Does an onlooker stop an evolving quantum system?

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Abstract. The evolution of quantum mechanics has followed the critical analysis of “gedanken” experiments. Many of these concrete speculations can become implemented today in the laboratory – thanks to now available techniques. A key experiment is concerned with the time evolution of a quantum system under repeated or continuing observation. Here, three problems overlap: 1. The microphysical measurement by a macroscopic device, 2. the system’s temporal evolution, and 3. the emergence of macroscopic reality out of the microcosmos.

A well-known calculation shows the evolution of a quantum system being slowed down, or even obstructed, when the system is merely observed. An experiment designed to demonstrate this “quantum Zeno effect” and performed in the late eighties on an ensemble of identical atomic ions confirmed its quantum description, but turned out inconclusive with respect to the very origin of the impediment of evolution.

During the past years, experiments on individual electrodynamically stored and laser-cooled ions have been performed that unequivocally demonstrate the observed system’s quantum evolution being impeded. Strategy and results exclude any physical reaction on the measured object, but reveal the effect of the gain of information as put forward by the particular correlation of the ion state with the detected signal. They shed light on the process of measurement as well as on the quantum evolution and allow an epistemological interpretation.

1. “Gedanken” experiments and quantum measurement
The exceedingly successful modelling of the microscopic world by quantum mechanics has been achieved on the expense of non-intuitive peculiarities that are associated with this description. In spite of this dilemma – or, perhaps, because of it – the historic evolution of quantum mechanics has proceeded in step with the critical analysis of ”gedanken” experiments. At the very heart of these concrete speculations resided Erwin Schrödinger’s concept of ”entanglement”: the non-separability of the wave function of a composite system that quantitatively models this system. To a large extent, the debate encircled the problem of knowing what can be known in principle, and what not – which is, after all, the fundamental epistemological problem. A particularly acute embodiment is the plot of Einstein, Podolsky, and Rosen [1], in the version of David Bohm [2], which has the inevitable consequence: Of a bipartite quantum system with zero total spin, that is, being in the singlet state, let only one part be detected, and its spin component in an arbitrary direction be measured. Then, the result of this measurement determines the corresponding component of the remote other part - irrespective of the selected direction and of the distance!

Einstein commented on this consequence which points to the intrinsic non-locality of quantum mechanics: ”...it is spooky action on a distance...”

Another kind of entanglement refers to different features of an individual atomic particle, say, to its internal and external degrees of freedom. Such a concept was inaccessible to experimental scrutiny at
Einstein’s time. The very idea of experimenting with single atoms has been ridiculed by Schrödinger even in 1952 as a proposal of “…raising ichthyosauria in the zoo…” [3]. But today this idea does no longer remain the mere basis of lofty gedanken experiments. Rather the basis is solid experimentation, since we have learnt, more than 25 years ago, how to manipulate individual atomic particles [4-6]. That this concept seems less “spooky” to us is only because the distance of the electron from the vibrating centre of mass is so small on a human scale.

There is another consideration of entanglement needed in the attempt of unravelling an actual observation that is claimed to be a “measurement”: namely, when we have to include in the analysis the detector apparatus, or “meter”. Let us assume, in another gedanken experiment, an atom being prepared in a superposition of its ground state and a metastable state. One of these eigenstates, say, the ground state, may become identified by excitation and detection of light scattering on a resonance line: Presence or absence of scattered light makes the atom appear in this “bright” ground state or in the “dark” excited metastable state, respectively, depending on the scattered-light signal recorded by the detector found “on”, or “off”. This is a prototype of what John von Neumann had labelled “state reduction” by a measurement [7]. It was sometimes considered a transmogrification of the measured system caused by the reaction of the meter on the atom, as suggested in Heisenberg’s scheme of microscopically detecting a diffracted electron [8] – which is still another gedanken experiment! Repeated observations of the prepared atom’s state via probing by scattered light will provide us with a string of “on” or “off” results that recalls a “random telegraph” signal. Its statistics certainly will obey the laws of quantum mechanics [9], although the particular, individual trajectory of the data is unpredictable.

