Frictional duality observed during nanoparticle sliding

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The dynamics of frictional motion are critical to fields ranging from nanomachines [1] to the study of earthquakes [2] whose scales range up to hundreds of kilometers. Frictional motion involves a huge range of time and length scales [3], coupling the elastic fields of two blocks under stress to the dynamics of the myriad interlocking microscopic contacts that form the interface at their plane of separation. In spite of the immense practical and fundamental importance of friction, much of the basic physics of the problem is not well understood and a detailed fundamental theory describing the dynamics of frictional motion along rough interfaces is far from complete. As a result, the study of frictional motion has excited an abundance of recent interest in the Physics community [5]. One of the interesting research directions that have evolved in the field is the study of friction at nano scales, or "nanotribology" [6].

In nanotribology the frictional properties of systems whose scales are in the nanometer range are probed. This "bottom-up" type approach to understanding friction has its origins in the idea that the frictional behavior of a "single contact" is a clean laboratory to understand the micro-scale contributions to the dissipation inherent in frictional processes. One may then be able to utilize this knowledge to derive fundamental understanding of friction at macroscopic scales. This upsurge in interest in friction at nano-scales is not purely academic. Recent advances in nano-technology and the development and fabrication of micron scale mechanical instruments have emphasized the need to both understand and manipulate friction at these scales. Here, frictional wear and dissipation can be especially destructive and our knowledge of how classical lubricants and protective coatings work is severely tested.

How does one probe the physics of friction at these scales? One method, which has been widely used, adapts atomic force microscopy (AFM) to measure forces applied to an AFM tip. This method, called FFM (friction force microscopy), basically consists of sliding an AFM tip across a surface and measuring the lateral force applied to the tip to maintain its motion. The vast majority of the applications of this method have been used to probe the direct interactions between the AFM tip and an atomically flat surface.

When used in this way, FFM's have a number of limitations. First, one is restricted to the study of materials from which atomically "sharp" materials can be constructed. This limits the range of materials that can be studied. In addition, the precise structure and shape of the tip can be critical to quantitative understanding of the tip-substrate forces measured and, in general, this precise tip shape is the least defined property of the system. For example, MD simulations by the Robbins group [7] have demonstrated that widely different tip-substrate forces can occur for tips that have ostensibly the same geometry; the interaction of a smooth "curved" tip is vastly different from the case where the curvature is approximated by either an atomically rough surface or when curvature is obtained by building an atomically stepped surface. Even if the initial tip structure is known, tip structure will change with use - as the tips can "wear down" or pick up "debris" as they scan. Thus, characterization of the experimental system (which often is a stumbling block for understanding friction in macroscopic systems) is still very much a difficult problem on the atomic level.

Even if the structure of an AFM tip can be perfectly characterized, both the lattice orientation and "what the tip picks up along the way" can matter tremendously. For example, recent observations of "superlubricity" (frictionless motion) between a tungsten tip and graphite have been explained by graphite flakes, dislodged from the substrate, that have stuck to the tungsten tip [8] and create the actual contact between the tip and substrate. When the flakes are oriented appropriately (so that the lattice spacings of the tip and substrate become incommensurate) the friction coefficient of the device goes to zero. Such superlubricity can occur between two flat surfaces where opposing atoms can not align [9, 7]. This is because any lattice mismatch between the surfaces prevents relative motion of the two surfaces to change the overall energy of the system. When the system is not aligned, statistically any atoms that approach each other are balanced by those that increase their relative distance. If the total energy is unchanged by sliding, no dissipation can occur and friction is negligible.

In a recent paper by Dirk Dietzel, Claudia Ritter, Tristan Monninghoff, Harald Fuchs, Andre Schirmeisen and Udo D. Schwarz [10] intriguing new Physics were revealed by means of a novel implementation of the FFM technique [11] which circumvents many of the above difficulties. These authors first thermally evaporate 50-750nm diameter nano-particles of antimony on a graphite surface (contact areas are between 8,000 nm^2 and 90,000 nm^2). The FFM is now used in two ways. The first is as a contact mode AFM to obtain an image of the particles on the surface. In this mode, the AFM exerts a negligible force on the particles and thereby does not move them, but instead records their topography and location on the substrate. The cantilever attached to the FFM stylus is now stiffened - so that the cantilever is able to apply non-negligible force to the particles. The FFM is now used to laterally push the particles - essentially performing a "block on block" sliding experiment at the nano-scale. The advantages of this technique are two-fold. First the working materials in nano-friction experiments are the nano-particles on surfaces and are therefore not limited to whatever materials can be shaped into viable FFM tips. This allows much more flexibility in the choice of working materials and conditions. The second advantage of this technique is that the geometry of the force apparatus is now both well-defined and controlled. The interpretation of the experimental results is no longer dependent on unknown quantities such as the precise shape and condition of the tip.

The results of the experiments described in the paper indicated two very different modes of frictional behavior. The first mode shows a roughly linear increase of the frictional force with the measured (nominal) contact area of an island. Assuming that the measured nominal area of the nano-particles being pushed is proportional to the real contact area (probably a reasonable assumption in this system) this behavior is that predicted by the Bowden and Tabor theory of friction [12], which is the classic explanation of the Amontons-Coulomb friction law.

The second mode of friction, which is observed for a fraction of the particles in these experiments, is entirely different. These particles exhibit superlubricity, i.e. nearly *zero* frictional resistance.

Both frictional modes were observed for both UHV conditions as well as for ambient conditions (although the number of frictionless events in the latter conditions was much smaller). The authors observe a systematic increase in the number of particles exhibiting superlubricity with the quality of the vacuum - the better the vacuum conditions, the higher percentage of frictionless particles.

What is going on here? The authors suggest that the scenario best supported by the results of the experiment is one first suggested by He, Muser and Robbins some time ago [7]. In this picture, the *default* state of an interface composed of two flat surfaces, whose atoms are arranged in an incommensurate fashion, would be frictionless behavior. He, Muser and Robbins authors suggested that the friction between the two surfaces is due to a very small number of "dirt" particles that get trapped between the two surfaces. Molecular dynamic simulations have shown that this simple scenario can produce Amontons-Coulomb friction where, surprisingly, the precise number of dirt particles that are trapped does not have a large effect on the resulting friction coefficient. Even in UHV conditions small amounts of contaminants exist in the system. Their number increases, however, as the quality of the vacuum is degraded. This explains the authors' observations of a large percentage of frictionless particles in the cleanest conditions to a minute number (which lose there frictionless properties after sliding approximately 100nm) under ambient conditions.

In conclusion, the results described in this paper are extremely interesting and serve to substantiate a "dirt-driven" picture of the foundations of friction in these nearly ideal nano-scale systems. The clean "block-on-block" technique used here may provide an important new way to probe our fundamental understanding of frictional processes. With these tools in hand, it becomes feasible to address important questions such as the scale-dependence of the underlying laws of friction. For example, one can now perform direct comparisons between "block-on-block" macroscopic descriptions of friction that been extremely successful in describing the rich behavior beyond the simple Amontons-Coulomb law of friction. These "rate-and-state" type theories [13] quantitatively describe frictional properties such as "aging" and sliding velocity dependence of the friction coefficient in macroscopic systems. It would be of extreme interest to determine if/how these empirical descriptions carry over to the nano-scale.

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