# Superconductivity in $MgB_2$: Magneto-Raman Measurements

G. Blumberg*, A. Mialitsin*, B.S. Dennis* and J. Karpinski†

*Bell Laboratories, Lucent Technologies, Murray Hill, NJ 07974, USA
†Solid State Physics Laboratory, ETH, CH-8093 Zürich, Switzerland

**Abstract.** Polarization-resolved Raman scattering measurements of $MgB_2$ superconductor as function of excitation, temperature and magnetic field have revealed four distinct superconducting features: a clean gap below 35 $cm^{-1}$ and three superconducting coherence peaks at 50 and 110 $cm^{-1}$ for the $E_{2g}$ symmetry and at 75 $cm^{-1}$ for the $A_{1g}$ symmetry. Their temperature and field dependences have been established. Superconductivity induced renormalization of the $E_{2g}$ phonon consistent with electron-phonon coupling $\lambda \approx 0.3$ has been observed.

**Keywords:** Superconductivity, Raman Scattering, Magnetic Field
**PACS:** 74.70.Ad, 74.25.Ha, 74.25.Gz, 78.30.Er

The two superconducting (SC) gaps nature of $MgB_2$ is experimentally established by a number of spectroscopies. The SC gaps have been assigned to distinctive ($\sigma$- and $\pi$-band) Fermi surface (FS) sheets by means of ARPES [1]. The larger gap, $\Delta_\sigma = 5.5-6.5\,\text{meV}$, is attributed to $\sigma$-bonding states of the boron $p_{x,y}$ orbitals and the smaller gap, $\Delta_\pi = 1.5-2.2\,\text{meV}$, to $\pi$-states of the boron $p_z$ orbitals. Scanning tunneling microscopy (STM) has provided a reliable fit for the smaller gap, $\Delta_\pi = 2.2\,\text{meV}$ [2]. This value is close to the absorption threshold energy $2\Delta_0 = 31\,cm^{-1}$ obtained from magneto-optical far-IR studies [3]. The nominal upper critical field $H^\pi_{c2}$ deduced from the coherence length $\xi_\pi = 49.6\,\text{nm}$ by vortex imaging is $H^\pi_{c2} \approx 0.13\,\text{T}$ [2] that is much smaller than the critical field $H^{optical}_{c2} \approx 5\,\text{T}$ found by magneto-optical measurements [3]. To explain near 40 K SC $T_c$ in $MgB_2$ a large, in order of unity, electron-phonon coupling constant $\lambda$ is required [4]. This coupling is expected to manifest itself in strong self-energy effects across the SC phase transition.

Raman scattering from the *ab* surface of $MgB_2$ single crystals with $T_c \approx 38$ K was performed in back scattering geometry using circularly polarized light. The data in magnetic fields was acquired with a continuous flow cryostat inserted in the horizontal bore of a superconducting magnet. We used the $\lambda_L = 482.5$ and $752.5\,\text{nm}$ excitation lines of a $Kr^+$ laser and a triple-grating spectrometer for the analysis of the scattered light.

In Fig. 1 we show evolution of the SC coherence peaks for both the $E_{2g}$ and the $A_{1g}$ scattering channels across the SC transition for two cases: varying temperature at zero magnetic field (a, c) and varying the magnetic field at 8 K (b, d). The coherence peaks lose their intensity and move to lower energies by either increasing the temperature or field. In the SC state we observe a clean threshold of Raman intensity, $2\Delta_0 = 35\ cm^{-1}$ for all

