A strange, elusive phenomenon called supersymmetry was conceived for elementary

Uncovering Supersymmetry

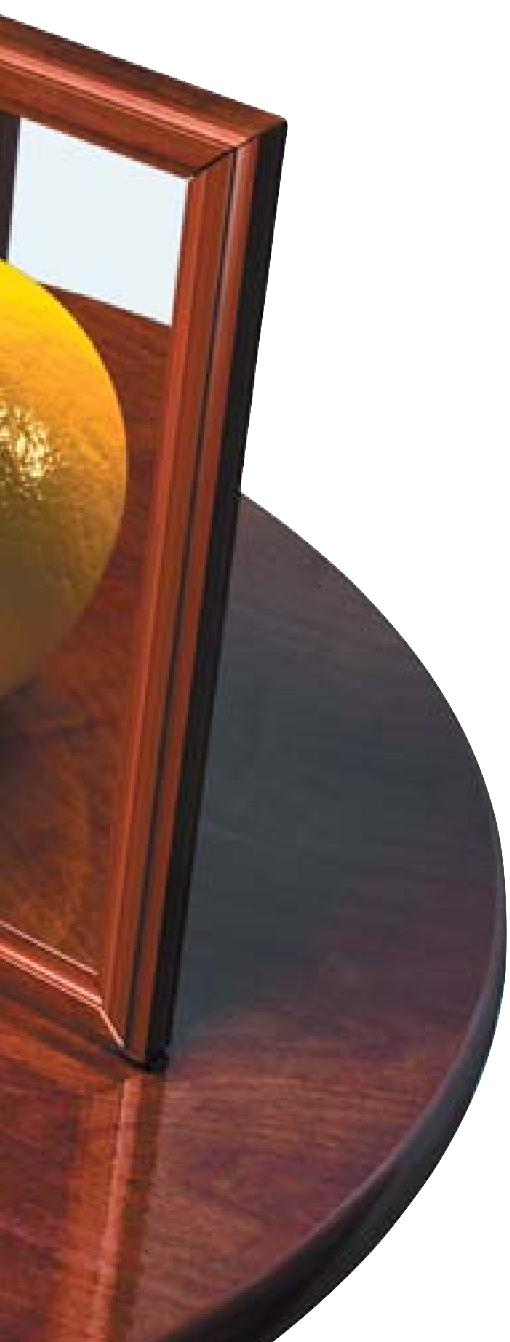
PROVERBIAL APPLES AND ORANGES are as different as the types of quantum particles called fermions and bosons. Just as an ordinary mirror cannot make an apple look like an orange, no ordinary symmetry in physics can transform a fermion into a boson, or vice versa. To do that trick requires supersymmetry, an extraordinary class of symmetries that may hold the key to a deep understanding of the universe.

particle physics—but has come to light in nuclei of platinum and gold

Uncovering Supersymmetry

By Jan Jolie

Illustrations by Bryan Christie Design



Supersymmetry is a remarkable symmetry. In elementary particle physics, it interchanges particles of completely dissimilar types—the kind called fermions (such as electrons, protons and neutrons), which make up the material world, and those called bosons (such as photons), which generate the forces of nature. Fermions are inherently the individualists and loners of the quantum particle world: no two fermions ever occupy the same quantum state. Their aversion to close company is strong enough to hold up a neutron star against collapse even when the crushing weight of gravity has overcome every other force of nature. Bosons, in contrast, are convivial copycats and readily gather in identical states. Every boson in a particular state encourages more of its species to emulate it. Under the right conditions, bosons form regimented armies of clones, such as the photons in a laser beam or the atoms in superfluid helium 4.

Yet somehow in the mirror of supersymmetry, standoffish fermions look magically like sociable bosons, and vice versa. Figuratively, you might say it is a symmetry that lets you compare apples and oranges. Hold up an apple to the supersymmetry mirror, and its reflection looks and tastes like an orange. All the ordinary symmetries of physics lack that sorcery. Those symmetries may act like the distorting mirrors of a funhouse, making familiar electrons look like ghostly neutrinos, for instance, but they can never change a fermion into a boson. Only supersymmetry does that.

At least that's the theory. Elementary particle theorists have studied supersymmetry intensively since its invention in the 1970s, and many believe it holds the key to the next major advance in our understanding of the fundamental particles and forces. Experimenters, however, have searched at their highest-energy colliders for particles predicted by supersymmetry, so far to no avail.

