exponential decay law.

Please note also that in quantum mechanics, there are interesting constraints on the condition that N at infinity must go to zero and

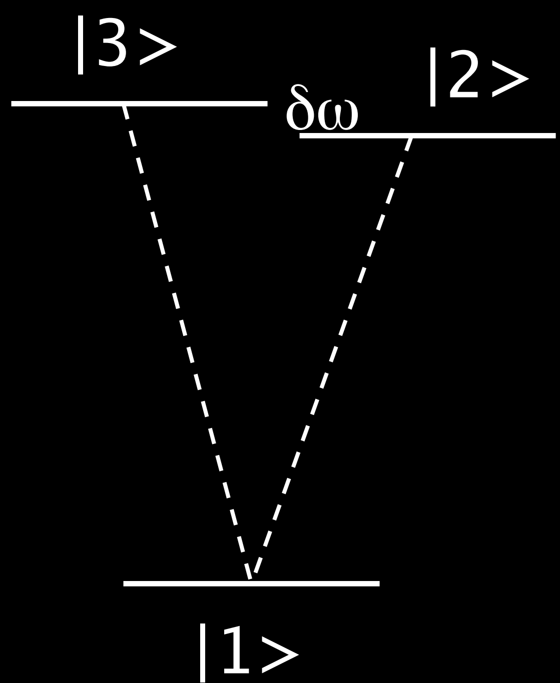
That the things are equally likely to decay at any time, because of finite energy differences between initial and excited states and renormalizability.

These are interesting effects, but not what we're talking about here.

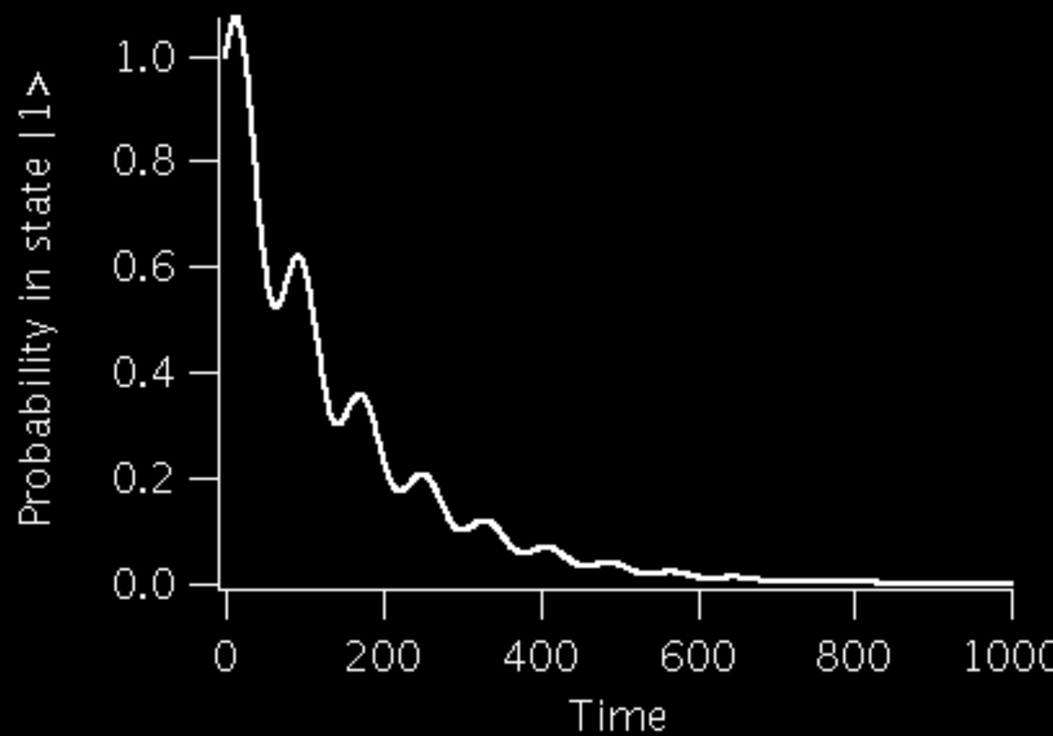
# An example of non-exponential decay
# Quantum beats

Some specially prepared “things” fail to meet these conditions:

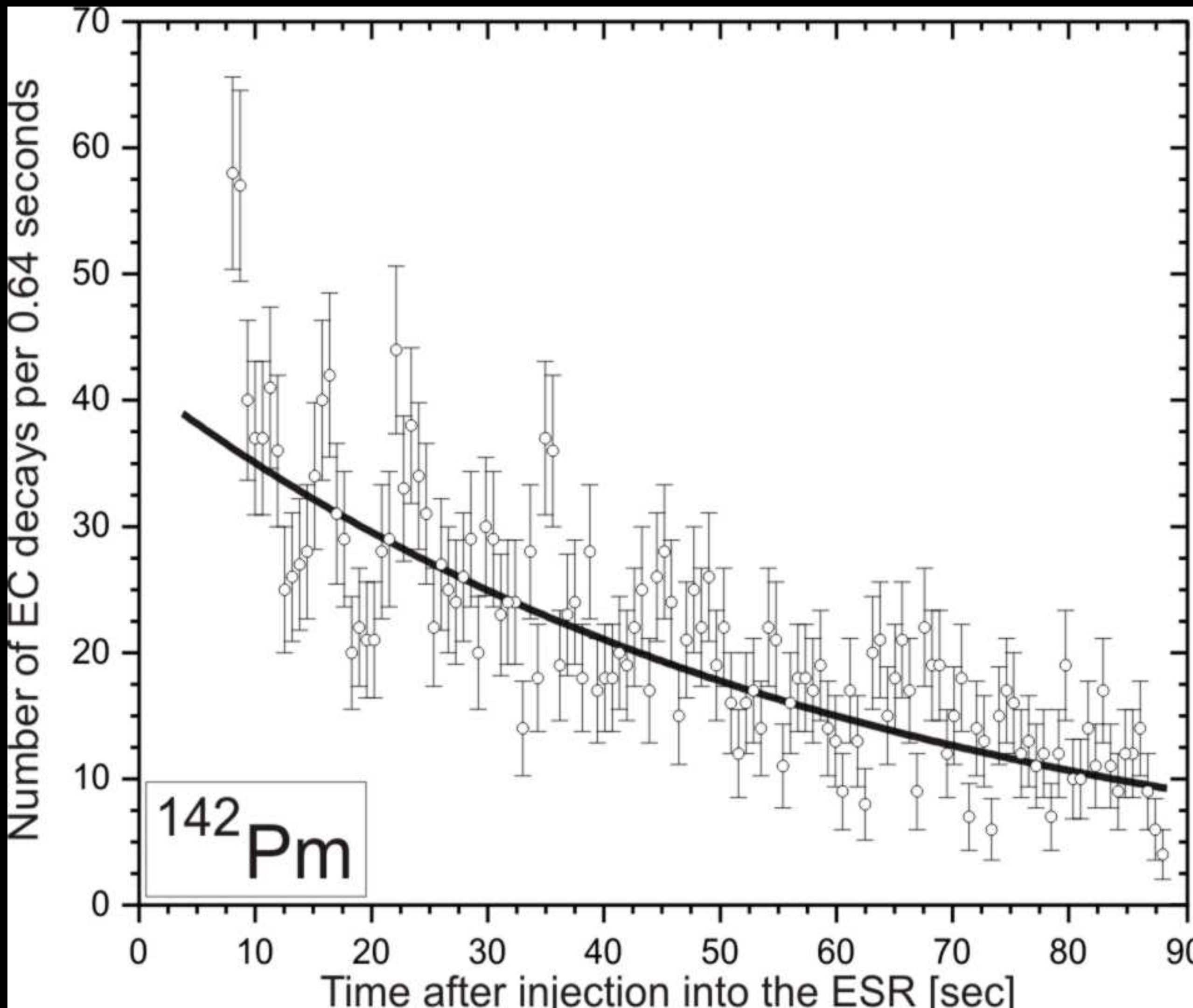
- The decay of each thing is independent of the other ones (no dependence on initial conditions)
- A thing is equally likely to decay at any time



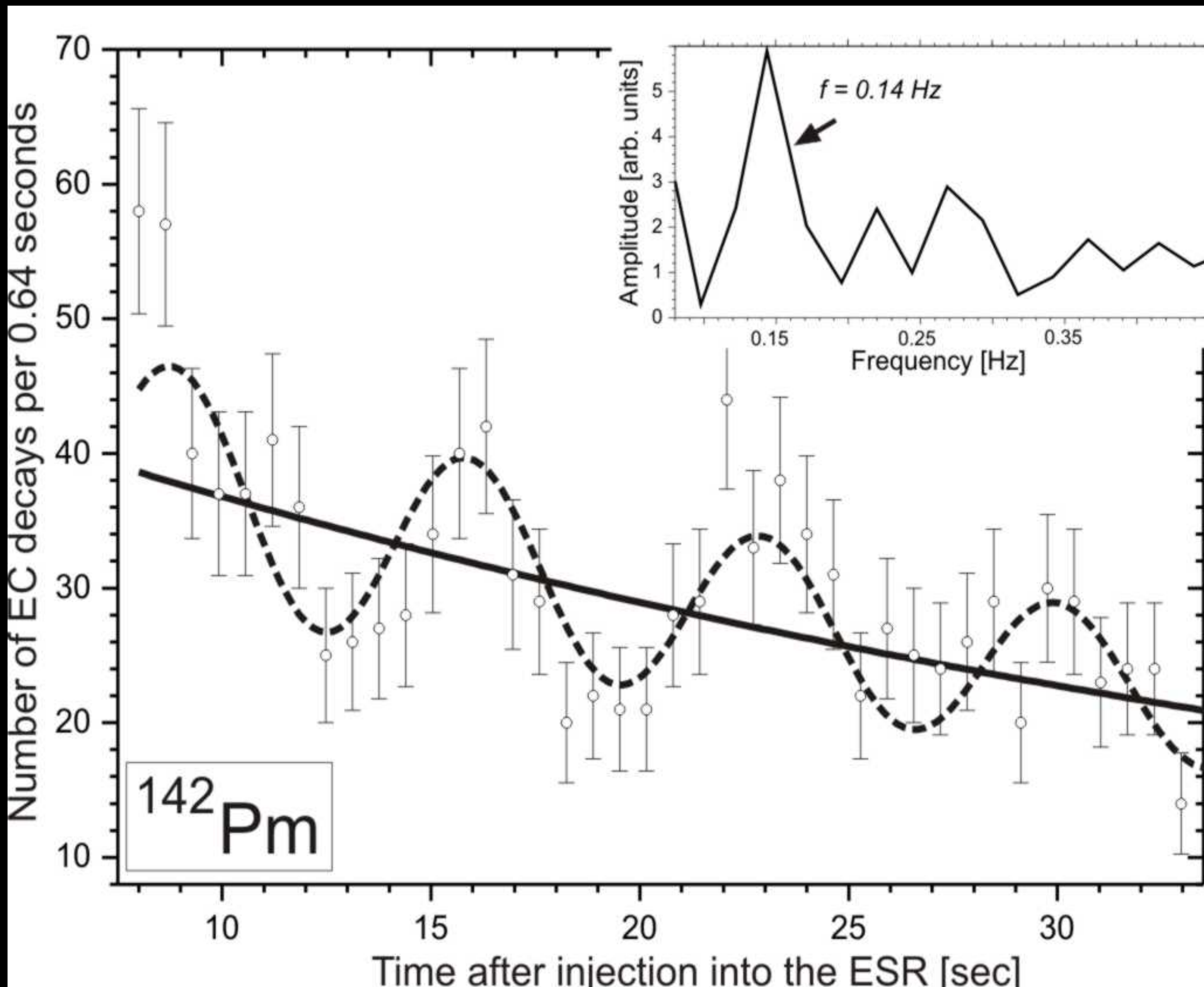

$|\Psi_0\rangle = A\,|3\rangle + B\,|2\rangle$



# Unusual Result from GSI



# Unusual Result from GSI



# Unusual Result from GSI

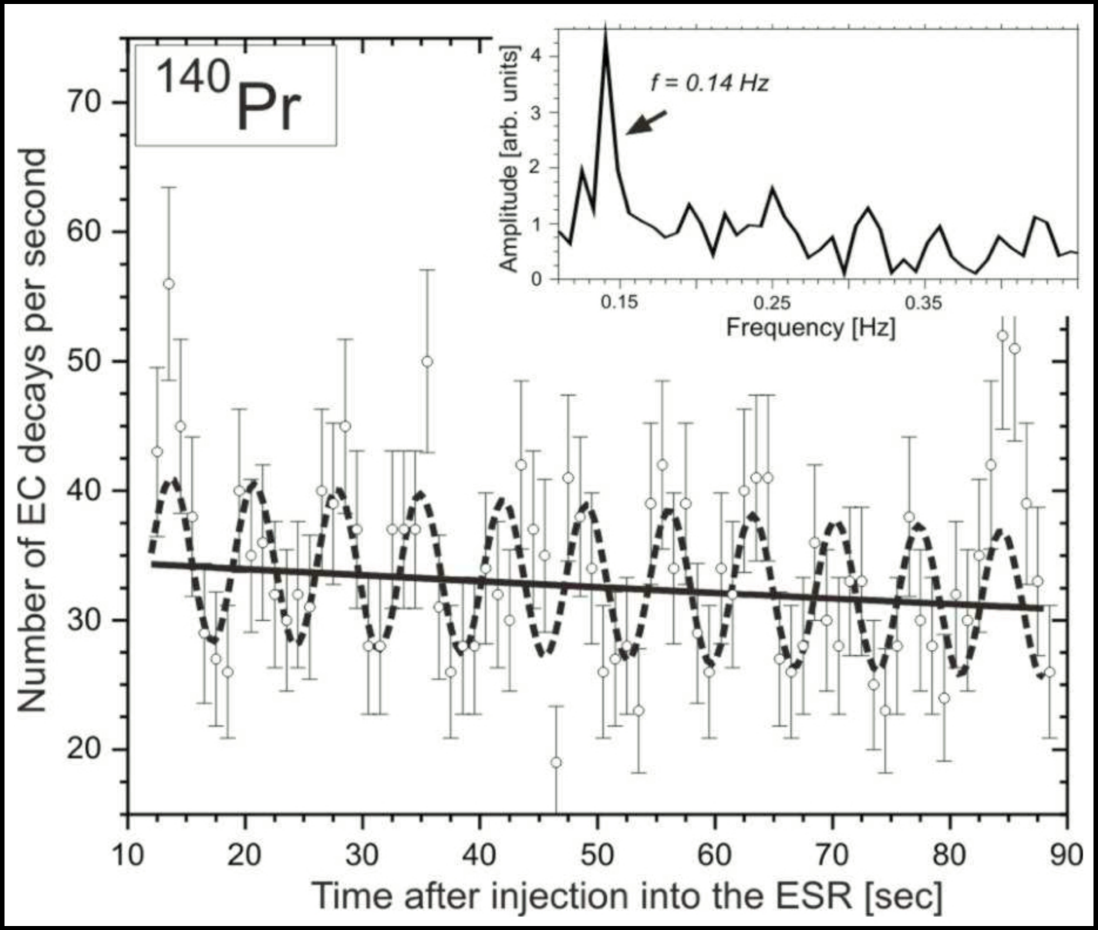
Phys. Lett. B **664**, 162 (2008)

arXiv:nucl-ex/0801.2079 14 Jan 2008

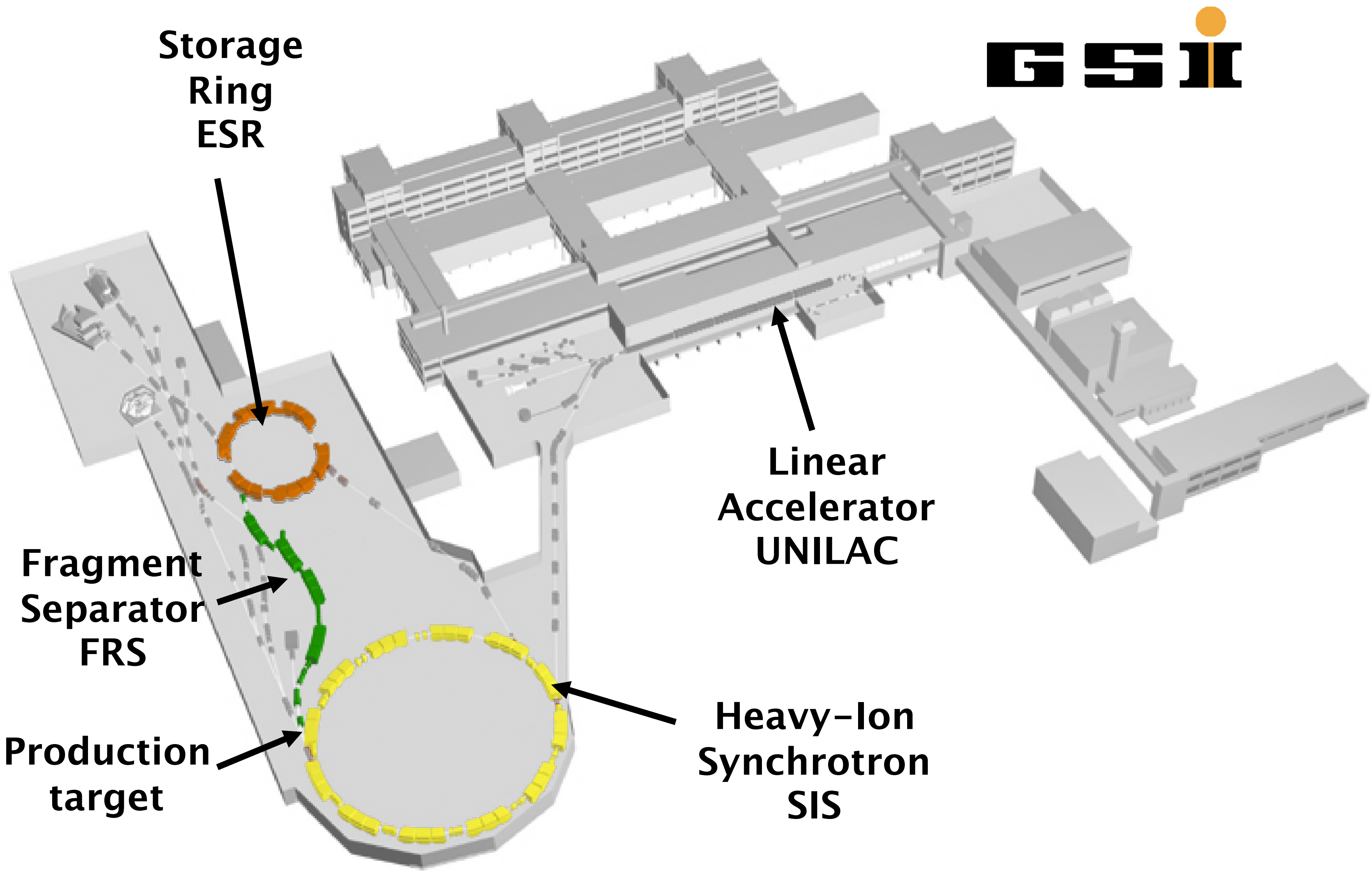
Time modulated two-body weak decays (electron capture) in $^{140}$Pr and $^{142}$Pm

Decay time histogram
shows oscillations
in decay rate/probability

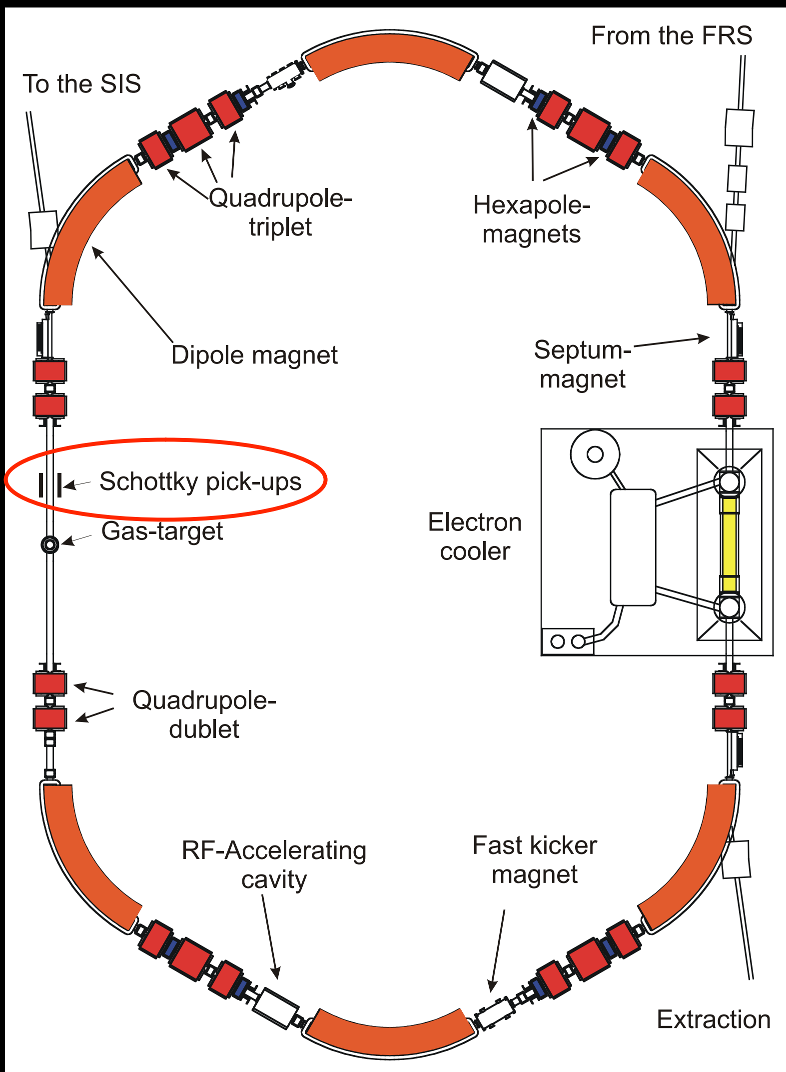
T = 7.060(8) seconds
A = 0.20(3)

