Atomic Memory

Atomic systems that have decayed From some ordered states can be induced to recover their initial order. The degree to which order is restored allows investigation of interactions difficult to observe

by Richard G. Brewer and Erwin L. Hahn

In 1872 Ludwig Boltzmann, a founder of modern thermodynamics, gave a lecture in which he said that the entropy, or disorder, of isolated systems increases irreversibly as time passes. On hearing this the physicist Joseph Loschmidt rose in protest. He argued that the laws governing the motions of all particles are symmetric with respect to time. Thus any system that had decayed from order to chaos could be made orderly once again simply by reversing the momentum of each particle, without affecting the total kinetic energy of the system. In defiance Boltzmann pointed his finger at Loschmidt and said, "You reverse the momenta."

This scholarly conflict illustrates the paradoxical nature of the second law of thermodynamics, which states that systems tend toward maximum entropy. Yet Loschmidt's argument remains cogent. If one were able to film the motions of any small group of particles and show the film to a physicist, he or she would have no way of telling in principle whether the projector was running forward or backward. Consequently, according to Loschmidt's criticism (which has come to be called the Loschmidt paradox), any law that governs the behavior of large collections of particles should be symmetric with respect to time. While the meaning and implications of the second law are still active topics of research and disagreement [see "The Arrow of Time," by David Layzer; SCIENTIFIC AMERICAN, December, 1975], there now exist several methods by which Loschmidt's time reversal can be realized. In other words, a system of particles that has apparently decayed from a highly ordered state can be returned to that state by reversing the motions (or some other degree of freedom) of its constituent particles. In effect an assembly of atoms is able to exhibit a kind of memory of its earlier condition.

If a system is to display this kind of atomic memory, it must be prepared so that it has some kind of order, often hidden, in its apparently disordered state. In the atomic systems we shall discuss, this hidden order is provided by exposing samples (which may be solid, liquid or gaseous) to coherent electromagnetic radiation of various types, including radio waves, microwaves and laser beams. Sound waves can also play this role. The reemergence of an ordered state in such systems becomes evident when the sample emits its own coherent electromagnetic pulse, an echo of the earlier radiation. Apart from their inherent interest, these echo pulses and related forms of coherent emission provide novel ways to study the fundamental behavior of atomic interactions.

The concept of hidden order can be demonstrated by an analogy. Imagine a group of runners poised at the starting line of a circular racetrack [see *illustration on page 52*]. The starter fires a gun, the race begins and the runners spread out along the course, each running at a different fixed speed. Once they have circled the track several times, some runners will have lapped others and there will be no obvious visible correlation between the runners' relative positions and their various speeds. Someone who had not seen the start of the race might assume that there was no particular order in the disposition of the runners, that they represented a disordered system.

Now suppose the runners have contrived to turn around and retrace their paths at some prearranged signal (perhaps a second firing of the starter's gun) that is given *t* minutes into the race. If all the runners maintain their speeds, albeit in the opposite direction, they will come together and cross the starting line in unison exactly *2t* minutes after the beginning of the race. They will have recovered their initial order. (This order will, of course, disappear once again after the runners cross the line.)

The even simpler case of all runners traveling together at the same radial speed is not to be ignored either. Here the initial order is preserved and there is no need to reverse the runners' direction. This example has an electromagnetic analogue, called the "free induction decay" effect, that has found wide use in both radio- and optical-frequency regions.

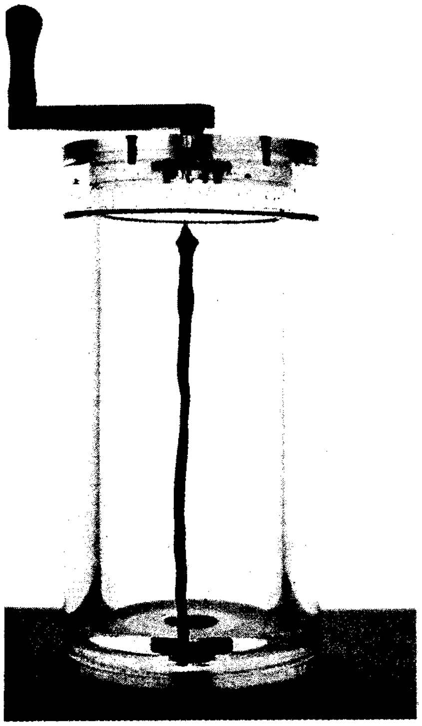
A more concrete example of a memory effect can actually be demonstrated by mechanical means. A viscous fluid is placed in the ring-shaped space between two concentric plastic cylinders. Whereas the outer cylinder is stationary, the inner one is free to rotate about its axis A streak of colored dye, representing an initial alignment of particles, is injected into the fluid. When the inner cylinder is turned, the dye disperses throughout the liquid. If one were to show the volume between the cylinders to a thermodynamicist, he or she would say that the dye is completely disordered (that the entropy is at a maximum) and that the mixing process is complete and irreversible. Actually the liquid is in a state of hidden order (or constant entropy): reversal of the rotation of the inner cylinder reverses the mixing process; after an equal number of reverse rotations the dye streak reappears.

In 1950 one of us (Hahn), then at the University of Illinois, discovered a memory effect that is similar in principle to the cases of the runners and the dye but that operates on the atomic scale. A sample of glycerin was placed in a magnetic field and exposed to two short bursts of electromagnetic radiofrequency (rf) radiation, separated by an interval *t* of a few hundredths of a second. The sample retained a memory of the pulse sequence, and at time *2t* seconds after the first rf pulse the sample itself emitted a third pulse, an echo. This phenomenon is known as the nuclear-spin echo.

