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ONCLUSION

We point out two general characteristics of the thermal conductivity of uasi 1D CDW systems. First is the minimum in the region of the Peierls ransition and the second is a small anomaly just below the transition emperature. We hope that the results will stimulate further theoretical forts towards final explanation of the measured thermal conductivity of DW materials.

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The possible explanation for this damping follows from the result of



# THERMAL CONDUCTIVITY OF QUASI-ONE DIMENSIONAL CONDUCTORS *

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ABSTRACT

The thermal conductivity of $K_{0.3}MoO_3$, $(TaSe_4)_2I$ and $TaS_3$ have been measured by two different methods and are found to be independent, within experimental uncertainties, of applied electric field. The enhanced zero-field thermal conductivity observed at the Peierls transition is possibly from extra heat carried by the soft mode associated with the structural distortion.

Since the discovery of quasi-one dimensional materials[1] in the early 1970's and the observation of non-ohmic electrical conductivity[2] in $NbSe_3$, the charge transport properties of the incommensurate charge-density-wave (CDW) systems in $NbSe_3$ and related materials have been studied extensively[3]. It is also well known that interesting field-dependent behavior is observed for the thermopower and related Peltier heat coefficient[4]. These two observations have prompted experimental efforts to measure all the Onsager transport coefficients related to CDW motion. However, for various reasons, the change in the thermal conductivity from a sliding CDW remains unknown. The following is a brief report on the thermal conductivity of the CDW systems $K_{0.3}MoO_3$, $(TaSe_4)_2I$ and $TaS_3$, measured by two different methods with and without an applied electric field.

The zero-field thermal conductivity of $K_{0.3}MoO_3$ and $(TaSe_4)_2I$ have been measured using a steady-state linear heat-flow method described in detail elsewhere[5], and the results are shown in Figs.1(a) and (b), respectively. The overall temperature dependence of $\kappa_T$ is similar for both materials, with the slightly stronger temperature dependence above $T_P$ for $(TaSe_4)_2I$ probably related to the stronger fluctuations in this material[6]. A sharp peak is observed at $T_P$ in all of the

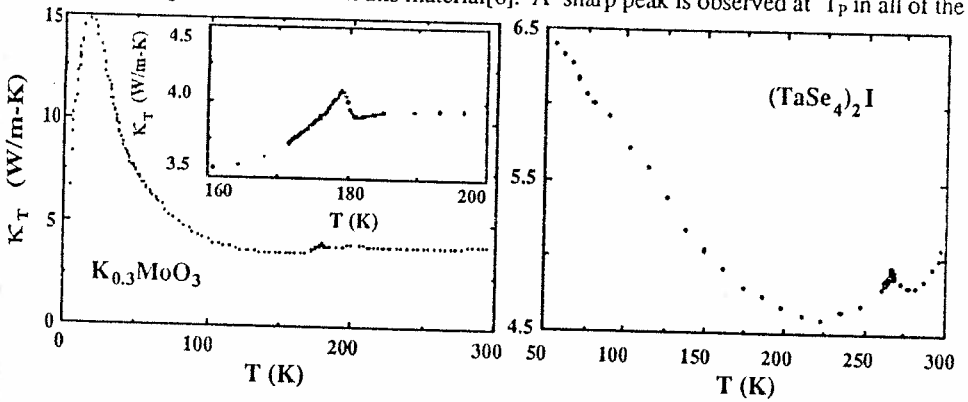


FIG.1 – Thermal conductivity of (a) $K_{0.3}MoO_3$ and (b) $(TaSe_4)_2I$ measured by a linear heat-flow method.

* not presented at the conference.

lue bronze and $(TaSe_4)_2I$ samples that were measured, even though the details of the peak depend n the quality of the samples. We also observed that samples with a higher $\kappa_T$ maximum at low emperature have a sharper and narrower anomaly at $T_P$. Since all samples measured have similar eometrical dimensions, it is likely that the correlation is from lattice defects.

