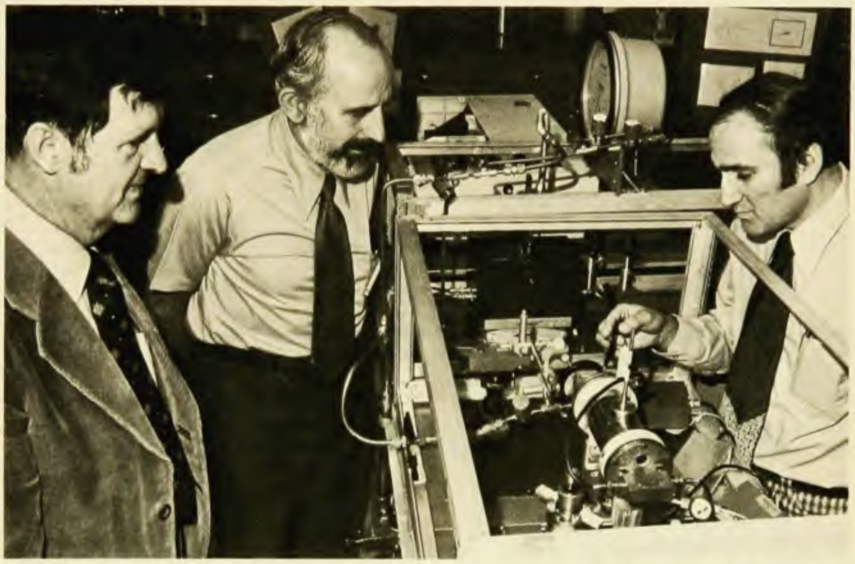
search & discovery

Resonance electron spectroscopy detects single atoms

A group at Oak Ridge National Laboratory reports that by means of the new technique of resonance ionization spectroscopy they have observed single atoms of cesium. They say that one atom in an environment of 10^{19} atoms or molecules of another kind can be measured with their method, and they do not believe this to be a limit. In subsequent experiments, the group has observed density fluctuations of atoms, absolute photodissociation cross sections, time-resolved diffusion and chemical reaction of atoms, and the detection of cesium atoms from the spontaneous fission of californium nuclei.

In 1975 William M. Fairbank Jr (now at Colorado State University), Theodor W. Hänsch and Arthur L. Schawlow (Stanford University) reported detecting as low as 100 atoms/cm^3 using cw resonance fluorescence in sodium vapor. A single atom was contained in the detector beam at any instant. The technique required a steady-state concentration of atoms.

That same year G. Samuel Hurst, Marvin G. Payne, Munir H. Nayfeh, John Judish, E. Bryan Wagner, Chung-hsaun Chen and Jack P. Young (Oak Ridge) developed the resonance ionization spectroscopy method. Each atom in a selected quantum state was converted to a positive ion and a free electron by the absorption of two photons, one of which is resonant with an intermediate state, lying more than half the distance to the ionization continuum. With relatively small energy per pulse in a pulsed dye laser with a linewidth of several angstroms, the intermediate state comes into quasiequilibrium with the ground state. Then other photons from the same laser pulse photoionize the intermediate state. The method was initially applied to measuring the number of excited atoms created by proton interactions in a given volume. The group also showed that if enough photons/cm^2 are available, all the excited states would be ionized.



The single-atom detector at Oak Ridge National Laboratory, with experimenters (left to right) G. Samuel Hurst, Jack P. Young and Munir H. Nayfeh. The group reports that with this device they have detected cesium at a concentration as low as one cesium atom in 10^{19} other atoms.

