

search & discovery

Central peaks due to microdomains, impurities or . . . ?

Although in 1969 certain structural phase transitions were predicted to have a so-called "central peak," the experimental observations of the phenomenon show it to be more widespread than originally predicted. By now central peaks have been found in insulators, metals, materials with high transition temperatures, materials with low transition temperatures, materials that undergo acoustic-mode instabilities and materials that undergo optical-mode instabilities. A variety of theoretical explanations have been offered recently, including a picture involving microdomains or solitons and an alternative picture involving impurities. As James Krumbhansl, a proponent of microdomains told us, "The explanation has not yet been wrapped up and put on the shelf."

At the Conference on Low Lying Lattice Vibrational Modes held in San Juan, Puerto Rico early in December there was considerable interest in reports by three groups on very recent experiments on potassium dihydrogen phosphate (KDP) and its isomorphs that show the existence of a finite width in the central peak.

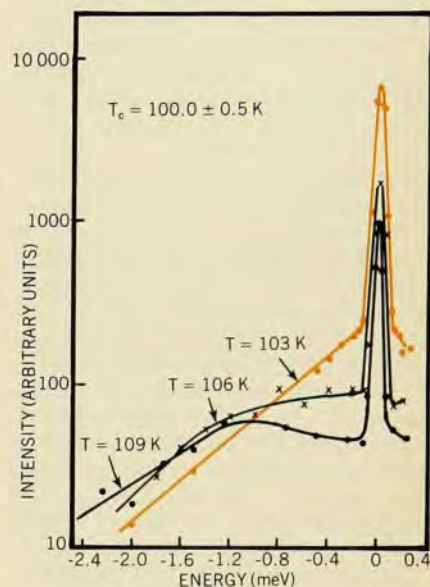
History. The soft-mode picture of structural phase transitions was introduced about 1960 and is generally attributed to Philip Anderson (Bell Labs) and William Cochran (University of Edinburgh). In this picture, certain crystals that exhibit phase transitions

have some normal modes whose frequency goes to zero at the transition temperature—the soft modes.

In 1969 Roger Cowley (University of Edinburgh) had realized that a piezoelectric-ferroelectric substance might not show a softening mode near the transition, but instead a temperature-independent mode with additional scattering near zero-energy transfer.

The terms "central peak" and "central mode" in connection with structural transitions in solids were used in 1971 papers on SrTiO_3 (a material for which the theory of Cowley is not applicable) by Tormod Riste, Emil Samuelsen and Kaare Otnes (Institute for Atomic Energy, Kjeller, Norway) and by Jens Feder (University of Oslo, Norway). At the time of the discovery it was realized that the central mode is a general phenomenon at *any* second-order phase transition, Riste told us, and this is now becoming widely accepted through later experiments on a great number of substances.

In a neutron inelastic-scattering experiment the number of neutrons observed with a given momentum and energy change is proportional to the dynamic structure factor of the target material. At a fixed momentum transfer the structure factor will normally have peaks corresponding to the energies of the phonons at that momentum. According to the soft-mode theory, there will be a phonon energy that approach-



Central peak in strontium titanate. Neutron-scattering analysis of critical fluctuations shows two components, a broad "soft-phonon" sideband that becomes overdamped near T_c , and a narrow central peak that grows to dominate the spectrum. Figure from Shapiro, Axe, Shirane and Riste.

es zero as the temperature is lowered towards the phase-transition temperature. What the Norwegian group saw instead was a very narrow "central

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Muonic-atom data dispel lingering doubts on QED

The last remaining discrepancy between predictions of quantum-electrodynamics theory and experimental observations has now been removed, leaving QED unquestionably the most successful dynamical theory in all of physics. Measurements of x-ray transitions in muonic lead and muonic barium, made at the Space Radiation Effects Lab (College of William and Mary, Newport News, Virginia) and at CERN agree with theoretical predictions based on a muon-nucleus interaction that includes quantum-electrodynamics corrections such as vacuum polarization and Lamb shift. The vacuum-polarization corrections had been causing concern

for the last five years because the apparent lack of agreement with experiment represented the only failure in the otherwise phenomenal success of QED.

