## Comment on "Brownian Motion of Microscopic Solids under the Action of Fluctuating Electromagnetic Fields"

Recently, Dorofeyev *et al.* [1] have observed Brownian motion of a small metal particle connected by a spring to a holder, and located in ultrahigh vacuum in the vicinity of a gold surface. It was observed that the particle performed a stochastic oscillatory motion, and that the damping of the motion increased as the particle approached the gold surface. It was suggested that this increased damping is due to the coupling to the fluctuating electromagnetic field. However, we have studied this "vacuum" friction in several earlier papers and found it to be extremely weak [2]. Thus in this Comment we show that vacuum friction gives a contribution which is 11 orders of magnitude less than the friction force observed in the measurements by Dorofeyev *et al.*

Consider two metallic bodies with flat surfaces separated by a vacuum slab of thickness $d$ and sliding with the relative velocity $v$. The frictional stress acting on the surfaces can be written as $\sigma = \gamma v$ where $\gamma \to 0$ as $T \to 0$. In Ref. [2] we have shown that the vacuum friction

$$\gamma \approx \frac{\hbar}{2\pi^2}\int_0^\infty dq\, q^3 e^{-2qd}\int_0^\infty \frac{d\omega\hbar}{k_B T}\,\frac{e^{-\hbar\omega/k_B T}}{(1-e^{-\hbar\omega/k_B T})^2} \times\left(\frac{\mathrm{Im}R_{1p}\,\mathrm{Im}R_{2p}}{|1-e^{-2qd}R_{1p}R_{2p}|^2}+\frac{\mathrm{Im}R_{1s}\,\mathrm{Im}R_{2s}}{|1-e^{-2qd}R_{1s}R_{2s}|^2}\right),$$

where $R_{1p}(q,\omega)$ and $R_{1s}(q,\omega)$ are the reflection factors for $p$- and $s$-polarized electromagnetic waves, respectively, for solid 1, and $R_{2p}$ and $R_{2s}$ similar quantities for solid 2. Figure 1 shows the $s$ (upper solid curves) and $p$ (lower dashed curves) contributions to $\sigma$ as a function of the distance $d$ between the two metal surfaces for two temperatures, $T = 70$ and 300 K. We have assumed $v = 1$ m/s and used the dielectric function of silver. The theory presented above is based on a local dielectric function and the $p$-wave contribution must be modified at short distances $d$ to take into account nonlocal effects. The full nonlocal theory gives the $p$-wave contribution shown by the lower solid curves in Fig. 1. Note that the $s$-wave contribution dominates for $d > 10$ Å and that the frictional stress equals $\sim 10^{-5}$ Pa for $d = 10$ Å. The friction force observed in [1] corresponds to a frictional stress $\sigma \approx 10^6$ Pa where we have assumed two flat surfaces separated by $d = 10$ Å, and moving with the relative velocity $v = 1$ m/s. This stress is 11 orders of magnitude larger than the frictional stress found above.

In the discussion above we have assumed perfect (single crystal) solids. Most real solids consist of grains that may expose different facets with different work functions. This gives rise to a (static) inhomogeneous electric field distribution in the vicinity of the surfaces. It is clear that when two macroscopic bodies are slid relative to each other, a finite contribution to the friction force will arise from surface imperfections. However, this process gives a negligible contribution to the friction force [3].

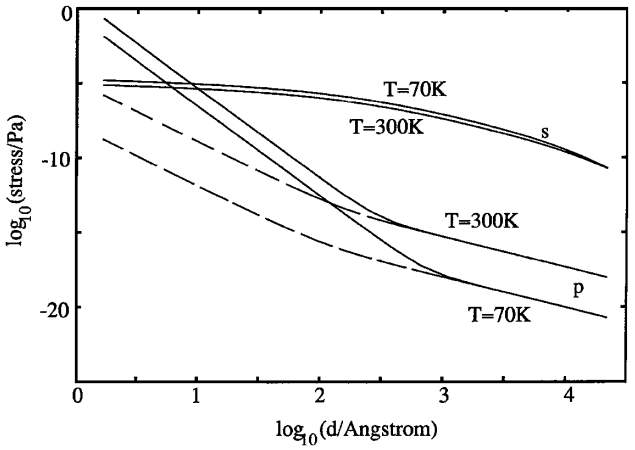


FIG. 1. The frictional shear stress as a function of the separation $d$ between the surfaces (see text for details).

We have used the theory of viscoelasticity to estimate the contribution to the friction force from the internal energy dissipation in the solids as a result of the pulsating stresses acting on the solids during the vibrational motion [3]. This coupling is, of course, also mediated via the electromagnetic field, but is not included in the theories of vacuum friction described in Refs. [1,2]. There are many different sources of the internal friction, e.g., thermal currents or grain-boundary slip, but the most important contribution may be thermally activated point-defect flipping. Using typical parameters and $d = 10$ Å we obtain a contribution to the damping which is 9 orders of magnitude larger than the contribution from the vacuum friction [3]. There exists a similar surface effect: If adsorbates occur on the surface, e.g., gold atoms along steps on the Au(111) surface (or Al atoms at steps on the tip), then they tend to accumulate in the region under the tip because of the van der Waals attraction from the tip. When the tip oscillates, the concentration of adsorbates below the tip will also fluctuate in time. This driven flow of adsorbates in and out of the tip region will give rise to energy dissipation due to the adsorbate-substrate friction force. We have estimated this contribution, and found it (at room temperature) to be roughly 8 orders of magnitude larger than that arising from the vacuum friction [3].

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