Velocity tuning of friction with two trapped atoms

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Our ability to control friction remains modest, as our understanding of the underlying microscopic processes is incomplete¹–³. Atomic force experiments⁴–¹⁴ have provided a wealth of results on the dependence of nanofriction on structure⁵,⁶, velocity⁷–¹⁰ and temperature¹¹–¹³, but limitations in the dynamic range, time resolution, and control at the single-atom level have hampered a description from first principles⁴. Here, using an ion-crystal system with single-atom, single-substrate-site spatial and single-slip temporal resolution¹⁵,¹⁶, we measure the friction force over nearly five orders of magnitude in velocity, and contiguously observe four distinct regimes, while controlling temperature and dissipation. We elucidate the interplay between thermal and structural lubricity for two coupled atoms, and provide a simple explanation in terms of the Peierls–Nabarro potential¹⁷. This extensive control at the atomic scale enables fundamental studies of the interaction of many-atom surfaces, possibly into the quantum regime.

In the simplest scenario for stick–slip friction, a single atom at an object–substrate interface experiences a force resisting its motion due to a periodic potential created by the substrate². A finite external force is then required to cause the atom to slip from one potential well to the next across an energy barrier \(U_b\). Interestingly, in the case of more than one atom forming the contact interface, friction can be greatly reduced by a structural mismatch of the object and substrate, an effect coined superlubricity⁵,⁶,¹⁵,¹⁸, and observed in friction force microscopy⁸,⁹, colloidal monolayers¹⁹, and recently in our friction simulator¹⁵. Thermally activated transitions between neighbouring potential wells at temperatures \(T \sim U_b\) can also reduce the friction force significantly, making it velocity-dependent¹⁷,¹⁸–³⁰,¹³,²⁰–²⁴. Separate observations have spanned from the high-temperature regime of thermolubricity²² to the low-temperature regime of strong stick–slip². In the present work, as a function of velocity, we observe the continuous transition between four regimes: thermal drift²¹, where friction is small and (nearly) velocity-independent; thermal activation²⁴,²⁶,³⁰,³¹, where friction increases logarithmically with velocity; the friction plateau²⁰, where friction is large and nearly velocity-independent; and velocity weakening²⁰, where friction decreases with velocity because the damping is not fast enough to remove the energy released in a slip. For a two-atom contact, we observe that the measured friction force is substantially reduced by the interaction between the atoms when they are arranged so as to cancel the forces from the substrate. In our previous work³², we had observed this effect for multiple atoms as a continuous transition from stick–slip to superlubricity when varying the arrangement of the atoms, while driving at a fixed large velocity where thermal effects are minor. In the present work, we link this structural lubricity to a reduced barrier \(U_b ≪ U_h\) in the Peierls–Nabarro potential¹⁷,²⁵,²⁶, and distinguish structurally induced thermolubricity \((T \sim \tilde{U}_b)\) from structural lubricity \((T \ll \tilde{U}_b)\) by observing the full velocity dependence.

Our implementation¹⁵,¹⁶,²⁷ of a friction interface, which simulates solid-state nanofriction²⁶,²⁸,²⁹ with an atomically sharp tip⁴, consists of one or two electrically trapped atomic ions pulled against the sinusoidal potential (Fig. 1a,b) of a standing wave of light (optical lattice)¹⁶,³⁰,³¹. We observe each ion’s trajectory with resolution finer than the lattice period by means of the ion’s position-dependent fluorescence¹¹. Each time the ion slips into the next well, its fluorescence reaches a maximum and decreases as the ion is laser-cooled into the new potential minimum (Fig. 1c,d). Hysteresis in the timing of the slip as the electrostatic parabolic trapping potential is pulled back and forth reveals the maximum static friction force exerted by the lattice on the ion (Fig. 1d). At finite ion temperature \(T\), the observed hysteresis and corresponding friction force are reduced (Fig. 1c,d).

At zero temperature²,³,²², the dynamical behaviour is determined by the ratio of the lattice confinement frequency \(ω_l \propto \sqrt{U_l}\) to the electrostatic confinement frequency \(ω_e \propto \sqrt{K}\), where \(U_l\) is the depth of the lattice potential, and \(K\) is the spring constant of the electrostatic trap (Fig. 1a). The corresponding dimensionless corrugation parameter \(η = \omega_l^2/\omega_e^2\) determines the number of minima in the overall potential energy landscape. For \(η ≤ 1\), there is no stick–slip friction as only a single minimum is translated with the applied force. In our regime of interest, \(1 < η < 4.6\), there are at most two local minima in the overall potential at any time, separated by a maximum energy barrier \(U_h/\tilde{U}_l \sim (n – 1)^2/η^2\).