Here, obviously, three problems overlap each other: 1. The temporal evolution of a quantum-mechanical system, 2. the measurement on such a micro-physical system, and 3. the emergence of the classical world out of the quantum micro-cosmos. Attempts of tackling these problems are therefore supposed to benefit from deeper analysing the scenario of an evolving quantum system under repeated or continued measurement, and from an experimental embodiment.

2. Evolution frustrated by observation?

Substantial obstacles thwart addressing a quantum system on a fundamental level: The control of all degrees of freedom of a quantum object is hard to achieve. Moreover, any measurement requires the interaction of quantum object and classical meter, and the object is supposed to suffer intolerable back action. However, there is a loophole based on “indirect null-result” measurements [10]. In addition and fortunately enough, there are predictions, stated more than half a century ago, that may be matched with the results of measurements on a well-isolated and available type of microphysical system. A very counterintuitive prediction proclaims: The evolution of a measured quantum system becomes slowed down, or, in the extreme, is even completely frustrated [11,12]. This prediction, the “quantum Zeno effect” (QZE) [13], has evoked a wealth of theoretical work [14] but very little, and highly controversial experimental evidence.

A macroscopic and even completely classical experiment seems to demonstrate the structure of what has been considered the Zeno effect: While linearly polarised light propagates in an optically active medium, the concomitant variation of light polarisation turns out impeded by the insertion of analysers [15,16]. A simple implementation is the following one (Fig. 1): The polarisation of a light beam, set by polariser $P_0$ and probed at distance $L$ by analyser $P_1$, is found rotated by the angle $\theta$. Another analyser $P_2$ inserted at $L/2$ with its direction of transmitted field parallel to $P_2$ leaves the light polarisation at $P_1$ rotated by $\theta/2$ only. Insertion of $n - 1$ of such analysers separated by $L/n$ yields, at the position of $P_1$, the total rotation $\theta/n$. With $n$ growing larger, the rotation measured at $P_1$ tends to zero, and the original polarisation $P_0$ shows up. The loss of amplitude from the repetitive projection of the rotated light polarisation on the direction $P_0$ does not invalidate this result: Since the loss per inserted analyser is $(\theta/n)^2$, the total loss is $\theta^2/n$ and vanishes with the rotation.

For a discussion of this scheme, the polarisation of a light beam may be represented by a vector in a three-dimensional configuration space whose symmetry group is SO(3). The apices of all possible
A light beam of polarization $P_0$ propagates through a polarization-rotating medium. After path length $L$, the polarization is $P_1$, rotated by the angle $\theta$. With a second analyser ($P_2 \parallel P_0$) inserted at $L/2$, the final rotation is $\theta/2$. With $n-1$ analysers (all $\parallel P_0$) inserted at distances $L/n$, the final rotational angle at $P_1$ approaches zero for $n \to \infty$.

Polarization vectors fill the unit sphere, the "Poincaré sphere", whose north and south pole may be chosen as locations of the two eigenstates of linear polarization, horizontal and vertical (Fig. 2). States of complete polarization are placed on the surface, and a transformation of a state corresponds to a rotation of the state vector. In particular, the rotation of linear light polarization corresponds to the rotation of the state vector along a particular meridian whose plane stands vertically on the plane of the figure. Each increment of propagation along the pathlength $L/n$ turns the state vector by a finite angle $\theta/n$, but the subsequent transit through the next analyser sets it back. Thus, in the large-$n$ limit, the state vector is left unaltered.

Although this concept seems convincing, letting it pass as a model of the genuine quantum Zeno effect...
is questionable: Although an analyser plate is required for measuring the polarisation of light, its mere insertion into a beam may not qualify as a measurement. The inhibition of polarisation may be ascribed, instead, to the filtering action of the set of analysers – not to measurements, understood as acts of gaining information. Moreover, any result of this classical experiment, that a nineteenth-century physicist could have recognized, is deterministic, since every real measurement on the light polarisation repeated again and again at anyone particular stage of light propagation leads to the same result – within the boundaries set by the standard deviation around the average value. The results are not random, as are the results of measurements on an individual quantum system in a superposition state. This latter restriction does not apply, however, when this experiment makes use of light at the single-photon level.

