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

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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 $t = 0$.

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

Confirmed in countless cases!

- For a single unstable particle:

\[
p(t) = e^{-\Gamma t}
\]

is the survival probability for a single unstable particle created at $t = 0$.
(Intrinsic probability, 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 probability amplitude at \( t > 0 \):
\[
a(t) = \langle S | e^{-iHt} | S \rangle
\]

Survival probability:
\[
p(t) = |a(t)|^2
\]
Deviations from the exp. law at short times

Taylor expansion of the amplitude:

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

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

It follows:

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

where \( \tau_Z = \frac{1}{\sqrt{\langle S | H^2 | S \rangle - \langle S | H | S \rangle^2}} \).

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

\[ p(t) = 1 - t^2/\tau_Z^2 + ... \]

\[ e^{-\Gamma t} = 1 - \Gamma t + ... \]

\( \tau_Z \) is the `Zeno time´.

p(t) decreases quadratically (not linearly); no exp. decay for short times.

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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: 
\[
\int_{-\infty}^{+\infty} d_{S}(E)dE = 1
\]

\[
a(t) = \int_{-\infty}^{+\infty} d_{S}(E)e^{-iEt}dE
\]

In stable limit: 
\[
d_{S}(E) = \delta(E - M) \rightarrow a(t) = e^{-iMt} \rightarrow p(t) = 1
\]
The Breit-Wigner energy distribution cannot be exact.

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

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

2) Mean energy finite: $\langle E \rangle = \int_{E_{\text{min}}}^{+\infty} d_s(E)E dE = \int_{E_{\text{min}}}^{+\infty} d_s(E)E dE < \infty$
A very simple numerical example

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

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

\[ \Gamma_{\text{BW}}, \text{ such that } d_{\text{BW}}(M_0) = d_S(M_0) \]

\[ a(t) = \int_{-\infty}^{\infty} d_S(E) e^{-i\omega t} dE ; \quad p(t) = |a(t)|^2 \]

\[ p_{\text{BW}}(t) = e^{-\Gamma_{\text{BW}} t} \]
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 $T = Nt_0$.

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

under the assumption that $t_0$ is small enough.

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

For large but finite $N$:
$\rightarrow$ slowing down of the decay.
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 probability after a single measurement at time \( T \)
\[ p(T) = e^{-\gamma(T)T} \]

Survival probability after \( N \) measurements:
\[ p(\tau)^N = e^{-\gamma(\tau)\tau^N} = e^{-\gamma(T)T} \quad \text{wenn} \quad \gamma(\tau) < \gamma(T) \quad \text{Zeno effect} \]

For \( \tau \to 0, \gamma(\tau \to 0) \to 0, \ p(\tau)^N \to 1 \)

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

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

A. Degasperis (*) and L. Pozza
*International Centre for Theoretical Physics - Trieste

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

QUANTUM ZENO EFFECTS WITH “PULSED” AND “CONTINUOUS” MEASUREMENTS

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

INTERNATIONAL CONFERENCE
TAQMSB

TIME’S ARROWS, QUANTUM MEASUREMENT AND SUPERLUMINAL BEHAVIOR
Part 2: Experimental evidence of non-exponential decay
Experimental confirmation of non-exponential decays (1)

Cold Na atoms in a optical potential

\[ V(x,0) = V_0 \cos(2k_L x - k_L at^2) \]

\[ U(x') = V_0 \cos(2k_L x') + Max' \]

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Experimental confirmation of non-exponential decays (2)

Measured survival probability $p(t)$

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

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(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.

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 \( t_{\text{tunnel}} = 0 \) 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 \( a_{\text{tunnel}} = 15,000 \text{ m/s}^2 \), \( a_{\text{int}} = 2000 \text{ m/s}^2 \), \( t_{\text{tunnel}} = 50 \mu s \), and \( V_0/h = 91 \text{ kHz} \), 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: \( a_{\text{tunnel}} = 15,000 \text{ m/s}^2 \), \( a_{\text{int}} = 2800 \text{ m/s}^2 \), \( t_{\text{int}} = 40 \mu s \), and \( V_0/h = 116 \text{ kHz} \).
Late-time deviations

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
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 \( (n, a) \) reaction in a thin \(^6\text{LiF}\) 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.

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Exp. results: beam vs trap/bottle

\[ \tau_n^{\text{beam}} = 888.1 \pm 2.0 \text{ s} \]

\[ \tau_n^{\text{trap}} = 879.45 \pm 0.58 \text{ s} \]

\[ \Delta \tau = \tau_n^{\text{beam}} - \tau_n^{\text{trap}} = 8.7 \pm 2.1 \text{ s} \]

\[ \Gamma_n^{\text{trap}} / \Gamma_n^{\text{beam}} = 1.0098 \pm 0.0024 \]
Measurements of the Neutron Lifetime

F. E. Wietfeldt

beam average = 888.1 ± 2.0 s

bottle average = 879.45 ± 0.58 s (expanded error)
Hidden decay(s) of the neutron?

the proposal of Fornal and Grinstein


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:

Standard model calculation (and exp.) on gA

A. Czarnecki, W. J. Marciano and A. Sirlin,
Radiative Corrections to Neutron and Nuclear Beta Decays Revisited,

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

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

Using post2002 measurements (including the two most recent ones)

\[
g_A = 1.2762(5)
\]

\[
\tau_n^{SM} = 878.7 \pm 0.6 \text{ s}
\]

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Additional references

A. Czarnecki, W. J. Marciano and A. Sirlin,
Neutron Lifetime and Axial Coupling Connection,

D. Dubbers, H. Saul, B. Märkisch, T. Soldner and H.~Abele,
Exotic decay channels are not the cause of the neutron lifetime anomaly,

B. Märkisch et al.,
Measurement of the Weak Axial-Vector Coupling Constant in the Decay of
Free Neutrons Using a Pulsed Cold Neutron Beam,
Part 4: IZE and neutron decay
1906.10024

Neutron decay anomaly and inverse quantum Zeno effect

Francesco Giacosa\textsuperscript{(a,b)*} and Giuseppe Pagliara\textsuperscript{(c)†}

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IZE as a possible explanation of the neutron decay anomaly

Environment and effective decay width

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

\( \Gamma(\omega) \) is the decay width, \( f(\tau, \omega) \) the response of the environment

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

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

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

Two explicit forms of the response function $f(\tau, \omega)$

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

This is for ideal collapses at $\tau, 2\tau, 3\tau, \ldots$

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

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

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

\[ g_n \propto g_V V_{ud} \]

\[ \Gamma_{n}^{\text{on-shell}} = \Gamma_n(\omega_n) = g_n^2\omega_n^5 = \hbar/888.1 \text{ sec}^{-1} = 7.41146 \times 10^{-25} \text{ MeV} \]

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

**Note:** for very large \( \omega \) the decay width function should go to zero

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The basic idea

Integral over $\Gamma(\omega)$ and $f(\tau,\omega)$
Introducing an upper ‘energy’ for convergence

\[ \Gamma^\text{measured}_n(\tau, \omega_C) = \int_0^{\omega_C} f(\tau, \omega) \Gamma_n(\omega) d\omega \]

\[ \omega_C \] measures the maximal off-shellness of the neutron; it should be of the order of 1-10 MeV.

\[ \Gamma^\text{measured}_n(\tau, \omega_C) = \Gamma^\text{on-shell}_n \left(1 + \frac{\hbar}{\tau} \frac{\omega_C^4}{4\pi \omega_n^5}\right) \]

\[ \Gamma^\text{measured}_n(\tau, \omega_C) > \Gamma^\text{on-shell}_n \]
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

For the beam: exponential on-shell result

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

For the trap: possible increase of $\Gamma$ (IZE)

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

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

$$\omega_C = 6.19\omega_n$$

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

See 1906.10024 for details
$\omega_C$ vs $\tau$

1906.10024

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Discussion

- 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

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

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

(Ex: Jaynes-Cummings approach)

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

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

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

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

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

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

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)

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

where

\[ f(k) = \begin{cases} 
0 & \text{for } k < E_{\text{min}} \\
1 & \text{for } E_{\text{min}} \leq k \leq E_{\text{max}} \\
0 & \text{for } k > E_{\text{max}}
\end{cases} \]

This is what I have said at the beginning of the talk, but now “well done”
Non-exponential case (2)

\[ dp(t) = -h(t) \, dt \]

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

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

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

\[ \int_0^t h(u) \, du = 1 - p(t) \]

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)

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

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

\[ f_1(k) = \begin{cases} 
0 & \text{for } k < E_{i,\text{min}} \\
1 & \text{for } E_{i,\text{min}} \leq k \leq E_{i,\text{max}} \\
0 & \text{for } k > E_{i,\text{max}} 
\end{cases} \]

\[ M_0 = 2; \ E_{1,\text{min}} = 0; \ E_{2,\text{min}} = 0; \ E_{1,\text{max}} = E_{2,\text{max}} = 5; \]

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

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Two-channel case (b)

\[ h_1(t)dt = \text{probability that the state } |S\rangle \text{ decays in the first channel between } (t, t+dt) \]
\[ h_2(t)dt = \text{probability that the state } |S\rangle \text{ decays in the second channel between } (t, t+dt) \]

\[ \frac{h_1(t)}{h_2(t)} \]

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

Measurable effect???

Details in:

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

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 $|1\rangle$.

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

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

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

5000 Ions in a Penning trap

Short laser pulses 1-3 work as measurements.

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

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

With \( n \) measurements in between the transition probability decreases!
The electron stays in state 1.

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Other experiments about Zeno/Streed et al

Use of BEC (with Rb). QZE confirmed.

The intensity of a continuous observation of a quantum state is equivalent to a certain $t_0$ (Shulman, PRA 57, 1509 (1997)).
Other experiments about Zeno/Haroche

Cavity QED: the nr of photons is frozen.

Another verification of QZE.

Direction QFT.
Other experiments about Zeno/Balzer

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 series of null-measurements.
Quantum Zeno dynamics, Quantum computations, ...

Quantum Zeno dynamics and quantum Zeno subspaces

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Zeno Effect for Quantum Computation and Control

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