In the 1980s nuclear theorists proposed that superviolent collisions were not necessarily the only way to see supersymmetry; they predicted that a different form of supersymmetry could exist in certain atomic nuclei. Here, too, the symmetry relates what in physics are quite dissimilar objects: nuclei with even numbers of protons and neutrons and those with odd numbers. (This again involves fermions and bosons, because a composite particle made of an odd number of fermions is itself a fermion, whereas an even number produces a boson.)

To better understand the nuclear supersymmetry, picture a roomful of ballroom dancers in place of the nucleons that make up a nucleus. When there are an even number of dancers, everyone has a partner and the room is neatly described as couples dancing. The odd case is marred by one additional person stumbling around the floor without a partner. In the supersymmetric mirror, that person magically looks like another couple, dancing in step with all the others. Similarly, the nucleus with an odd number of protons and neutrons, collectively called nucleons, is related to one in which all the nucleons are paired.

Experimenters recently observed a version of this extraordinary symmetry in isotopes of gold and platinum, with protons and neutrons acting as two separate groups of dancers—students from two high schools holding their proms in the same ballroom, perhaps. In this nuclear supersymmetry, four cases instead of two are tied together: the one in which both schools have an odd man out (odd numbers of protons and neutrons), the two in which one school does (an even number of protons but an odd number of neutrons, or vice versa), and the one in which everyone is partnered (even numbers of protons and neutrons).

The atomic nucleus is a fascinating quantum system holding many secrets. Its study over the decades has been a continuous source of unexpected observations. Theorists must use many tools to understand all the facets of the very complicated physics of nuclei. The new result adds supersymmetry to the toolkit—and it shows that supersymmetry is not just a mathematical curiosity but exists in the world.

Nuclear physics research also provides tools needed to understand other quantum systems that have general features similar to nuclei—the so-called finite many-body systems, containing anything from a few particles to hundreds of them. Experimental methods now allow the study of such objects built from small numbers of atoms or molecules. Supersymmetry might also be important to those fields of physics.

Mysterious Nuclei

EVERYTHING OF SUBSTANCE in the world around us is made of atoms, clouds of electrons surrounding tiny massive atomic nuclei. Physicists and chemists understand very well how the electrons arrange themselves and how the properties that govern our material world arise from those structures. Some of the most precise predictions in science relate to fine details of energy levels of electrons in atoms. Atomic nuclei, in contrast, have remained far more inscrutable.

The fundamental reason for this disparity is the nature of the forces involved. Electrons are held in their orbitals around atoms by the electromagnetic force, which is relatively weak. The dominant force inside nuclei is about 100 times stronger (hence the name: the strong nuclear force). Theoretical techniques that successfully describe weak forces such as electromagnetism break down for one as strong as the nuclear force. In addition, electrons are structureless elementary particles, whereas protons and neutrons are themselves complex bundles of particles called quarks and gluons. The force between these nucleons is not directly a fundamental force like electromagnetism, whose equations we know exactly. Instead the nuclear force acting between nucleons is a complicated by-product of the interactions of their constituent quarks and gluons.

The nuclear force is strongly attractive for a few femtometers (10^{-15} meter) and then falls to zero. This force packs the nucleons closely together, and each nucleon interacts strongly with all the other nucleons that are within range. (In contrast, electron orbitals lie some 10,000 times farther away.) The resulting structure is one of the most challenging quantum systems known, and over the decades physicists have developed many theoretical models to try to describe it [*see box on opposite page*]. Some models treat the nucleus as a droplet of quantum fluid that can vibrate and oscillate in specific ways. Others mimic the structure that works so well for the orbiting electrons: shells of discrete orbitals that the nucleons steadily fill up, starting from the lowest energy level.

The different models tend to work best for specific classes of nuclei, depending on how many nucleons are involved overall and how full the outermost shells of protons and neutrons are. Because the protons and neutrons like to form pairs, the behavior of a nucleus depends critically on whether it has even or odd numbers of protons and neutrons [*see illustration on page 74*]. So-called even-even nuclei tend to be simplest, followed by even-odd, with odd-odd the most difficult of all.

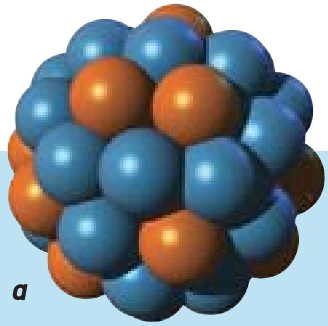
Symmetry is an important and powerful tool for developing and using such models. Symmetry principles occur throughout physics, often in ways that one wouldn't expect. For example, the law of conservation of energy can be derived from a symmetry principle involving the flow of time. The shells of orbitals, both for electrons and nucleons, are distinguished by properties related to symmetries, such as the angular momentum of particles in the orbital and whether the orbital is unchanged if it is reflected (a property called parity). The equations governing elementary particle physics are fundamentally based on symmetries.

