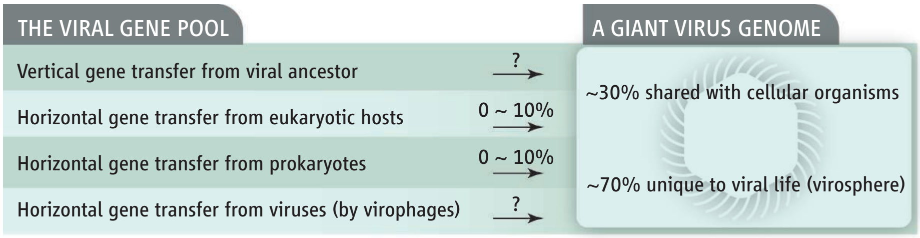

Origin of genes in large eukaryotic viruses. The distribution of sequence database matches suggests diverse origins for the genes of large DNA viruses. Horizontal gene transfer may occur through exposure to host or prokaryotic DNA. The many genes unique to viruses are vertically or horizontally transferred between viruses—a process in which the newly discovered virophages may play a key role.

and results in "sick" APM virions with aberrant morphologies. Sputnik thus behaves as a true parasite with a detrimental effect on APM reproduction.

Small viruses requiring other larger viruses for their reproduction have previously been documented. These "satellite viruses" lack essential functions for multiplication, for which they exploit their "helper viruses." La Scola *et al.* (*8*) argue that Sputnik is more than a satellite virus, because it uses its partner's virus factory and impairs its fitness. They therefore call Sputnik a "virophage."

What is the origin of the Sputnik virophage? The authors provide evidence suggesting the existence of related virophages in the oceans (*8*). Marine virologists have reported small viruses occurring with larger ones in marine protist populations (*9*, *10*). During recurrent infection of a cell by the two viruses, one virus may begin to benefit from the other. Like Sputnik, the small marine viruses multiply faster than the larger ones. If the viral genomes can physically interact, genes can be exchanged, and the two viruses may evolve into various states of dependency, from mutualisms to parasitism. In this context, it is worth noting that Sputnik has an integrase (an enzyme that inserts pieces of DNA from one DNA molecule into another). The genome of a marine virus, infecting the planktonic species *Emiliania huxleyi* contains a strange 176-kb central segment (*11*): Genes in this segment lack homologs in other viruses, but harbor a unique promoter. This segment is expressed much earlier than the rest of the viral genome and may be the integrated genome of an unknown virophage.

The genes in giant eukaryotic viruses have multiple origins (see the figure). The APM genome contains eukaryotic- or prokaryotic-like genes. Recent horizontal gene transfers from its eukaryotic hosts or prokaryotic organisms partially account for these genes. However, giant viral genomes also contain genes that are unique to viruses, the origin of which is hotly debated (*6*, *12*, *13*). Do these genes originate in vertical gene transfer from a very old viral common ancestor? The small number of genes shared among modern viruses argues against this possibility. Viral genome mosaicism is also suggested by the occurrence of very similar genes in different viruses (*14*). Furthermore, a substantial amount of horizontal gene transfer may occur between viruses. The Sputnik virophage now provides a new potential vehicle for such horizontal gene transfers. In fact, the Sputnik genome encodes several genes that may originate in vastly different viruses.

Assessing the proportions of vertical gene transfer and virus-virus horizontal gene transfer now appears crucial for understanding the evolution of giant viruses, refining the concept of virus lineage, and elucidating gene flow in the virosphere. The unusual features of the giant Mimivirus revived the popular, yet unresolved question: "Are viruses alive?" The discovery that some of them can get sick adds a new twist to this old debate.

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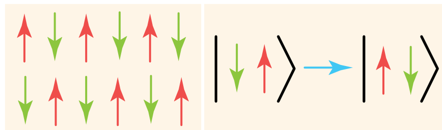
PHYSICS

An End to the Drought of Quantum Spin Liquids

Patrick A. Lee

After decades of searching, several promising examples of a new quantum state of matter have now emerged.