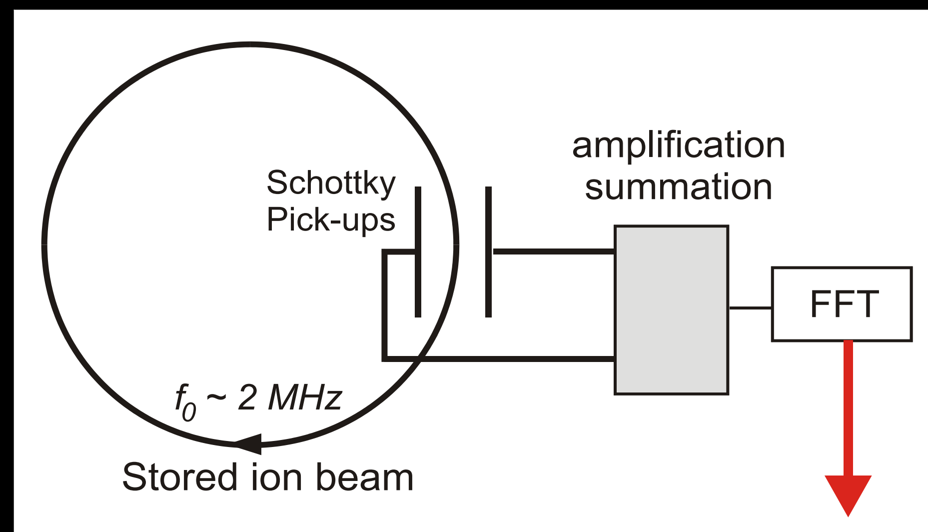


# GSI Stored Ion Beta Decay



# Ion detection and identification

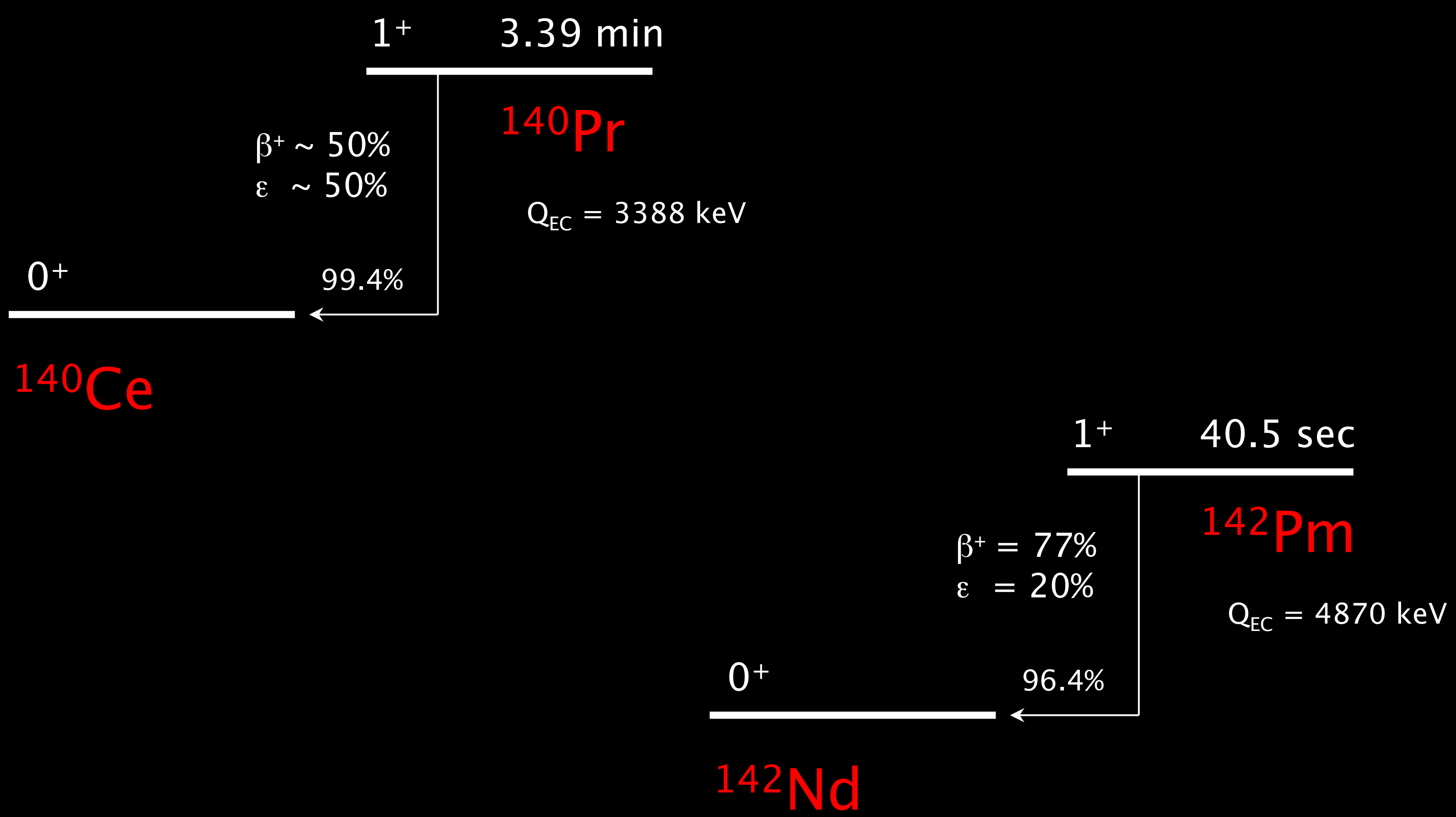


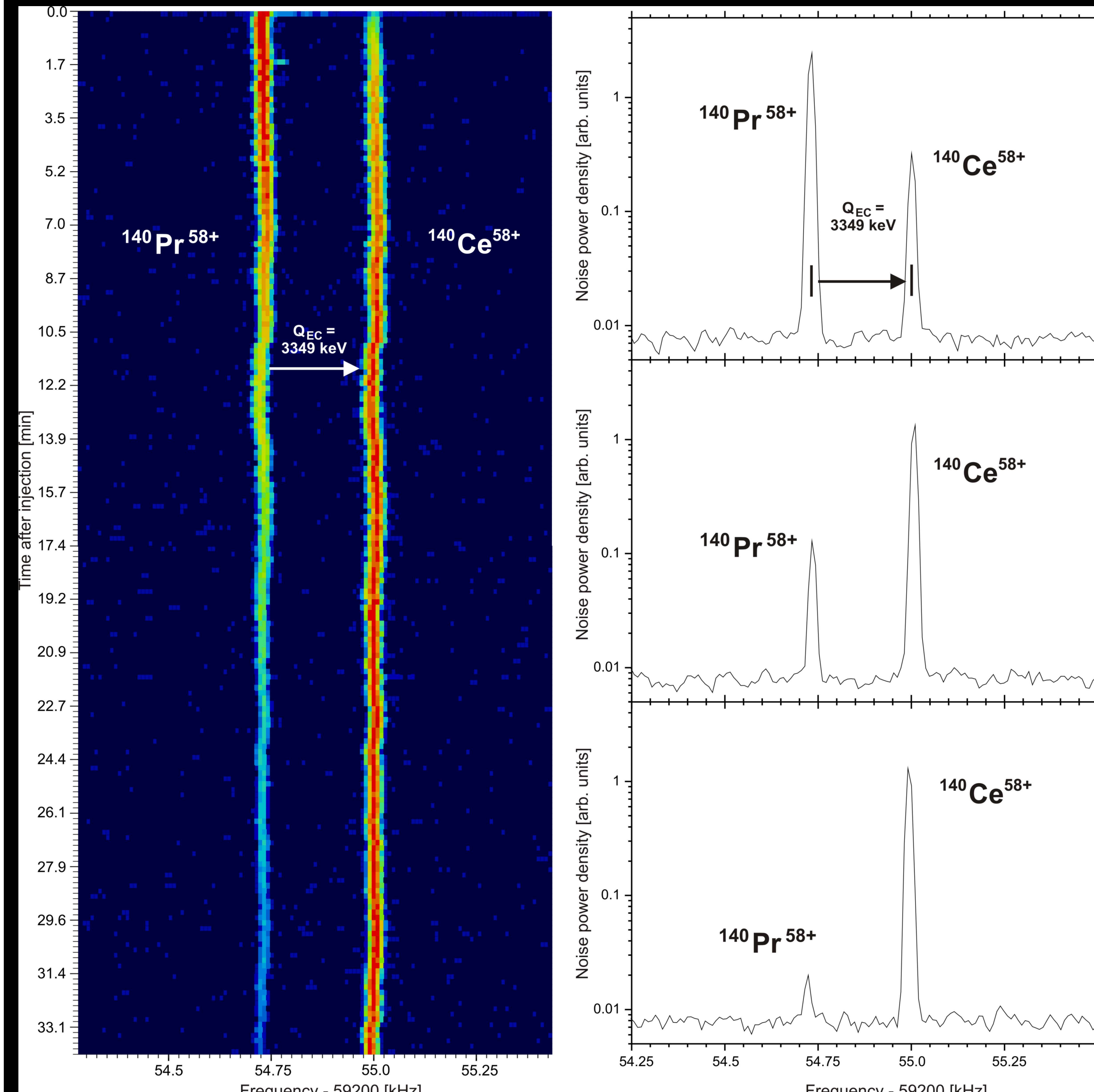

Frequency peaks

Identification of Q/M

# The Isotopes



# Raw Data




"Waterfall" plots of intensity at a given frequency

Number of ions at this (Q/M)

Decay changes (Q/M) abruptly

Long time bins: ~ 0.5 seconds or so

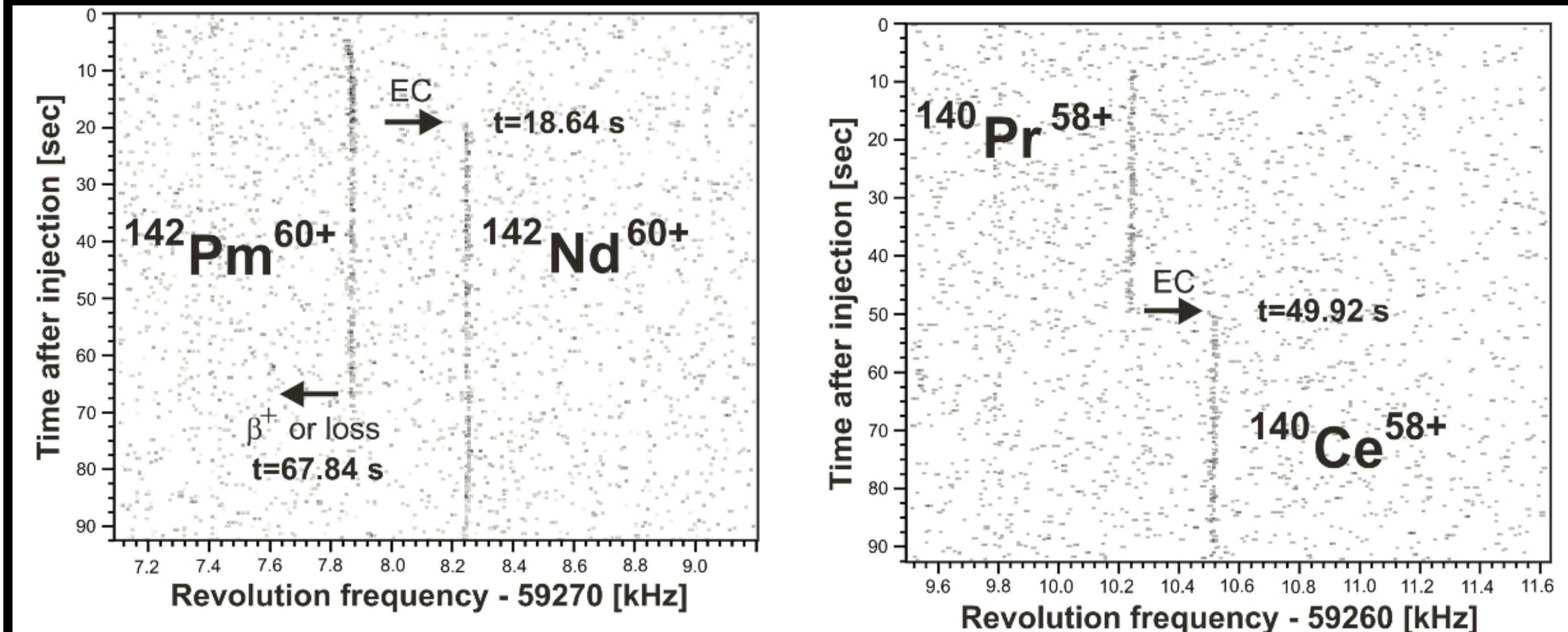
**Daughter ion remains stored only for electron capture decay**

**Daughter ion has delayed appearance due to cooling time**

**Parent ion has delayed appearance due to cooling time (T< 10 sec)**

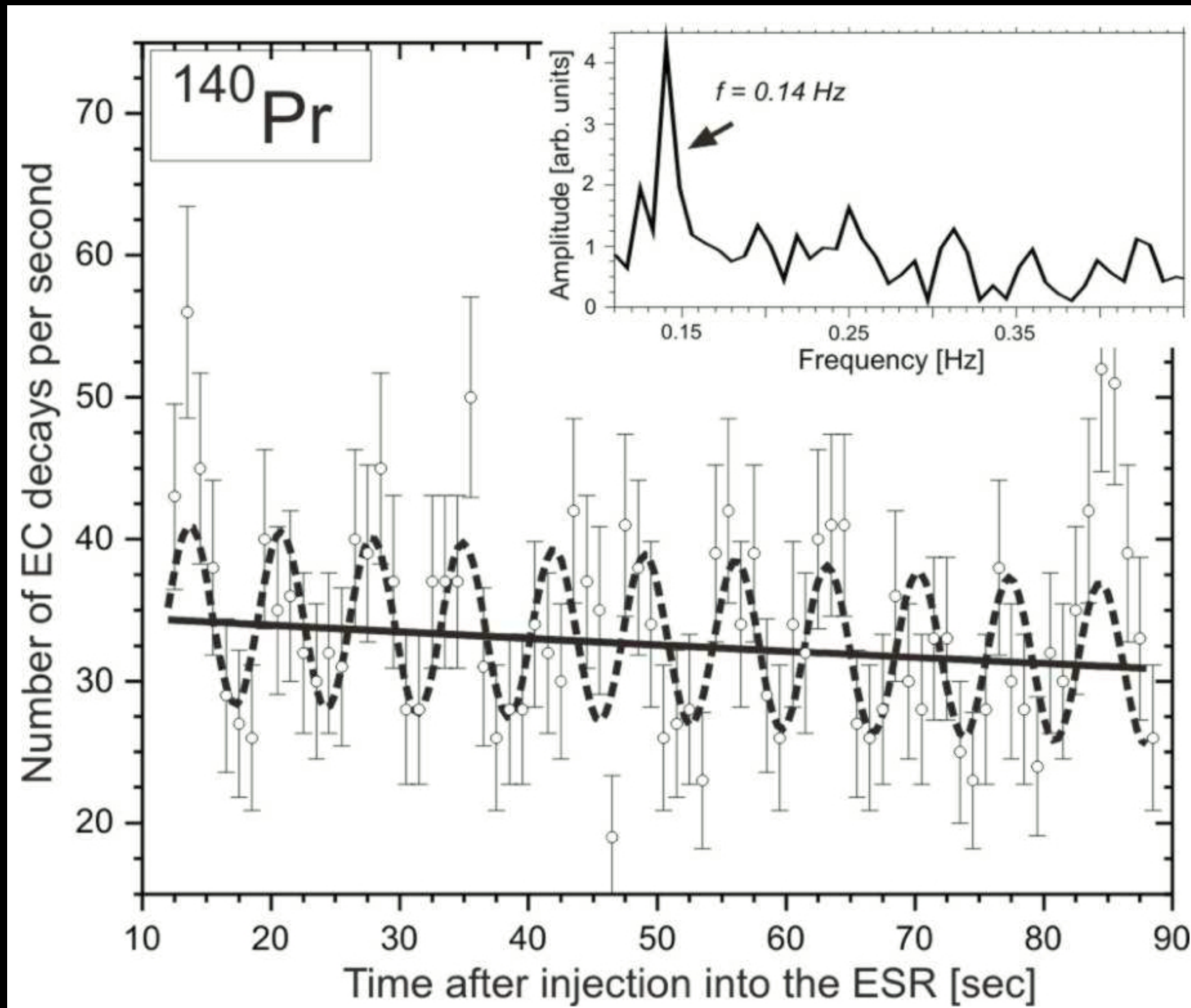
# Raw Data

Data from arXiv:0801.2079




Note tiny delay time here
Btwn appear/disappear

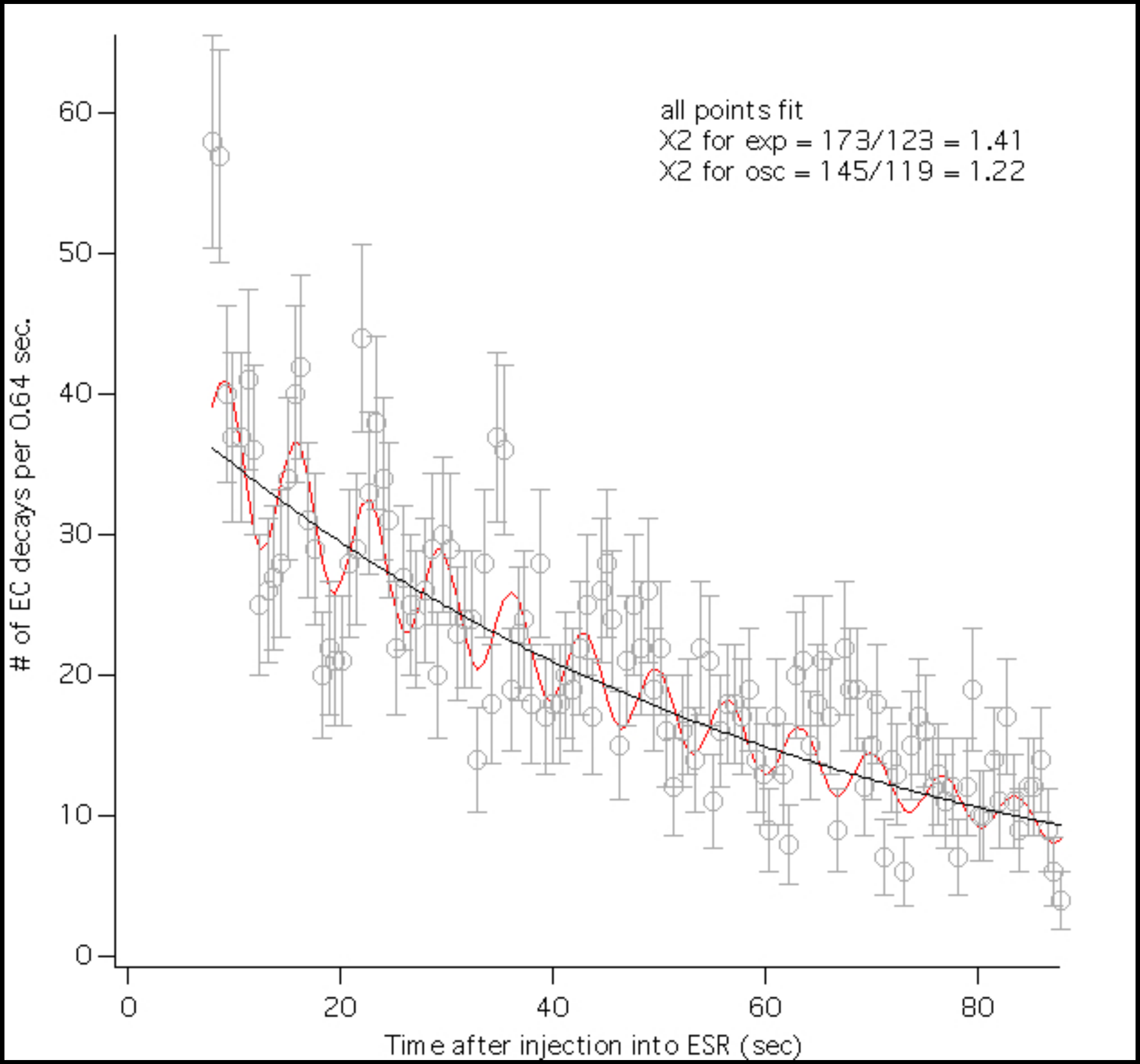
# Histogram of Decay Times



# Is it real?

Does the data contain real oscillations?

