Anomalous Hooke's law in disordered graphene

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The discovery of graphene has provided an experimental demonstration of stability of 2D crystals. Although thermal fluctuations of such crystals tend to destroy the long-range order in the system, the crystal is stabilized by strong anharmonic effects. This competition is the central issue of the crumpling transition – a transition between flat and crumpled phases, Fig. 1.

We show that anharmonicity-controlled fluctuations of a graphene membrane around the equilibrium flat phase lead to unusual elastic properties [1,2,3]. We demonstrate that stretching of a flake of graphene is a nonlinear function of the applied tension at small tension [1], both for clean and strongly disordered graphene (Fig. 2), thus showing "anomalous Hooke's law". In both cases, scaling of the deformation with the external force obeys a fractal power law in the limit of weak forces. This behaviour is dominated by the thermal fluctuations for clean graphene, while for strongly disordered graphene it is governed by static ripples [2]. Remarkably, the same coupling between the in-plane and flexural vibration modes that enhances the bending rigidity, thus rescuing the flat phase of the membrane, leads simultaneously to a dramatic softening of the in-plane elasticity.

Our results compare well with a recent detailed experimental study of graphene elasticity [4]. It was found there that the room-temperature in-plane stiffness of graphene is reduced compared to its value for 'ideal' graphene (no disorder, T = 0) by a large factor (up to ~40) at low stretching.

References

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Figures

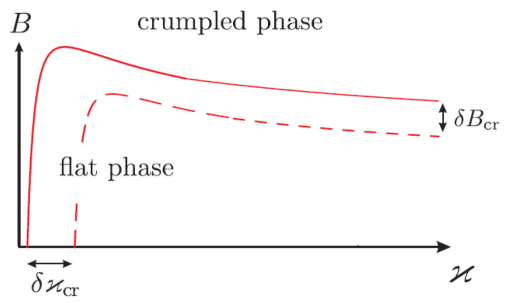

Figure 1: Phase diagram of graphene in the plane of parameters κ (bending rigidity) and B (disorder) at non-zero tension

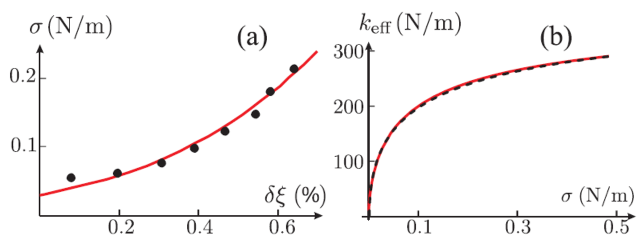

Figure 2: (a) Stress-strain dependence. Dots – experiment [4], line – theory for strongly disordered case; (b) Effective stiffness vs. stress in clean graphene at T = 300K. Dashed line – numerical simulations [5], solid line – present analytical theory [1].