Rotational Quantum Friction

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Abstract

Casimir force is the interaction between the instantaneous charges arising from quantum fluctuations on one surface and the induced opposite image charges on the other. When two surfaces are in relative motion, the induced image charges that lag slightly behind will pull the fluctuating charges back. That gives a non-touching friction named 'quantum friction' [1]. However, the existence of quantum friction was recently questioned by some theoreticians [2], because previous theoretical studies are extremely difficult to be implemented in real experiments due to the tininess of the force or unrealistic geometries. Recently, we investigate the enhanced frictional forces acting on a small sphere rotating near a surface [3]. The frictional force for the sphere rotating near a surface can be several orders of magnitude larger than that in vacuum studied in [4]. Quantum friction is maximized by choosing materials with poor conductivity like graphite or semiconductors. For semiconductor materials which support surface plasmon polaritons, quantum friction can be further enhanced by several orders of magnitude. The prominent enhancement and the realistic geometry open up the possibility of experimental verification.

Introduction

➢ **Quantum Friction [1]:**

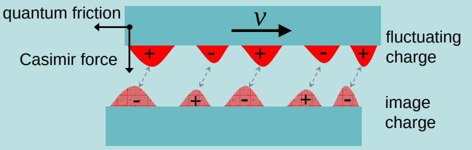
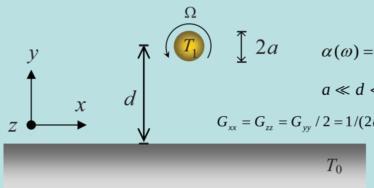


Fig. 1. Casimir force and quantum friction.

➢ **Rotational Quantum Friction [3]:**



$$\alpha(\omega) = a^3\frac{\varepsilon(\omega)-1}{\varepsilon(\omega)+2}$$

$$a \ll d \ll c/\Omega, \hbar c/k_B T_j$$

$$G_{xx} = G_{zz} = G_{yy}/2 = 1/(2d)^3[\varepsilon(\omega)-1]/[\varepsilon(\omega)+1]$$

Fig. 2. A spherical particle rotating near a surface.

High Rotation Speed and High Temperature

➢ **High Rotation Frequency Limit but Low Temperature :**

$$M = -3\hbar a^3 J/8\pi d^3,$$

$$J \overset{\Omega\gg\sigma_0}{=} \frac{8\pi^2\sigma}{3}\left[\frac{2\ln(\Omega/\sigma)-\ln(8\pi^2/3)}{\Omega/\sigma}\right]$$

➢ **Maximum at Zero Temperature :**

$$J_{\max} = 2.6088\sigma_0 \quad @\ \Omega = 24.7679\sigma_0$$

➢ **Maximum at High Temperatures :**

$$J_{\max} = 0.25\theta \quad @\ \Omega = 10\pi\sigma_0/3$$

➢ **Discussion :**

- Match the rotation frequency with the conductivity to maximize the quantum friction.
- For diatomic molecules, the rotational constant: $10^9 - 10^{12}\ s^{-1}$
- Depending on the impurity concentration, conductivities of germanium and silicon: $10^8 - 10^{14}\ s^{-1}$

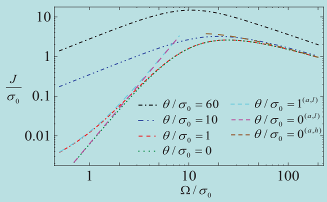


Fig. 4. J versus the rotation frequency at different temperatures. The dashed curves are the asymptotic results in the low and high rotation frequency limits.

Theory

➢ **Two Contributions [4]:**

- Fluctuating electromagnetic field: $\mathbf{E}^{\rm fl}(\omega)$ $\qquad \mathbf{p}^{\rm ind}(\omega) = \alpha(\omega)\mathbf{E}^{\rm fl}(\omega)$
- Fluctuating electric dipole moment: $\mathbf{p}^{\rm fl}(\omega)$ $\qquad \mathbf{E}^{\rm ind}(\omega) = \mathbf{G}(\omega)\mathbf{p}^{\rm fl}(\omega)$

$$M_p = < p_x^{\rm fl}(\omega)E_y^{\rm ind}(\omega) - p_y^{\rm fl}(\omega)E_x^{\rm ind}(\omega) >$$

$$M_E = < p_x^{\rm ind}(\omega)E_y^{\rm fl}(\omega) - p_y^{\rm ind}(\omega)E_x^{\rm fl}(\omega) >$$

➢ **Symmetric Expression [4]:**

$$M = \frac{\hbar}{\pi}\int_{-\infty}^{+\infty} d\omega[n_1(\omega)+\frac{1}{2}]{\rm Im}\{\alpha(\omega)\}[{\rm Im}\{\bar{G}(\omega-\Omega)\}-{\rm Im}\{\bar{G}(\omega+\Omega)\}]$$
$$+\frac{\hbar}{\pi}\int_{-\infty}^{+\infty} d\omega[n_0(\omega)+\frac{1}{2}]{\rm Im}\{\bar{G}(\omega)\}[{\rm Im}\{\alpha(\omega-\Omega)\}-{\rm Im}\{\alpha(\omega+\Omega)\}]$$

