

Experimental study of Mpemba effect in an energy Langevin system

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We experimentally investigate the Mpemba effect, where a hot system cools faster than a colder one when quenched to the same low temperature, within a programmable energy Langevin system using optically levitated nanoparticles in vacuum. By constructing an asymmetric double-well energy effective potential, we systematically compare the relaxation dynamics of systems initialized at different temperatures and quenched to a cold equilibrium state. Energy trajectory analysis reveals fundamentally distinct cooling pathways: The hot state achieves rapid equilibration through barrier-free relaxation, while the warm state exhibits prolonged dynamics due to metastable trapping in local potential minima. Quantitative measurements of population redistribution show nonmonotonic cooling timescales governed by initial state-dependent barrier crossing probabilities. Further modulation of the potential confirms the exponential scaling of equilibration time with the well barrier height, in agreement with Kramers's theory. This work establishes optical levitation as a powerful platform for investigating energy dynamics in nonequilibrium thermodynamics, providing a pathway for energy thermodynamic engineering applications, including microscopic heat engine and biomolecular structural transition simulations.

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Introduction. The Mpemba effect describes a counterintuitive phenomenon where an initially hotter system equilibrates faster than an initially colder one when both are quenched to a temperature lower than either of them. This analogous cooling was first observed in the freezing of water 2300 years ago [1], but it was not until the 1960s that the first systematic study was conducted by Mpemba [2]. Beyond water, the Mpemba effect has also been observed in various systems, including magnetic systems [3], polylactides [4], clathrate hydrates [5], colloidal systems [6–8], and quantum systems [9–11]. There are also theoretical predictions in other systems [12–26]. Regarding the mechanism behind the Mpemba effect, several theoretical studies suggest that, in Markovian dynamical systems, the effect arises from different relaxation paths at different temperatures [6,27,28]. Many relevant theoretical studies discuss the influence of factors such as the shape of the potential [29–31], active colloids [32,33], boundary coupling [22], and time-delayed effects [34] on the Mpemba effect in Langevin systems.

However, there are still very few experimental studies investigating the mechanism behind the Mpemba effect, and the existing ones are realized through optical tweezers in liquid

[6]. As an evolved version of optical tweezers, vacuum-based optical levitation systems have been successfully employed for investigating microscopic thermodynamics [35], including but not limited to relaxation of nonequilibrium steady state [36], Kramers turnover [37], Kovacs memory effects [38], and generalized second law of thermodynamics [39]. Optical levitation systems exhibit tunable environment interactions spanning from overdamped to underdamped regimes [37]. These platforms provide comprehensive energy manipulation capabilities, including cooling [40,41], resonant driving [42], phonon laser [43,44], and even the construction of arbitrary nonequilibrium steady states [45].

In previous experimental frameworks, the system's states were expanded based on the spatial states of the research object. However, certain systems, such as energy-level systems [46] and phase transition systems [47], cannot or are inconveniently characterized by states formulated from spatial coordinates [48]. Results derived from spatial configurations may not align with actual conditions. Similar to how the Langevin equation models the motion dynamics of microscopic particles in a thermal environment, energy dynamics under a heat bath can also be described as a Langevin system [36]. By precisely controlling energy flow, arbitrary effective energy potential can be engineered [45].

Here, leveraging the capability of optical levitation platforms to engineer energy structures, we experimentally investigate the Mpemba effect in an asymmetric double-well energy potential within the energy landscape. After preparing the system in warm or hot states with different initial temperatures, we measure the cooling time, which is the time it takes for the system to reach thermal equilibrium, and the

