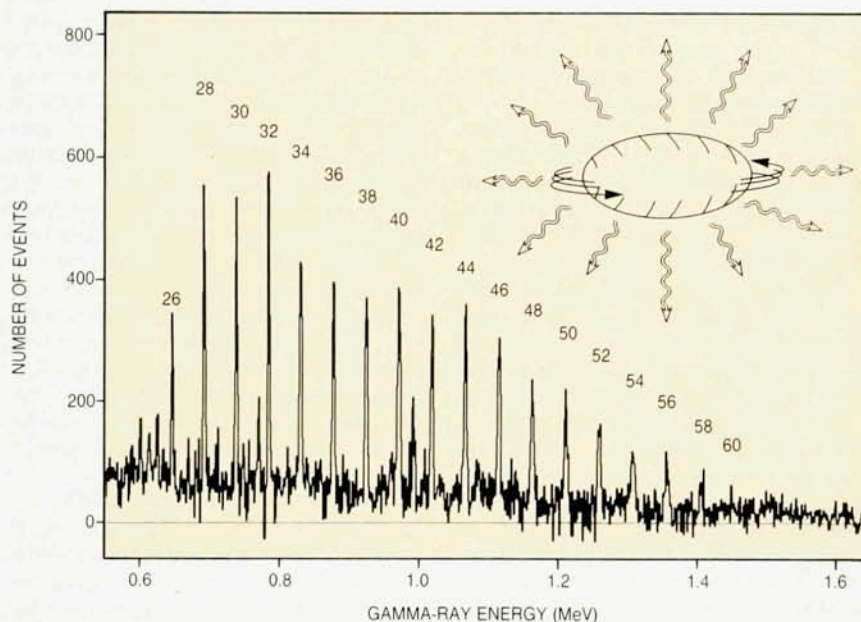


SUPERDEFORMED NUCLEI ROTATE SO FAST THEY MAKE HEADS SPIN

Spin a nucleus fast enough and it will stretch into an elongated shape. Spin it even faster and it will fission. But below the angular momentum at which fission can occur, some nuclei can be relatively stable, especially those whose lengths are twice their widths. Nuclear theory has long predicted such rapidly rotating, superdeformed states.¹ Only recently, however, have experimenters been capable of producing such nuclei, through heavy-ion collisions, and of observing them, with large arrays of high-resolution germanium detectors. In 1986, a group working at the Daresbury Laboratory in Great Britain succeeded in measuring the largest angular momentum reported until then for a nucleus.² They found dysprosium-152 to be rotating with a spin of $60\hbar$ —or about 2×10^{20} revolutions per second in a classical estimate. Several months ago the same team confirmed³ that this state of Dy^{152} has a superdeformed shape: It resembles a prolate ellipsoid rotating about a minor axis. (A prolate ellipsoid has one major and two equal minor axes, and the length ratio of the major to minor axes is 2:1 for superdeformed nuclei.)

The gamma-ray spectrum from Dy^{152} contains a series of 19 discrete lines, corresponding to transitions within the rotational band as the nucleus slows down. The regular spacing of these lines indicates that the moment of inertia becomes nearly constant at high spin—behavior suggestive of a rigid rotor. Theorists are puzzled by the unexpectedly high fraction of Dy^{152} nuclei produced in the superdeformed states, the rapidity with which they are formed and the abruptness of their transition to less exaggerated, oblate shapes at a spin of about $22\hbar$. The properties of this rare earth nucleus and of several others now being studied are challenging theorists to understand the



Rotating superdeformed nuclei remain in a highly elongated state (shown in schematic) while slowing down by emitting a cascade of gamma rays. The "picket fence" of peaks from dysprosium-152 are labeled here by the spins of the decaying states. Spacing between each peak is about 47 keV. Below $22\hbar$ the superdeformed state decays abruptly into more normally deformed states.

nucleus in extreme conditions.