A key aspect of symmetry in quantum physics is the division of particles into bosons and fermions, which have fundamentally dissimilar quantum states and completely different behaviors. Fermions obey the Pauli exclusion principle, meaning that two fermions of the same species cannot be in the same quantum state at

Overview/*Dances with Nucleons*

- In quantum physics, all particles and fields are divided into two extremely dissimilar types: fermions and bosons. Fermions include the electrons, protons and neutrons that make up matter. Bosons include photons (responsible for electromagnetism) and gluons (which bind quarks together).
- Symmetries play major roles throughout physics. All ordinary symmetries respect the distinction between bosons and fermions. Supersymmetry theories incorporate powerful mathematical properties that interchange bosons and fermions. Such theories may be crucial for deeply understanding particle physics, but experimenters have not yet detected supersymmetry of elementary particles.
- In atomic nuclei, protons and neutrons each form pairs that behave like composite bosons. Nuclei thereby form four distinct classes (even-even, even-odd, odd-even and odd-odd) depending on whether the protons and neutrons can each completely pair off. Physicists predicted that a variant of supersymmetry should relate a "magic square" of four nuclei of these types. Experimenters have now confirmed that prediction.

Nuclear Models



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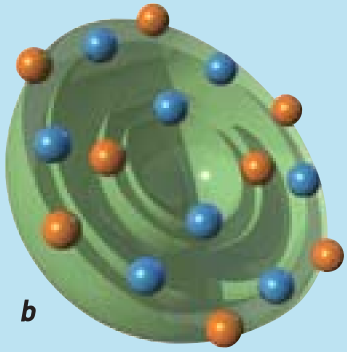

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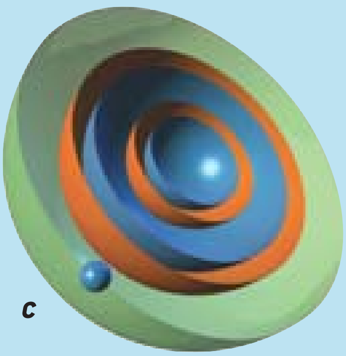

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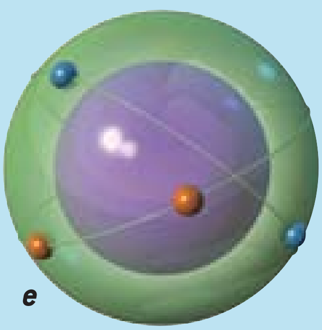


e

ONE HUNDRED TRILLION (10^{14}) times denser than water, nuclei (*a*) are very tightly packed bundles of protons (*orange*) and neutrons (*blue*). Because of the strength and complexity of the strong nuclear force that holds nuclei together, physicists have long resorted to approximate models to describe the quantum states of nuclei.

The shell model (*b*) is very similar to the description of electrons in atoms. It considers the atomic nucleus to be an ensemble of weakly interacting neutrons and protons (nucleons) held in a potential energy well. The nucleons can occupy various orbits, analogous to the orbits of electrons around an atom, but now with two sets of them—one for protons, one for neutrons. Like electrons, nucleons are fermionic particles and the exclusion principle applies, so two cannot occupy the same orbit. The orbits form shells, or groups of orbits having similar energies with large energy gaps between them. Nuclei with a closed (full) shell of protons or a closed shell of neutrons (and especially those with both) show great stability, similar to noble-gas atoms with full shells of electrons.

For nuclei with a few additional nucleons beyond a closed shell (*c*), one can neglect to an extent the individual nucleons in the closed shell and concentrate on the few that are outside the shell. Interactions among these outer nucleons, however, must also be taken into account. In heavy nuclei with many nucleons outside the last closed shell, the calculations become prohibitively complex even with modern computers.

The collective, or liquid-drop, model (*d*) applies to heavy nuclei, which are formed by about 100 or more nucleons. The model does not track individual nucleons but instead views the nucleus as a droplet of a quantum liquid that can undergo various vibrations and rotations. The properties of the nucleus are encapsulated in features such as the density and surface tension of the liquid and the electric charge distributed throughout it. This model has been extremely successful in describing certain classes of nuclei far from closed shells—that is, those that have a large number of nucleons in the outermost shell.

