100-Fold Reduction of Electric-Field Noise in an Ion Trap Cleaned with *In Situ* Argon-Ion-Beam Bombardment

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Motional heating of trapped atomic ions is a major obstacle to their use as quantum bits in a scalable quantum computer. The detailed physical origin of this heating is not well understood, but experimental evidence suggests that it is caused by electric-field noise emanating from the surface of the trap electrodes. In this study, we have investigated the role of adsorbates on the electrodes by identifying contaminant overlayers, implementing an *in situ* argon-ion-beam cleaning treatment, and measuring ion heating rates before and after treating the trap electrodes' surfaces. We find a 100-fold reduction in heating rate after treatment. The experiments described here are sensitive to low levels of electric-field noise in the MHz frequency range. Therefore, this approach could become a useful tool in surface science that complements established techniques.

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Trapped atomic ions can potentially be employed as quantum bits (qubits) in a scalable quantum computer, where deterministic entanglement and multiqubit logic gates require precise control of the ions' collective motion [1]. These operations incur errors caused by heating of the ions' motion from electric-field noise. The heating has inhibited progress in scalability, miniaturization, and logic gate fidelity. It is often referred to as ''anomalous'' because its exact origin is unknown. Operation at low temperature can substantially reduce the heating [2,3]; however, the detailed reasons for these improvements are not understood. Research groups have also addressed this problem by investigating different electrode materials and processing techniques, but there are wide variations in the observed heating for apparently identical traps, even at low temperature. Some experimental evidence suggests that electrode surface contaminants may play a role [2–7]. Recently, application of a pulsed laser beam to trap electrode surfaces resulted in a reduction in heating rate by approximately a factor of 2 [8]. In this Letter, we report a reduction in ion heating by 2 orders of magnitude, in a room-temperature surface-electrode ion trap [9] that has been subjected to an *in situ* cleaning treatment by argon-ion-beam bombardment. This suggests that anomalous heating can be significantly reduced or perhaps eliminated, without the need for, or in combination with, cryogenic cooling.

Ion heating is caused by electric-field noise at the location of the ion whose spectrum overlaps the frequency of the ions' motional modes (typically in the range of 100 kHz to 10 MHz). The physical origin of this noise has been debated for more than a decade. Johnson noise is one source, but, in many experiments, its contribution is estimated to be orders of magnitude smaller than the observed heating. If the noise is caused by independently fluctuating potential patches on the electrodes that are small compared to the ion-electrode distance d, the noise spectral density (proportional to the ion heating rate) is approximately proportional to d^{-4} [5]. These potential fluctuations may be due to adsorbate-dipole fluctuations [10,11] or adatom-diffusion-induced work-function fluctuations on the electrode surface [4,12]. Therefore, we have focused on removing contamination from the surface.

The trap electrodes were microfabricated with 5-μm gaps in a 10-μm-thick Au film, electroplated on a crystalline quartz substrate. The trap electrode layout, the same as in [13], is shown in Fig. 1. To clean the electrode surfaces, we applied *in situ* Ar^+ bombardment, a technique that is well established in surface science studies [14]. The integration of Ar^+-bombardment capabilities with the ion-trap

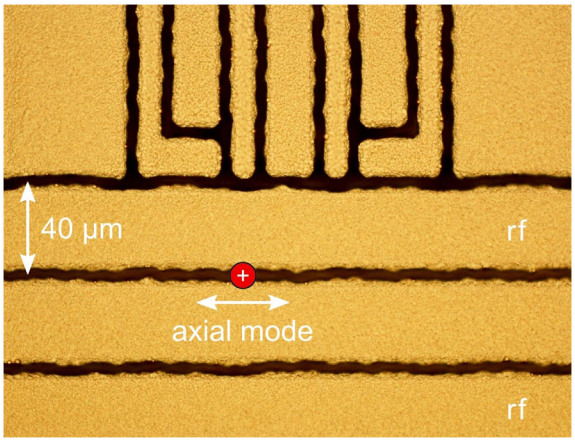

FIG. 1 (color online). Micrograph of ion-trap electrodes. The radio-frequency (rf) and static-potential electrodes are microfabricated using a 10-μm-thick, electroplated Au film with 5-μm gaps between the electrodes (darker areas). The red dot represents the location of the ion.

