a computation that can bring about meaningful behaviour. ■

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1. Laubach, M., Wessberg, J. & Nicolelis, M. A. L. *Nature* **405,** 567–571 (2000).
2. Vaadia, E. *et al. Nature* **373,** 515–518 (1995).
3. Hebb, D. *The Organization of Behaviour. A Neurophysiological Theory* (Wiley, New York, 1949).
4. von der Malsburg, C. Internal Report 81-2. Max-Planck-Institute for Biophysical Chemistry, Göttingen. Reprinted in *Models of Neural Networks* Vol. II (eds Domany, E., van Hemmen, J. L. & Schulten, K.) 95–119 (Springer, Berlin, 1981).
5. Abeles, M. *Local Cortical Circuits: An Electrophysiological Study* (Springer, Berlin, 1982).
6. Byrne, J. H. & Kandel, E. R. *J. Neurosci.* **16,** 425–435 (1996).
7. Mitz, A. R., Godschalk, M. & Wise, S. P. *J. Neurosci.* **11,** 1855–1872 (1991).
8. Georgopoulos, A. P., Schwartz, A. B. & Kettner, R. E. *Science* **233,** 1416–1419 (1986).
9. Schwartz, A. B. & Moran, D. W. *J. Neurophysiol.* **82,** 2705–2718 (1999).
10. Richmond, B. J. & Optican, L. M. *J. Neurophysiol.* **57,** 147–161 (1987).
11. Gray, C. M., König, P., Engel, A. K. & Singer, W. *Nature* **338,** 334–337 (1989).
12. Maynard, E. M. *et al. J. Neurosci.* **19,** 8083–8093 (1999).

Quantum decay

A watched pot boils quicker

Peter W. Milonni

Repeated observations of an unstable quantum state — such as a radioactive atom — can make it live forever, or at least much longer than its natural lifetime. This 'watched pot' or 'quantum Zeno effect' has been studied intensively over the past decade. Writing on page 546 of this issue, however, Kofman and Kurizki[1] suggest that a 'quantum anti-Zeno effect' — the shortening of a lifetime due to repeated observations — may be more common.

An unstable state evolves in time into a linear superposition of states. For instance, an excited state of an atom in a vacuum evolves into a superposition of itself and the (stable) states in which the atom is unexcited and has released a photon into the surrounding space. A measurement to determine whether the initial state survives can be formally described as a projection of the superposition back onto the initial state. The quantum Zeno effect can occur when measurements are repeated so rapidly that the time between them is much shorter than the natural lifetime, or 'coherence time', of the state. Coherence times are typically so short that this condition is not satisfied.

Ten years ago[2] an experiment to test the predicted Zeno effect used a radio-frequency field to excite atoms from a state 1 to a state 2, plus a sequence of laser pulses inducing transitions from state 1 to a higher excited state 3. The detection of a spontaneously emitted photon by the $3 \rightarrow 1$ (fast) transition amounts to a measurement of the survival probability of state 1, because spontaneous emission from state 3 can occur only after the atom has already been in state 1, where it can absorb a laser photon. It was found that radio-frequency transitions from state 1 to 2 were diminished by frequent measurements of the survival of state 1. Whether this confirms the quantum Zeno effect is arguable, or perhaps semantic, in that the enhanced survival of state 1 can be understood as an interference effect — rather than projecting the atom into state 1, the laser pulses ('measurements') produce superpositions of states[3,4].

Another example where the survival of a quantum state is affected by sequential measurements occurs in the propagation of a photon through N polarization rotators, each of which rotates the initial ('horizontal') polarization by the angle $\pi/2N$. Left to themselves, the rotators in series rotate the polarization by $N(\pi/2N) = \pi/2$, that is, from horizontal to vertical. Suppose now that a horizontal polarizer is placed after each rotator. The probability of the photon being transmitted by each of these polarizers is $p = \cos^2(\pi/2N)$, and the probability of transmission through all of them is $P = p^N \approx 1 - \pi^2/4N$. The probability of absorption is $1 - P \approx \pi^2/4N$. Many (large N) sequential polarization measurements therefore result in a high survival probability of the initial state. Again it is arguable whether this effect embodies the quantum Zeno effect as originally proposed, but it has been used to demonstrate 'quantum-interrogation' measurements[5,6].

The original prediction[7] of a quantum Zeno effect referred to a spontaneous decay of an unstable particle or state. It is this general situation, where decay is a consequence of a 'reservoir' of possible states to which transitions can occur, that has been revisited by Kofman and Kurizki[1]. They focus attention on the dependence of the decay rate on the energy spectrum of the reservoir states and on the energy spread of the unstable state.

