search & discovery

Interacting-boson model emphasizes symmetry groups

Over the past few years a new model for even–even nuclei has been developed, in which one considers the nucleus as if it is made up of nucleon pairs that behave like bosons. Although many nuclear physicists were originally skeptical of the model, it is looking increasingly promising as some of its predictions are being experimentally observed. Recent attempts to establish a connection between the interacting-boson model and the microscopic behavior of nuclei are attracting attention, but the work is still controversial. Proponents of the theory think that they have already achieved a simple unified picture of several types of collective nuclear motion. They hope that their efforts will also lead to a unification of the collective and microscopic descriptions of nuclei. An important consequence of the model is that it predicts the presence of several kinds of dynamical symmetries in nuclei.

The search for symmetries in nuclear physics goes back to the work of Eugene Wigner in 1937. He introduced a symmetry based on the spin and isotopic spin of the nucleon. This symmetry works well for light nuclei. In 1958 J. P. Elliott (now at Sussex University), by studying the symmetries of the harmonic-oscillator potential, introduced the group SU(3) in nuclear physics. His approach worked for atomic mass, A, between 16 and 24. For higher values of A the symmetries of the harmonic-oscillator potential are destroyed by the spin-orbit potential.

Throughout the 1960's it was widely believed that because the nucleus is a complex many-body system, symmetry considerations other than those having a geometrical basis were not very useful in

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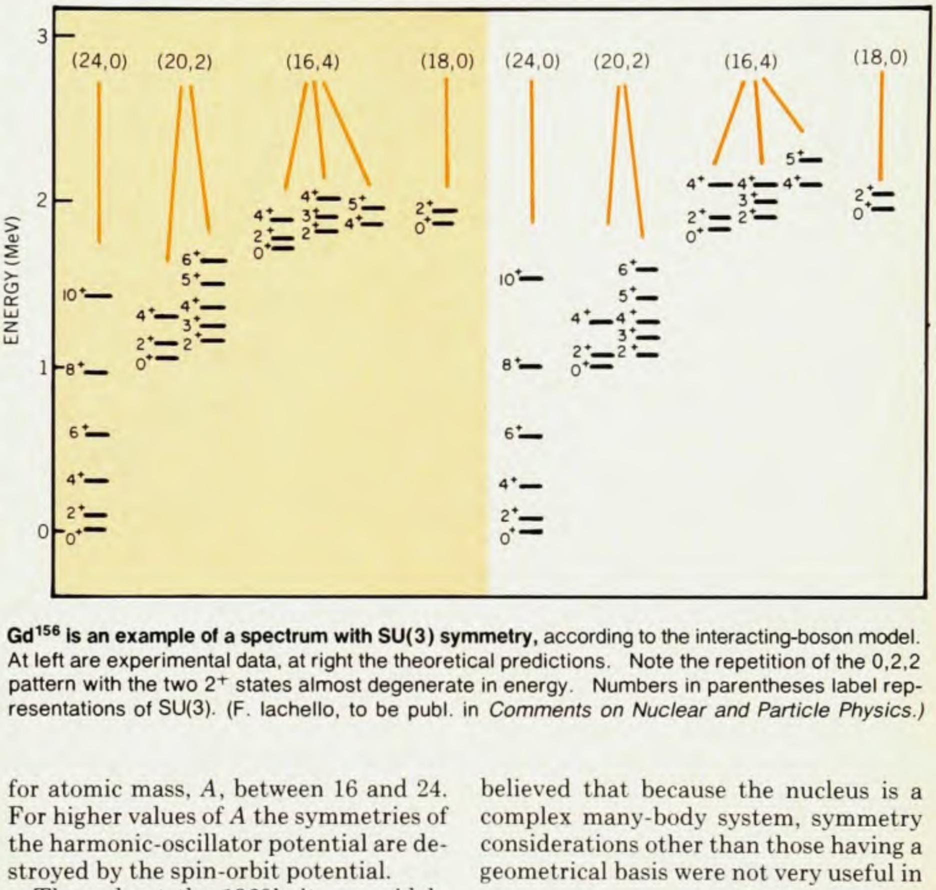