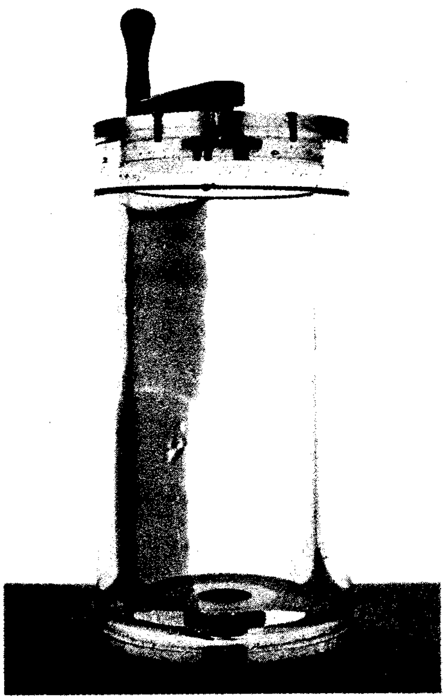
The nuclear-spin echo is a consequence of the gyromagnetic properties of atomic nuclei, such as the proton that constitutes the nucleus of most hydrogen atoms. Because the proton spins and is electrically charged, it has a magnetic moment, which is similar in some ways to the angular momentum of a gyroscope. The spin axis of a proton that is out of alignment with a constant magnetic field, like the axis of a tilted gyroscope in a constant gravitational field, precesses: it traces a circle about a line parallel to the force field [*see illustration on page 54.*] The precession frequency, the rate at which the proton's axis goes around its circle, depends in part on the length of the external magnetic field. This tendency of the proton's spin axis to precess about an applied constant field is the basis of the spin-echo effect.

In a spin-echo experiment the constant components of the spin axes of the protons in the sample are initially aligned parallel to a constant external magnetic field. Since they are exactly parallel to the field, they do not precess (as a perfectly vertical gyroscope would not precess). The first radio-frequency pulse is then applied. This rf pulse contains a circularly polarized component-a small rotating magnetic field-that rotates at the rate at which the protons' spin axes would precess if they were out of alignment with the constant field and if it were the only field present.

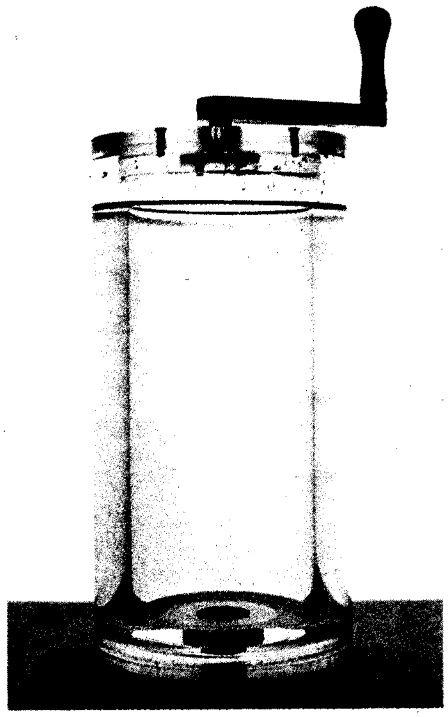
The rf pulse causes the ensemble of protons to execute a complicated motion, best described as a combination of two less complex precessional motions

