Quantum pot watching

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One of the striking predictions of quantum mechanics is the Zeno effect which inhibits the time evolution of a system by either repeated, frequent measurements on it (the 'watched pot effect'[1]) or by continuous coupling to its environment (the 'watchdog effect'[2]). The recent verification of the 'watched pot effect' by Itano *et al.*[3] using trapped ions has evoked considerable interest[4]. For the 'watched pot effect' to occur the measurements must repeatedly project the system back to its initial state. In other words, the wave function of the system must repeatedly 'collapse'. It is also necessary that the time interval between successive measurements must be much shorter than the critical time of coherent evolution of the system, called its Zeno time[5]. For decays this Zeno time is the time before the irreversible exponential decay sets in and is governed by the reciprocal of the range of energies accessible to the decay products. For most decays this is extremely short and very hard to detect[6]. In the case of non-exponential time evolution, the relevant Zeno time can be much longer.

Credit goes to the group (W. Itano, D. Heinzen, J. Bollinger and D. Wineland) at the National Institute of Standards and Technology in Boulder, Colorado, for identifying an atomic transition with a long enough Zeno time. They used[9] a magnetic trap as a pot to hold several thousand Be ions, the 'water'. At the beginning all the ions were brought to a single electronic state (Level 1) by optical pumping. When these ions were exposed to a radio frequency field (at 320.7 MHz) for exactly 256 msec, all of them moved up to a higher energy state (Level 2)—the 'water' had boiled when no one was watching. The researchers then started to peep in before 256 msec were up. They used very short pulses (2.4 msec) of laser light at 313 nm to excite only transitions from Level 1 to a strongly fluorescing high-lying Level 3 (Figure 1). If at the time of these quick 'peeps' the ions are in Level 1, they can be driven up to Level 3 and the subsequent fluorescence observed by photon counting. If they have not remained in Level 1 and have moved up to Level 2, they cannot be excited to Level 3 by the laser pulses, and no fluorescence is seen. The fluorescing of Level 3 is therefore a very efficient indicator of the survival probability of the ions in Level 1. Itano *et al.* found that the number of ions surviving in Level 1 when the first measurement with the laser pulse was made after 256 msec was zero. However, as the frequency of these measurements was increased, the survival probability also increased and was almost unity when the pulses were sent every 4 msec, that is 64 times in 256 msec. Clearly the 'watched pot' refused to 'boil'. This is clinching evidence of 'wave function collapse' in the sense of 'the destruction of coherent superposition by measurement' and lends considerable support to the notion of 'continuous observation' as a limiting case of repeated measurements.

An alternative way of affecting the natural free time evolution of a quantum system is to couple it continuously to its environment. Then its coherent Schrödinger evolution can be dynamically altered (without involving and 'collapse') if the characteristic time associated with the coupling is much smaller than the characteristic Zeno time of the system[7].

The quantum Zeno effect is a general consequence of the principles of quantum mechanics and is expected to occur in a wide variety of quantum phenomena whenever the timescales involved are right, irrespective of the details of the dynamics involved. Consequently, it is expected to persist even in the conventional classical limit (large quantum numbers or coherent states). In this note we shall point out a few examples of the Zeno effect from different areas of physics to highlight its pervasive character.

Consider first the old problem of cloud chamber tracks. Its basic physics can be understood in terms of the Zeno effect in the following way without going into any detailed dynamics as was discussed by Mott[8] and Heisenberg[9]. The first encounter of the incoming charged particle with a vapour molecule in the cloud chamber ionizes it and results in a localized wave packet. If the incident wavelength λ is much smaller than the diameter a of the molecule, the wave packet will propagate in the direction of the initial momentum without appreciable diffraction. This constitutes a position measurement with an uncertainty of the order of a. Now, the width of every localized wave packet becomes appreciably larger than its initial width in a time determined by its initial localization and mass. This is a measure of its Zeno time τ. If the density of the vapour molecules in the cloud chamber is such that the time between successive ionizing encounters is much smaller than τ, the spreading will be inhibited by these repeated interruptions and the track will be linear and in the direction of the initial momentum.

Another very interesting example comes from sugar molecules which occur in two distinct optically active isomeric states left-handed and right-handed sugar. It is a two state problem in quantum mechanics with an effective Hamiltonian which has reflection symmetry. Let us denote the left-handed and right-handed states of the sugar molecule by $|L>$ and $|R>$ respectively. These states are not the eigenstates of the effective Hamiltonian which is expected to induce an oscillation between them through its off-diagonal terms. Nevertheless, if one of the two kinds of sugar is prepared, it is found to remain in that state ($|L>$ or $|R>$) almost for ever. (All biologically prepared sugar molecules happen to be right-handed). Harris and Stodolsky[10] have shown that this stability in a sugar solution can be understood in terms of