The group working at SREL consists of: Madhu Dixit, Alfred Carter, Edward Hincks, Dan Kessler and Jim Wadden of Carleton University, Ottawa; Clifford Hargrove, Robert McKee and Hans Mes of the National Research Council of Canada, Ottawa, and Herbert Anderson of the University of Chicago. At CERN the measurements were made by G. Backenstoss and L. Tauscher (University of Basel), H. Koch (University of Karlsruhe) and A. Nilsson (Research Institute for Physics, Stockholm). The

results were first reported at the High-Energy Physics and Nuclear Structure conference held at Santa Fe and Los Alamos last June (see the survey by Vernon Hughes¹) and described in recent publications.^{2,3}

The problem. To calculate the energy levels of a muonic atom one can first assume that the muon behaves like a heavy electron and solve the Dirac equation for the muon in the electrostatic field of the nucleus. The radii of the muon orbits are reduced by a factor equal to the muon-electron mass ratio, 207, compared with the equivalent electron orbits; this reduction puts muonic-atom transition energies up into the

emf experiments and the creation of artificial comets constitute a sampling of experimental activities urged by the working group for investigations in these areas.

One of the Payload project's departures from previous efforts to investigate the near-space environment of the Earth is its merging of a manned space-flight program (which would permit on-the-spot modification of experimental setups) with the performance of research in the areas of atmospheric, magnetospheric and plasma physics. Thomas Donahue, head of the Department of Atmospheric and Oceanic Science of the University of Michigan, told us that in his opinion the best place for atmospheric researchers is on the ground.

Another atmospheric scientist, Sidney Bowhill at the University of Illinois Department of Electrical Engineering, disagrees. Noting that he has not been one to criticize the manned Apollo program for absorbing needed research funds, Bowhill asserts that the Payload project should include an on-board expert to supervise experiments while the Spacelab is in orbit. He acknowledges that some research areas—the type that use mostly passive experiments in space—would not need a manned mission, but he sees atmospheric, magnetospheric and plasmas-in-space research profiting from such an approach.

Margaret Kivelson, a magnetospheric and plasma researcher at the UCLA Institute of Geophysics and Planetary Physics, takes a middle position; she views the manned aspect of the program as not of the highest priority, but interesting nonetheless.

Kivelson also warns that other valuable research approaches ought not to be slighted. She feels that such worthwhile missions as the placing of a craft in a trajectory from which it could examine conditions outside of the ecliptic plane might be endangered by excessive concentration on the facility research mode. Donahue, too, is wary of potential limitations on research in his field due to emphasis on laboratory-type experiments to the exclusion of more traditional efforts and due to the constraints on apparatus imposed by the facility approach. However, this approach is intended to open the field of space physics to a much larger body of scientists than have been involved in the past. Previously, the expensive hardware requirements have tended to restrict space research efforts to those from large affluent institutions.

Of particular interest is the "quick-reaction capability" that NASA scientists envision for the project. By using easily retuned equipment, the project would acquire a versatility that would allow it to investigate new areas of research as they become prominent, with-

out undergoing overly long delays.

Overall, the project draws mostly favorable comment. Bowhill refers to it as an "exceptionally well-conceived program," and the Payload facility is viewed as being eminently capable, in terms of the scientific questions to be tackled, of fulfilling its promise and performing important tasks. —FCB

Central peaks

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peak" centered at zero-frequency shift whose intensity became very large as the transition temperature was approached.

At about the same time John Axe and Gen Shirane (Brookhaven) saw similar behavior associated with the phase transition in Nb_3Sn . These results suggested there was trouble with the soft-mode picture.

Subsequently various groups have found central peaks connected with a number of solid-state phase transitions. The most puzzling feature of these observations is the narrow energy width of the central peak—well below the resolution of conventional neutron spectroscopy. As Axe explains, the challenge to the theorist searching for an intrinsic lattice dynamical explanation is to discover some way of coupling phonons together to produce a more complicated mode of excitation with a lifetime three or four orders of magnitude longer than that of the phonons themselves.

Experiments on KDP. In 1974 Nicholas Lagakos and Herman Cummins (City College of the City University of New York) found a central peak in KDP—the first material to fit Cowley's original picture. In a Brillouin-scattering experiment they found a very strong peak centered around zero that was too narrow to resolve.

At the San Juan conference, three groups reported their preliminary indirect observations of a finite width in the KDP central peak. E. M. Alexander (Naval Research Laboratory) and Robert W. Gammon (University of Maryland) discussed an ultrasonic absorption technique. Analyzing attenuation data, they found that the frequency dependence could be explained by postulating that the acoustic phonons are coupled to a central mode. Their estimated width (with large error bars) is 8 MHz.