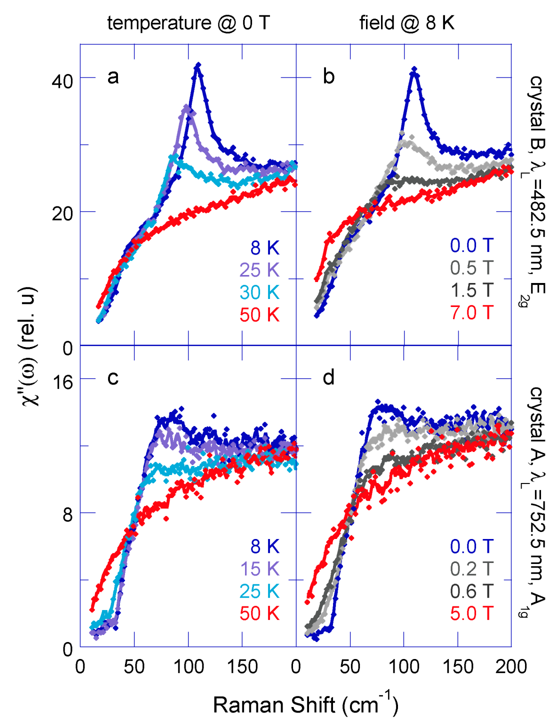


**FIGURE 1.** Evolution of low-frequency Raman response as function of temperature at zero field (a,c) and field at 8 K (b,d). The $E_{2g}$ channel, right-left ($RL$) polarization, with $\lambda_L =$ 482.5 nm excitation is shown in (a,b) and the $A_{1g}$ channel, right-right ($RR$) polarization, with $\lambda_L = 752.5$ nm in (c,d).

scattering geometries. This threshold appears along with two SC coherence peaks in the $E_{2g}$ scattering channel, $2\Delta^E_L = 110\,cm^{-1}$ and $2\Delta^E_S = 50\,cm^{-1}$, and another peak in $A_{1g}$ channel, $2\Delta^A = 75\,cm^{-1}$. The energy scales $\Delta_0$ and $\Delta^E_L$ are consistent respectively with $\Delta_\pi$ and $\Delta_\sigma$ from one-electron spectroscopies [1, 2].

CP850, *Low Temperature Physics: 24th International Conference on Low Temperature Physics;*
edited by Y. Takano, S. P. Hershfield, S. O. Hill, P. J. Hirschfeld, and A. M. Goldman

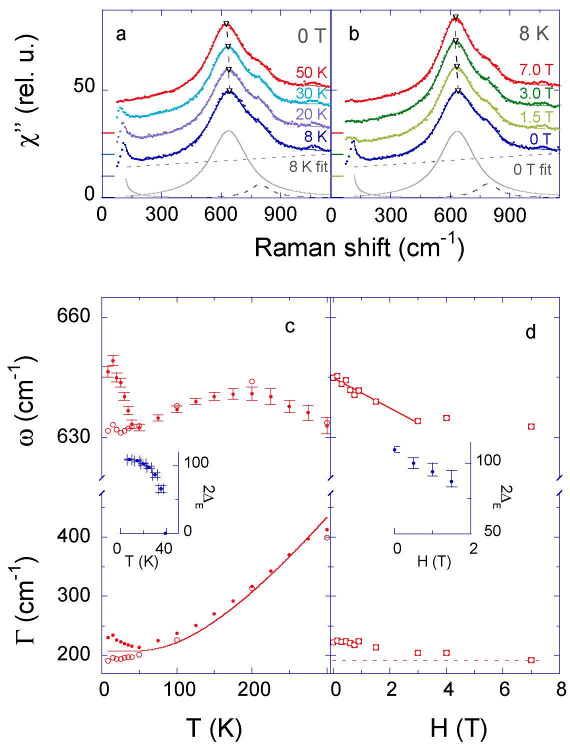


**FIGURE 2.** Phononic self-energy effect due to SC transition. Evolution of the Raman response in the $E_{2g}$ channel $(RL)$ across the SC transition as function of temperature in zero field (a) and as function of field applied parallel to the $c$-axis at 8 K (b), $\lambda_L = 482.5$ nm. The data (dots) are fitted (solid line) with two phononic oscillators and SC coherence peak on electronic continuum (decompositions for the lowest spectra are shown). The $E_{2g}$ phonon frequency $\omega(T,H)$ and the damping constant $\Gamma(T,H)$ are drawn as functions of temperature (c) and field (d). In (c) zero field cooling (solid symbols) and 7 T cooling (empty symbols) are shown. The low temperature limit of $\omega_0^{SC}$ and $\omega_0^N$ are approximated for corresponding cooling. Solid line is fit in normal state to a model of anharmonic decay, $\Gamma(T) = \Gamma_0 + \Gamma_3[1+2n(\Omega/2)] + \Gamma_4[1+3n(\Omega/3)+3n^2(\Omega/3)]$. Here $\Omega(T) = hc\omega_h/k_BT$, harmonic frequency $\omega_h = 515$ cm$^{-1}$ [5, 6], $n$ is the Bose-Einstein distribution function, the internal temperature independent line width $\Gamma_0$ is small, $\Gamma_3 = 190$ and $\Gamma_4 = 20$ cm$^{-1}$ are broadening coefficients due to the cubic and quartic anharmonicity. Since $\Gamma_3 + \Gamma_4 \gg \Gamma_0$ we conclude that the anharmonic decay is primarily responsible for the large damping constant of the $E_{2g}$ phonon. Insets show temperature (b) and field (c) dependences of the $2\Delta_L^E$ SC coherence peak.

