the viroid character of the genome of [hepatitis delta virus] encourages speculation about its possible plant origin."

It so happens that during the past year several researchers have noted structural similarities between viroids and the group of introns known as group I.

Group I introns include those in mitochondrial messenger and ribosomal RNA genes, chloroplast transfer RNA genes, and nuclear ribosomal RNA genes. These introns are characterized by the possession of a series of conserved regions, which impose certain secondary and tertiary structure constraints. What is most intriguing about these introns is that at least some of them are able to self-splice, that is to excise themselves and ligate the parental strands in the absence of enzymes, releasing a small circular RNA molecule.

In separate studies Gail Dinter-Gottlieb, of Drexel University, and A. Hadidi, of the Plant Protection Institute, Beltsville, Maryland, noted echoes of the group I intron conserved regions in most viroid structures they examined. In addition, parts of the central conserved region were also to be found in the introns. Both authors suggested some kind of evolutionary relationship between the two groups of RNA molecules, and Dinter-Gottlieb wondered whether viroids may be "escaped introns."

"When we saw Dinter-Gottlieb's paper we immediately looked at the hepatitis delta virus to see if there were any group I intron homologies to be found," Houghton told *Science*. "What we saw wasn't particularly striking, but there are some homologies that are probably statistically significant." The link between the delta virus, the viroids, and the group I introns is therefore complete.

Several interpretations of what this might mean are possible. For instance, perhaps both plant viroids and the hepatitis delta virus (including any other similar agents) are escaped introns. Instead, all three classes of RNA molecule may have derived from an as yet unidentified ancestor molecule. Or perhaps some other relational combination applies. As Houghton says, "It is hazardous to speculate too firmly about it." The guessing game will be settled only by more detailed sequence comparisons. ■

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ADDITIONAL READING

K.-S. Wang *et al.*, "Structure, sequence and expression of the hepatitis delta viral genome," *Nature (London)* **323**, 508 (1986).

A. Kos *et al.*, "The hepatitis delta virus possesses a circular RNA," *ibid.* **323**, 558 (1986).

G. Dinter-Gottlieb, "Viroids and virusoids are related to group I introns," *Proc. Natl. Acad. Sci. U.S.A.* **83**, 6250 (1986).

A. Hadidi, "Relationship of viroids and certain other plant pathogenic nucleic acids to group I and II introns," *Plant Mol. Biol.* 7, 129 (1986).

An Optical Measurement of Berry's Phase

Overlooked for 60 years, a phase factor that can creep into quantum mechanical wave functions has implications in areas ranging from molecular physics to unified field theories

THREE years ago while lecturing in the United States, Michael Berry of the University of Bristol found himself unable to field a question on the behavior of certain types of quantum mechanical wave functions when time-reversal symmetry was violated. Berry went home, spent 2 weeks thinking through the question, and discovered what he called the quantum adiabatic phase, although everyone else now calls it Berry's phase. The quantum adiabatic theorem, which Berry's phase modifies, is almost as old as quantum mechanics itself. "It should have been discovered 50 years ago," says Barry Simon of the California Institute of Technology.

The path dependence is what makes Berry's phase a geometric effect.

The finding triggered a flurry of theoretical papers showing how Berry's phase turns up in contexts ranging from the mature field of molecular physics to the arcane world of the quantum field theories known as gauge theories. A key paper by Simon recast Berry's result, which is geometrical in origin, in the compact language of differential geometry. Simon's treatment not only makes computation less ponderous, but it also underscores the close connection between geometry and modern theoretical physics, where the topological properties of curved surfaces have become of decisive importance.

While the theoretical work has left no doubt as to the existence of Berry's geometrical phase, direct experimental confirmation was lacking until recently. In August, Akira Tomita, who is now at the Raychem Corporation, Menlo Park, California, and Raymond Chiao of the University of California at Berkeley published the first experimental measurement of Berry's phase. In short, as predicted by Chiao and Yong-Shi Wu of the University of Utah, the angle of rotation of linearly polarized laser light on passing through a helical, single-mode optical fiber is a measure of the geometrical phase. It is conceivable, says Chiao, that this kind of optical activity in a fiber will have applications in optical devices, such as wavelength-independent phase shifters and optical rotators. Although highly speculative at the moment, Berry's phase could also be the basis for optical fiber gyroscopes and memory devices.

