might be introduced into some portion of the wavefront to cancel the constructive interference with destructive interference. This might be done by varying the thickness of the mask. But the variation of mask thickness would have to be specific to the particular pattern on the mask, and the technique may not work on all types of patterns.

Researchers have now turned their minds to proving the practicality of the method in commercial production. This year two Japanese firms—Oki and Hitachi—announced production of very simple devices with features of 0.17-0.18 micron using phase-shifted masks. In the US, Advanced Microstructure Devices in Santa Clara, California, Du Pont and IBM now have programs in phase-shift masks. Levenson feels that the technique has the potential to extend optical lithography to linewidths below 0.20 micron.

The balance of the system

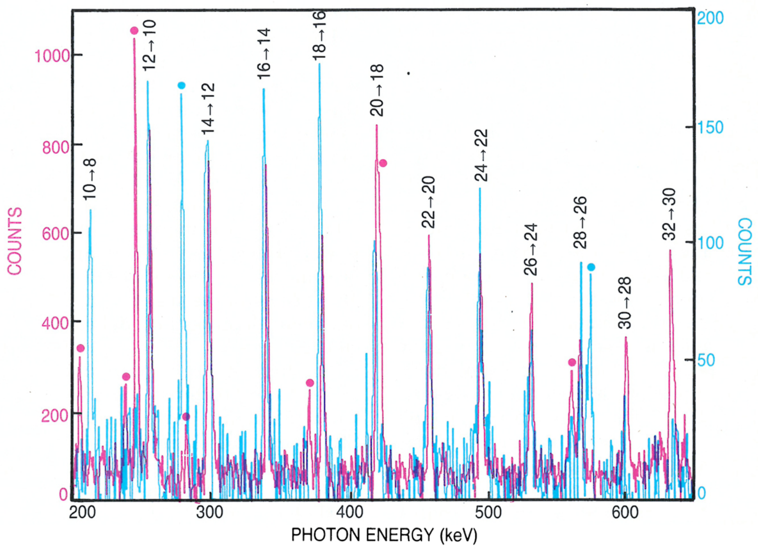
X-ray sources are of course only one part of the entire system that needs to be developed and integrated to make x-ray lithography a practical commercial tool. For example, Franco Cerrina, director of the Center for X-Ray Lithography at the University of Wisconsin, told us that the US has fallen a bit behind in the development of aligners that can position the image correctly to within 50 nm over areas about 3 cm wide, while progress is being made in process development. Henry Smith of MIT advocates a stronger emphasis on improving mask patterning, mask inspection and repair, and alignment systems. Smith would also like to see more work on granular x-ray sources and on collimators for them. Work on some of these components, as well as on integrated systems, is being done at many active centers around the world. —BARBARA GOSS LEVI

A NEW GENERATION OF GAMMA DETECTORS FOR NUCLEAR PHYSICS

The construction of Gammasphere, an important new photon detector for nuclear physics, began last month at the Lawrence Berkeley Laboratory. The principal purpose of this $20 million spherical array of germanium and bismuth germanate crystals will be to measure simultaneously the energies of as many as half a dozen gammas from the step-by-step deexcitation of a single excited nucleus.

Such multifold coincidence measurements are particularly important for unearthing extensive spectral patterns that would be hopelessly lost in background noise if one could measure only one or two gammas at a time. Patterns of this kind, laboriously uncovered by the present generation of smaller gamma detectors in spectra from the angular deceleration of high-spin nuclei, have in recent years taunted experimenters and theorists with some spectacular surprises.

Gammasphere is to be a national user facility. Its siting at Berkeley's 88-inch cyclotron is not permanent. The expectation is that after an initial period of about two years at LBL, the detector will sojourn at other heavy-ion accelerators around the country. The Holifield tandem Van de Graaff at Oak Ridge and the Atlas linac at Argonne, for example, were avid competitors of the LBL 88-inch cyclotron for the initial siting of Gammasphere.



