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Nearly frictionless transport of solid helium-4 at higher temperature regime

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ABSTRACT

Eyal et al. recently reported that there might be supersolidity of ^{4}He around the temperature range: 1.3–1.9 K. By using the transition-state model together with the specific activation energy and activation volume, we found that the possible supersolidity of ^{4}He might occur at the similar temperature range as Eyal et al. reported.

1. Introduction

Quite recently Eyal et al. [1] have carried out torsional oscillator experiments on solid ^{4}He at temperatures around the range 1.3–1.9 K and found behavior which is qualitatively very similar to that seen at low temperatures [2–4]. The appearance of the effects seen in their experiment is directly correlated with the creation of disorder (grain boundaries) in a single crystal [1]. They still observed phenomena similar to those referred to as supersolidity [5,6], which were so far observed at temperatures below 0.2 K. These phenomena include a partial decoupling of the solid helium mass from the oscillator, a change of the dissipation, and a velocity dependence of the decoupled mass. These were all observed both in the bcc and hcp phases of solid ^{4}He. Note that the superfluidity [7], i.e., the ability to transport without resistance of solid ^{4}He [8,9] has recently been observed at low temperatures, with a similar dependence on annealing and on ^{3}He concentration [8]. In fact it was suggested [9–12] that quenched-in glassy phase in solid helium is the most likely origin for superfluidity of solid ^{4}He. Meanwhile as suggested in Ref. [1]: *Another possibility has to do with the presence of two-level systems in the solid* [12], *which are characteristic of disordered systems like glasses. In glassy systems there is no typical energy scale, and so there is no a priori reason why similar phenomena should not be present over a wide range of temperatures as we have observed.* We have investigated the almost frictionless transport of solid helium at a very low temperature regime using a verified model [9,13–15]. In this paper we shall further study around the temperature range mentioned in Ref. [1] about the nearly frictionless transport of solid helium (^{4}He). This higher temperature was seldom considered in previous works about the possible superglass [10] and/or quantum glass states [12].

The material behavior of amorphous as well as glassy matter such as polymers [16] and bulk metallic glasses [13,14,16] continues to present great theoretical challenges. While dislocations have long been recognized as playing a central role in plasticity of crystalline systems, no counterpart is easily identifiable in disordered matter. In addition, yield and flow [17] occur very far from equilibrium, where the state of the system may have a complex history dependence. Note that in Ref. [1] once the cell reaches the triple point at $T = 1.464$ K [18], liquid appears in the cell and the decoupling effect vanishes.

In recent years, considerable effort was geared towards understanding how glasses respond to shear (cf. Refs. [9,16]). Phenomena such as shear thinning, i.e., the higher the shear rate is, the smaller the flow resistance, and rejuvenation are

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common when shear flow is imposed. Unlike crystals, glasses age, meaning that their state depends on their history. When a glass falls out of equilibrium, it evolves over very long time scales. Meanwhile most of the classical solutions of contact problems, starting from the Hertzian case, rely on the assumption of nominally smooth geometries, which is reasonable at large enough scales. However, real surfaces are rough at the micro- or even at the meso-scale [19], and the effect of multi-point contact is important for a series of phenomena.

In this presentation we shall consider the nearly frictionless transport of solid ^{4}He at a rather low temperature regime in micropores which have radius- or transverse-corrugations along the cross-section. The solid ^{4}He will be treated as a locally amorphous material [13–15]. To consider the transport of this kind of matter in microscopic domain, we adopt the verified transition-rate dependent model [9,13,15] which was successfully used to study the annealing as well as transport properties of locally amorphous matter.

We noticed that Eyring [15] tried a hyperbolic sine law between the shear (strain) rate: $\dot{\Gamma}$ and (large) shear stress: τ because the relaxation at the beginning was steeper than could be explained by the bimolecular law and obtained the close agreement with experimental data. They can obtain the law of annealing of glass for explaining the too rapid annealing at the earliest time. This model has a sound physical foundation from the thermal activation process [15] (a kind of quantum tunneling which relates to the matter rearranging by surmounting a potential energy barrier was proposed therein). With this model we can associate the locally glassy matter with the momentum transfer between neighboring atomic clusters on the microscopic scale and reveal the atomic interaction in the relaxation of flow with (viscous) dissipation.