Grab data, re-analyze past 33 seconds**




It was strangely analyzed

The data are marginal

… but yes, it oscillates

# Interpretation: Neutrino Mixing

nucl-th/0801.2121 Ivanov *et al.* 14 Jan 2008

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

According to recent experimental data at GSI, the rate of the number of daughter ions $^{140}Ce^{58+}$, produced by the nuclear K–shell electron capture (EC) decay of the H–like ion $^{140}Pr^{58+}$, is modulated in time with a period $T_d = 7.06(8)$ sec and an amplitude $a_{EC} = 0.20(2)$. We show that this phenomenon can be explained by neutrino–flavour mixing and derive a value for the quadratic mass difference $\Delta m^2_{21} = m^2_2 - m^2_1 = 4.44(5) \times 10^{-4}\,\mathrm{eV}^2$.

PACS: 12.15.Ff, 13.15.+g, 23.40.Bw, 26.65.+t

# Neutrino mixing and decay rate oscillations

Final state neutrino is a flavor eigenstate: $$|\nu_e\rangle = \sum_k U_{ek}^* |\nu_k\rangle$$

To calculate the decay rate for the weak process:

$$I_i \rightarrow I_f + \nu_e$$

Use time-dependent perturbation theory to arrive at an amplitude for each neutrino (mass) species

$$A_k(t) = \int_0^t d\tau \, \langle I_f, \nu_k | H_W(\tau) | I_i \rangle$$

And the total amplitude is summed over these species:

$$A(t) = \sum_k A_k(t)$$

And the decay RATE comes from squaring the amplitude giving interference

$$\Gamma(t) \propto \left| \sum_k A_k(t) \right|^2$$

# Neutrino Mixing Interpretation

**nucl-th/0801.2121 Ivanov *et al.***

Neutrinos are emitted as a mixture of mass eigenstates, with the mixing matrix $U_{ej}$

$$H_W(t) = \frac{G_F}{\sqrt{2}} V_{ud} \int d^3x \left[\bar{\psi}_n(x)\gamma^\mu \left(1 - g_A\gamma^5\right)\psi_p(x)\right] \times \sum_{j=1,2,3} \left[U_{ej}\bar{\psi}_{\nu_j}(x)\gamma_\mu \left(1-\gamma^5\right)\psi_e(x)\right]$$

Suggesting a decay AMPLITUDE:

$$A\left({}^{140}Pr \to {}^{140}Ce + \nu_e\right)(t) = i \sum_{j=1,2,3} \int_0^t d\tau \left\langle {}^{140}Ce(\vec{q})\nu_j(\vec{k}_j)\left|H_W(\tau)\right|{}^{140}Pr(\vec{0})\right\rangle$$

And therefore a decay RATE:

$$N(t) = \mathrm{stuff} \times \left|\mathrm{A}({}^{140}\mathrm{Pr} \to {}^{140}\mathrm{Ce} + \nu_{\mathrm{e}})(\mathrm{t})\right|^2$$

**Add the amplitudes before squaring**

interference terms which depend non-trivially on time from j = j'

# Neutrino Mixing Interpretation

Usual decay law: $$N = N_0 \exp(-\lambda t)$$

becomes

$$N = N_0 \exp(-\lambda t) \left[1 + a \cos(\omega t + \phi)\right]$$

Oscillation frequency is related to the neutrino squared mass difference ($\Delta m_{21}{}^2$)

$$\omega = \frac{\Delta m_{21}^2}{4 \gamma M_d}$$

Oscillation amplitude related to the neutrino mixing angle $\theta_{12}$

$$a = \sin 2\theta_{12} \; e^{-\delta^2 \Delta \vec{k}_{21}^2}$$

# If that's true, then what's $\Delta m^2$?

$$\omega = (7.06 \pm 0.08\ \mathrm{s})^{-1} = \frac{\Delta m^2_{21}}{8\pi\gamma M_d}$$

2

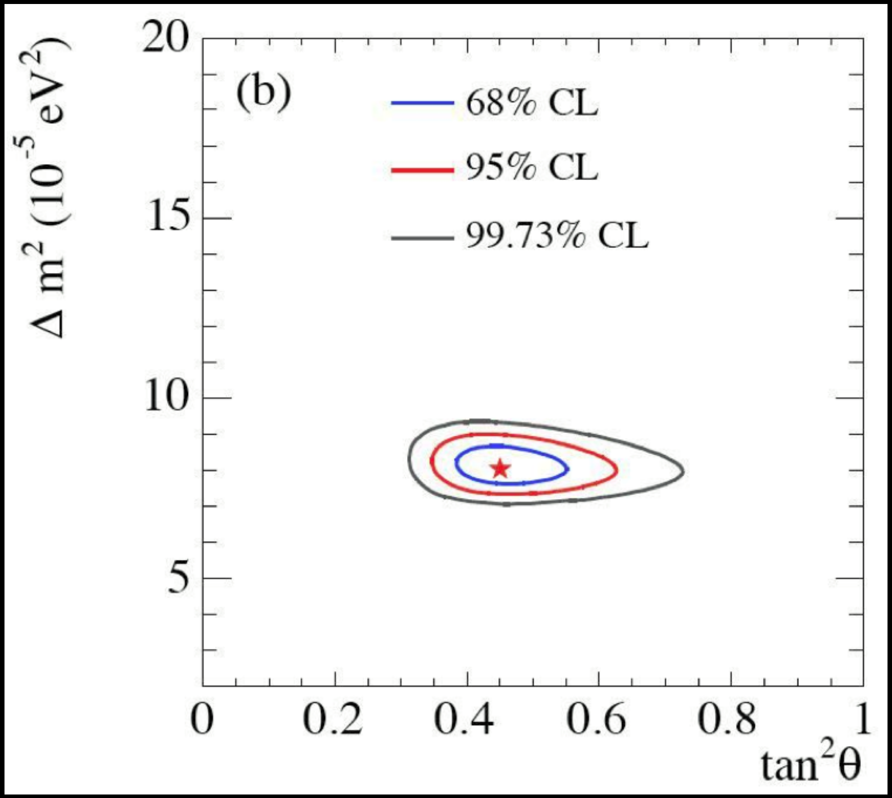
Not sure on this factor

$$\Delta m^2_{21} = (2.20 \pm 0.05) \times 10^{-4}\ \mathrm{eV}^2$$

What's $\Delta m^2$?

KAMLAND and Solar $\nu$ data, averaged

$$\Delta m^2_{21} = 0.759^{+19}_{-21} \times 10^{-4} \mathrm{eV}^2$$



# What's $\Delta m^2$?

Method 1:

M. Faber, nucl-th/0801.3262

$$\boxed{\Delta m^2_{21} = 0.763(8) \times 10^{-4} eV^2}$$

Versus KAMLAND and Solar $\nu$ data, averaged

$$\boxed{\Delta m^2_{21} = 0.759^{+19}_{-21} \times 10^{-4}\mathrm{eV}^2}$$

Nice, but…

Funny reasoning
Strangely accurate result
Ridiculously high precision…

Note that these are TWO DIFFERENT calculations of the delta msquared mass difference.
Faber, 0801.3262 uses 25 digit precision in a calculation involving an integral
over rapildy oscillating phase differences, uses no mass renormalization, uses no Lorentz factor.

# What's $\Delta m^2$?

Method 2:

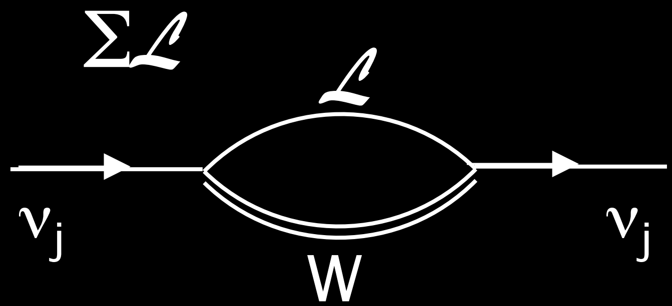
Ivanov *et al.*, nucl-th/0804.1311

Corrections from Coulomb interaction with heavy nucleus (Z)

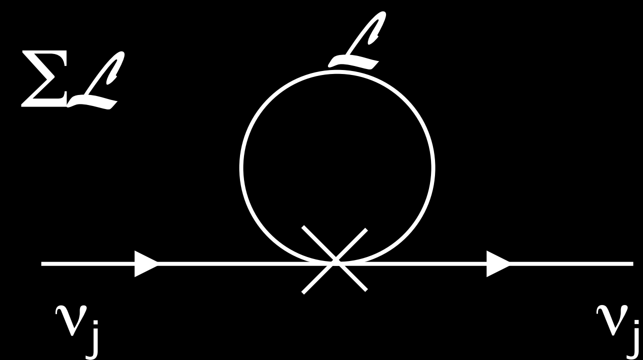
W-lepton pair emitted in nuclear field (Ze)

At short distance, looks like a mass diagram:

Neutrino masses become heavier than naïve estimate.  Calculate…

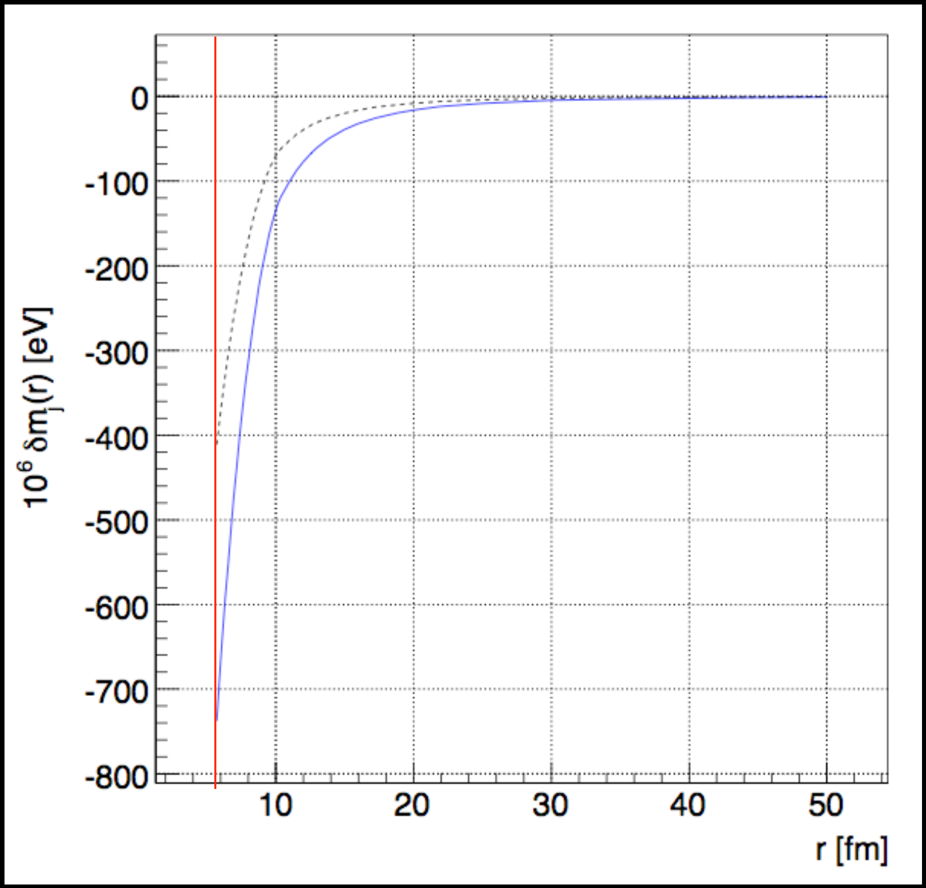



Becomes…



# What's $\Delta m^2$?

Method 2:



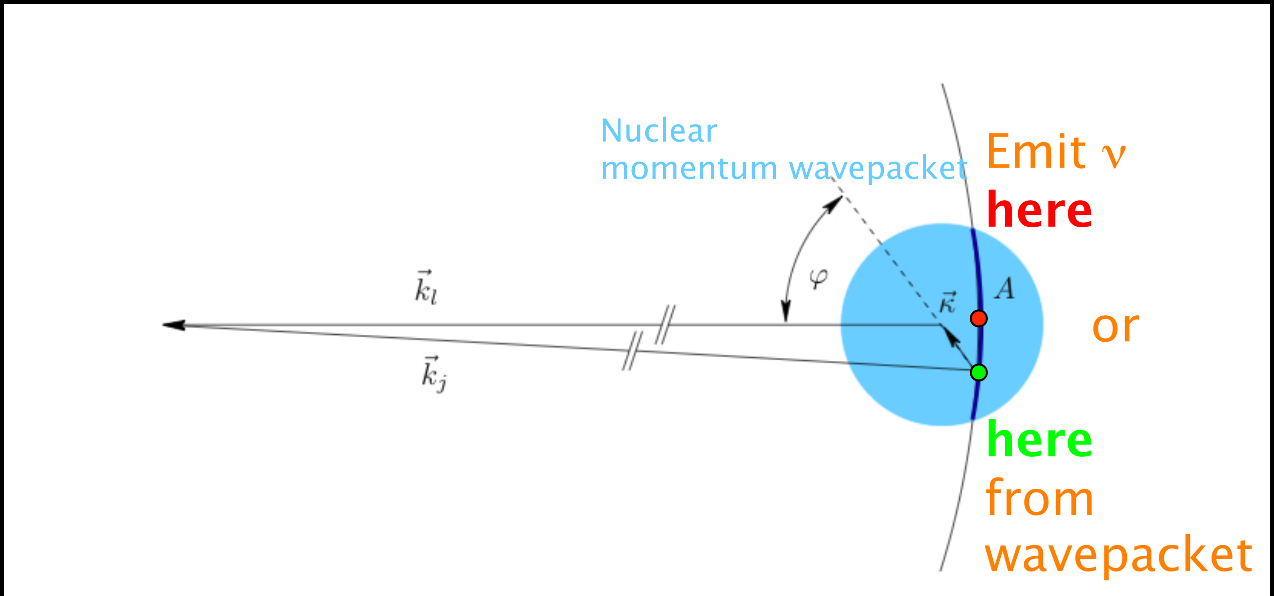

Evaluate correction for $m_1$ ,$m_2$ , $m_3$ at nuclear surface (5.7 fm)

Amazingly, combining this with the KamLAND value allows an extraction of the absolute mass scale of neutrinos!

$m_1 \sim m_2 \sim m_3 = 0.11$ eV (!)

Normal hierarchy!

# Momentum spread of initial nucleus is key




M. Faber, nucl-th/0801.3262

$$a = \sin 2\theta_{12}\ e^{-\delta^2 \Delta \vec{k}^2_{21}}$$

# Papers discussing neutrino mixing models

It's neutrino flavor mixing:

Initial state interference

H. Lipkin, hep-ph/0801.1465; hep-ph/0805.0435

H. Kleinert, P. Kienle, nucl-th/0803.2938

Final state interference

Ivanov *et al.*, nucl-th/0804.1311

M. Faber, nucl-th/0801.3262

It can't be (final state) neutrino flavor mixing:

C. Giunti, hep-ph,nucl-th/0801.4639; 0805.0431

A. Gal, nucl-th/0809.1213

Several others -- summaries, talks, brief comments

http://arxiv.org/cits/0801.2079

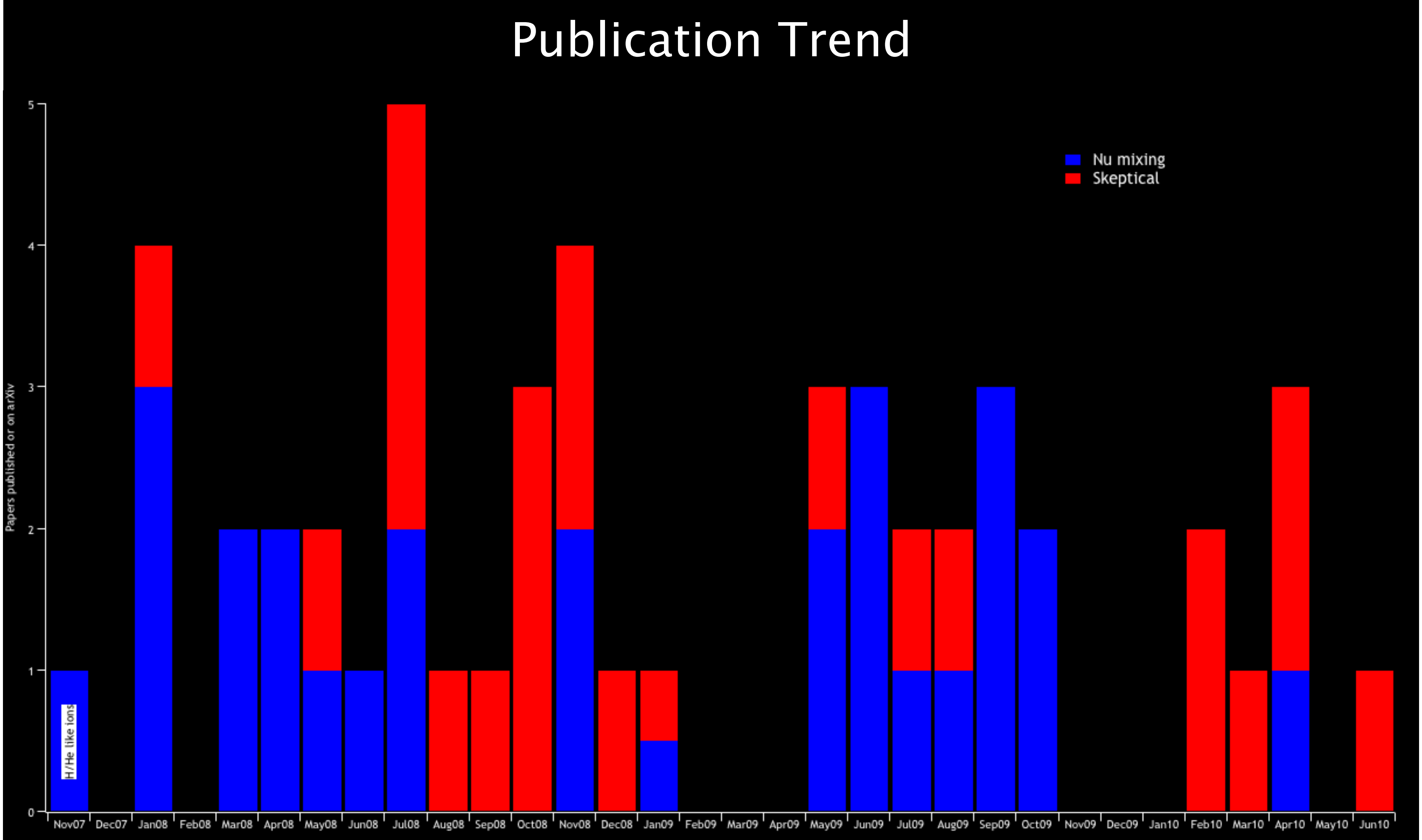
# Proposed Neutrino Mixing Mechanisms

The momentum spread of the initial nucleus is key

The momentum spread of the final nucleus is key

It's coupling to the filled Fermi sea states of neutrinos by different initial momentum states of the parent nucleus

It's the time uncertainty of the detection technique -- $\Delta T \Delta E > h$




But look -- physics is not a democracy.
You don't count up the number of people who think one thing and the number of people who think something else and then let that be the true thing...