The team that studied Dy^{152} at Daresbury consisted of Peter Twin, Andrew Nelson and John Simpson (all of Daresbury), Michael Bentley, Howard Cranmer-Gordon, Peter Forsyth, Debbie Howe, Rahman Mokhtar, David Morrison and John Sharpey-Schafer (all of the University of Liverpool), Barna Nyakó (Hungarian Academy of Sciences) and Geirr Sletten (Niels Bohr Institute, Copenhagen). They produced the highly deformed nucleus by accelerating calcium-48 ions onto a palladium-108 target. Following the collision several neutrons can boil off: Dy^{152} results when four neutrons are emitted. Radiation from other isotopes is also

present in the background.

Cascades of gamma rays

The experimenters hoped to populate the so called yrast levels of the superdeformed state. "Yrast" is a Swedish term meaning "dizziest," and an yrast level is the lowest energy level corresponding to a given state of angular momentum. In the reaction between the target and projectile, the Dy^{152} nucleus is formed at very high energy and angular momentum. As this nucleus cools, it drops at some point into the yrast set of levels, usually a rotational band. Once a nucleus drops into the yrast level, it slows down by emitting quadrupole gamma rays, with each one carrying

off two units of angular momentum. The signal for the presence of a nucleus in the superdeformed configuration is thus a rapid cascade of regularly spaced gamma rays.

The TESSA³ spectrometer at Daresbury was designed to study such events. It consists of a 50-element bismuth germanate crystal ball surrounding the target. Positioned outside periodic holes in the ball are 12 germanium counters equipped with shields to detect and suppress gamma rays from Compton scattering. The inner ball of this arrangement counts the number of gamma rays produced at the target and measures the total energy deposited. These data serve to select only those events that emit multiple gamma rays with a high total energy. The germanium counters record the energy of gammas detected in double or triple coincidence.

After making appropriate selections on the data, Twin and his colleagues determined the spectrum of gamma rays shown in the figure on page 17. One would predict evenly spaced gamma rays for a perfectly rigid rotor. The energy of a rigid rotor is proportional to $L(L+1)$, where L is the angular momentum. The particularly even spacing of the lines from Dy¹⁵² at high spins suggests that the moment of inertia, which is inversely proportional to the difference in energy between consecutive gamma-ray energies, is constant in that region. The value of the moment of inertia deduced experimentally is close to what one might estimate for a rigid rotor with the density of nuclear matter. From the total intensity of gammas in the cascade, the experimenters deduce that 1% of the Dy¹⁵² nuclei are in the superdeformed state. This small percentage is still much higher than expected.

The sequence of gamma rays from transitions within the superdeformed band stops abruptly below a well-defined spin. Apparently the transition probability out of the superdeformed band is rapidly increased at this spin value, allowing a precipitous decay out of the superdeformed states and into the normally deformed states. (In Dy¹⁵² these states are slightly oblate, having two equal major axes.) The superdeformed state most likely makes this transition by emitting dipole radiation, a process that changes the energy of the state without greatly altering its spin. The collaboration working at Daresbury studied the intensity pattern of the radiation leading to formation of normal oblate states and deduced that the transition was occurring at a spin of about 22 $\hbar$. Thus they assigned a

value of 60 $\hbar$ to the highest spin observed, 19 transition lines above this lowest value.

These observations strongly implied but did not prove that the Dy¹⁵² nucleus was being seen in its superdeformed state. The same group, joined by Gordon Ball (Chalk River Nuclear Laboratories), Bjorn Fant (University of Helsinki) and Costas Kalfas (Nuclear Research Center Demokritos, Greece), determined the quadrupole moment by measuring the lifetimes of the superdeformed states.³ They found the lifetimes by studying the attenuation of the Doppler shifts of the gamma-ray energies: States with higher spin, which are formed before the nucleus slows appreciably within the target material, have higher Doppler shifts than the lower-spin states. The pattern of attenuation, which thus reflects the lifetimes of each state in the cascade, is consistent with an extremely large quadrupole moment: 19 e barns. One would expect such a value of the quadrupole moment for a prolate nucleus whose major axis is twice as long as the minor axis.

