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Low temperature state of charge density waves – facts and fiction

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Charge density wave (CDW) ground state consists of coherent superposition of bound electron-hole pairs from opposite sides of quasi one-dimensional (q1d) Fermi surface with $2k_F$ common wavevector [1]. The properties of new state at sufficiently low excitation energies can be described by spatio-temporal variations of corresponding order parameter. As CDW has zero net spin, majority of CDW models does not discriminate between different spin channels and, moreover, consider only the low lying excitations of CDW phase (phasons).

So called Fukuyama-Lee-Rice model [2] of elastic CDW has been particularly successful in explaining numerous phenomena observed experimentally in the temperature range not too far below the Peierls transition temperature T_P. In this model interaction of CDW with impurities or commensurate lattice sets the preferred phase, while the residual free carriers screen electrostatically the phase distortions. Qualitative changes in CDW behavior occurring below about $T_P/4$, such as transition from activated to hopping conductivity [3], have been usually attributed to the disorder and not considered specially.

However, a series of low temperature heat capacity (c_p) measurements [4] have demonstrated markedly glass-like properties of basically all CDW systems known, such as the existence of Boson peak, power-law contribution to c_p , non-exponential relaxation and ageing. Subsequent dielectric measurements [5] have shown that there exists a dynamical glass-like transition below T_P at which a subset of CDW degrees of freedom freezes. In conjunction with previous results, it led to the idea of the existence of new low temperature CDW glass phase. Recent measurements, such as the conductivity of thin and doped samples [3], photoconductivity [6], magnetic susceptibility [7] and magnetic field dependence of heat capacity [8] corroborate this idea. Moreover, several new approaches are currently considered in order to explain these new findings.

Low temperature heat capacity of different CDW systems can be decomposed in several contributions, as shown in Fig. 1 for $K_{0.3}MoO_3$ [4]. In addition to the regular (Debye) one, a power-law contribution $c_p \sim T^\nu$ and a maximum in c_p/T^3 (Boson peak) are found. These are generic features of glasses which are attributed to localized vibrational modes induced by the frozen-in disorder. Such features have definitely not been expected for the system with regular crystalline structure and CDW superstructure, which is moreover insulating at these temperatures.

In glasses the Boson peak has been explained as the contribution from the high frequency scattering of acoustic modes on short range order domains. In CDW systems a similar model of acoustic-like phason modes scattering on the frozen-in phase domains successfully describes the Boson peak. However, in CDW it introduces a low frequency cutoff, i.e. a small gap in the phason spectrum, as typical domains sizes are of the order of µm.

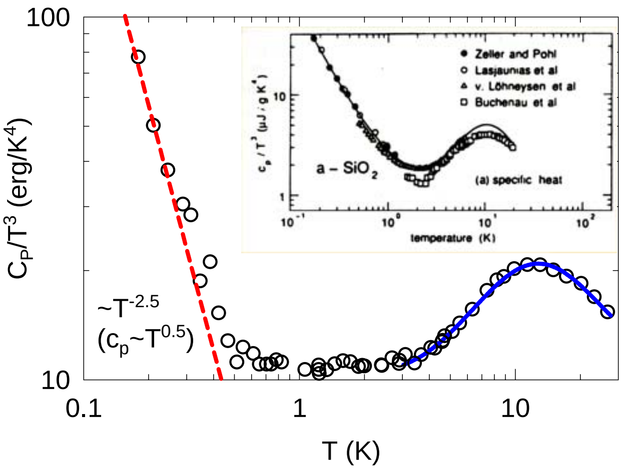

Figure 1. Heat capacity c_p of $K_{0.3}MoO_3$ presented as c_p/T^3. Solid line is the fit to the gapped phason model and the dashed line is the low temperature power-law contribution. Inset is corresponding plot for SiO_2 glass.

The origin of the power-law contribution ascribed, in the analogy with glasses, to the low energy excitations (LEEs) has been elucidated only recently, thanks to the precise magnetic susceptibility (χ) measurements [7] presented in Fig. 2 for o-TaS_3. It turned out that below about 100 K χ follows the power law as well, $\chi \sim T^\alpha$ and that this exponent is related to ν from c_p measurements as $\alpha = \nu - 1$.

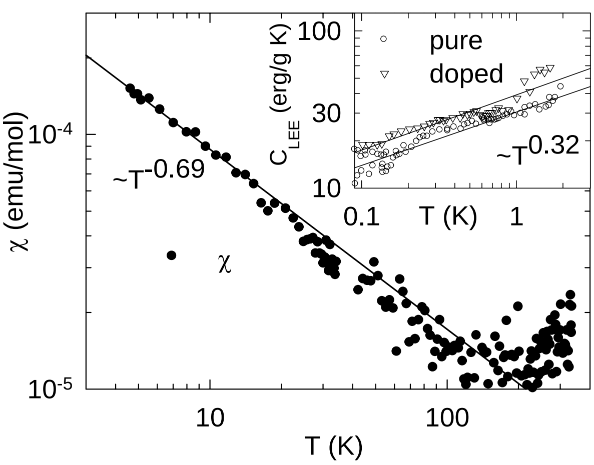

Figure 2. Magnetic susceptibility χ of o-TaS_3. In the inset is the LEEs contribution to c_p.

