Electric-field noise from thermally-activated fluctuators in a surface ion trap

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We probe electric-field noise near the surface of an ion trap chip in a previously unexplored high-temperature regime. A saturation of the noise amplitude occurs around 500 K, which, together with a small change in the frequency scaling, points to thermally activated two-state fluctuators as the origin of the noise. The data can be explained by considering noise from fluctuators with a broad distribution of activation energies around 0.5 eV. These energies suggest defect motion as a relevant microscopic mechanism, likely taking place at the metal trap surface. Our results show that high-temperature studies of surface noise are a key to identifying the origin of “anomalous heating” - a major source of ion motional decoherence in surface traps that limits their performance as quantum devices.

Electric field noise is a major limiting factor in the performance of ion traps and other quantum devices [1, 2]. Despite intensive research over the past decade, the nature and cause of electric field noise near surfaces is not very well understood. Progress in this field has wide-ranging applications for precision measurements close to surfaces. For instance, the effect of patch potentials has to be taken into account for Casimir force measurements between surfaces [3] and research efforts are directed at reducing those effects [4]. Patch potentials further limit the sensitivity of gravitational experiments using test masses, such as the LISA pathfinder mission [5, 6]. Electric field noise from surfaces is detrimental to the performance of solid-state quantum bits in diamond [7, 8]. For ions in surface electrode traps, electric field noise manifests as decoherence of the motional modes, which are generally relied on to entangle ions in the same trapping potential. It is one of the main obstacles to realizing a large-scale ion trap quantum processor [9]. A better understanding is not only important for the fabrication of low-noise quantum devices, but may also answer fundamental questions about the physics of noise at surfaces, such as the effect of adsorbates or defects and their dynamics.

Experiments with ions in surface traps have explored the scaling of noise with frequency, distance to the surface, and temperature of the surface using the heating of motional modes as a sensitive probe of electric field fluctuations [10–17]. Research has also focused on the influence of trap characteristics such as the trap material and surface treatments [16, 18–20]. The results of these studies have varied widely and, with few exceptions, inconsistently between individual surface traps. Several models have been proposed to explain the electric field noise and shed light onto physical noise mechanisms [10, 21–27], but the wide range of measurements has made confirming or rejecting specific models challenging.

Among the parameters accessible in trapped ion experiments, temperature may be most revealing with respect to the physical causes of electric field noise. Considering the dependence on ion-surface distance $d$ one finds the same $d^{-4}$ scaling for uncorrelated microscopic noise sources, regardless of their physical origin [21–24]. With regard to the frequency dependence, while measurements have shown a wide spread between individual traps, they cluster around a $1/f$ scaling that is common to many noise phenomena [2]. Predictions for the temperature dependence, on the other hand, vary strongly according to the specific model and its parameters. This sensitivity to underlying noise mechanisms makes temperature a particularly interesting variable to study in surface ion traps.

Previous measurements of the temperature scaling of surface trap electric field noise were taken below room temperature in cryogenic trapping systems [14, 16, 17]. In these experiments, the temperature dependence follows a power-law scaling where the scaling exponent varies between 1.5 and 4. Below 70 K, some measurements show a low-temperature plateau of the noise [14, 17] while in another case the power law exponent decreases [16]. To our knowledge, measurements for which a single model explains the scaling of noise as a function of both temperature and frequency have not been reported so far.

Here we present the temperature dependence of electric field noise in a surface trap for temperatures significantly above room temperature (295 - 530 K). Instead of the previously observed power-law scaling at lower temperatures we find electric field noise to saturate at high temperatures. This behavior can be explained by considering an ensemble of thermally activated fluctuators (TAFs) with a broad range of activation energies that peak around 0.5 eV. The TAF model also predicts a small change in the frequency dependence over the explored temperature range which we confirm experimentally. Our results are not explained by other models such as simple adatom diffusion [2, 26], adatom dipoles as proposed by Safavi-Naini [24, 25] or dielectric noise as discussed by Kumph [27].