3. Observation on a driven quantum system

It seems that a better suited approach should make use of a series of actual measurements on an evolving material quantum system. In fact, two-level atoms, equivalent to spin systems, show a formal analogy with light polarisation. Whereas the configuration space of polarisation transforms according to symmetry group SO(3), the symmetry of spin transformation is SU(2), which is a double covering of SO(3), and locally isomorphic with the latter one [17]. Thus, similar visualisations of the dynamics of both systems apply.

In an ensemble of two-level atoms, all of them may be initially prepared in state 0, and driven by a long pulse of radiation resonant with the transition \(0 \rightarrow 1\). When we neglect relaxation, for simplicity, the excitation probability for each atom is

\[
P_{01}(1) = \sin^2(\theta/2),
\]

where the "pulse area" is \(\theta = \Omega \tau\), the pulse duration is \(\tau\), and the Rabi frequency \(\Omega\) of the driving field varies as the field amplitude at the atomic location [18]. At \(\theta = \Omega T = \pi\), all atoms are supposed to be found, after the driving pulse, in state 1 with certainty. Simultaneous irradiation of the ensemble by \(n\) short pulses of "probe" light tuned to a neighbouring resonance line has been considered to interrupt the atoms’ coherent evolution, and to make this evolution disintegrate into intervals of length \(\tau = T/n\) [19]. Then, the final probability of having excited one of the atoms during anyone of these \(n\) intervals is

\[
P_{01}(n) \cong n(\Omega \tau/2)^2 = \pi^2/4n,
\]

which vanishes in the large-\(n\) limit. Recording the amount of scattered light generated by the last probe pulse allows one to measure the chance of finally finding the atoms in state 1, i.e. the net transition probability

\[
P_{01}(n) = \frac{1}{2} \left[1 - \cos^n(\pi/n)\right] \xrightarrow{n \to \infty} 0
\]
Along this line, an interesting experiment has been performed on the ground-state hyperfine transition of an ensemble of 5000 beryllium ions in an electromagnetic ion trap [20] (Fig. 3). The results of this experiment showed complete agreement with the predictions of quantum mechanics as expressed by eqs. (1) through (3), and this agreement was considered a proof of the QZE.

During the nineties, more and more points of criticism had been raised against the outlined interpretation of this experiment. Arguments that related either acceptance or refusal of the interpretation to the applicability of the postulate of state reduction have been shown irrelevant [21]. However, more disquieting questions have remained controversial:

1. Recording the net probability of finally finding the ions in their excited state 1 was said neither to establish the intermediate probe interactions as measurements, nor to reveal the transition probability: individual transitions, back and forth, may compensate each other and finally leave detectable, at best, the probability of retrieval in the ground or excited state [22].

2. The obstruction of the ion’s evolution was said comprehensible, at least in principle, in terms of physical reaction of the apparatus on the ion ensemble, and as such not being too surprising. Only the non-local correlation of system and meter, and a null result of the detection, however, would exclude dynamical coupling and qualify as back-action-free measurement. Such a procedure would prove the obstruction of the evolution by measurement, that is, by gain of information, and would establish a real QZE, or ”quantum Zeno paradox” (QZP) [21].

3. Moreover, a measurement on an ensemble of quantum systems does not indicate increased surivial in the initial state. Also, it seems fundamentally unable to discriminate a potentially non-local effect of such a measurement from physical actions of neighbours, environment, or of the measuring device, as by the recoil of light on the members of the ensemble [23,24].

The last argument is based on an essential of the quantum description: In a measurement, an ensemble reveals an expectation value that allows the observer to learn about an average value of the observable, that characterises the ”macro-state” of the system. Any measurement on an individual system, however, yields an eigenvalue, and repeated observations provide a string of information on this system that defines a ”micro-state” of the ensemble of the repeated measurements. The particular features of measurements on individual quantum systems have been recognized as prerequisite for various applications, as time-keeping, quantum information processing, and cryptography (s. Table 1).

For the unequivocal demonstration of the ”real” QZE, it seems indispensable to address a single quantum system. Let us examine in more detail how incomplete information from an ensemble disqualifies an attempted proof.