apparatus required accommodation for a hot-cathode backfill-type ion source and Ar gas-handling components (i.e., bakeable gas lines, valves, and turbomolecular pump), all of which must be compatible with ultrahigh vacuum. To determine the effects on electrode surfaces from this treatment, Ar^+ bombardment was also applied under near identical conditions on several duplicates of the ion-trap electrodes in a separate surface analysis system, equipped with Auger electron spectroscopy (AES). Both the trap and analysis chambers (containing the electrodes) were vacuum baked to 475 K, reaching a base pressure $<8 \times 10^{-9}$ Pa. As seen in Fig. 2 (top trace), after exposure to air and then vacuum baking, the duplicate electrode surfaces are covered with 2–3 monolayers (ML) of oxygen-free carbon contamination [15], most likely from hydrocarbon deposition from the gas phase (the presence of hydrogen is undetectable by AES). Because of the near-surface sensitivity of AES [16], the features characteristic of Au are small, indicating a contaminant overlayer (Fig. 2—top trace). After ion-beam application (Fig. 2—bottom trace), the absence of AES peaks not associated with Au indicates a surface free of these contaminants, to within the sensitivity of AES (~ 0.05 ML) [17].

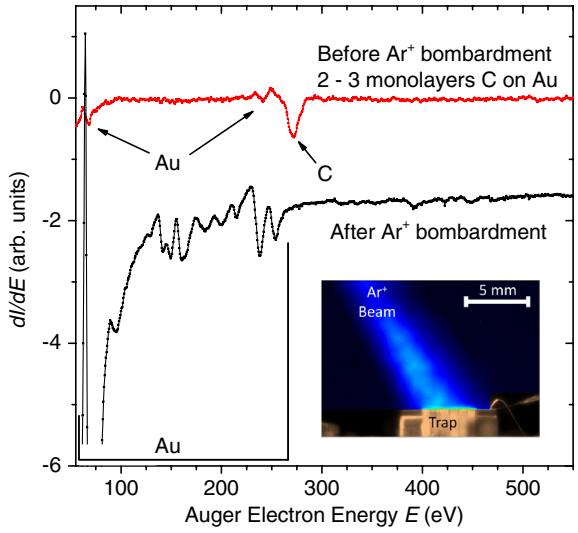

FIG. 2 (color online). Auger electron spectra of Au electrode surfaces. The vertical axis (same scale for both traces) displays the differential Auger electron intensity, dI/dE. Before Ar^+ bombardment, carbon is observed as the only significant contaminant, probably resulting from oxygen-free hydrocarbon contamination. Oxygen, if present, would be indicated by a feature near 515 eV. The spectrum after Ar^+ bombardment, offset downward by 1.7 units for clarity, shows only features that indicate a Au surface free of these contaminants. Typical Ar^+ cleaning conditions in the surface analysis system are 0.5–2 kV beam voltage and 100–300 C/m^2 over $\sim$45 minutes at 6×10^{-3} Pa Ar pressure. Inset: enhanced, false-color image of the Ar^+ beam (30° incidence from normal) in side view of the initial ion-trap apparatus, operated briefly at 3×10^{-2} Pa Ar pressure for imaging.

To determine the electric-field noise, a $^9Be^+$ ion was trapped 40 μm above the electrodes in the ion-trap chamber. After the ion was laser-cooled to near its motional ground state, heating rate measurements were made with the Raman-sideband technique [5] on a motional mode parallel to the trap surface (axial mode), which had a frequency $\omega/2\pi \sim 3.6$ MHz. The electric-field noise spectral density $S_E(\omega)$ and the heating rate in terms of rate of increase in motional quanta, $\dot{\bar{n}} \equiv d\bar{n}/dt$, are related by [5]

$$S_E(\omega) = \frac{4m\hbar\omega}{q^2}\dot{\bar{n}}, \tag{1}$$

where q is the charge of the ion, m is its mass, and $\hbar$ is Planck's constant divided by 2π. In an initial set of experiments, an Ar^+ beam, with 2 kV and $\sim$400 C/m^2 integrated ion-flux density estimated for the central portion of the beam, was directed towards the trap chip and applied for 45 minutes at 5×10^{-3} Pa Ar pressure. However, subsequent to these initial experiments, the Ar^+ beam was determined to be somewhat misaligned, precluding a precise statement of the ion-flux density at the trap center. Nevertheless, this treatment yielded a reduction in heating rate from 7020 ± 140 quanta/s to 58 ± 2 quanta/s. The heating rate measurements are shown in Fig. 3. An additional treatment (2 kV, $\sim$600 C/m^2, 45 min, 5×10^{-3} Pa Ar) further reduced the heating rate to 43 ± 2 quanta/s. The electric-field noise spectral densities corresponding to the above heating rates are $S_E = 4.0 \times 10^{-11}$, 3.3×10^{-13}, and 2.5×10^{-13} $V^2\,m^{-2}\,Hz^{-1}$, respectively.