In June, Guy Delacrétaz and Ludger Wöste of the Swiss Federal Institute for Technology in Lausanne, Edward Grant and Josef Zwanziger, who are now at Purdue University, and Robert Whetten of the University of California at Los Angeles reported a spectroscopic study of triatomic sodium clusters in a supercooled molecular beam. Although the experiment did not measure Berry's phase, it did show that the so-called pseudorotational quantum numbers of a cluster are half integers, which is a direct consequence of Berry's phase. Ordinarily, pseudorotational quantum numbers are integers only.

It turns out that other hints of Berry's phase have appeared in the molecular physics literature for almost 30 years, but no one interpreted them to mean that standard treatments of the quantum adiabatic theorem were incomplete. In both classical and quantum mechanics, adiabatic refers to a change that takes place very slowly in the environment of a physical system. For example, molecular physicists commonly assume that the vibrational and rotational motions of the nuclei are so slow compared to the orbital motion of the electrons that the nuclear movement constitutes an adiabatic change in the environment of the electrons.

According to the quantum adiabatic theorem, which was discussed as early as 1928, if the change is slow enough, the wave function of the physical system will instantaneously adjust to the change. In particular, if the environment returns to its original condition after an adiabatic excursion, the wave function will also return to its original value multiplied by what is called a dynamic phase factor whose value depends on the time duration of the excursion. Except in special cases where interference effects may arise, the dynamic phase factor has no measurable consequences.

What Berry showed is that there is a second, geometric phase factor that is generated during an adiabatic excursion of any parameter that characterizes the environment of a physical system. This phase factor is independent of the duration of the excursion, but its value does depend on the particular path taken in an abstract coordinate system or "parameter space" through which the trajectories of environmental changes can be imagined as traveling. The path dependence is what makes Berry's phase a geometric effect.

An essential ingredient in the generation of Berry's phase is the existence of a curved surface, each point of which represents the wave function for a different value of the environmental parameter. The adiabatic excursion traces out a closed curve on this surface. The idea is easily visualized with the aid of a globe. Hold a pencil tangent to the surface of the globe so that it is on the equator and parallel to it. Keeping the pencil tangent to the surface at all times and without rotating it in any manner when making turns, make the following circuit. Move the pencil around the equator 90°. Then, move it toward the North Pole along a longitude line. Upon reaching the North Pole, move it back down the longitude line that intersects the starting point. At the end of the circuit, the pencil will have rotated 90°.

The rotation occurs, despite the best efforts of the pencil carrier to maintain the pencil in a fixed orientation with respect to the local environment, because of the curvature of the surface of the globe. In particular, the integral around the circuit of the curvature of the surface is nonzero. A similar excursion, which mathematicians call parallel transport of vectors, will result in no rotation if it is made on a flat surface, such as a tabletop.

Berry derived a general, if somewhat cumbersome, expression for the geometric phase that was published in 1984. In his reformulation of Berry's phase in the language of differential geometry, Simon equated the geometric phase with the holonomy for the connection of a Hermitian line bundle in Hilbert space. The holonomy is associated with the curvature of the line bundle. Without trying to translate this language back into English, suffice it to say that the situation is formally equivalent to parallel transport of a vector. The important point for theorists is that computation is made easier by taking the differential geometry point of view.

The gauge fields that permeate modern theoretical physics also have a strong geometrical character, so it may not be surprising that there is a conceptual connection between Berry's phase and gauge fields. The simplest example of a gauge field is the electromagnetic field. The vector and scalar potential functions that generate the classical electromagnetic field arise from the requirement that the Schrödinger equation, which governs the motion of nonrelativistic electrons, be invariant when the phase of an electron wave function is a function of position and time. The same idea holds in an appropriately generalized way all the way up to the grandest of the grand unified field theories.

Molecules provide a natural stage for Berry's phase to do its act because of the central role of the quantum adiabatic theorem.

Aharonov-Bohm oscillations, named for Yakir Aharonov of the University of Tel Aviv and David Bohm of Birkbeck College (London), illustrate the relation between gauge fields and Berry's phase. Fittingly, Aharonov and Bohm were both visiting at the University of Bristol in 1959, when they predicted the oscillations, and R. G. Chambers, who verified the existence of the oscillations experimentally the following year, is still there.

The oscillations arise when a coherent electron beam is split into two parts that pass on opposite sides of a solenoid before recombining. When detected, the recombined electrons form a characteristic interference pattern owing to their different path lengths and hence dynamic phases. However, there is a magnetic field that is entirely inside the solenoid, so that it perturbs neither the paths of the electrons nor their dynamic phases. Yet the positions of the peaks and valleys of the interference pattern depend on the magnetic flux in the solenoid. In particular, they shift periodically with the value of the magnetic flux, hence the term "oscillations."