This year, Hurst, Nayfeh and Young

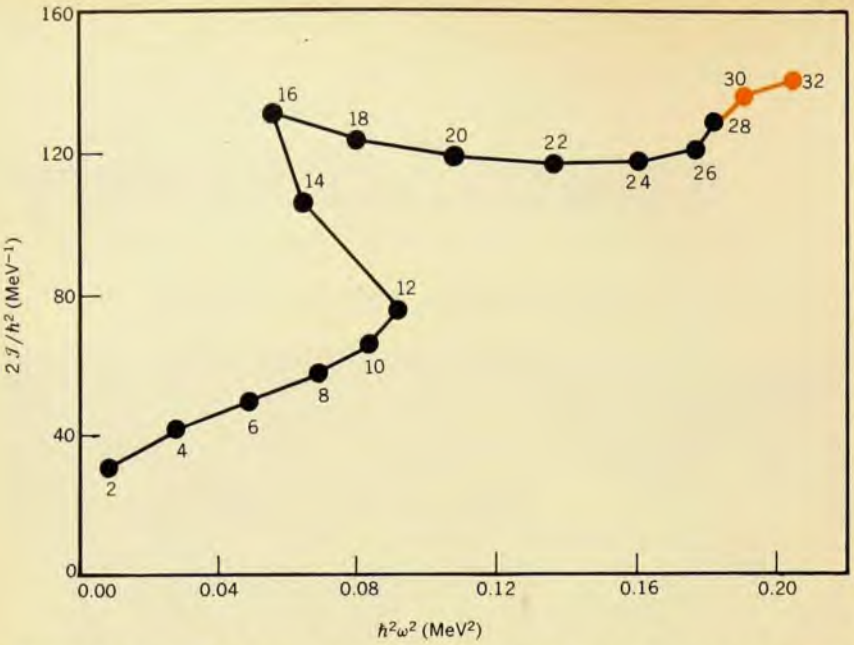
continued on page 20

Second "back bend" helps explain nuclear band crossing

A kink discovered in a curve describing the behavior of the moment of inertia of a nucleus at high angular momentum is providing a new clue to nuclear structure. The unusual behavior was found by making measurements on nuclei with spins as high as $32\hbar$ in an experiment done by a group at the Lawrence Berkeley Laboratory and reported in the 20 June 1977 *Physical Review Letters*.[1] The members of the group are I-Yang Lee, Marie-Madeleine Aleonard, Marie-Agnes Deleplanque, Youssef El-Masri, John Newton, Reinhard Simon, Richard Diamond and Frank Stephens.

At low spin values—up to about $12\hbar$—a deformed (that is, non-spherical) nucleus with even numbers of both neutrons and protons rotates, experiments have shown, somewhat like a rigid body, with many of its nucleons joined in a collective motion. Stephens points out that the nucleus exhibits superfluid effects that generally reduce the moment of inertia to one half to one third of its rigid-body value. In such nuclei, the lowest energy E corresponding to a given angular momentum I varies in a smooth parabola with the angular momentum, that is, $E \propto I(I+1)$; these lowest states are known as "yrast" (from the Swedish word for "dizziest") states. But at higher spins there occurs a peculiarity known as "backbending," which was first observed in 1971, by Arnie Johnson, Hans Ryde and J. Sztarkier (Research Institute for Physics, Stockholm): The curve of the energy of the yrast states against their angular momentum has a slight but distinct kink. Plotted as the effective moment of inertia against the square of the angular velocity, the effect shows up as a turning back of the curve on itself and a subsequent bending forward. A sharp increase in the moment of inertia is accompanied (due to conservation of angular momentum) by a decrease in rotation rate, and hence an energy that is lower than expected.

By observing and identifying transitions to angular momenta considerably higher than had been seen before, the Berkeley group has now found, as reported in their Letter, a second discontinuity in the yrast levels of erbium 158. In



Backbending behavior of the moment of inertia $\mathcal{J}$ in erbium 158, decaying by gamma emission from 32 $\hbar$, showing a second, newly discovered, discontinuity around spin $I = 28\ \hbar$. The abscissa is proportional to the square of the angular velocity, $\hbar^2\omega^2 = (E_t/2)^2$, where E_t is the energy difference $E_I - E_{I\text{-}2}$; the ordinate is $2\mathcal{J}/\hbar^2 = (4I - 2)/E_t$. The data points shown in color have somewhat greater uncertainty, but this does not affect the conclusions. The two bends probably represent rotational band crossings caused by the breaking of pairs of nucleons. From reference 1.

this new kink the angular velocity does not actually decrease; rather, its rate of increase with spin is greatly diminished.