Gd^{156} is an example of a spectrum with SU(3) symmetry, according to the interacting-boson model. At left are experimental data, at right the theoretical predictions. Note the repetition of the 0,2,2 pattern with the two 2^+ states almost degenerate in energy. Numbers in parentheses label representations of SU(3). (F. Iachello, to be publ. in *Comments on Nuclear and Particle Physics.)*

Laser annealing shows promise for making p-n junctions

Ion implantation, a powerful technique for producing p–n junctions—the lifeblood of solid-state electronics and photovoltaic solar cells—has run into snags, and now there is a promising new way to cut through these snags: laser annealing.

In ion implantation, ions of a particular impurity element, such as boron, phosphorus or arsenic, are shot from an accelerator into a crystal of the substrate semiconductor, such as silicon. (Boron, a group-III element, forms a p-type layer, while P and As, which are group-V elements, form n-type layers in Si.) The choice of the injecting energy determines the depth to which the material is doped. The snags in ion implantation—more precisely, the major problems limiting its application—are twofold:

- The bombardment with high-energy ions disrupts the orderly arrangement of the crystal lattice, leaving dislocations and dislocation loops, stacking faults and clusters of point defects, all of which act as unwanted traps for holes and electrons.
- The ions do not all settle in substitutional lattice sites, to carry out their intended task as electron donors or acceptors.

What is needed to complete the process, then, is an annealing step. In current industrial practice, this is accomplished by placing the sample in a high-temperature furnace for times of the order of an hour. This treatment, known as "thermal annealing," cures some but not all types of lattice damage; in particular, dislocation loops and stacking faults resist it. Furthermore, it often degrades the electrical properties of the substrate and the device. Specifically, the minority-carrier lifetime typically drops from 100–200 microsec to 20–30 microsec. Therefore, although thermal annealing is satisfactory for many types of devices, it is inadequate for solar cells, where long lifetimes are important. What is needed is a method of heating only the ion-implanted region. This requires a strong, highly controllable source of energy; hence, the proposed alternative is annealing with lasers, which have the addi-

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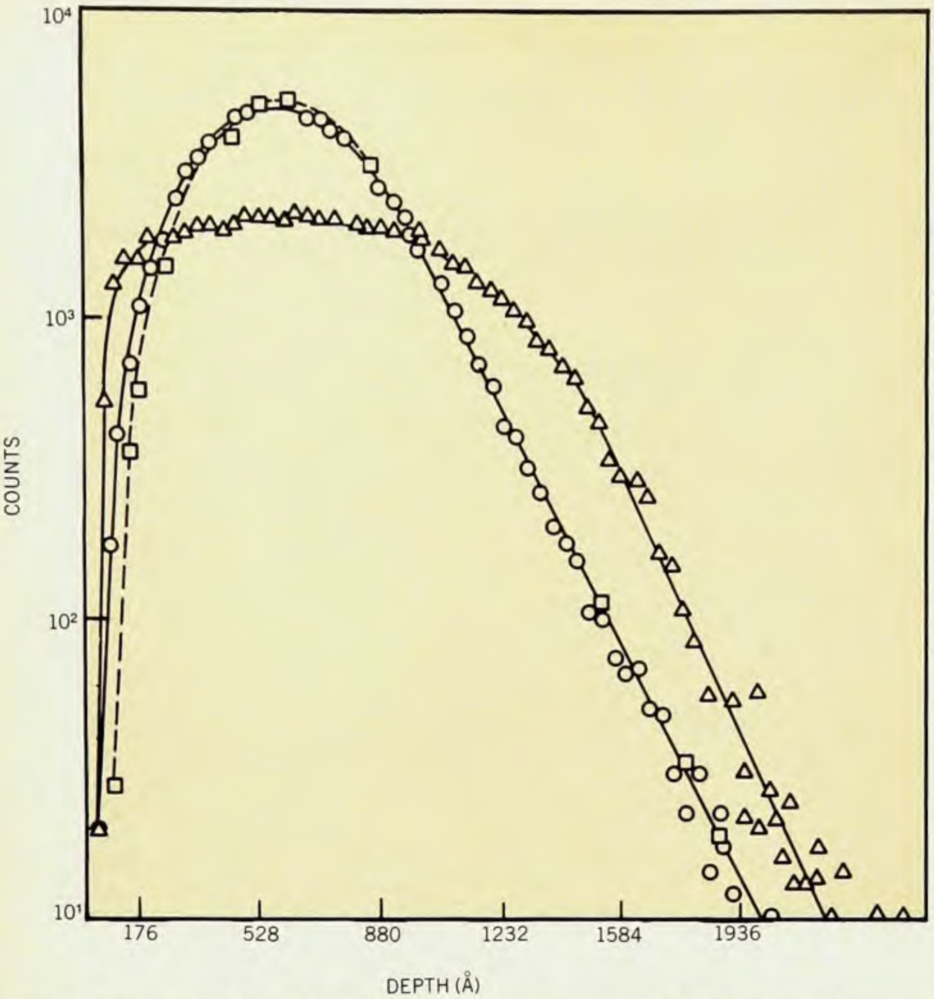


