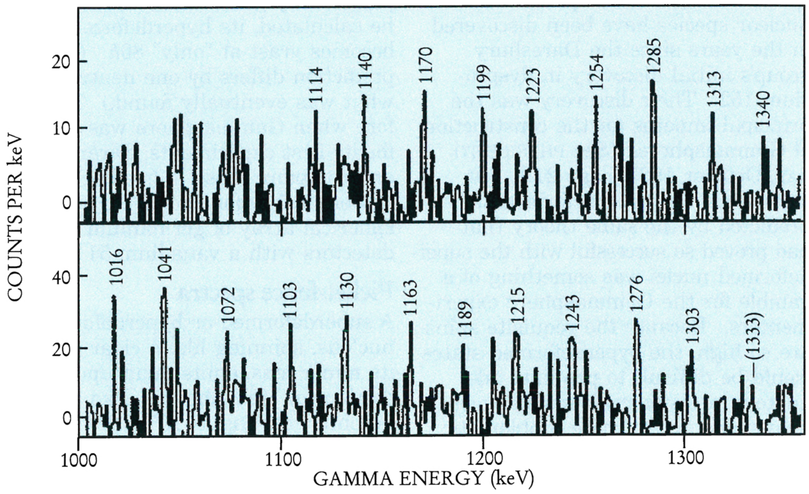
New Gamma Detector Array Finds Evidence of Hyperdeformed Nuclei

Some heavy nuclei, if you can make them spin fast enough, seem to acquire a surprisingly stable cigar shape three times as long as it is wide.



PICKET-FENCE GAMMA-RAY SPECTRA of ^{147}Gd, measured at Gammasphere, show two energy sequences with the roughly 30-keV spacing suggestive of nuclear hyperdeformation at very high spin. If these are hyperdeformation bands, each successive gamma carries off $2\hbar$ of angular momentum as the nucleus spins down. (Adapted from reference 1.)

How much spin can a nucleus take before centrifugal force pulls it apart? A surprising answer is proffered by one of the first physics results from the Gammasphere facility at the Lawrence Berkeley National Laboratory. Gammasphere is the first of a new generation of nuclear-physics photon detector arrays. In June the Berkeley, Oak Ridge, Washington University collaboration at Gammasphere published evidence that gadolinium-147 nuclei might be reaching angular momenta as high as $90\hbar$ without succumbing to fission.[1] "That's embarrassingly high," says collaboration leader Demetrios Sarantites, "because the theory says that the barrier against fission should vanish at around $80\hbar$."

The embarrassment is getting worse. In more recent Gammasphere runs, not yet published, the group appears to be seeing spins as high as $100\hbar$. That would bolster earlier indications, from an experiment with older-generation detector arrays at Chalk River in Canada[2] and Legnaro in Italy,[3] that dysprosium nuclei can reach $100\hbar$.

The predicted dependence of the "fission barrier" on angular momentum comes from theoretical models that treat the nucleus as a liquid drop held intact by surface tension. "So if these spins are really as high as they seem to be," says Sarantites, "the theorists will have to look beyond the conventional liquid-drop model to explain why the nuclei aren't torn apart."

The new data also offer a challenge, and a unique opportunity, to nuclear shell models. Complementary to the liquid-drop models, the shell models concentrate on the atomlike discrete energy levels of individual protons and neutrons within a time-averaged nuclear potential well. The celebrated triumphs of the shell models in explaining properties such as the special stability of nuclei with certain "magic numbers" of neutrons and protons have generally involved nuclei that are spherical, or very nearly so. The new results from Gammasphere, Chalk River and Legnaro suggest that some nuclei are so grossly deformed by extreme angular momenta that they deserve to be called "hyperdeformed." Calculating energy levels with nuclear potentials so far from spherical symmetry provides demanding new tests of the theory. And perhaps newly revealed shell effects will explain why hyperdeformed nuclei are so surprisingly resistant to fission.

Hyperdeformation

Astronomical and other classical analogies are useful in discussing the shapes of spinning nuclei. The rotation of a fluid celestial body flattens it at the poles. Less well known is the instability, first pointed out by Carl Gustav Jacobi in 1834, that would transform it from oblate to prolate at sufficiently high spin; the body would come to look like a cigar spinning around a toothpick (the minor axis) stuck through it the short way.