Such correspondence is typical for random exchange Heisenberg antiferromagnetic chain (REHAC), consisting of isolated spins in 1d. The linear density of spins estimated from REHAC model matches well the average distance between the edges (walls) of CDW domains.

Finally, recent heat capacity measurements [8], presented in Fig. 3 for o-TaS_3, have demonstrated strong magnetic field dependence which includes irreversible changes and hysteresis as well.

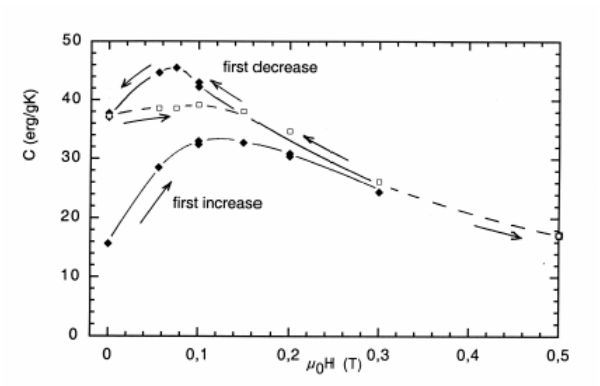

Figure 3. Magnetic field dependence of c_p of o-TaS_3 at 100 mK.

In summary, these measurements indicate that at sufficiently low temperatures the CDW phase domain structure becomes frozen and develops a finite magnetic moment. We believe that the key for understanding these low temperature properties can be found in our measurements of the low frequency dielectric response [5].

We have found that the relaxational dynamics of CDW changes qualitatively at finite temperature. The relaxational process dominant below T_P (named α) freezes at finite temperature T_g (glass transition temperature), as presented in Fig. 4 for $K_{0.3}MoO_3$ and o-TaS_3. It means that the corresponding degrees of freedom do not contribute to the response of CDW system at lower temperatures.

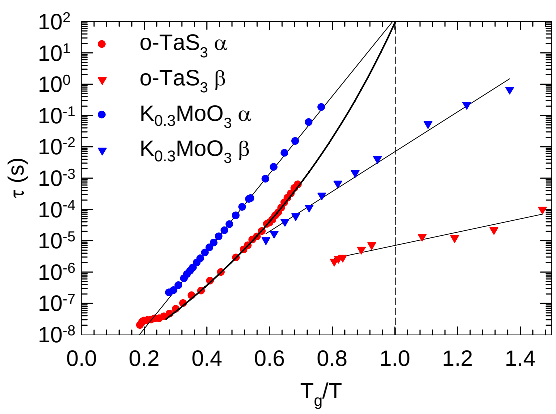

Figure 4. Temperature dependence of the relaxation times of two processes observed in $K_{0.3}MoO_3$ and o-TaS_3. The temperature scale is renormalized to T_g equal 23 K and 50 K respectively.

Extensive theoretical work [9] has demonstrated that α process corresponds to the local modes of elastic CDW in FLR model, so below T_g, where these local modes are frozen, FLR model is no longer applicable. The freezing can be naturally attributed to the Coulomb hardening of CDW when long range spatial distortions of (charged) CDW are not allowed in the absence of free carrier screening. It occurs when there is less than one free carrier per phase domain, as can be estimated from experiment [5].

Above T_g another process (β) at higher frequencies emerges from α process, becoming dominant below T_g. We have attributed it to the local topological distortions of CDW phase (solitons) which are allowed near impurities even at low temperatures due to the nonlinear screening [10]. According to recent photoconductivity [6] and conductivity of thin and doped samples [3] measurements, localized (soliton-like) excitations are indeed dominant mechanism of conductivity in the absence of Fermi-like free carrier contribution. However, in order to exist in 3d, these solitons are required to have both spin and charge component [11], which would lead to magnetic effects as well.

Two new approaches are currently considered. One is the model of Luttinger liquid state stabilized in 3d through localization by impurities [12], which gives naturally the variable hopping conductivity observed at low temperatures and allows for magnetic degrees of freedom as well [13]. Another one considers decoupled spin channels in modeling the solitons localized at impurities [14] in order to incorporate the magnetic field effects.

In conclusion, it is evident that there exist a quantitatively distinct low temperature state of CDW systems in which phase domains are frozen and the dynamics is due to the topological distortions. Unusual magnetic field dependence and exciting new models make the CDW systems interesting even 30 years after discovery.

References

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