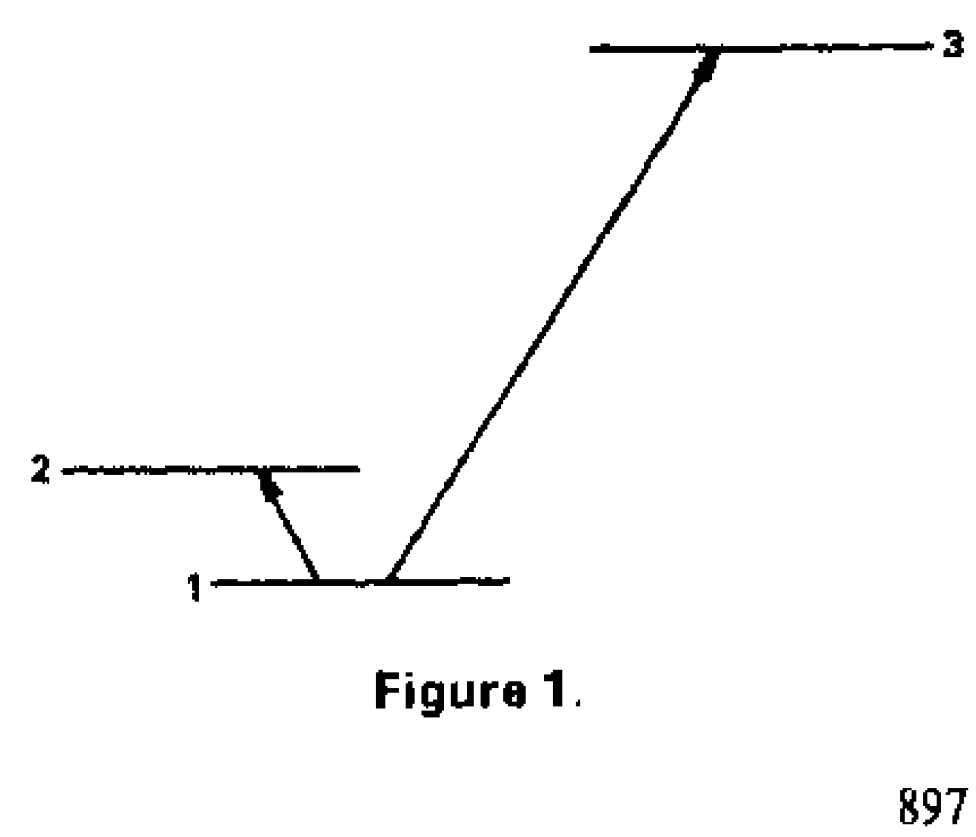

Figure 1.

the 'watched pot effect' resulting from frequent collisions with solvent molecules. They have also pointed out that if the stability persists in vacuum, it could be understood in terms of what is now called the 'watchdog effect' arising from the inhibiting influence of weak interactions on the molecules.

There is an analogous situation in particle physics associated with the solar neutrino problem. Earth-based observations indicate that only about 1/3 of the electron type neutrinos ν_es produced in the sun and expected to reach the earth can be detected. Since the solar structure is very well known and is unable to account for this depletion, one attractive possibility is the conversion of ν_es into muon type neutrinos ν_μ (which escape detection in the apparatus used) as a result of neutrino oscillations. Such oscillations are theoretically possible if the neutrinos have a small mass. When neutrinos travel through a gas of electrons, there is an additional coherent amplitude for electron-ν_e scattering through the charged weak current (exchange of W^+ bosons), an option not open to ν_μs because of their different flavour quantum number (Figure 2). This additional interaction can produce a maximum conversion of ν_es into ν_μs in an electron gas of appropriate density. This is known as the Wolfenstein–Mikheyev–Smirnov effect[11]. Since the electron density inside the sun varies from the core to the surface, this resonance condition can be realized inside the sun. This is really an example of a 'reverse' watchdog effect inasmuch as it occurs basically as a result of continuous coupling of the neutrinos to their solar environment, but here the effect is one of enhancement rather than suppression and takes place due to resonance between the time scales of vacuum oscillations and the coupling to the environment.

Similar oscillations involving neutrons and antineutrons are predicted from grand unified theories as a result of the violation of baryon number conservation[12]. However, just as neutrino oscillations in vacuum have not yet been observed, n–$\bar{n}$ oscillations too have not been observed either in vacuum (as in reactor experiments[13]) or in nuclear media (as in Fe^{56} nuclei[14]) where the oscillation time is predicted to be much longer than in vacuum (a 'watchdog effect'). Are there any interesting implications for neutron stars?

