A Raman Scattering Study of Superconductivity in MgB_2

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Abstract

Measurements of the in-plane and out-of-plane electronic Raman continuum in MgB_2 single crystals show markedly different behaviour below T_c, indicative of a complex gap structure. In xx and xy polarisation configurations, a sharp pair-breaking peak is seen near 100 cm^{-1} but no scattering threshold forms directly below the peak. In zz and zx polarisations, a threshold is seen at 30 cm^{-1} but no pair-breaking peak appears. This behaviour can be understood in terms of band-dependent impurty scattering effects on two separate gaps.

Key words: Raman spectroscopy; Superconducting gap; MgB_2

1. Introduction

Measurement of the characteristics of the superconducting energy gap, such as temperature dependence, magnitude and symmetry, is always an important step in the determination of the underlying mechanism of superconductivity in a novel superconductor. This is particularly true of MgB_2 where the unexpectedly high critical temperature $T_c \approx 40$ K places it in an intermediate region between "conventional" and "high-temperature" superconductors. While it appears that MgB_2 can be broadly understood as a strongly-coupled conventional superconductor, reports of the gap magnitude vary widely and debate continues regarding the presence of either a single anisotropic gap or two superconducting gaps in MgB_2. Raman spectroscopy provides a convenient means of elucidating the gap properties in MgB_2 by observing the renormalization of the electronic Raman continuum in the superconducting state [1–3].

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2. Results and Discussion

The MgB_2 single crystals studied had T_c = 38.0–38.4 K [4]. Raman spectra were measured with 514.5 nm laser light and a power density around 10 W/cm^2; further experimental details may be found in Ref. [3]. Figure 1 shows superconducting state and normal state spectra from single crystals of MgB_2. The yy and xy spectra were measured from the ab-plane of one single crystal, while the zz, zx and xx spectra were measured from the ac-face of a second crystal. Spectra in xx and yy polarisations measure $A_{1g} + E_{2g}$, xy measures E_{2g}, zx measures E_{1g} and zz measures A_{1g} symmetry excitations.

The broad E_{2g} symmetry phonon, centred around 620 cm^{-1}, is seen to follow the expected polarisation selection rules and is absent from the zz and zx spectra. Despite theoretical indications that this phonon should undergo a renormalization of 70 cm^{-1} in the superconducting state [5], no strong renormalization is observed in any of the crystals measured.

In contrast, strongly polarisation dependent superconductivity-induced renormalizations are apparent in the electronic continuum, where a sharp pair-breaking peak appears around 110 cm^{-1} in xx, yy and xy spectra but only a threshold is seen at around

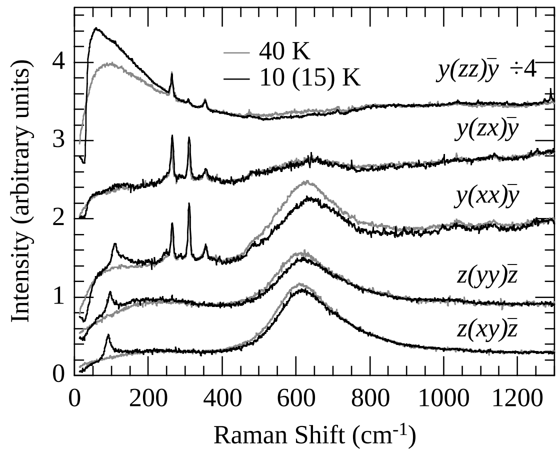

Fig. 1. Raman spectra from MgB_2 crystals in various polarisation configurations. The grey curves are spectra taken at 40 K, while the black curves are spectra taken at 10 K (zz, zx and xx) or 15 K (yy and xy).

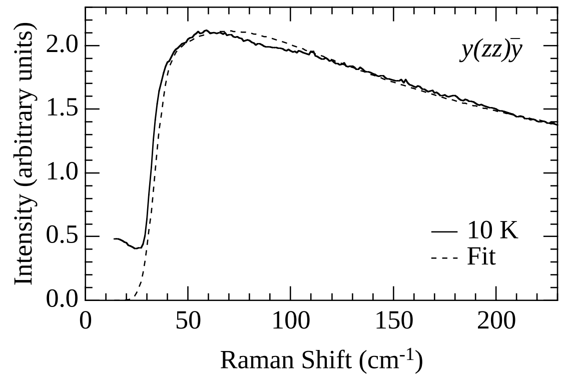

Fig. 2. (solid line) Raman spectrum in zz polarisation at 10 K, showing the threshold that forms at low temperatures; (dashed line) fit to a model of Raman scattering in dirty superconductors.

30 cm^{-1} in zz and zx spectra. Other sharp peaks near 300 cm^{-1} in some spectra are due to surface contamination. Also noteworthy is the polarisation dependence of the normal state electronic continua, where zz is significantly more intense and is broadly peaked at low frequencies.

For the pair-breaking peak seen in xx, yy and xy spectra we have established that the temperature dependence follows the BCS-predicted curve, with a gap-to-T_c ratio of $2\Delta_0/k_BT_c = 4.0 \pm 0.1$, and a k-dependence which is nearly isotropic in-plane [3]. A scattering threshold below the pair-breaking peak is expected [1] but absent in these spectra, which is attributable, at least in part, to surface effects and contamination. Meanwhile, the zz polarised spectrum shows only a threshold at 30 cm^{-1} and no pair-breaking peak. An examination of the normal-state spectra suggested that the zz polarised continuum could be described by electronic scattering effects [6], with a frequency-dependent electronic scattering rate. Just above T_c, the static-limit electronic scattering rate is estimated to be $\Gamma(0) \approx 100$ cm^{-1}. Under these conditions, the pair-breaking peak intensity is expected to be strongly reduced [2]. Indeed, a fit with this model to the 10 K zz continuum produced good agreement, as shown in Fig. 2.

Recalling the complex band structure in MgB_2 [7], it is natural to associate the sharp peak at 110 cm^{-1} and negligible impurity scattering seen in xx, yy and xy spectra with the 2D σ-bands, while the threshold at 30 cm^{-1} and strong impurity scattering seen in zz and zx spectra is associated with the 3D π-bands. Reflecting their 3D character, only the π-band gap appears the zz spectra. In this case, there must be negligible inter-band impurity scattering [8] otherwise T_c would also be strongly suppressed.

3. Conclusions

The polarisation dependence of the superconducting state Raman spectra in MgB_2 reveal two gap features. The larger, associated with the σ-bands, experiences negligible impurity scattering and sharply peaks at around 110 cm^{-1}. The smaller, associated with the π-bands, is strongly damped and appears as a threshold at around 30 cm^{-1}.

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