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 Krumhansl, a proponent of microdomains told us, "The explanation has not yet been wrapped up and put on the shelf."

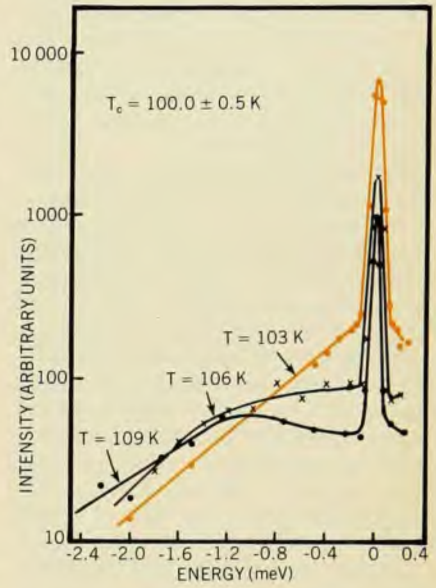
At the Conference on Low Lying Lattice Vibrational Modes held in San Juan, Puerto Rico early in December there was considerable interest in reports by three groups on very recent experiments on potassium dihydrogen phosphate (KDP) and its isomorphs that show the existence of a finite width in the central 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 approaches zero as the temperature is lowered towards the phase-transition temperature. What the Norwegian group saw instead was a very narrow "central



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.

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Muonic-atom data dispel lingering doubts on QED

The last remaining discrepancy between predictions of quantum-electrodynamic 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-electrodynamic 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 Hughes[1]) 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 gamma-ray region. Low-lying muon orbits in heavy atoms turn out to have radii comparable to the nuclear radius; so the usual "point-nucleus" approximation will not work and a correction for finite nuclear size is needed.

Further important corrections for deeply bound muon levels are required for vacuum polarization (screening of the nucleus by a cloud of virtual electron–positron pairs), Lamb shift, electron screening and so on. The vacuum-polarization effect is especially significant for 100–500 keV transitions in medium and high-Z atoms. Comparison of theory and observation for these transitions is therefore a sensitive test of QED corrections for vacuum polarization to higher orders.

Measurements reported by the CERN group in 1970 and the Ottawa–Chicago group in 1971 of certain muonic x-ray lines disagreed with each other, by about 120 eV in 430 keV, although the CERN group's data agreed with contemporary calculations (see figure).

The more recent experiments at CERN and SREL are essentially repeats of the earlier ones, but with increased resolution in the detectors, improved determination of the primary calibration standard, and extra care all round. The measured transitions were 5g–4f in lead and 5g–4f and 4f–3d in barium.

Lithium-drifted germanium detectors picked up the radiation from a negative muon beam stopped in appropriate targets. The Ottawa–Chicago group used dual signals, time and amplitude; the time signal provided a time slot for each event, to ensure measurement only of prompt x rays from the transition of interest and not the later radiation from muon capture events, while the amplitude signal provided pulse-height data. Ge(Li) detectors with high resolution (525 eV FWHM at 122 keV and 1050 eV at 468 keV) were calibrated with a gold-198 standard (412 keV) and gamma rays based on this standard. R. D. Deslattes, E. G. Kessler, W. C. Sauder and A. Heiss (National Bureau of Standards) recently redetermined the energy of this standard, finding it 12 eV higher than previously thought.

The figure shows how these two new experimental determinations of the 5g–4f transition in muonic lead are now essentially in agreement with each other and with recent calculations, some of which were reported to the High-Energy Physics and Nuclear Structure meeting by M. K. Sundaresan and P. J. S. Watson (Carleton University) and by G. A. Rinker (Los Alamos) and L. Wilets (University of Washington).