The interpretation of the backbending phenomenon has been a puzzle. Erbium 158 is a rare-earth nucleus with a deformed ground state, and it rotates like a football tumbling end over end. The evidence strongly supports the idea that the backbending results from the intersection of a rotational band characterized by a larger moment of inertia with the ground-state (low-spin) rotational band. What is the nature of this upper band?

1. Does it correspond to a different shape of the nucleus?
2. Is there a collapse of the pairing of the nucleons? Ben Mottelson and J. G. Valatin pointed out in 1961 that there might be an analogy between the pairing in nuclear and superconducting-metal systems: Just as in the Meissner effect the magnetic field destroys the superconducting state by a breakup of pairs of particles so in the nuclear system the Coriolis force would be responsible for a similar collapse of pairing in this model.
3. Or, as Simon (now at GSI, Darmstadt, Germany) and Stephens suggested, do two of the high-spin nucleons separate from the collective motion and align their spins (oppositely paired in the ground state) with the rotational angular momentum of the nucleus?

To generate data for choosing between these three suggested alternatives it has been necessary to study states with higher and higher spin.

Three special techniques used by the Berkeley group made possible their measurements to spins as high as $32\hbar$:

- Heavy ions were used as projectiles to bring large angular momenta into the system.
- Doppler broadening due to the velocity distribution of the product nuclei (and the finite size of the gamma detector) was avoided by using a thin foil target and looking in the forward direction, a technique developed in a similar context by Dirk Schwalm, Hans Emling, Eckart Grosse and Dietrich Pelte at GSI.
- Gamma rays emanating from high-angular-momentum nuclei were selected by a multiplicity filter of six sodium-iodide detectors. This technique was developed in somewhat similar experiments by Gudrun Hagemann, Raffael Broda, Bent Herskind, N. Ishihara and Stanislaus Ogaza at the Niels Bohr Institute, Copenhagen.

The Berkeley experimenters bombarded tin-122 nuclei with an argon-40 beam from the 88-inch cyclotron to form a compound nucleus, from which four neutrons "evaporated" to produce erbium 158 with 10–30 MeV of excitation energy. These nuclei are in unstable high-spin states from which they decay by a series of gamma emissions, the deexcitation gamma rays forming a spectrum of strong peaks above an unresolved background. The use of coincidence counters shows that these peaks represent transitions through the last steps in a cascade of intermediate states (there are perhaps 25–30 of these transitions, roughly half in the continuum and half discrete).

The sequence by which this cascade occurs is then worked out under the assumption that a peak with a *larger* number of counts is from a *lower* level, which is reasonable because branching out of the yrast level is not expected in even–even nuclei. The probable spin is determined from the angular distribution of gamma rays; for example, an intensity ratio for gamma radiation at 0° to those at 90° of about 1.3 indicates a transition that reduced the spin of the system by two units.

In a Lawrence Berkeley–Oak Ridge collaboration, the backbend region was also reached recently by Coulomb excitation,[2] a method that gives information on lifetimes and cross sections. The experimenters—Lee, Douglas Cline, Simon, Peter Butler, Pascal Colombani, Michael Guidry, Stephens and Diamond of Berkeley, and Noah Johnson and the late Eugene Eichler of Oak Ridge—measured the electromagnetic-transition strengths through the backbend region and showed conclusively, Cline told PHYSICS TODAY, that the intersecting-band picture is correct.