# Could the neutrino mixing interpretation be tested?

- **Spectacularly easy way to measure neutrino oscillation?**
- Neutrino mixing interpretation doesn't depend on hydrogen-like charge state:
  Correlation with final state recoil momentum allows neutrino mixing to alter decay rate.
  In E.C. decay, impulse approximation sets recoil momentum at decay
- Prepare an electron capture decay isotope, look for oscillation in E.C. branch
- Need short bombardment time to preserve fast oscillation compared to $T_{1/2}$
- Predicted (T ~ Mass) dependence: 0.15 s ($^{3}H$) < T < 11.5 s ($^{235}U$)
- Has anyone else ever seen this in EC decay?
- What about positron decay branch? Look for systematic errors here?

# Oscillation of Positron Decay

Ivanov *et al.*, nucl-th/0806.2543

Positron decay would oscillate,
but because the phase space is much larger,
The integration which picks up the oscillation tends to be less robust

A ~ 0.02
T ~ 5e-5 s

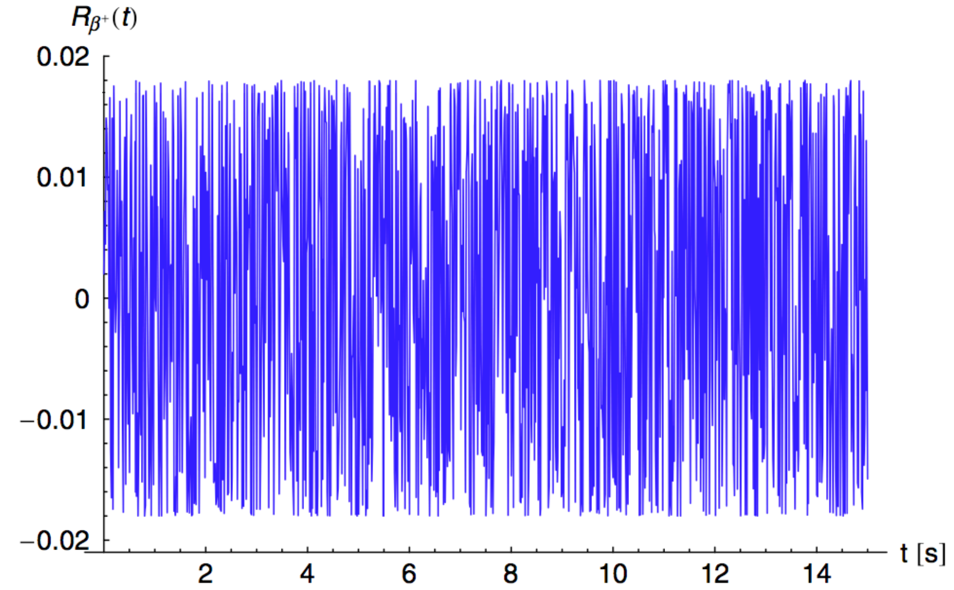



FIG. 1 (color online). The behavior of the function $R_{\beta^+}(t)$, given by Eq. (13), in the time interval $0 \leq t \leq 2T_{\rm EC} = 14$ s. The jitter is caused by a period of variations of order $T_{\beta^+} \sim 5.4 \times 10^{-5}$ s.

# Oscillation of Positron Decay

Students: do not create something as useless as this.

Teachers: do not pass a student who presents a graph like this

Reviewers: do not recommend publication of a graph like this

Phys. Rev. Lett. 101, 182501 (2008)

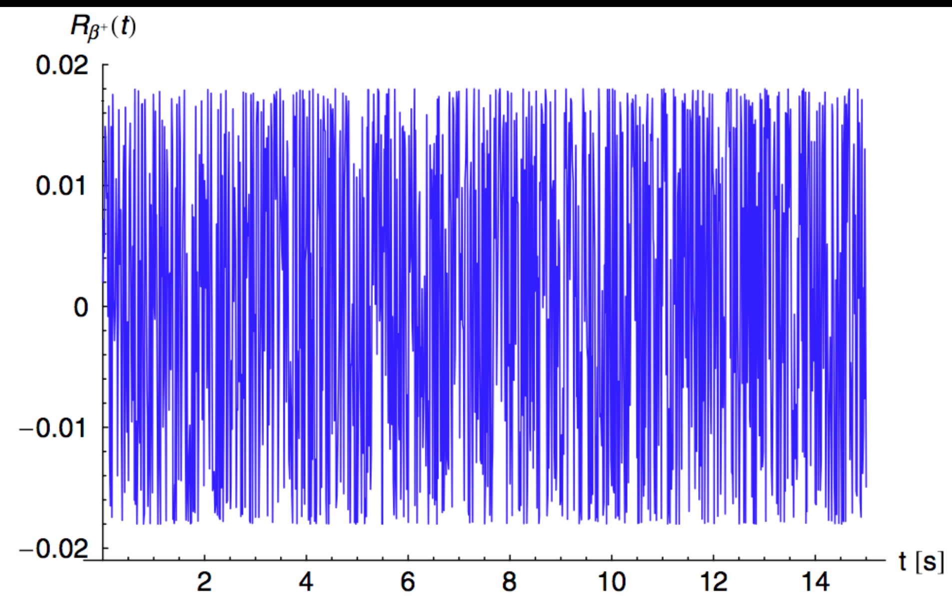
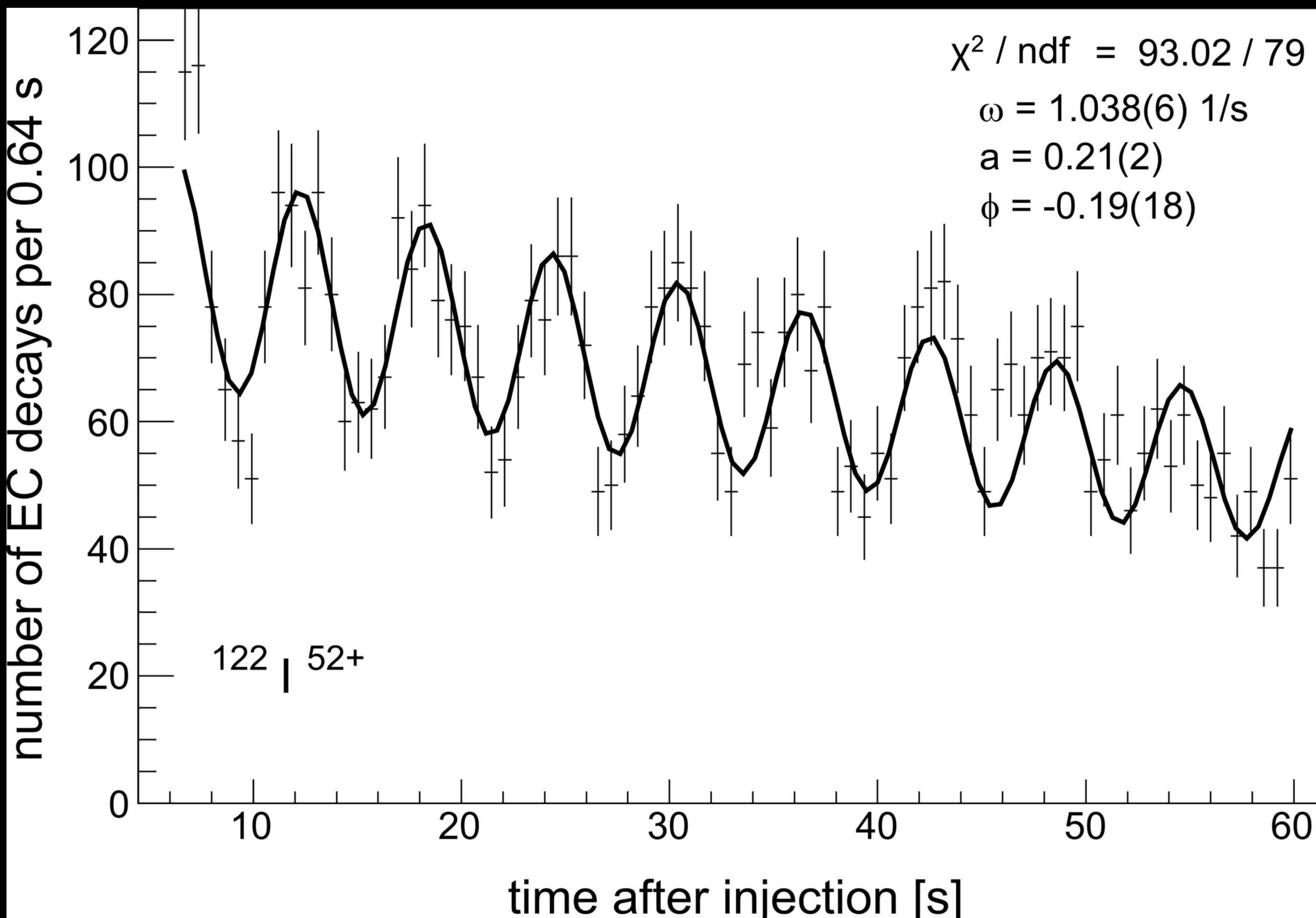


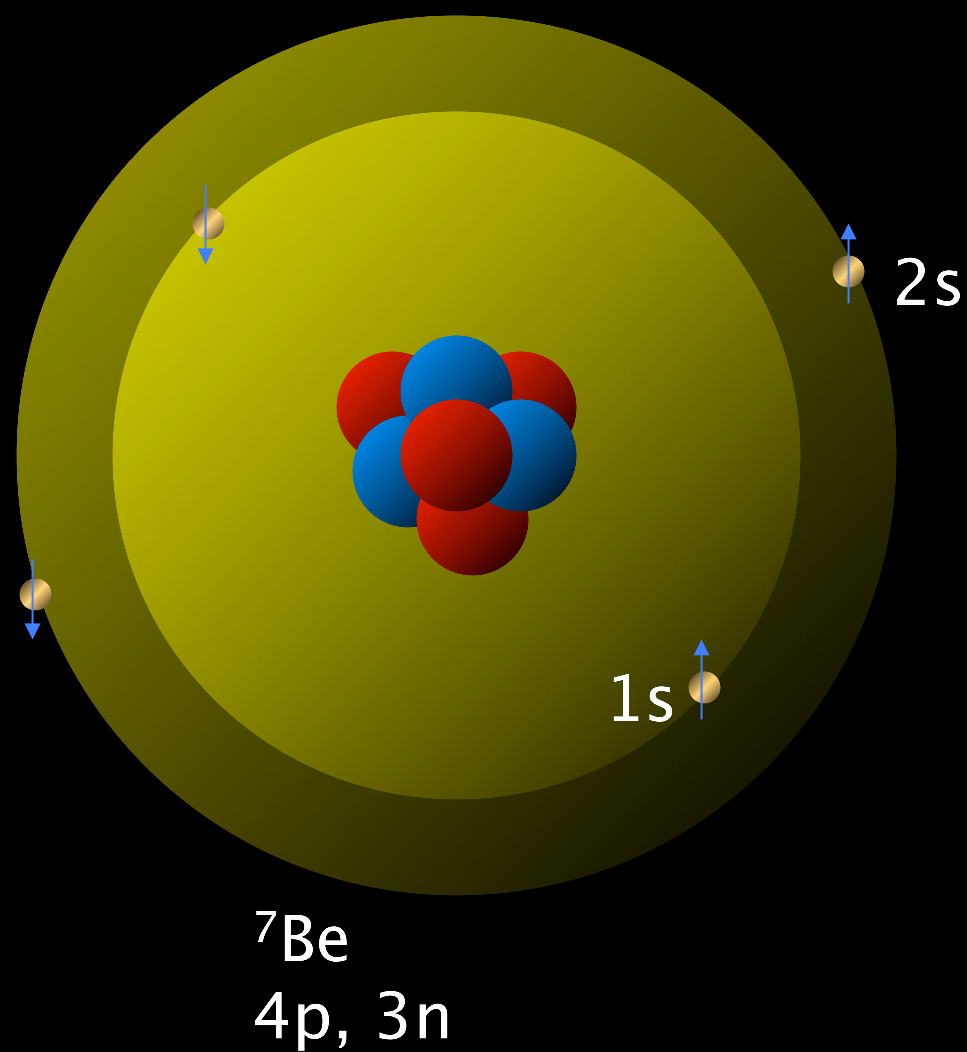

FIG. 1 (color online). The behavior of the function $R_{\beta^+}(t)$, given by Eq. (13), in the time interval $0 \le t \le 2T_{EC} = 14$ s. The jitter is caused by a period of variations of order $T_{\beta^+} \sim 5.4 \times 10^{-5}$ s.

# New Species, $^{122}$I

credit



# Cartoon version of electron capture



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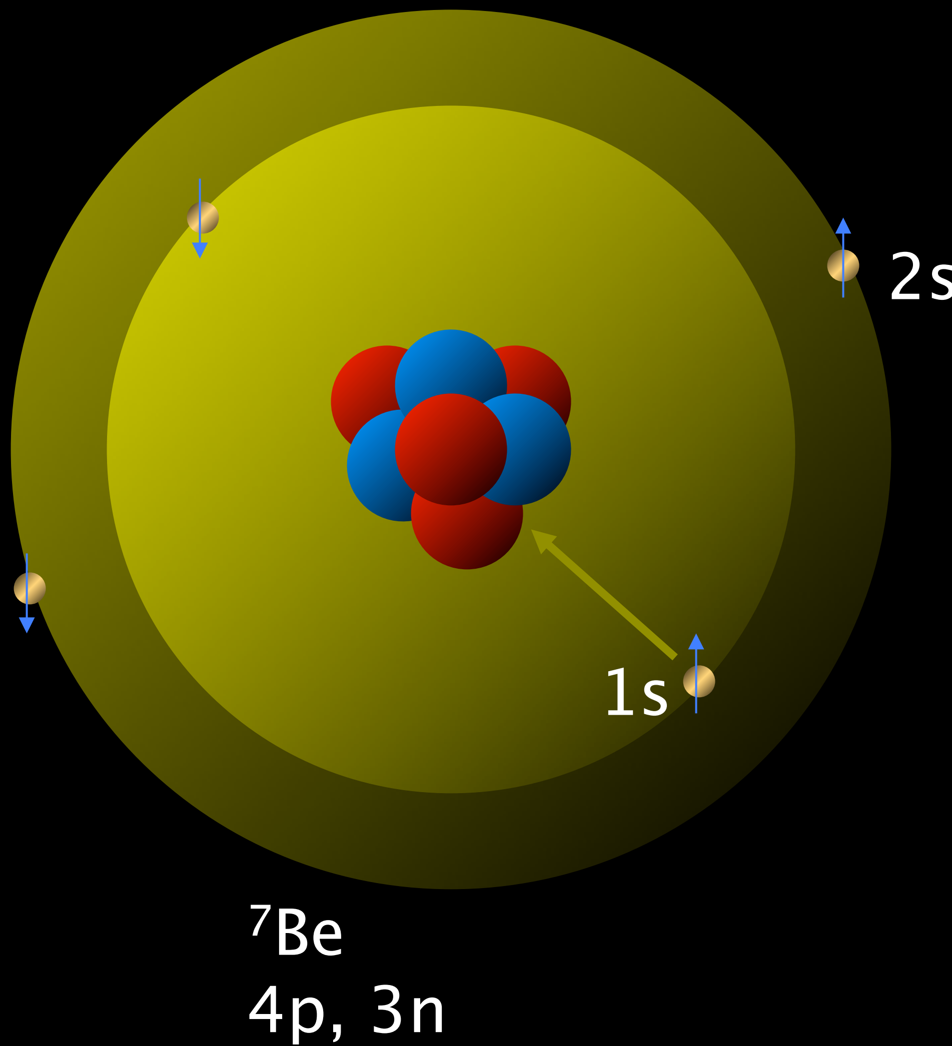

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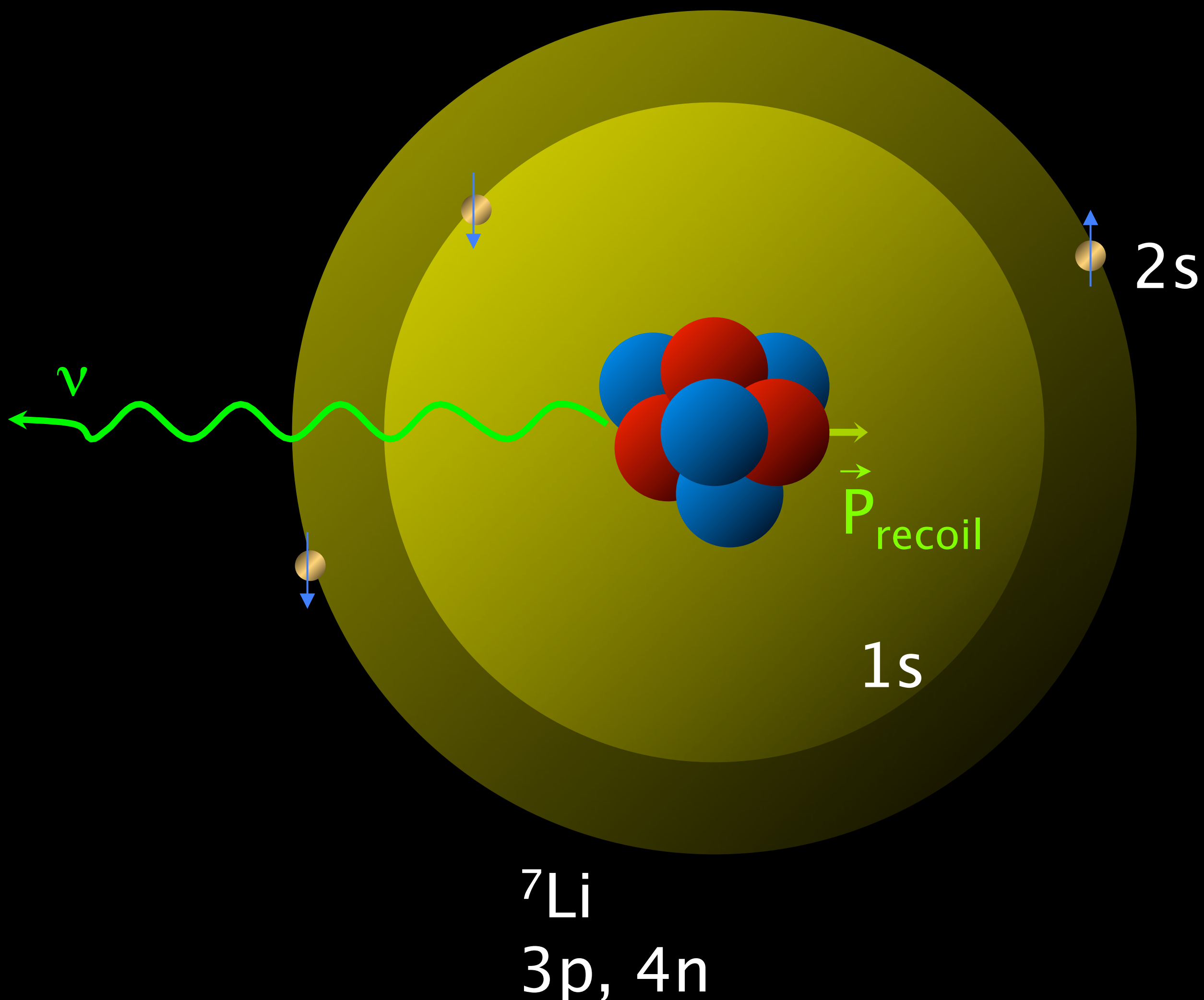
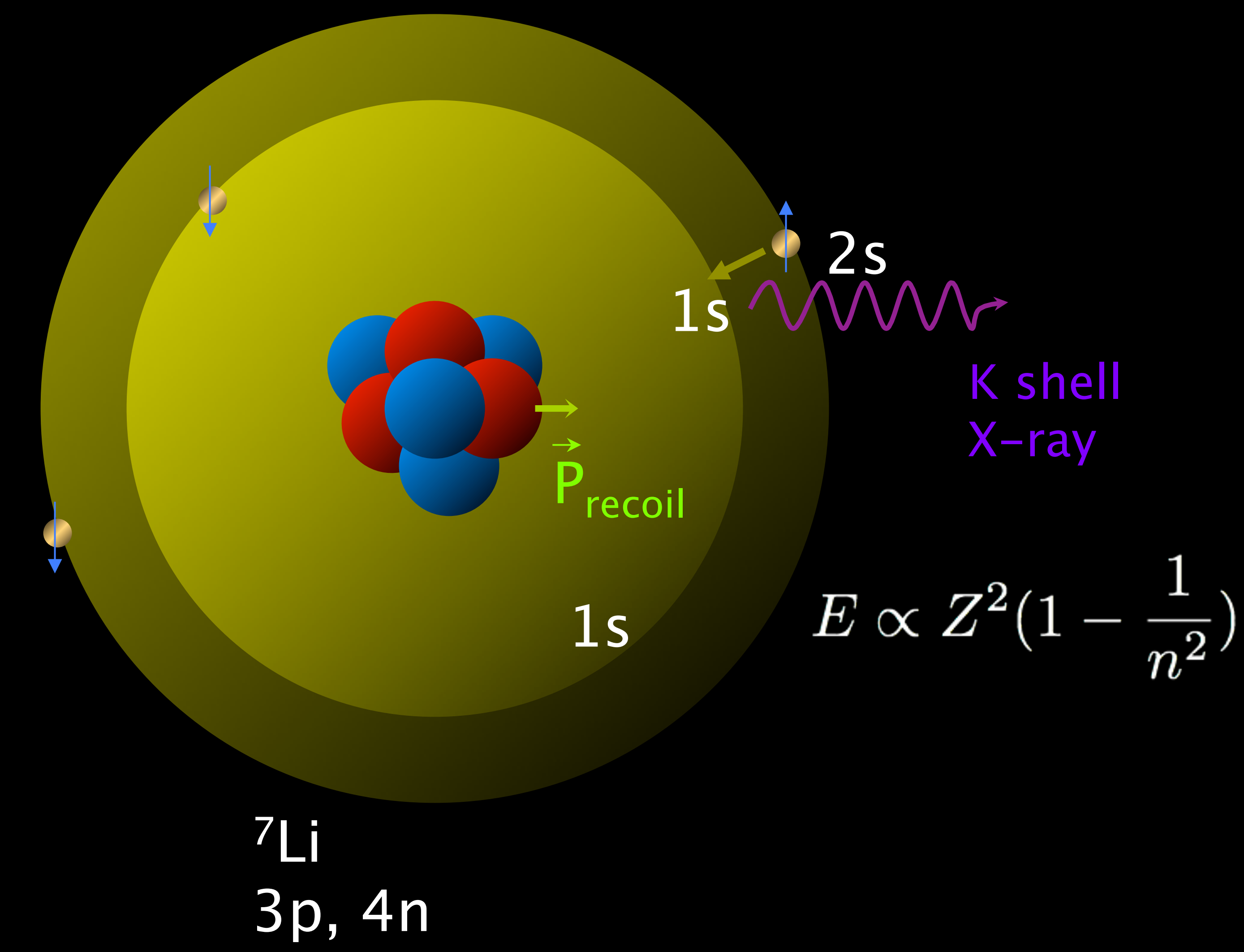