It is clear that the decay rate must depend on the spectrum of reservoir states, simply because the decay is due to transitions to these states. Measurements interrupt and randomize the oscillations of the system and, according to the energy–time uncertainty relation, cause an energy spread $\sim h\nu$, where h is Planck's constant and ν is the frequency of the sequential measurements. This energy spread determines the range of accessible reservoir states and must also affect the decay rate.

The main conclusions of Kofman and Kurizki follow from an analysis of the dependence of the decay rate on the energy spread and the reservoir spectrum. The quantum Zeno effect should occur when the energy spread due to repeated observations is large compared with both the width of the reservoir spectrum and the separation in

Geomorphology

Case of the bends

NATHAN BENN/CORBIS

Paul Hudson and Richard Kesel have returned to the Mississippi River of Mark Twain to investigate the rates of movement (migration) of river meanders. The inspiration for their study was not literary, however, but old surveys of the 1,700-km lower stretch of the river from Cairo, Illinois, to the Gulf of Mexico. The surveys concerned were carried out between 1877 and 1924 — a time when the river was still largely unconstrained by human influence. The photograph here is a recent one of the river in the delta region.

Data from smaller river systems and from modelling point to a specific relationship between meander migration rate and the ratio between meander-bend radius and channel width. But as they describe in *Geology* (**28**, 531–534; 2000), Hudson and Kesel find that the lower Mississippi does not follow this relationship. The reason, they suggest, lies in the heterogeneity of the deposits through which the river flows. In particular, clay plugs limited the rate of meander migration — the incidence of these plugs is higher in the northern part of their study area (average meander migration 45.2 m yr^{-1}) than in the delta (59.1 m yr^{-1}). **Tim Lincoln**

energy between the unstable state and the centre of gravity of the reservoir distribution. In the seemingly more general situation where this energy spread is small compared with the separation between the unstable state and the nearest maximum in the reservoir spectrum, however, the unstable state should decay faster as ν increases. In this case the quantum anti-Zeno effect should be observed because, as ν and therefore the energy spread of the unstable state increases, so does the number of accessible reservoir states into which transitions can occur.

Judging by typical decay processes and the nature of the reservoirs used to model them, one surmises that the anti-Zeno effect is more common than the Zeno effect[1,8,9]. As yet there are no known experiments corroborating this idea, but it has already been suggested[8] that the anti-Zeno effect is cause for concern in connection with error-correction schemes for quantum computing. Moreover, Fearn and Lamb[4] reported "quite the reverse of the Zeno effect" in a computational study involving barrier penetration. So watch that pot closely. ■

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1. Kofman, A. G. & Kurizki, G. *Nature* **405,** 546–550 (2000).
2. Itano, W. M., Heinzen, D. J., Bollinger, J. J. & Wineland, D. J. *Phys. Rev. A* **41,** 2295–2300 (1990).
3. Ballentine, L. E. *Phys. Rev. A* **43,** 5165–5167 (1991).
4. Fearn, H. & Lamb, W. E. Jr *Phys. Rev. A* **46,** 1199–1205 (1992).
5. Kwiat, P., Weinfurter, H., Herzog, T., Zeilinger, A. & Kasevich, M. in *Fundamental Problems in Quantum Theory* (eds Greenberger, D. M. & Zeilinger, A.) 383–393 (New York Acad. Sci., 1995).
6. Kwiat, P. G. *et al. Phys. Rev. Lett.* **83,** 4725–4728 (1999).
7. Misra, B. & Sudarshan, E. C. G. *J. Math. Phys.* **18,** 756–763 (1977).
8. Lewenstein, M. & Rzazewski, K. *Phys. Rev. A* **61,** 022105-1–022105-5 (2000).
9. Kaulakys, B. & Gontis, V. *Phys. Rev. A* **61,** 1131–1137 (1997).

Immunology

The footprint of a killer

Klas Kärre and Gunter Schneider

Class I molecules of the major histocompatibility complex (MHC) are normally expressed on the surface of most cells in the body. They serve two purposes in the immune system. T cells use MHC molecules to identify and kill cells that are infected by foreign material, such as viruses. Natural killer (NK) cells, meanwhile, use them to identify and spare the lives of cells that are normal and healthy[1]. On page 537 of this issue[2], Boyington and colleagues reveal the structural nature of a life-saving liaison between a human MHC molecule and its receptor on an NK cell.