In quantum physics, excitations such as the vibrations of a droplet take on many properties of particles and can behave like fermions or bosons. When the collective model is applied to the simplest systems—even-even nuclei, which have even numbers of both protons and neutrons—the basic constituents of the model, the surface vibrations, behave as bosons. For an odd number of nucleons, the last nucleon occupies an orbit that depends on the state of the droplet, and excitations are fermions.

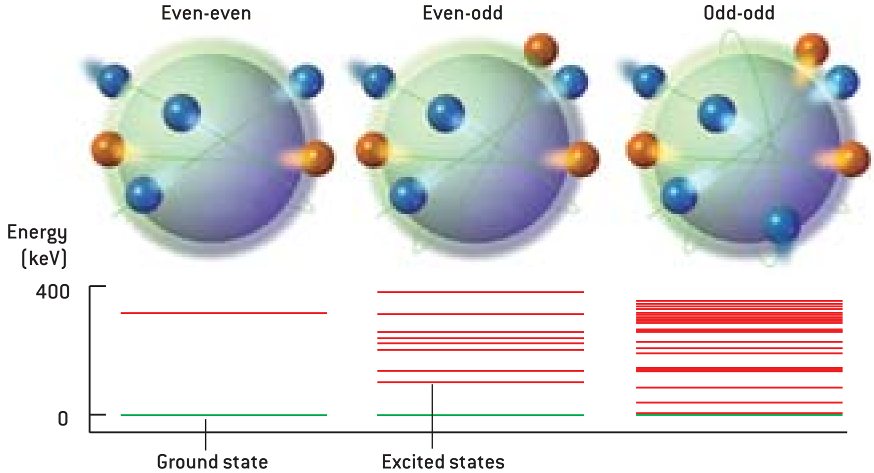
The interacting boson model (*e*) connects the shell model and the liquid-drop model by making use of the pairing property of the nuclear force [*see box on next page*]. The model analyzes heavy even-even nuclei as collections of pairs of nucleons outside a closed shell, like describing people on a dance floor as couples (rather than individuals) moving about. When two nucleons pair up, they resemble a boson, but different types of pairs are possible. In the dance analogy, some couples are doing a slow waltz while others are rushing around in a polka. *—J.J.*

once. Bosons, in contrast, prefer to collect in identical states, as demonstrated by helium 4 atoms in a superfluid.

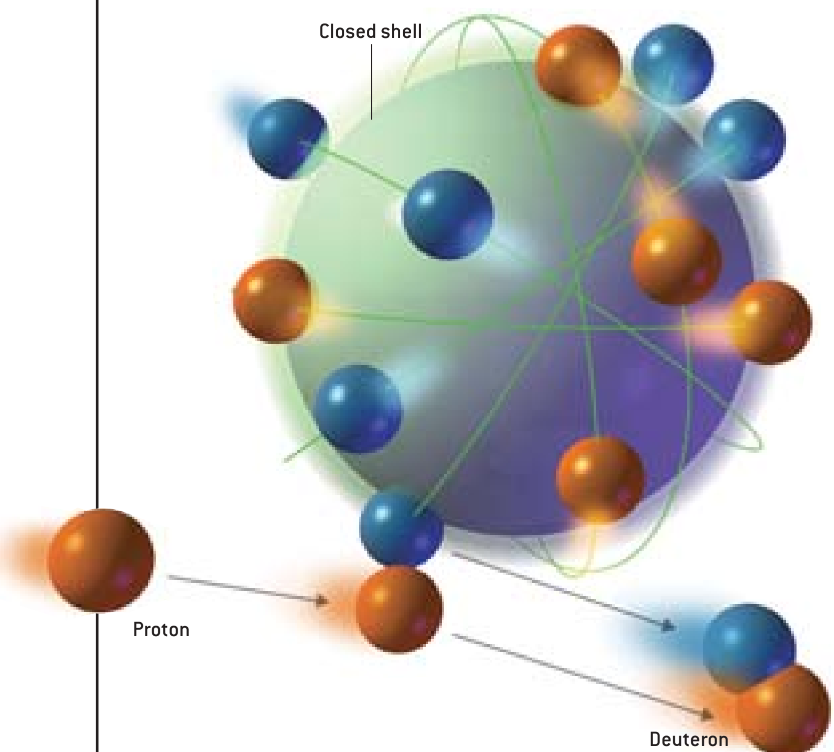
Helium 4 is an example of a composite particle that is a boson. It is made up of six fermions (two protons, two neutrons and two electrons). Nucleons themselves are actually composite fermions, containing three fundamental fermions (quarks). The general rule is that an even number of fermions make up a composite boson, whereas an odd number make up a composite fermion. Ordinary symmetries necessarily map bosons onto bosons and fermions onto fermions. By mapping bosons onto fermions, and vice versa, supersymmetry opens up a new class of possible relations among particles. Also, the novel mathematics of these relations results in far greater computational power for analyzing or predicting a system's behavior.

