Neutron decay anomaly: hint to BSM physics, a QM effect, or just a systematic error?

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Talk based on 1906.10024 and 1909.01099 and prepared for:

Epiphany conference 2020
LHC physics: standard model and beyond
IFG PAN Krakow

7-10/1/2020

Outline

1. General discussion of the decay law: non-exp. decays, QZE and IZE
2. Experimental proofs
3. The neutron decay anomaly
4. The Inverse-Zeno-effect as an explanation of the anomaly
5. Conclusions

Part 1: General discussion

Exponential decay law

- N_0 : Number of unstable particles at the time t = 0.

  $$\boxed{N(t) = N_0 e^{-\Gamma t}}\,, \quad \tau = 1/\Gamma \text{ mean lifetime}$$

  Confirmend in countless cases!

- For a single unstable particle:

  $$\boxed{p(t) = e^{-\Gamma t}}$$

  is the survival probability for a single unstable particle created at t=0. (Intrinsic probabilty, see Schrödinger´s cat).

For small times: $p(t) = 1 - \Gamma t + \ldots$

Basic definitions

Let $|S\rangle$ be an unstable state prepared at $t = 0$.

Survival probabilty ammplitude at $t > 0$:

$$a(t) = \langle S | e^{-iHt} | S \rangle$$

Survival probability: $p(t) = |a(t)|^2$

Rep. Prog. Phys., Vol. 41, 1978. Printed in Great Britain

Decay theory of unstable quantum systems

L FONDA, G C GHIRARDI and A RIMINI

Deviations from the exp. law at short times

Taylor expansion of the amplitude:

$$a(t) = \langle S|e^{-iHt}|S\rangle = 1 - it\langle S|H|S\rangle - \frac{t^2}{2}\langle S|H^2|S\rangle + \ldots$$

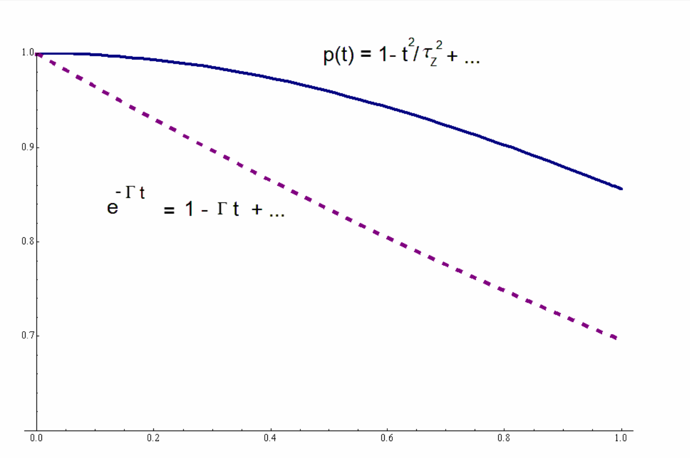
$$a^*(t) = \langle S|e^{-iHt}|S\rangle = 1 + it\langle S|H|S\rangle - \frac{t^2}{2}\langle S|H^2|S\rangle + \ldots$$

It follows:

$$\boxed{p(t) = |a(t)|^2 = a^*(t)a(t) = 1 - t^2\left(\langle S|H^2|S\rangle - \langle S|H|S\rangle^2\right) + \ldots = 1 - \frac{t^2}{\tau_Z^2} + \ldots}$$

p(t) decreases quadratically (not linearly);
no exp. decay for short times.
τ_Z is the `Zeno time´.

where $\tau_Z = \dfrac{1}{\sqrt{\langle S|H^2|S\rangle - \langle S|H|S\rangle^2}}$.



Note: the quadratic behavior holds
for any quantum transition, not only for decays.
It is an absolutely general property.

Time evolution and energy distribution (1)

The unstable state $|S\rangle$ is not an eigenstate of the Hamiltonian H.

Let $d_S(E)$ be the energy distribution of the unstable state $|S\rangle$.

Normalization holds: $\int_{-\infty}^{+\infty} d_S(E)dE = 1$

$$\boxed{a(t) = \int_{-\infty}^{+\infty} d_S(E) e^{-iEt} dE}$$

In stable limit : $d_S(E) = \delta(E - M) \rightarrow a(t) = e^{-iMt} \rightarrow p(t) = 1$

Time evoluition and energy distribution (2)

Breit-Wigner distribution:

$$d_S(E) = \frac{\Gamma}{2\pi} \frac{1}{(E-M)^2 + \Gamma^2/4} \rightarrow a(t) = e^{-iM_0 t - \Gamma t/2} \rightarrow p(t) = e^{-\Gamma t}.$$

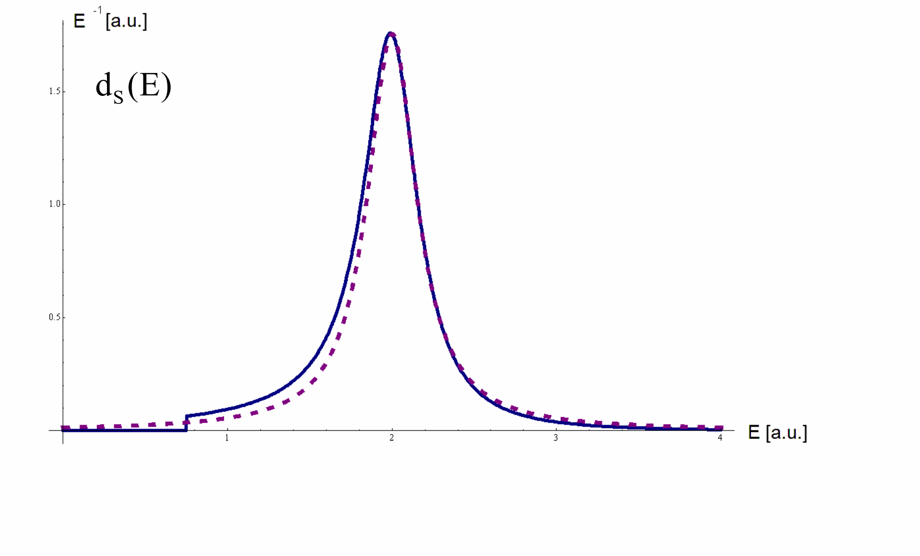
The Breit-Wigner energy distribution cannot be exact.

Two physical conditions for a realistic $d_S(E)$ are:

1) Minimal energy: $d_S(E) = 0 \text{ for } E < E_{\min}$

2) Mean energy finite: $\langle \mathrm{E} \rangle = \int_{-\infty}^{+\infty} d_S(E) E dE = \int_{E_{\min}}^{+\infty} d_S(E) E dE < \infty$

A very simple numerical example

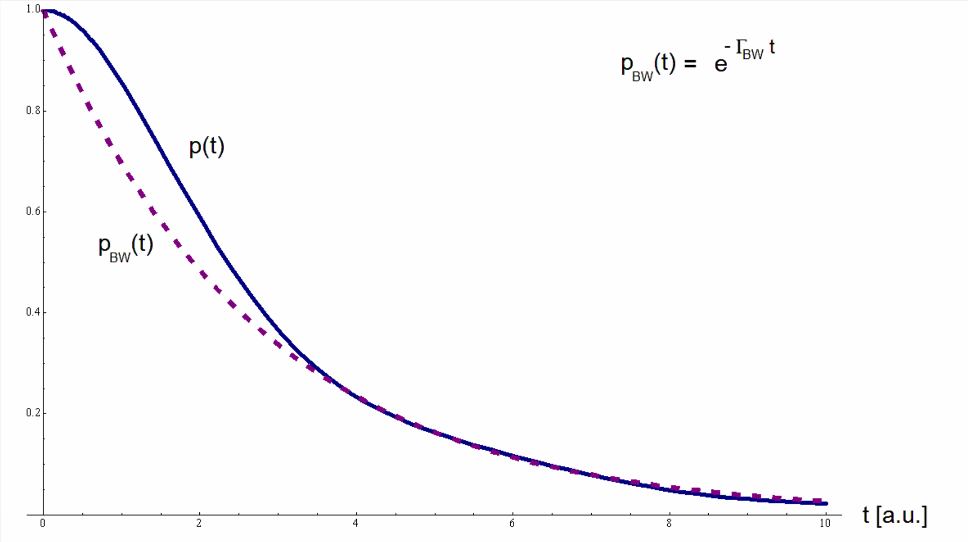


$$M_0 = 2;\ E_{min} = 0.75;\ \ \Gamma = 0.4;\ \Lambda = 3$$

$$d_S(E) = N_0 \frac{\Gamma}{2\pi} \frac{e^{-(E^2 - E_0^2)/\Lambda^2}\theta(E - E_{min})}{(E - M_0)^2 + \Gamma^2/4}$$

$$d_{BW}(E) = \frac{\Gamma_{BW}}{2\pi} \frac{1}{(E - M_0)^2 + \Gamma_{BW}{}^2/4}$$

Γ_{BW}, such that $d_{BW}(M_0) = d_S(M_0)$



$$a(t) = \int_{-\infty}^{+\infty} d_S(E) e^{-iEt} dE\ ;\quad p(t) = |a(t)|^2$$

$$p_{BW}(t) = e^{-\Gamma_{BW} t}$$

Francesco Giacosa

The quantum Zeno effect

We perform N inst. measurements:

the first one at time $t = t_0$, the second at time $t = 2t_0$, ..., the N-th at time $T = Nt_0$.