At finite temperature, the ion can also slip owing to thermal activation before the barrier height is reduced to zero by the applied force (Fig. 1c), leading to a reduced hysteresis and friction (thermolubricity) that depend on the transport velocity \(v\).

We observe, for the first time in a single experiment, four contiguous regimes of friction with distinct velocity dependences (Fig. 2a). These regimes can be organized by the hierarchy of three timescales, namely the thermal hopping time between lattice wells \(τ_0\), the transport time for the external trap to move by one lattice well \(a/v\), and the ion recoiling time \(τ_c\). When \(τ_0 ≪ a/v\), thermal hopping dominates, and the ion remains in thermal equilibrium, following the slowly moving ion trap—a regime called thermal drift, where the friction force due to stick–slip (almost) vanishes²⁰. In the thermal activation regime \(τ_0 \sim a/v\), the stick–slip process is only partially suppressed by thermal fluctuations and contributes to an average friction force, which grows logarithmically with velocity². For even larger velocities \(τ_0 \gg a/v \gg τ_c\), thermal hopping across lattice wells is negligible on the transport timescale \(a/v\). This is the friction plateau regime, where the friction force reaches its maximum value². We also observe a fourth regime of friction, sometimes called velocity weakening²⁰, where the friction force decreases logarithmically with velocity². In our system, this regime arises because the ion does not have sufficient

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error bars are

\[ d \approx 4.6 \, \text{MHz} \]

along the radiofrequency

\[ F \approx 10 \, \text{kg} \]

and

\[ v \approx 10 \, \text{m} \text{s}^{-1} \]

almost unaffected. Here,

\[ F \approx a \]

by applying a

| Velocity dependence of stick–slip friction for one atom.

The transport time \( \tau / v \) should be compared to two timescales: the thermal hopping time between two lattice wells, given by \( \tau_n = t_0 \exp (U_0 / k_B T) \) for a maximum barrier height \( U_0 \) (where \( k_B \) is the Boltzmann constant and \( t_0 \) is the hopping attempt time\(^{3,24} \)); and the recoiling time after a slip \( \tau_c \). Here \( \tau_n \approx 10 \, \text{ms} \) and \( \tau_c \approx 100 \, \mu \text{s} \). Four regimes of friction are observed. The friction force is normalized by its zero-temperature maximum value for \( \eta = 2.2 \), \( F_{\eta=2.2} \approx 0.36 \, \mu \text{N} / \mu \text{s} \). Here \( U_l / h = 9.5 \, \text{MHz} \) and \( k_B T / U_l = 0.15(4) \). The solid orange line shows the expected result

\[
F / F_{\eta=2.2} = 1 - \left( \langle 3 / 2 \sqrt{2} \rangle k_B T / U_l \log (v_\text{th} / v) \right)^{2/3},
\]

where \( v_\text{th} \approx 1 \, \text{mm} / \text{s} \), from an analytical model in the thermal activation regime\(^{22,24} \). Similarly in the velocity weakening regime, we model the friction as

\[
F / F_{\eta=2.2} = 1 - \left( \langle 3 / 2 \sqrt{2} \rangle k_B T / U_l \log (v_i / v_f) \right)^{2/3},
\]

(orange dotted line), where \( k_B T / U_l = 0.3 \) and \( v_i = a / t_c \approx 2 \, \text{mm} / \text{s} \) (Supplementary Information). The Langevin simulation (dashed green line) is in good agreement with the data over all four velocity regimes for parameters \( \eta = 2.2 \), \( k_B T / U_l = 0.15 \), \( \tau_c = 100 \, \mu \text{s} \). b. At a larger lattice depth \( U_l / h = 20 \, \text{MHz} \), where \( \eta = 4.6 \), increasing the temperature from \( k_B T / U_l = 0.04(1) \) (blue squares) to \( k_B T / U_l = 0.17(1) \) (red diamonds) reduces the friction in the thermal activation region \( 10^{-3} \, \text{m} / \text{s} < v < 10^{-2} \, \text{m} / \text{s} \) while leaving the friction plateau in the region \( 10^{-3} \, \text{m} / \text{s} < v < 10^{-2} \, \text{m} / \text{s} \) almost unaffected. Here, \( \tau_c \approx 50 \, \mu \text{s} \). The friction force is normalized by its zero-temperature maximum value for \( \eta = 4.6 \), \( F_{\eta=4.6} \approx 0.61 \mu \text{N} / \mu \text{s} \). Solid lines show the expected results from the analytical thermal activation model. Data from a, normalized to \( F_{\eta=4.6} \), is shown as open black circles. Langevin simulations (inset, solid lines) are in good agreement with the data for parameters \( \eta = 4.6 \), \( k_B T / U_l = 0.05 \) (blue), \( k_B T / U_l = 0.13 \) (red). \( \tau_c = 50 \, \mu \text{s} \). Error bars are statistical and represent one standard deviation.