MHC class I molecules bind intracellular peptides and present them to the immune system for scrutiny. If the MHC molecules present foreign peptides — for example, those from a degraded virus protein — T cells are activated and will eventually destroy the infected cells. This limits replication and spread of the infection. NK cells also rely on MHC molecules for decision-making, but in the opposite way. On recognizing self-MHC molecules on target cells (Fig. 1a, overleaf), the MHC receptors on NK cells generate inhibitory signals[3]. These cancel an activating signal initiated previously by other receptors on NK cells that have recognized ubiquitously expressed ligands on the target cells. If self-MHC molecules are not adequately displayed — as occurs in some cancerous or transplanted cells, for example — the NK receptors cannot deliver the inhibitory signal and will go on to kill the target cell.

Human NK cells can express MHC class I receptors of either the immunoglobulin family (the receptors of which are called killer-cell immunoglobulin-like inhibitory receptors, or KIRs) or the C-type-lectin family. It is the structure of an immunoglobulin-type receptor, KIR2DL2, in complex with its MHC class I ligand, HLA-Cw3, that is described by Boyington *et al.*[2].

The structure of the extracellular parts of a KIR consists of two globular immunoglobulin-like domains linked by a hinge region[4]. In the MHC–receptor complex described by Boyington *et al.*, the receptor binds with both of its globular domains in a 1:1 stoichiometry to the MHC molecule, across the MHC's 'business end', consisting of the groove-containing peptide. Six loops located close to the hinge region contact the MHC molecule.

Mouse NK cells do not express KIRs. Instead they have inhibitory MHC receptors from the Ly49 subfamily of C-type lectins. At the end of last year, the structure of such a receptor, Ly49A, in complex with its MHC class I ligand, H-2D^d, was described[5]. The interactions between receptor and ligand in this structure differ completely from those described by Boyington *et al.* (Fig. 1b, d), for the mouse receptor binds at one side of the peptide-binding groove. At first sight, however, the major 'footprint' of the human NK-cell receptor on its MHC ligand seems remarkably similar to that of the T-cell antigen receptor on an MHC ligand[6] (Fig. 1c). Both receptors span the two α-helices of the MHC molecule and the peptide, covering a surface area of about 1,500–1,700 Å. But a closer examination reveals that the binding site of the NK-cell receptor is shifted towards the carboxy-terminal part of the peptide. The T-cell receptor, by contrast, binds more centrally. Another difference is that the KIR footprint is dominated by charged and hydrophilic interactions, whereas the T-cell receptor relies mainly on hydrophobic, and less on electrostatic, contacts.

The degree of overlap between the two footprints indicates that the T-cell antigen receptor and the KIR probably cannot bind to the MHC molecule at the same time. This is an important issue, as T cells may, under certain circumstances, express both an activating MHC receptor and an inhibitory KIR. Might one MHC molecule be used to deliver both activating and inhibitory signals to the same T cell? This appears impossible for the human KIR studied by Boyington *et al.* (Fig. 1b, c), but might arise for mouse NK cells bearing the Ly49A receptor (Fig. 1b, d).

The role of the MHC-presented peptide in recognition by the NK-cell receptor is much debated. For some receptors, such as mouse Ly49A, there is no influence of the peptide sequence. But the opposite appears to be true[7] for the group of receptors that includes that studied by Boyington *et al.* This difference is beautifully explained by the three-dimensional structures of the two receptor–ligand complexes[2,5] (Fig. 1b, d). The binding site of the murine receptor is distant from the peptide. But there are direct interactions between the peptide and the human receptor. Two positions in the nonameric peptide participate in these interactions in the structure — a finding that agrees well with biochemical binding studies using a series of peptide variants[2].

MHC molecules are polygenic (each individual has several genetic loci that encode MHC molecules) and polymorphic (each locus expresses but one of many possible alleles). Why does one group of KIRs, such as that to which KIR2DL2 belongs, bind to MHC molecules encoded by just one particular locus, termed HLA-C for this group? And why do different KIRs within this group bind to mutually exclusive subgroups of allelic products from this locus? This is usually referred to as the allospecificity of the receptor, believed to be important for the role of NK cells in reactions between donor and host in bone-marrow transplantation[8]. The allospecificity of KIRs has been analysed in several studies[9], the results of which are explained and extended by Boyington *et al.*'s complex. Of 16 amino acids involved in contacts with the MHC molecule, 14 are conserved between the KIR studied by Boyington *et al.* and another KIR, both of which react with HLA-C ligands but with different allospecificity. Boyington *et al.* found that one of the two amino acids