### Table 1. Preparation and addressing of an ensemble and an individual quantum system

| quantity: expectation value $\langle \hat{O} \rangle$ | perturbation: interaction with neighbours | observed: macro state, average | result: deterministic |
|-----------------------------------------------|-----------------------------------------|-----------------------------|---------------------|
| eigenvalue $O_i$                               | no                                      | micro state                | stochastic           |

| application | frequency standard | quantum information processing | cryptography |
|-------------|-------------------|-------------------------------|--------------|
|             |                   |                               |              |
The quantum states admissible by a two-level atom, and by a corresponding ensemble, may be visualised in the configuration space of SU(2) symmetry, as well as what these objects reveal to their observer. The states of a two-level system [18,25] are placed on the surface of the doubly covered unit sphere, the Bloch sphere. On the other hand, an ensemble’s Bloch vector can describe mixed states located in the interior of the Bloch sphere. A measurement of the excitation of an ensemble yields an expectation value that corresponds to a particular energy of excitation. This value is deterministic save the small variation on the order of its standard deviation - the ”projection noise” [26]. The measured value corresponds to a great variety of near-degenerate quantum states, and the actually prepared state cannot be identified from this result. Moreover, the coherent driving should have generated a pure superposition state, but uncontrolled decoherence may have left over a mixed state.

In contrast, a single two-level system is necessarily prepared in a pure state. The result of a measurement on this system is random, within the boundaries required by the actual composition of the state, which is determined by the mixing angle $\theta$. However, repeated measurements on the identically prepared system allow the observer to identify $\theta$.

A string of measurements, each of them including reiterated driving the system by pulses of radiation, subsequent probing, and recording scattered probe light, yields a trajectory of results that represents the history of the system’s evolution. Any such sequence of results on a single system in the time domain, a particular trajectory, corresponds to a ”micro-state” in an ensemble of systems. Whereas the ensemble’s micro-state is inaccessible by measurement, the single system’s trajectory may become documented. But only the fully documented evolution of the state complies with the requirements for a valid demonstration of the QZE, since neither non-locality nor the absence of any physical reaction could be warranted otherwise. In short, ”... the essence of the quantum Zeno effect is that it is a nonlocal negative-result effect between a microscopic system and a macroscopically separated macroscopic measuring device...” [21]. These requirements call for the demonstration of QZE on an individual quantum system.

Finally, the complete documentation of the quantum system’s evolution entails recording the data acquired along each trajectory. Detection of the scattered light in each cycle of probing allows the observer to identify the results of the probing and to distinguish intermediary signals from null signals. On the other hand, recording only the final result after a series of cycles lacks the complete control necessary for the identification and acceptance of a true null-result measurement.

These preconditions determine a strategy that allows to unequivocally demonstrate the obstruction of a quantum system’s evolution as being caused by the reiterated acts of measurement.

4. Measurement on single ions

It is well known how individual atomic ions are singled out, confined in vacuo, and cooled as well as controlled by laser light [6,27-30]. Recently, preparation of individual quantum systems has been achieved with neutral atoms and molecules [31-33]. Ions may be stored in a superposition of a homogeneous magnetic field and an electrostatic quadrupole field, the ”Penning” ion trap [34], or in an ac electric quadrupole field, the electrodynamic, or ”Paul” ion trap [35]. The quadrupole field of a Paul trap is generated inside a ring electrode of 1mm diameter on whose axis of symmetry (z) are placed two grounded cap electrodes facing each other. The ring is loaded by ac voltage of, say, 1kV and 20MHz frequency. At any instant of time, a saddle potential extends across any plane $(r,z)$ containing the trap axis with the caps. The direction of the saddle switches back and forth, at the ac frequency, between the $r$- and $z$-directions. Averaging over many ac periods yields a net dc potential well, on the order of 1V deep, that derives from the ”ponderomotive” electric force. An ion is generated inside the trap volume by impact of an evaporated atom with an electron from a small electron gun. It is retained in this potential well and moves harmonically at about 1MHz vibrational frequency. In addition, it is driven far off resonance at the ac frequency, with its excitation growing in proportion to its distance from the trap centre, and to the ac amplitude. Since the ac field vanishes at the point of symmetry, a single ion at the trap centre is free of this ”micro-motion”. The ion approaches this location when its ”secular” motion in the potential well is laser-cooled [4,5], and by application of small auxiliary dc voltages to the caps. Fig. 4 shows a single
trapped and cooled barium ion \(^{(138}\text{Ba}^+)\) in the light of its 492nm resonance fluorescence, recorded by a CCD camera. The ion may be transferred, either by means of additional laser light from its ground level, or by spontaneous decay from a resonance level, into a metastable state, here \(^2D_{5/2}\). Such an event is signaled by extinction of the resonance fluorescence [36,37]. In fact, another ion being "dark" resided at the location imaged on the lower right part of the Figure. This ion decayed to the ground state and took up scattering probe light again a few milliseconds after the image had been recorded.