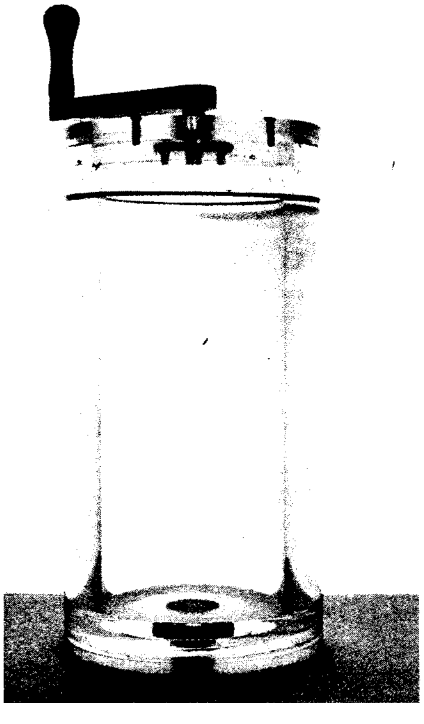


2

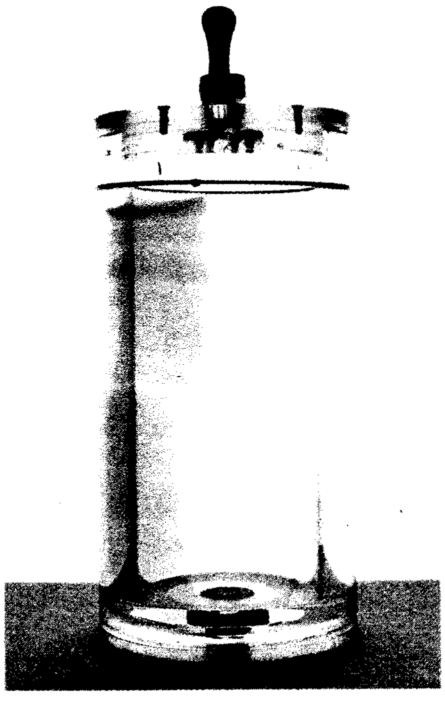


3

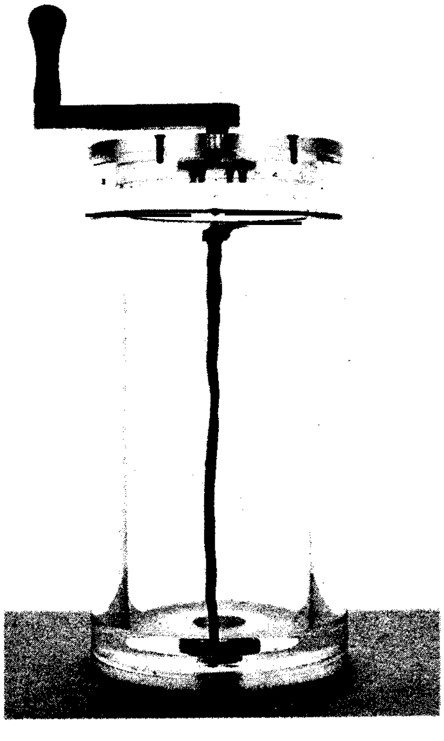




5

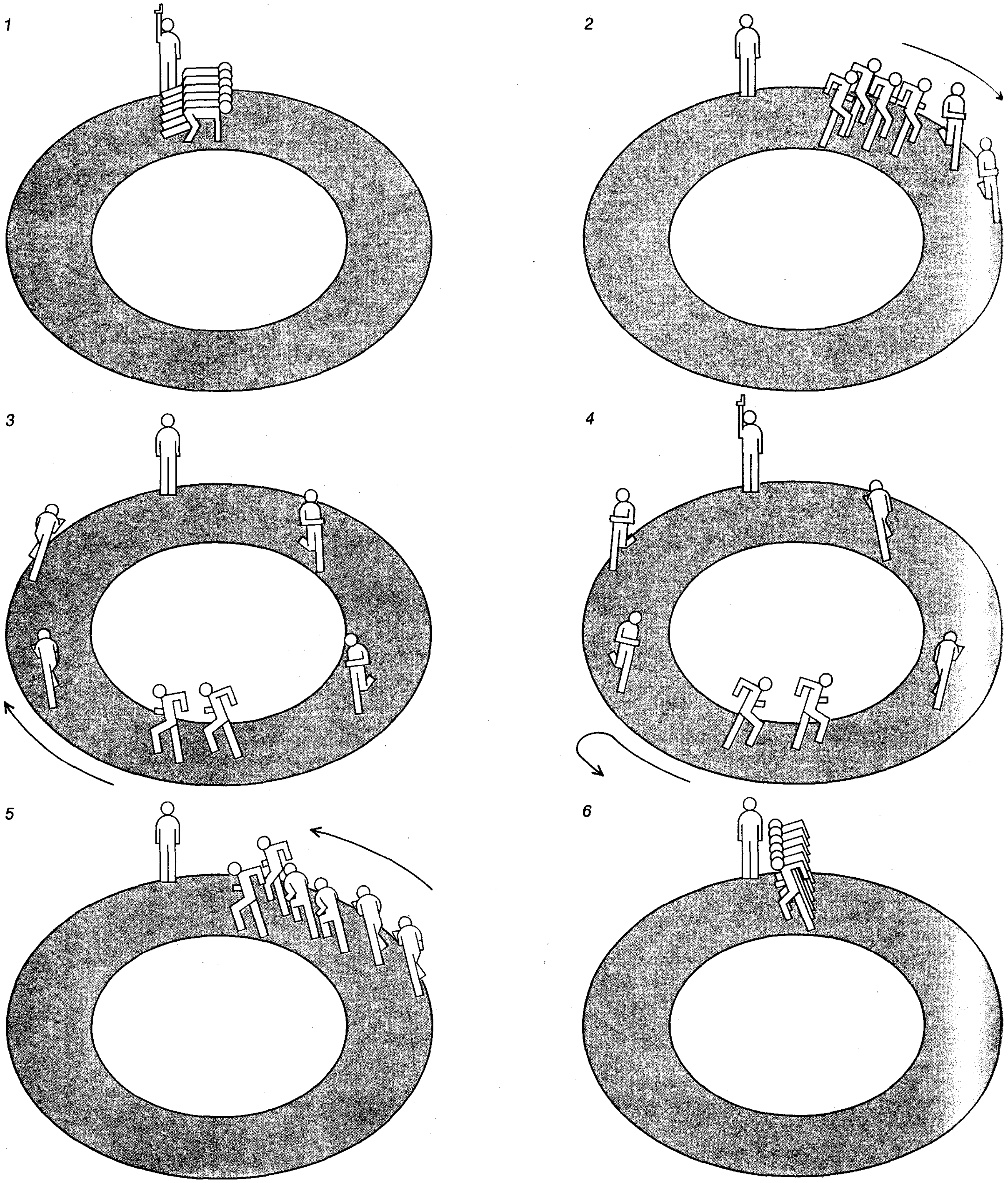


6



HIDDEN ORDER is demonstrated by a device consisting of two clear plastic cylinders that share a common axis. The volume between the cylinders is filled with a clear, viscous fluid. A streak of dye, consisting of an initial orderly alignment of particles, is injected into the fluid (1). While the outer cylinder is held still, the inner one is turned (2) until the dye appears to be completely mixed with the fluid (3). Apparently the initial alignment has been lost, but when the inner cylinder is reversed (4, 5), the particles realign and the streak reappears (6).

[see illustration on page 55]. The simpler of these two motions is a precession about the static external field: the rf pulse tilts the spin axes out of alignment with the constant field (although they remain essentially in alignment with each other during the short pulse time) and they begin to precess about the static field lines at their normal rate of precession. Since the magnetic field contained in the pulse also rotates at this rate, the angle between the rotating rf field and any proton spin axis remains constant as the proton spins precess. From the vantage of the protons the pulse field seems constant in direction Consequently the proton spins precess about both the pulse field and the constant field. The combination of these two precessions is a downward spiral traced by the spin axis of each proton



ELECTROMAGNETIC ECHO PHENOMENA find an analogy in the patterns formed by runners on a track. At the start (1) they are in a highly ordered state: in line. When the starter fires his gun and the race begins, they spread out (2) until the relation of one to another appears disordered (3). (The relation seems most disordered if some runners have lapped others.) The starter fires his gun again (4), and the runners reverse direction, so that the former leaders are now at the rear. In 6 they have caught up and the original order is restored.

The angle through which the protons tip is determined by the strength and duration of the rf pulse. in a typical spin-echo experiment this first pulse might be timed so that it tilts the proton spins exactly 90 degrees from the vertical: in other words. they come to lie on the plane that is perpendicular to their original orientation.

If the constant magnetic field is left on, the proton spins will precess in unison in this new plane: in a sense they will resemble one giant spinning magnet. Like such a spinning magnet. the protons emit an oscillating electromagnetic pulse. the free induction decay signal. so named because the synchronized free precession of spins induces a decaying electromagnetic signal. This signal corresponds to the start of the race: the spin axes are now in a state of dynamic order.

In time this order decays. One reason for the decay of the free induction signal may be that the static magnetic field does not have exactly the same strength throughout the sample. Since the protons' precession frequency depends on the strength of the external field, a proton in a region where the magnetic field is stronger will precess more rapidly than the others. just as some runners are faster than others. The spin axes come to point in different directions. They gradually fan out, like the runners on the track: the spin axes of those protons that precess rapidly will point ahead of the axes of the slower-precessing protons [*see illustration on page 56*]. The angle formed between any two spin axes that come to point in different directions is called the phase angle; the magnitude of the phase angle is a measure of how much the two spin axes are out of synchronization. As the protons desynchronize they no longer emit the oscillating electromagnetic field. the free induction decay. The sample is now in a state of apparent chaos.