Electrons possess magnetic behavior through the quantum mechanical property of spin. The magnetic properties of materials then arise from the collective interaction of electrons on atoms within the crystal. Below a transition temperature, the electron spins of normal magnets "freeze" into an ordered array of magnetic dipoles. Whether the ordering is ferromagnetic (all the dipoles point in the same direction) or antiferromagnetic (the dipoles on adjacent sites point in opposite directions) is determined by the sign and strength of the interaction between the electrons. Early theoretical work has indicated a departure from these ordered states, suggesting that quantum mechanical fluctuations of the spin could be so strong that ordering would be suppressed and the spin ensemble would remain in a liquid-like state, even down to the lowest temperatures. Experimental evidence, which has until recently remained elusive, is emerging in favor of this long-predicted state of quantum matter.



Ordered spins. (**Left**) Néel's picture of antiferromagnet ordering with an alternate spin-up–spin-down pattern across the lattice. (**Right**) Quantum fluctuations lead to mutual spin flips, which Landau argued would disorder Néel's state.

To understand the controversy surrounding this exotic quantum spin liquid state, it is instructive to go back to the description of antiferromagnetism. Soon after the invention of quantum mechanics, Heisenberg pointed out that electron spins on neighboring atoms can have short-range interaction due to quantum mechanical exchange. Louis Néel

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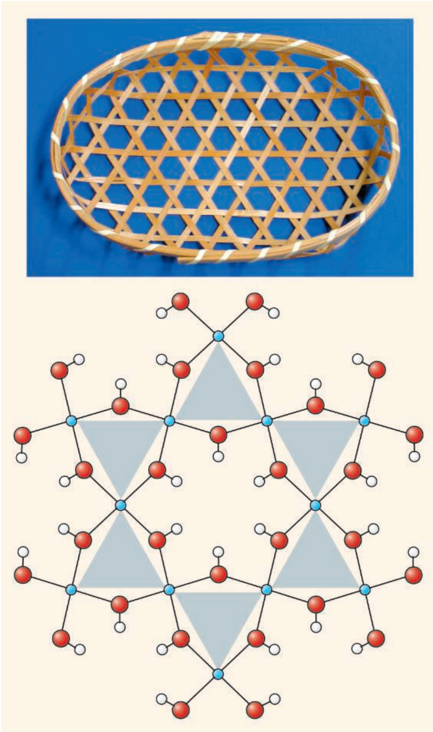
showed that a negative exchange interaction results in an antiparallel arrangement of neighboring spins, and that at low temperatures the spins order in an alternating up-down pattern (see the first figure, left panel) (*1*). This antiferromagnetic, or Néel, state was initially greeted with skepticism—Lev Landau was among the doubters (*2*).

Landau did not publish his objection, but on the basis of Friedel's comments (*2*) we can surmise that his argument was that the correct application of quantum mechanics to such a system would lead to fluctuations (see the first figure, right panel), which may completely randomize the spin order. It was not until 1949, when antiferromagnetic order was directly observed by neutron scattering, that Néel was fully vindicated. In fact, Néel's theory was far more successful than he had the right to expect: For 70 years the Néel state has prevailed.

In 1973, Philip W. Anderson reasoned that the best chance to defeat Néel ordering came in the form of "frustrated" spin systems (*3*), with the special example of spins on a triangular lattice. This lattice is "frustrated" because if an up- and down-spin occupy two corners of a triangle, the spin on the third corner does not know which way to point to obtain the lowest-energy configuration. Instead of a Néel state, Anderson proposed a ground state made up of a quantum mechanical superposition of singlet pairs that cover the lattice. He called this a resonating valence bond (RVB) state, an explicit example of a quantum spin liquid. Unfortunately, it was soon shown that neighboring spins in a triangular lattice manage to order at a 120° angle, and Néel once again won out.