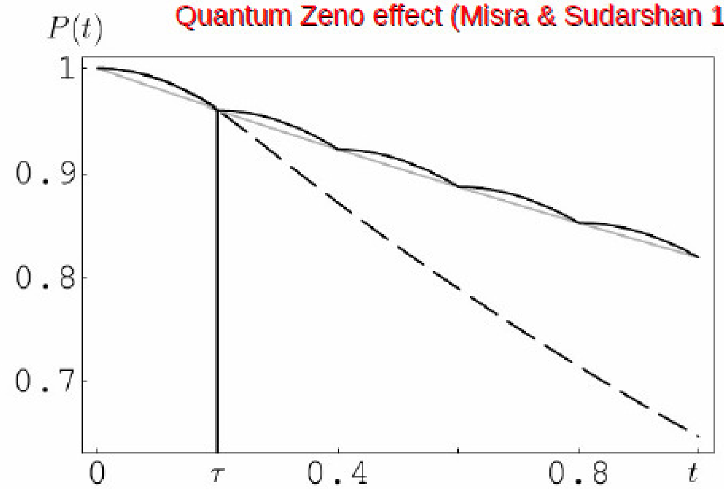
$$p_{\text{after N measurements}} = p(t_0)^N \approx \left(1 - \frac{t_0^2}{\tau_Z^2}\right)^N = \left(1 - \frac{T^2}{N^2 \tau_Z^2}\right)^N$$

under the assumption that t_0 is small enough.

If $N >> 1$ (at fixed T): $p_{\text{after N measurements}} \approx e^{-\frac{T^2}{N\tau_Z^2}} \approx 1.$

For large but finite N :
→ slowing down of the decay.

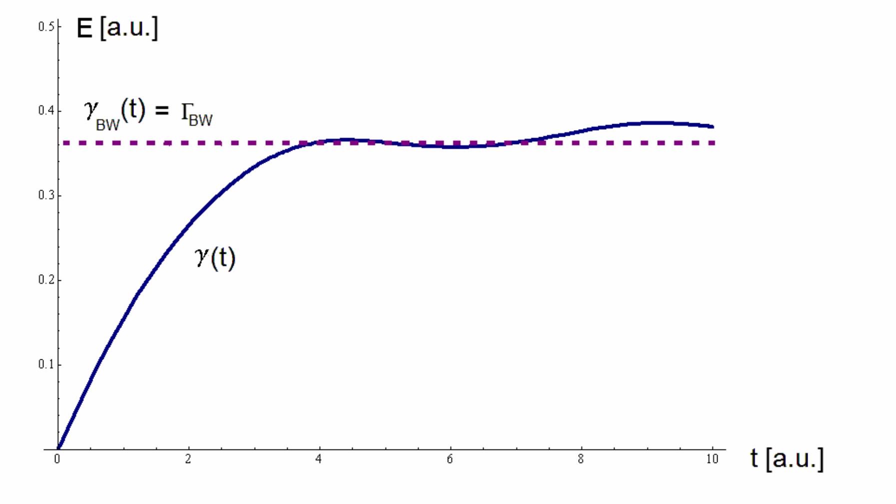
Quantum Zeno effect (Misra & Sudarshan 1977)



See Facchi & Pascazio quant-ph/0202127

General description of the Zeno and anti-Zeno effects

$$p(t) = e^{-\gamma(t)t} \Rightarrow \gamma(t) = -\frac{1}{t}\ln p(t)$$



Survival probabilty after a single measurement at time T

$$p(T) = e^{-\gamma(T)T}$$

Survival probability after N measurments:

$$p(\tau)^N = e^{-\gamma(\tau)\tau N} = e^{-\gamma(\tau)T} > e^{-\gamma(T)T} \quad \text{wenn} \quad \gamma(\tau) < \gamma(T)$$

Zeno effect

$$\text{For } \tau \to 0,\ \gamma(\tau \to 0) \to 0,\ \ \mathrm{p}(\tau)^{\mathrm{N}} \to 1$$

How it is also possible that: $\gamma(\tau) > \gamma(\mathrm{T}) \ \Rightarrow \ \mathrm{p}(\tau)^{\mathrm{N}} = \mathrm{e}^{-\gamma(\tau)\tau\mathrm{N}} = \mathrm{e}^{-\gamma(\tau)\mathrm{T}} < \mathrm{e}^{-\gamma(\mathrm{T})\mathrm{T}}$ Anti-Zeno-Effekt

See: P. Facchi, H. Nakazato, and S. Pascazio, Phys. Rev. Lett. **86**, 2699 (2001).

IL NUOVO CIMENTO VOL. 21 A, N. 3 1 Giugno 1974

Does the Lifetime of an Unstable System Depend on the Measuring Apparatus? (*)

A. DEGASPERIS (**) and L. FONDA
International Centre for Theoretical Physics - Trieste

G. C. GHIRARDI

The Zeno's paradox in quantum theory

B. Misra and E. C. G. Sudarshan*
Center for Particle Theory, University of Texas at Austin, Austin, Texas 78712
(Received 24 February 1976)

letters to nature

Acceleration of quantum decay processes by frequent observations

A. G. Kofman & G. Kurizki

NATURE | VOL 405 | 1 JUNE 2000

QUANTUM ZENO EFFECTS WITH "PULSED" AND "CONTINUOUS" MEASUREMENTS

P. Facchi[(1)] and S. Pascazio[(2)]

INTERNATIONAL CONFERENCE
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TIME'S ARROWS, QUANTUM MEASUREMENT AND SUPERLUMINAL BEHAVIOR

Part 2: Experimental evidence of non-exponential decay

Experimental confirmation of non-exponential decays (1)

NATURE | VOL 387 | 5 JUNE 1997

Experimental evidence for non-exponential decay in quantum tunnelling

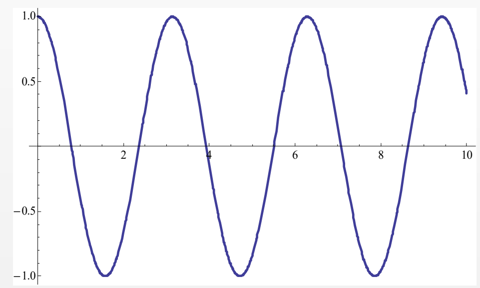
Steven R. Wilkinson, Cyrus F. Bharucha, Martin C. Fischer, Kirk W. Madison, Patrick R. Morrow, Qian Niu, Bala Sundaram* & Mark G. Raizen

Department of Physics, The University of Texas at Austin, Austin, Texas 78712-1081, USA

An exponential decay law is the universal hallmark of unstable systems and is observed in all fields of science. This law is not, however, fully consistent with quantum mechanics and deviations from exponential decay have been predicted for short as well as long times[1–8]. Such deviations have not hitherto been observed experimentally. Here we present experimental evidence for short-time deviation from exponential decay in a quantum tunnelling experiment. Our system consists of ultra-cold sodium atoms that are trapped in an accelerating periodic optical potential created by a standing wave of light. Atoms can escape the wells by quantum tunnelling, and the number that remain can be measured as a function of interaction time for a fixed value of the well depth and acceleration. We observe that for short times the survival probability is initially constant before developing the characteristics of exponential decay. The conceptual simplicity of the experiment enables a detailed comparison with theoretical predictions.

Cold Na atoms in a optical potential

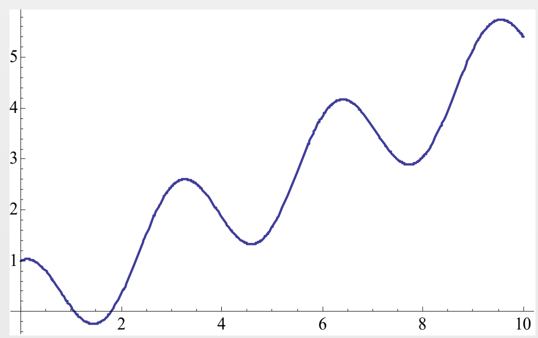
$V(x,0)$



x [a.u.]

$$V(x,t) = V_0 \cos\left(2k_L x - k_L a t^2\right)$$

$U(x')$



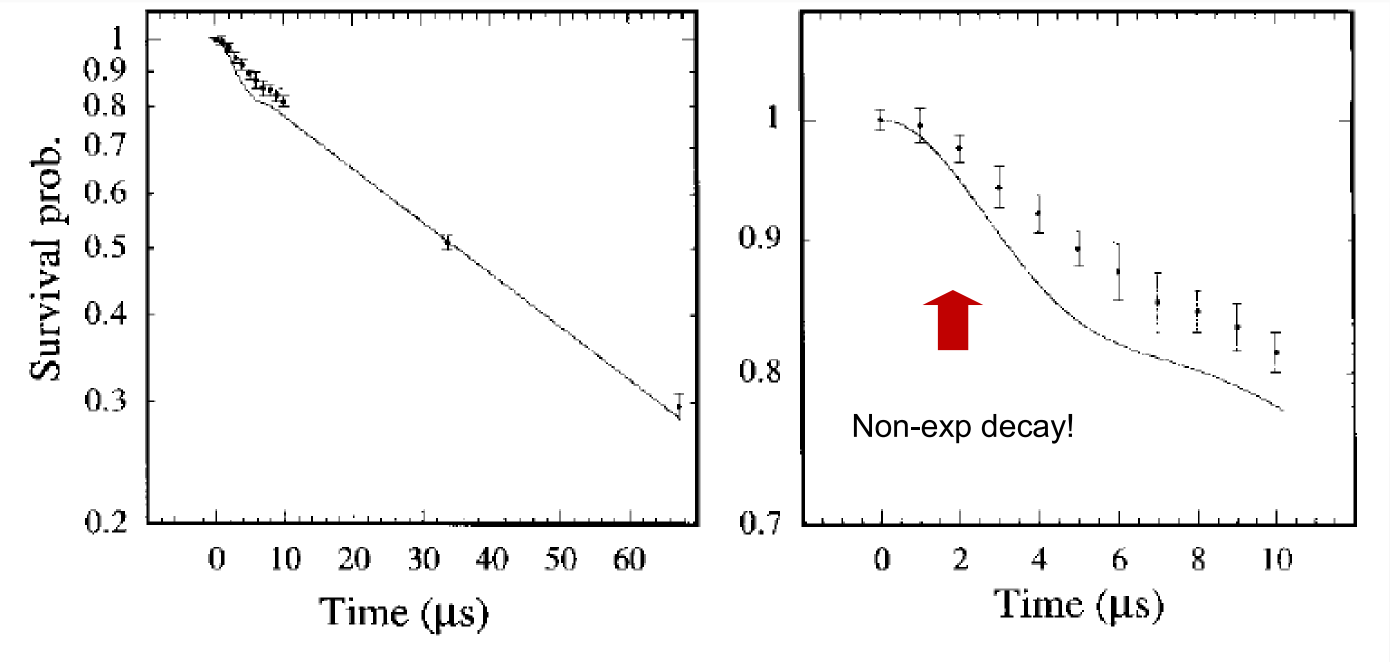
x' [a.u.]