Moreover, the highest-spin states are fully Doppler shifted and must have been formed in less than a few femtoseconds. No one knows how the hot compound nucleus cools so quickly into the relatively cold yrast levels.

Other superdeformed nuclei

Is Dy¹⁵² especially magic, or might other nuclei form high-spin, superdeformed states? The search is on for similar effects in other nuclei. So far two other nuclei have manifested equivalent deformations but less constant moments of inertia.

A Canadian team from the University of Montreal, McMaster University, Chalk River and Laval University, joined by researchers from the Center for Nuclear Studies (Strasbourg, France), have studied⁴ the high-spin states in gadolinium-149. The Chalk River MP Tandem produced a 150 MeV beam of silicon-30 ions that struck a tin-124 target to form Gd¹⁴⁹, after five neutrons boiled off. The target is surrounded by a detector similar to that at Daresbury except that it features 20, rather than 12, germanium detectors and a 71-element inner ball.

The gamma-ray spectrum has 19 discrete lines, with the highest line corresponding to a spin of approximately $127/2 \hbar$, slightly higher than the spin seen in Dy¹⁵². The quadrupole moment is nearly as large as that for Dy¹⁵² while the dynamic moment of inertia is smaller and decreases with increasing spin. The decrease indi-

cates a lower collectivity and a less stable deformation in this nuclei.

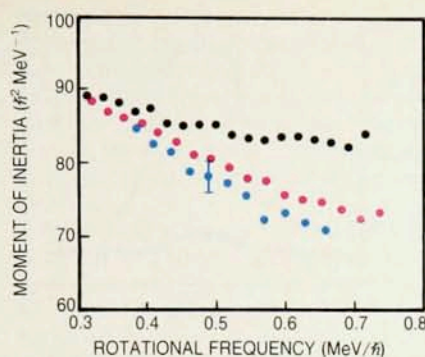
A team at the Lawrence Berkeley Laboratory⁵ has been using the 88-inch cyclotron to study the isotope Gd¹⁴⁸, formed by the fusion of calcium-48 with ruthenium-104 or of silicon-29 with tin-124. Their HERA detector has 20 Compton-suppressed germanium counters. The fraction of Gd¹⁴⁸ nuclei entering the superdeformed levels is slightly lower than that found in the other two studies of superdeformed nuclei. The signal for the superdeformed state is not as clear as that for Dy¹⁵², but the Berkeley team is able to discern 12 lines in the gamma spectrum. The moment of inertia decreases with spin even faster than it does in Gd¹⁴⁹. (See figure on page 19.)

Evidence for strong deformations has also appeared recently in high spin states of nuclei with mass numbers in the range 100–140, but their deformations have been only about 60% of those seen in dysprosium and gadolinium.

Theoretical studies

Superdeformed nuclei are not just now making their debut. They first came out in connection with studies of fission in the early 1960s, when researchers were measuring the fission rates for the excited states of some actinide nuclei whose ground states had long half-lives for fission. The delayed fission of excited states was attributed to the particular stability they acquire in a superdeformed shape. Vilen M. Strutinsky (Institute for Nuclear Research, Kiev, USSR) studied these fission isomers in the late 1960s and showed that the energy levels of single-particle states generally develop a secondary shell structure for deformations that correspond to integer ratios of the major to minor axis.⁶ The secondary shell structures are similar in nature to—although weaker than—those of the well-known magic-number nuclei.

Strutinsky proposed a method of analysis that is complementary to but less cumbersome than the Hartree-Fock method. In the expression for total energy, he separated the dominant terms, which vary smoothly with atomic number and atomic mass number, from those having a more rapid fluctuation. The dominant terms are the same as those in the classical liquid-drop model, which predicts a broad dip in energy at large deformations for spinning nuclei. The smaller quantum terms add several significant local minima, or "dimples," to the potential energy landscape, even for nonrotating nu-



Moments of inertia have been measured for superdeformed states of Dy¹⁵² (black circles), Gd¹⁴⁹ (red) and Gd¹⁴⁸ (blue). The dynamic moment of inertia for the first of these remains fairly constant over a wide range of rotational frequencies, while the latter two are smaller and decrease with increasing frequency. The constancy of the moments of inertia for Dy¹⁵² suggests that this nuclear state is behaving very much like a rigid rotor. A representative error bar is given for Gd¹⁴⁸.

clei. Fission isomers fall into one of these dimples, just inside the fission barrier.

