Recent results on energy relaxation in disordered charge and spin density waves

R. Mélin$^1$, K. Biljaković$^2$, J. C. Lasjaunias$^1$ and P. Monceau$^1$

$^1$ Centre de Recherches sur les Très Basses Températures (CRTBT)$^1$, Boîte Postale 166, F-38042 Grenoble Cedex 9, France

$^2$ Institute of Physics, Hr-10 001 Zagreb, P.O. Box 304, Croatia

Abstract

We briefly review different approaches used recently to describe collective effects in the strong pinning model of disordered charge and spin density waves, in connection with the CRTBT very low temperature heat relaxation experiments.

1 INTRODUCTION

Extensive investigations of energy relaxation at very low temperature (below 0.5 K) in disordered charge and spin density waves (CDWs and SDWs) (see for instance [1–5]) have revealed ageing in the heat response, in the sense that the temperature signal $T(t_w, \tau)$ measured at a time $t_w + \tau$ depends on the “waiting time” (the duration $t_w$ of the heat perturbation), as well as on time $\tau$ elapsed since $t_w$. Ageing is “interrupted” [6]: $T(t_w, \tau)$ does not depend on $t_w$ if $t_w$ is larger than the maximal relaxation time $\tau_{\text{max}}$.

These properties, observed in a variety of different compounds, are likely to originate from the interplay between impurities that pin the phase of the CDW, and the commensurate potential, as first discussed by Abe [7]. Fukuyama [8] discussed in a similar model the possibility of a transition to a density wave glass. More recently, Larkin [9] and Ovchinikov [10] discussed metastability, explaining why the CDW or SDW can absorb and restitute energy over long time scales. We provided recently a discussion of collective effects in disordered CDWs and SDWs [11, 12].

2 EXPERIMENTAL RESULTS

Let us first summarize the experiments. (i) As the temperature decreases, the total specific heat first follows a $T^3$ behavior at “high” temperatures (due to phonons), followed by a minimum, followed by a $T^{-2}$ behavior at low temperature. (ii) The residual specific heat follows with a power-law temperature dependence once the $T^3$ and the $T^{-2}$ contributions have been subtracted. (iii) The amplitude of the $T^{-2}$ term decreases strongly as the waiting time decreases. (iv) The spectrum of relaxation times shows a power-law distribution for intermediate waiting times, and interrupted ageing for larger waiting times (see Fig. 1). (v) Commensurate systems relax faster than incommensurate systems.

(i), (iii), (v) can be explained qualitatively by the properties of independent strong pinning impurities [9,10]. We explain (iv) by collective effects in the strong pinning model [11,12]. We explain (ii) by collective effects for substitutional disorder [12,13].
Fig. 1. Out-of-equilibrium relaxation time spectrum of the incommensurate CDW compound TaS$_3$ at the temperature $T = 165$ mK. Thermal equilibrium has been reached for the waiting time $t_w = 90$ min. The long-time tail of the spectrum of relaxation times is well fitted by a power-law (solid lines). From Ref. [11].

3 PHENOMENOLOGICAL REM-LIKE TRAP MODEL

The trap model inspired from the random energy model (REM) [14] with an exponential distribution of trap energies shows a divergence of the average relaxation time at the glass temperature $T_g$ [6]. The distribution $p(E) = \exp \left(-E/T_g\right)$ of the trap energies $E$, combined to the Arrhenius time $\tau = \tau_0 \exp \left(E/T\right)$ (with $\tau_0$ the “microscopic” time and $T$ the temperature), leads to a power-law relaxation time spectrum $p(\tau) \sim (\tau_0/\tau)^{1+T/T_g}$, having an infinite first moment if the temperature $T$ is lower than the glass transition temperature $T_g$.

We have shown [11] that heat relaxation experiments in CDWs and SDWs can be well described phenomenologically by a REM-like model with an exponential trap energy distribution and with an energy cut-off $E_{\text{max}}$. This model leads both to interrupted ageing with a relaxation time $\tau_0 \exp \left(E_{\text{max}}/T\right)$, and to a power-law relaxation. The temperature $T_g$ in the REM-like model relevant to CDWs and SDWs corresponds to a cross-over temperature, with no genuine divergence of the average relaxation time.

4 INDEPENDENT STRONG PINNING IMPURITIES

The starting point is the local model of strong pinning (see the recent review by Brazovskii and Nattermann [15] and references therein), defined by the Hamiltonian

$$\mathcal{H} = \frac{\hbar v_F}{4\pi} \int dy \left( \frac{\partial \varphi(y)}{\partial y} \right)^2 + w \int dy \left[ 1 - \cos \varphi(y) \right] - \sum_i V_i \left[ 1 - \cos (Qy_i + \varphi(y_i)) \right], \quad (4.1)$$
where $\varphi(y)$ is the phase of the CDW or SDW with $y$ the coordinate along the chain, $v_F$ is the Fermi velocity, $w$ the commensurate potential due to interchain interactions and $V_i$ the pinning potential of the impurity located at site $y_i$. Metastability due to bisolitons occurs for a sufficiently strong impurity pinning potential [9, 15], from what it is possible to define an effective two-level system with a ground state separated from a metastable state by an energy barrier. This explains the $T^{-2}$ contribution to the specific heat, as the high temperature tail of a Schottky anomaly of the effective two level system [9,10,12]. A maximum in the specific heat is predicted at a temperature even lower than the very low temperatures used in experiments. Moreover, there exists for this model a qualitative difference between commensurate and incommensurate systems already for independent impurities [5]: in commensurate systems, the metastable state is degenerate with the ground state, leading to a degenerate effective two-level system that cannot absorb or restitute energy. This agrees qualitatively with the experimental trend (v) in section 2.