In our experiment, we employ single $^{40}$Ca$^+$ ions in a linear surface trap as electric field noise sensors. Relevant parts of the experimental setup, the trap geometry
and structural information on the electrode metal surface are depicted in Fig. 1. The trap chip is clamped onto a resistive heater compatible with ultra-high vacuum operation (see Fig. 1 (a) for an exploded view). The ion trap was fabricated by laser-etching trenches of 100-μm depth and 20-μm width into a fused silica substrate to define the electrode geometry (Translume, Ann Arbor, Michigan) and evaporating layers of 20 nm titanium (Ti), 1 μm aluminum (Al), and 40 nm copper (Cu) on top. A grey-scale optical micrograph of the central area of the trap chip is shown in Fig. 1 (b). Individual $^{40}$Ca$^+$ ions are trapped 72 μm above the surface along the central trap electrode. In this manuscript we report on measurements from three locations along the trapping axis, as indicated by the labels. Prior to the measurements reported here the trap chip went through several cycles of exposure to atmospheric conditions and week-long bakes in the vacuum chamber at 160 °C. Figure 1 (c) displays a scanning electron microscope (SEM) image of a similarly fabricated trap, revealing a fine-grained structure.

Electric field noise is measured by probing the ion motional heating rate. The spectral density of the electric field noise $S$ is related to the heating rate $\dot{n}$ of a motional mode by

$$S(\omega, T) = \frac{4m\hbar\omega}{q^2} \dot{n}(\omega, T),$$

where $m$ and $q$ are the mass and the charge of the ion, respectively, $\omega$ is the motional mode frequency and $\hbar$ the reduced Planck constant. In this study, heating rates are determined by Doppler cooling the ion and measuring its temperature $\dot{n}(t_{\text{wait}})$ after a variable wait time $t_{\text{wait}}$ in the dark [28]. We use the decay of carrier Rabi flops to obtain $\dot{n}(t)$ for the axial mode which is parallel to the surface and the central electrode in Fig. 1 (b). The effect of the radial modes on the measurement can be neglected here as they are nearly orthogonal to the measurement laser and at significantly higher frequencies (around $2\pi \times 5$ MHz) than the axial mode.

First, we describe measurements of the temperature dependence of $S(\omega, T)$. The secular axial frequency is set to $\omega = 2\pi \times 1$ MHz here. The trap temperature is measured with a thermal imaging camera positioned outside the vacuum chamber, allowing us to determine the difference to room temperature with a systematic uncertainty of ±10% as the trap is heated. We are able to trap ions and measure heating rates from room temperature up to about 530 K. Short ion lifetimes, attributed to local out-gassing around the heater and the trap, prevent us from measuring at higher temperatures. Data from the three trapping locations are displayed in Fig. 2 (a)-(c). The initial increase in heating rates between 300 and 400 K can be described by a power law $S(2\pi \times 1$ MHz, $T) \propto T^{1.7(0.3)}$, matching the dependence observed in some previous studies at lower temperature [14, 17]. Above 400 K the heating rates start to level off at all three trapping locations, overall roughly doubling between room temperature and 500 K.

The breakdown of the power-law scaling at high temperatures is a non-trivial and somewhat unexpected result. We find that of the proposed theories for electric field noise, only thermally activated fluctuators can produce such a behaviour and we will discuss our results in this context. Applying the formalism developed by Dutta, Dimon and Horn [29] for $1/f$-noise in metal films we can associate the electric field noise temperature dependence with energies of a TAF distribution.

A TAF describes a charged particle moving between two metastable states separated by an energy barrier $E_a$, see Fig. 3 (a) [30]. Hopping between the sites gives rise to random telegraph electric field noise. We assume here that $E_a \gg k_B T$, where $k_B$ is the Boltzmann constant, and, for simplicity, that the two sites are at the same energy. The characteristic transition rate for a single TAF is then given by

$$\Gamma = \frac{1}{\tau_0} e^{-E_a/k_B T},$$

where the hopping attempt time $\tau_0$ can be approximated to be the oscillation period of an atom in a solid-state lattice, which is of order $10^{-13}$ seconds [30]. The power spectrum of such a process is described by a Lorentzian centered at zero frequency, with a corner frequency $\Gamma$.