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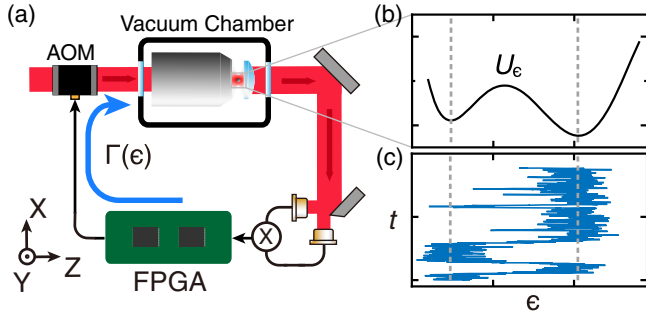


FIG. 1. (a) The schematic diagram of optical levitation in vacuum. A nanoparticle is optically trapped in a vacuum chamber. A feedback signal along the X-axis motion is generated through an FPGA to achieve modulation feedback control $\Gamma(\epsilon)$ via an acousto-optic modulator (AOM). (b) Schematic of the energy effective potential U_ϵ , which is achieved by $\Gamma(\epsilon)$. (c) The detected energy trajectory $\epsilon(t)$, when employed the double-well potential U_ϵ in panel (c).

population change due to net barrier crossing between the two wells. The experimental results demonstrate that when starting from the warm state with a lower temperature, some particles have to cross the barrier in the asymmetric double well, which takes more time to relax to equilibrium. In contrast, the system in the hot state follows a direct, quick relaxation path to equilibrium without well barrier crossing, hence exhibiting the Mpemba effect. Moreover, the barrier-crossing process is prolonged by a higher barrier, as verified by measuring the relationship between cooling time and barrier height.

Principles and experimental setup. The dynamical process of the energy square root ϵ can be described via a Langevin equation. By artificially introducing ϵ -dependent damping or antidamping mechanisms $\Gamma(\epsilon)$, an energy effective potential U_ϵ can be engineered. The equilibrium distribution of the system's energy square root ϵ within U_ϵ follows the Boltzmann distribution. To realize the experimental energy Langevin system, we constructed a vacuum optical levitation setup as illustrated in Fig. 1. A 1064 nm laser is focused by an objective (N.A. = 0.9) to trap a 165 nm diameter silica nanosphere in vacuum (10^{-2} mbar). The particle's position is monitored through the homodyne detection of forward-scattered light. The X-axis trajectory is processed through a field-programmable gate array (FPGA) to generate the ϵ -related parametric feedback control signal, which is used to apply $\Gamma(\epsilon)$ to establish effective potential U_ϵ to the particle. We construct the U_ϵ in the form of an asymmetric double well [6]:

$$U_\epsilon(\epsilon) = E_b \left[1 - 2 \left(\frac{\epsilon - \epsilon_{\text{mid}}}{\epsilon_m} \right)^2 + \left(\frac{\epsilon - \epsilon_{\text{mid}}}{\epsilon_m} \right)^4 \right] - \frac{1}{2} \Delta E \frac{\epsilon - \epsilon_{\text{mid}}}{\epsilon_m}, \quad (1)$$

where E_b is the barrier height and ΔE is the tilt in the potential. ϵ_{mid} is the center of the barrier and ϵ_m is the distance between the minima of the well and the barrier's center when $\Delta E = 0$. As the magnitude of the ΔE is insufficient to