After the protons' free induction decay the sample is excited with the second rf pulse. which is like the second firing of the starter's gun. This pulse is at the same frequency as the first one, but in a typical experiment it lasts twice as long; consequently the plane in which the proton spin axes lie is flipped through a full 180 degrees. ending once again in an orientation perpendicular to the constant field. It is as though the plane in which the spin axes lie has been turned upside down or reflected in a mirror.

Following the first rf pulse. the phase angles between faster- and slower-precessing spins had gradually grown larger. Just after the second pulse, which flips the plane in which the axes lie. the phase angles between the various axes are the same as before but the relative positions of the faster- and slower-precessing axes are reversed. In other words, prior to the second pulse the faster-precessing axes had gradually come to point slightly ahead of the direction in which the slower-precessing ones pointed: after the second pulse the plane in which the axes lie has been turned upside down (or mirror-reflected) and the slower-precessing axes point slightly ahead of the faster-precessing ones.

The faster-precessing proton spins are now behind the slower ones, just as the faster runners were behind the slower runners after the starter's second signal. As in the race, rapidly precessing spin axes will eventually catch up with the slower ones, and so the axes will realign. At this moment the atoms will emit another burst of radiation. the echo pulse. showing that the seemingly lost order has now been recovered.

In the spin-echo effect the applied rf bursts are said to be in resonance with the proton spins because the frequency of the bursts exactly matches the protons' natural frequency of precession. This spin-flipping property of resonant radiation is the cornerstone of the nuclear-magnetic-resonance (NMR) techniques discovered independently in 1946 by Edward M. Purcell of Harvard University and by the late Felix Bloch. then at Stanford University. in NMR spectroscopy the investigator excites a sample in order to determine which frequencies of radiation will induce spin flipping; each resonant frequency corresponds to **a** unique nuclear spin in a particular nuclear environment. For example. the strength of the local magnetic field can vary in different parts of a molecule because an electron cloud partially shields its nucleus from an external field. Once an NMR technician knows the spin-flipping frequencies. he or she can determine the chemical makeup of the sample. Spin echoes are among the most useful of NMR imaging techniques. The externally applied fields can be controlled to determine the occurrence of a given precession frequency over a large sample. even one as large as a human body.

There is another way that spin-echo effects can be used to study properties of various substances. In our racetrack analogy the runners will not all finish simultaneously if some of them have tired and have reduced their speeds during the race: in a sense any change of speed introduces a disorder within the hidden order. A corresponding disorder in an atomic sample could involve collisions between the atoms, magnetic interactions between neighboring atoms or movement of an atom from a region where the external magnetic field is high to one where it is lower. thereby changing its rate of precession. if the delay between the two rf pulses is lengthened, the random disorder introduced between pulses will increase and the echo signal will be weaker. A physicist or chemist can thus use the strength of the echo. or its decay time. as a measure of such random processes in matter as thermal agitation. internal motion and the fluctuation of local fields.

With the development of coherent laser light the echo concept was extended in 1964 to optical frequencies by Norman A. Kurnit. Isaac D. Abella and Sven R. Hartmann of Columbia University [see "Photon Echoes." by Sven R. Hartmann: SCIENTIFIC AMERICAN, April, 1968]. The physical principles underlying the spin and photon echoes are the same: both are examples of hidden order produced and revealed by coherent radiation. The spin echo, however, involves atomic nuclei whereas the photon echo usually involves atomic electrons. As Richard P. Feynman, Frank L. Vernon. Jr., and Robert W. Hellwarth, then at the California Institute of Technology, were able to show, both situations can be described by the same mathematical formalism, which is a generalization of Bloch's original gyroscopic equations.

The above experiments show that the hidden order within seemingly disordered systems can sometimes be revealed. It has also been shown that certain phenomena. such as molecular collisions, can introduce elements of disorder into the hidden order. causing the echo strength to decay. Can echo experiments be devised that will negate even such randomly occurring, seemingly irreversible effects?

The suggestion seems to contradict one's intuition that the large-scale consequences of such random events as collisions between molecules are in principle irreversible. In this instance intuition is misleading, because it is sometimes possible to eliminate even the disordering effects of elastic molecular collisions. This result is achieved by applying a large number of incident pulses spaced close together. These multipulse experiments were first done in NMR by Herman Y. Carr. now at Rutgers University, and Purcell. Jan Schmidt of the State University of Leiden, Paul R. Berman of New York University and one of us (Brewer) later extended the multipulse work into the optical region. We shall describe such a case. a photon-echo experiment on a gaseous sample.

The photon-echo effect is in principle very similar to the nuclear-spin echo. In the spin echo an incident rf pulse resonates with proton axes to align them in a state of dynamic order: this order seems to decay but is recalled by a second resonant rf pulse, which reverses the relative phase angles of the protons. causing them to realign and produce an echo. The photon echo is analogous. except the incident radiation is provided by a laser (that is, in the optical and it resonates with oscillations of the electron cloud surrounding each gaseous atom to produce an echo pulse.

The gaseous atoms of a typical photon-echo experiment are in a state of chaotic thermal motion; they behave like billiard balls, undergoing elastic collisions, which change their velocities but not their internal states. If the atoms are elastically scattered after being excited by the first laser pulse, they experience slightly altered trajectories and velocities. Because of the Doppler effect, each affected atom's emission frequency (which is analogous to the precession rate of a proton axis) is changed. The ensemble of atoms is no longer in a state of hidden order. In the racetrack analogy it is as though collisions between the runners had changed each runner's velocity. In the NMR case the same kind of decay occurs because some molecules of the liquid sample diffuse randomly to regions of differing magnetic field strength.

Returning to the racetrack analogy, imagine that the starter fires the gun many times in rapid succession, each time causing the runners to reverse their paths. Even if a runner's speed has changed slightly (because of a collision) between gunshots, he will still be in approximate alignment with the other runners as they cross the starting line, because he will not have deviated very far from his "ordered" position in the short time between shots.