In a second experimental setup, reusing the previous trap chip, a gold mask with a (3×4)-mm^2 aperture was installed $\sim$2 mm above the trap electrodes. This enabled measurement of the ion-flux density and alignment of the Ar^+ beam on the trap center. Currents measured from individual electrodes were also used to determine the

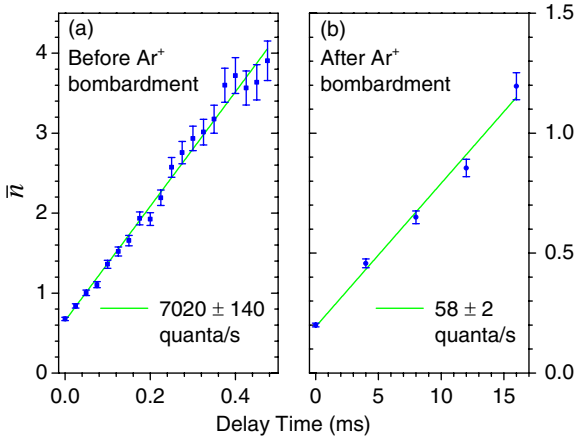

FIG. 3 (color online). Heating rate measurements (a) before and (b) after treatment. Heating rates are obtained by measuring the average number of motional quanta, $\bar{n}$, with a variable delay time after initial laser cooling [5].

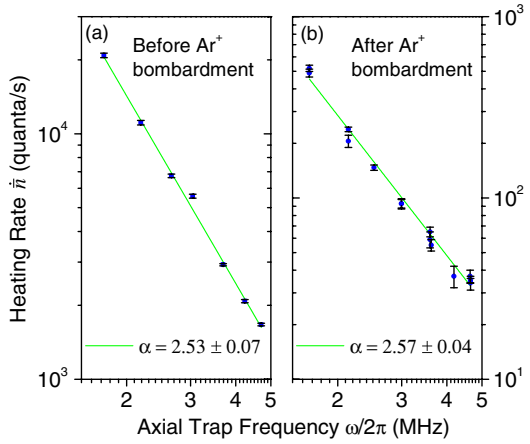

FIG. 4 (color online). Heating rate vs trap frequency, fitted with $\dot{\bar{n}} \sim 1/\omega^{\alpha}$. The power-law exponents $\alpha = 2.53 \pm 0.07$ and $\alpha = 2.57 \pm 0.04$, (a) before and (b) after treatment in the initial experiments, respectively, are consistent with various adsorbate-induced noise models [4,10–12].

ion-flux density. After repeating an exposure to air and vacuum baking, the heating rate at $\omega/2\pi \sim 3.6$ MHz was observed to be $16\,000 \pm 2300$ quanta/s. Following an Ar^+-beam treatment of 2 kV and 90 ± 20 C/m^2 applied to the trap center for 45 minutes at 4×10^{-3} Pa Ar pressure, the heating rate was reduced to 134 ± 9 quanta/s. In this second set of experiments, to within our ability to measure the ion-flux density, the flux that reduced the ion heating rate and that for surface layer removal in the analysis chamber were the same. This low heating rate increased slightly to ~200 quanta/s over three days, then remained constant within ~25% for 4 weeks in ultrahigh vacuum, while collecting heating rate data approximately each week.

The dependence of the heating rate on ion motion frequency can possibly give insight into the physical mechanisms responsible for the noise. In many experiments, $\dot{\bar{n}}$ is seen to follow a $1/\omega^{\alpha}$ dependence ($S_E \sim 1/\omega^{\alpha-1}$), where values of α tend to group around 2 [10]. In the initial experiments, we measured a power-law dependence with $\alpha = 2.53 \pm 0.07$ before and $\alpha = 2.57 \pm 0.04$ after treatment, for $\omega/2\pi$ between 1.7 and 4.7 MHz (Fig. 4). This is consistent with the surface-diffusion-noise model [4,12] and certain parameter ranges of other models [10,11]. This unchanged dependence, before and after the treatments, may indicate that the noise is dominated by the same mechanism, albeit significantly reduced. We note that the residual noise may be compatible with surface contaminants in amounts below the sensitivity limit of AES.