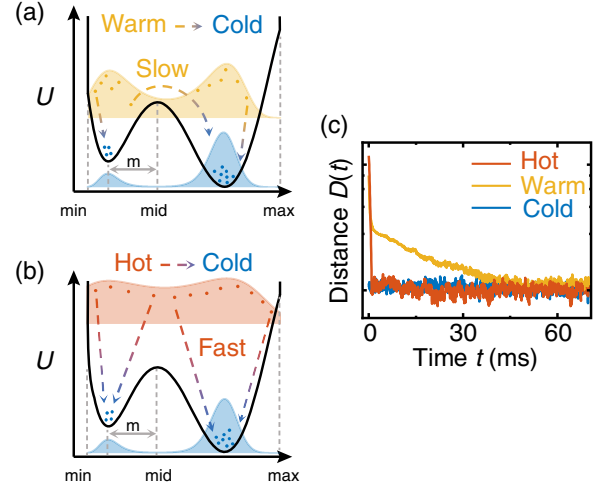


FIG. 2. (a), (b) The cooling process from the warm or hot state to the cold state. The schematic of the energy effective potential U_ϵ , shown by the black line, is a tilted double well. The temperatures of hot, warm, and cold states are $T_h > T_w > T_c$. The distribution of the three states adheres to the Boltzmann distribution, shown by orange, yellow, and blue shaded areas, respectively. The arrows indicate the relaxation paths, highlighting that the warm state requires a portion of the particles to cross the barrier, whereas the hot state does not. (c) The cooling process in energy effective potential U_ϵ is characterized by the “distance” of distribution $D(t)$. The initial temperatures of hot, warm, and cool states are $500T_c$, $10T_c$, and T_c , respectively. The hot state reaches equilibrium faster than the warm state, illustrating the existence of the Mpemba effect.

conspicuously alter the position of the well's minimum in our experiment, the positions of the two wells are approximately $\epsilon_{\text{mid}} - \epsilon_m$ and $\epsilon_{\text{mid}} + \epsilon_m$. The landscape of U_ϵ and a related fragment of $\epsilon(t)$ are shown in Figs. 1(b) and 1(c). The hot and warm states are prepared through potential modulation (see the Supplemental Material for details on U_ϵ and thermal state construction [49]).

Figure 2 illustrates the Mpemba effect in the energy Langevin system. Typically, for an equilibrium system at a given temperature, its probability distribution follows the Boltzmann distribution. Figures 2(a) and 2(b) depict the potential landscape of the system along with the equilibrium distributions of the warm, hot, and cold states. We can describe the system's cooling process in the double well U_ϵ using the cooling-time-varying probability distribution $P_\epsilon(t)$. To determine which state cools more rapidly, we measure the “distance” $D(t) = \int |P_\epsilon(t) - P_{\epsilon,\text{eq}}| d\epsilon$ [6] between the probability distribution at certain time t and that of the equilibrium state $P_{\epsilon,\text{eq}}$. Figure 2(c) presents $D(t)$ at different initial states. Throughout the cooling process, the initial hot state approaches the cold state more quickly than the warm state, confirming the presence of the Mpemba effect.

Many researchers have proposed that the mechanism of the Mpemba effect in the Langevin system is the different relaxation paths of warm and hot states [6,27,29–31]. For systems where the potential is an asymmetric double well, the cooling process can be divided into two stages: fast flow into the local well to reach the local equilibrium and slow barrier crossing under fluctuation to reach the global equilibrium, as illustrated

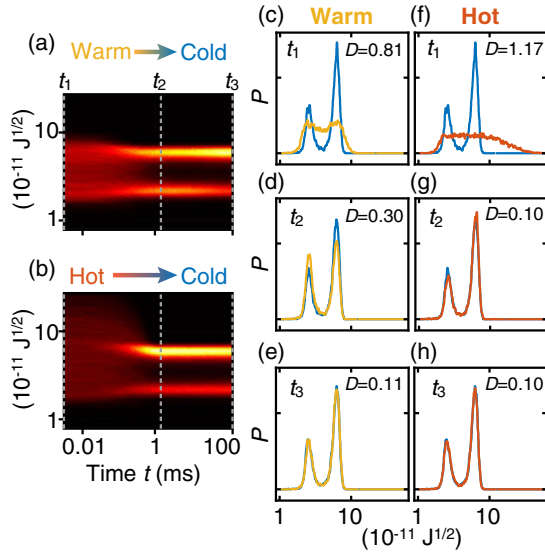


FIG. 3. Dynamics of system relaxation to equilibrium with different initial temperatures. (a), (b) Relaxation from equilibrium distributions at (a) warm and (b) hot states. (c)–(h) The distribution of ϵ at different times: $t_1 = 0$ ms, $t_2 = 1.3$ ms, and $t_3 = 100$ ms. The left column starts from warm state. The right column starts from hot state. The hot, warm, and cold states correspond to initial temperatures of $500T_c$, $10T_c$, T_c , respectively.