In a postdeadline paper K. Alex Müller, N. Dalal and W. Berlinger (IBM Research Center, Zurich) reported on electron-spin resonance measurements on KDP and some of its isomorphs, in which a Cr^{5+} paramagnetic impurity had been deliberately imbedded to act as a probe. The spectrum of the spin-resonance line differs dramatically if the dominant motion of the lattice is

faster or slower than a characteristic time given by the line splitting. So by changing the temperature of the sample and observing the spectrum, the IBM workers could establish the temperature at which the local lattice frequencies change, from greater to less than the one given by the splitting of the spin-resonance lines. This means Müller and his collaborators find that this characteristic frequency in KDP is smaller than 100 MHz below $T_c + 60$ K.

A third experiment was reported by R. Blinc (Institut Jožef Stefan, Ljubljana, Yugoslavia), who did nuclear-magnetic resonance studies to obtain the width of the central peak in KDP. His results are essentially similar to the esr studies.

A variety of measurements on strontium titanate, made earlier, had also suggested a very narrow central peak (less than or equal to 100 MHz).

Theory. The original picture of Cowley for piezoelectric-ferroelectrics was that a central peak is produced by coupling between the soft mode and the density of acoustic phonons.

In 1971 Feder wrote that a central peak is produced by a nonlinear coupling between a soft mode and temperature fluctuations. The original Cowley model treated only third-order anharmonicity. Then Richard Silbergliitt (now at the National Research Council) in 1972 extended this type of calculation to the fourth-order case. The following year Cowley and Geoffrey Coombs (University of Edinburgh) extended their work using the same many-body perturbation theory approach. Cowley told us that the new measurements suggest that this theory does not account for these results.

Another explanation had been offered by Axe, and independently by Franz Schwabl (then at Jülich) who realized that a static defect could produce an infinitely narrow central peak with a divergent intensity if it could properly couple to the soft mode. Axe says the static-defect explanation is out, at least for those materials where experiments show a finite width to the peak.

Although the static-defect explanation does not appear to work, Bertrand Halperin and Chandra Varma (Bell Laboratories) have hopes for a dynamic-impurity explanation. If an impurity is frozen into a site in which it breaks the symmetry of the high-temperature phase, a local domain will be formed with a fixed spin for the distorted phase. Halperin told us that the width of the central peak is determined by the lifetime of domains in the material and that experimentally these are about 10^{-9} sec. He and Varma find that very small impurity concentrations (about 1 part of 10^4) might be sufficient to account for the results if the impurity moves to another site with opposite

sign in 10^{-9} sec; the hopping would give a breadth of 10^9 sec^{-1} to the line. A similar effect might occur with a frozen defect, if the defect goes into a high-symmetry site, but locally alters the spring constants to stabilize the distorted phase. Halperin points out that at this time there is no direct evidence that defects are present. Axe believes that it will be extremely difficult to distinguish experimentally between the dynamic-impurity effect and other explanations.

Another approach has come from molecular dynamics computer simulation of models for structural phase transitions. These were done for two dimensions by Toni Schneider and Eric Stoll (IBM Research Center, Zurich), and for one-dimensional systems by Serge Aubry (Saclay), and Thomas R. Koehler (IBM, San Jose). What all of these have in common is the appearance of microscopically substantial clusters (microdomains) of the new structural phase, appearing before the transition temperature has really been reached; moreover, according to Krumhansl, numerical analysis shows that these are responsible for the strong zero-frequency or central-peak spectral component. (Schneider and Stoll have produced a film showing the formation of clusters, which is available on request.)

Until recently, though suggested occasionally on heuristic grounds, no direct theoretical demonstration from the starting Hamiltonian explained the appearance of these microdomains. At the San Juan conference Krumhansl reported on work done by him and J. Robert Schrieffer (Penn), in which they demonstrated formally (in one dimension) that both the statistical mechanics and the dynamics of the nonlinear displacement field indeed lead to such structures. Last year Krumhansl and Alan Bishop (Cornell) showed that the two-dimensional structural phase transition could be described using the same model.

Recently David Moncton and Frank Di Salvo (Bell Labs) working with Axe found a central peak in a layered metal—tantalum diselenide; it shows a charge density wave instability. R. Bhatt and William L. McMillan (University of Illinois) have attributed this central peak to electronic effects.