Another way to get information about high-spin states in the backbending region and above is to study long-lived states known as isomers, which permit the study of the sequence after the decay of the intense prompt radiation. Isomerism often arises because a nucleus needs to dispose of more than two units of angular momentum in decaying to the next level. The existence of isomers in such even–even nuclei appears at present to be rare, but when they occur they provide detailed information about the nuclear structure. Many searches for such high-spin isomers, known as yrast traps, are in progress. Teng Lek Khoo (Michigan State, now Argonne National Laboratory) reported evidence last fall at the APS Nuclear Physics Division meeting of the existence of such an isomer with spin $22\hbar$ at 5 MeV in hafnium 176.

The evidence gathered by researchers in the last five years for backbending in nuclei like erbium 158 has come to favor the third of the above explanations—that a nucleon pair is broken and that the two particles then become lined up with their angular momenta parallel to that from the collective nuclear rotation. These aligned particles then carry a large part—up to half—of the total angular momentum of the system. The evidence of the new irregularity therefore suggests that a second pair-breaking occurs, so that the states above the irregularity would have four unpaired particles.

The extension to states of even higher angular momentum leads to the idea, Stephens told PHYSICS TODAY, that eventually all the angular momentum will be carried by such lined-up particles, reinforcing an early prediction based on the liquid-drop model. The system would then no longer rotate as a whole, and theory indicates that the nucleus would become oblate in shape. If this is indeed what happens, the two observed discontinuities represent only the first and second steps in this process. —HRL

References

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2. I. Y. Lee, D. Cline, R. S. Simon, P. A. Butler, P. Colombani, M. W. Guidry, F. S. Stephens, R. M. Diamond, N. R. Johnson, E. Eichler, Phys. Rev. Lett. 37, 420 (1976).

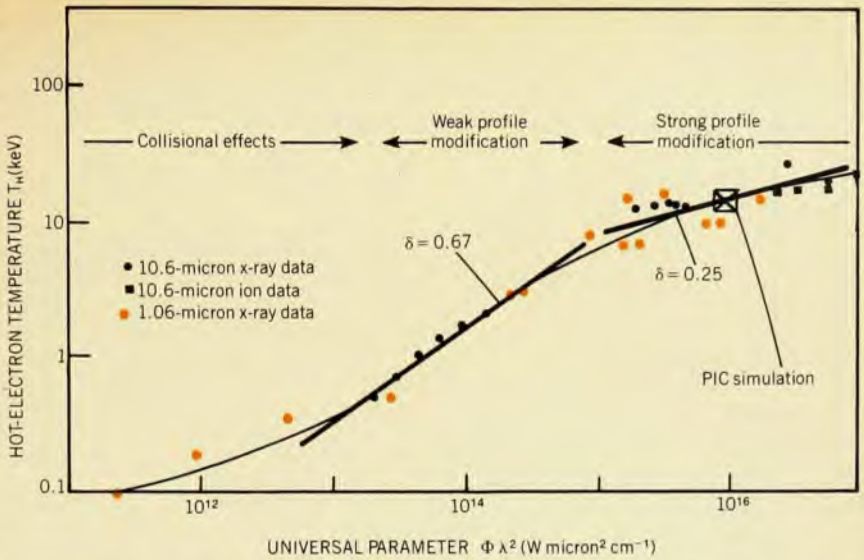
Tests show CO_2 laser is suitable for fusion

Two kinds of lasers are widely used for laser-fusion research, the neodymium-glass laser with 1.06-micron output and the carbon-dioxide laser with 10.6 micron output. It has been a widely held belief that the neodymium-glass laser was far superior for compression of the pellet because of its shorter wavelength. However, recent results at Los Alamos, which were reported at the Conference on Laser Engineering and Applications held in Washington in June, have called this belief into question. The Los Alamos group has compared results with the two kinds of lasers and finds striking similarities despite the factor of ten difference in wavelength. The report was made by Damon Giovanielli, Dale Henderson, Gene McCall and Roger Perkins.

Carbon-dioxide lasers have a calculated efficiency of 3%, the group notes, whereas neodymium glass has an efficiency of 0.1% when operated with the required short pulse lengths. Furthermore, because the carbon-dioxide lasing medium is a gas, it can have a higher repetition rate, and it is therefore of great interest for laser fusion.