in Figs. 2(a) and 2(b). For the warm state at a low temperature, the relaxation path is rapid flow into the separated local well and then barrier leap, which takes more time. However, for the initial hot state at a high temperature, the population on either side of the barrier already aligns with the cool state's global equilibrium, eliminating the need for barrier crossing. Consequently, the hot state cools faster than the warm state, and the Mpemba effect exists. The initial rapid decline and the subsequent gradual decrease of $D(t)$, beginning with the warm state, correspond to the rapid transition into the local well and the subsequent barrier crossing, respectively, as shown in Fig. 2(c).

Dynamics of energy relaxation. The energy relaxation processes of different initial states are depicted in Fig. 3. Figures 3(a) and 3(b) show the probability distribution of ϵ , denoted by P_ϵ , during the cooling process for different initial states. The initial temperatures of the warm and hot states are $T_w = 10T_c$ and $T_h = 500T_c$, respectively, where T_c is the temperature of the cold state, equal to the ambient temperature. The distribution is obtained through 10^4 trajectories of $\epsilon(t)$. The dynamics of P_ϵ indicate that both the warm and hot states rapidly reached the local equilibrium. We plot the distributions of different initial states at times $t_1 = 0$ ms, $t_2 = 1.3$ ms, and $t_3 = 100$ ms, which are shown in Figs. 3(c)–3(h). At the initial moment $t_1 = 0$ ms, the distributions of the warm and hot states follow a Boltzmann distribution. The warm state is more evenly distributed between the two wells, while the hot state is concentrated at much higher values of ϵ , which makes the distribution of the warm state closer to the final equilibrium, and the distance D is smaller than that of the hot state. At $t_2 = 1.3$ ms, when the distributions of both states have concentrated at the local well, the distribution of the warm state still does not reach the global equilibrium,

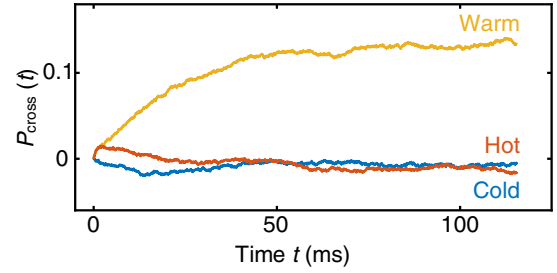


FIG. 4. The change in the right well's population due to net barrier crossing from the left well to the right well. Lines are shown for different initial states: hot (orange), warm (yellow), and cold (blue). The hot, warm, and cold states correspond to initial temperatures of $500T_c$, $10T_c$, and T_c , respectively.

whereas the hot state has already reached it. At $t_3 = 100$ ms, both states reach the equilibrium distribution, as shown in Figs. 3(e) and 3(h). The changes in the probability distribution of ϵ are consistent with the theoretical description of the cooling process [6,27,29–31]. Exploring the relationship between cooling time and barrier crossing is crucial. We measure the population change of ϵ due to net barrier crossing from the left to the right well as $P_{\text{cross}}(t) = P_{\epsilon,r}(t) - P_{\epsilon,r}(0)$ at initial warm, hot, and cold states, where $P_{\epsilon,r}$ is the sum of the population on the right side of the barrier: $P_{\epsilon,r}(t) = \int_{\epsilon_{\text{mid}}}^{\infty} P_\epsilon(t) d\epsilon$. If ϵ crosses from the right well to the left, $P_{\text{cross}}(t)$ decreases. This reflects the population of barrier crossing from the metastable state to the global equilibrium. The results are shown in Fig. 4. For the initial warm state, $P_{\epsilon,r}$ increases over time, and the value at equilibrium is much higher than those of the hot and cold states. In contrast, for the initial hot state, the population on either side of the barrier is much closer to the cold state, due to the wider distribution of ϵ at much higher values. Thus, there is less net barrier crossing and $P_{\text{cross}}(t)$ generally remains unchanged. According to Kramers's theory [50], the time for barrier crossing is much longer. This experimental result is consistent with the theory that the cooling time primarily depends on the time of barrier crossing.