A trapped ion is sensitive to the component of the noise spectrum at its secular frequency $\omega$. Figure 3 (b) illustrates how the noise spectrum for a single TAF evolves

![FIG. 1. (a) An exploded image of the heater and trap set-up. The trap is clamped at two corners onto the cylindrical button heater and wire-bonded to the chip carrier below. (b) Grey-scale optical microscope image of the trap electrodes with numbers indicating the three trapping locations. The electrodes are made of an Al-Cu alloy. (c) Scanning electron microscope image of the trap electrodes showing sub-micron structure.](image-url)
FIG. 2. (a)-(c) Heating rates of the axial mode at a frequency of \( \omega = 2\pi \times 1 \text{ MHz} \) as a function of trap temperature for the three trapping locations labeled in Fig. 1 (b). Data are shown as closed symbols and smoothing of the data gives the continuous curves. (d)-(f) Density of thermally activated fluctuators (TAF) with respect to their activation energy for each trapping location according to eq. (3). Data points are derived from the heating rate data in (a)-(c), and the continuous curve is from the smoothed data. Error bars represent one s.d. uncertainty.

with temperature, here using \( E_a = 0.4 \text{ eV} \) for concreteness. When tracking the noise power for a single TAF at a fixed frequency \( \omega \), the noise amplitude peaks at the temperature where \( \Gamma = \omega \) and falls as the TAF fluctuates faster at higher temperatures (see inset).

Next, we consider the case where many TAFs with varying activation energies contribute to the noise. Figure 3 (c) illustrates the noise power spectra for four independent TAFs, again at a fixed frequency of \( 2\pi \times 1 \text{ MHz} \) (continuous curves), and the resulting combined spectrum (dashed curve). At higher temperatures, fluctuators with higher energy barriers contribute to the noise.

For a continuous distribution of fluctuator activation energies \( D(E_a) \) that varies slowly compared to \( k_B T \) we can make the approximation [29]

\[
S(\omega, T) \propto \frac{k_B T}{\omega} D(\bar{E}),
\]

directly linking the noise spectrum to the fluctuator distribution. Here, \( \bar{E} \) represents the activation energy when \( \Gamma = \omega \) for a given \( T \).

Using Eq. (3) we calculate the shape of \( D(\bar{E}) \) directly from the measured \( S(\omega, T) \). The results are shown in Fig. 2 (d)-(f). The temperature range of our heating rate measurements gives access to fluctuators with activation energies in the range of 0.35-0.65 eV. The distributions for all locations evolve fairly gently in this range, and all three show a peak around 0.5-0.6 eV. We note that the TAF distribution function given by Eq. (3) is not unique, that is, other distribution functions can produce the same temperature dependence of \( S(\omega, T) \). In particular, \( D(E_a) \) may have sharper features than those we obtain in Fig. 2 (d)-(f).

Before discussing the distribution of activation energies in the context of physical processes, we will now present another aspect to the TAF model: equation (3) gives a frequency dependence \( S(\omega, T) \propto 1/\omega^{\alpha=1} \) only when \( D(\bar{E}) \) is constant. For a non-uniform distribution function, as is obtained in Fig. 2, the exponent \( \alpha \) is both frequency and temperature-dependent. The frequency scaling exponent is then given by [29]:

\[
\alpha(\omega, T) = 1 - \frac{1}{\ln \omega T_0} \left( \frac{\partial \ln S}{\partial \ln T} - 1 \right).
\]

We compute \( \alpha(2\pi \times 1 \text{ MHz}, T) \) from the smoothed temperature-dependent heating rates in Fig. 2 (a)-(c) (solid curves) and display the results in Fig. 4 (solid curves). We employ local regression smoothing with a span of about 0.8, which allows us to extract the global change in \( \alpha \) over the temperature range of our measure-
ments at the expense of knowledge about its local temperature dependence. For all three locations α is predicted to be slightly above one at room temperature, and to drop to just below one at high temperatures.

To test this prediction, we measure the noise frequency scaling at room temperature and at about 480 K. We confirm that the frequency dependence of heating rates in the range of about 0.6 MHz to 1.2 MHz follows a power law scaling and obtain a precise estimate of α by measuring 10-20 heating rates for each trapping location at low and high temperatures, and low and high trap frequencies. The frequency scaling exponents α from the weighted average heating rates are shown as solid points in Fig. 4. We observe a statistically significant decrease in α across the three measurement locations when the trap temperature is raised. This trend is consistent with the predictions from Eq. (4) implying that both our temperature and frequency-dependent data can be described by the same model. The small offset between the prediction and the measurement may be due to features in S(T) which are not well resolved in our heating rate measurements. We also note that the approximation Eq. (3) relies on a smooth change in \( D(E_a) \) and is less accurate at the limits of our temperature range where the gradient is not well defined.