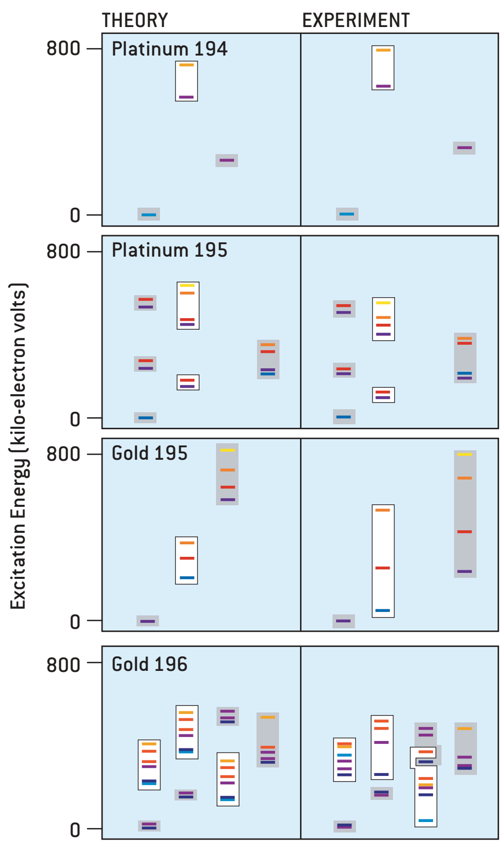
MEASURING AND IDENTIFYING NUCLEAR STATES

NUCLEI DIFFER GREATLY depending on whether they have even or odd numbers of protons and neutrons (*right*). These differences occur because the protons (and, separately, the neutrons) in a nucleus tend to form pairs that move in stable, coordinated states. Maria Goeppert Mayer introduced this concept in the 1950s while at the University of Chicago. In the simplest type of nuclei, even-even, all the protons and all the neutrons are paired up. These nuclei have very few low-energy excited states. In even-odd nuclei, which have an even number of one nucleon type and an odd number of the other, the one unpaired nucleon introduces more excitations. Odd-odd nuclei have an unpaired proton and an unpaired neutron and are correspondingly more complicated.



TRANSFER REACTIONS provided crucial data for observing nuclear supersymmetry by determining the excited states of gold 196. In a typical transfer reaction (*below*), an accelerated proton strikes a nucleus and carries off one of its neutrons, forming a deuteron. The daughter nucleus will be in an excited state whose energy can be determined directly from the energy of the deuteron.





NUCLEAR SUPERSYMMETRY is revealed in the lowest energy states of four nuclei, as modeled by the supersymmetry theory (*above, left*) and as measured (*above, right*). Colors signify angular momenta of the states, which are grouped in accord with the supersymmetry. The agreement between theory and experiment, though not exact, is impressive for such a complicated nuclear system.

Nuclear Symmetries

SYMMETRY PLAYS a key role in the so-called interacting boson model of nuclei, which was introduced in the mid-1970s by Akito Arima of the University of Tokyo and Francesco Iachello, then at the University of Groningen in the Netherlands [*see box on page 73*]. This model analyzes nuclei as being made of paired protons and neutrons—the pairs are the bosons of the model. Arima and Iachello found three special types of even-even nuclei in their model, each one associated with a particular symmetry. Two of the classes and their symmetries were already known from the older liquid-drop model and had been studied in experiments, but the third involved a symmetry that had never been seen in nuclei. In the late 1970s Richard F. Casten and Jolie A. Cizewski, both then at Brookhaven National Laboratory, discovered that platinum nuclei displayed the new symmetry, greatly boosting the interacting boson model. Soon it became evident that the interacting boson model was a good approximation for many nuclei.

The symmetries predicted by the interacting boson model are of a special type known as dynamical symmetries. Ordinary (nondynamical) symmetries can be pictured as being much like the everyday symmetries that we see around us. An object has mirror symmetry, for example, if it looks the same when viewed in a mirror. Your left hand is approximately the mirror image of your right hand. Dynamical symmetries, in contrast, relate not to the objects themselves but to the equations that govern the dynamics of the objects. Unfortunately for experimenters, only a limited class of nuclei can exhibit dynamical symmetries.