This multiple-reversal sequence has an even more dramatic effect. Suppose a certain runner's speed has been slightly increased by a collision. He will thus run a greater distance per unit of time than he would have if no runner had collided with another. Since he repeatedly reverses his direction, however, he deviates from his ordered position, first in one direction and then in the other, by equal amounts. The distance by which he deviates from his ordered position will therefore average out to zero. He will stay roughly in alignment with the other runners. In a sense it is as though the collision never happened.

In the same way, if a gaseous sample was excited with many closely spaced pulses, then the Doppler shifts caused by elastic collisions would be averaged out to zero. An atom that has changed its velocity will indeed have an emission frequency different from that of the average atom. Since, however, each of the multiple pulses will reverse that atom's phase (as each gunshot will reverse a runner's direction), the atom's emission frequency will alternate between being higher and lower than the mean. On the average the atoms will be excited in unison. Since the atoms remain synchronized, the effect of elastic collisions is minimized.

After each of the many pulses the atoms will come back into alignment, as the runners do between the multiple gunshots, and each time the atoms realign they emit another echo pulse. The chain of many pulses thus produces a chain of many echoes, one echo between each pair of pulses.

The Carr-Purcell multipulse experiment is really a way of enhancing the ordinary echo effect; the experimenter applies many incident pulses in order to produce many echoes, prolonging the sample's state of order.

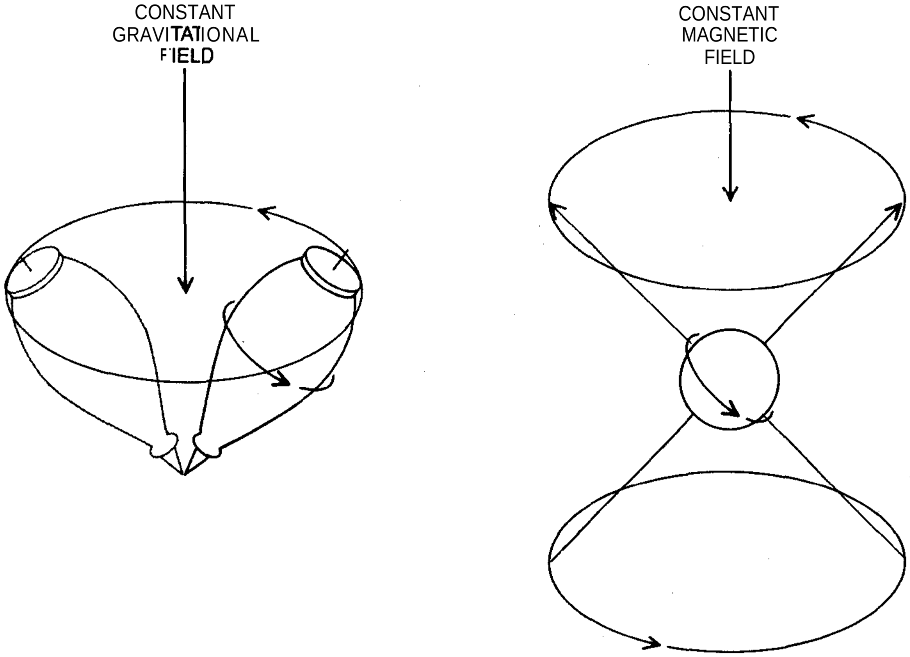
There is another type of multiple pulse experiment which is even more striking. Called the "magic-sandwich echo" effect, it was first demonstrated by John S. Waugh, along with Won-Kyu Rhim and Alex Pines, who were then students of his at the Massachusetts Institute of Technology. The effect involves subjecting a sample to a long series of specially processed pulses in order to produce a single echo. What is special about the magic-sandwich echo effect is that it can be demonstrated in a sample that would ordinarily not produce any echo at all. Without the application of this unusual train of pulses, the sample's earlier state of order could never be recovered.

In a typical magic-sandwich experiment a calcium fluoride crystal is placed in a constant magnetic field. As in the spin-echo experiment, an rf pulse that tips the spin axes of the fluorine nuclei by 90 degrees is applied to the sample. The crystal then emits a free induction decay signal, like that emitted by the liquid sample in a spin-echo experiment. After the signal has died out another 90-degree pulse is applied, followed immediately by a long series of 180-degree pulses in rapid succession and then by another 90-degree pulse. This is the sandwich: the two 90-degree pulses represent the bread and the series of 180-degree pulses is the filling.

