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Universal scaling relations in molecular superconductors

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Abstract

Recent work on molecular superconductors has identified a number of trends in their physical properties. A power law correlation between the superconducting penetration depth and the superconducting transition temperature T_c has been observed. Evidence has also been seen for power law correlations between the superconducting properties and the normal state conductivity just above T_c. These scaling properties of molecular superconductors are compared with the scaling properties observed in other groups of superconductors such as high T_c cuprates and possible interpretations and challenges for theory are briefly discussed. ***To cite this article: Francis Pratt, C. R. Chimie 10 (2007).***

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Superconductivity has now been seen in a broad range of materials, including many examples of molecular metals. It is useful in trying to understand the origins of the superconductivity in such molecular systems to search for trends that might exist across the broad class of molecular superconductors, independent of the finer details of each system. Such universal trends could present valuable pointers towards the underlying mechanisms responsible for the superconductivity, giving guidance for developing theories of superconductivity and providing a stringent test for 'good' theories.

One trend in superconducting properties that was originally identified from μSR studies of high T_c cuprate superconductors is the Uemura law [1] describing a linear scaling between the two primary experimental observables of a superconductor: ρ_s, the strength of a superconductor against applied magnetic fields ($\rho_s = c^2/\lambda^2$, where λ is the penetration depth), and T_c, the superconducting transition temperature, which is related to the energy scale of the pairing interactions. This scaling applies in the underdoped region of cuprate superconductors where a local pairing model might be considered more appropriate and one interpretation of the law follows from noting that both the Bose–Einstein Condensation (BEC) temperature of preformed pairs in the 2D layered case and also ρ_s are proportional to the carrier concentration [2].

Although at first sight the molecular superconductors appeared to be consistent with the linear Uemura scaling [2], closer investigation of μSR data across a wider range of molecular superconductors suggested a scaling law better described as something closer to $T_c \propto \rho_s^{3/2}$ or equivalently $T_c \propto \lambda^{-3}$ (Fig. 1a) [3,4]. The presence of any such Uemura-style scaling law in the molecular systems is actually quite remarkable,

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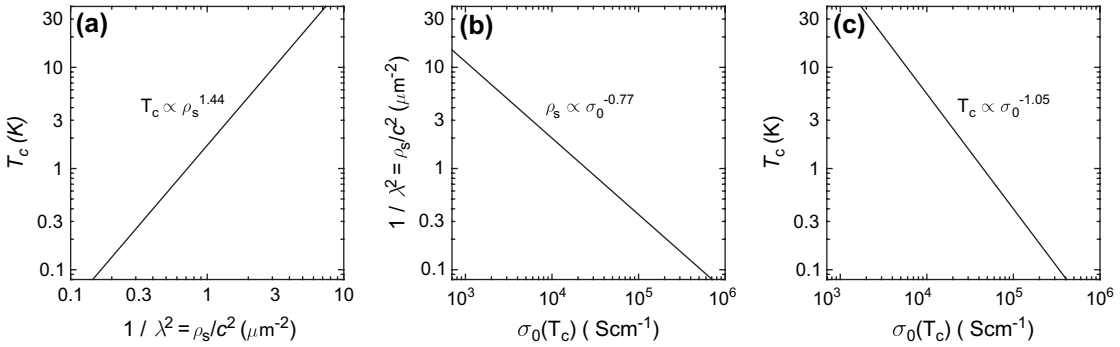

Fig. 1. Empirical scaling relations between ρ_s, T_c and σ_0 obtained from data on a range of molecular superconductors [5].

since the nominal carrier concentration hardly varies across the family, unlike the case of the high T_c cuprates where carrier doping controls the properties. From consideration of these scaling properties it was concluded that one possible explanation is that the effective superconducting carrier concentration is significantly reduced in the lower T_c molecular systems [4–6]. Departures from the Uemura scaling were also considered in the BEC scenario [2], where dimensionality effects on the carrier dispersion and differences in inter-site hopping between single carriers and carrier pairs in boson-fermion models were identified as possible factors [4].

Another type of scaling property is revealed by consideration of the normal state dc conductivity σ_0 just above the superconducting transition, measured in the most highly conducting direction. In the case of cuprates, Homes et al. [7] showed that ρ_s increases with increasing σ_0, whereas T_c is not apparently strongly correlated with σ_0 and it was found that ρ_s scales linearly with the product $\sigma_0 T_c$ [7] for the full range of doping. In the case of molecular superconductors, a completely different behaviour was observed: both ρ_s and T_c decrease rather than increasing with increasing σ_0 (Fig. 1b,c) and no scaling of ρ_s with the product $\sigma_0 T_c$ was seen [5].

For the molecular superconductors, the dominant control parameter for the scaling was suggested to be U/W, the ratio of the on-site (i.e. molecular) electron correlation energy to the electronic bandwidth [5]. Chemical or physical pressure can be used to tune the value of U/W within a particular subclass of molecular superconductors. For example in the κ-phase ET salts, U/W can be reduced by applying pressure, with a corresponding drop in ρ_s and T_c and an increase in σ_0. Dynamical Mean-Field Theory (DMFT) has emerged in recent years as a powerful way of calculating properties of strongly correlated electronic systems over the full range of U/W, however, both DMFT [8] and Resonating Valence Bond (RVB) theory [9] clearly predict an increase in ρ_s with pressure, as the system is pulled away from the metal–insulator transition by decreasing U/W. This is

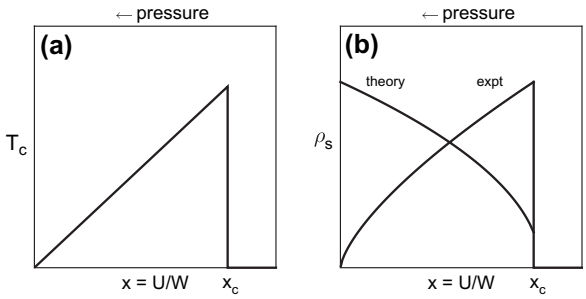

Fig. 2. Illustration of the effect of the correlation parameter $x = U/W$ on (a) T_c, where both theory and experiment suggest enhancement as the metal–insulator transition at x_c is approached and (b) the behaviour of ρ_s, where theory and experiment suggest opposite dependences on x.

completely contrary to experiment (see Fig. 2). Thus current theoretical approaches to the physics of molecular superconductors appear to be missing some important features of their behaviour and this is clearly an area where further theoretical progress is needed.

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