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THE PUZZLING COLLAPSE OF ELECTRONIC SLIDING FRICTION ON A SUPERCONDUCTOR SURFACE

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Abstract

In a recent paper [Phys. Rev. Lett. **80** (1998) 1690], Krim and coworkers have observed that the friction force, acting on a thin physisorbed layer of N_2 sliding on a lead film, abruptly decreases by a factor of ~ 2 when the lead film is cooled below its superconductivity transition temperature. We discuss the possible mechanisms for the abruptness of the sliding friction drop, and also discuss the relevance of these results to the problem of electronic friction.

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The frictional forces and dissipation experienced by thin physisorbed layers of inert atoms or molecules, such as Kr, Xe or N_2 while sliding on metallic surfaces can nowadays be measured, owing to an ingenious method devised by J. Krim and collaborators.[1]

The frequency shift and, most importantly, the change in the Q-factor experienced by a quartz crystal microbalance (oscillating at about $\sim$ 10MHz), upon adsorption of the gas on the metal film, itself part of the microbalance, provide direct information on the molecule-surface frictional processes.

In this manner both the phononic and electronic contribution to friction can be accessed. In particular, when the substrate is a metal that can be cooled down below the superconducting T_c, one can gauge the importance of the electronic contribution, as this alone should presumably change below T_c. This is precisely what was done in a very recent experiment,[2] where about 1.6 ML of N_2 was adsorbed on a lead film, which can be cooled below the lead film superconducting temperature $T_c \approx 7$K.

The result is striking: dissipation due to friction drops at T_c to about half of its normal state value. The drop is clearly connected with superconductivity of the metal substrate, and is very abrupt. While the phenomenon confirms predictions about the importance of electronic friction (see below), its abruptness is entirely unexpected, and has not as yet been explained or even discussed to any level of detail. The purpose of this note is to debate on the possible mechanisms for the abruptness of the sliding friction drop, and also to discuss the relevance of these results to the problem of electronic friction.

At first one may think that the explanation for the abruptness is trivial. When the metal film is in the normal state, at $T > T_c$, it is known that the electronic contribution to the sliding friction is directly proportional to the resistivity change of the metal film induced by the adsorbate layer.[5] This is proven by comparing the energy "dissipation" calculated in the reference frame where the metal film is stationary and the adsorbate layer moves with the velocity $\mathbf{v}$ ("frictional energy dissipation"), with that calculated in the frame where the adsorbate layer is stationary and the metal electrons move with velocity $-\mathbf{v}$ ("ohmic energy dissipation").[5] If this argument were to remain valid also when the metal film is in the superconducting state, then the electronic contribution to the sliding friction would correctly drop abruptly to zero at $T = T_c$, since the film resistivity vanishes abruptly at T_c.

We argue however that this argument is incorrect, unfortunately, when the metal film is in the superconducting state. First we note that the superconductivity transition is continuous, so that the fraction of the electrons in the superconducting condensate increases *continuously* from zero to one as the temperature is reduced from T_c to zero. The DC resistivity of the metal film drops nonetheless discontinuously from its normal state value above T_c to zero at $T = T_c$. The reason is, of course, that the electrons in the condensate short circuit the metal film. Thus, no drift motion (current) occurs in the "normal" electron fluid of thermal excitations, even though just below T_c almost all the electrons belong in this "normal" fluid. Let us now consider the system in a reference frame where the adsorbate layer is stationary.

In this reference frame all the electrons in the metal film move (collectively) with the speed $-\mathbf{v}$ relative to the adsorbate layer. The "normal" electrons in the system will scatter from the adsorbates and give rise to energy dissipation, just like in the normal state (i.e., $T > T_c$). This is precisely what happens, for example, in ultrasonic attenuation.[3] By analogy, one would thus expect the electronic sliding friction to decrease *continuously* as the system is cooled below T_c, in a way which correlates with the fraction of electrons in the condensate, and in sharp contrast to what is observed experimentally.

Of course, the perturbation represented by the sliding adsorbate film is localized at the surface, rather than extended as in the case of ultrasonic attenuation. The localized processes should necessarily involve k_z-nonconservation, corresponding to a strong spatial variation, which is not present in bulk ultrasonic attenuation (but which might be achievable in *surface* ultrasonic attenuation). There is however no immediate reasoning suggesting that precisely this fact should cause the switching from continuous to abrupt.

Again by analogy to ultrasonic attenuation, a jump in the electronic friction at $T = T_c$ could still be explained, if a transverse electromagnetic field were somehow involved in the excitation process. The superconducting condensate (even if very weak, near T_c), will screen out the transverse electromagnetic field in the metal and hence abruptly eliminate the coupling between the normal electrons and the adsorbate. This effect is well known and is, e.g., the reason why the damping of transverse acoustic phonons jumps abruptly, by roughly a factor of two, at $T = T_c$.[3]

On the other hand, existing understanding of the electronic sliding friction in the normal state[6] suggests that the short-range, unretarded coupling between the fluctuating coulomb field associated with virtual electronic transitions in the adsorbates should be quite adequate. Within the short depth below the surface where most of the sliding-induced electron-hole excitations in the metal are generated, this fluctuating field can be considered as longitudinal. Consequently one would not expect an abrupt drop in the electronic friction due to this coupling mechanism.

The N_2 layer adsorbed on lead at this low temperature must be essentially solid, probably incommensurate. The friction jump could in principle signal a supersolid behavior of the film. However, again we see no reason why this should happen, and why precisely at the substrate superconducting T_c.

The lead surface employed by Krim was not a clean one, but had been exposed for some time to atmospheric contamination. It could therefore be covered by a thin layer of nonmetallic material, including oxide. Friction on a nonmetal, particularly if polar, may give rise to time-varying electric fields (triboelectricity), at least partly tranverse, which in turn could be dissipated in the underlying metal and be responsible for the observed jump. At present however this kind of possibility is purely speculative and unsupported by any known fact.

The abruptly jumping friction remains therefore a puzzle, to which we wish to call attention, and for which we can offer at present no clear-cut explanation.

The new phenomenon[2], if confirmed, definitely proves the importance of the electronic friction in the sliding of incommensurate adsorbate layers. In the present system, at least half of the sliding friction in the normal state must be of electronic origin. This result is all the more remarkable since the evaporated lead film is certainly not perfect and crystalline, and moreover was exposed to air for 10-15 minutes. The resulting oxide layer should have reduced the coupling between the sliding molecular film and the metal conduction electrons, while enhancing the coupling to phononic excitations in the sliding film, in virtue of a larger atomic corrugation than that of a clean metal surface.

These results and arguments suggest that on a clean well-defined metal surface, e.g., Xe on clean silver and gold films,[7] electronic friction should be even more important than in Krim's latest experiment, possibly dominating the whole sliding friction of incommensurate adsorbate layers. This conclusion is consistent with ideas previously put forward by one of us[4] but not with those of other authors.[8]

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