The interacting boson model naturally works best for even-even nuclei. Odd-even nuclei always have an unpaired nucleon left over, like one extra person wandering among a room of dancers. Such a nucleus is described in the model by *n* bosons and one fermion, the unpaired nucleon. In some cases, dynamical symmetries can be used for analyzing odd-even nuclei, but the procedure is much more complicated than in the even-even case. In 1980 Iachello, by then at Yale University,

Supersymmetry in Particle Physics

IN THE STANDARD MODEL of particle physics, all the particles that make up matter—quarks and electrons—are fermions, as are the related particles the muon, the tau and the neutrinos. All the particles that generate forces—photons, gluons, and *W* and *Z* particles—are bosons. So, too, are the postulated graviton and Higgs particle.

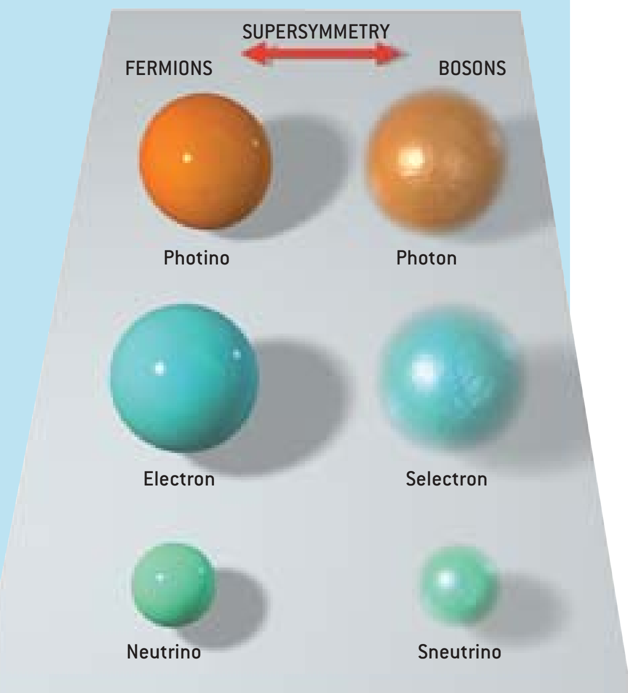
Symmetries form the foundation of the Standard Model. Electrons and electron neutrinos, for example, are related by one symmetry, which also relates "up" quarks to "down" quarks. A different manifestation of the same symmetry associates *Z* and *W* particles. Gluons are all related by a "color" symmetry, which also relates different "colors" of quarks. All these symmetries relate fermions to fermions and bosons to bosons; the quantum states of bosons and fermions are too dissimilar for an ordinary symmetry to connect them.

The underlying difference between bosons and fermions is this: in a collection of particles, if two identical fermions are swapped (for instance, switch two electrons), the total quantum state of the collection is inverted (imagine crests and troughs of a wave being interchanged). Swapping two identical bosons, in contrast, leaves the total state unaltered. Those characteristics lead to the Pauli exclusion principle, which prevents two fermions from occupying the same state, and to bosons' propensity to collect together in a common state, as in laser beams and Bose-Einstein condensates.

Ordinary symmetries are described by mathematics called groups and Lie algebras (named after Norwegian mathematician Sophus Lie). Lie algebras and groups cannot introduce or cancel the strange inversion that occurs when fermions are swapped, so they cannot transform fermions to bosons, or vice versa. Supersymmetry, devised in the 1970s, uses "graded Lie algebras," or superalgebras. In essence, the supersymmetry transformations add another fermionic component to each particle, which suffices to interchange fermions and bosons.

For the known particles to obey supersymmetry, they must each have a "superpartner"—every boson must have a fermionic counterpart, and vice versa. The known particles do not have the right properties to be one another's partners, so new particles are predicted. The Standard Model is extended to the supersymmetric standard model. The postulated fermionic partners go by the names photino, gluino, Wino, Zino, gravitino and higgsino. The bosonic partners have an "s" added to their names: selectron, smuon, sneutrino, squark and so on. None of these particles have yet been detected.

This elementary particle supersymmetry is also intimately related to the symmetries of spacetime that underlie Einstein's theory of special relativity. That is, the supersymmetry extends those symmetries. The supersymmetry of nuclei is fundamentally different because it does not have that connection to spacetime. The common ground between these two applications of supersymmetry in physics is that they both rely on superalgebras. *—J.J.*



The Symmetric Universe

THE NATURAL WORLD AROUND US abounds with symmetries and approximate symmetries—the bilateral symmetry of most animals, the rotational symmetry of the sun, the fivefold symmetry of many starfish, and the manifold symmetries of fruit and flowers. Symmetry becomes so commonplace it takes something as extraordinary as a snowflake to awaken our awe.