Much the same thing can happen to nuclei: In 1986 Peter Twin and colleagues at the Daresbury Nuclear Structure Facility in England reported the first evidence for "superdeformed" nuclei, with angular momenta from about 20 to $60\hbar$. The evidence, both theoretical and experimental, was that these were indeed prolate nuclei with the major diameter twice as long as the minor diameter.

Classical calculations of orbits in anisotropic harmonic-oscillator fields exhibit special stability when the natural frequencies in orthogonal directions have integer ratios to one another. Shell-model calculations reveal a closely analogous stability at the quantum mechanical level: If one treats the nucleus, for simplicity, as an anisotropic harmonic-oscillator well, large energy gaps appear at the Fermi level for certain magic-number populations if the oscillator frequencies have integer ratios. That is to say, in these heuristic calculations the shell configurations are particularly stable in spin-distorted nuclei that are precisely twice—or even three times—as long as they are wide. The term "hyperdeformed" refers to prolate nuclei with a 3:1 ratio of major to minor diameter.

These qualitative features remain essentially unchanged when one replaces the harmonic-oscillator well with more realistic nuclear potentials. But such added complexity introduces some uncertainty into the magic numbers at which the experimenters are to look for superdeformed and hyperdeformed nuclei.

The telltale gamma de-excitation spectra of dozens of superdeformed nuclear species have been discovered in the years since the Daresbury group's initial discovery in dysprosium-152. Their discovery was the principal impetus for the construction of Gammasphere. (See PHYSICS TODAY, October 1991, page 21.) But looking for the hyperdeformed states predicted by the same theory that had proved so successful with the superdeformed nuclei was something of a gamble for the Gammasphere experimenters. Because the requisite spins are so high, the hyperdeformed states would be difficult to populate adequately in fusion collisions between heavy ions. Even more problematic was the competition from nuclear fission. The very high spins needed to reach hyperdeformation are perilously close to the fission limit. Could enough nuclei survive unsplit at such extreme angular momenta?

Heavy-ion fusion

To produce high-spin heavy nuclei of a given atomic number Z, the Gammasphere experimenters bombard target nuclei with ions chosen so that the sum of the beam and target atomic numbers is $Z + 1$. The ion beam is accelerated in LBNL's 88-inch cyclotron to 4.5 MeV per nucleon. The hope is that sufficiently peripheral fusion collisions will produce nuclei of very high angular momentum. One then looks for the telltale "rotational band" spectrum of de-excitation gammas, in coincidence with a single decay proton that signals the production of a nucleus of atomic number Z. Why the circuitous route from $Z + 1$ to Z? Only about one collision in ten thousand produces a hyperdeformed nucleus. Therefore the sought-after rotational-band spectra are obscured by a horrendous background of extraneous gammas. Requiring a coincident decay proton yields a significantly enriched sample of hyperdeformed nuclei, for reasons that are not really understood. The experimenters' folk wisdom asserts that very deformed nuclei with pointy ends are more likely to radiate protons, for the same reason that pointy electrodes emit electrons.

To minimize competition from fission and thereby have a fighting chance of seeing hyperdeformity, one wants a nuclear species for which the hyperdeformed 3:1 configuration becomes "yrast" (the lowest energy state for a given spin, from the Swedish word for "dizziest") at the lowest possible spin. Two years ago theorist Sven Åberg at Lund University in Sweden predicted[4] that ^{146}Gd was a particularly good candidate, because, he calculated, its hyperdeformed state becomes yrast at "only" $80\hbar$. (This prediction differs by one neutron from what was eventually found.) Therefore when Gammasphere was ready for its first experiments, Sarantites and company chose to bombard a molybdenum-100 foil in the center of its spherical array of germanium gamma detectors with a vanadium-51 beam.

Picket-fence spectra

A superdeformed or hyperdeformed nucleus, spinning like a cigar about its minor axis, emits quadrupole radiation (in MeV photons) like a tiny antenna rotating at 10^{20}–10^{21} hertz! As each photon carries off $2\hbar$ of angular momentum, the rotation slows down. Eventually, after emitting a dozen or two of these gammas, the nucleus abruptly loses its deformation. To the extent that the nuclear moment of inertia remains constant during the spin-down of the deformed state, each gamma will be less energetic than its predecessor by a constant energy difference. This striking "picket fence" spectral pattern of evenly spaced gamma energies was what led to the discovery of the superdeformed states in the 1980s.