5 COLLECTIVE EFFECTS

The power-law spectrum of relaxation times obtained in experiments (see Fig. 1) can hardly be explained by the dynamics of independent bisolitons. In a first approximation, we consider local deformations of the CDW induced by impurities, and include the possibility that several impurities can pin a given local deformation of the CDW. Noting $\xi$ the width of the soliton, a given chain is divided in a set of clusters, in such a way that two neighboring impurities belong to the same cluster if they are at a distance smaller than $\xi$. It can be shown [12] that this “cluster” model leads to the exponential energy barrier distribution discussed previously within the REM-like trap model. Moreover, the waiting time dependence of the energy relaxation can be addressed within this model. As a weak point, there exists a genuine glass transition and no interrupted ageing, due to the fact that the CDW is considered to be rigid in between two impurities.

To include the deformations of the CDW in between two impurities at an arbitrary distance, we simulated the evolution of a system of randomly distributed bisolitons following a quench by a dynamical renormalization group (RG) [16], from what we deduce the spectrum of relaxation times. We then obtain a power-law relaxation and interrupted ageing, like in the experiments and like in the REM-like trap model (see Fig. 2).

6 SUBSTITUTIONAL IMPURITIES

The model of substitutional disorder proposed in Ref. [13] for a dimerized system is quite different from the strong pinning model. Substitutional disorder interpolates between edge states obtained by cutting a chain, and solitons at the junction of two distinct ground states. We generalized Ref. [13] to substitutional disorder in incommensurate systems [12]. The bound states generated by substitutional impurities are exactly in the middle of the gap for independent impurities. The degeneracy is lifted for two neighboring impurities, with oscillations of the bound state levels in incommensurate systems, and an overall exponential decay. Combining the exponential distribution of the spacing between impurities to an exponential decay of the effective hopping, leads to a power-law temperature dependence of the specific heat, apparently observed in CDWs and SDWs [see (ii) in section 2].
Fig. 2. Spectrum of relaxation times deduced from dynamical renormalization group following a quench. The different curves correspond to different values of $x\xi$, where $x$ is the concentration of impurities and $\xi$ the soliton width. We use $x\xi = 1.5$ (squares), $x\xi = 1$ (circles) and $x\xi = 0.5$ (triangles). From Ref. [12].

7 CONCLUSIONS

To conclude, we have summarized recent results on energy relaxation in disordered CDWs and SDWs, with an emphasis on collective effects, both in the strong pinning model and for substitutional disorder. This provides an explanation to several experimental observations.

References

[1] K. Biljaković, J.C. Lasjaunias, P. Monceau, and F. Levy, Phys. Rev. Lett. 62, 1512 (1989).
[2] K. Biljaković, J.C. Lasjaunias, P. Monceau, and F. Levy, Phys. Rev. Lett. 67, 1902 (1991).
[3] J.C. Lasjaunias, K. Biljaković and P. Monceau, Phys. Rev. B 53, 7699 (1996).
[4] J.C. Lasjaunias, P. Monceau, D. Staresinic, K. Biljaković, C. Carcel, and J.M. Fabre, J. Phys. Condens Matter 14, 8583 (2002).
[5] J.C. Lasjaunias, R. Mélin, D. Staresinić, K. Biljaković, and J. Souletie, Phys. Rev. Lett. 94, 245701 (2005).
[6] J.P. Bouchaud, J. Phys. I France 2, 1705 (1992); J.P. Bouchaud, E. Vincent, and J. Hamman, J. Phys. I France 4, 139 (1994); J.P. Bouchaud and D.S. Dean, J. Phys. I France 5, 265 (1995). C. Monthus and J.P. Bouchaud, J. Phys. A 29, 3847 (1996).
[7] S. Abe, Physica 143 B, 85 (1986).
[8] H. Fukuyama, J. Phys. Soc. Jpn. 41, 513 (1976); H. Fukuyama, J. Phys. Soc. Jpn. 45, 1474 (1978).
[9] A.I. Larkin, Zh. Eksp. Teor. Fiz. 105, 1793 (1994); A.I. Larkin Sov. Fiz. JETP 78, 971 (1994).
[10] Yu. N. Ovchinnikov, K. Biljakovic, J.C. Lasjaunias, and P. Monceau, Europhysics Letters 34, 645 (1996).
[11] R. Mélin, K. Biljaković, J.C. Lasjaunias, P. Monceau, Eur. Phys. J. B 26, 417 (2002).
[12] R. Mélin, K. Biljaković, J.C. Lasjaunias, Eur. Phys. J. B 43, 489 (2005).
[13] M. Fabrizio and R. Mélin, Phys. Rev. Lett. 78, 3382 (1997); M. Fabrizio and R. Mélin, Phys. Rev. B 56, 5996 (1997); M. Fabrizio, R. Mélin and J. Souletie, Eur. Phys. J. B 10, 607 (1999).
[14] B. Derrida, Phys. Rev. B 24, 2613 (1981).
[15] S. Brazovskii and T. Nattermann, Advances in Physics 53, 177 (2004).
[16] D.S. Fisher, P. Le Doussal and C. Monthus, Phys. Rev. Lett. 80, 3539 (1998); D.S. Fisher, P. Le Doussal and C. Monthus, Phys. Rev. E 64, 066107 (2001).