$$x' = x - \frac{1}{2} a t^2$$

$$U(x') = V_0 \cos\left(2k_L x'\right) + Max'$$

Experimental confirmation of non-exponential decays (2)

Measured survival probabilty p(t)



Experimental confirmation of non-exponential decays and Zeno /Anti-Zeno effects

VOLUME 87, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 2001

Observation of the Quantum Zeno and Anti-Zeno Effects in an Unstable System

M. C. Fischer, B. Gutiérrez-Medina, and M. G. Raizen
Department of Physics, The University of Texas at Austin, Austin, Texas 78712-1081
(Received 30 March 2001; published 10 July 2001)

We report the first observation of the quantum Zeno and anti-Zeno effects in an unstable system. Cold sodium atoms are trapped in a far-detuned standing wave of light that is accelerated for a controlled duration. For a large acceleration the atoms can escape the trapping potential via tunneling. Initially the number of trapped atoms shows strong nonexponential decay features, evolving into the characteristic exponential decay behavior. We repeatedly measure the number of atoms remaining trapped during the initial period of nonexponential decay. Depending on the frequency of measurements we observe a decay that is suppressed or enhanced as compared to the unperturbed system.

Same exp. setup,
but with measurements in between

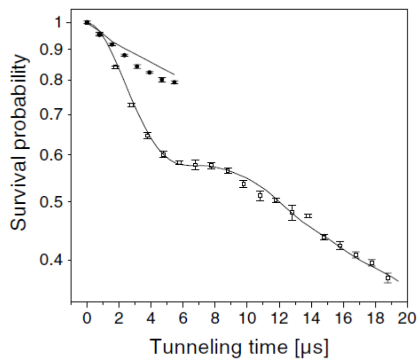


FIG. 3. Probability of survival in the accelerated potential as a function of duration of the tunneling acceleration. The hollow squares show the noninterrupted sequence, and the solid circles show the sequence with interruptions of 50 μs duration every 1 μs. The error bars denote the error of the mean. The data have been normalized to unity at $t_{\mathrm{tunnel}} = 0$ in order to compare with the simulations. The solid lines are quantum mechanical simulations of the experimental sequence with no adjustable parameters. For these data the parameters were $a_{\mathrm{tunnel}} = 15\,000\ \mathrm{m/s^2}$, $a_{\mathrm{interr}} = 2000\ \mathrm{m/s^2}$, $t_{\mathrm{interr}} = 50\ \mu\mathrm{s}$, and $V_0/h = 91$ kHz, where h is Planck's constant.

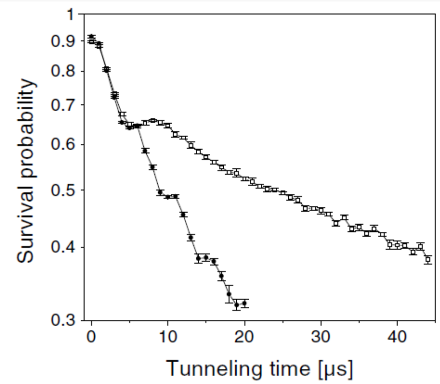


FIG. 4. Survival probability as a function of duration of the tunneling acceleration. The hollow squares show the noninterrupted sequence, and the solid circles show the sequence with interruptions of 40 μs duration every 5 μs. The error bars denote the error of the mean. The experimental data points have been connected by solid lines for clarity. For these data the parameters were: $a_{\mathrm{tunnel}} = 15\,000\ \mathrm{m/s^2}$, $a_{\mathrm{interr}} = 2800\ \mathrm{m/s^2}$, $t_{\mathrm{interr}} = 40\ \mu\mathrm{s}$, and $V_0/h = 116$ kHz.

Zeno effekt

Anti-Zeno effect

Late-time deviations

PRL 96, 163601 (2006) PHYSICAL REVIEW LETTERS week ending 28 APRIL 2006

Violation of the Exponential-Decay Law at Long Times

C. Rothe, S. I. Hintschich, and A. P. Monkman

Department of Physics, University of Durham, Durham, DH1 3LE, United Kingdom

(Received 4 July 2005; published 26 April 2006)

First-principles quantum mechanical calculations show that the exponential-decay law for any metastable state is only an approximation and predict an asymptotically algebraic contribution to the decay for sufficiently long times. In this Letter, we measure the luminescence decays of many dissolved organic materials after pulsed laser excitation over more than 20 lifetimes and obtain the first experimental proof of the turnover into the nonexponential decay regime. As theoretically expected, the strength of the nonexponential contributions scales with the energetic width of the excited state density distribution whereas the slope indicates the broadening mechanism.

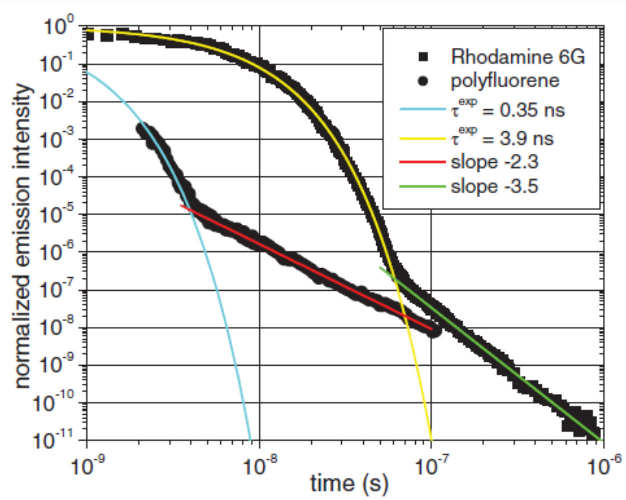


FIG. 2 (color). Corresponding double logarithmic fluorescence decays of the emissions shown in Fig. 1. Exponential and power law regions are indicated by solid lines and the emission intensity at time zero has been normalized.

Confirmation of: L. A. Khalfin. 1957. 1957 (Engl. trans. Zh.Eksp.Teor.Fiz.,33,1371)

Considerations

- No other short- or long-time deviation from the exp. law was seen in unstable states.
- Verification of the two aforementioned works (Reizen + Rothe) would be needed.
- The measurement of deviations in simple natural systems (elementary particles, nuclei, atoms) would be a great achievement.

Part 3: neutron decay anomaly

Neutron decay: exp. methods

- There are two methods to measure the lifetime of neutrons: beam and trap
- Beam: one measures the protons out of a neutron beam
- Trap: one measures the neutrons that survive in a certain neutron trap

Beam method

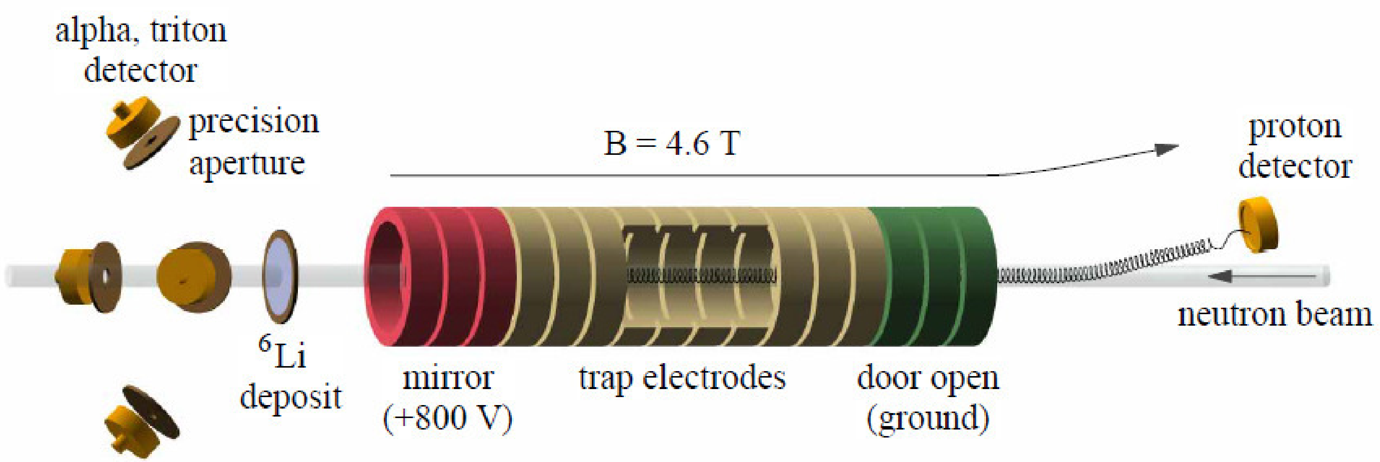


Figure 2. Scheme of the beam neutron lifetime experiment using the Sussex-ILL-NIST method [25]. The neutron beam passes through a segmented quasi-Penning trap. Decay protons are trapped by the elevated door and mirror electrode potentials and counted periodically by lowering the door to ground as shown. Neutrons are counted by detecting the alphas and tritons from the (n, α) reaction in a thin ^{6}LiF deposit.