Concentration profiles of arsenic implanted in silicon. Triangles indicate data for thermal annealing at 1000°C for 30 min; the distribution is flattened and spread deeper into the sample. No such redistribution occurs with laser annealing (circles), as a comparison with a calculated profile before annealing (squares) indicates. The figure is from A. Gat and collaborators, reference 2.

tional advantage of yielding monochromatic light.

Research in laser annealing is still new, and with divergent approaches. Some of these stem from differences in goals—solar cells or integrated-circuit devices—and others, from disagreements as to the best way to reach these goals. In 1974 Charles Marquardt and his collaborators at the Naval Research Laboratory reported their studies on laser damage in phototransistors. About two years ago, laser annealing was carried out by Soviet physicists, particularly I. B. Khaibullin and his associates at the Physical Technical Institute in Kazan, and A. Kh. Antonenko, G. A. Katchurin and their collaborators at the Institute of Semiconductor Physics in Novosibirsk. Much of the laser annealing work in the United States is done at Oak Ridge, Stanford University and Bell Labs.

Oak Ridge. Rosa T. Young and her colleagues at Oak Ridge[1] use a pulsed ruby laser, because its photon energy (1.79 eV for a wavelength of 0.694 micron) exceeds the band gap of silicon, 1.1 eV. The absorption length of this radiation is about 0.5 micron, a few times the depth of the implant layer. The power of the Q-switched ruby laser is high enough to melt the surface to a depth of 1 micron with pulse lengths of about 50 nanosec. Young and her co-workers found that the threshold energy density for removing radiation damage is about 1.3 J/cm^2; a single pulse does the job. For complete annealing, Young told PHYSICS TODAY, some melting is necessary. The crystal, restored by epitaxial regrowth from the interface, is completely free from damage, transmission electron microscopy shows. Furthermore, 100% of the dopant atoms are in substitutional lattice sites, and there is no degradation of the substrate.

The Oak Ridge investigators are primarily interested in developing solar cells that are both efficient and suitable for high-speed automatic fabrication. For cells of phosphorus-doped silicon, Young has achieved 12–14% efficiency.