- Dispersion of the imaginary parts of Green tensor and the polarizability
- Frequency splitting due to rotation
- According to the fluctuation dissipation theorem,

$$\mathbf{p}^{\rm fl}(\omega) \leftrightarrow {\rm Im}\{\alpha\}$$
$$\mathbf{E}^{\rm fl}(\omega) \leftrightarrow {\rm Im}\{G\} \leftrightarrow {\rm LDOS}$$

➢ **Compact Expression [4]:**

$$M = -\frac{2\hbar}{\pi}\int_{-\infty}^{+\infty} d\omega[n_1(\omega-\Omega)-n_0(\omega)]{\rm Im}\{\alpha(\omega-\Omega)\}{\rm Im}\{\bar{G}(\omega)\}$$

$$@T=0, \begin{cases} n_1(\omega-\Omega)-n_0(\omega) = -1, & \omega\in[0,\Omega] \\ n_1(\omega-\Omega)-n_0(\omega) = 0, & \omega\notin[0,\Omega] \end{cases}$$

Enhanced Quantum Friction and SPP Excitations

➢ **Indium Antimonide (InSb):**

$$\varepsilon = \varepsilon_\infty\left[1+\frac{\omega_L^2-\omega_T^2}{\omega_T^2-\omega^2-i\gamma\omega}-\frac{\omega_p^2}{\omega(\omega+i\gamma_p)}\right], {\rm Re}\{\varepsilon\} = -1(-2)\ @ \begin{cases}\omega_1 = 2.18(2.12){\rm THz} \\ \omega_2 = 5.75(5.73){\rm THz}\end{cases}$$

➢ **Zero Temperature:**

- High rotation speed

➢ **High Temperatures:**

- Whole range of the rotation speed

➢ **Four Singular Lines:**

$\omega = \omega_1$

$\omega = \omega_2$

$\omega = \Omega - \omega_1$

$\omega = \Omega - \omega_2$

- Taking advantage of the huge LDOS of propagating SPPs at the surface and the strong response of localized SPPs on the sphere.

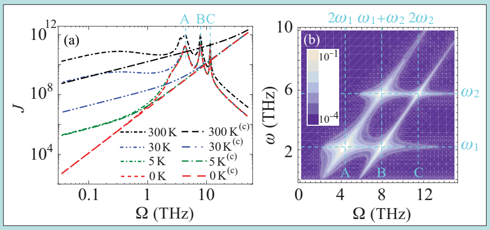


Fig. 5. (a) J versus the rotation frequency at different temperatures for InSb (short dashes) and a metallic material with an equivalent conductivity $\sigma_0 = \varepsilon_\infty\omega_p^2/4\pi\gamma$ (long dashes). The peaks are marked by A, B, and C. (b) Integrand of J versus the rotation frequency and optical frequency at T = 0. The plot in (b) is saturated below 10^{-4}.

Enhanced Quantum Friction and LDOS near a Surface

➢ **Metallic Materials:**

$$\varepsilon(\omega) = 1+\frac{i4\pi\sigma_0}{\omega}$$

➢ **Low Rotation Frequency Limit :**

$$M = -\frac{3\hbar}{256\pi^3\sigma_0^2}\frac{a^3}{d^3}(\theta_1^2+\theta_0^2+2\Omega^2)\Omega,$$

where, $\theta_j = 2\pi k_B T_j/\hbar$.

- $\Omega \ll \theta_j \ll \sigma_0, \Omega(t) = \Omega(0)\exp(-\frac{t}{\tau})$

$$\tau = \frac{256\rho\hbar\pi^2 a^2 d^3\sigma_0^2}{45 k_B^2 T^2}$$

- The stopping time is several orders of magnitude smaller than that in vacuum (Fig. 3(a)): from 4 days to 30 s.

- Due to large LDOS close to the surface:

$$\frac{\rho_s}{\rho_v} = \frac{9c^3}{64\pi d^3\omega^2\sigma}$$

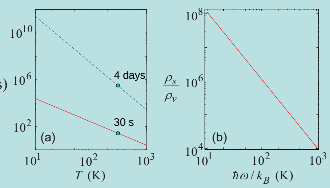


Fig. 3. (a) Characteristic stopping time of a graphite sphere rotating close to a graphite surface (solid line) and in free space [4] (dashed line). (b) Ratio of the LDOS near a surface to that in free space at low frequencies. The frequency is converted to temperature by $\hbar\omega/k_B$. We take *a* = 5 nm and *d* = 30 nm. The conductivity of graphite is $\sigma_0 = 2.1\times10^{14}\,s^{-1}$.

Conclusion & Future Work

➢ **Conclusion:**

- The existence of quantum friction at absolute zero temperature is confirmed.
- The friction near the surface is several orders of magnitude larger than that in free space because of the huge density of electromagnetic states close to the surface.
- For metallic materials, maximizing the quantum friction requires matching the rotation frequency with the conductivity, which means materials with poor conductivity are thus favored for plausible experiments.
- Quantum friction can be further enhanced by several orders of magnitude when the characteristic temperature frequency $k_B T/\hbar$ or the rotation frequency is high enough to reach the surface plasmon resonance frequencies in some semiconductor materials.

➢ **Future Work:**

- The challenges for experiments are to enable particles to rotate at a high speed and close to a surface.

References & Acknowledgements

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