The field of quantum spin liquids languished until 1987, when high-temperature superconductivity was discovered. Anderson pointed out a connection between the RVB spin liquid and the Cooper pairs of a superconductor (*4*). Attempts to justify the RVB theory of superconductivity led to rapid developments of the spin liquid theory. It is now understood that the spin liquid (defined as having an odd number of electron spins on each lattice unit cell) is a new state of matter with properties we have never encountered before. For example, the excited states may be spinons—charge-neutral objects that possess magnetic properties. Depending on the type of spin liquid, the spinon may obey Fermi or Bose statistics and there may or may not be an energy gap. Furthermore, these spinons cannot live by themselves but are generally accompanied by gauge fields, just as electrons are always accompanied by electromagnetic gauge fields (*5*). This is a dramatic example of emergent phenomena, where new particles and fields emerge at low-energy scales but are totally absent in the Hamiltonian that describes the initial system.

Confirmation of the existence of the spin liquid state has been elusive, and only recently have several promising examples surfaced. The first is an organic solid called κ-$(ET)_2Cu_2(CN)_3$ (*6*, *7*) in which the active ingredients are dimers of an organic molecule, ET [bis(ethylenedithio) - tetrathiafulvalene]. A single electron is localized on each dimer, which forms layers of approximately triangular lattices. Despite an exchange energy of ~250 K, no magnetic order was detected down to 30 mK. This material is an insulator but becomes a superconductor (critical temperature $T_c = 3.5$ K) and then a metal under pressure. It is believed that the proximity to an insulator-to-metal transition implies that the spins interact with a more complicated Hamiltonian than the Heisenberg model and allows the spin liquid state to form (*8*, *9*). Remarkably, the spin susceptibility goes to a constant at low temperatures and the specific heat is linear in temperature (*7*). These properties are normally associated with metals, being consequences of the electron Fermi surface. The linear specific heat is particularly unusual for an insulator that is relatively defect-free. Furthermore, the ratio of magnetic susceptibility to the linear temperature coefficient of the specific heat is close to that of free fermions. These observations strongly suggest that the excitations are indeed fermionic spinons that form a Fermi sea, and thus offer strong evidence for a spin liquid ground state.



Meeting with frustration. (**Top**) A Kagome basket. (**Bottom**) Structure of $ZnCu_3(OH)_6Cl_2$ (*10*) showing that the Cu ions (blue) occupy a Kagome lattice; O-H is red-white.

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Last year an entirely different class of spin liquid was discovered. It has long been suspected that spins on a Kagome lattice support a spin liquid ground state. Kagome is the Japanese name for the weave pattern of a basket (see the second figure, top panel). The structure consists of corner-sharing triangles and is even more frustrated than the triangular lattice considered by Anderson. Last year saw the synthesis of such a solid-state Kagome system: $ZnCu_3(OH)_6Cl_2$, where a single electron spin resides on the Cu (*10*) (see the second figure, bottom panel). Although the exchange energy is ~200 K, this material does not show any magnetic ordering down to millikelvin temperatures. The magnetic excitations are apparently gapless, but unlike the organic compound, the large specific heat at low temperatures is sensitive to magnetic field, which suggests that the low-temperature properties may be dominated by a few percent of local moment defects.

Spin liquids are not limited to two-dimensional systems. A newly synthesized material, $Na_4Ir_3O_8$, has Ir ions that form a three-dimensional network of corner-sharing triangles, termed a hyper-Kagome structure (*11*). Despite an exchange energy of ~300 K, no magnetic order was found down to 1 K and below.

It is an exciting time in the history of antiferromagnetism. After decades of searching, three examples of the defeat of Néel order by quantum fluctuations have been discovered in quick succession. There are good reasons to believe that fermionic spinons will emerge as the low-energy excitations, but more work will be needed to confirm this. An even more intriguing question is whether their partner, the emergent gauge field, can make its presence felt as well. We can be optimistic that even more exciting discoveries lie ahead.

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