Much of fundamental physics, it turns out, amounts to uncovering other kinds of symmetries that characterize the universe. Einstein's theory of special relativity, for example, is a theory of the symmetries of empty space and time, which are governed by the Poincaré group. (Groups are the mathematical structures that describe symmetries.) Effects such as length contraction and time dilation, which flatten fast-moving clocks and make them run slow, are operations of the symmetry group, similar to rotating your point of view in space, but with time as part of the "rotation."

Particle physics is replete with symmetries: in particular, the fundamental forces are dictated by symmetries called gauge symmetries. Specify the gauge group and the interaction strength, and essentially all the behavior of the force is determined. For instance, electromagnetism involves a gauge symmetry group called U(1), which is the symmetry of rotations of a circle in a plane.

Conservation of electric charge is a consequence of the U(1) symmetry. As proved by mathematician Emmy Noether in 1915, whenever a symmetry appears in mechanics, there is also a conservation law. Her theorem works for both classical and quantum mechanics and tells us, for instance, that the law of conservation of energy follows from symmetry with respect to translations in time. That is, energy is conserved because the equations of motion yesterday are the same as those today. Conservation of momentum (symmetry under translation in space) and angular momentum (symmetry under rotations) are similar.

Finally, take the very definition of a "particle" in quantum field theory that originated with physicist Eugene Wigner: a particle is an "irreducible representation of the Poincaré group." This direct linkage of symmetry to the most basic structure of matter and forces is what requires electrons and other particles to have an intrinsic quantity of angular momentum known as spin. The spin acts as a label specifying which "irreducible representation" the particle is and happens to associate with rotations and hence with angular momentum. A particle's mass is also a symmetry-related label.

Compared to the symmetries that govern the universe, snowflakes start to seem quite mundane. *—Graham P. Collins, staff writer and editor*

SNOWCRYSTALS.NET

THE AUTHOR

JAN JOLIE began his career as a theorist, receiving his Ph.D. in theoretical physics from the University of Ghent in Belgium in 1986. After five years at the Laue-Langevin Institute in Grenoble, France, Jolie turned his focus to experimental work when, in 1992, he accepted a position at the University of Fribourg in Switzerland. In addition to the experiments reported in this article, he has worked on more down-to-earth applications, such as gamma-ray and neutron tomography and the construction of tunable gamma-ray sources. He now leads the Institute for Nuclear Physics at the University of Cologne in Germany. In 2000 Jolie was awarded Yale University's Leigh Page Prize for his work on dynamical symmetries and supersymmetries in atomic nuclei.

suggested a daring extension of the interacting boson model to describe odd-even nuclei in a neater fashion.

Iachello proposed using supersymmetry to relate the nucleus with n bosons and one fermion to that with $n + 1$ bosons. If this dynamical supersymmetry occurred in nature, it would reveal itself in the pattern of excited states of an odd-even nucleus and the adjacent even-even one—for example, in the states of arsenic 75 (33 protons and 42 neutrons) and selenium 76 (34 protons and 42 neutrons). Quantum states are classified by their quantum numbers, which organize the states into groups according to properties such as their angular momentum. With dynamical supersymmetry, a single set of quantum numbers would serve to classify the states of two nuclei into related groups. One could start with the simpler states of the even-even selenium 76 and predict the states of arsenic 75 (that is, predict which states would exist and properties such as their angular momentum and approximate energy).

During the 1980s experimenters gathered data from nuclei capable of exhibiting dynamical symmetries and found hints of supersymmetry, but they could not confirm Iachello's idea unambiguously. The structure of an odd-even nucleus could not be determined completely starting from the associated even-even nucleus.

Magic Squares

IN 1984 Pieter Van Isacker, Kristiaan L. G. Heyde and I (all then at the University of Ghent in Belgium), together with Alejandro Frank of the University of Mexico, proposed an extension of Iachello's supersymmetry. The idea was to keep track of the neutron and proton pairs separately. This extended supersymmetry allows one to describe a quartet of nuclei in a common framework. This quartet, called a magic square, consists of nuclei having the same total number of bosons (paired nucleons) and fermions (unpaired nucleons). It consists of an even-even nucleus, two odd-even nuclei and an odd-odd nucleus. Heavy odd-odd nuclei, those having more than 100 or so nucleons, are the most complex objects found in the study of low-energy nuclear structure, but if this new dynamical supersymmetry worked in nature, one could predict the energy spectrum of the odd-odd nucleus from the simpler spectra of its three partners. Observing such a symmetry experimentally was of importance not only for nuclear physics but for all other applications of supersymmetry in physics: though widely used by theorists, supersymmetry lacked experimental verification.