After the discovery of the fission isomers, two groups of theorists^{7,8} studied nuclear deformations produced by rotations and discovered that for rotating nuclei, large deformations can also produce significant shell structure stabilization. In the case of fission, the strong Coulomb force of the heavy actinide nuclei helps to stabilize the nucleus in an elongated shape, because the protons are on average further apart in an ellipsoid. In lighter nuclei such as the rare earths, the centrifugal force plays a similar role.

While theory predicted what has now been observed in high-spin nuclei, it has not yet answered many of the questions posed by the new measurements. One challenge is to understand which parameters—such as number of valence nucleons, atomic number or mass number—determine the formation of a stable superdeformed state. Some theorists have proposed that abundances and regularities seen in the spectra of single-particle states as a function of deformation might be related to approximate symmetries of the nuclear average potential—pseudo SU(3) or pseudospin.⁹

A second challenge is to understand the dynamics of transitions among the deformed states. By what collective motion, for example, can the hot compound nucleus cool into a minimum-energy superdeformed state in a matter of femtoseconds?

The sudden transition between the prolate superdeformed states and the

oblate states at a certain spin also invites explanation. In the normal states pairs of nucleons are strongly correlated. The nucleus behaves then somewhat like a superfluid, in analogy with the superconducting states in condensed matter. At high spins these pair correlations seem to disappear. This effect is reminiscent of the disappearance of superconductivity in magnetic fields, although the analogy is far from perfect. In any case, the superdeformed nuclei offer the opportunity to study these pairing correlations.

The superdeformed nuclei also offer the opportunity to study another possible type of transition—from a somewhat ordered, fluid-like behavior to a more ordered, solid-like behavior. Wladyslaw Swiatecki of Lawrence Berkeley Lab has undertaken a macroscopic analysis to deduce certain elementary physical properties of the rapidly spinning Dy¹⁵² nucleus directly from the small deviations of its rotational spectrum from that of a rigid rotor.¹⁰ Swiatecki told us he is interested in exploring the transition from order to chaos in a quantum system that is predicted to be associated with a solid to fluid transition.

Others are interested in learning more about the nuclear giant dipole resonance from its possible influence on the superdeformed state. The giant dipole resonance arises when all the protons in a nucleus oscillate against all the neutrons. Its energy is inversely proportional to the length of the axis of oscillation. Therefore, in a deformed nucleus, which has at least two axes of different length, the giant dipole resonance will split. In a superdeformed nucleus, the energy of the lower component, corresponding to an oscillation along the longer axis, is further decreased. Nuclear physicists are trying to understand how this splitting might affect the population and decay of the superdeformed band.¹¹

Among the more interesting predictions to emerge from the current spate of theoretical work is the suggestion made by Jerzy Dudek (Center for Nuclear Research, Strasbourg,

France) and his collaborator Thomas Werner (Warsaw University) at an international conference on nuclear shapes held in Crete during the summer of 1987. They proposed that "super superdeformed" nuclei might exist, corresponding to major-minor axis ratios perhaps as large as 3:1.

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STUDIES OF NEW SUPERCONDUCTORS REVIVE OLD QUESTIONS

Lanthanum copper oxide, which is now regarded as the prototype for the new high-temperature superconductors, undergoes a phase transition to an antiferromagnetic state. The critical temperature for this transition, at

which the magnetic moments on copper ions begin to order antiferromagnetically, depends sensitively on the oxygen concentration. Confirmation of the existence of this antiferromagnetic phase in La₂CuO_{4-y} and the