time to recoil after the slip for \( \tau / v \leq \tau_c \). This effectively increases the ion’s kinetic energy before the next slip event and reduces the friction force (Fig. 2a). Having direct access to all system parameters through independent microscopic measurements, we also show a full-dynamics simulation\(^{22,23} \), without any free parameters, that closely follows our data over all four regimes of friction. Figure 2a furthermore shows that, in the thermal activation and velocity weakening regimes, simple analytical models for the velocity-dependent friction developed previously\(^{3,24} \) match our data quantitatively.
The friction reduction can be due to pure structural lubricity (stick–slip motion in a Peierls–Nabarro potential\(^2\) with reduced energy barrier \(U_B \gg k_B T\) or to structurally induced thermolubricity \((U_B \sim k_B T)\), easily distinguished experimentally, as only the latter is velocity-dependent.

In the matched case, the two-ion system is expected to behave as a rigid object akin to a single particle, because only the centre-of-mass mode is affected by lattice forces. Figure 4a shows that the observed velocity dependence of friction in the matched case indeed agrees with the one-ion case. In the mismatched case, the lattice forces on the centre-of-mass mode cancel out, and we observe that, for the same temperature, friction is significantly reduced compared to the matched case (Fig. 4b), in good agreement with Langevin simulations. When comparing the friction in the mismatched case to the matched case, we find that there is no reduction in the thermal drift regime, and reduction by a factor of \(~4.8\) in the friction plateau regime (Fig. 4c). A calculation of the two-ion energy landscape (Fig. 4d,e) shows that in the matched case the barrier is identical to the one-ion case, whereas in the mismatched case it is approximately four times lower \((U_B/\bar{U}_B \approx 3.7)\). The additional \(~20\%) friction reduction compared to \(U_B/\bar{U}_B\) can be explained by structurally induced thermolubricity at fixed temperature due to the lower barrier depth \(U_B\) (Fig. 3). The high-velocity friction reduction plateau of Fig. 4c, where thermal hopping is negligible, then represents a direct observation of structurally induced lubricity or ‘superlubricity’\(^8,11,13,18\). This interpretation is consistent with the observation that, in this regime, the ions pass the barrier one at a time (Fig. 4e inset), reminiscent of a kink defect being transported across the two-atom chain\(^17\). Thus, measuring the reduced friction force directly reveals the Peierls–Nabarro barrier \(U_B\) for two atoms in a periodic potential.

To facilitate comparison of our ion-crystal system with typical solid-state systems, Table 1 summarizes the important physical parameters at play. Although parameters such as the lattice spacing \(a\), the lattice depth \(U_l\), the spring constant \(K\), and the temperature \(T\) differ by several orders of magnitude, the important dimensionless parameters\(^2,3,2\) that govern the frictional behaviour take on the same range of values in the two systems. In the future, the ion-crystal system could be used to study the more complex behaviours found in the multi-slip friction regime\(^4\), and many-body phenomena arising from the strong particle interactions in the corrugated potential, such as the Aubry transition\(^17,24,29\). Furthermore, cooling to the vibrational ground state may provide access to a regime of quantum friction dominated by quantum tunnelling.

| Table 1 | Comparison of parameters in solid-state systems and in the present study. |  |
| --- | --- | --- |
| Solid state | Ion crystal |  |
| Lattice constant \(a\) (nm) | 0.2–0.5 (refs 4,8) | 185 |
| Lattice depth \(U_l\) (eV) | 0.1–2 (refs 8,13) | 8 \times 10^{–8} |
| Temperature \(T\) (K) | 100–500 (ref. 11) | 4 \times 10^{–5},4 \times 10^{–4} |
| Tip/trap stiffness \(K=\omega_0^2N\m^{-1}\) | 0.1–5 (refs 10,12) | 1.5 \times 10^{–12} |
| Lattice depth \(v\) (nm s\(^{-1}\)) | 1–10\(^6\) (ref. 9) | 500–2 \times 10^{7} |
| Attempt frequency | 2,1000 | 500 |
| \(f_0=\tau^{-1}\) (kHz) | (refs 9,21,24) |  |
| Damping rate | 10\(^{-10}\) (ref. 23,24) | 10\(^4\), 2 \times 10^{4} |
| Transport rate \(\nu\) (s\(^{-1}\)) | 10\(^{-7}\) | 2,10\(^5\) |
| Corrugation parameter | 1–8 (refs 6,21) | 2,2, 4,6 |
| \(\eta\propto U_l/Ka^2\) | 0.02–0.5 (refs 11,12) | 0.04–0.4 |
| Temperature parameter |  |  |
| \(k_B T/U_l\) |  |  |

### Supplementary Information

The good agreement between experimental data and theoretical models is attained when we change the barrier depth \(U_B\) or the temperature \(T\) (Fig. 2b).