During the past years, individual ions of barium and ytterbium have been prepared in the outlined way at Hamburg University in order to study the interaction of these ions with light and radio frequency radiation [38-43]. Some of this work was devoted to the problem addressed here, i.e. the very observation of the obstruction of a free ion’s evolution by its repeated measurement [41-43].

Initially, a laser-driven individual ytterbium ion \((^{172}\text{Yb}^+)\) was studied [41,44]. When the ion in its ground state \(^2S_{1/2}\) is irradiated by a probe pulse of near UV laser light at 369 nm wavelength, resonance light is scattered and detected. A subsequent pulse of highly coherent blue laser light at 411 nm may (or may not) drive the ion into the metastable \(^2D_{3/2}\) state via the corresponding E2 transition. If this attempt succeeds (fails), probing by another UV light pulse fails (succeeds) to generate a scattered-light “on” signal. Eventually, alternating irradiation by driving and probing pulses yields a trajectory of on and off data whose distribution contains full information on the history of the addressed degree of freedom of the quantum system.

The strategy of the data evaluation is outlined in the context of a second experiment on a single ytterbium ion \((^{171}\text{Yb}^+)\) that has involved the ion’s hyperfine transition with the driving (Fig. 5) [43]: After the ion having been prepared initially in its state 0 – the hyperfine level \(F = 0\) of the ground state \(^2S_{1/2}\), it is irradiated by alternating pulses of microwave radiation (12.6GHz) and resonant laser light at 369nm wavelength. The microwave pulses coherently drive the ion on the hyperfine resonance into a superposition of the two hyperfine states. Subsequently, a light pulse probes the \(F = 1\) hyperfine level by attempting to excite resonance scattering, via the \(^2S_{1/2}(F = 1) - ^2P_{1/2}\) line, which succeeds only if the \(F = 1\) level had been actually populated before. A photon counter, activated synchronously with the probe light, records possibly scattered resonance light. A pair of subsequent drive and probe pulses complete with the activation of the counter represents a single measurement, whose result is one out of the two possible outcomes: scattered light ”on”, or ”off”. These alternatives are strictly correlated with the ion being found in hyperfine level 1, or 0, respectively. Reiterated measurements yield a trajectory.
Its particular shape is conditionally random, that is, its distribution of the two alternative results depends on the area $\theta = \Omega \tau$ of the driving pulses which agrees with the mixing angle of the generated state. The special values $\theta = \pi$ or $2\pi$ would yield deterministic trajectories: alternations of "on" or "off", or a string of exclusively "off" results, respectively. In general, a trajectory is made up of alternating strings of "on" and "off" results of irregular length. They contain sequences of two, three, four, ... $q$ ... equal results, whose occurrence is subject to statistical analysis. The "frequency" $U(q)$ is defined by the number of such a sequence of length $q$ found in the entire trajectory. In a long trajectory containing a large enough number of individual measurements, the normalised frequency is a reliable measure of the probability for the appearance of a sequence of specific length. Then, we have

$$U(q) = U(1) V_i(q-1), \quad (4)$$

since the probability of a sequence of $q$ results (all either "on", or "off") equals the probability for the appearance of one of these results, multiplied by the conditional probability for $(q - 1)$-fold survival in this state. This latter factor is

$$V_i(q-1) = p_i^{q-1} (i = 0 \text{ or } 1), \quad (5)$$

where the probability of survival an individual driving attempt is $[18,25]$

$$p_0 = p_1 = \cos^2 (\theta/2), \quad (6)$$

if relaxation is negligible, as with the hyperfine ground levels. In a log plot vs $q$, eq. 5 is represented by a straight line of negative slope (Fig. 6). The complement of $p_i$ is the transition probability

$$p_{ij} = 1 - p_1 = \sin^2 (\theta/2), \quad (7)$$

where $ij = 01$ or 10. Now, the observed normalised numbers of sequences $U(q)/U(1)$ may be compared to the calculated probability of survival (5). The observed data of $U(q)/U(1)$ have turned out fully compatible with the linear dependence of $V_i$ on $p$. Data and evaluation have been published elsewhere $[43-45]$.