# Cartoon version of electron capture



# Literature Search:
# Study of Isomeric $^{142}$Eu

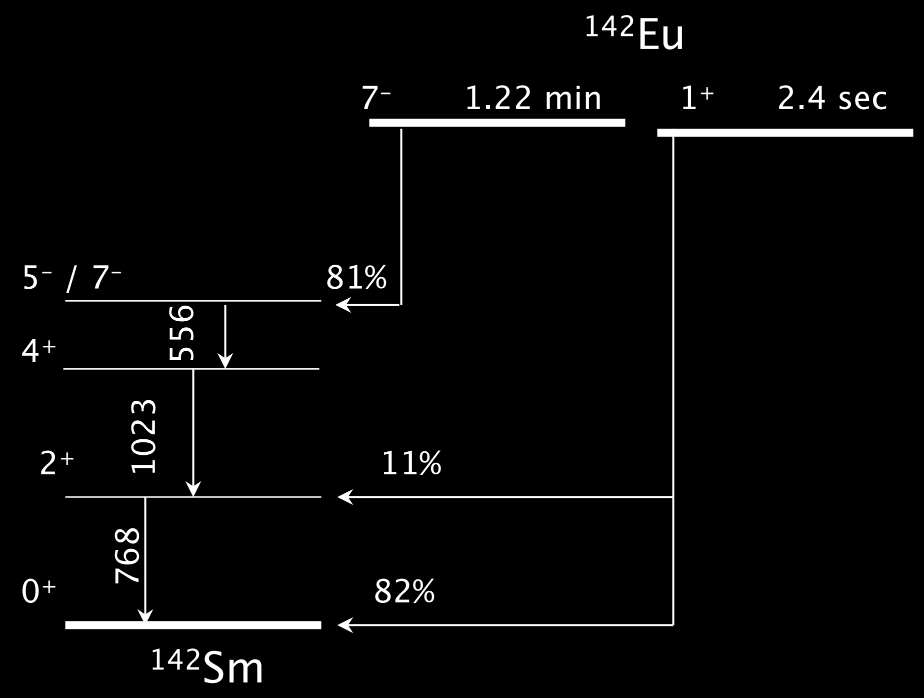
"Structure of $^{142}$Sm from the decay of $^{142}$Eu"
G.G. Kennedy, S.C. Gurathi, and S.K. Mark, *Phys. Rev. C* **12**, 553 (1975).

Gamma spectroscopy identifies isomeric states in parent

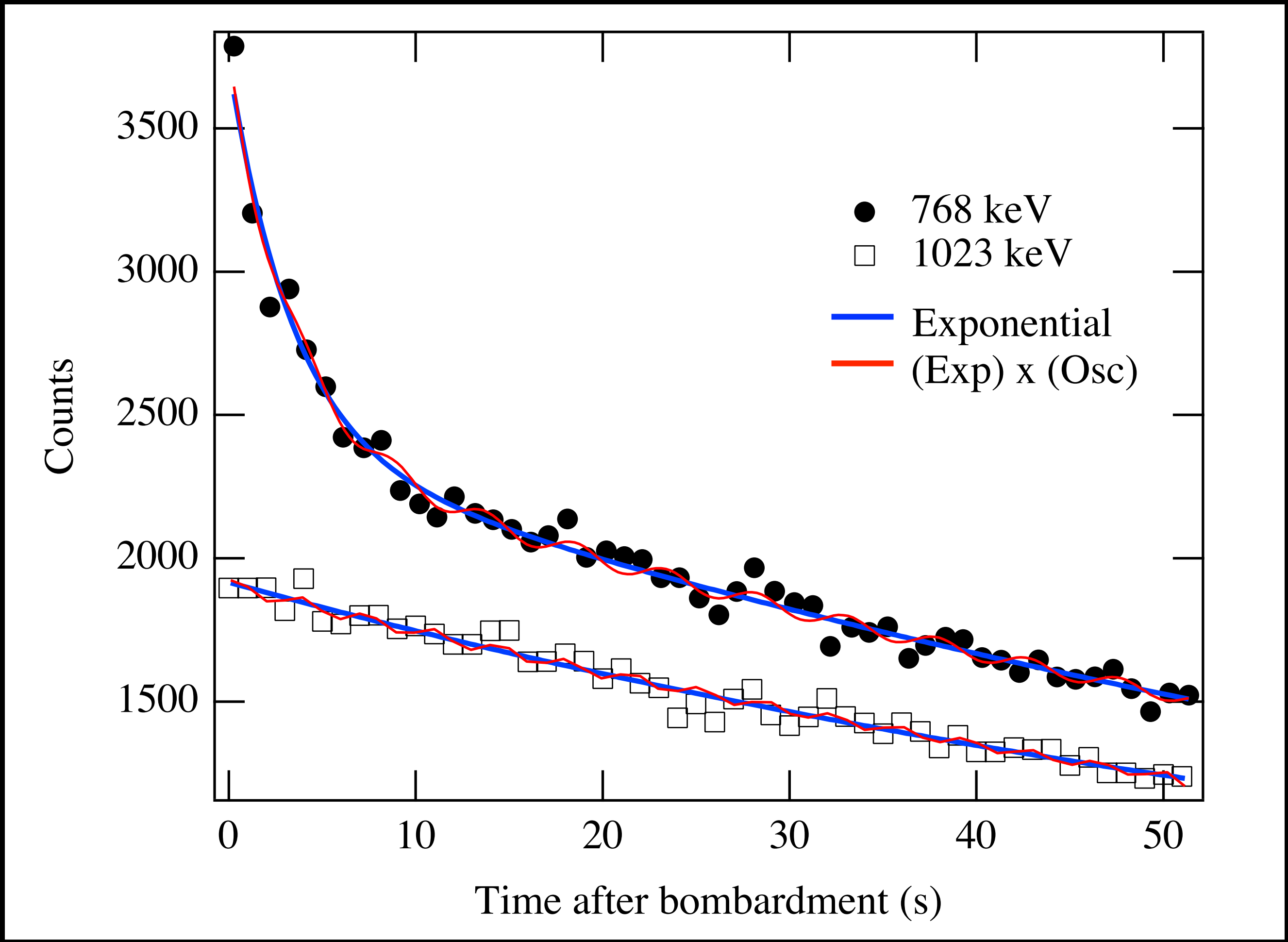
Fast production

Lifetime measurements

17% electron capture



# Re-fit data from $^{142}$Eu




**1023 keV data**

$a = 0.0136(55)$
$T = 3.540(53)$ sec
$\phi = 5.6(8)$ rad

**768 keV data**

$a = 0.0133(84)$
$T = 4.854(73)$ sec
$\phi = 1.13(55)$ rad

**No oscillation**

# Independent Experiment using Berkeley Gas Filled Separator (BGS)

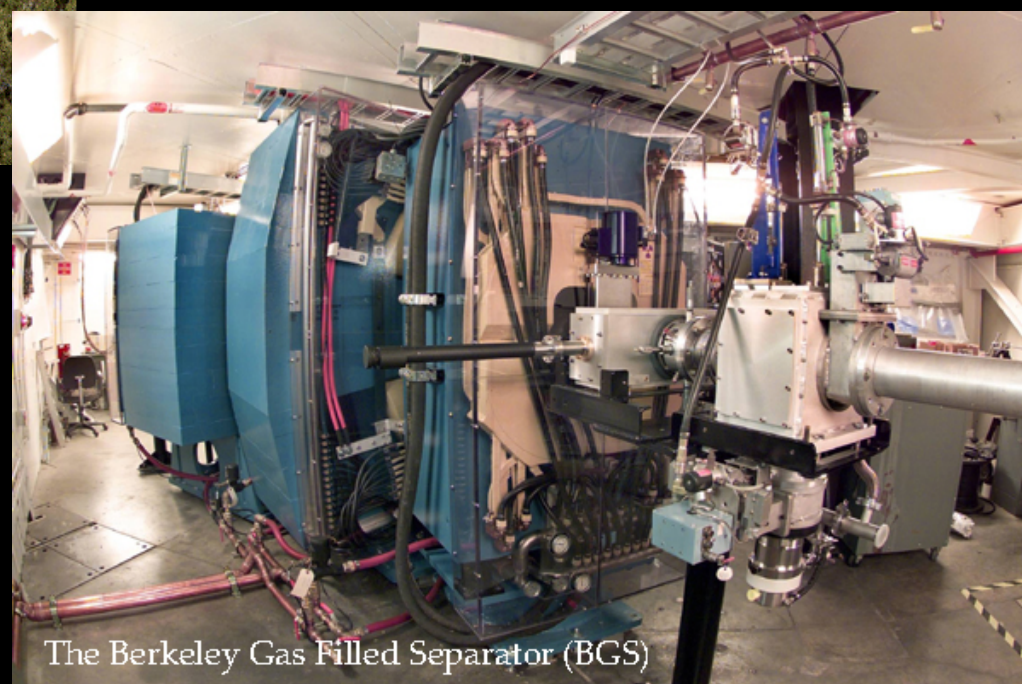

**Same isotope: $^{142}$Pm**
**$^{124}$Sn($^{23}$Na,5n) $^{142}$Pm, 95 MeV, 100 pnA**

**Clover Ge detector in focal plane**

**K-Shell X-ray strongly selects Electron Capture decays**

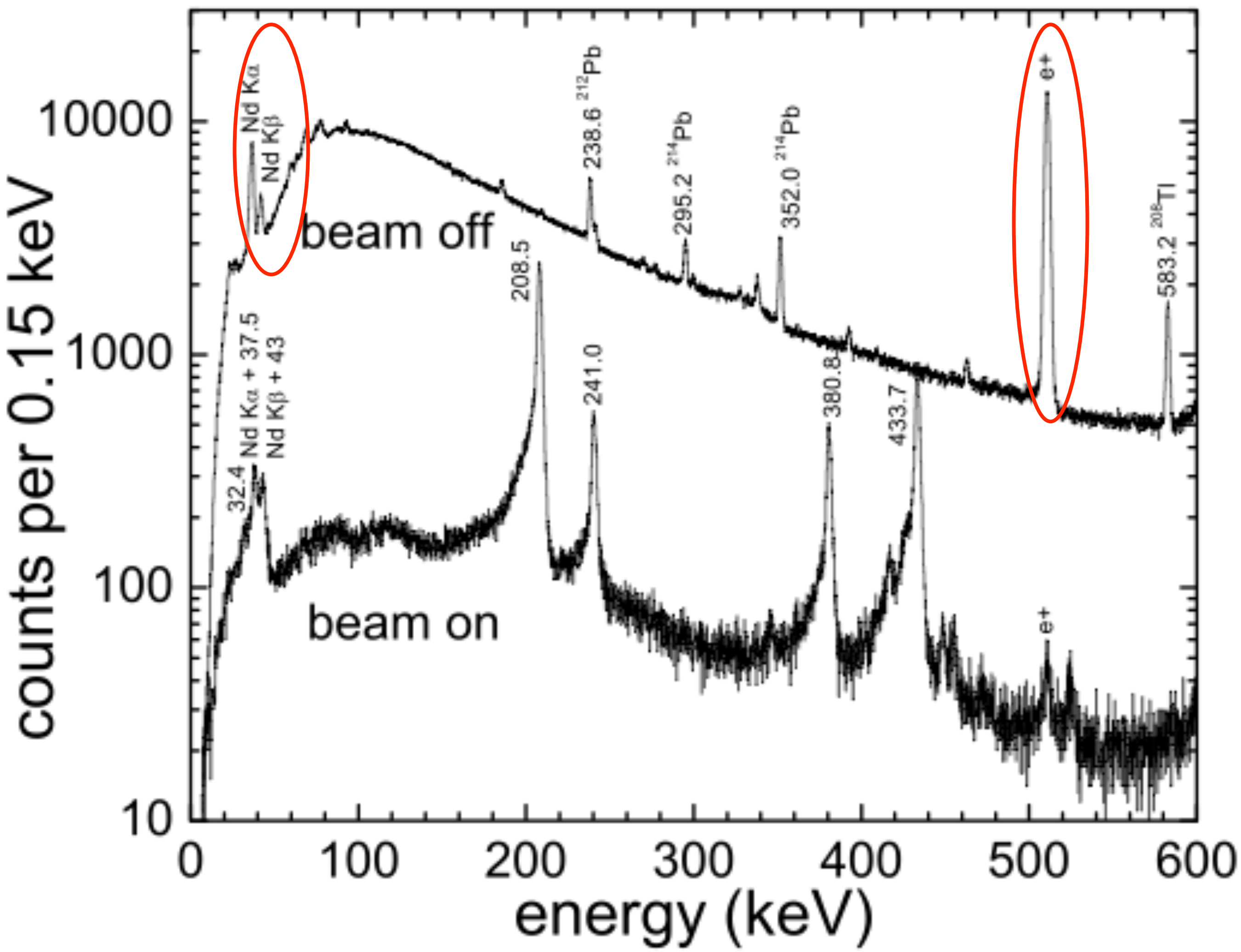
**Recoil momentum undisturbed**

0.5 second bombard
300 second count

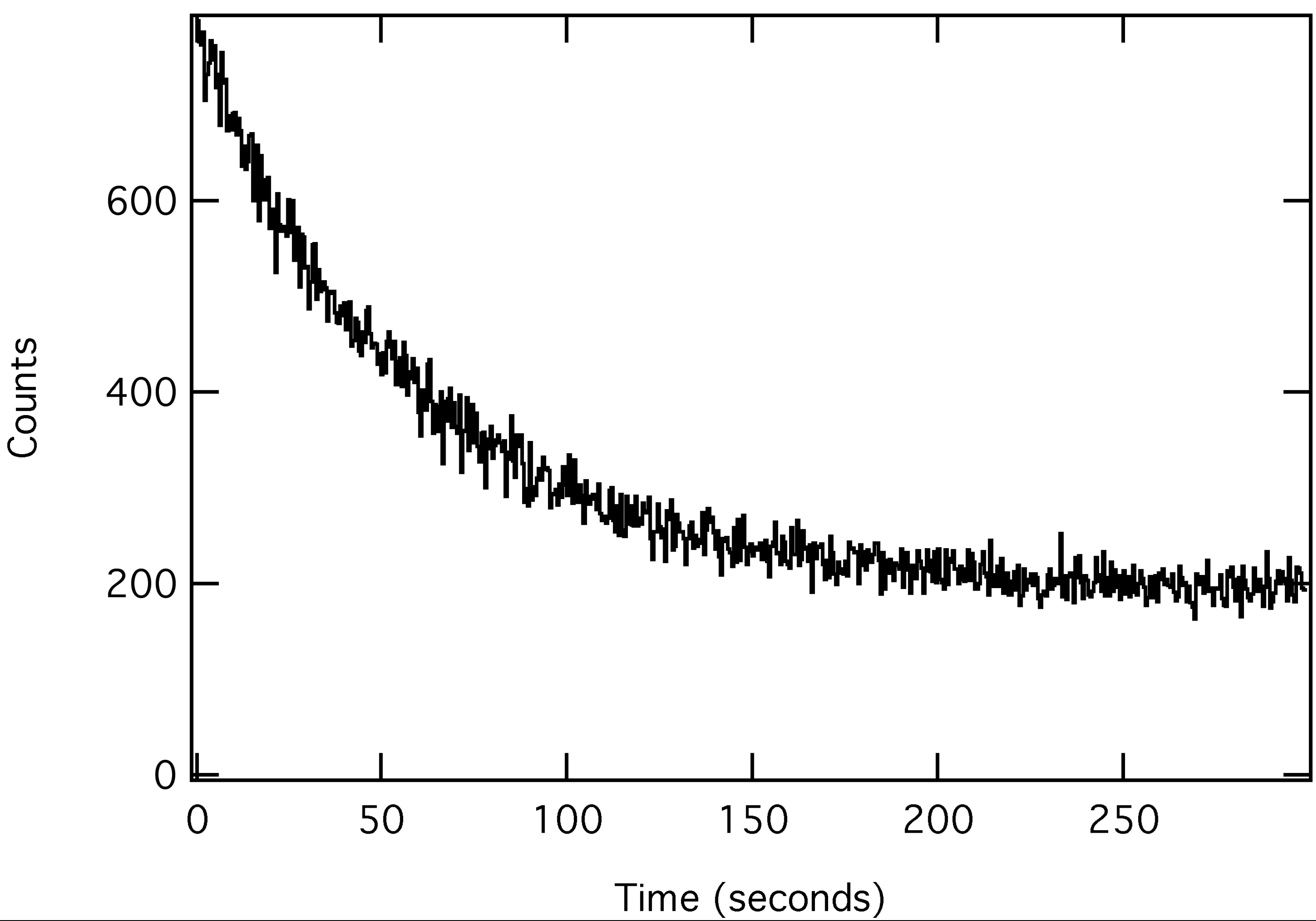


# Germanium detector energy spectrum

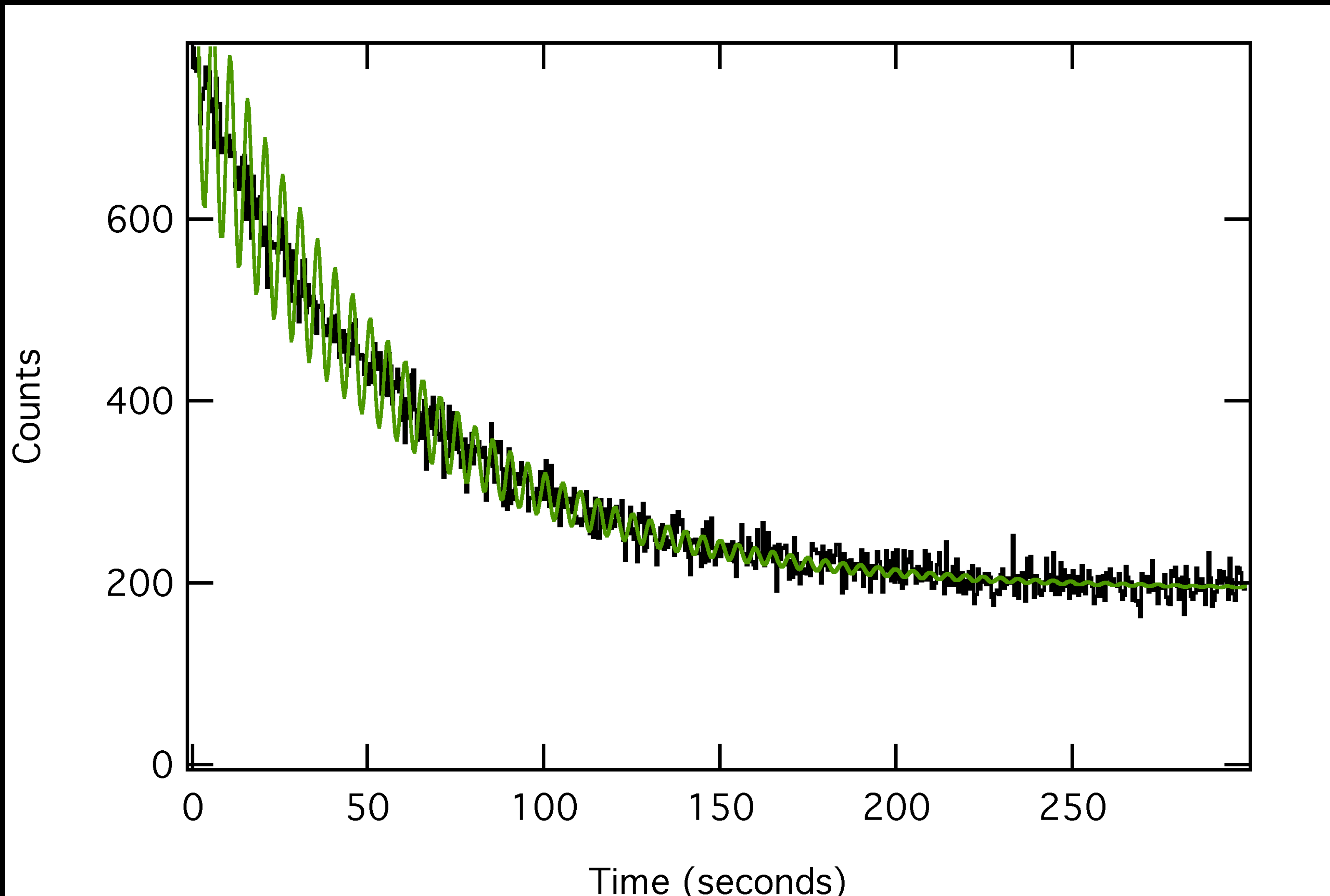
Bombard 0.5 seconds
Count 300 seconds
5 keV window on Kα peak