Almost identical gamma spectra from the angular deceleration of two superdeformed nuclei—mercury-192 (red) and lead-194 (blue)—measured by the HERA detector array with different ion beams at Berkeley's 88-inch cyclotron. Each of the angular-deceleration peaks gives the energy of a quadrupole-radiation gamma that carries away $2\hbar$ of spin from the blimp-shaped nucleus. These peaks are labeled by the initial and final spin of the transition, in units of $\hbar$. The superdeformed ^{194}Pb spectrum only goes up to the $32\hbar$ peak shown here, but the ^{192}Hg spectrum continues all the way up to $42\hbar$. Other peaks in the figure, marked with dots whose colors indicate which nucleus they belong to, are known lines from gammas emitted *after* the nuclei have spun down below $10\hbar$ and are no longer superdeformed.

Across the Atlantic a similar gamma-detector facility, named Eurogam, is nearing completion at the embattled Daresbury Laboratory near Liverpool. Although Gammasphere was proposed before this British–French joint venture, Eurogam has benefited from more expeditious funding. Its first phase will be ready for experiments next spring. Gammasphere is scheduled for completion in 1994, but it should go into partial operation early in 1993.

Eurogam will also be an itinerant facility. After a year of first-phase operation at Daresbury's tandem Van de Graaff, it will move across the Channel to the new Vivitron Van de Graaff at Strasbourg. Brushing aside vehement protests from the nuclear physics community worldwide, Britain's Science and Engineering Research Council has recently decided that the country cannot afford to maintain Daresbury's experimental nuclear physics facilities after the departure of Eurogam.

Superdeformed nuclei

The various heavy-ion accelerators of the host laboratories will serve to direct beams of low-energy nuclei (typically 5 MeV per nucleon) at a fixed target at the center of the detector array. Two nuclei colliding at these energies can fuse into a composite state of astonishingly high spin. Off-center collisions can produce nuclei with angular momenta as high as $60\hbar$. That's about 10^{20} rotations per second. At these dizzying spins, centrifugal and Coriolis forces, in concert with shell effects, can "superdeform" a nucleus into a prolate (blimp-shaped) spheroid whose major axis is twice as long as its minor axis. (See PHYSICS TODAY, February 1988, page 17.) Shell-model theorists predicted in the 1970s that particularly stable superdeformed nuclei could be formed in the atomic-mass-number regions near 150 and 190.

Much of the impetus for building the new generation of gamma-detector arrays comes from the extraordinary spectral patterns that have been seen as such superdeformed nuclei lose angular momentum by quadrupole radiation in a neat sequence of little quantum steps. In 1986 Peter Twin and colleagues at Daresbury reported the first "picket fence" gamma spectrum from the spinning-down of a superdeformed nucleus: dysprosium-152. The Daresbury group's TESSA spectrometer recorded a sequence of 18 gamma-energy peaks as the ^{152}Dy nuclei, created in collisions between a calcium beam and a palladium target, spun down from about $60\hbar$ to $24\hbar$. Each peak gives the energy of a gamma that takes away $2\hbar$ of angular momentum.

The first great surprise, aside from the extraordinarily high spins these nuclei can acquire, was the uniformity of the spacing—about 47 keV—between consecutive peaks. That implies an unexpected constancy of the deformed dysprosium nucleus's moment of inertia over a great range of angular momenta. As more such picket-fence spectra were found for other superdeformed nuclei over the next few years, it became clear that the spacing was not always so uniform. In some spectra the spacing increases gradually with decreasing spin, as one might expect from the inverse dependence of the spacing on the moment of inertia. But in other cases the spacing is found to *decrease* as the nucleus spins down.

In 1989 the superdeformed nuclei sprung a much greater surprise. As Gammasphere project head Frank Stephens and colleagues describe it in a 1990 *Physical Review Letter*,[1] "Only occasionally in any area of science is something really unexpected found. But that seems to be the case in nuclear-structure physics right now. Rotational bands . . . in *different* superdeformed nuclei have been found that have identical . . . transition energies to within . . . 1 keV—much more similar than expected." That is to say, experimenters were beginning to find pairs of picket-fence rotation spectra that coincided perfectly, within the limits of resolution, even though they came from superdeformed nuclei differing by 1, 2 or 3 atomic mass units. (See the figure on page 21.) If the spacings vary with decreasing spin, they do so in precisely the same way for both nuclear species.

For some of these pairs the spectra are not strictly identical, but the differences are a few keV at most. All this is very puzzling, because one expects various effects of adding an extra neutron or proton to be on the order of tens of keV. One would have thought, for example, that the moment of inertia increases like the $^5/_3$ power of the mass. There appears to be some as yet undeciphered principle at work suppressing the differences between neighboring deformed nuclei.