The foremost result of the above experiments is the agreement of the empirical distributions $U(q)/U(1)$ with the $(q - 1)$-fold conditional survival probability. The latter one has been calculated under the precondition that the coherent evolution of the microwave-driven ion’s wave function is broken by just the possibility of observing scattered light during the intermittent irradiation by probe light. If
such breaks were not to happen, the evolution of the ion’s wave function should continue during the subsequent intervals of driving. An uninterrupted evolution would require a different calculation of the conditional probabilities of survival [46], namely

\[ V_c(q - 1) = \prod_{n=1}^{q-1} V'(n), \]  

where

\[ V'(n) = \cos^2 \left( \frac{n\theta}{2} \right). \]

The step-like function (8), as shown in Fig. 5 is incompatible with the distributions of the recorded data.

Is the pulse area \( \theta \) of the microwave drive small enough, a second measurement will most probably reproduce the result of the first one, since the chance of survival in (6) deviates from unity only as the square of \( \theta \). The quantum state that we ascribe to the ion, based on the previous result, has evolved after the next driving pulse, as well as the associated expectation value. This ascribed state could be verified only by a set of observations on the (equally prepared) system. In fact, the unvaried result of a second measurement makes jump back our best knowledge to what we knew before the driving pulse; it is an updating of information, by the measurement. This is why the evolution ascribed to the ion is retarded, or frustrated, by reiterated observation even when scattered light, as in an "off" result, does not show up.

5. An alternative strategy

Still another strategy is capable of divulging the impeding effect of measurement. This alternative approach makes use of effective driving pulses of total pulse area \( \theta = \pi \), i.e., of sequences composed out of \( n \) fractional pulses. Such a composite pulse is expected – at vanishing relaxation – to transfer the ion from its lower ground level 0 into its upper ground level 1 to a certainty. Any residual population left over in state 0, as brought about by the intermittent irradiation of probe-light pulses, is considered evidence for QZP.

So far, this approach recalls the strategy applied with the experiment on an ensemble of \( Be^+ \) ions mentioned above [19,20]. However, the present one is characterised by essential and distinctive features:

1. The quantum object is in fact a single ion. 2. The effective driving pulse is split up in \( n \) fractional pulses of area \( \pi/n \). During the intermittent intervals, the ion’s driven evolution is supposed to halt. 3. There is no spurious decoherence effect expected to impair the overall coherent evolution, since perturbations that affect the ion’s internal state are minimised by its solitary positioning in the trap centre, within ultra-high vacuum. 4. The probe pulses are applied within the intermissions of the coherent driving, not during the driving pulses. Thus, nonlinear interaction of the ion with simultaneously present drive and
probe fields is avoided. 5. The photon counter is activated during all the probe-light irradiations such that actual detections of the scattered light form sequences of \( n \) recorded results each. This recording provides control of the ion state whenever probe light examines the ion.

The complete documentation of the ion's history allows one to select sequences that prove the ion to survive in state 0, and to discriminate those other sequences that contain some events of transition to state 1. The latter kind of sequences goes unnoticed when merely recording the final result of the sequence. From a large number of recorded sequences, one determines the fraction of histories of \( n \)-fold survival in state 0. This fraction, a set of "selective" measurements, is supposed to approach the conditional probability of survival,

\[
P_{00}^{(s)}(n) = \left[p_0(\theta_n)\right]^n = \cos^{2n}(\pi/2n),
\]

where \( \theta_n = \pi/2n \) [43]. This distribution increases monotonously with \( n \).