The cooling time in energy Langevin system depends on the initial temperature; however, the relation between them is nonmonotonic. It is defined as the time when “distance” $D(t)$ decays within the noise level [6]. The dynamic of $D(t)$ for different initial temperatures is plotted in Figs. 5(a)–5(d). The cooling time at different initial temperatures is shown in Fig. 5(e). As the initial temperature increases, the cooling time t_{eq} first increases and then decreases. When the initial temperature exceeds $500T_c$, the cooling time increases again. This is because when the temperature exceeds $500T_c$ the net barrier crossing from the right well to the left increases as the temperature rises. Figure 5(f) shows the population change due to barrier crossing at equilibrium $|P_{\text{cross}}(t_{\text{eq}})| = |P_{\epsilon,r}(t_{\text{eq}}) - P_{\epsilon,r}(0)|$, for different initial temperatures. The trend of the curve matches that of the cooling time, indicating that the cooling time is related to the population of barrier crossing.

Moreover, the barrier height influences the cooling time in energy Langevin system. Utilizing the modulation capability of energy effective potential, we adjust the height (E_b) of the barrier between the two wells, as shown in Fig. 6(a). The cooling times from the initial warm states for different barrier

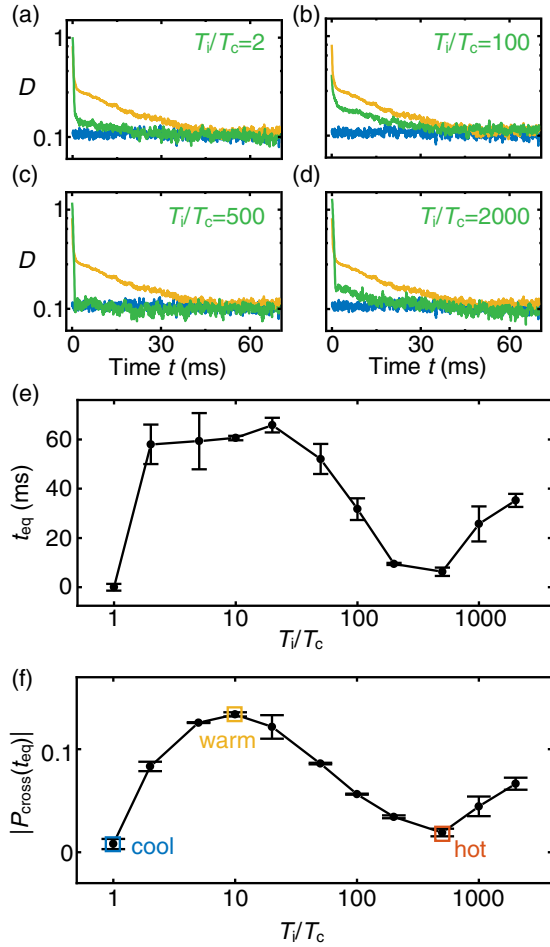


FIG. 5. (a)–(d) $D(t)$ at different initial temperatures $T_i = 2T_c$, $100T_c$, $500T_c$, and $2000T_c$ (green curve). For comparison, $D(t)$ at initial temperature $T_i = T_c$, $10T_c$ is shown as blue and yellow curves. At higher initial temperatures, the system cools faster than at a lower initial temperature ($T_i = 10T_c$). (e) Cooling time for different initial temperatures, with error bar indicating the statistical error. In each measurement, the relaxation process is repeated 10^4 times. (f) The probability of barrier crossing after reaching equilibrium, $|P_{cross}(t_{eq})|$, for different initial temperatures.

