SUPERDEFORMED NUCLEI GO FOR A SPIN

Physicists are head over heels about rapidly rotating, superdeformed nuclei

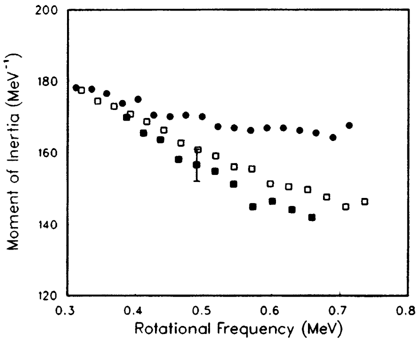
By STEFI WEISBURD

Nuclei come in assorted shapes. Some are spherical like basketballs, while others resemble stubby footballs. Spin a nucleus fast and its shape will change. A basketball-like nucleus when spun, for example, will smear out into a shape looking something like a curling stone. Eventually, if rotated fast enough, the nucleus will deform so much it fissions, or breaks in two.

Before reaching that point, however, some rapidly spinning nuclei settle into a "superdeformed" shape, a prolate ellipsoid reminiscent of a more elongated football spinning about its short axis. In assuming this superdeformed state, such nuclei become relatively stable, resisting the pull to resume less distorted configurations as they lose energy and slow down. Nuclear physicists have long predicted the existence of such states, but not until 1986 did experimentalists get their first glimpse of a superdeformed, rapidly spinning nucleus. English scientists observed dysprosium-152 rotating at 60 $\hbar$ (quantum spin units), or an estimated 10^{20} times per second, which at the time was the highest angular momentum ever measured in a nucleus. Subsequently the researchers showed that the dysprosium indeed had a superdeformed, prolate ellipsoidal shape, with a 2:1 ratio between its longest and shortest axes.

Since then, a dizzying array of other spinning nuclei with either superdeformed or other, less exaggerated shapes have popped up, bringing with them a batch of intriguing questions about the behavior of the nucleus. As was evident at a conference on high-spin nuclear structure and shapes held at Argonne (Ill.) National Laboratory last month, the recent discoveries have set the nuclear physics community awhirl.

"In a sense, this is a new kind of nuclear matter," says Argonne's Teng Lek Khoo. "It's not something we're able to put our hands on, so to speak, on a day-to-day basis. Unlike the normal 'off the shelf' nucleus, this is clearly something very unusual because it has such an exotic shape."



Deleplanque et al./PHYS. REV. LETT.

As a dysprosium-152 nucleus is rotated over a range of frequencies (circles), its moment of inertia stays nearly constant, indicating that it keeps its shape. The moments of inertia of gadolinium-149 (open squares) and gadolinium-148 (filled squares), however, are more susceptible to changes in rotational frequency. If scientists find that heavier, superdeformed nuclei also have more variable moments of inertia, this will confirm that there is something special about the dysprosium-152 superdeformed nucleus.

Because much of their behavior is yet to be explained, superdeformed nuclei are providing a new window on the inner workings of the nucleus. The superdeformed, high-spin states, for instance, offer a way to study how the collective motions and organization of the protons and neutrons within a nucleus change as it spins faster and faster. Such observations not only promise to enrich nuclear physics, but also may have some spinoffs to other disciplines—such as the study of how a system goes from an ordered to a chaotic state.

The recent discoveries trace their roots to Soviet fission research during the 1960s. Scientists noticed then that when certain heavy nuclei from the actinide region of the periodic table are produced in excited states they take a surprisingly short time to break apart. In modeling fission, physicists think of a nucleus as residing in a valley of low potential energy; to fission, the nucleus must "tunnel" through a neighboring hill known as the fission barrier. The excited actinide nuclei, it was determined, don't sit at the bottom of the valley, but rather in a little crevice farther up the fission hill. This means that less energy is required to get through the fission barrier than for "ground state" nuclei sitting in the valley, and so the excited nuclei split up more easily. The crevice, or energy minimum, is created by the Coulomb force, which causes positively charged protons to repel one another, together with quantum mechanical effects, elongating the nucleus into a superdeformed shape and giving the nucleus a measure of stability.

Several years later theorists predicted that lighter elements, such as dysprosium and other rare earths, could also assume a relatively stable, superdeformed shape if they were rapidly rotated; the rotational energy would play the same role as

Coulomb interactions in the actinide elements. The theory suggested that the most stable superdeformed shapes would have 2:1 or other integer ratios. Theorists targeted spinning nuclei with masses around 150 as having the particularly right combination of protons and neutrons to favor stability.

But scientists could not hunt for superdeformed nuclei until they developed the means to produce and observe them. Finally, two years ago, researchers at England's Daresbury Laboratory created spinning dysprosium-152 by colliding calcium-48 and palladium-108 ions, which fused into a compound nucleus. Using an array of germanium detectors, they recorded the gamma rays that dysprosium-152 nuclei emit in order to cool off and slow down.

The distinctive signature of a superdeformed state is a strikingly regular gamma-ray spectrum — the nucleus sequentially casts off 19 gamma rays, each of which carries two units of spin, thereby slowing down the dysprosium rotation step by step from 60 $\hbar$ to about 22 $\hbar$. According to Jim Waddington at Chalk River Nuclear Laboratories in Ontario, that is the largest number of successive transitions between different spin states ever observed in the decay of a nucleus.

From the gamma-ray spectrum, Daresbury scientists calculated the nucleus' moment of inertia, which is a measure of its deformation. They found the moment of inertia remains fairly constant, indicating the dysprosium maintains its superdeformed configuration throughout the 19-gamma-ray cascade.