In general, $\kappa_T$ is modelled as a sum of the lattice $\kappa_p$ and electronic $\kappa_e$ contributions. For ormal metals, $\kappa_e$ can be estimated from the Wiedemann-Franz law. The situation here is omplicated by the presence of a pseudo-gap and Peierls gap in the electronic spectrum above and elow $T_P$, respectively. This will in general enhance the total thermal conductivity due to an extra ontribution from recombination of electrons and holes[7]. As in the case of the new high-emperature superconductors[8], the opening of the energy gap at $T_P$ decreases the phonon-electron cattering and therefore enhances the lattice contribution $\kappa_p$. On the other hand, enhanced luctuations near the phase transition shorten the mean-free-path of the heat carrying phonons. As consequence, a 'dip' is expected in the measured $\kappa_T$, as in the case of the antiferromagnets[9]. uch analyses have been carried out but could not explain the sharp peak observed in $\kappa_T$[10,11]. ecently, Deland et al.[12] also observed an extra 'bump' in the lattice thermal conductivity of blue ronze around $T_P$, although the anomaly is somewhat smeared out compare to what we report here. he authors suggested that the excess contribution was related to the fluctuation effects.

The thermal conductivity can also be measured by a steady-state self-heating echnique[13] in which the specimen is heated directly by passage of an electric current. Such a nethod has been employed by Brill et al.[14] for measurement on $NbSe_3$. Using this technique, ve have measured $\kappa_T$ of orthorhombic $TaS_3$. Results for the zero-field limit are shown in Fig.2. he overall magnitude of $\kappa_T$ is the same as previously reported[15]. However, the peak at $T_P$ was ot observed using the indirect method of Ref.[15]. The $\kappa_T$ feature of $TaS_3$ around $T_P$ is similar o, but significantly larger than that of blue bronze and $(TaSe_4)_2I$, indicating that the anomaly bserved at $T_P$ is an intrinsic property of CDW systems.

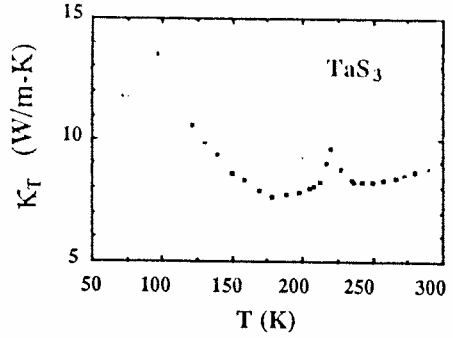


FIG.2 – Thermal conductivity of $TaS_3$ measured by a self-heating method.

The specific heat of blue bronze has been measured by a relaxation method[5]. A non-mean-field type of anomaly observed at $T_P$ [10,16] indicated that the lattice contributed significantly to the specific heat anomaly[17]. Since the softening of phonons near $q=2k_F$ results in a non-zero group velocity $d\omega/dk$, it is possible that the increase in $\kappa_T$ is a result of extra heat carried by the soft phonons.

To study the electric field dependence of $\kappa_T$ of blue bronze, the linear heat-flow method



was modified slightly[18]. The result is that, within the 2% uncertainty of our apparatus, $\kappa_T$ of blue bronze is field independent up to 6 times the threshold field.

We were motivated to study the field dependence of the thermal conductivity of $TaS_3$ because the field dependence of the thermopower of that material is stronger than that of the blue bronze[4]. Due to the fragility of $TaS_3$, the linear heat-flow method is replaced by the self-heating technique described in Ref.[13]. By thermally anchoring the ends of the specimen to a base temperature $T_o$ and measuring the mid-point temperature $T_{max}$, one can calculate $\kappa_T$ (assuming $\kappa_T$ and the electrical resistance R are weak functions of temperature) using :

$$\kappa_T = P\ell/8A\Delta T \qquad (1)$$

where $\Delta T \equiv T_{max} - T_o$, $P=I^2R$ is the joule heat applied to the sample of cross-sectional area A and length $\ell$. Also, the resistance of the sample is given by :

$$R = \frac{1}{A}\int_{-\ell/2}^{\ell/2} \rho(x)dx = R_o\left\{1 + \frac{I^2\ell}{12\kappa A}\frac{dR}{dT}\right\} \qquad (2)$$

where $\rho$ is the resistivity and $R_o$ is the zero-field resistance of the sample.