Beam (or bottle) method

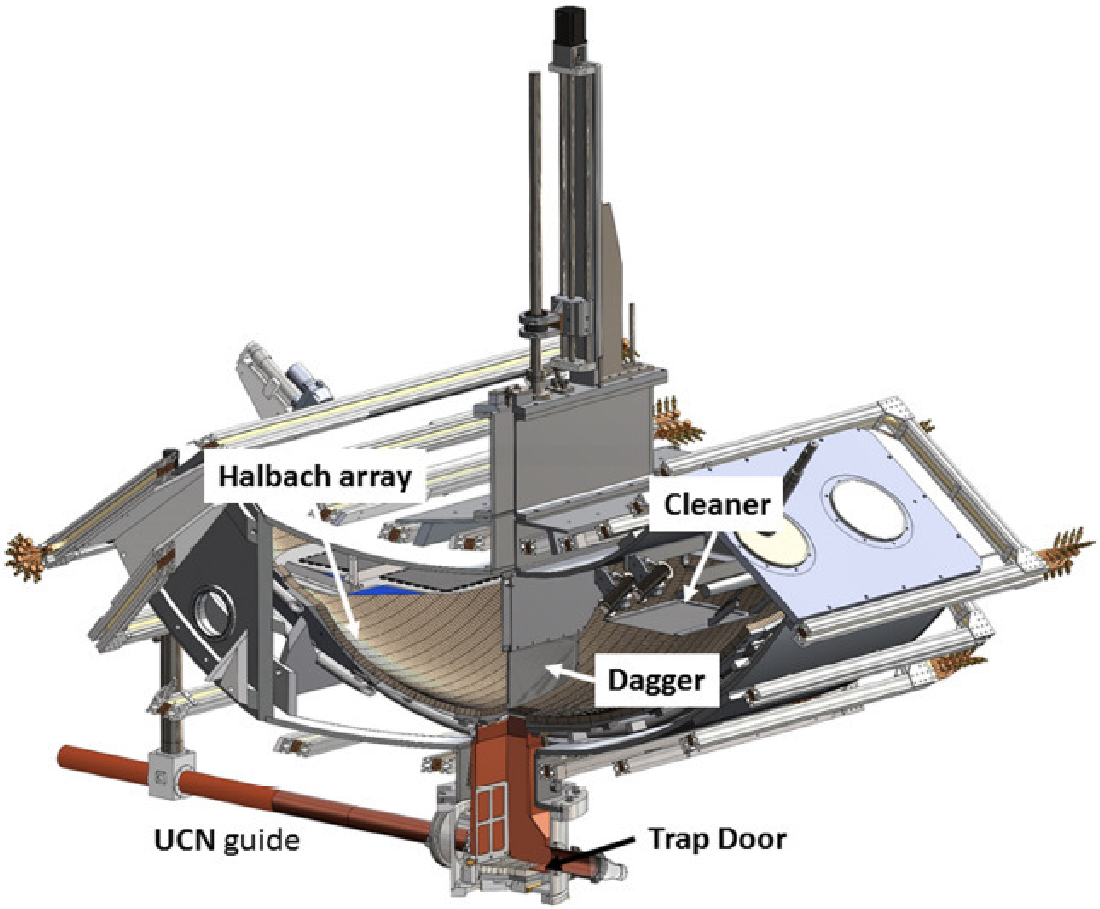


Figure 6. A rendering of the UCNτ apparatus [45,46] showing the Halbach array installed on the walls of the UCN storage vessel, the polyethylene sheet used to clean the initial neutron velocity spectrum, and the insertable in situ neutron scintillation detector (dagger). To fill the vessel, polarized neutrons are admitted via the trap door at the bottom.

Exp. results: beam vs trap/bottle

$$\tau_n^{\mathrm{beam}} = 888.1 \pm 2.0\ \mathrm{s}$$

$$\Delta\tau = \tau_n^{beam} - \tau_n^{trap} = 8.7 \pm 2.1\ \mathrm{s}$$

$$\tau_n^{\mathrm{trap}} = 879.45 \pm 0.58\ \mathrm{s}$$

$$\Gamma_n^{\mathrm{trap}} / \Gamma_n^{\mathrm{beam}} = 1.0098 \pm 0.0024$$

atoms

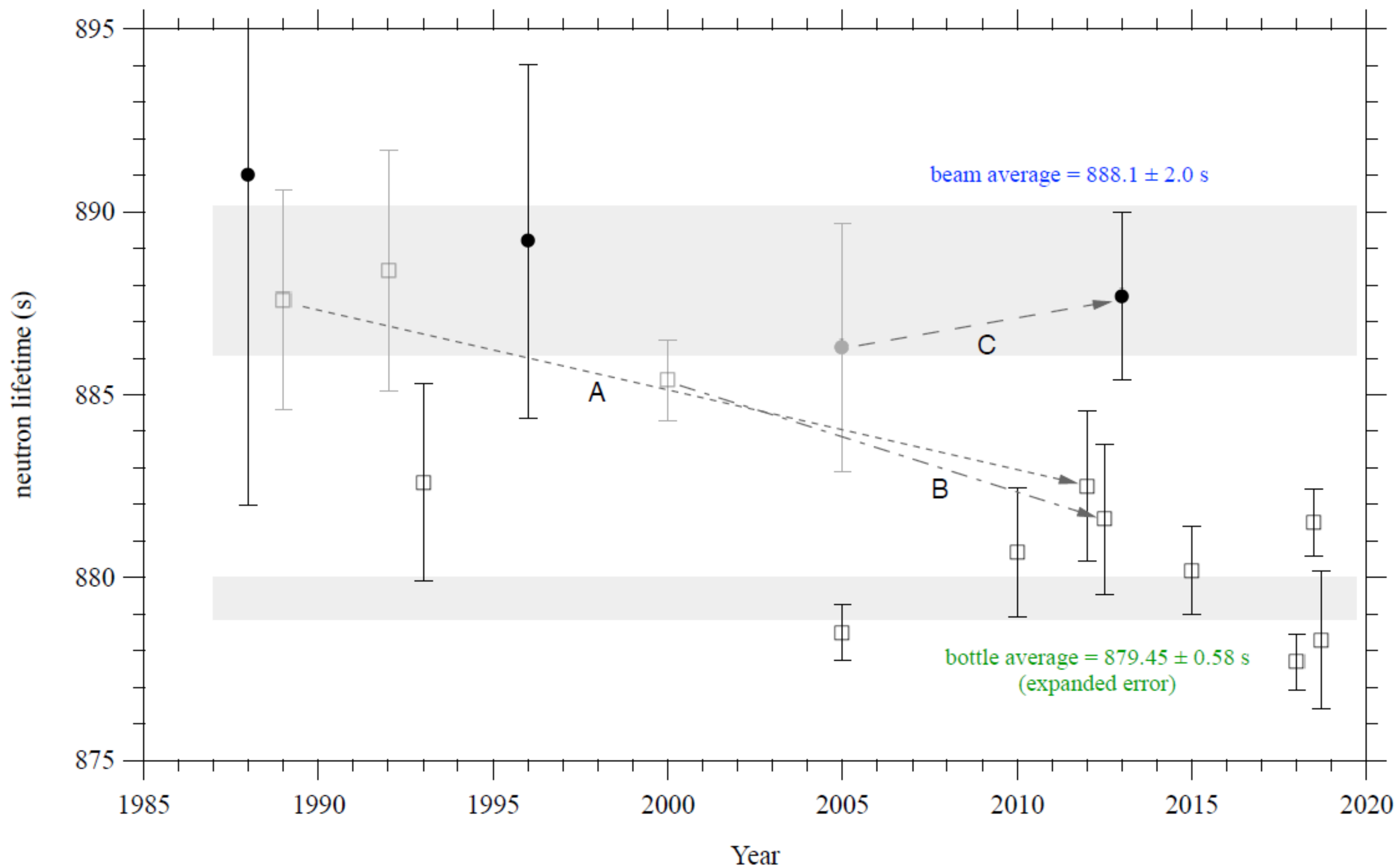
MDPI

Uniwersytet Jana Kochanowskiego w Kielcach

Article

Measurements of the Neutron Lifetime

F. E. Wietfeldt



Hidden decay(s) of the neutron?

the proposal of Fornal and Grinstein

B. Fornal and B. Grinstein, Phys. Rev. Lett. **120**, 191801 (2018), 1801.01124.

The beam experiments shows a larger lifetime because it misses of a BSM decays of the neutron. In particular, decays into a light fermion.

However, the existence of such a light fermion is at odds with bounds from neutron stars, see:

D. McKeen, A. E. Nelson, S. Reddy, and D. Zhou, Phys. Rev. Lett. **121**, 061802 (2018), 1802.08244.
G. Baym, D. H. Beck, P. Geltenbort, and J. Shelton, Phys. Rev. Lett. **121**, 061801 (2018), 1802.08282.
T. F. Motta, P. A. M. Guichon, and A. W. Thomas, J. Phys. **G45**, 05LT01 (2018), 1802.08427.