# Decay time spectrum of Ka x-rays

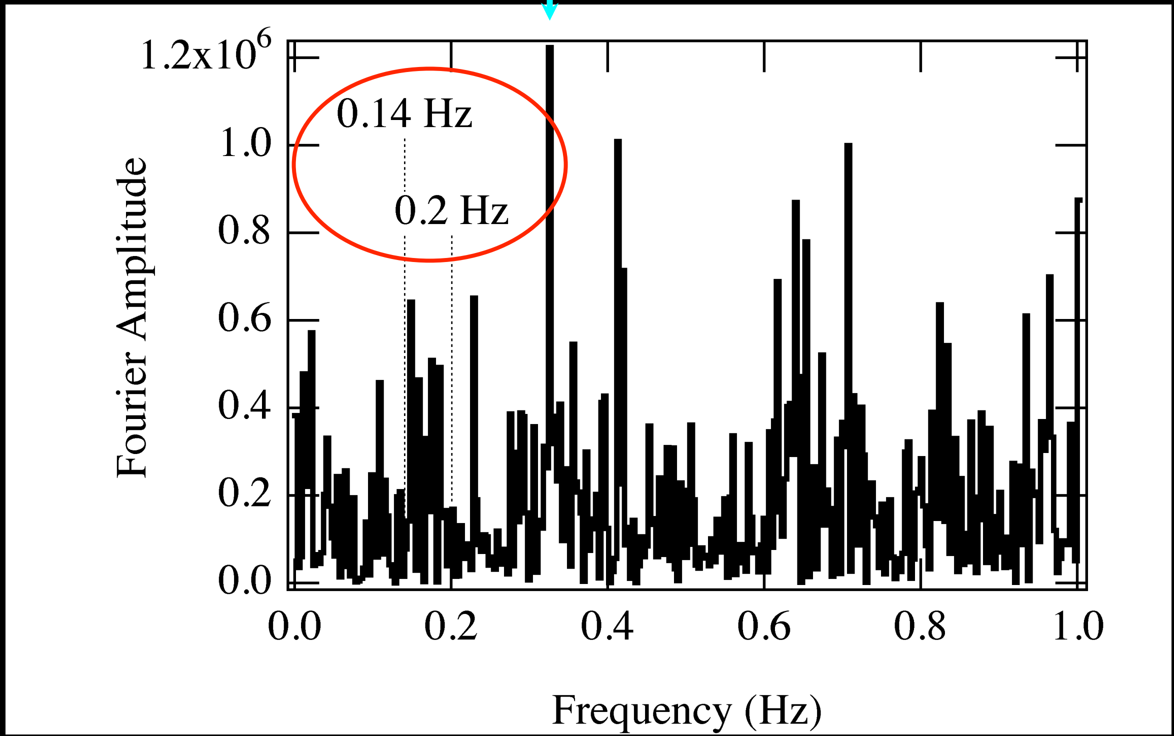


# Decay time spectrum of Ka x-rays



# Fitting

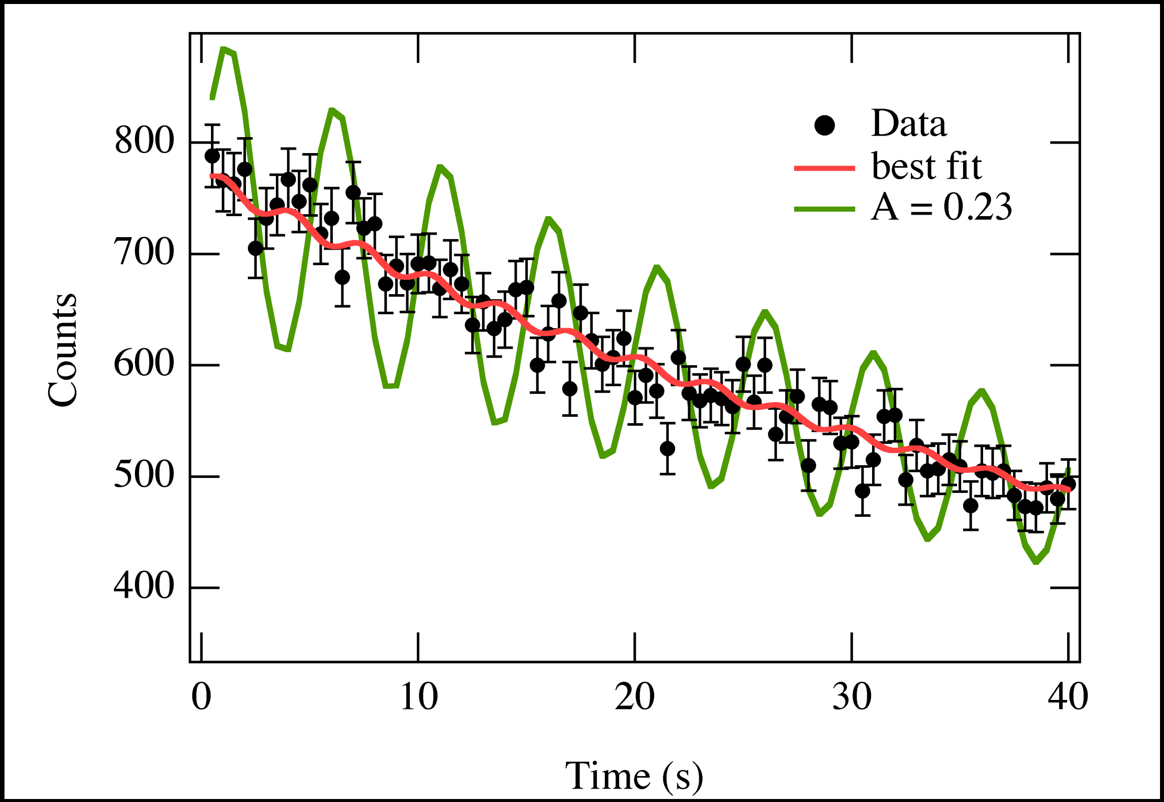
Fit to just exponential decay
Generate residuals
Fourier transform
Identify biggest peak
Re-fit to exponential times oscillation



# First 40 seconds of data, for clarity

P.A. Vetter et al. nucl-ex/0807.0649 3 July 2008

P.A. Vetter *et al.* Phys. Lett. B **670**, 196 (2008)




Best Fit:

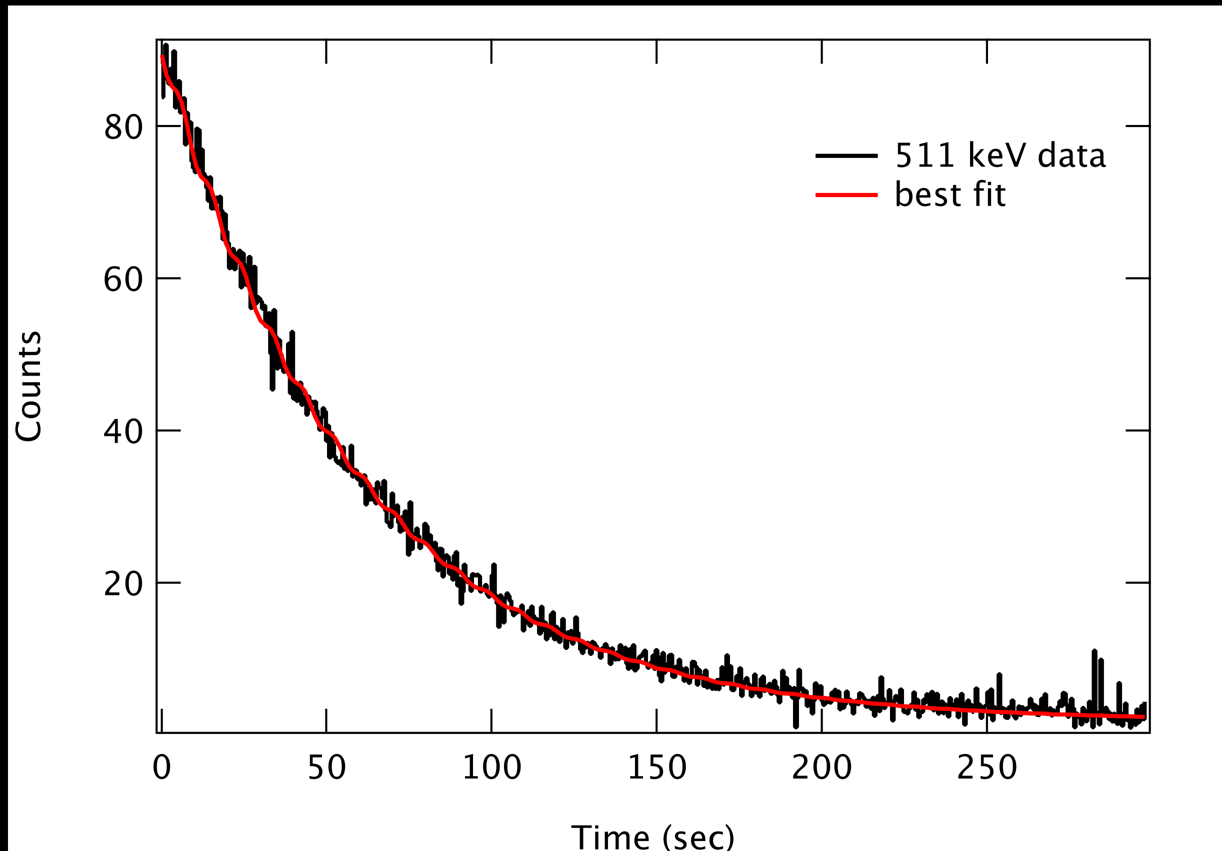
a = 0.0145(74)

T = 3.178(36) sec.

$\phi$ = −1.93(76) rad

$T_{1/2}$ = 40.68(53) sec

# Check positron decay




Best fit:

a = 0.0173(70)

T = 0.8129(8) sec.

$\phi$ = 2.15(59) rad

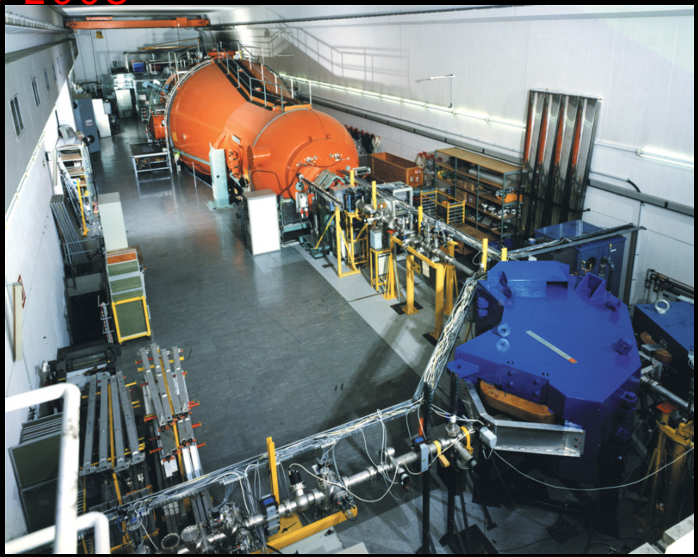
$T_{1/2}$ = 41.11(38) sec

# Another Experiment

Faestermann *et al.*, nucl-ex/0807.3297  21 July 2008

T.U. Munich

3 authors from original GSI paper



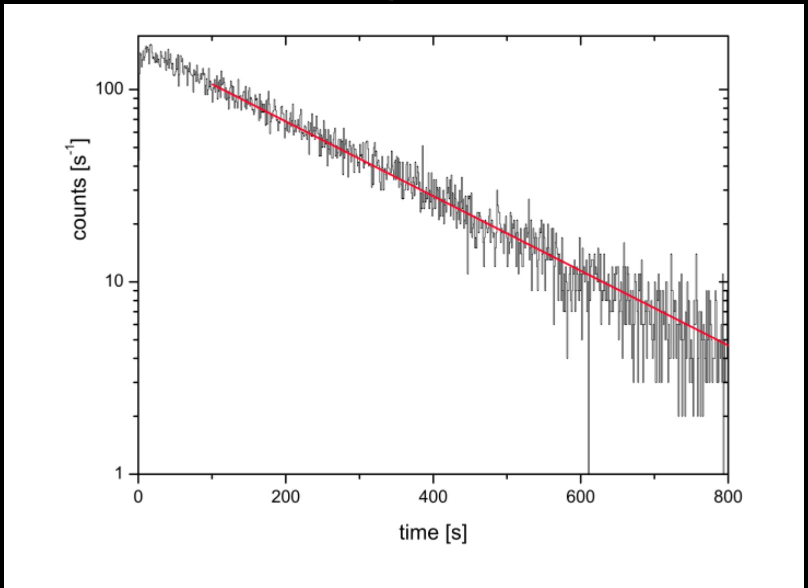
$^{180}$Re decay $T_{1/2}$ = 2.44 min

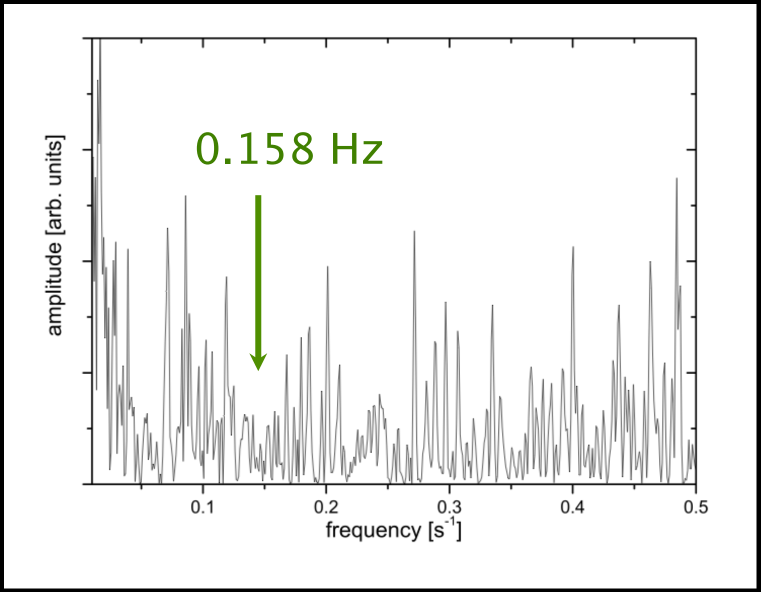
Thick tantalum target/source

Bombardment 0.5 - 1.0 sec

Detect 903 keV gamma

90% Electron Capture



# Another Experiment

Faestermann *et al.*, nucl-ex/0807.3297  21 July 2008
Phys. Lett. B 672, 227 (2009)

Conclusion of this manuscript, and other arXiv manuscripts:

Conventional experiments did not observe decay rate oscillations

Therefore, the decay rate oscillations seen in the stored ions must be "smeared out" in conventional experiments. (Phonon interactions, X-ray, gamma emission…)

Neutrino-mixed decay rate oscillations must be observable only in the stored hydrogen-like ions. (Wait, but what about the electron cooling?…)

What about: "Neutrino mixing does not cause decay rate oscillations because if it did, the conventional experiments would have seen it."

# Response to Experiment Results

Arxiv 0807.2308, 0807.2350, 0811.2922, 0905.1904
Nature 453, 864-865 (12 June 2008)

The experiments don't count:

Interactions with target material phonons in the final state would "smear out" the coherence.

Final state interactions with emitting x-rays, gamma rays, atomic electrons "smear out" the coherence.

But what about the electron cooling of the ions at GSI after the decay? They have to shed many electron-volts of energy, which should also remove the coherence.

It must be two nearly degenerate initial states -- something like an isomer?

No, it can't be!

# Rebuttal

A.N. Ivanov, P. Kienle, and M. Pitschmann, arxiv:0905.1904

Claim:

The oscillation period should be much, much smaller in the case where a subsequent de-excitation photon happens.

