Magnetic Penetration Depth in the New Layered Carbide Halide Superconductors $Y_2C_2X_2$ (X = Br, I) Determined by Muon - Spin Rotation Experiments

Since the discovery of superconductivity in the rare-earth carbide halides $RE_2C_2X_2$ (RE = Y, La; X = Cl, Br, I) some work has been devoted to an understanding of their superconducting properties. Extensive experiments on the $Y_2C_2X_2$ system have revealed a number of characteristic details: For example, it has been demonstrated that by a proper adjustment of x in samples of $Y_2C_2Br_{2-x}I_x$ the superconducting transition temperature can be raised to 11.6 K. An increase of the transition temperature of $Y_2C_2Br_2$ by 1.2 K has also been achieved by an intercalation of Na atoms into the van der Waals coupled doublelayers of halogen atoms. By a careful comparison with the superconducting properties of the dicarbide YC_2 which crystallizes in a three-dimensionally connected crystal structure (CaC_2 structure-type) it has been shown that the pronounced crystalline anisotropy in the layered yttrium carbide halides leads to a significant increase of the electron-phonon coupling strength. As a consequence of the anisotropy (e.g. anisotropy ratio $\gamma = 5.2 \pm 0.2$ for $Y_2C_2I_2$) the upper critical fields in the layered yttrium carbide halides are enlarged by almost two orders of magnitude as compared to YC_2. A clear $^{12}C\,/\,^{13}C$ isotope effect has been detected in YC_2. In contrast, there is no indication of a decrease of T_c when istope enriched ^{13}C is substituted e.g. in $Y_2C_2Br_2$. Deviations from a simple Korringa law seen in the ^{13}C NMR relaxtion rate of $Y_2^{13}C_2X_2$ (X=Br, I) evidence a structured electronic density of states close to the Fermi energy arising from electronic bands of low dispersion.

While the upper critical fields B_{c2} could be very well extracted from investiagations of the high - field magnetization data, a determination of the lower critical fields B_{c1} and the related London peneration depth $\lambda(0)$ from magnetization measurements is notoriously difficult. On the other hand, the London penetration depth contains important information about the superconducting state and is therefore an essential parameter to characterize a superconductor: For an isotropic superconductor in the clean limit the London penetration depth is related to the density of superfluid pairs at zero temperature $n_S(0)$ and the effective mass of the superconducting pairs m^* via the simple relation

$$1/\lambda^2(0) \;=\; \mu_0\, e^2\, n_S(0)\,/\,m^* \tag{1}$$

To determine the London penetration depth of $Y_2C_2X_2$ and YC_2 more precisely we performed muon - spin - rotation (μ^+SR) measurements at the Paul Scherrer Institut (Switzerland) in a temperature range from T_c to 0.1 K. The external magnetic field was applied perpendicular to the muon polarization direction. In the μ^+SR - technique, highly spin - polarised positive muons are introduced into the sample which itself is exposed to an external magnetic kept within the London - limit ($B_{c1} \ll B_{ext} \ll B_{c2}$). Once come to rest at interstitial sites in the samples, the muons start to perform a Larmor precession in their local magnetic field. The time - resolved spin polarization of the muons is determined via the parity violation in the muon decay in which two neutrinos and a positron are generated. The positron is preferentially emitted into the direction of the muon spin. The positron emission rate thus contains information about the Larmor precession and the depolarization of the muons. Via its Fourier transform the distribution of internal magnetic fields, ΔB, can be calculated. In a type - II superconductor ΔB is directly related to the penetration depth:

$$\langle \Delta B^2 \rangle \;\propto\; \Phi_0^2/\lambda_{ab}^4 \tag{2}$$

From the muon-spin depolarization rates $\sigma(T)$ measured on polycrystalline samples of $Y_2C_2X_2$ and YC_2 we were able to extract the London penetration depths in a polycrystalline average with high accuracy (Tab. 1).

Taking into account the anisotropy ratio of $\gamma = 5.2 \pm 0.2$ for $Y_2C_2I_2$ we determined the in plane and out of plane penetration dephts λ_{ab} and λ_c that amount to 257±3 nm and 1645±10 nm, respectively. In Fig. 1 $\lambda(T)$-data are compared to the predictions of the BCS weak coupling theory and the two fluid (2FL)