Standard model calculation (and exp.) on gA

A. Czarnecki, W. J. Marciano and A.Sirlin,
Radiative Corrections to Neutron and Nuclear Beta Decays Revisited,
Phys. Rev. D **100** (2019) no.7, 073008 [arXiv:1907.06737 [hep-ph]].

$$\frac{1}{\tau_n} = \frac{G_\mu^2 \left|V_{ud}\right|^2}{2\pi^3} m_e^5 \left(1 + 3g_A^2\right)(1 + RC) f$$

$$\tau_n^{\mathrm{SM}} \left(1 + 3g_A^2\right) = 5172.0 \pm 1.1 \text{ s.}$$

Using post2002 measurements (including the two most recent ones)

$$g_A = 1.2762(5)$$

$$\tau_n^{\mathrm{SM}} = 878.7 \pm 0.6 \text{ s}$$

Additional references

A. Czarnecki, W. J. Marciano and A. Sirlin,
Neutron Lifetime and Axial Coupling Connection,
Phys. Rev. Lett. **120** (2018) no.20, 202002 [arXiv:1802.01804 [hep-ph]].

D. Dubbers, H. Saul, B. Märkisch, T. Soldner and H.~Abele,
Exotic decay channels are not the cause of the neutron lifetime anomaly,
Phys. Lett. B 791 (2019) 6 [arXiv:1812.00626 [nucl-ex]].

B. Märkisch et al.,
Measurement of the Weak Axial-Vector Coupling Constant in the Decay of Free Neutrons Using a Pulsed Cold Neutron Beam,
Phys. Rev. Lett. **122** (2019) no.24, 24250 [arXiv:1812.04666 [nucl-ex]].

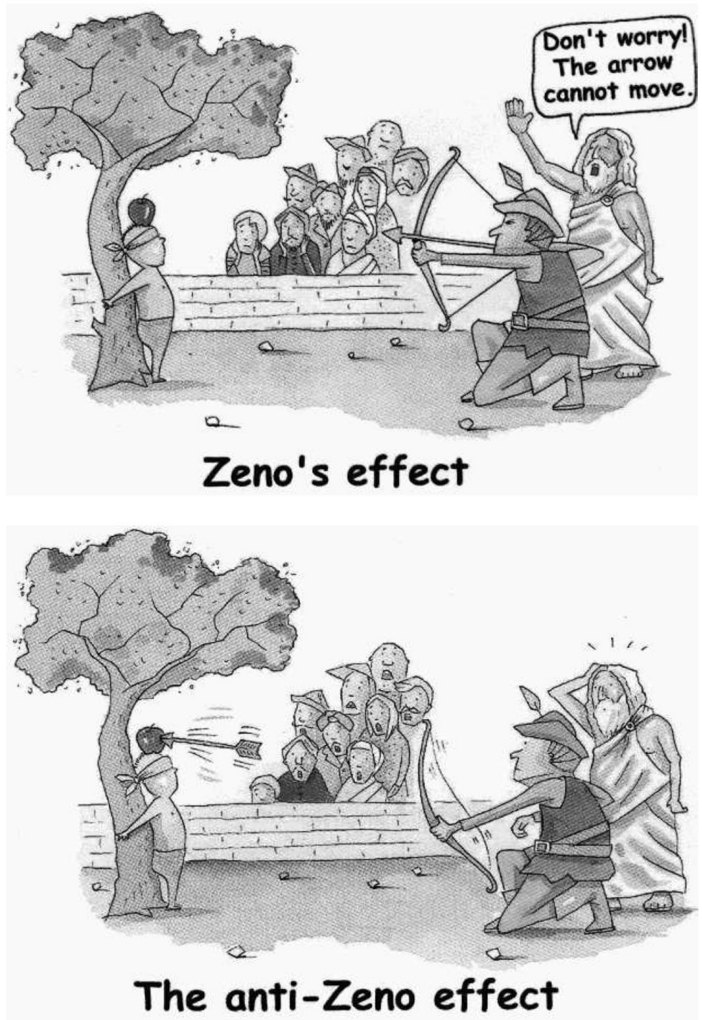
Part 4: IZE and neutron decay

1906.10024

Neutron decay anomaly and inverse quantum Zeno effect

Francesco Giacosa[a,b]* and Giuseppe Pagliara[c]†

IZE as a possible explanation of the neutron decay anomaly



A. Kofman and G. Kurizki, Zeitschrift fr Naturforschung A **56** (2001).

Environment and effective decay width

$$\Gamma_n^{\text{measured}}(\tau) = \int_0^\infty f(\tau,\omega)\Gamma_n(\omega)d\omega$$

Γ(ω) is the decay width, f(τ,ω) the response of the environment

$$\int_0^\infty f(\tau,\omega)d\omega = 1$$

$$f(\tau \to \infty,\omega) = \delta(\omega - \omega_n)$$

$$\Gamma_n^{\text{measured}}(\tau \to \infty) = \Gamma_n^{\text{on-shell}}$$

$$f(\tau \to 0,\omega) = \text{small const}$$

A. Kofman and G. Kurizki, Nature **405**, 546 (2000).
A. Kofman and G. Kurizki, Zeitschrift fr Naturforschung A **56** (2001).
P. Facchi and S. Pascazio, Fortschritte der Physik **49**, 941 (2001).

Two explicit forms of the response function f(τ,ω)

$$f(\tau,\omega) \;=\; \frac{\tau}{2\pi}\frac{\sin^2[(\omega-\omega_n)/2]}{[(\omega-\omega_n)/2]^2}$$

This is for ideal collapses at τ, 2τ, 3τ, ….

$$f(\tau,\omega) = \left[(\omega-\omega_n)^2+\tau^{-2}\right]^{-1}/\pi\tau$$

This is for a continuous measurement

As shown in F.G., Modelling the inverse Zeno effect for the neutron decay,"
APB 51 (2020) 77 [arXiv:1909.01099 [hep-ph]], the differences are negligible.

The case of the neutron

$$\Gamma_n(\omega) = g_n^2 \omega^5 \ \text{ for } \ \omega \lesssim \omega_{\text{on-shell}} + m_\pi$$

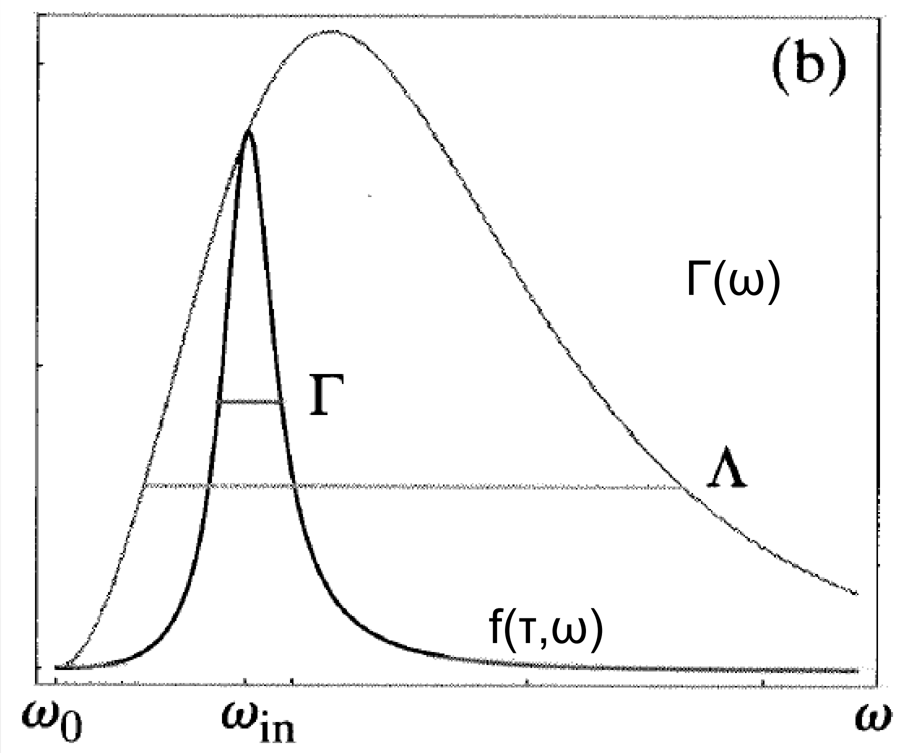
$$g_n \propto g_V V_{ud}$$

$$\Gamma_n^{\text{on-shell}} = \Gamma_n(\omega_n) = g_n^2 \omega_n^5 = \hbar/888.1 \text{ sec}^{-1} = 7.41146 \cdot 10^{-25} \text{ MeV}$$

$$\omega_n = \omega_{\text{on-shell}} = m_n^{\text{on-shell}} - m_p - m_e = 0.782333 \, \text{MeV}$$

Note: for very large ω the decay width function should go to zero

The basic idea



Integral over $\Gamma(\omega)$ and $f(\tau,\omega)$

QUANTUM ZENO EFFECTS WITH "PULSED" AND "CONTINUOUS" MEASUREMENTS

P. Facchi[(1)] and S. Pascazio[(2)]

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TIME'S ARROWS, QUANTUM MEASUREMENT AND SUPERLUMINAL BEHAVIOR

Introducing an upper ‘energy’ for convergence

$$\Gamma_n^{\text{measured}}(\tau,\omega_C)=\int_0^{\omega_C} f(\tau,\omega)\Gamma_n(\omega)d\omega$$

ωC measures the maximal off-shellness of the neutron;
It should be of the order of 1-10 MeV.

$$\boxed{\Gamma_n^{\text{measured}}(\tau,\omega_C)=\Gamma_n^{\text{on-shell}}\left(1+\frac{\hbar}{\tau}\frac{\omega_C^4}{4\pi\omega_n^5}\right)}$$

$$\Gamma_n^{\text{measured}}(\tau,\omega_C)>\Gamma_n^{\text{on-shell}}$$

Discussion

- Beam: how often is the decay determined? Not that often, $\tau=10^{-9}$ s.