Rigid bodies have constant moments of inertia. But nuclei are far from being rigid bodies. Like raw eggs, they have moveable insides, and their external shapes are flexible. So the nuclear moment of inertia usually depends on spin. Why then do the de-excitation spectra of superdeformed and hyperdeformed nuclei exhibit the characteristic picket-fence pattern one would expect only from a rigid rotator? For one thing, the special stability conferred by the integer ratio of diameters keeps the external shape constant while the nucleus is spinning down. For another, as Oak Ridge theorist Witold Nazarewics explains it, "the strong Coriolis force at ultrahigh spin would destroy the Cooper-pair bonding of nucleons that ordinarily makes the nuclear interior a kind of free-sloshing superconductor."

The energy spacing between adjacent gamma lines is inversely proportional to the moment of inertia. For superdeformed spectra the spacing is typically about 50 keV. For ^{147}Gd the Gammasphere experiment found a mean spacing of 29 keV, consistent with the supposition that hyperdeformed nuclei are 50 percent more elongated than their superdeformed cousins. But surprisingly, the ^{147}Gd spacings, which vary irregularly from from 25 to 32 keV, are not as constant as those seen in the superdeformed spectra.

The figure on page 17 shows the two ^{147}Gd hyperdeformation spectra published in June.[1] "Both were unearthed from the background jumble by my sharp-eyed postdoc Dennis LaFosse," Sarantites told us. It is not uncommon for a given nuclear species to have two or more distinct but overlapping superdeformation sequences. The same, it appears, is true for hyperdeformed nuclei.

One cannot with certainty assign specific spins to individual transition lines. But if one assumes, as does the standard theory, that the two different ways (dynamic and kinematic) of defining the moment of inertia are equivalent, one gets the individual spins from the line energies and their spacings. That exercise gives $70\hbar$ and $90\hbar$ for the lowest and highest spins in these published spectra. If you have trouble believing that $90\hbar$ nuclei can resist fission, you can always quarrel with the assumption about the moments of inertia.

Gammasphere

The interval between consecutive gamma emissions in the de-excitation of a hyperdeformed nucleus is just a few femtoseconds, much too short for the detector array to discern a time sequence. It must look for a pulse of essentially simultaneous gammas in coincidence with the decay proton that signals the possible creation of a hyperdeformed nucleus with the desired Z.

Gammasphere, when it is finally completed, will consist of 110 germanium crystals in a tight spherical array surrounding the collision target. Even this hermetic coverage provides only a 10% chance that a given gamma will have its full energy recorded by a Ge crystal. In fact, each crystal is backed by a bismuth germanate veto shield that serves to warn of departing gammas. So even with Gammasphere at full strength one cannot hope to detect, on average, more than five gammas in coincidence from among the dozens emitted in the de-excitation of any one deformed nucleus.

But Gammasphere was not anywhere near full strength last March when the data were taken for the June paper.[1] "We had only 36 Ge crystals in place," Sarantites told us, "and that limited our statistics. But in July we ran with 57 crystals, and we hope the new data will confirm the bands and their origin." Even in its unfinished state, Gammasphere is much more powerful than the previous generation of detectors, which had only a 1–2% chance of recording a given gamma. They almost never saw more than two gammas in coincidence. With the overwhelming background of gammas from other processes, multigamma coincidences are crucial to the detection of hyperdeformation spectra.

Europe's answer to Gammasphere, the Eurogam II detector in Strasbourg, has joined the search for hyperdeformed nuclei. But picket-fence spectra, by measuring moments of inertia, can provide only indirect proof of hyperdeformation. The ultimate confirmation must await lifetime measurements of these femtosecond states, from which one can determine their quadrupole deformations.

David Ward, whose Chalk River group was the first to present evidence for nuclear spins of $90\hbar$ and above, points out a provocative puzzle: "If you think of the colliding nuclei in these experiments as billiard balls," he told us, "then the maximum impact parameter can't get you anywhere near $90\hbar$." So, in addition to worrying about fission, if the spins really are that high, one may have to invoke novel tidal forces that elongate the nuclei just as they are about to collide.