However, it was generally believed that the carbon-dioxide laser would be less suitable for laser fusion because, for a given amount of energy, one would produce hotter electrons than with neodymium glass. These hot electrons have a very long range and heat the entire target, making it more difficult to compress, McCall told us. A relatively cold fuel is required because one wants heating to be the result of *PdV* work. If energy is supplied from outside the target, the process is no longer adiabatic and more energy is needed to compress the target. Very early theoretical predictions were that for a given input intensity, the electron energy would be 100 times higher from carbon dioxide than from glass.

In a series of experiments at Los Alamos, both carbon dioxide and neodymium glass were used, each with an intensity of 3×10^{15} W/cm^2. The group found a hot-electron temperature produced by carbon-dioxide radiation of 15–20 keV, three times the energy found with the glass.[1]



Comparison of data from CO_2 and neodymium-glass laser-fusion experiments. The temperature of high-energy electrons is plotted as a function of the product of laser intensity Φ and the square of the wavelength λ for the two types of lasers. Note that $\Phi\lambda^2$ is a universal scaling parameter. The break in the curve coincides with the laser flux at which profile modification becomes important. Two straight-line fits to the data are marked with their slopes δ.

This unexpectedly low temperature occurs because of a steep density gradient produced by light pressure. The position in the target at which the laser energy is absorbed is not very different when the two sources are compared by x-ray pinhole photography, for either flat or spherical targets. Typically the radiating radius of a spherical target is 20 microns larger than the original target radius. Similarly, for flat targets, x-ray emission occurs from a region about 20 microns thick.

The group plotted the hot-electron temperature for both lasers as a function of $\Phi\lambda^2$, where Φ is the laser intensity and λ is the wavelength, and found a single curve with a very shallow rise at intensities relevant to laser fusion. Theoretical calculations of resonant absorption in self-consistently steepened profiles agree very well with the experimental results. The slopes δ of the straight lines in the figure on this page are predicted by this theory.

Most of the basic physics experiments on electron transport were done on a slab target, with thickness varying from 100 Å to hundreds of microns. Polyethylene (plain and deuterated), solid deuterium and solid hydrogen were used. Most of the work was done with a single-beam laser, but recently the group has used a two-beam device.

The group determined electron energy from the x-ray spectrum emitted by the target, extracting the temperature from the time-integrated spectrum. The team has used x-ray imaging, x-ray line spectra and total emission.

For flat targets, the Los Alamos workers found that for both carbon dioxide and neodymium glass, the absorbed energy fraction was 45±7% for flat polyethylene targets over a wide intensity range.

Another problem anticipated with carbon-dioxide irradiation was that the heated surface would boil off fast ions. It was feared that 90% of the absorbed laser light energy would be carried away by fast ions. Instead, Los Alamos measurements show that the loss of energy is at most 20% of the absorbed energy and does not depend on which laser wavelength is used.

Pellets. After convincing themselves that laser-light–plasma-interaction physics produces similar results for both wavelengths, the group revised their computer codes to incorporate the new data and designed glass microballoons filled with deuterium–tritium gas.[2] They bombarded the pellets with the two-beam carbon-dioxide laser, which began operating for target experiments last December. Total laser power available on target was 0.3–0.4 TW. Pulse lengths were 1–1.5 nanosec, although the implosion time is only 0.2–0.3 nanosec, so that some of the laser energy is lost. As targets are made bigger, however, the pulse length will become better matched to the implosion time, McCall said.

Neutron yields from the target were 10^4–3×10^5 neutrons/pulse, in agreement with predictions. McCall believes that the observed neutrons were indeed thermonuclear in origin because of the similarity of the results to earlier neodymium-glass results and because the low density of hot electrons is unlikely to accelerate particles into the high-density fuel. Because yields were so small, it was not possible to measure a neutron or alpha-particle spectrum from the carbon-dioxide bombardment, as has been done for neodymium glass, where yields