- Traps: Here, we have typically a set of 10^8 cold neutrons entangled in a Slater determinant. Measuring one means to collapse them all. $\tau=10^{-17}$ s.

IZE: Beam vs Trap

$$\Gamma_n^{\text{beam}} \simeq \Gamma_n^{\text{measured}}(\tau \sim 10^{-9}\,\text{s}, \omega_C \sim 2\text{-}10\omega_n) \simeq \Gamma_n^{\text{on-shell}}$$

For the beam: exponential on-shell result

$$\Gamma_n^{\text{trap}} \simeq \Gamma_n^{\text{measured}}(\tau \sim 10^{-17}\,\text{s}, \omega_C \sim 2\text{-}10\omega_n) \gtrsim \Gamma_n^{\text{on-shell}}$$

For the trap: possible increase of Γ (IZE)

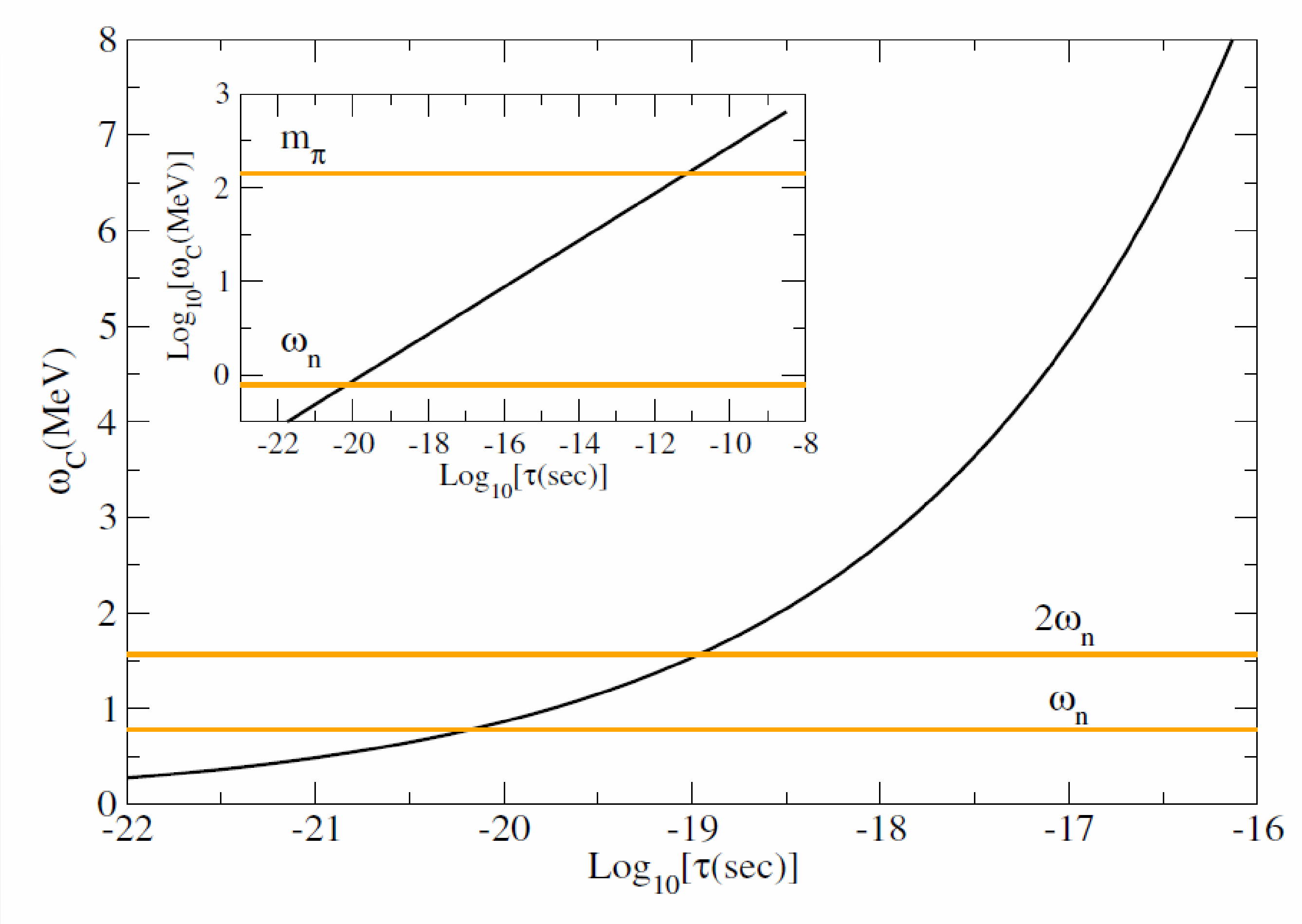
$$\tau \sim 10^{-9} \cdot 10^{-8} = 10^{-17}\ \text{s.}$$

$$\Gamma_n^{\text{trap}} = 1.0098\Gamma_n^{\text{on-shell}} = 1.0098\Gamma_n^{\text{beam}}$$

$$\omega_C = 6.19\omega_n$$

See 1906.10024 for details

ωC vs τ



1906.10024

Discussions

- Assume that the beam experiments are ‘wrong’,
- Then, hard answer: our explanation can be thrown away…
- Yet: even in this case, our work shows that trap experiment are not far from the IZE! So, even if we are not there yet, we could use trap experiments to test the IZE.
- Question of the referee: Can one Zeno the beam exp? No, it does not work!

Conclusions

- QZE and IZE are a well-established part of QM
- The IZE has been presented as a possible solution of the neutron decay anomaly
- Increasing/decreasing of nr of neutrons in the trap may have an influence on the measured values.
- Measuring the protons in trap exps should confirm the smaller decay width (no influence)

Thank You

Lee Hamiltonian

$$H = H_0 + H_1$$

$$H_0 = M_0 \left| S \right\rangle \left\langle S \right| + \int_{-\infty}^{+\infty} dk \omega(k) \left| k \right\rangle \left\langle k \right|$$

$$H_1 = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} dk (g \cdot f(k)) (\left| S \right\rangle \left\langle k \right| + \left| k \right\rangle \left\langle S \right|)$$

|S> is the initial unstable state, coupled to an infinity of final states |k>. (Poincare-time is infinite. Irreversible decay). General approach, similar Hamiltonians used in many areas of Physics.

(Ex: Jaynes-Cummings approach)

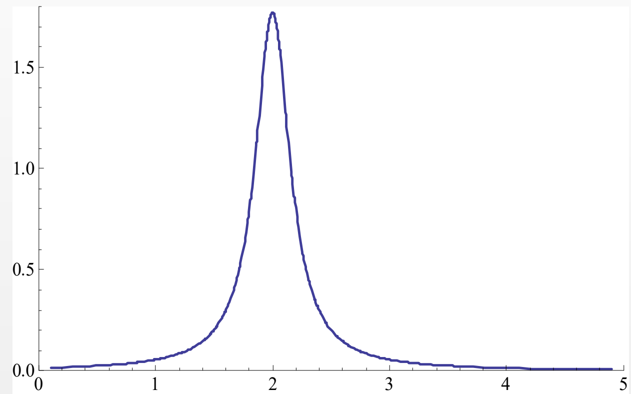
Example/1: spontaneous emission. |S> represents an atom in the excited state, |k> is the ground-state plus photon.

Example/2: pion decay. |S> represents a neutral pion, |k> represents two photons (flying back-to-back)

Exponential limit

$$H = H_0 + H_1 \ ; \ H_0 = M_0 |S\rangle\langle S| + \int_{-\infty}^{+\infty} dk\omega(k) |k\rangle\langle k| \ ; \ H_1 = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} dk(g \cdot f(k))(|S\rangle\langle k| + |k\rangle\langle S|)$$

$$\omega(k) = k \ ; \quad f(k) = 1 \quad \Rightarrow \quad \Pi(E) = ig^2/2 \ ; \ \Gamma = g^2$$



$$d_S(E) = \frac{\Gamma}{2\pi} \frac{1}{(E - M_0)^2 + \Gamma^2/4}$$

$$\Rightarrow a(t) = e^{-i(M_0 - i\Gamma/2)t} \Rightarrow p(t) = e^{-\Gamma t}$$

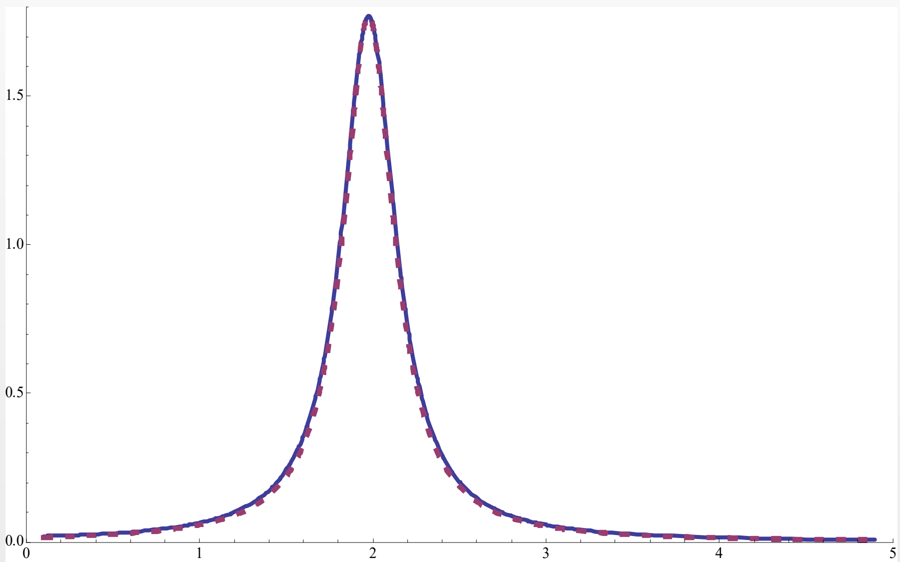
The exponential limit is obtained when the unstable state couples to all the states of the continuum with the same strength