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References

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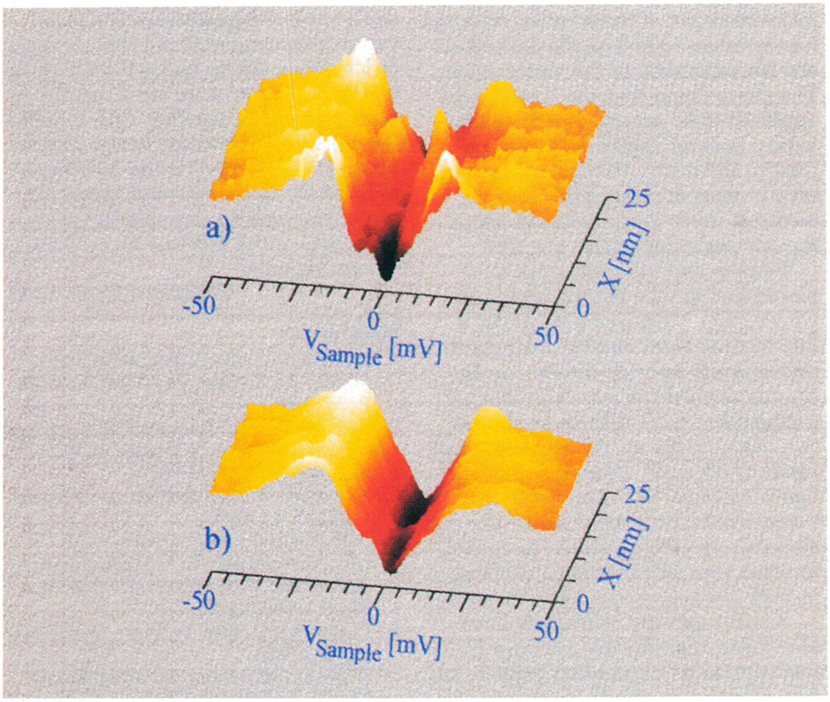
STM Gets to the Core of the Matter in a High-T_c Superconductor

Researchers at the University of Geneva have succeeded in applying scanning tunneling microscopy to one type of high-T_c superconductor, opening the door to further study of the vortex cores.

Since the 1986 discovery of high-temperature superconductors, researchers have been struggling to understand the nature of the magnetic flux lines that thread through these copper-oxide materials when the field is above a few tens of gauss. The flux lines take the form of vortices, swirling supercurrents that confine the magnetic field to a cylindrical region around a quiescent center. Understanding them is more than an academic exercise: Motion of the vortices, when pushed by a high enough current, introduces resistivity and limits the long-sought high-field applications. (See PHYSICS TODAY, October 1992, page 17.)



DIFFERENTIAL CONDUCTANCE SPECTRA measured by scanning tunneling microscopy on the surface of a YBCO crystal in 6 T. The conductance measures the electronic density of states. It is plotted here as a function both of voltage and of distance X along a line on the crystal surface. **a:** Conductance spectrum along a line that passes through a vortex. (The vortex core lies at the midpoint of the line.) **b**: Spectrum along a line between vortices. Going from dark red to white, one ranges from low to high values of differential conductance. The peaks seen around 20 mV remain constant between vortices (**b**), but they disappear at the core (**a**); they are replaced there by conductance peaks separated by 11 mV. (Adapted from reference 1.)

You don't actually have to see the vortices to learn about them, as we know from the very productive studies with such techniques as neutron diffraction. Nevertheless it's useful to see real-space pictures of the vortices, which display visually the regular triangular lattices that form under certain conditions or the glasslike state they manifest under others. One method for producing such visual images is the magnetic decoration technique, in which tiny iron particles cluster around points of high magnetic field. Yet another technique—scanning tunneling microscopy—has now been demonstrated by a group led by Oystein Fischer at the University of Geneva in Switzerland to map the vortices of one of the most widely studied high-T_c materials, yttrium barium copper oxide (known as YBCO).[1] The results raise hopes that this technique can provide a new kind of information about the vortex lattices and especially about the vortex cores.

Electronic signature

The information provided by scanning tunneling microscopy is different from that available by other direct-imaging techniques such as magnetic decoration, scanning SQUID microscopy, Lorentz microscopy or scanning Hall probe microscopy. Rather than directly mapping the magnetic field, STM measures the current, or the