Since then, researchers have observed superdeformed states in a handful of other nuclei, although these produce slightly less regular gamma-ray spectra and have more variable moments of inertia. Chalk River researchers discovered superdeformations in rapidly rotating gadolinium-149 nuclei. In the April 18 Physical Review Letters, Marie-Agnès Deleplanque, Richard M. Diamond and their colleagues at Lawrence Berkeley Laboratory in California report superdeformed high-spin states in gadolinium-148. At the Argonne meeting, Daresbury scientists noted the effect in gadolinium-150 and Argonne researchers reported a superdeformed energy band in dysprosium-151.

In addition, scientists have found high-spin states and deformation in many lighter nuclei — including various forms of palladium, neodymium and cerium — although these are less dramatically deformed than the 2:1 superdeformed complexes. And some preliminary evidence hints that different isotopes of osmium, which is heavier than dysprosium, may assume a deformed shape at high spin as well.

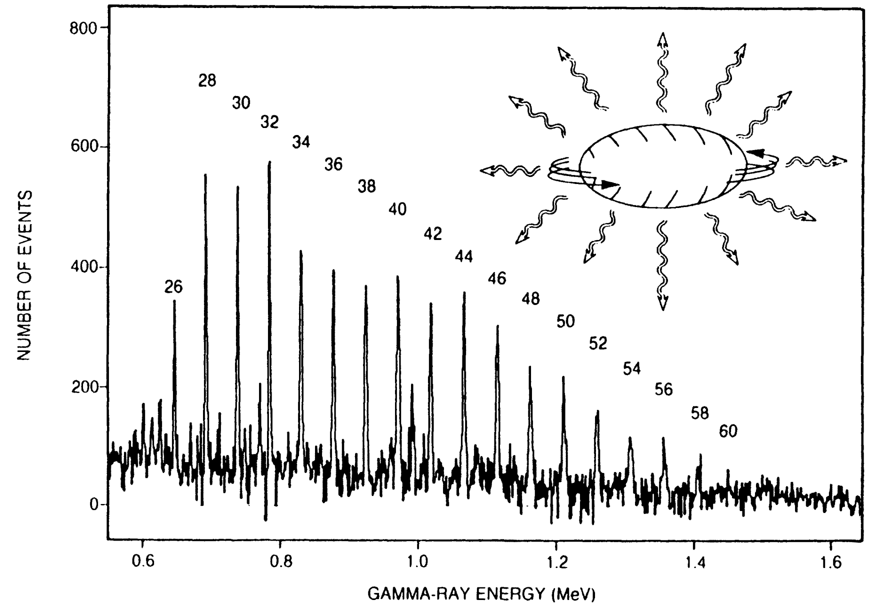
While nuclear theory predicted the existence of superdeformed nuclei, it falls short of explaining many of the recent observations. In the dysprosium-152 experiments, about 1 percent of the nuclei went through the lowest-energy, superdeformed cascade (this is known as the superdeformed "yrast" energy band after the Swedish word for "dizziest"). This is considerably higher than theorists expected. Because millions of other kinds of states are available to a nucleus in that energy region, it is surprising that enough nuclei would "choose" to go into this single superdeformed, high-spin band to be seen experimentally. "The band is populated beyond our wildest hopes," says Khoo.

Researchers are similarly puzzled by how the dysprosium-152 superdeformed nucleus abruptly transforms, after the gamma-ray cascade, into a less deformed, "normal" state at rotations below about 22 $\hbar$. "It goes from a superdeformed to spherical state in a way that nobody understands," notes Diamond. Scientists also want to unravel the collective motions of protons and neutrons inside superdeformed nuclei as well as to examine the way their pairing is affected by increasing spin. And researchers remain uncertain what to make of recent discoveries in other nuclei and particularly in lighter elements that some scientists argue do not behave as true superdeformed nuclei.

Dysprosium-152 remains the best and clearest example of a superdeformed nucleus, but exactly how special is it? Researchers need to canvass the periodic table to find and analyze, as one scientist says, the "personalities" of the superdeformed states of more nuclei — especially those slightly more massive than dysprosium-152 — to answer that question. This also would help them determine the nuclear properties, such as nucleon number, that give rise to the most stable superdeformed states. Perhaps dysprosium-152 is indeed a "magic" nucleus, says Diamond, or perhaps "there is a whole chain of nuclei that are deformed — although not as much as dysprosium's 2:1 shape — that will be unusually stable." Experimentalists may search for even more exaggerated nuclear shapes, which, according to one prediction, will have 3:1 axis ratios.

Doing all of this "is going to be extremely difficult," Diamond says, "and it may be beyond the capabilities of the present detector arrays, which contain about 20 germanium devices." That is one reason researchers at 21 universities and three national laboratories recently made a formal proposal that the Department of Energy construct a $15 million facility to house an array of 110 germanium detectors.

With such an array, scientists may be able to probe the structure of nuclei under extreme conditions as never before. This is exciting "because the nucleus is a very special laboratory," Diamond says. On one hand, it contains many particles and so shares properties with solid-state and other many-body systems. But because the nucleus contains far fewer particles than solid-state materials, it also exhibits single-particle properties, and these interact with the collective, many-body properties of the nucleus in a very special way, notes Diamond. "This makes the nucleus a very interesting and sometimes a very difficult system to unscramble," he says. ☐



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Rapidly rotating, superdeformed dysprosium-152 nuclei slow down by casting off gamma rays in a highly regular pattern.