heights are presented in Fig. 6(b) as square blocks. The initial warm temperature is $10T_c$. As the barrier height increases, the cooling time t_{eq} of warm state also rises. According to Kramers's theory [37], the time for barrier crossing is proportional to $E_b^{-1/2} e^{-E_b/k_B T}$. The theoretical line fits the measured cooling time well, as shown in Fig. 6(b). Also, we measure the cooling times of the initial optimum hot state, which are shown as triangle symbols in Fig. 6(b). The temperatures of the optimum hot state are set to keep the population at the right well close to the cold state: $P_r(0) = P_r(\infty)$. Compared with the warm state, the cooling times of the hot state are almost unaffected by the barrier height. Thus, the greater the barrier height E_b , the more apparent the Mpemba effect becomes.

Conclusion. We have demonstrated a Langevin system based on the energy effective potential using the vacuum optical levitation system. In this framework, the spatial states of the system are neglected, and the fluctuation of energy under the influence of stochastic processes is used as the

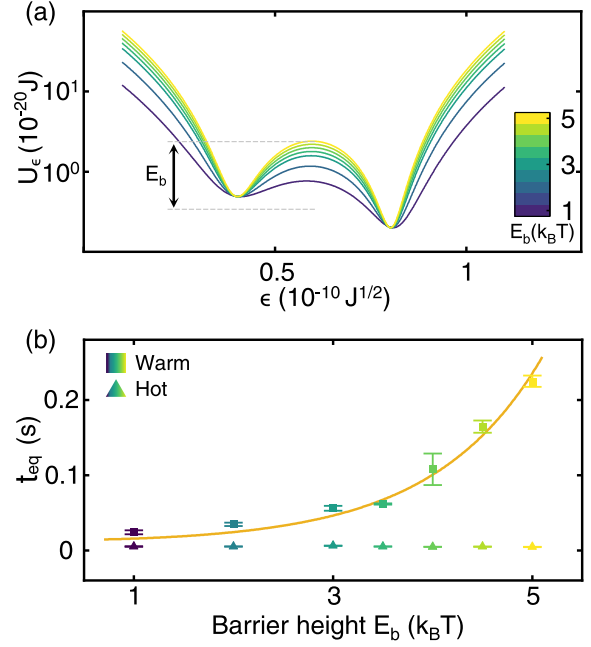


FIG. 6. Equilibration times with varying barrier heights. (a) The effective potential of energy U_ϵ near the barrier at different barrier heights E_b . (b) The equilibration time for different barrier heights E_b when the initial state is the cold state (square marks) and the optimum hot state (triangle symbols). The error bars indicate the statistical error. The solid line represents the fitting curve. In each measurement, the relaxation process is repeated 10^4 times.

basis for thermodynamic research. Based on this, we have experimentally investigated the underlying mechanisms that give rise to the Mpemba effect. We studied the influence of initial temperature, barrier crossing, and barrier height on the Mpemba effect. The experimental results support the theory that the Mpemba effect in Langevin systems arises from different relaxation paths, where the slow path, dominated by barrier crossing, governs the cooling time.

The energy Langevin system can be used to study stochastic thermodynamic processes that do not primarily rely on Brownian motion, such as energy level transitions, phase transitions, and molecular structural changes. From the perspectives of energy fluctuations, pumping, and dissipation, this framework could provide insights into novel thermodynamic phenomena, including the Mpemba effect, the role of potential barriers in supercooled water, the Kovacs memory effect, and asymmetries between heating and cooling [51,52]. Additionally, energy thermodynamic engineering could help improve the efficiency of microscopic heat engines, simulate biomolecular conformational transitions, and enable precise control over thermodynamic pathways, among other applications.

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Data availability. The data that support the findings of this Letter are not publicly available. The data are available from the authors upon reasonable request.

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