Ignoring the results of the intermediate recordings by the photon counter makes contribute, to the set of data with final result "off", many more recorded sequences: namely those data that reveal one or more intermediate back-and-forth transitions. All these sequences with a final "off" form a set of "non-selective" measurements. The compiled results do not approach the survival probability, but rather the probability of retrieval in state 0,

\[
P_{00}^{(ns)}(n) = 1/2 \left[ 1 + \cos^n(\pi/n) \right] \rightarrow 1 \quad n \rightarrow \infty
\]

which is the complement of (3).

A set of non-selective measurements cannot indicate the survival of the ion. Rather, it conveys information analogous to that from an experiment on an ensemble of quantum systems [19,20]. In both cases, agreement of the observed distributions with (3) or (11) does not qualify as proof of measurement-induced survival of the quantum system.

The results of the evaluation of recorded data according to this alternative strategy have been published elsewhere [43,45]. The distribution of sequences that never show an "on" result and represent selective measurements indeed agrees with the predicted distribution of the conditional probability of survival (10) within the error limits. This agreement proves the frustration of the quantum mechanical evolution by the repeated acts of measurement, that is, it proves QZP. The essential feature of the observed data set is its exclusive composition of null results. Any reaction to the quantum object by the measuring device cannot account for the result of a corresponding measurement. Measurements of this kind leave the system untouched - they are in fact "quantum non-demolition" measurements [10].

The reported experiments prove a quantum system's evolution being impeded by a measurement that involves no physical back action. The very existence of such an impedance, the QZP, requires reinspection of epistemological positions in the context of quantum-mechanical measurement.

6. Summary
The experiments outlined in sections 4 and 5 have allowed the reiterated detection of the internal state of a free, isolated, and evolving quantum system while not perturbing it. The results show that mere observation and recognition of the results – the "gain of knowledge" – retards or inhibits the temporal evolution of the system, as it is predicted by quantum-mechanical modelling. This effect is the consequence of an intentionally prepared correlation of the system with the detected signal – a particular entanglement of quantum states and meter states [21]. Whereas in most kinds of actual measurement on a quantum system the detected signal in fact physically reacts on the measured system, the above results show that such a reaction seems irrelevant for both the definition and the comprehension of the measurement process. This situation forbids dynamical explanations of the fundamental uncertainty of micro-physical measurements, as in the early concept of the "Heisenberg microscope", that relied on this very reaction for the vindication of the limitations imposed upon the measurement process by quantum mechanics [8].
The empirical findings seem to support a simple interpretation: The results of measurements convey information on the measured object; they establish an element of reality, embodied in the data strings of the trajectories. Predictions provided by quantum mechanics on the basis of these results represent the potentiality of the future evolution of the system, not its reality. The predicted evolution passes a discontinuity as soon as a new result of a measurement is available. The well-known consequences of such a discontinuity are (1) loss of coherence of the quantum system’s evolution as an intrinsic effect of potentially allowed measurements, and (2) the renormalisation of the predictions, requested by the factual outcome of the novel measurement that updates the initial conditions for the predicted evolution. On the other hand, if one insists on attributing reality to the predicted quantum mechanical evolution, ”real” discontinuities of this evolution must be traded in, and also the acceptance of state reduction as a dynamic effect.

Taking into account the consequences of the two alternative positions, it seems more acceptable to restrict the role of quantum modelling to the potential future, in the tradition of Wolfgang Pauli [47]. Although state reduction plays an important role as a tool in computational applications [14], it seems to reflect only the stepwise gain of knowledge in the course of subsequent measurements.

Aside from the epistemological notion, there is a more down-to-earth motivation to the reported work: It has demonstrated how to achieve, by microwaves and even by light, a crucial manipulation of an individual two-level atom, equivalent to a spin system, in its configuration space, the deliberate ”coherent rotation”. This process, fundamental for preparation and application of micro-physical systems, is associated with maximally controlled absorption and emission of radiative energy by an atom. A spin system is the physical representation of a ”qubit”, the smallest unit of quantum information. Thus, the demonstration of coherent rotation of this unit in configuration space, especially in the optical domain is a small but essential step in the progress towards technical applications of manipulations on individual quantum systems [48]. These techniques promise to put into reality, in a not too distant future, the long-proclaimed quantum computing that will herald a new level of quantum information processing.

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