Non-exponential case (1)

$$H_1 = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} dk (g \cdot f(k)) (|S\rangle\langle k| + |k\rangle\langle S|)$$

$$f(k) = \begin{cases} 0 \text{ for } k < E_{min} \\ 1 \text{ for } E_{min} \le k \le E_{max} \\ 0 \text{ for } k > E_{max} \end{cases}$$

$d_S(E)$

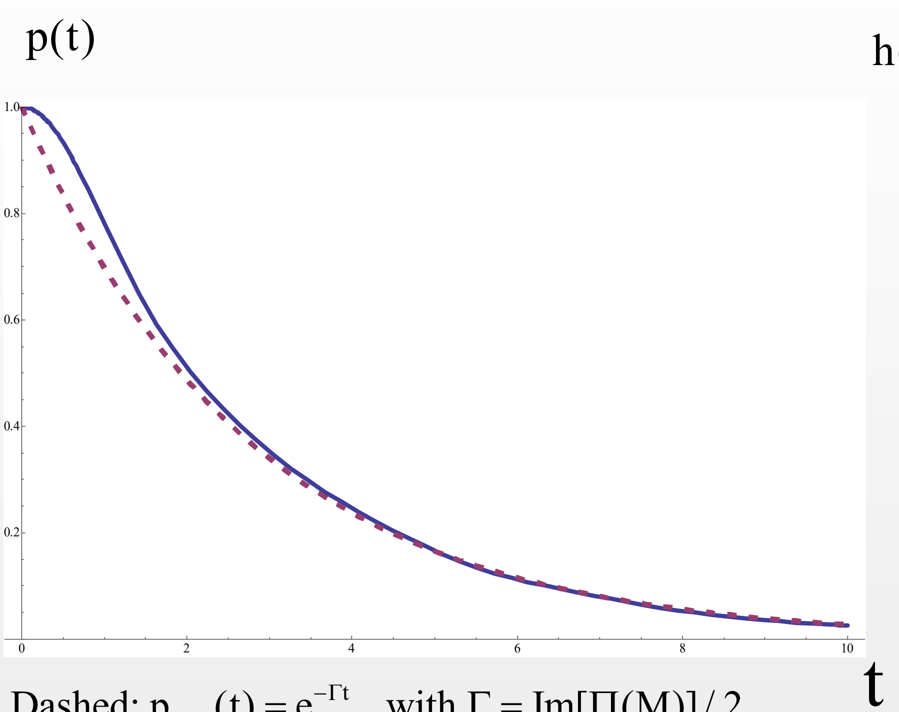


$M_0 = 2;\ E_{min} = 0;\ E_{max} = 5;\ g^2 = 0.36$ (all in a.u. of energy)

E

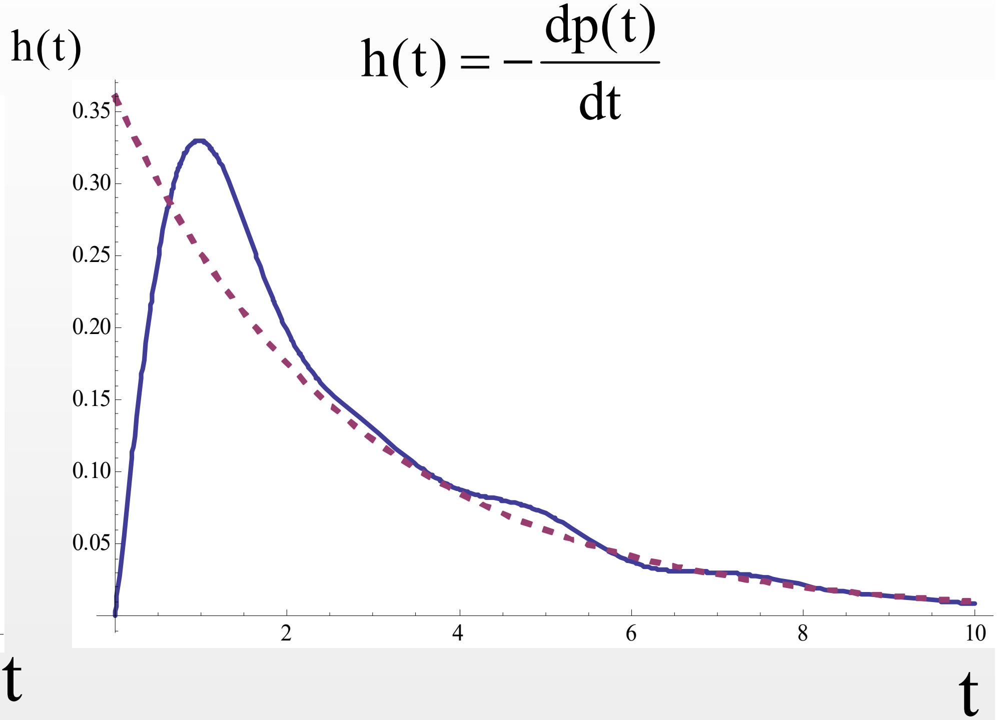
This is what I have said at the beginning of the talk, but now “well done”

Non-exponential case (2)



Dashed: $p_{BW}(t) = e^{-\Gamma t}$ with $\Gamma = \mathrm{Im}[\Pi(M)]/2$

$$h(t) = -\frac{dp(t)}{dt}$$



Dashed: $h_{BW}(t) = \Gamma e^{-\Gamma t}$ with $\Gamma = \mathrm{Im}[\Pi(M)]/2$

$$\int_0^t h(u)du = 1 - p(t)$$

Namley: $h(t)dt = p(t) - p(t+dt)$ is the probability that the particles decays between t and t+dt

Two-channel case (a)

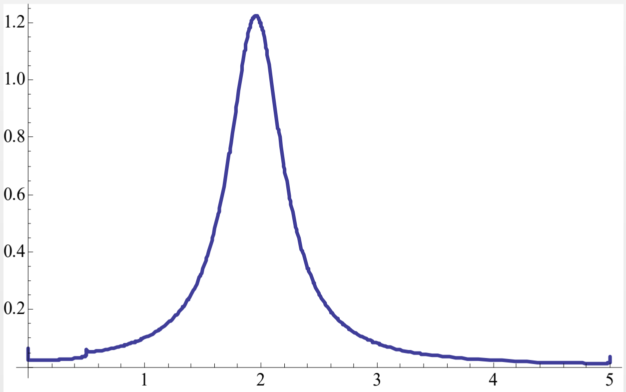
Found Phys (2012) 42:1262–1299
DOI 10.1007/s10701-012-9667-3

Non-exponential Decay in Quantum Field Theory and in Quantum Mechanics: The Case of Two (or More) Decay Channels

Francesco Giacosa

$$H_1 = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} dk (g_1 \cdot f_1(k)) (|S\rangle\langle k,1| + |k,1\rangle\langle S|) + \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} dk (g_2 \cdot f_2(k)) (|S\rangle\langle k,2| + |k,2\rangle\langle S|)$$

$$f_i(k) = \begin{cases} 0 \text{ for } k < E_{i,min} \\ 1 \text{ for } E_{i,min} \leq k \leq E_{i,max} \\ 0 \text{ for } k > E_{i,max} \end{cases}$$