Here we shall demonstrate a possible higher onset temperature ($\sim$1.62 K) of supersolid ^{4}He based on a microscopic thermal activation model proposed before and the verified boundary perturbation technique [9,19,20]. The role of ^{3}He concentration will be considered using an effective interaction, say, the activation energy and activation volume [9,13–15]. Detailed results about our calculations for almost frictionless transport of solid ^{4}He and discussion will be given finally.

2. Theoretical formulations

The beginnings of theoretical molecular mechanisms of deformation in amorphous matter are as old as the subject of atomic mechanisms of deformation and yield in metals. The first specific molecular mechanism of deformation for amorphous matter was published by Eyring [12]. In 1931 Eyring and Polanyi using the London equation provided a semi-empirical calculation of a potential energy surface (PES) of the $H + H_2$ reaction describing the journey of nuclei from the reactant state of the system to the product state, passing through the crucial transition of activated complexes (cf. the details in, e.g., Ref. [13]; the birth of reaction dynamics).

The molecular theory of deformation kinetics came from a different stream of science than that of structure and motion of crystal defects (in particular dislocations). Its roots stretch to the developmental stages of theories of chemical reactions and thermodynamic description of their temperature dependence, culminating in the key formulation by Arrhenius of the equation for reaction rates (the transition-state theory [15] is to assume the equilibration of the population between reactants and the transition state: $\mathbf{A} + \mathbf{B} \leftrightarrow [\mathbf{TS}] \rightarrow$ **Products**; thus, the rate constant can be related to the equilibrium constant for formation of the transition state and hence the barrier energy (with the zero-point energy corrections) along the reaction coordinate [13,15]). By the beginning of the 20th century the concept of activation entropy was included in the model, and it was considered that molecules go both forwards (product state) and backwards (reactant state).

The development of statistical mechanics, and later quantum mechanics, led to the concept of the potential energy surface. This was a very important step in our modern understanding of atomic models of deformation. Eyring's contribution to this subject was the formal development of the transition state theory which provided the basis for deformation kinetics, as well as all other thermally activated processes, such as crystallization, diffusion, polymerization, etc.

The motion of atoms is represented in the configuration space; on the potential surface the stable molecules are in the valleys, which are connected by a pass that leads through the saddle point. An atom at the saddle point is in the transition (activated) state. Under the action of an applied stress the forward velocity of a (plastic) flow unit is the net number of times it moves forward, multiplied by the distance it jumps. Eyring proposed a specific molecular model of the amorphous structure and a mechanism of (plastic) flow. With reference to this idea, this mechanism results in a (shear) strain rate given by [13–15]

$$\dot{\Gamma} = 2\frac{V_h}{V_m}\frac{k_B T}{h}\exp\left(\frac{-\delta G}{k_B T}\right)\sinh\left(\frac{V_h \tau}{2k_B T}\right) \tag{1}$$

where

$$V_h = \lambda_2\lambda_3\lambda, \qquad V_m = \lambda_2\lambda_3\lambda_1,$$

λ_1 is the perpendicular distance between two neighboring layers of molecules sliding past each other, λ is the average distance between equilibrium positions in the direction of motion, λ_2 is the distance between neighboring molecules in this same direction (which may or may not equal λ), λ_3 is the molecule to molecule distance in the plane normal to the direction of motion, τ is the local applied stress, δG is the activation energy, h is the Planck constant, k_B is the Boltzmann constant, T is the temperature, V_h is the activation volume for the molecular event and V_m is the sheared (flow) volume [13,15]. This was the earliest microscopic theory of yield behavior in amorphous glasses, and Eyring presented a theoretical framework which