As Halperin noted, there may not be a unique explanation for all the observed central peaks. —GBL

French heavy-ion laboratory under way

Last fall the French national heavy-ion laboratory was authorized for construction at Caen in Normandy. The project is known as "GANIL" (Grand Accélérateur National d'Ions Lourds), and the

accelerator is expected to be capable of producing heavy ions from carbon to uranium.

Total cost is estimated at 210 million francs, including the building, beam transport and experimental area. The first building is now under construction; it is expected to house a group of engineers and technicians by the end of the year. By 1980 the machine is expected to be completed.

Some years ago it was decided to concentrate French nuclear-physics efforts on nuclear-structure studies with medium-energy light particles (Saturne accelerator) and construction of a large heavy-ion accelerator (GANIL) (PHYSICS TODAY, April 1974, page 121). The GANIL laboratory is jointly sponsored by the Commissariat à l'Energie Atomique and the Institut National de Physique Nucléaire et de Physique des Particules.

The accelerator will consist of two separated sector-focused cyclotrons, the first one acting as an injector for the second after the beam is passed through a stripper. The characteristics of the two cyclotrons are exactly the same—four sectors, each weighing 400 tons, internal radius 0.75 m, external radius 3 m, $K = 400 \text{ MeV}$ (where $E = Kq^2/A$ and E is the energy gained by an ion with charge number q and mass A)—so that the energy gain in each is equal to 16. The accelerating system will operate through two dees at a voltage of 250 kV.

In front of the first separated sector cyclotron is a small circular injector delivering any type of ion between C^{2+} and U^{9+} . The energy reached at the exit of the first cyclotron is high enough for most of the ions being stripped off so that the charge is multiplied roughly by four. Because the beam entering into the second cyclotron transports ions with four times the charge of those exiting from the first cyclotron, the revolution frequency should be four times greater. The matching problem for the accelerator system has been resolved in a very simple manner by using the same oscillator frequency (in a range 3–14 MeV) for both cyclotrons but with harmonic number eight for the first cyclotron and two for the second.

With such an accelerating system, O^{2+} ions are accelerated to 5.2 MeV/nucleon in the first cyclotron and after stripping into O^{8+} , to 95 MeV/nucleon by the second machine; U^{36+} reaches around 9 MeV/nucleon.

The planned energy/nucleon will be approximately 100 MeV/A for light ions up to neon, decreasing with increasing mass (around 50 MeV/A for krypton) and 15 MeV/A for gold. Marc Lefort (Institut de Physique Nucléaire, Orsay) told us that the justification for the choice of cyclotrons was the desire for intense and energetic beams of light

and medium-mass ions (between $A = 10$ and $A = 100$) as well as very strict requirements for beam qualities, such as very good emittance and very good energy resolution. For that purpose, the second cyclotron will employ a flat-topping technique. Thus, Lefort said, GANIL's capability will differ from UNILAC in Darmstadt, Germany. Two beams will be available simultaneously in the experimental area, and it will also be possible to use each cyclotron separately for ions at smaller energies and higher intensities, because there will be no stripping.

During 1976 magnets will be ordered, plans for the injector will be completed, and models for accelerator cavities will be made. The main building for the accelerator is expected to be finished in mid-1978; so the magnets could be set up and magnetic-field measurements could begin by the end of 1978. In 1977 the construction of accelerating cavities and rf amplifiers is expected to begin so that they would be in place by the end of 1978. The first beam is expected to be produced in 1980.

The GANIL laboratory will be used as a national facility with many connections with other European heavy-ion machines, particularly UNILAC and the Nuclear Structure Facility at Daresbury, UK. Most of the physicists will prepare experiments at their own laboratories (Strasbourg, Grenoble, Lyon, Orsay and Saclay), moving to Caen only when they need the beam. However, Lefort notes, there will certainly be a lively new nuclear-physics center in Caen.

A users committee has been created recently that will define needed ancillary equipment, and an advisory board will look after connections between GANIL and the main nuclear-physics laboratories existing in France and Europe.

Oak Ridge to study tokamak impurities

The Impurities Study Experiment, a tokamak with easily replaceable inner chamber walls, will be built at Oak Ridge National Laboratory. The \$2.5-million research device is expected to begin operation in early 1977.

Investigations into impurities that impede the energy-release process in experimental fusion plasmas will employ the ISX facility in tests of chamber walls with varying shapes and compositions. Researchers hope to learn which materials and configurations result in the least foreign matter entering the plasma.

The ISX will be operated by Oak Ridge and General Atomic of La Jolla, California; the two organizations conducted conceptual design studies for the device in the 1974–75 period. □