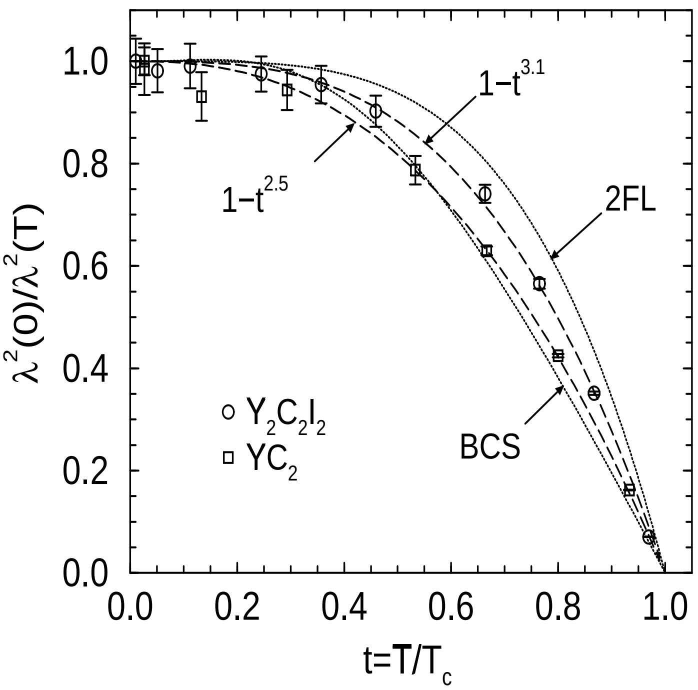

Figure 1: Fits of the temperature dependence of the London penetration depth of YC_2 (squares) and $Y_2C_2I_2$ (circles) by a power law 1 - $(T/T_c)^p$ (dashed lines). The temperature dependence expected for the weak - coupling BCS model and the two - fluid (2FL) model are indicated by the full lines.

compound	T_c [K]	$\sigma(0)$ [μs^{-1}]	$\lambda_{poly}(0)$ [nm]
YC_2	3.85	1.25±0.03	246±4
$Y_2C_2Br_2$	5.05	0.35±0.02	554±5
$Y_2C_2I_2$	9.97	1.07±0.02	317±3

Table 1: Critical temperatures T_c, depolarization rate $\sigma(0)$, and absolute values for the London penetration depht $\lambda_{poly}(T \to 0)$ of the investigated compounds.

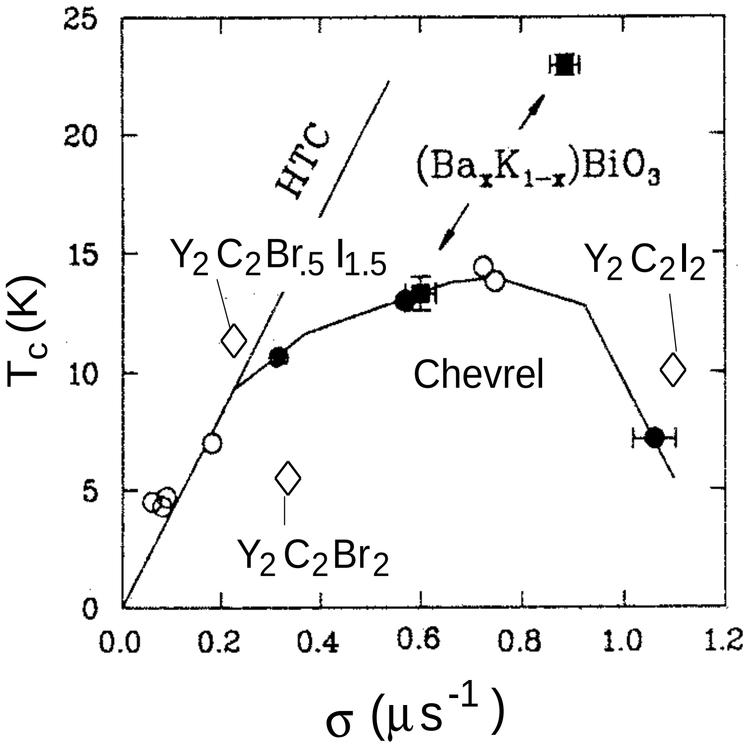

Figure 2: Superconducting transition temperature T_c versus relaxation rate σ (T → 0) ('Uemura plot'). In the Uemura plot $Y_2C_2X_2$ fall in a region close to the Chevrel - phases.

model. The results are in qualitative agreement with the analysis of the specific heat jump at T_c: data taken on YC_2 pass along the BCS weak coupling curve, while $Y_2C_2I_2$-data are shifted towards the 2FL model indicating an enhanced electron - phonon coupling.

In Fig. 2 the superconducting transition temperatures are plotted as a function of the $\mu^+\mathrm{SR}$ depolarization rate at zero temperature ('Uemura plot'). The results for $Y_2C_2Br_2$ and $Y_2C_2Br_{0.5}I_{1.5}$ lie close to the so - called Uemura-line for the underdoped $\mathrm{H}T_c$ systems while $Y_2C_2I_2$ deviates to higher $\sigma(0)$ values as has been found for the overdoped $\mathrm{H}T_c$ systems.

Judging from the behaviour in the Uemura plot, the $Y_2C_2(\mathrm{Br},\mathrm{I})_2$ compounds appear to be similar to the Chevrel phases.

(R.W. Henn, Th. Gulden, Ch. Bernhard, R.K. Kremer, A. Simon, Ch. Niedermayer (U Konstanz), Th. Blasius (U Konstanz))