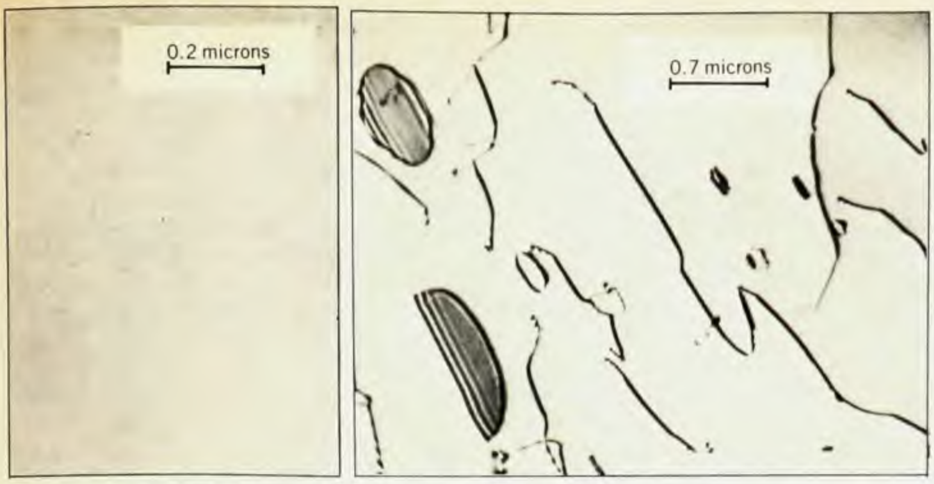
Stanford. James Gibbons and his colleagues at Stanford University are using a scanned cw laser beam to obtain the same general effects as Young and her co-workers, but with some differences. The Stanford group has used a scanning laser anneal under conditions such that no melting occurs. The process is essentially a solid-phase epitaxial regrowth, similar to that which occurs in thermal annealing. However, because the absorption of laser energy is limited to roughly the first 0.5–1 micron, annealing is confined to that region. They have obtained annealing in silicon with both argon and krypton lasers, focussed by a 79-mm lens to a 20-micron spot, with a beam power of about 9 W. The beam is scanned across the sample at a rate of approximately 2.5 cm/sec. They have obtained essentially 100% electrical activity in both arsenic- and boron-implanted samples.

An interesting feature of the Stanford work is that no diffusive redistribution of the implanted ions takes place during annealing with the scanning system. Gibbons told us that this feature, not present in pulsed laser annealing, will very likely permit significant improvements in the design and fabrication of high-performance transistors and integrated circuits. The absence of lateral diffusion will also permit a reduction in the size of transistors in an integrated circuit. Although these results are relevant to solar cells, an exciting application is in fabricating integrated circuits with very high packing density—Gibbons sees the possibility of reducing the minimum feature size in an integrated circuit to 0.5 micron or less, and thus increasing the density of transistors in a memory chip by more than an order of magnitude.

Bell Labs. Walter Brown and his co-workers at Bell Labs and Western Electric are studying two modes of laser annealing, that of liquid-phase epitaxial regrowth (as at Oak Ridge) and solid-phase epitaxy (as at Stanford). For the liquid-phase case they have used a neodymium–YAG laser at a wavelength of 1.06 microns, corresponding to an energy of 1.17 eV, just at the band edge of silicon. At this wavelength, the coupling of the laser energy to the silicon is strongly increased by the presence of implanted impurities and implantation-produced defects. As a result, the light is selectively absorbed just where it is needed. A potential disadvantage, however, is that the threshold for annealing depends on the density of implanted impurity atoms. Brown said that typically some 5 J/cm^2 in a pulse of about 100 nanosec is required to reach the melting regime.

In the solid-phase regime the Bell Labs workers have used a focussed cw argon-ion laser to raise the temperature of the silicon to 900–1300°C in a highly localized region, but not to the 1400°C melting point. They have verified the results of the Stanford group that there is no redistribution of impurities during annealing.

Because the work of Brown and his collaborators is aimed primarily at producing patterned regions, such as those used in integrated circuits, they have concentrated on annealing small spots. Their Nd:YAG laser heats a spot 30 microns in diameter, which they move suc-



No damage is visible in the sample on the left, annealed by a single pulse from a Q-switched ruby laser, while the sample on the right, subjected to thermal annealing at 1100°C for 30 min, shows extensive lattice damage. Both samples are boron-implanted silicon. Photo from Rosa Young.

cessively in 8-micron steps; their argon-ion laser has annealed regions as small as 1.6 microns. They have also done annealing studies in ion-implanted gallium arsenide, for which laser annealing appears particularly attractive, because thermal annealing causes GaAs to decompose.