(K-shell x-ray in $^{142}$Pm or EC selective 903 keV $\gamma$ in $^{180}$Re)

$$\omega = \frac{\Delta m_{21}^2}{2Q_{EC}}$$

Instead of

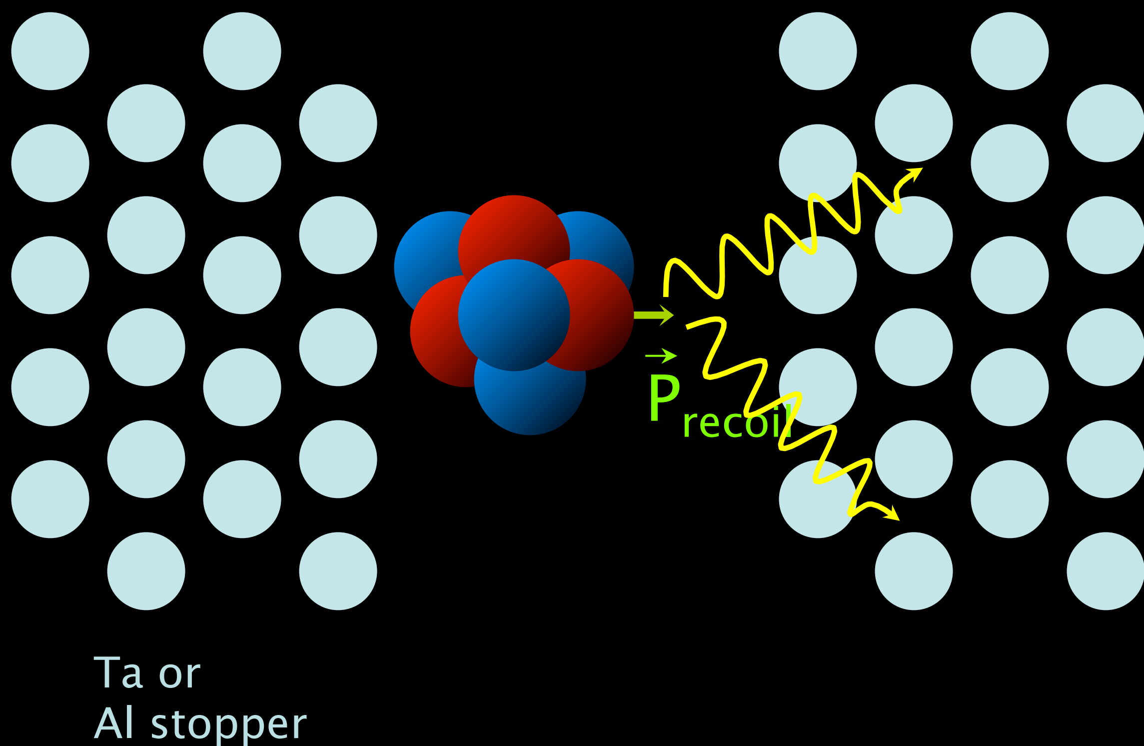
$$\omega = \frac{\Delta m_{21}^2}{4\gamma M_d}$$

$$\boxed{T_{EC} = \frac{2\pi}{\omega_{EC}} \approx 0.2 \text{ ms}}$$

# Rebuttal

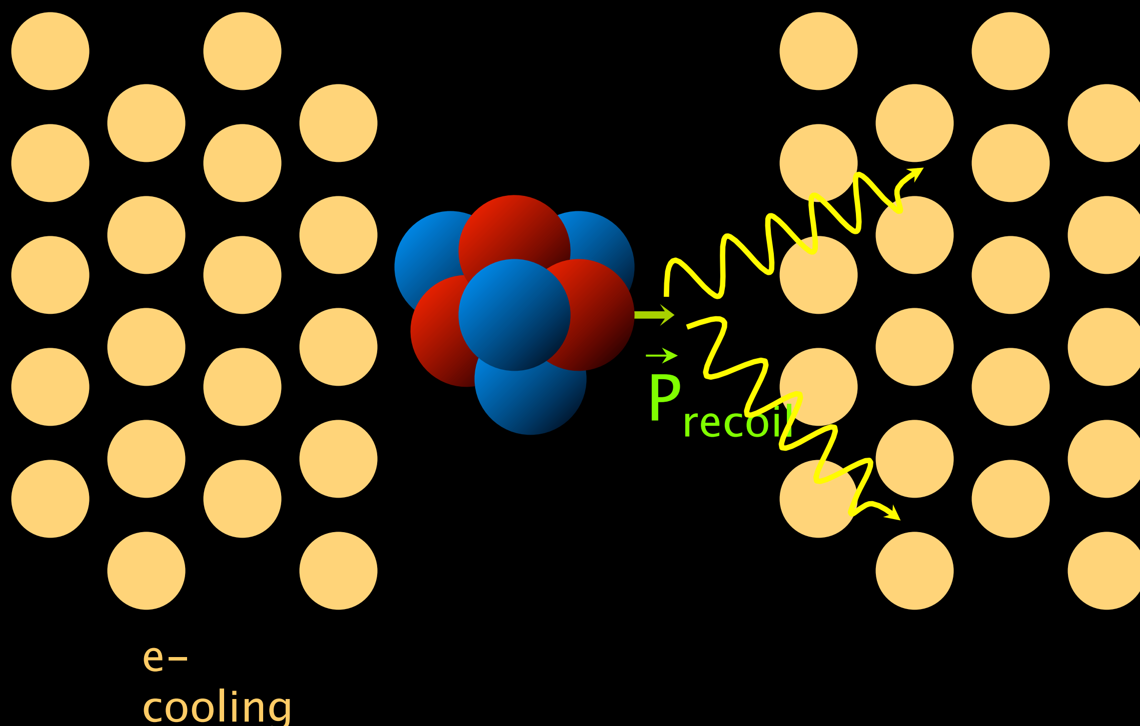
Stopped beam experiments would miss the oscillation:

Interactions of the recoil nucleus with the stopper via phonons would decohere the necessary correlation of $\vec{p}_\nu$ with $\vec{p}_{recoil}$



# Rebuttal

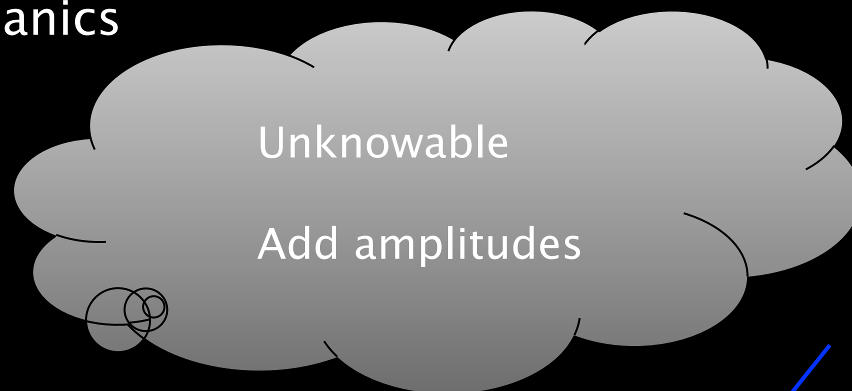
But that also applies to the stored ions, which are re-cooled after the EC decay, and interact with the storage ring orbit potential?

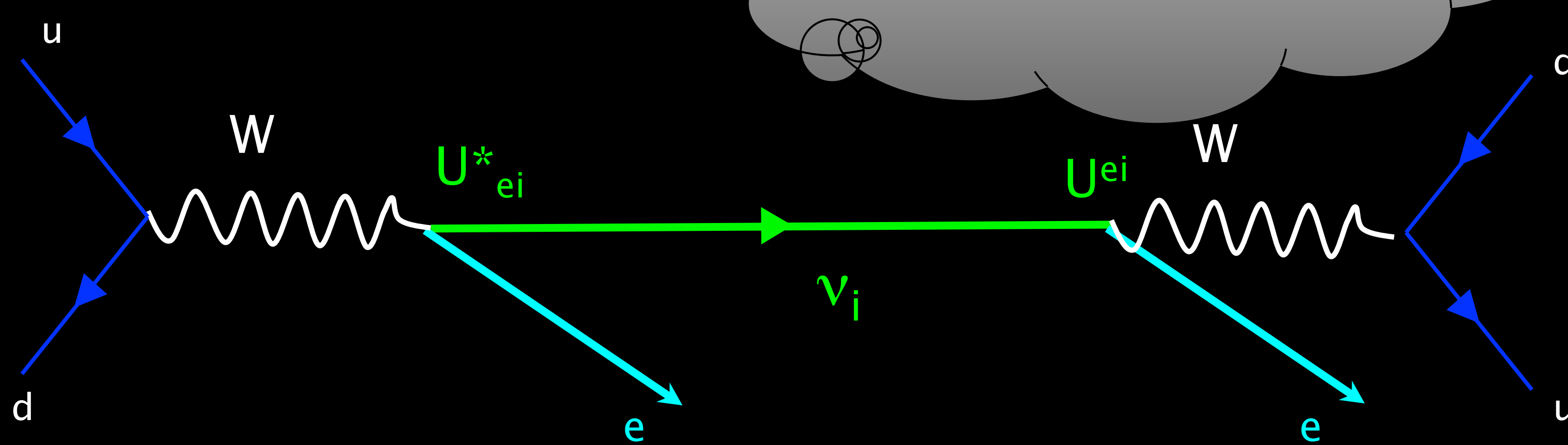


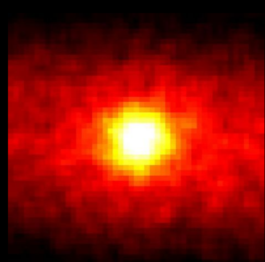
# Why it isn't neutrino flavor mixing

Error in basic quantum mechanics

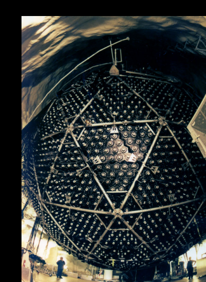
This is neutrino oscillation:



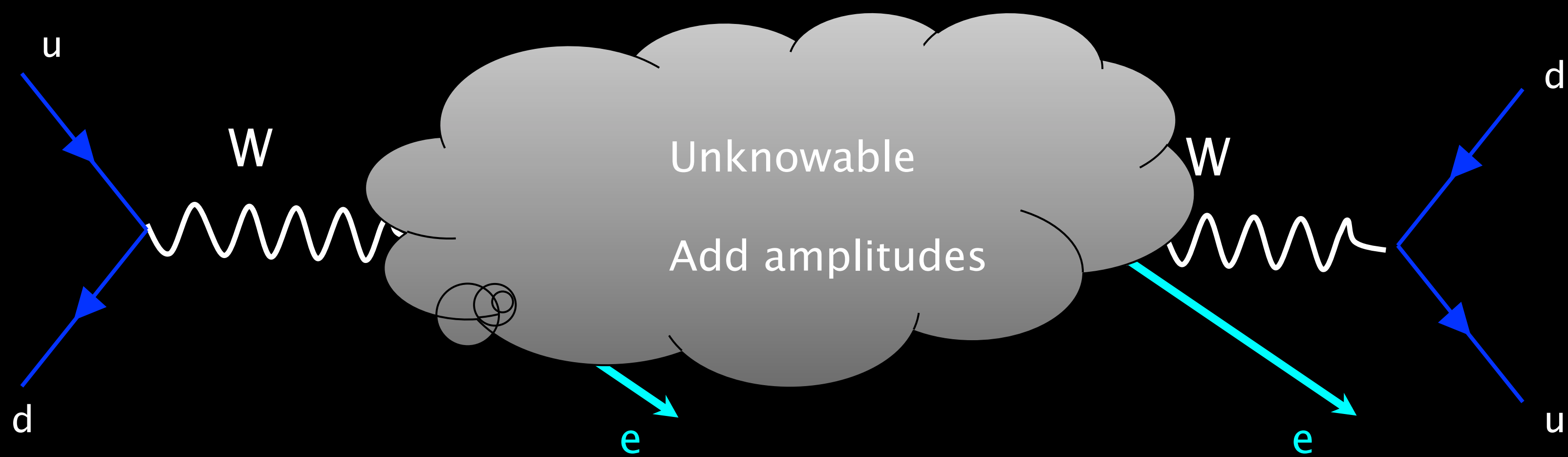



$$A_{ee} = \sum_i |U_{ei}|^2 e^{-ip_i^{\mu} x_{\mu}}$$



# Why it isn't neutrino flavor mixing

Neutrino oscillations

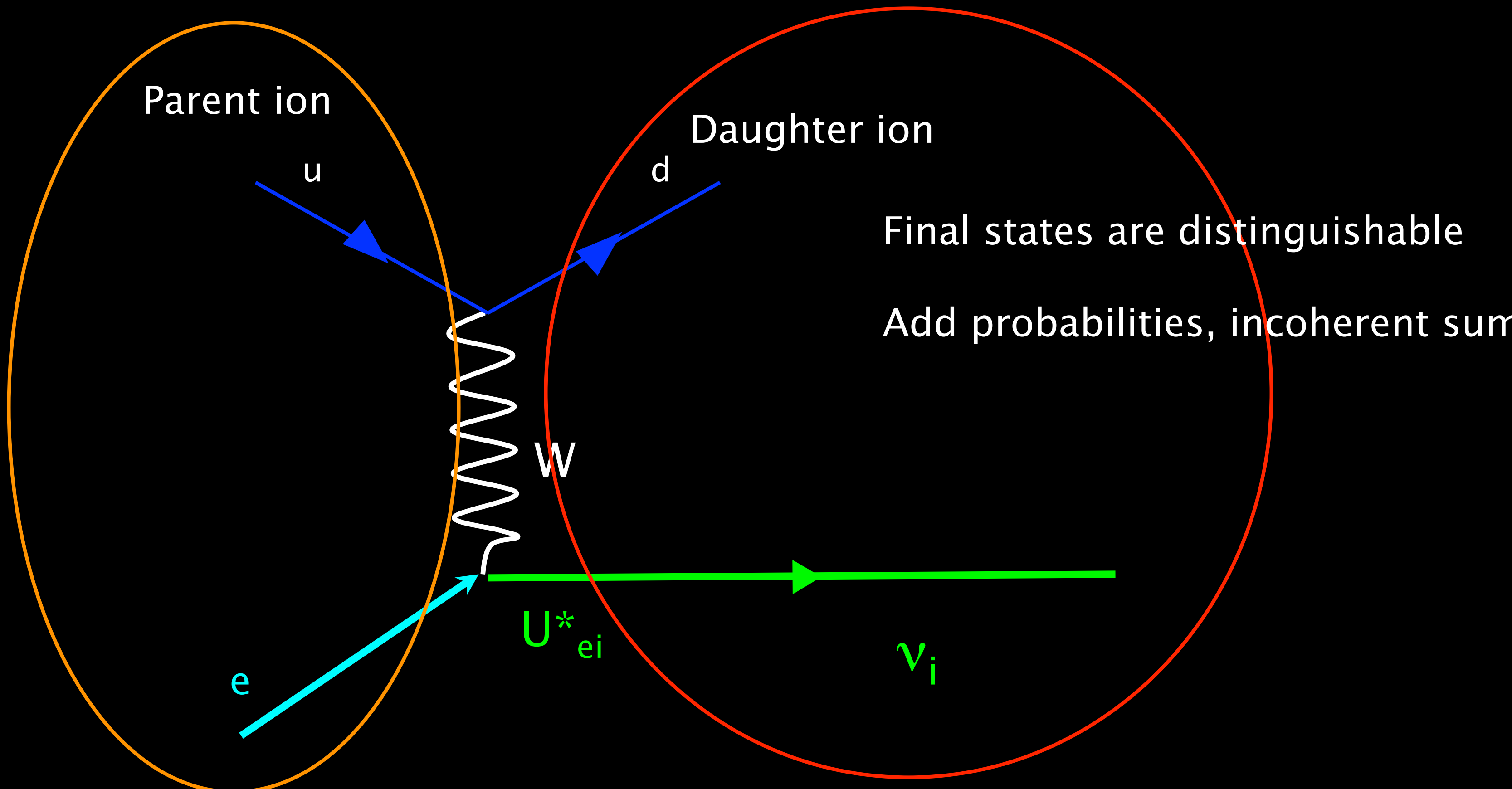



$$P_{\alpha\rightarrow\beta} = |\langle\nu_\beta|\nu_\alpha(t)\rangle|^2 = \left|\sum_i U^*_{\alpha i} U_{\beta i} e^{-i m_i^2 L/2E}\right|^2$$

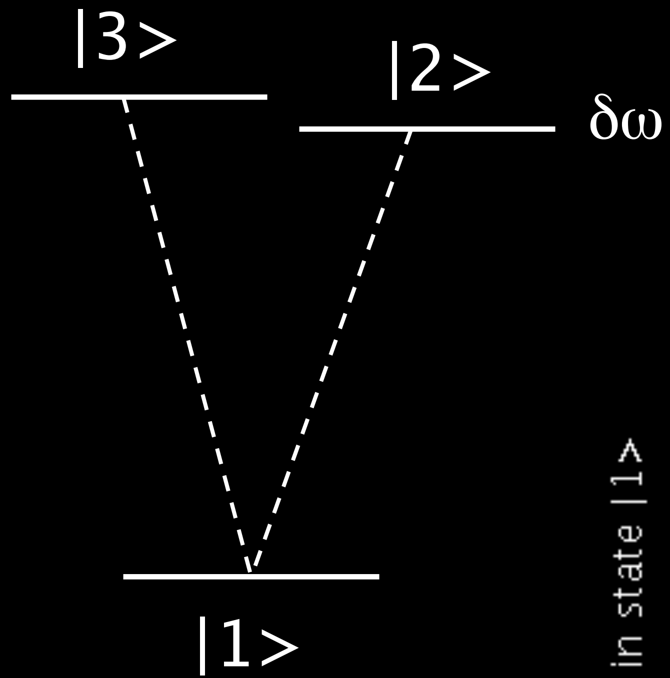
$$P_{\alpha\rightarrow\beta,\alpha\neq\beta} = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

# Why it isn't neutrino flavor mixing

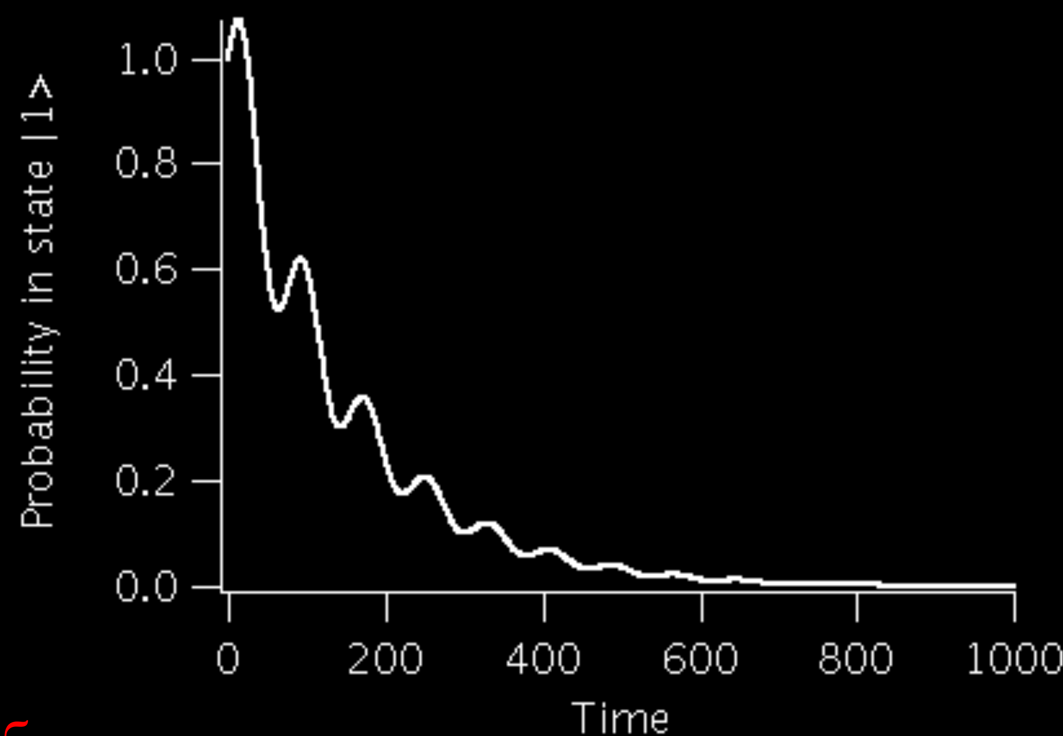
What GSI performs with electron capture decays:



# Quantum Beats

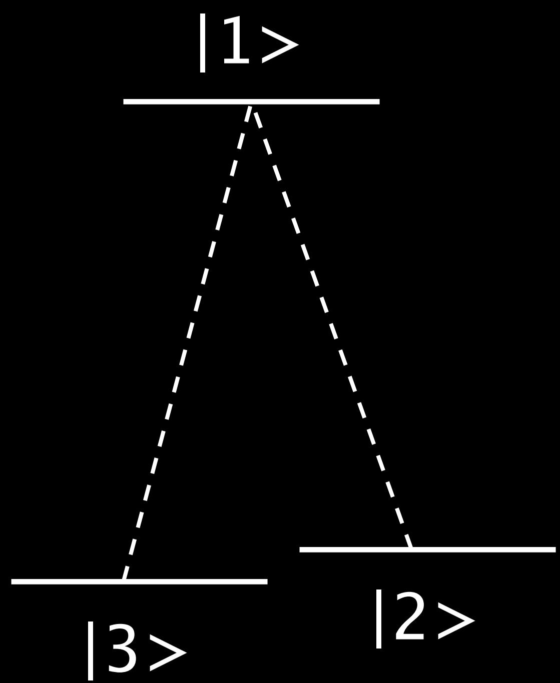



$$|\Psi_0\rangle = A\,|3\rangle + B\,|2\rangle$$

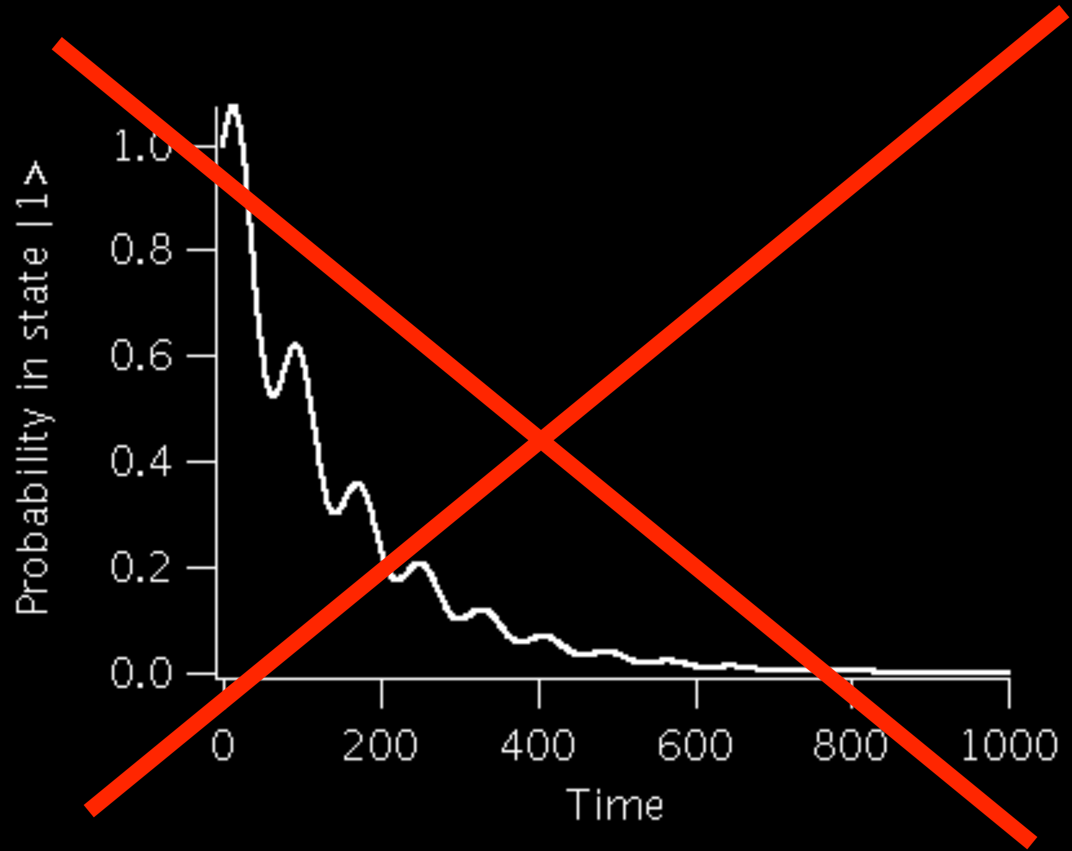



Would need $\delta\omega \sim 10^{-15}$ ες

# Quantum Beats




Final states are distinguishable
Eigenstates are orthogonal, by definition



# Hypotheses which are not $\nu$ mixing

Artifact in the data **X**

Quantum beats **X**

must be extremely small energy splitting between initial states

$10^{-15}$ eV

must be produced coherently, maintain coherence

Hyperfine changing transitions **?**

initially polarized ions prepared in F = 1/2 (lower hyperfine state)

for single particle ions, helicity projection is conserved

But if the hyperfine state changes to F = 3/2, EC decay is forbidden

# Conculsions and Status

GSI time oscillation data

Seems real, statistically significant**

Analysis of “null check” data -- charge exchange and beta decay loss find no oscillations -- consistent with neutrino mixing model

Experiment

Several experiments do not observe the phenomenon (UCB, TU Munich)

Would these have missed it because of phonon interactions in solid target?