To confirm these ideas required detailed knowledge of heavy odd-odd nuclei, and many experimental and theoretical groups around the world began such studies. Some limited evidence of the supersymmetry was found, but the holy grail of such investigations, a detailed map of the states of gold 196, remained out of reach. This nucleus, with 79 protons and 117 neutrons, is considered to be the ultimate test of supersymmetry in nuclear physics for three reasons. First, its region of nuclei (those that have about 80 protons and about 120 neutrons) is known to exhibit dynamical symmetries and to fulfill other technical conditions needed for the supersymmetry to be present. Second, its region is the most difficult in which to describe odd-odd nuclei. Finally, in 1989, when we used supersymmetry to predict a major group of its states, none of those states was experimentally known; experiments could confirm or kill the theory.

The Experimental Quest

TO STUDY ATOMIC NUCLEI, physicists bombard them with neutrons, photons or accelerated particles to excite them and observe how they react. The excited states are unstable, and the nucleus quickly returns to its lowest energy state by cascading down through a series of states, emitting energetic gamma- or x-ray photons, which can be measured precisely.

The radiation observed from odd-odd nuclei is extremely complex, however, because very many states are populated, and the photons' energies are the differences in energies between states. Even-even and even-odd nuclei are simpler, having fewer such states at low energies. The gold 196 isotope presents an additional challenge because it is radioactive and decays in about a week, most often by capturing an electron and turning into platinum 196. Experimenters have to create it continuously by bombarding a stable isotope with accelerated particles such as protons.

The structure of gold 196 turned out to be so difficult to deduce from such measurements that some teams abandoned the effort. One team proposed that the experimental data must mean that the dynamical supersymmetry was broken. At that moment of despair in the mid-1990s, a new collaboration was established, joining my group at the University of Fribourg in Switzerland and the groups of Christian Günther at the University of Bonn and Gerhard Graw at the University of Munich. Later Casten's group at Yale also contributed. We planned to make one last attempt to study gold 196 using in-beam spectroscopy, which measures radiation emitted by gold 196 ions created in a beam of particles. We used three facilities: the Philips cyclotron of the Paul Scherrer Institute in Switzerland, the Bonn cyclotron, and the WSNL Tandem accelerator at Yale.

Graw's group performed a "transfer" experiment that complemented the in-beam results and solved a fundamental puzzle—the reason for the difficulties that had stymied earlier efforts. In a transfer experiment the projectile hits the target nucleus and carries away one of its nucleons, leaving behind a daughter nucleus in an excited state [*see illustration on page 74*]. We identify the outgoing particle and measure its energy. When we balance the books, the excitation energy of the daughter nucleus will be "missing." In this way, transfer experiments produce different data than the in-beam spectroscopy does: they directly determine the energy of excited states of a nucleus instead of the much larger number of energy differences between states. Moreover, by using beams of polarized projectiles and studying how the collision products fly away, we can learn about the angular momenta of the excited states.

To study the very closely spaced energy levels of gold 196, we used the state-of-the-art instrumentation provided by the magnetic Q3D spectrometer of the accelerator laboratory in Munich. When Alexander Metz and his collaborators at the University of Munich analyzed the transfer experiments, they found that the ground state of gold 196 is a doublet—two very closely spaced energy levels. This discovery was crucial for solving the problems encountered before in analyzing the nucleus's states. These experiments also revealed directly the energies of most of the excited states. With this framework in place, the in-beam data could then be used to establish the spin and parity of each excitation.

The results agreed well with the theoretical predictions based on dynamical supersymmetry [*see illustration on page 74*]. The states of all four nuclei could be classified by a common set of supersymmetric quantum numbers, and a single mathematical expression with only a few parameters matches the energy levels reasonably well. That this is possible for one of the most complex atomic nuclei is a strong confirmation of dynamical supersymmetry, but it also presents a new challenge to theoreticians. One can study gold 196 as an individual case of many quantum objects interacting. The theorists should explain, from that perspective of quantum many-body theory, why the excitations of gold 196 are governed by dynamical supersymmetry. Several groups are working intensively on this question.

Paired fermions behaving as bosons occur in various fields of physics, including superconductivity. Dynamical supersymmetry like that seen in atomic nuclei might be useful in those fields as well. One thing is certain: symmetries, whether "super" or ordinary, will continue to lead the dance in quantum physics. SA

MORE TO EXPLORE

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