The interest in laser annealing is worldwide; active groups cited by Gibbons include the University of Catania (Italy), Hitachi Central Research Laboratories and Toshiba R&D Center (Japan), Philips Research Lab and FOM Laboratory (Netherlands), Atomic Energy Research Establishment, Harwell (UK) and the Hopei Institute of Semiconductors (People's Republic of China). Laboratories in the US with active programs in progress include, in addition to the ones mentioned, Lockheed Palo Alto Research Labs, Caltech, RCA, Rockwell Science Center, Air Force Geophysics Labs, Hughes Research Labs, Hewlett-Packard and Texas Instruments, according to Gibbons.

A related method for ion-implant annealing is the use of pulsed electron beams, being developed since 1973 by Allen Kirkpatrick and his associates at the SPIRE Corp, Bedford, Mass. They report solar cells of 15% efficiency, produced in a high-speed production process.[4] Their method employs a 10-keV electron beam 7 cm in diameter in 0.1-microsec pulses. Kirkpatrick feels that the large processing area and effective energy utilization make pulsed electron beams particularly attractive for large-scale production. —HRL

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Fusion computer center expands at Livermore

Groundbreaking for a new building to house the National Magnetic Fusion Energy Computer Center recently took place at Lawrence Livermore Laboratory. The $5-million, 44 000-square-foot facility is scheduled for completion in February 1979, and will house two large computers, a Cray-1 and a CDC 7600.

The NMFECC was founded in 1974 to provide large-scale computational support to the US magnetic fusion-energy community (PHYSICS TODAY, October 1974, page 19). Presently housed in a World War II vintage barracks building, it has 55 employees and a $6-million operating budget from the Department of Energy in 1978.

The Center's most powerful computer, a Cray-1, was installed in April. (It has the same configuration as the computers being used at the National Center for Atmospheric Research and at Los Alamos.) The Cray-1 is a vector computer able to set up many operations simultaneously. It can perform 138 million floating-point operations per second over a sustained period of time; an even higher rate of 250 million operations per second can be attained in short bursts. The computer has a one-million-word semiconductor memory. Four Cray Research DCU-2 disk control units, each controlling four DD-19 disk storage units, make up the disk storage system; together the storage units hold nearly 2½ billion bits of useful data. The Center's CDC 7600 computer can perform 20 million mathematical operations per second. It has 65 000 words of semiconductor memory and 512 000 words of magnetic core memory.

The Center also has a CDC 6400 computer for file management and two PDP-11/50 computers—one for central communications control and the other for network control. A 500-billion-bit CDC 38500 mass storage device is planned for operation late this year.

More than 800 researchers have access to the Center's computers. At seven fusion research centers located at various points in the US, user service centers each have a PDP-11/40 computer functioning as a remote control communications processor and a PDP-10 computer that allows the service center to function as a remote output or a remote job entry station. Thirty other fusion research groups at universities, national laboratories and industry have access to the Center through dial-up telephone lines from remote terminals. —CBW

Interacting-boson model

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nuclear physics. Proponents of the interacting-boson model think that, on the contrary, nuclear physics may be a very rich field for theories involving symmetries.

In addition to emphasizing symmetries in nuclear physics, the model is also useful in analyzing experimental data in medium and heavy-mass nuclei. Most of these data have been analyzed in the past in terms of the collective model of the nucleus developed by Aage Bohr and Ben Mottelson in Copenhagen, and for which they won the 1975 Nobel Prize. In their earlier work on the model, one describes the nucleus as a liquid drop capable of performing oscillations and rotations. The model has been extremely successful in describing deformed nuclei.

Interacting bosons. About ten years ago Herman Feshbach (MIT) and his student, Francesco Iachello, attempted to construct a boson model by considering particle-hole pairs, and more generally, quasi-particle pairs. It was applied to a closed-shell nucleus, and thus in that case emphasized excitations across major shells instead of within a shell. Because these particle-hole excitations were across major shells, they had negative parity. Feshbach and Iachello found some difficulties in constructing a boson Hamiltonian.

In 1974 Iachello (now at the University of Groningen and soon to be at Yale University) decided to attempt an approach similar to that used with Feshbach, but