Finally, we would like to point out a possible application of the 'watchdog effect' in nuclear physics. A free neutron decays spontaneously via weak interactions with a half-life of approximately 10.83 minutes but this decay is suppressed inside a β-stable nucleus. Since the energy released in neutron β-decay is of the order of 1 MeV, its Zeno time is of the order of 10^{-21} sec. There is therefore a prima facie case to expect that this decay would be suppressed inside a nucleus where other nucleons are present to which the neutron is continuously coupled with a strength whose time scale is of the order of 10^{-23} sec. This suppression of the weak interaction-induced decay is indeed tacitly assumed in the usual quantum-mechanical treatment of, for example, the deuteron, for without such an assumption the effect of weak interactions would be to make the effective Hamiltonian of the n–p system non-hermitian, and one would get *only* decaying states (not bound states) as solutions. It seems therefore that it is the 'watchdog effect' which can provide an 'explanation' from first principles of the stability of the neutron in β-stable nuclei. The environment in which a neutron 'finds itself, however, varies from state to state within a given nucleus (e.g. in odd nuclides, the neutron in the outermost shell is loosely bound) and also from one nucleus to another. This gives rise to variations in the coupling of neutrons to their nuclear environment, and the efficacy of the 'watchdog effect' for a particular neutron therefore depends on the details of its environment. In some cases, a 'reverse' effect might also occur, leading to a shorter life time, a feature not possible with the 'watched pot effect' as first noted in this context by Peres[15]. This therefore might provide a general way of dealing with the problem of neutron stability in different environments (such as nuclei or the early universe) whose implications, we believe, should be further explored.

The influence of one fundamental interaction on another that could come into play is a novel feature of the quantum 'watchdog effect'. It is most likely to have implications of far reaching importance.

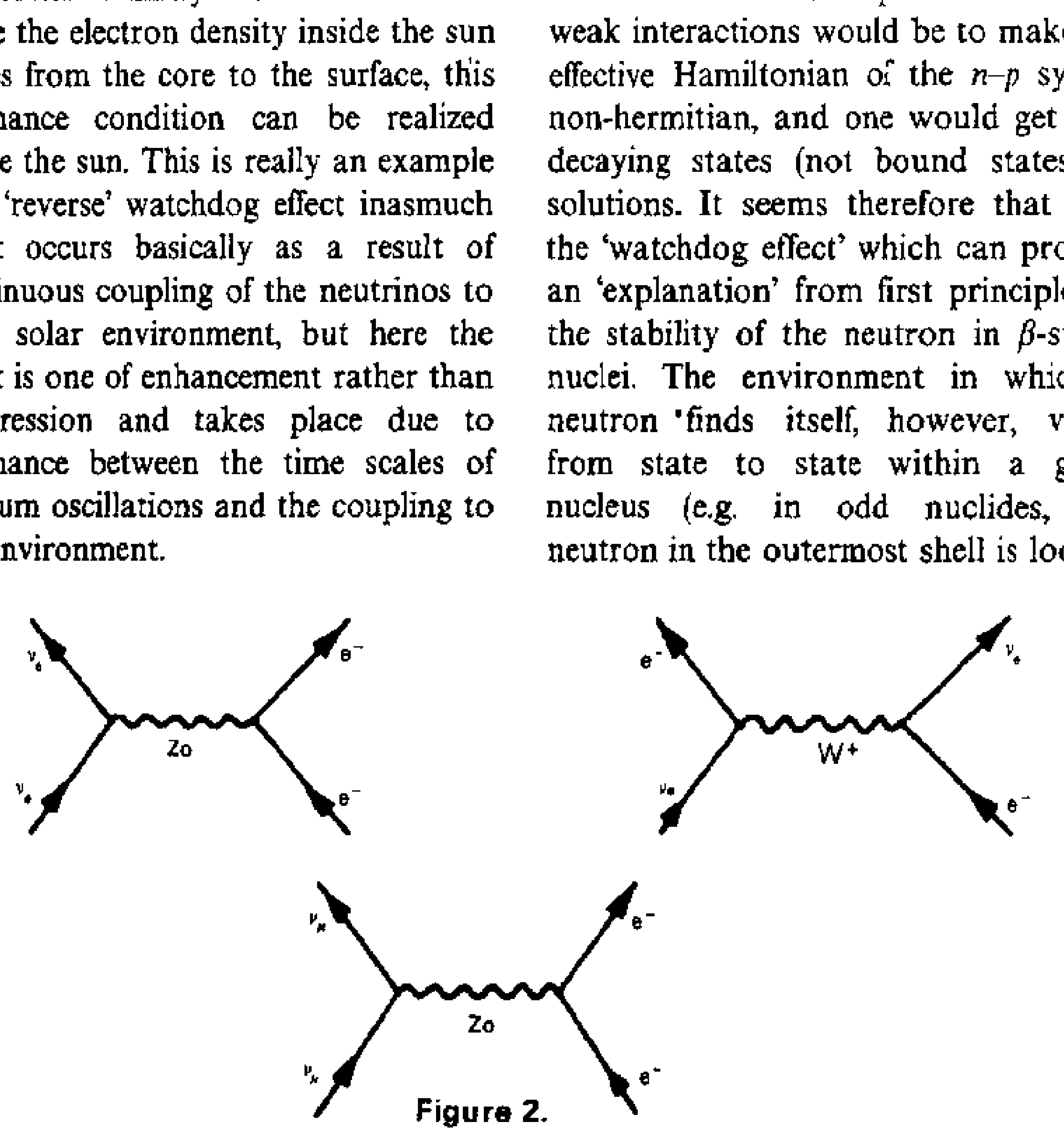

Figure 2.

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