The first identical pairs discovered in 1989 were terbium-151 and dysprosium-152, found by the Daresbury–Strasbourg collaboration, and the two mercury isotopes ^{192}Hg and ^{194}Hg, found by Stephens and company at Berkeley. Almost half of all the picket-fence rotation spectra found in the 190 atomic-mass region belong to such pairs. But in the 150 mass region one finds fewer spectral pairings, almost always between nuclear species differing by just 1 atomic mass unit.

"Although the nuclear shell model explains why we should see superdeformed rotation spectra in these two regions," Stephens told us, "it hasn't yet explained the identical pairs. But there's no shortage of ideas." The theoretical speculations go by names like pseudospin symmetry, triplet pairing, systematic SU(3) cancellation and strong particle–core coupling.

Resolving spectra

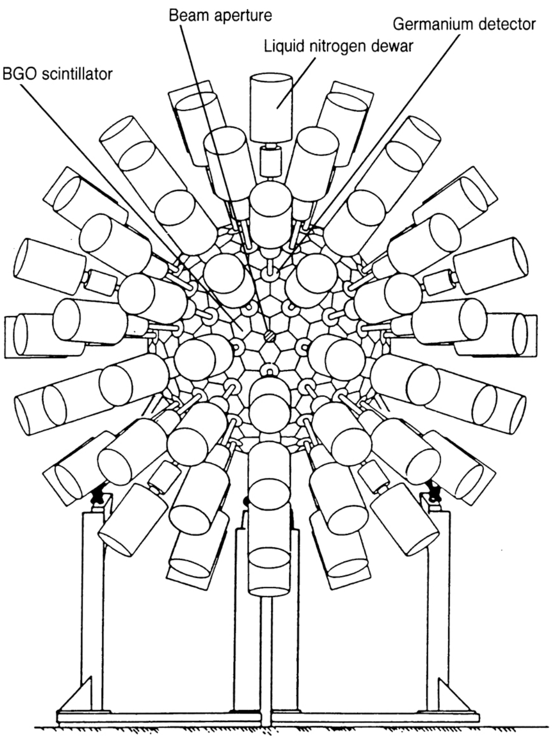
Solving the puzzles posed by the superdeformed nuclei will require many more of these intriguing rotation spectra. But they're not to be had for the asking. On a raw, ungated data record of detected gamma energies, a typical picket-fence spectrum would be just about undetectable, sitting as it does on a background 400 times higher than the peaks one is looking for. The background gammas come not only from other transitions of the nucleus under study, but also from other nuclear species created in the collisions. For a given beam and target, the resultant fused species depends on the (variable) number of neutrons, protons or alphas the compound state emits before settling down to radiate gammas.

In TESSA and the other gamma arrays of its generation (HERA at Berkeley [not to be confused with the collider of the same name in Hamburg] and "8π" at Chalk River, Ontario) a 1-MeV gamma has only about a 1 or 2% chance of having its full energy recorded by one of the germanium crystals. In Gammasphere and Eurogam, that probability will go up to almost 10%. That sounds like a five- or tenfold improvement. But in practice it's a gain of two or three orders of magnitude in the experimenter's ability to isolate a spectrum from background.

Multi-gamma-coincidence measurements are the essential trick of this business. Whenever several gammas are detected within a time interval short enough to imply that they came from the same nucleus, their energies are recorded for later analysis. Two-gamma events are the bread and butter of TESSA and its contemporaries. These older detectors rarely see a four-gamma coincidence. Gammasphere, by contrast, won't even bother to record two-gamma events. In the new detectors, four-gamma events will be as common as two-gamma events are in the old. (Remember, that's still only 4 of the 20 or so gammas a superdeformed nucleus radiates as it spins down.)

Searching a data record of coincidence events for an interesting spectrum hidden in the noise, the experimenter can set a software gate requiring that one of the gammas have an energy within a narrow range around some known or suspected spectral line. By thus selecting an enriched sample of events, that single gate raises the intensity of the spectrum by about a factor of 10 relative to background.