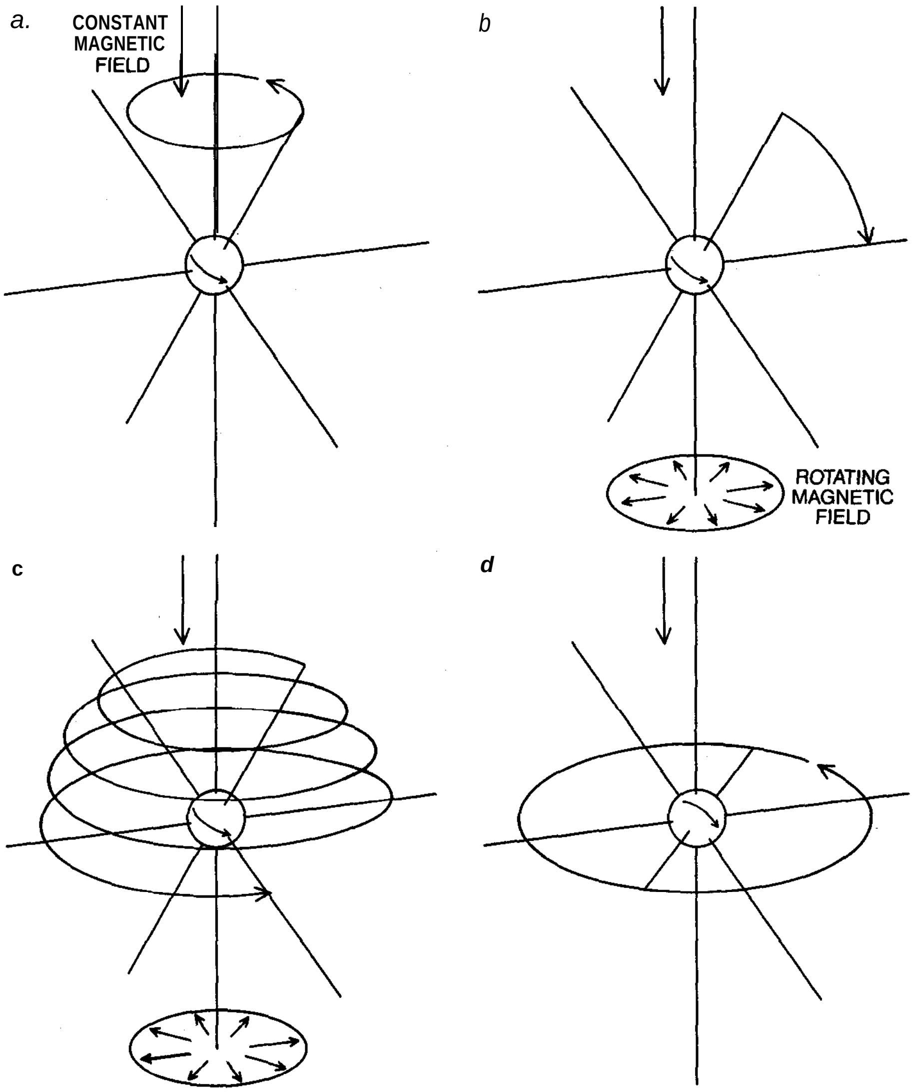
There is still no simple pictorial model for describing what happens during the magic-sandwich effect. It can only be said (according to the currently accepted mathematical description) that the magic sandwich actually changes the sign of the equation of motion for the fluorine nuclei; that is, it achieves precisely the momentum reversal that Loschmidt described to Boltzmann.

Even in an experiment involving multiple pulses there is still some decay of the echo signal; succeeding echoes grow weaker. This decay, in the case of a gas is due primarily to inelastic collisions, which are collisions violent enough to produce irreversible quantum changes in the energy levels of the atoms involved. The echo decay in a multipulse experiment is therefore a measure of the rate of inelastic collisions and diffusion in a sample. This means that a multipulse experiment can be used to select specific types of atomic interactions for study without the complication of competing dynamic processes.

There is yet another way to produce atomic memory, one in which time reversal is not required. The basic idea appears in the racetrack analogy. It is possible to have all the runners travel at



GYROSCOPIC PRECESSION in a gravitational field models the precession of a proton in a magnetic field. The axis of a spinning, tilted gyroscope (left) moves in a horizontal circle, a motion called precession about a constant force (in this case the force of gravity). In the same way a proton (right), a charged particle with intrinsic spin, precesses about a constant magnetic field.



PRECESSION OF A SPINNING PROTON subjected simultaneously to a constant magnetic field and a rotating (circularly polarized) magnetic field is the combination of two simpler precessions. The first is a precession about the constant magnetic field (a, color). If the second, rotating field rotates at precisely the rate at which the proton's spin axis precesses, the angle between the two remains constant; from the vantage of the precessing proton the rotating field seems to be a constant one, and the axis precesses downward about this horizontal field (b, color). The combination of these two motions, as seen by an outside observer, is a downward spiral (c, color). The rotating field is turned off once the spin axis lies in the plane perpendicular to the constant field, and the axis continues to precess about the constant field (d, color), staying in this plane.

the same radial speed, preserving their initial alignment. This is the simplest case of all, but how can it be achieved?

In gaseous sample it is possible to select all the atoms that have one specific velocity by exciting the sample with a nearly monochromatic (single frequency) continuous wave (cw) laser beam of the appropriate resonant frequency. Because of the Doppler effect, identical atoms moving at different velocities will absorb light at slightly different frequencies. If the laser frequency is spectrally pure, that is, if it is essentially a single frequency, then only the atoms with one particular velocity will be selected and prepared coherently. To return to the racetrack analogy, it is as if runners of only one particular speed were allowed to start the race.