Since S_E exhibits an approximate $1/\omega$ dependence in many ion-trap experiments, we plot $\omega S_E(\omega)$ in Fig. 5, for a number of traps discussed in the literature, to approximately compensate the frequency dependence (see [10] for a similar compilation and discussion). The inferred S_E (2.5×10^{-13} V^2 m^{-2} Hz^{-1}) from the post-treatment heating rate is comparable to the lowest values observed in cryogenic ion traps. The Johnson-noise electric-field spectral density at the ion position is estimated as follows. The trap is formed by static and rf potentials applied to the trap electrodes. The potential for each static field electrode is filtered by two RC filters in series. The Thévenin equivalent is a capacitor in series with a resistor. The latter is dominated by the loss in the final capacitor that terminates the electrode to ground, which corresponds to $0.15 \pm 0.05\ \Omega$ series resistance. The Johnson voltage noise from this resistance gives rise to an electric-field noise (S_{E_J}) at the site of the ion, which we determine through simulation. The incoherent sum of these noise fields from all electrodes along the relevant mode axis at 3.6 MHz is $S_{E_J}(\omega) \sim 2.5 \times 10^{-15}$ V^2 m^{-2} Hz^{-1}. This corresponds to $\dot{\bar{n}}_J = 0.46$ quanta/s, approximately 2 orders of magnitude below the measured heating rate (Fig. 5). The contribution

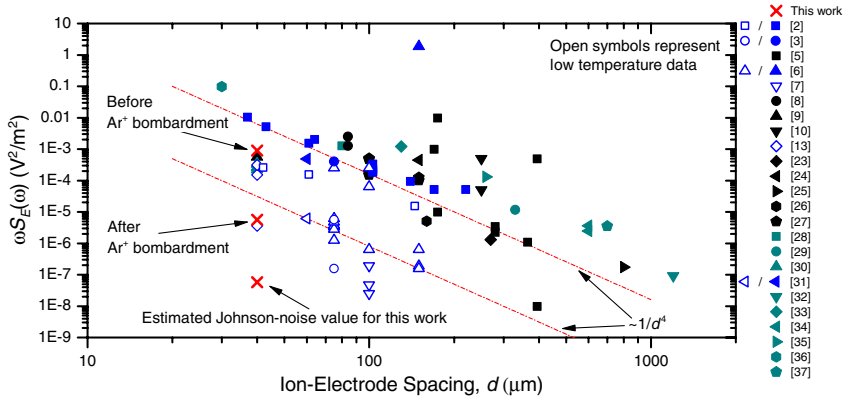

FIG. 5 (color online). Normalized electric-field noise spectral density, $\omega S_E(\omega)$, plotted versus ion-electrode distance, d. Data for initial experiments in this work (red crosses) indicate a reduction of anomalous heating by 2 orders of magnitude after Ar^+-beam treatment. Data from other experiments employing room-temperature trap electrodes are depicted with filled symbols, whereas data from electrodes at cryogenic temperatures are represented with open symbols. The dash-dotted lines indicate the d^{-4} trendlines, predicted by small-patch noise models [5,10,11] (vertical position not relevant).

from the accompanying electronics and resistance in rf electrodes is estimated to be negligible.

In summary, we find that *in situ* electrode treatment by Ar^+ bombardment has reduced the rate of anomalous ion heating in a surface-electrode ion trap by more than 2 orders of magnitude. We correlate this with the removal of contaminant overlayers on the trap's electrode surfaces. The measured frequency dependence is consistent with various adsorbate-induced noise models [4,10–12]. These results suggest that adsorbates play a significant role in electric-field noise above metal surfaces. In our experiments, these adsorbates appear to result from air exposure and/or vacuum baking. Although the results of this experiment are encouraging, more work is needed to identify the responsible mechanisms, refine the effects of the treatment, and/or find alternative surface cleaning methods that are simpler to integrate with ion-trap experiments. Future studies can benefit from better controlled treatment with *in situ* analysis of electrode surfaces in a dedicated surface science apparatus, perhaps along the lines suggested in [18]. The measurement of the heating of ions located near surfaces might be a new probe of electric fields from surfaces in an as-yet unexplored frequency regime. The sensitivity of the method is much higher than required for the observations here. If electrode noise is sufficiently small, delay times to observe changes in $\overline{n}$ could be lengthened by orders of magnitude, limited perhaps by background-gas collision rates of approximately once per minute, even at room temperature [19]. Finally, electric-field noise of the type observed in this study may be important in other fields as well, from nanomechanical cantilevers [20,21] to measurements of weak forces [22].

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