Berry argued that the circulation of the electrons around the solenoid is a special case of the more general adiabatic excursion already discussed. In the translation of the language of differential geometry to that of physics, a connection on a line bundle corresponds to a vector potential of a gauge field. For Aharonov-Bohm oscillations, the adiabatic excursion takes place in real space containing a physical gauge field, and the result is the generation of an extra phase that depends both on the strength of the field and on the direction the electrons take around it. Generation of Berry's phase during a more general adiabatic excursion through parameter space can similarly be traced to the influence of a gauge field, although in general it is a fictitious, nonphysical field.

One example of such a fictitious field discussed by Berry occurs when a physical system with a nondegenerate wave function makes an adiabatic excursion that takes it near a degeneracy. "Degenerate" means that more than one wave function has the same energy; normally nondegenerate wave functions may become degenerate for certain values of environmental parameters. Nondegenerate electronic wave functions of a molecule may become degenerate for certain internuclear separations, for example. The fictitious field that generates Berry's phase during an adiabatic excursion around such a degeneracy is that of a stationary magnetic monopole. Here "fictitious" means that the field does not exist, but the physical system behaves as if its equation of motion contained the vector potential for the field. The Coriolis force in rotating coordinate systems is a more familiar example of a fictitious force.

Molecules provide a natural stage for Berry's phase to do its act because of the central role of the quantum adiabatic theorem in calculating electronic and vibrational properties. For example, in the Born-Oppenheimer approximation, the electronic wave functions can be calculated with the slow-moving nuclei assumed to be motionless. And the nuclear motion can be calculated as if the electrons, which are the "springs" that hold the twisting, vibrating molecule together, respond immediately. In some sense, Berry's phase in molecules is due to electronic springs that do not respond instantaneously.

In any case, reports of strange behavior now understood to be attributable to Berry's phase date back at least as far as 1957. In a 1963 publication, H. C. Longuet-Higgins of the University of Sussex and Gerhard Herzberg of the Canadian National Research Council in Ottawa showed that if the internuclear coordinates of a molecule make an adiabatic circuit around an electronic degeneracy, then the electronic wave function changes sign; that is, its phase changes by π. In 1979, C. Alden Mead and Donald Truhlar of the University of Minnesota discussed the need for the addition of a vector potential term in the quantum mechanical equation of motion for nuclear wave functions near an electronic degeneracy.

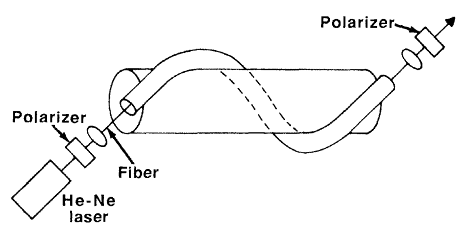
The experiment by Delacrétaz and his coworkers is the first in molecules to be interpreted in terms of Berry's phase, although the prediction that fractional pseudorotational quantum numbers should exist in certain molecules was made in 1961 by Longuet-Higgins. Pseudorotation refers to the motion in molecules undergoing so-called dynamic Jahn-Teller distortions. A static Jahn-Teller distortion occurs when a nominally symmetric molecule, such as a triatomic sodium cluster in the shape of an equilateral triangle, can lower its energy by adopting a nonsymmetric configuration. However, the molecular configuration may change continuously with time in a periodic manner, which is the dynamic Jahn-Teller effect.

In the course of one period, the dynamic Jahn-Teller motion for triatomic sodium corresponds to the rotation of a distorted triangle, hence the term "pseudorotation." Pseudorotation takes the cluster on an adiabatic circuit around the symmetric, electronically degenerate configuration, which is the signal for Berry's phase to come into play. The phase manifests itself in the pattern of peaks in the two-photon photoionization spectrum for the cluster, which the investigators could only fit by assuming half-integer pseudorotational quantum numbers. The result is quite striking because angular momentum quantum numbers for atoms and molecules that do not involve spin are always integers.

Half-integer quantum numbers correspond to a Berry's phase of π; that is, to a sign change in the wave function. It may be possible to measure Berry's phase directly in a sodium cluster by means of the fluorescence emitted when a cluster is excited to a particular quantum state by light from a picosecond-pulse laser. The consequences on the fluorescence should be dramatic as the sign of the electronic wave function changes, says Whetten. However, molecular systems provide no opportunities for exploring other values of the phase and demonstrating its topological character.