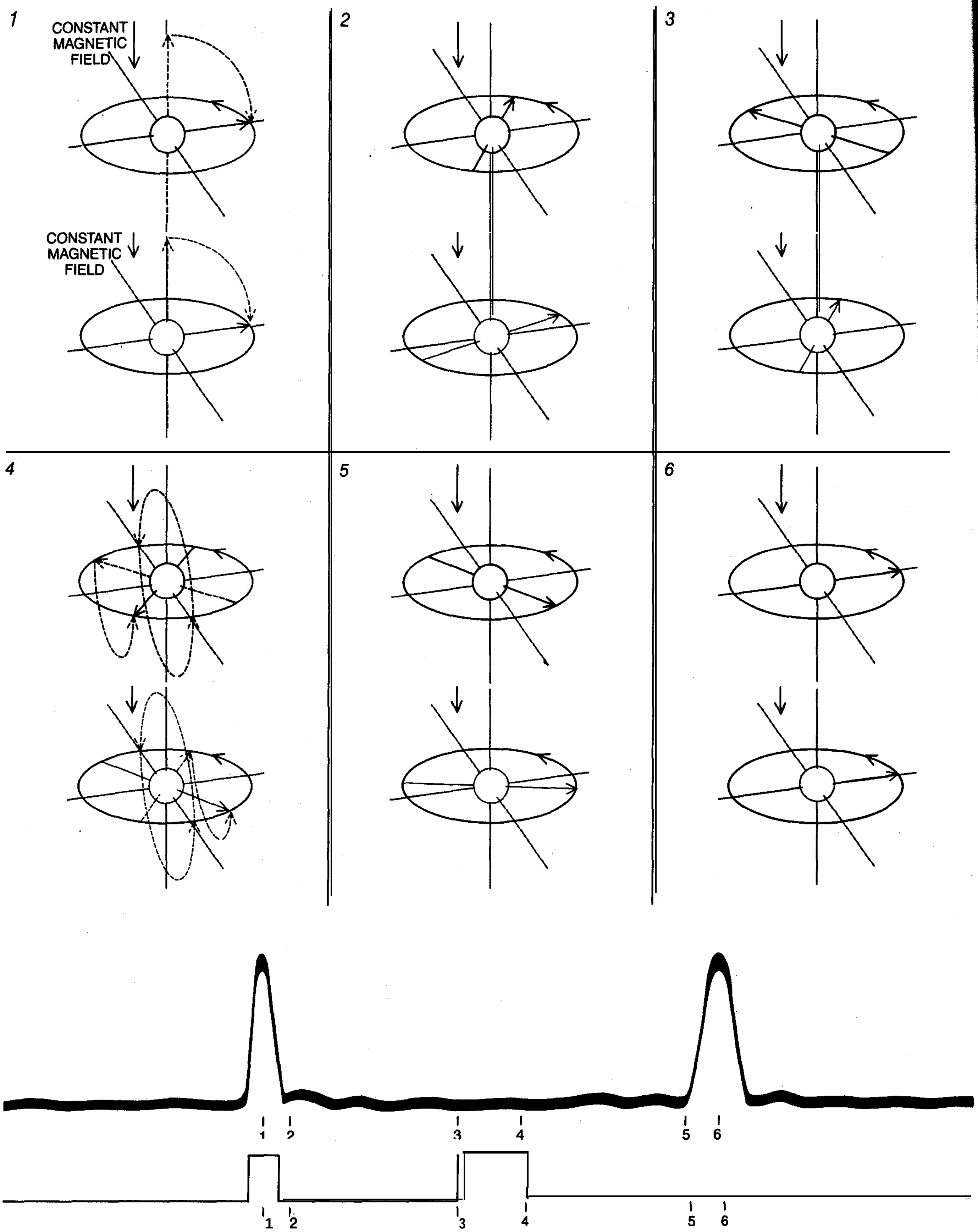
The alignment of these coherently preparred atoms is demonstrated in a laser-frequency-switching apparatus: after a long excitation period the frequency of the laser beam is suddenly switched to a new value so that it is no longer in resonance with the prepared group of atoms. This switching ends the excitation. The coherently prepared atoms, however, now act like a set of identical tuning forks that have been struck simultaneously: since they all have the same resonant frequency, they reinforce one another and radiate in unison an intense, coherent beam of light in the forward direction. The beam has all the properties of laser light (coherence, directionality and a single frequency) because the atoms retain a memory of their ordered state. This is the optical analogue of the free induction decay associated with magnetic resonance.

The free induction decay effect was first discovered in NMR in the radio-frequecy region by one of us (Hahn) and in the optical region by the other of us and Richard L. Shoemaker, now at the University of Arizona. Like the echo effect free induction decay enables the physicist or chemist to measure, in materials of many types, properties that are ordinarily difficult to observe. By studying the decay of various emission frequencies under different conditions, one can achieve a better understanding of the interactions within and among the molecules of a sample.

Laser frequency switching was introduced at the International Business Machines Corporation's San Jose Research Laboratory by one of us (Brewer) in collaboration with Azriel Z. Genack. It has been used to observe not only free induction decay but also an entire class of atomic memory phenomena. The process of tuning the laser into and out of resonance with an atomic sample is equivalent in a sense to applying pulses of laser light; thus switching a laser into resonance with a sample for two short periods of time is essentially equivalent to applying two short laser bursts and will produce the same echo phenomenon. The frequency-switching technique has the advantage that switching processes can be more precisely timed and controlled by electro-optic devices. In addition interference between the sample's emission and the laser light (at its new frequency) produces a strong (heterodyne) beat signal that can be used to distinguish the sample's emission from any background noise.

One of us (Brewer), with Ralph G. DeVoe of IBM, has recently used the laser-frequency-switching technique to examine the fundamental gyroscopic equations used by Bloch in his first description of NMR. According to Bloch's equations, the nuclear-memory decay time should not depend on the strength of the applied fields. In 1955 Alfred G. Redfield showed, using thermodynamic arguments, that these equations required modification. He observed the nuclear magnetic resonance of a pure metal and found that an intense radio-frequency field can actually lengthen the memory lifetime (that is, reduce the rate of decay) through a time-averaging effect that is similar in some ways to a time reversal.

DeVoe and Brewer have extended Redfield's argument into the optical region. To do so they used one of the stablest tunable lasers in existence (the laser's emission frequency can be adjusted and, when it is set, is stable to five parts in 10 million million). With this laser DeVoe and Brewer performed a

