Cooper pair breaking and superconducting state recovery dynamics in MgB$_2$ probed by time-resolved THz spectroscopy


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Abstract: We measured the Cooper pair breaking and condensate recovery dynamics in MgB$_2$ by means of time-resolved optical pump – terahertz probe spectroscopy. The observed photoexcitation intensity dependence of Cooper-pair breaking is attributed to the presence of two superconducting gaps in MgB$_2$.

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We present the first femtosecond time-resolved studies of Cooper-pair breaking and subsequent condensate recovery dynamics in newly discovered superconductor (SC) MgB$_2$ [1], using time-resolved optical pump – terahertz probe spectroscopy[2]. MgB$_2$ is found to have a rather complicated Fermi surface, consisting of quasi-2D cylindrical sheets (s band), and a 3D tubular network (p band) [3]. Due to pronounced anisotropy of the electron-phonon coupling constant several measurements of the superconducting gap suggest the presence of two distinct energy gaps $2\Delta^{\sigma_\sigma}/kT_c \sim 4-5$, $2\Delta^{\pi_\pi}/kT_c \sim 1-2$ opening below $T_c$ on the two Fermi surfaces [4]. Since the technique has the ability to differentiate between different processes due to their different time-scales, temperature, and photoexcitation intensity (F) dependences, it presents an ideal tool to investigate the complicated low-energy electronic structure of MgB$_2$.

Fig 1: $\sigma_i$ and $\sigma_r$ at different time delays after photoexcitation (T=7K). Insets: the time evolution of $\sigma_i$ and $\sigma_r$ at $\nu= 0.8$ THz.

The experiments have been performed on 80 and 100 nm thin films ($T_c = 34$K) on sapphire, using the experimental set-up presented in [2]. Fig. 1 shows the time evolution of the real and imaginary conductivity ($\sigma_r$ and $\sigma_i$) at different times after the excitation with 100 fs optical pulse with $F \sim 4 \mu$J/cm$^2$. The rise-time dynamics corresponding to pair-breaking process is on the ps timescale, while the condensate recovery time $\tau_R$ is hundreds of ps. To study the $T$-dependence and $F$-dependence of the processes we utilize the fact that at low $F$ change in conductivity $\Delta \sigma$ (both $\Delta \sigma_i$ and $\Delta \sigma_r$ have the same time dependence) is in a superconductor proportional to the change in the phase of the transmitted THz electric field E - see inset to Fig. 2a.
Fig. 2a) shows $\Delta \sigma(t)$ at different temperatures. $\tau_R$ is plotted in Fig. 2b). $\tau_R$ does not depend on F nor film thickness; therefore it is attributed to anharmonic decay of high-energy phonons ($\omega_{\text{ph}} > 2\Delta$, where $2\Delta$ is the superconducting gap) [5]. The $T$-dependence of $\tau_R$ is consistent with the model [5], where $\tau_R \propto 1/\Delta$ as $T \to T_c$ (dashed line is a fit using Eq.(28) of Ref.[5] with $\Delta=1.3kT_c$).

The pair-breaking dynamics is found to be two-exponential, $\Delta E_{\text{sam}}(t) = A(1-\exp(-t/\tau_a)) + B(1-\exp(-t/\tau_b))$, where $\tau_a$ and $\tau_b$ are the two rise-times, and A:B = 1:1 at low F. While the shorter time, $\tau_a$, is resolution limited ($\sim 1$ ps) at all fluences, $\tau_b > 10$ ps at the lowest intensities measured and is inversely proportional to F - see Fig.3b. We argue, that the peculiar cascade-like pair-breaking dynamics originates from the two-gap nature of MgB$_2$. Here $\tau_a$ corresponds to the initial intra-band pair-breaking, while $\tau_b$ originates from inter-band thermalization, and is proportional to the quasiparticle density, consistent with the intensity and temperature dependence data.

In conclusion, we presented the first femtosecond studies of pair-breaking and superconducting state recovery dynamics in MgB$_2$, with a focus on the early time-scale dynamics, governed by pair-breaking processes. The data
suggest that in the superconducting state two distinct gaps open on two Fermi surfaces leading to a peculiar cascade in the pair-breaking dynamics.