We study the effect of magnetic field on the superconductivity induced spectral features. The intensity threshold $2\Delta_0$ and the $2\Delta_S^E$ features smear out already at magnetic field as weak as 0.2 T, consistent with $H_{c2}^{\pi}$ deducted from vortex imaging [2]. The $2\Delta^A$ SC coherence peak persists up to 0.6 T while the $2\Delta_L^E$ peak is suppressed only beyond 2 T. $2\Delta_L^E(T,H)$ are shown in the insets of Fig. 2, it exhibits BCS-like temperature dependence and a linear reduction in field with an anomalously rapid slope about -15 cm$^{-1}$/T. A linear continuation for the $2\Delta_L^E$ gap collapse approximates to 7 T, field higher than $H_{c2}^{optical}$ [3].

In Fig. 2 we summarize temperature dependence of the $E_{2g}$ Raman response for $MgB_2$ crystal measured on cooling in zero- and 7 T field and as function of field at 8 K. We fit the data with a model containing two phononic oscillators on electronic Raman continuum including the coherence peak in the SC state. The temperature and field dependences of the $E_{2g}$ phonon frequency $\omega(T,H)$ and the damping constant $\Gamma(T,H)$ are shown in panels (c-d).

Following Refs. [7, 8] we relate the electron phonon coupling constant $\lambda$ to $\kappa = (\omega_0^{SC}/\omega_0^N) - 1$ as $\lambda = -\kappa(T)\,\Re(\frac{\sin u}{u})$, where $u \equiv \pi + 2i\cosh^{-1}(\omega^N/2\Delta_L^E)$. Using $2\Delta_L^E = 110$ cm$^{-1}$ we estimate $\lambda$ at about 0.3.

In summary, we have measured the polarization, excitation, temperature and field dependence of the Raman response for $MgB_2$ single crystal superconductor and observed four distinct superconductivity induced features: (1) a clean gap below 35 cm$^{-1}$ consistent with the SC gap in $\pi$-states of the boron $p_z$ orbitals; (2) a shoulder at 50 cm$^{-1}$ in $E_{2g}$ spectra; (3) a SC coherence peak of $A_{1g}$ symmetry at 75 cm$^{-1}$; and (4) the largest gap in $E_{2g}$ spectra at 110 cm$^{-1}$ consistent with the SC gap in $\sigma$-bonding states of the boron $p_{x,y}$ orbitals. The features (1-3) are shown to be fragile to magnetic field applied along the $c$-axis. The largest gap (4) shows BCS-like temperature dependence and $2\Delta_L^E/k_BT_c$ ratio about 4 indicating a moderately strong coupling limit. While the $2\Delta_L^E$ coherence peak intensity sustains up to 2 T field the gap magnitude is suppressed at very rapid rate of -15 cm$^{-1}$/T. We study temperature dependence of the $E_{2g}$ boron stretching phonon and conclude that the anharmonic decay is primarily responsible for the anomalously large damping constant of this mode. For this phonon we observe superconductivity induced self-energy effects from which we estimate the electron-phonon coupling $\lambda \approx 0.3$.

## REFERENCES


1. S. Tsuda *et. al.*, *Phys. Rev. Lett.* **87**, 177006 (2001); S. Souma *et. al.*, *Nature* **423**, 65 (2003).
2. M. R. Esklidsen *et. al.*, *Phys. Rev. Lett.* **89**, 187003 (2002).
3. A. Perucchi *et. al.*, *Phys. Rev. Lett.* **89**, 097001 (2002).
4. A. Y. Liu, I. I. Mazin, and J. Kortus, *Phys. Rev. Lett.* **89**, 087005 (2001).
5. A. Shukla *et. al.*, *Phys. Rev. Lett.* **90**, 095506 (2003).
6. J. Kortus, *et. al.*, *Phys. Rev. Lett.* **86**, 4656 (2001).
7. R. Zeyher and G. Zwcknagl, *Z. Phys. B* **78**, 479 (2002).
8. C.O. Rodriguez *et. al.*, *Phys. Rev. B* **42**, 2692 (1990).