It is now apparent that the QED correction for vacuum polarization has been correctly understood and applied, at least to the 20 parts per million precision of the most recent determinations. But many theoretical speculations concerning possible breakdowns in the theory—put forward when large discrepancies still existed—remain to be explored. They may yet come into their own when high-intensity beams from the new meson factories, and the use of crystal-diffraction spectrometers, bring about another round of improvements in measuring technique. —JTS

References

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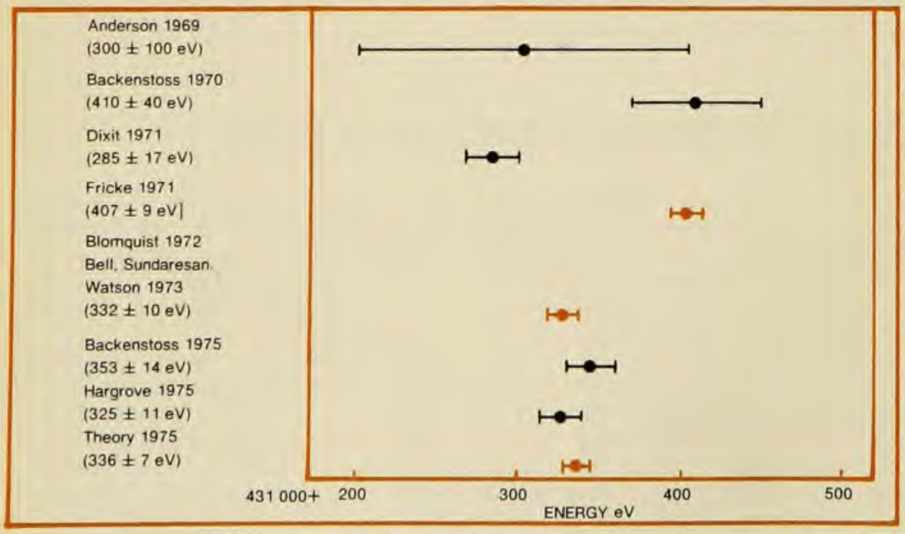

Recent history of experimental (black) and theoretical (color) values of the $5g_{9/2}$–$4f_{7/2}$ transition in muonic lead. The 1975 theory point combines various values presented to the 1975 High-Energy Physics and Nuclear Structure Conference. (Adapted from V. W. Hughes, ref. 1.)

Shuttle studies to include atmospheres and plasmas

The Science Definition Working Group associated with the Atmospheres, Magnetospheres and Plasmas-in-Space Payload has identified scientific objectives for the project. The group has named outstanding problems in each of the three areas and reviewed possible experimental techniques to be used with the Payload, which is to be placed in orbit by means of NASA's Spacelab–Shuttle system.

Those space workers with whom we discussed the Payload program express enthusiasm for the present plans. One significant element cited is NASA's so-called "facility approach" (whereby researchers could supplement their apparatus with some equipment from a group of expensive project-supplied core instruments). Another is the use of active probing techniques; these would be made possible by use of electron accelerators and high-power transmitters capable of interaction with fields and particles in the near-space environment. Some division exists over NASA's manned-mission approach among those we consulted.

The working group, headed by project study scientist Charles Chappell, lists the following categories of atmospheric-science experimentation as feasible within the Payload program: the measurement of minor constituent (chlorine compounds or atomic oxygen, for example) distributions in the atmosphere, studies of atmospheric energetics and dynamics, the study of how changes in solar activity influence climate and the investigation of atomic and molecular processes. Data bearing on theoretical predictions about the depletion of stratospheric ozone could be obtained in experiments that would determine the concentrations and chemistry of atmospheric chlorine compounds and check for a correlation between high-energy proton precipitation and ozone variability. Other possibilities include a look at changes in the D region (65–90 km altitude) at middle latitudes during winter and following geomagnetic storms, and more precise measurement of global horizontal wind fields.

Among the problems in magnetospheric and plasma physics suggested for consideration are probing of convective processes in the ionosphere and magnetosphere, studies of wave injection and wave-particle phenomena, an inspection of magnetospheric particle-interaction processes, wave-propagation studies and investigations of beam-plasma interactions and plasma-flow interactions with material bodies. The measurement of field-aligned (Birkeland) currents, the generation of gravity waves in the upper atmosphere, plasma