Having discussed our data in the framework of thermally activated two-state fluctuators, it is important to compare the results to other proposed models for electric field noise in surface ion traps. In this context, recent theoretical work has treated noise arising from fluctuating adatom dipoles on gold surfaces [24, 25], adatom diffusion (carbon atoms on gold) [26], and the effect of a lossy dielectric layer at the surface [27]. Within their framework, and the somewhat idealized conditions, such as atomically clean surfaces for diffusion [26], or a temperature-independent loss tangent [27], these models predict temperature and frequency dependences of the spectral noise density that are qualitatively different from our observations. In particular, a saturation of noise at higher temperatures is not featured in these models.

To understand the origin of electric field noise in our trap, it is desirable to identify an underlying physical process which matches the TAF description. The link between the abstract TAF model and a physical process is provided by the distribution of activation energies. Looking beyond models developed to explain electric field noise in ion traps we can compare our results to other systems described by the TAF model.

The TAF model was very successful in explaining \( 1/f \)-resistance fluctuations in metal films. Metal film resistance noise originates from thermally activated defect migration around grain boundaries [30–32], and measured activation energies peak in the 0.5–1 eV range, depending on the micro-structure and the metal in question [33, 34]. Defects in aluminum are typically lower in energy than defects in other common metals, such as gold or silver [35] and we find intriguing similarities in the distribution of activation energies from our data in Fig. 2 and corresponding data from resistance fluctuation measurements for polycrystalline aluminum films [36, 37].

These similarities suggest a link between the microscopic mechanisms of resistance and electric field surface noise. We have to consider that resistance noise in metal films is due to defects in the bulk, however, while electric field noise in ion traps is dominated by surface processes [18–20]. This difference comes down to the measurement process: defect motion takes place everywhere across the
metal film, but resistance noise, measured by passing a current through the film, is not very sensitive to the dynamics at the surface. We expect a high defect density at the metal surface, and a trapped ion above the surface is sensitive to their dynamics. For our trap in particular, the metal-oxide interface on the surface of the Al-Cu electrodes provides a layer where energy barriers to atomic motion are lowered. The thermally driven rearrangement of metallic ions at and across this interface can cause electric field fluctuations compatible with the temperature and frequency properties we observe.

In a wider context, TAF distribution functions of varying amplitudes and activation energies could account for some of the large variations of heating rates found in surface traps of different material and microstructure. However, while the TAF model can fully describe the noise measurements in our system, other models may be necessary to explain the noise found in some other surface traps. For instance, the TAF model does not consider spatial information, or correlations between individual noise sources. It is likely that these effects play some role and differences in the microstructure or operation at a different temperature could have a large impact on noise characteristics. At cryogenic temperatures, for example, quantum tunneling provides an additional mechanism for switching between the states of a two-level system [38] and noise from these processes in known to cause decoherence in solid-state quantum systems, such as superconducting circuits [1].

If we consider defects at the metal surface as source of electric field noise, it is interesting to think of treatments that can create or annihilate defects, or change their energy, thereby changing the electric field noise spectrum. Annealing is a straightforward way to reduce defects in metals [37, 39, 40] and some evidence has been reported already for the effectiveness of noise reduction in ion traps by annealing electrodes [14]. Ion milling removes surface layers, leaving an ordered metallic surface behind [26], which should strongly modify the surface defect density and the distribution of activation energies. We note that while ion milling has been very successful at reducing noise in room-temperature traps so far, the physical milling process introduces new surface defects with different activation energies that could increase noise at other temperatures [41, 42]. Combining surface treatments with measurements of the noise temperature dependence will likely reveal further insight into the underlying physical noise mechanism.

In conclusion, we have presented electric field noise measurements in a surface ion trap in the temperature range of 295-530 K. Both the temperature and frequency-dependence of the noise can be described by the same distribution of TAF with activation energies around 0.5 eV. The activation energies we observe are in the range associated with defect motion in the solid state. The simple TAF model does not take spatial information or correlations between noise sources into account, but it provides a useful framework to classify average noise properties. Understanding the influence of electrode materials and surface structure, such as metal grain size, or the impact of surface treatments, such as ion milling and annealing, in the context of TAF may illuminate the microscopic origin of the noise and pave the way to low-noise surface ion traps.

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\[ \text{(1.15)} \]

\[ \text{Location 1} \]

\[ \text{Location 2} \]

\[ \text{Location 3} \]

**FIG. 4.** Frequency exponent $\alpha$ as function of temperature. Data points represent frequency scaling at each trapping location. Continuous curves give the predicted frequency scaling from Eq. (4) and the smoothed temperature scaling data in Fig 2 (a)-(c).
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