With more gammas in coincidence, one can set more such gates. To events with N gammas one can apply $N-1$ gates. For Gammasphere data, each additional gate will raise the spectrum another factor of 10 relative to background, so that if one



Gammasphere, the powerful new nuclear gamma detector array under construction at Berkeley. The hollow spherical array of germanium and bismuth germanate crystals surrounds a heavy metal target to be bombarded with ion beams from a cyclotron or Van de Graaff accelerator. The array's inner and outer diameters are 50 and 90 cm. The liquid nitrogen dewars that cool the Ge detector elements extend the total diameter of the system to 2 m.

starts out with a spectrum 400 times smaller than background, setting three gates for four-gamma events will lift the spectrum to about twice the background amplitude.

The new generation

Gammasphere will be a spherical array of detector crystals that surrounds the collision target almost completely at a distance of 25 cm. The configuration of Eurogam is much the same. With that kind of hermetic coverage, shouldn't these new-generation 4π instruments record gamma energies with efficiencies close to 100%? Why only 10%?

The problem is Compton scattering. A germanium crystal absorbing a 1-MeV gamma can measure its energy with a superb resolution of only 2 keV. But one can't grow single crystals much larger than 8 cm on a side. A 1-MeV gamma hitting such a crystal is more likely to scatter out than be fully absorbed. Thus the Ge crystal would measure only a fraction of the incident energy.

Unless one can discard the incomplete energies measured for scattered gammas, they will make a hash of the spectrum one is trying to record. But how does one know that a gamma has escaped from a Ge crystal? The trick is to surround each Ge crystal with crystalline bismuth germanate on all sides except the surface looking directly at the target. BGO crystals are scintillators with very poor energy resolution at 1 MeV, but their great virtue is stopping power. A gamma scattering out of a Ge crystal has very little chance of getting through the surrounding BGO veto shield. Any scintillation in one of the BGO elements tells the experimenter to ignore the coincident signal from the Ge crystal it surrounds.

Unfortunately these "Compton suppressors" take up solid angle. One needs enough thickness of BGO on the sides of each Ge crystal to flag the scattered gamma and keep it from passing through to the next detector element. In Gammasphere and Eurogam that takes up fully half the spherical surface facing in on the target, thus reducing the 4π coverage to 2π.

It would be much worse if one didn't have BGO. Sodium iodide, the most widely used scintillator before BGO came along in the 1980s, has significantly less stopping power. Therefore NaI Compton suppressors would have to be correspondingly thicker, taking away still more of the 4π target coverage from the Ge crystals.

Gammasphere will have 110 extremely pure n-type Ge crystals, each $8\frac{1}{2}$ cm long and 7 cm across. Every Ge crystal will be surrounded by a Compton suppressor module consisting of six BGO crystals. The first phase of Eurogam will have 45 Ge crystals about the same size as Gammasphere's. The original design for Eurogam's second phase in Strasbourg calls for 25 more Ge crystals of the same kind, but revised detector-module schemes for this phase are being considered.

The new gamma arrays are to be general purpose detectors of nuclear gamma radiation. They will do much more than just look at the rotation spectra of superdeformed nuclei. They should, for example, greatly facilitate the study of giant dipole resonances in hot nuclei. Many uses are also foreseen in the study of nuclei far from stability, nuclear symmetries, collective correlations and reaction dynamics at low energies.

The end of Daresbury

Eurogam's removal to Strasbourg in 1993 will, it seems inevitable, signal the closing of Daresbury's Nuclear Structure Facility. Last spring Mark Richmond, chairman of the Science and Engineering Research Council, announced his great regret "that the extra money needed for running [the facility beyond that time] cannot be made available from within SERC's financial provisions." That decision effectively marks the end of nuclear physics experimentation in Britain. But SERC will continue to fund British participation in nuclear physics at Strasbourg and other laboratories on the Continent.

After this portentous decision was taken, SERC convened a review panel to consider the future of nuclear science in the UK. The response of Herman Feshbach (MIT), a member of the panel, was typical. "Sir Mark's statement is, at best, disingenuous," he told the panel. "There is, in my opinion, no financial constraint that requires the closure of the Nuclear Structure Facility." But protestations of this kind seem, as of this writing, to have done no good.

"This is an example of egregious mismanagement," Feshbach told us. "Nuclear structure physics represents less than 2% of SERC's total research budget, a much lower percentage than in the US, Germany, France or Holland. To shut down this successful and relatively inexpensive facility, with its admirable past record and exciting future promise, cannot be justified."

—BERTRAM SCHWARZSCHILD

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