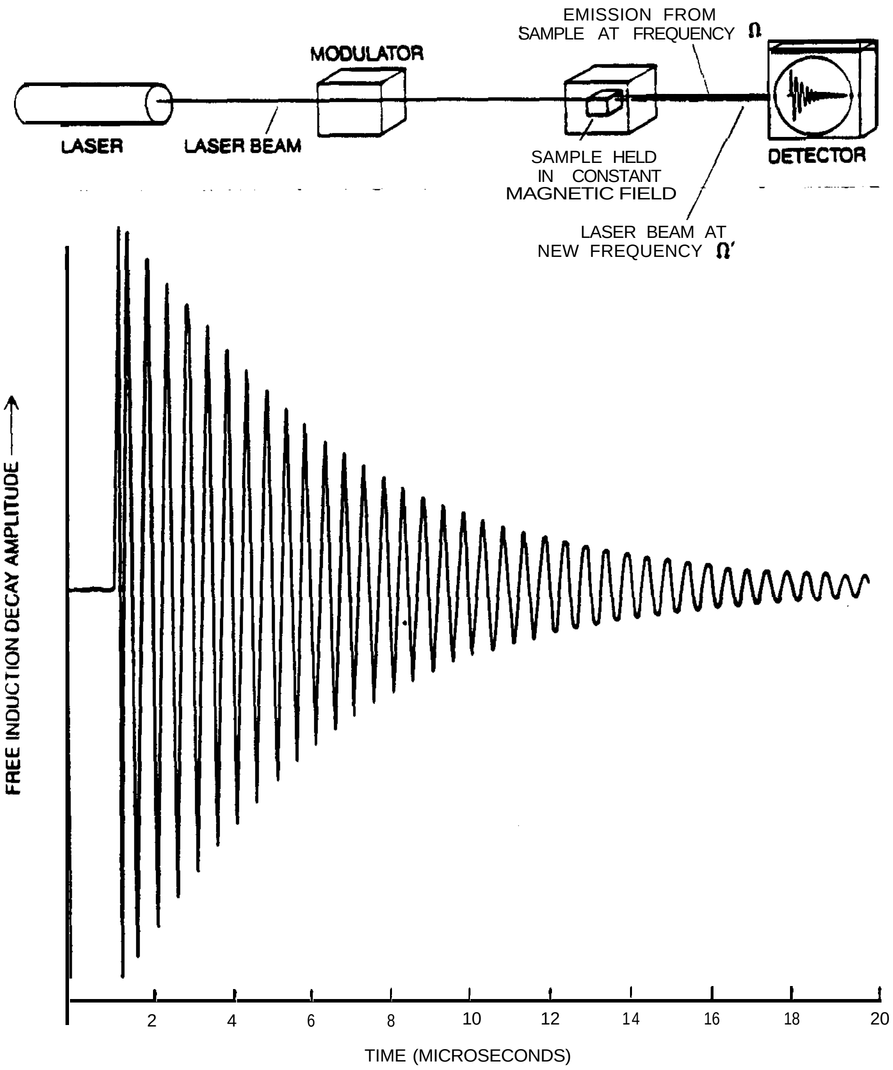


SPIN-ECHO EFFECT is induced by two radio-frequency (rf) pulses, which tip the spin axes of the protons in a liquid sample in a constant magnetic field. Two representative protons are shown; the magnetic field in the region of the black proton is stronger than the field in the region of the colored one. In I the first pulse tips the axes until they lie in a plane perpendicular to the constant field, where they continue to precess. Since the constant field differs from region to region within tbe sample, some axes will precess faster than others and will come to point in different directions (2, 3). A second rf pulse, twice as long as the first, then flips the plane in which the spin axes precess until they lie in the same plane as before but with the relative positions of faster- and slower-precessing axes reversed (4). The faster-precessing axes are now behind the slower ones (5). Like the faster runners, they will eventually catch up (6). The two oscilloscope traces represent the sequence of rf pulses (top) and the signals given off by the sample when the protons align (bottom), including the echo pulse (6).

free induction decay experiment. The sample examined was a crystal of lanthanum trifluoride containing praseodymium impurity ions. A nuclear magnetic interactton between the praseodymium and the neighboring fluorine nuclei caused the memory decay.

Like a proton. a fluorine nucleus behaves as a spinning charge, creating its own magnetic field. The fields of fluorine nuclei are strong enough to flip neighboring fluorine nuclei in the same way as an rf pulse can flip a proton. When a duorine nucleus flips, the resulting change in the local magnetic field is sometimes strong enough to flip yet another neighboring fluorine nucleus. Such random sequences of spin flipping are common in the lanthanum trifluoride crystal.

When a lanthanum trifluoride crystal is exposed to coherent laser radiation of the correct resonant frequency, the praseodymium ions become synchronized and emit their own coherent radiation. a free inductton decay signal. Fluorine nuclei that undergo random sptn flipping can desynchronize the neighboring praseodymium tons. causing the coherent optical emission to die out.



LASER-FREQUENCY-SWITCHING APPARATUS was used by one of the authors (Brewer) and Ralph G. DeVoe to observe another class of atomic memory effects. A laser beam of frequency Ω is used to excite a crystal sample, which is held in a constant magnetic field (center). Then the laser frequency is switched to a new value, Ω', by a modulator (left). The sample itself, resonating from the first laser beam, gives off coherent radiation, the optical free induction decay, at the original frequency Ω. Emission from the sample combines with the laser beam to produce an interference signal at a detector (right). The duration of this signal tells the experimenter how long the atoms of the sample retain a memory of the initial laser beam.

DeVoe and Brewer measured this decay time using the laser-frequency-switching technique described above. They excited a sample of lanthanum trifluoride with a tunable dye laser and then switched the frequency of the laser so that it no longer resonated with the praseodymium impurity ions. This required an extraordinarily frequency-stable laser in order to excite a very small range of frequencies: the linewidth of praseodymium is only 10 kilohertz. roughly 10 million times narrower than earlier optical measurements in solids. Once the laser frequency had been swttched. the praseodymium emitted the free induction stgnal. which decayed in about 17 microseconds.

It is possible to quench the magnetic interaction between fluorine and praseodymium by increasing the intensity of the laser used to excite the crystal. An increase in laser intensity drives the praseodymium ions more rapidly between higher and lower quantum states as they absorb and reemit photons. Each time the praseodymium ion goes through an absorption-emission cycle. the nuclear magnetic interaction between it and the neighboring fluorine nuclei changes sign; in other words, the interaction that had been present between a praseodymium ion and a fluorine nucleus will act in the opposite direction after the praseodymium ion has absorbed and reemitted a photon. Thus a fluorine nucleus that had been causing a praseodymium ion to desynchronize from the others will effectively reverse its effect on that ion and force it back into synchronization. This is similar to the reversal of phase order produced by the laser. in a multipulse Carr-Purcell experiment. If the time between reversals of phase order is shorter than the time between the desynchronizing events (in this case random fluorine flips), then the disturbances caused by the fluorine nuclei are compensated because their interactions with the praseodymium are reversed. With Axel Schenzle of the University of Essen in West Germany and Masaharu Mitsunaga of IBM, DeVoe and Brewer have developed a general microscopic quantum theory of this phenomenon that extends Redfield's thermodynamic argument into the optical part of the spectrum for the first tune.

The techniques of pulsed radio-frequency radiation. the principles of which have been known for nearly 40 years, are important tools in science and medicine. primarily in NMR body imaging and the structural analysis of chemical compounds and the solid state. With the development of extremely precise and stable lasers. these methods are just now being made possible in the optical region.

These atomic-memory phenomena would have delighted Loschmidt because they show that some types of decay, even decay caused by random collisions, can be reversed. Beyond their philosophical charm. however, atomic-memory phenomena can be very useful. By eliminating the decoy effects of some processes. they enable physicists to study other processes in greater detail. giving us a clearer view into the structure and interactions of materials on the atomic level.