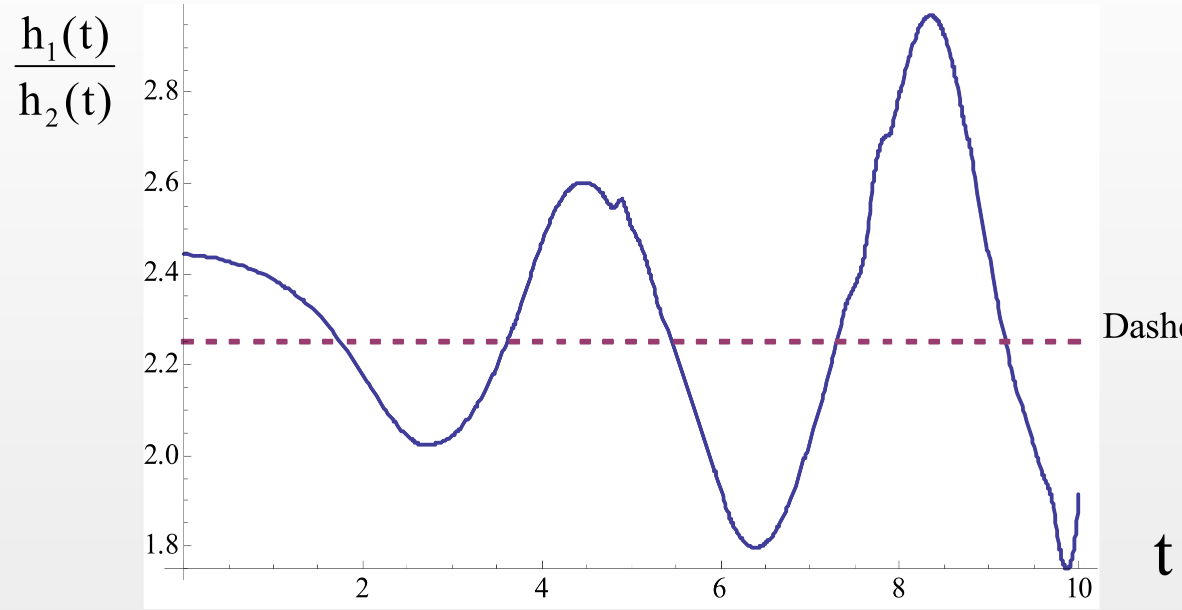
$$M_0 = 2;\ E_{1,min} = 0;\ E_{2,min} = 0\ ;\ E_{1,max} = E_{2,max} = 5;$$

$$g_1^2 = 0.36\ ;\ \ g_2^2 = 0.16 \qquad \text{(all in a.u. of energy)}$$

Two-channel case (b)

$h_1(t)dt =$ probabilty that the state $|S\rangle$ decays in the first channel between (t,t+dt)

$h_2(t)dt =$ probabilty that the state $|S\rangle$ decays in the second channel between (t,t+dt)



Dashed: $\frac{h_{1,BW}(t)}{h_{2,BW}(t)} = \frac{\Gamma_1}{\Gamma_2} = \text{const}$

Measurable effect???

Details in:

F. G., Non-exponential decay in quantum field theory and in quantum mechanics: the case of two (or more) decay channels, Found. Phys. 42 (2012) 1262 [arXiv:1110.5923].

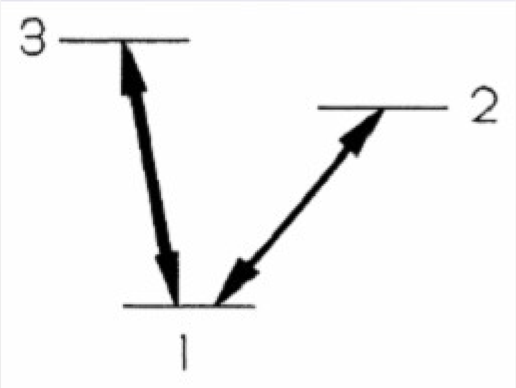
Experimental confirmation of the quantum Zeno effect - Itano et al (1)

PHYSICAL REVIEW A VOLUME 41, NUMBER 5 1 MARCH 1990

Quantum Zeno effect

Wayne M. Itano, D. J. Heinzen, J. J. Bollinger, and D. J. Wineland
Time and Frequency Division, National Institute of Standards and Technology, Boulder, Colorado 80303
(Received 12 October 1989)

The quantum Zeno effect is the inhibition of transitions between quantum states by frequent measurements of the state. The inhibition arises because the measurement causes a collapse (reduction) of the wave function. If the time between measurements is short enough, the wave function usually collapses back to the initial state. We have observed this effect in an rf transition between two $^{9}Be^{+}$ ground-state hyperfine levels. The ions were confined in a Penning trap and laser cooled. Short pulses of light, applied at the same time as the rf field, made the measurements. If an ion was in one state, it scattered a few photons; if it was in the other, it scattered no photons. In the latter case the wave-function collapse was due to a null measurement. Good agreement was found with calculations.



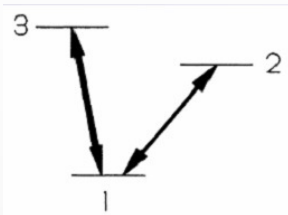
(Undisturbed) survival probability

At $t = 0$, the electron is in $|1\rangle$.

$$p(t) = \cos^2\left(\frac{\Omega t}{2}\right) = 1 - \frac{\Omega^2 t^2}{4} + \ldots$$

$$p(T) = 0 \text{ für } T = \pi/\Omega$$

Experimental confirmation of the quantum Zeno effect - Itano et al (2)



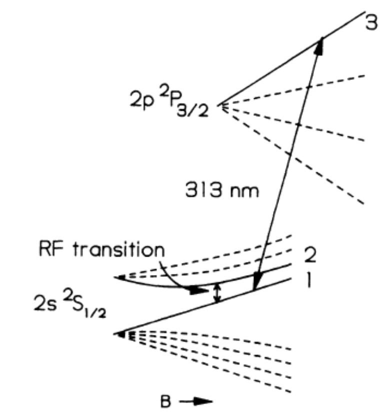


FIG. 2. Diagram of the energy levels of $^9Be^+$ in a magnetic field B. The states labeled 1, 2, and 3 correspond to those in Fig. 1 .

5000 Ions in a Penning trap

Short laser pulses 1-3 work as measurements.

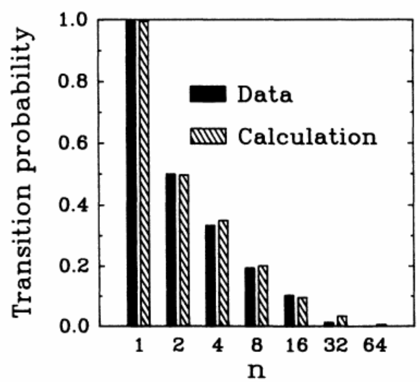


FIG. 3. Graph of the experimental and calculated $1 \rightarrow 2$ transition probabilities as a function of the number of measurement pulses n. The decrease of the transition probabilities with increasing n demonstrates the quantum Zeno effect.

$$p(t) = \cos^2\left(\Omega t/2\right) = 1 - \frac{\Omega^2 t^2}{4} + ... ; \quad p(T) = 0 \text{ für } T = \pi/\Omega$$

(Transition probability (without measuring) at time T) : $1 - p(T) = 1$.

Witn n measurements in between the transition probabilty decreases!
The electron stays in state 1.

Other experiments about Zeno/Streed et al

PRL **97,** 260402 (2006) PHYSICAL REVIEW LETTERS week ending 31 DECEMBER 2006

Continuous and Pulsed Quantum Zeno Effect

Erik W. Streed,[1,2] Jongchul Mun,[1] Micah Boyd,[1] Gretchen K. Campbell,[1] Patrick Medley,[1]
Wolfgang Ketterle,[1] and David E. Pritchard[1]
[1]*Department of Physics, MIT-Harvard Center for Ultracold Atoms, and Research Laboratory of Electronics, MIT, Cambridge, Massachusetts 02139, USA*
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(Received 14 June 2006; published 27 December 2006)

Use of BEC (with Rb). QZE confirmed.

The intensity of a continuous observation of a quantum state is equivalent to a certain t0 (Shulman, PRA 57, 1509 (1997)).

Other experiments about Zeno/Haroche

PRL 101, 180402 (2008) PHYSICAL REVIEW LETTERS week ending 31 OCTOBER 2008

Freezing Coherent Field Growth in a Cavity by the Quantum Zeno Effect

J. Bernu,[1] S. Deléglise,[1] C. Sayrin,[1] S. Kuhr,[1,*] I. Dotsenko,[1,2] M. Brune,[1,+] J. M. Raimond,[1] and S. Haroche[1,2]

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(Received 21 July 2008; published 28 October 2008)

Cavity QED: the nr of photons is frozen.

Another verification of QZE.

Direction QFT.

Other experiments about Zeno/Balzer

N·H
ELSEVIER
1 June 2000
Optics Communications 180 (2000) 115–120
OPTICS COMMUNICATIONS
www.elsevier.com/locate/optcom

The quantum Zeno effect – evolution of an atom impeded by measurement

Chr. Balzer, R. Huesmann, W. Neuhauser, P.E. Toschek *
Institut für Laser-Physik, Universität Hamburg, Jungiusstrasse 9, D-20355 Hamburg, Germany

Received 11 April 2000; accepted 14 April 2000

N·H
ELSEVIER
1 October 2002
Optics Communications 211 (2002) 235–241
OPTICS COMMUNICATIONS
www.elsevier.com/locate/optcom

A relaxationless demonstration of the Quantum Zeno paradox on an individual atom

Chr. Balzer, Th. Hannemann, D. Reiß, Chr. Wunderlich, W. Neuhauser, P.E. Toschek *
Institut für Laser-Physik, Universität Hamburg, D-20355 Hamburg, Germany

Received 3 April 2002; received in revised form 5 July 2002; accepted 2 August 2002

Same setup as Itano et al.(different ions are used, YB instead of Be),

But now the measurement takes place between 3 and 2.

Results in agreement with Itano, but here the QZE is associated by a seires of null-measurements.

Quantum Zeno dynamics, Quantum computations, ...

Uniwersytet
Jana Kochanowskiego w Kielcach

Sudarshan: Seven Science Quests IOP Publishing
Journal of Physics: Conference Series **196** (2009) 012017 doi:10.1088/1742-6596/196/1/012017

Quantum Zeno dynamics and quantum Zeno subspaces

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PRL **108,** 080501 (2012) PHYSICAL REVIEW LETTERS week ending 24 FEBRUARY 2012

Zeno Effect for Quantum Computation and Control

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Quantum Zeno dynamics in atoms and cavities

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Dynamique de Zénon quantique avec des atomes et des cavités

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