Electron-Phonon Coupling in High-T_c Superconductors: The Phonon Viewpoint.

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We discuss the effects of electron-phonon coupling (EPC) on the phonon spectra of superconductors, as measured by inelastic x-ray scattering. While, generally, understanding the electronic properties (e.g. superconductivity) are the main goal, it is highly desirable, really necessary, to have a complete picture of the EPC, including its effect on the phonon spectrum. Also, if there is some question as to the mechanism of superconductivity (consider the recent examples of MgB_2 and B-doped diamond) phonon measurements of the detailed features of the EPC can serve to either substantiate or repudiate specific models. Finally, and perhaps most important, for materials where the mechanism of superconductivity remains unclear despite long investigation, such as the copper-oxides, phonon investigations, and understanding hall-marks of EPC, are one more tool that can play a role in unraveling the mystery.

In lowest order, electron phonon coupling is generally expected to have two effects on the phonon system, and sometimes a third. The simplest, conceptually, is a decrease in phonon lifetime since EPC allows a phonon to decay into an electronic excitation, causing a commensurate increase in line-width. However, the line-width increase is often small (~0.1 meV) and as phonon modes usually disperse, and have other broadening mechanisms, it can be difficult to measure. The other mark of EPC is a change in phonon energies. In fact, the phonon energy shift and line-width due are related by a Kramers-Kronig (KK) transformation, being the real and imaginary parts, respectively, of the phonon self-energy, so changes in one imply changes in the other. The phonon frequency shift, especially when it occurs abruptly along a dispersion curve is perhaps the most readily accessible and well-known effect (Kohn anomaly) of electron-phonon coupling on the phonon system. Generally speaking, phonon modes are softened in regions where they are strongly coupled to the electron system. Finally, perhaps the most direct evidence of EPC is when a simple change in the electronic system (e.g. going through the superconducting transition) causes a change in the phonon system. For example, a mode with energy less than 2D might no longer couple to the electronic system after the gap opens, showing, potentially, fast changes in energy and line-width as a function of temperature.

Inelastic x-ray scattering (IXS) is a unique tool to investigate phonons in superconductors. The small x-ray beam size allows one to investigate samples with volumes < 0.01 mm^3, as compared to neutron techniques that are limited to samples of >~10^2 mm^3. Thus, IXS offers the possibility of "rapid response dynamics investigations" on samples of great current interest, such as MgB_2 and B-doped diamond. It also makes it possible to do systematic studies across a large range of difficult-to-grow materials, such as the high-Tc copper-oxide materials, where very few materials have been grown in sufficient quantity for neutron scattering. However, one should note that neutron scattering does offer advantages if large samples are available, or extremely good (< 1 meV) resolution is needed.

The talk will illustrate the above comments with data from several systems. Briefly, we will review work with MgB_2, which is a remarkable case where the EPC is very strong for a particular phonon mode, leading to huge broadening and softening of that mode, in excellent agreement with calculation [1] and strongly supporting a BCS/Eliashberg mechanism. Furthermore, on doping with C, the softening is removed at about the same level as Tc drops precipitously. Thus, in a material where robust calculations are possible, we see general confirmation of the characteristics of EPS above.

The copper-oxide high Tc materials present more of a challenge, as the mechanism of superconductivity is not understood and detailed calculations are very difficult. None-the-less, IXS, starting on a foundation of neutron scattering work in a few materials, has made important contributions, all the more so given recent ARPES data showing structure on the scale of phonon energies and isotope effect data showing effects on the magnetic penetration depth. Attention in the copper-oxide materials has generally focused on two phonon modes: a high energy, in-plane bond-stretching (LO) mode and an out-of plane c-axis buckling mode. Both have been investigated by INS in twinned samples of optimal YBCO, and, for the bond-stretching mode, in LSCO. The bond-stretching mode shows some softening that has been interpreted as evidence of EPC. Some of our early work showed that in fact this softening was also present in Hg1201, leading to some suggestion of universality [2]. However, one should be cautious. In fact the best available calculations of YBCO [3] show a similar softening in the dispersion. However, detailed comparison of these calculations to our IXS data [4] show that in fact the calculated intensities in the region of the softening are in poor agreement, while different portions of the Brillouin zone show much better agreement, confirming our that this region is anomalous. Furthermore, work with LSCO suggests that the magnitude of the softening in enhanced in the region of optimal doping [5]. Finally, we recently have begun to focus on the temperature dependence of both the bucking mode and the stretching mode in YBCO, and see evidence of relatively strong changes on crossing Tc [4][6].

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