Four representative curves of P vs. $\Delta T$ are shown in Fig.3 for four distinctive temperature ranges. For T>230K, $\kappa_T$ and R are weak functions of temperature and Eq.(5) predicts $\Delta T$ to be linear with P. Around the Peierls transition at about 220K, the curvature of $\Delta T(P)$ is dominated by the temperature dependence of $\kappa_T$. The measurement at $T_o$=205K shown in Fig.3 follows the prediction of $\kappa_T(T)$ from Fig.2 as $\Delta T$ rises. For 150K<T<210K, $\kappa_T$ is weakly temperature dependent as is the case for T > 230K. However, R is a stronger function of temperature and consequently, $T_{max}$ is much smaller than that predicted by Eq.(1) because the mid-point resistivity is much lower than the average $\rho$. This is revealed in the slightly concave down $\Delta T(P)$ of the $T_o$=160K curve in Fig.3. A calculation of $\kappa(I_{max})$ at $T_o$=160K from Eq.(2), using the measured I-V curve and the appropriate dR/dT, gives the result that $\kappa(I_{max}) \approx \kappa(0)$ to within 5%. Finally, for T<150K, the upturn of $\Delta T(P)$, due to the rapid decrease of $\kappa_T$ as $T_{max}$ increases, is partly compensated by the concave down effect due to the fast dropping mid-point

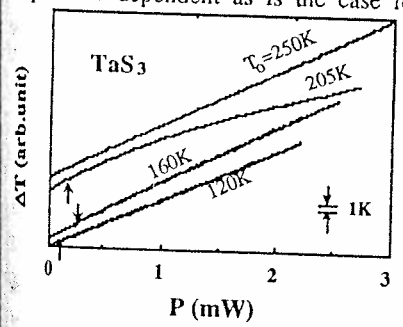


FIG.3 – Four typical $\Delta T$ vs. P curves for $TaS_3$ as discussed in text. Arrows show where the threshold field ($i_TV_T$) is from resistivity measurements.

resistivity. The net effect is a slight upward concavity of $\Delta T(P)$ as shown in the $T_0$=120K curve in Fig.3.

We have checked the previous result for $K_{0.3}MoO_3$ using the same method over the temperature range of 100-160K. $\Delta T$ is found to be linear with P, to within 1%, up to about 25mW or equivalently $\Delta T \approx 6K$. This corresponds to applied fields of about 8 times the threshold field. Combined with the earlier experiments, we conclude that $\kappa_T$ is field independent for $TaS_3$ as well as for blue bronze to within 5 and 1%, respectively.

In summary, we observed a peak in $\kappa_T$ of the CDW systems $K_{0.3}MoO_3$, $(TaSe_4)_2I$ and $TaS_3$. Together with the specific heat measurement on blue bronze, we suggested that the anomaly is related to the heat carried by phonons with q near $2k_F$. Furthermore, $\kappa_T$ of blue bronze and $TaS_3$ are found to be field independent within the uncertainty of our apparatus, which is about 1 and 5%, respectively.

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# LOW ENERGY EXCITATIONS AND RELATED PHENOMENA IN CDW COMPOUNDS AT VERY LOW TEMPERATURES

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ABSTRACT

We have measured the specific heat and the energy relaxation dynamics on several charge density wave compounds ($NbSe_3$, $TaS_3$, $(TaSe_4)_2I$, $K_{0.3}MoO_3$) at very low temperatures ($T \leq 1$ K). All these quasi one-dimensional compounds exhibit an excess heat capacity contribution $C_p$ following a $T^\nu$ law with $\nu < 1$. In the same temperature range the energy relaxation is not exponential and aging effects are present.

## INTRODUCTION

It has been shown that due to the randomness in the impurity distribution the charge density wave (CDW) ground state in the pinned state comprises many metastable states which can be defined as local deformations of the CDW phase with respect to the ion lattice [1]. The existence of a large number of metastable states is a common feature of disordered materials. This in general leads to anomalous behaviour of relaxation at long times. Relaxation studies are very useful in order to extract the barrier distribution and for better understanding of dynamics. As in other disordered materials (glasses, spin-glasses or polymers) the CDW metastable states are expected to contribute to the thermodynamical properties at very low temperature. We have performed measurements of specific heat and of dynamics in energy relaxation on several CDW compounds ($NbSe_3$, $TaS_3$, $(TaSe_4)_2I$, $K_{0.3}MoO_3$) at very low temperatures ($T \leq 1$ K). The technique we used is a transient heat pulse technique in which the specific heat is calculated from the decay of the temperature increment after a heat pulse, as $\Delta T(t) = \Delta T_o \exp(-t/\tau)$ with $\tau = C_p R_t$ ($R_t$ being the thermal resistivity of the thermal link to the cold sink). In the following we present our main results in three parts concerning the extra contribution to the specific heat below 1 K, the non-exponential relaxation of energy and aging phenomena in the energy relaxation.

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