The optical fiber experiment of Tomita and Chiao allows these kinds of measurements. In his original paper, Berry had suggested for such demonstrations an interference experiment with particles that have a magnetic dipole moment, such as a neutron. Some particles would pass through a magnetic field whose orientation changed slowly with time, carrying the magnetic dipole moment vector with it. The field would make a complete circuit back to the original orientation, so that there would be no net change in the dipole moment of the particle. Other particles would bypass the field. The positions of the peaks and valleys of the interference pattern when the two beams recombined would be a measure of the Berry's phase acquired by the particles traveling through the field.

Because this experiment is not so easy in practice, Chiao and Wu analyzed an analogous situation involving photons in a gently wound optical fiber. With circularly polarized light, for example, the spin angular momentum of the photon is in the direction of motion. In particular, the spin angular momentum vector smoothly follows the direction of the light through the fiber. After one winding of the fiber, the photon spin returns to its original orientation, but the photon wave function has acquired a Berry's phase determined by the pitch of the helical fiber. Interference could be observed between circularly polarized light that is divided between two helical fibers wound in opposite senses and then brought back together.



Measuring Berry's phase. *An optical fiber inside a Teflon sleeve winds helically around a cylinder. The plane of linearly polarized light from a helium-neon laser rotates when the light passes through the fiber.*

Alternatively, linearly polarized light passing through a helical fiber would have its plane of polarization rotated clockwise for a left-handed helix and counterclockwise for a right-handed helix. The angle of rotation is determined by both the dynamical and geometrical phases, but the former is negligible in fibers made of a material with no optical activity; that is, a material that cannot rotate linearly polarized light passing through a straight fiber. Tomita and Chiao did their experiment with linearly polarized light.

As it happens, in the last 2 years, other researchers have made similar measurements on optical fibers, have observed rotation of the plane of polarization, but did not make the connection with Berry's phase. Tomita and Chiao did two types of experiments. The first series involved uniform helices of different pitch. The second involved nonuniform helices of different average pitch. The variable environmental parameter is the momentum vector of the photon, which rotates as the photon makes its way through the fiber. The effect of the different types of helices was to vary the solid angle subtended in momentum space by the path of the fiber. For uniform helices, the path is a circle on a sphere, whereas for nonuniform helices the path is a noncircular closed curve. The essential finding was that the rotation angle of the plane of polarization depended only on this solid angle, in quantitative agreement with the calculations of Chiao and Wu.

Although these calculations were quantum mechanical, it happens that, as is usually the case with optical phenomena, classical optics provides the same results. Purists might insist, therefore, that Tomita and Chiao have demonstrated the classical analog of Berry's phase. John Hannay of the University of Bristol and Berry have independently discussed the geometrical phase in classical and semiclassical mechanics. The way to ensure measuring a truly quantum effect is by means of an experiment in which only a single photon is in the fiber at any instant, so that any interference must be due to the phase of the photon wave function; that is, to its quantum character. Chiao says that such experiments are under way.

If experiments demonstrating Berry's phase remain sparse, contributions on the theoretical side have been more numerous. Berry told *Science* that he gets two or three preprints a week to read. Already published are generalizations of Berry's theory to include degenerate physical systems and cases where the slowly varying environment is itself treated as a fully quantum mechanical system. For example, Frank Wilczek of the University of California at Santa Barbara and Anthony Zee of the University of Washington have shown how non-Abelian gauge fields of the type that dominate elementary particle theory arise in the adiabatic development of degenerate physical systems. Theorists have also shown that Berry's phase pops up in such fashionable topics as the quantum Hall effect and anomalies in gauge theories that cause them to violate conservation of energy or other cherished symmetries of physics.

All in all, if the full implications of Berry's phase are not yet apparent, its ubiquity makes it nonetheless surprising that the phase could have been overlooked for so long. ■ ARTHUR L. ROBINSON

ADDITIONAL READING

M. V. Berry, "Quantal phase factors accompanying adiabatic changes," *Proc. R. Soc. London, Ser. A* **392**, 45 (1984).

B. Simon, "Holonomy, the quantum adiabatic theorem, and Berry's phase," *Phys. Rev. Lett.* **51**, 2167 (1983).

G. Delacrétaz, E. R. Grant, R. L. Whetten, L. Wöste, J. W. Zwanziger, "Fractional quantization of molecular pseudorotation in Na_3," *ibid.* **56**, 2598 (1986).

A. Tomita and R. Y. Chiao, "Observation of Berry's topological phase by use of an optical fiber," *ibid.* **57**, 937 (1986).