The friction force is expected to be particularly sensitive to temperature when \(\tau_0 \lesssim a/v\), owing to exponential activation\(^2\), and almost independent of it when \(\tau_0 \gg a/v\). In Fig. 3, we verify experimentally\(^3,11\) that for low velocities \((\tau_0 \lesssim a/v)\) the friction force changes by an order of magnitude when we change the temperature by a factor of seven (Supplementary Information), whereas for high velocities \((\tau_0 \gtrsim a/v)\) the force varies by less than a factor of two. This confirms that an effectively zero-temperature stick–slip regime\(^2\) can be experimentally accessed at high transport velocity \(v \gg a/\tau_0\).

To study the interplay between structural lubricity, arising from mismatch between the object and substrate corrugations, and thermolubricity, we place a second ion in the trap along the optical lattice direction (Fig. 1a,b). If the effective spring force arising from the Coulomb interaction between the ions were infinitely stiff, the friction force on the two-atom system could be made to vanish by placing the two ions at positions where they experience opposite lattice forces. It is the essence of structural lubricity that a substantial friction reduction persists even for finite ion–ion interaction that is comparable to the substrate corrugation. When the ions experience opposite lattice forces, it is energetically favourable for them to pass the energy barrier between wells one at a time, as illustrated by the two-dimensional energy landscapes of Fig. 4d,e. This results in a reduced barrier depth \(U_B \ll \bar{U}_B\) and therefore a reduced friction force. Using the electrical trap, the spacing \(d\) between the ions can be tuned to be an exact multiple of \(a\) (that is, \(d \mod a = 0\)), or to be mismatched (that is, \(d \mod a = a/2\)). We have found in our previous work that mismatch greatly reduces the friction force\(^3\), as has been also observed for graphite flakes on a graphite substrate under certain orientations.\(^8\)
Figure 4 | Structural and thermal lubricity of two atoms. a–c. Velocity dependence of the friction force for two ions, for $\eta = 4.6$. a. In the matched case (red circles), where the ion spacing is an integer multiple of the lattice parameter $a$, for $k_B T / U_0 = 0.055(10)$ the data agree with one ion at approximately the same temperature (blue squares), and reach a maximal value near $F/F_{\text{mismatched}} = 4.6$. Langevin simulations (solid lines) are in good agreement with data for $\eta = 4.6$, $k_B T / U_0 = 0.05$. b. In the mismatched case (red diamonds) for a temperature of $k_B T / U_0 = 0.15(2)$, the maximal friction is $\sim 0.7F_{\text{mismatched}}$. By comparison, the friction for the mismatched case (green circles), where the two ions at their unperturbed position experience opposite forces by the optical lattice, at the same temperature of $k_B T / U_0 = 0.15(2)$, reaches a maximum of $\sim 0.15F_{\text{mismatched}}$. Finite-temperature Langevin simulations (solid lines) are in good agreement with data for $\eta = 4.6$, $k_B T / U_0 = 0.15$. c. The ratio of friction forces in the matched and mismatched cases (black circles, 3-point running average) is unity in the low-velocity thermal drift regime, and constant in the high-velocity friction plateau regime, where its value $\sim 4.8$ is mostly due to structural lubricity, in good agreement with Langevin simulations (solid gold line). Although barely visible in the data, the peak in the simulations is due to structurally induced thermolubricity; a window of velocities for which the structural friction reduction is enhanced by thermal activation over a reduced energy barrier $U_0$. d,e. Energy potential landscape for two interacting atoms. In the mismatched case (e), the energy barrier $U_0$ between the wells is reduced by a factor of $\sim 3.7$ and the ions pass the barrier one at a time (inset), compared to the matched case $U_0$ (d) where the ions pass the barrier simultaneously (inset). At fixed $T$ for a single ion in the friction plateau regime, this barrier reduction $U_0/\Delta U_0$ would lead to a thermal friction reduction of $\sim 1.4$, as can be inferred from the green data in Fig. 3. The expected total reduction of $3.7 \times 1.4 = 5.2$ is in good agreement with the observed reduction of $\sim 4.8$. Error bars are statistical and represent one standard deviation.

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Author contributions
D.G., A.B. and V.V. designed the experiments. D.G., A.B. and I.C. collected and analysed data. All authors discussed the results and contributed to the manuscript preparation.

Additional information
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Competing financial interests
The authors declare no competing financial interests.