If so, why does the cooling of the daughter ion in the GSI ESR not also spoil it via final state selection?

Theory

Neutrino flavor mixing in final state (Ivanov, Faber) cannot cause decay rate oscillations.

Neutrino flavor mixing in initial state (Lipkin) could ** (not really…)

Positron decay “should” oscillate with ~ millisecond period a ~ 0.02

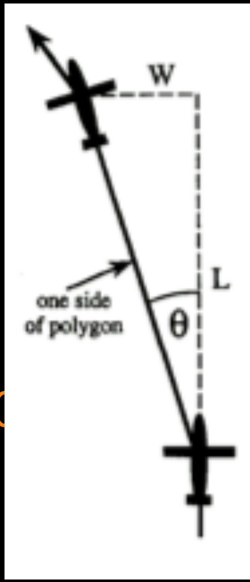
# Relativistic Spin Precession

G. Lambiase, G. Papini, G. Scarpetta, arXiv:0811.2302

As hydrogen-like ions orbit, they follow an accelerated trajectory: a non-inertial reference frame.

Any spin object in a non-inertial frame undergoes Thomas spin precession:

Why? Successive Lorentz transformations caused by velocity vector boosts are equivalent to one velocity boost times a rotation




# Thomas Precession References

B.R. Holstein, Am. J. Phys. **69**, 12 (2001)

R.A. Muller, Am. J. Phys. **60**, 313 (1992)

I.B. Khriplovich, arXiv:0801.1881 (Acta Physica Polonica,...)

J.D. Jackson arXiv:0708.4249; Am. J. Phys. 76, 704-719 (200

# Relativistic Spin Precession

Spin evolution equation: $$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S}$$

Where the precession frequency and direction is

$$\vec{\Omega} = \vec{\omega}_g + \vec{\omega}_T$$

Two terms:
one from magnetic moment, B

Thomas precession term
Depends on Lorentz factor

$$\vec{\Omega}_e = -\frac{eg}{2m_e}\vec{B} + \frac{e}{m_e}\frac{2(\gamma_e - 1)}{\gamma_e}\vec{B}$$

# Relativistic Spin Precession

This can be expressed as a hamiltonian for the spin of both electron and nucleus

$$H_{\text{spin}} = \vec{\omega}_{\text{tot}} \cdot \vec{s}$$

Total hamiltonian for the ions, containing perturbations for spin evolution:

$$H_{ion} = H_0 + H^e + H^n$$

Initial helicity states of the electron and nucleus will evolve

$$P^{(e)} = \left|\left\langle \psi_+^e \middle| \psi^e(t) \right\rangle\right|^2 = \frac{1}{2}(1 - \cos\Omega_e t)$$

$$P^{(n)} = \left|\left\langle \psi_+^n \middle| \psi^n(t) \right\rangle\right|^2 = \frac{e^{-\Gamma t}}{2}(1 - \cos\Omega_n t)$$

# Relativistic spin precession hyperfine state changes

Total time evolution for ion composed of nuclear and electron helicities:

$$P(\pm) \propto P^{(e)}P^{(n)} = \frac{e^{-\Gamma t}}{4}\left(1 - \cos\Omega_n t - \cos\Omega_e t + \frac{1}{2}\left[\cos(\Omega_e + \Omega_n)t + \cos(\Omega_e - \Omega_n)t\right]\right)$$

Transition to F=3/2

$$\Omega(\text{flip}) = \Omega_e - \Omega_n \approx -\left[a_e - 1 + \frac{2}{\gamma_e} + \left(\mu_{nuc} - \frac{2Z}{A}\right)\frac{m_e}{m_p}\right]\frac{eB}{m_e}$$

bound state electron anomalous moment

Electron Lorentz factor

nuclear anomalous moment

Storage ring field

# Hyperfine Selection

Initial nucleus has I = 1
Total ang. momentum (F) for H-like ion can be 3/2 or 1/2

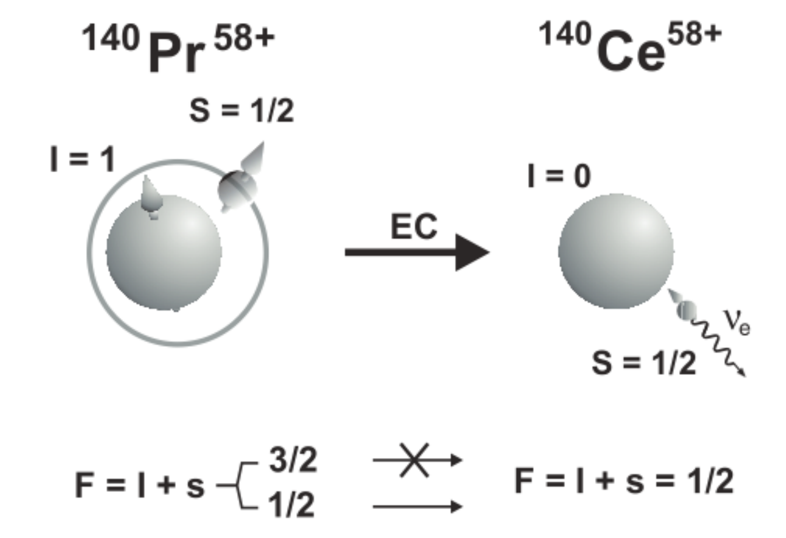


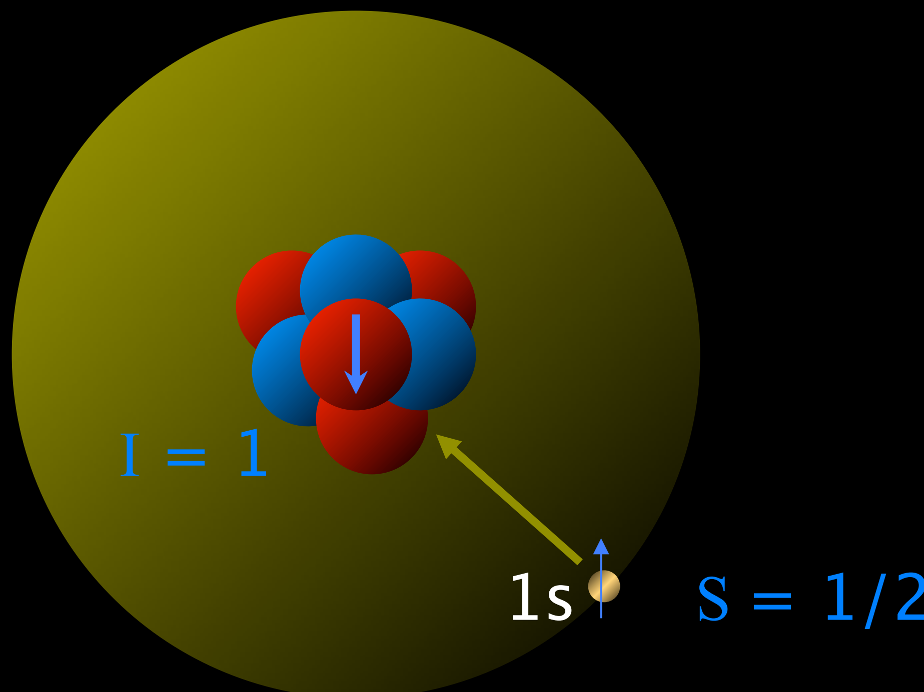

FIG. 3. Illustration of the EC decay of hydrogenlike $^{140}Pr^{58+}$ ions to bare $^{140}Ce^{58+}$ ions.

Final nucleus has I = 0
only one hyperfine state of total angular momentum

Electron Capture decay of F = 3/2 state is forbidden (suppressed at least $\alpha^2$)

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

# Cartoon version of electron capture



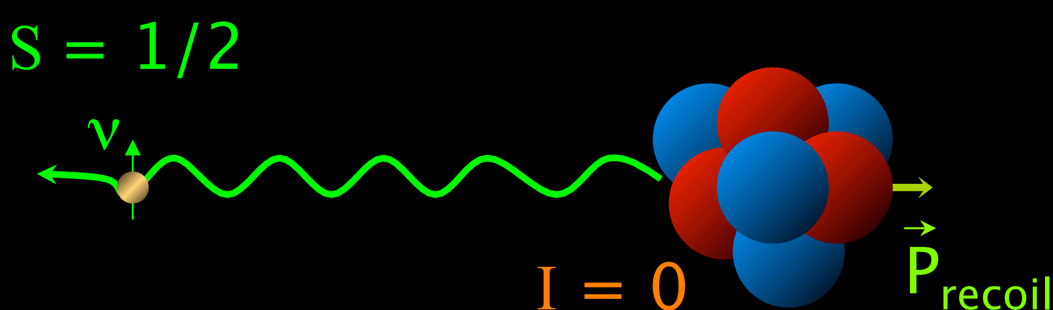

$^{140}Pr^{58+}$

59p, 81n

$$\vec{F} = \vec{I} + \vec{S} \quad \begin{matrix} 3/2 \\ \\ 1/2 \end{matrix}$$

# Cartoon version of electron capture

F = 3/2 is forbidden to EC




$^{140}$Pr
$^{142}$Pm All I = 1$^+$ to I = 0$^+$ g.s.
$^{122}$I transitions

$^{140}Ce^{58+}$
58p, 82n

# What's the Frequency?

$$\Omega(\text{flip}) = \Omega_e - \Omega_n \approx -\left[a_e - 1 + \frac{2}{\gamma_e} + \left(\mu_{nuc} - \frac{2Z}{A}\right)\frac{m_e}{m_p}\right]\frac{eB}{m_e}$$

bound state electron anomalous moment

Electron Lorentz factor

nuclear anomalous moment

Storage ring field

$$g_e^{\text{bound}}(^{142}\text{Pm}^{60+}) = 1.86365$$

$$g_e^{\text{bound}}(^{140}\text{Pr}^{58+}) = 1.87305$$

$$g_e^{\text{bound}}(^{122}\text{I}^{52+}) = 1.89899$$

$$\mu_{\text{nuc}} = 2.5\mu_N$$

$$\frac{QB}{M} = \frac{\gamma^2\,(2\pi f)\,\rho}{\beta c}$$

$B\rho$ = 6.44 T m
L = 108.3 m
$\gamma$ = 1.43
$\beta$ = 0.71

$$m_e \gamma_e v_e^2 = \frac{1}{4\pi\epsilon_0}\frac{Ze^2}{R}$$

R(140Pr) = 123 fm (0.145 $a_0$)
R(142Pm) = 128 fm (0.151 $a_0$)
R(122 I) = 108 fm (0.127 $a_0$)

# Rebuttal: It can’t be the spin evolution

M. Faber, A. N. Ivanov, P. Kienle, M. Pitschmann, N. I. Troitskaya arxiv:0906.3617

(June 19, 2009)

This manuscript “begs the question”.

The question at issue is:

Can the H-like ion (electron + nucleus) system have an evolution of its spin states out of the initially prepared helicity state $F = 1/2$ ?

Thomas precession of **composite objects** seems to have no literature at all, except for an offhand comment by

I.B. Khriplovich. This may be an experimental confirmation.

# How could you discriminate against different models?

**Neutrino mixing vs. Relativistic Spin Precession:**

**Parent ion nuclear spin?**

Neutrino mixing: independent of nuclear spin

Relativistic Spin Precession would not oscillate

**Interesting spin cases -- no hyperfine selection**

**Oscillation in He-like ions?**

Neutrino mixing should probably still oscillate in He-like**

Relativistic Spin Precession would not oscillate

(Gamow-Teller Electron Capture selection rules different in closed-1s shell)

**Frequency dependence on parent ion mass?**

Neutrino mixing: Period strictly proportional to M

Relativistic Spin Precession: complex storage ring parameter dependence

-- loosely mimics $T \propto M_d$

**Positron Decay Channel?**

Neutrino mixing: oscillates very rapidly**

Relativistic Spin Precession would not oscillate

# Neutrino mixing vs. Relativistic Spin Precession

Interesting electron capture cases: Remove sterile hyperfine state

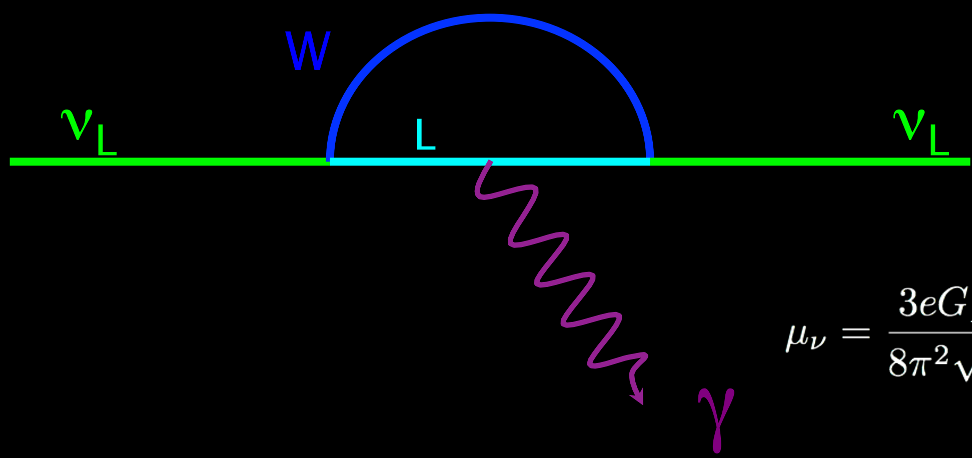
| Parent | $(J^\pi)$ | Daughter | $(J^\pi)$ | $T_{1/2}$ | Intensity to g.s. |
|---|---|---|---|---|---|
| $^{64}$Ga | $(0^+)$ | $^{64}$Zn | $(0^+)$ | 2.63 min | 29% |
| $^{63}$Ga | $(3/2^-)$ | $^{63}$Zn | $(3/2^-)$ | 32 sec. | 55% |
| $^{61}$Zn | $(3/2^-)$ | $^{61}$Cu | $(3/2^-)$ | 89 sec. | 66% |
| $^{93}$Ru | $(9/2^+)$ | $^{93}$Tc | $(9/2^+)$ | 59.7 sec. | 91% |
| $^{89}$Mo | $(9/2^+)$ | $^{89}$Nb | $(9/2^+)$ | 2.11 min. | 83% |
| $^{140}$Gd | $(0^+)$ | $^{140}$Eu | $(1^+)$ | 15.8 sec. | 46% |
| $^{109}$Sb | $(5/2^+)$ | $^{109}$Sn | $(5/2^+)$ | 17 sec. | 13% |
| $^{123}$Cs | $(1/2^+)$ | $^{123}$Xe | $(1/2^+)$ | 5.8 min. | 28% |

# Another possibility: Neutrino Magnetic Moment

arXiv:nucl-th/0809.1213v2, A. Gal
arXiv:nucl-th/0908.2039, V.V. Flambaum

Neutrino acquires a magnetic moment through radiative corrections

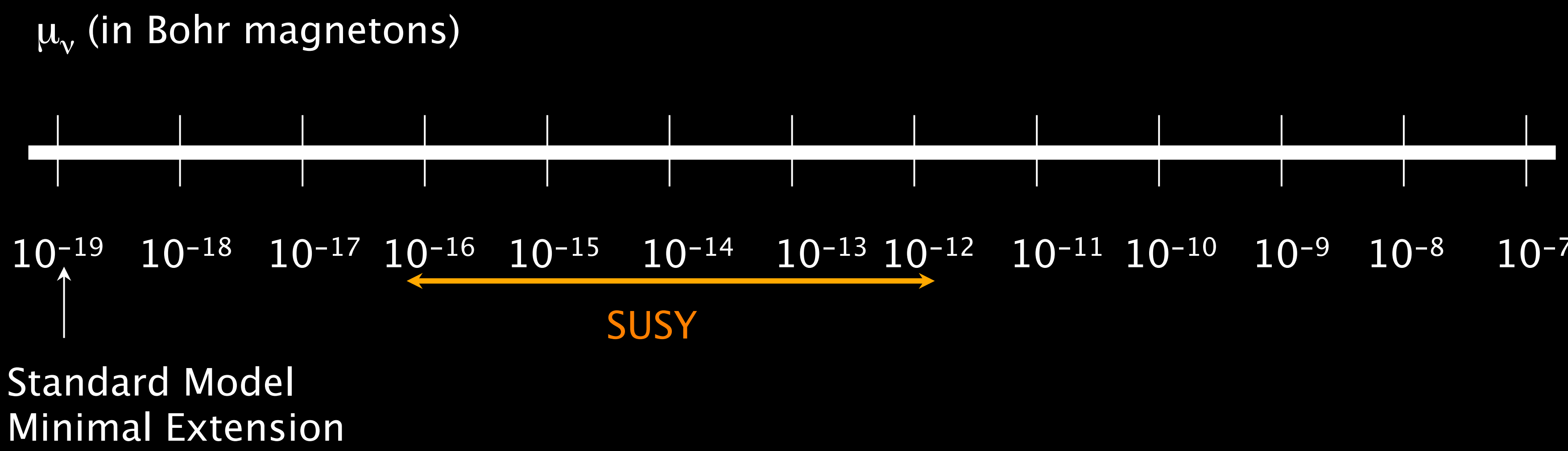
In the Standard Model (with neutrino mass), the magnetic moment is:




$$\mu_\nu = \frac{3eG_F}{8\pi^2\sqrt{2}} m_\nu \approx 3 \times 10^{-19} \mu_B \frac{m_\nu}{1\ \mathrm{eV}}$$

# Existing Limits on Neutrino Magnetic Moments

arXiv:hep-ph/0601113, B. Balantekin



# Conclusions about Neutrinos Proposed by GSI

You can extract the squared mass difference of the first two species.
January - March, 2008

You can extract the squared mass difference of the first two species. It disagrees with KamLAND, but perhaps it's a high mass solution.
March, 2008

You can extract the absolute mass scale of neutrinos, and indeed all three neutrino masses. It's 0.22 eV each (degenerate hierarchy).
April, 2008

You can extract the absolute mass scale of neutrinos, and indeed all three neutrino masses. It's 0.11 eV each.
March, 2009

You can conclude that the neutrino mixing matrix is non-unitary: there must be a sterile sector, or something else exotic. (Because the modulation depth isn't as big as it "should be".)
October, 2009

# Suppose you want to eliminate the phonon objection?

Perform experiment in vacuum -- no phonons, no lattice structure

But poor observation time unless you trap the species, which would have to have a long trap lifetime so as not to interfere with the long decay rate and relatively long oscillation period.  An ion trap would be best…

Perform in a solid with radically different lattice structure (different phonon spectrum) or an amorphous solid (no phonon spectrum)

Perform experiment with activity stopped in a gas (no phonon spectrum)

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