Efficient photoionization loading of trapped ions with ultrafast pulses


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Atomic cadmium ions are loaded into radiofrequency ion traps by photoionization of atoms in a cadmium vapor with ultrafast laser pulses. The photoionization is driven through an intermediate atomic resonance with a frequency-quadrupled mode-locked Ti:sapphire laser that produces pulses of either 100-fs or 1-ps duration at a central wavelength of 229 nm. The large bandwidth of the pulses photoionizes all velocity classes of the Cd vapor, resulting in a high loading efficiency compared to previous ion trap loading techniques. Measured loading rates are compared with a simple theoretical model, and we conclude that this technique can potentially ionize every atom traversing the laser beam within the trapping volume. This may allow the operation of ion traps with lower levels of background pressures and less trap electrode surface contamination. The technique and laser system reported here should be applicable to loading most laser-cooled ion species.

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I. INTRODUCTION

Electromagnetic ion traps have become a standard tool in many areas of physics, from mass spectroscopy [1,2] and precision frequency metrology [3,4] to quantum information science and fundamental studies of quantum mechanics [5–8]. An important practical aspect of operating an ion trap is the efficient and controlled loading of ions into the trap. The standard method for producing positively charged trapped ions is electron bombardment of neutral atoms, usually from electron beams having energies of order 100 eV, comfortably above typical ionization thresholds. While this method applies to any atomic or molecular species, electron-beam loading of ions can adversely impact ion trap performance by degrading vacuum quality, charging nearby insulators, and corrupting the surface quality of the trap electrodes [9]. For applications such as atomic clocks or quantum computing, where a specific ion species is to be loaded, photoionization loading is an attractive alternative that can be much more efficient and cleaner than electron bombardment loading [10].

Several groups have enjoyed the benefits of narrowband photoionization loading with particular atomic ions, including Mg+ [11,12], Cu+ [10,11,13], Yb+ [14,15], and Sr+ [16]. Loading of ions is fairly efficient in these systems, with the continuous-wave (cw) photoionizing lasers tuned to an intermediate atomic resonance en route to ionization. Furthermore, the use of narrowband photoionizing lasers allows isotopic selectivity, as the optical isotope shift in the intermediate resonance is typically larger than the resonant linewidth of the atom.

Here, we report the use of ultrafast laser pulses to photoionize and load cadmium ions (Cd+) in a variety of rf trap geometries, with even greater efficiency. The laser pulses are tuned to an intermediate resonance in the neutral Cd atom, and the same pulses (or a cw laser beam used for laser cooling the eventual ion) can then directly promote the electron to the continuum. The large bandwidth of the pulsed laser can ionize all velocity classes of atoms in a vapor or atomic beam and can provide nearly perfect ion trap loading efficiency. As a result, the density of atoms at the trapping region can be reduced to a level where the atomic coating of the electrodes is negligible. This not only permits a potentially lower vacuum level near the trapping region, but may also reduce anomalous heating of trapped ions that could arise from contaminated electrodes [8,9,17,18]. We finally note that the same type of ultrafast photoionization process reported here can potentially be applied to fast counting of large numbers of ultracold neutral atoms with single atom resolution [19].

II. PHOTOIONIZATION SCHEME AND EXPERIMENTAL SETUP

The relevant energy levels of the neutral Cd atom are shown in Fig. 1(a). The output of a frequency quadrupled mode-locked Ti:sapphire laser at a wavelength of 228.9 nm is resonant with the 5s2 5S0–5s5p 1P1 transition in Cd (radiative linewidth γ/2π=91 MHz). The same laser then promotes the intermediate P state population to the continuum, 1.84 eV above the ionization threshold. Figure 1(b) shows...
the energy levels of the singly ionized Cd atom. Typically during the ion trap loading process, a narrowband cw laser tuned near the 5s2 1S0 ground state and the continuum, so the same laser can subsequently ionize the atom. The resulting fluorescence light from the ions is collected and imaged onto a charge-coupled device (CCD) camera in order to detect the presence of ions loaded into the trap. Note that the photons in the cw laser-cooling beam have enough energy to ionize neutral Cd atoms from the intermediate P state.

Most trapped atomic ion species that are easily laser cooled (those whose neutral form have two valence S electrons: Be, Mg, Ca, Sr, Ba, Zn, Cd, Hg, and Yb) have an intermediate excited 1P1 state more than halfway in energy to the continuum, and can therefore be ionized using the same two-photon process described here. The various laser wavelengths required to couple the 1S0 ground state to a selected 1P1 excited state in these atomic species are shown in Table I. In the case of Yb, the intermediate state is just below halfway to the continuum, but in practice ionization is still effective with a single laser coupling to highly lying Rydberg states that rapidly ionize in the trap electric fields. For Ca, Sr, and Ba, the selected intermediate state is not the lowest 1P1 level.

The absolute rate of loading ions in a trap depends on the particular geometry of the ion trap and the flux of neutral atoms entering the trap. We report photoionization loading of Cd ions in a number of geometries, including an asymmetric quadrupole “ring-fork” trap, a three-layer linear trap, a microfabricated GaAs linear trap, a symmetric two-needle quadrupole trap, and a large four-rod linear trap. In Fig. 2, each ion trap is drawn along with corresponding dimensions. Relevant characteristics of the traps, such as trap depth, loading volume, ion oscillation and rf drive frequencies are listed in Table II. The trapping volumes span a wide range, from a linear dimension of 45 μm for the two-needle trap up to almost 1 mm for the four-rod trap. The trap depths range from below 0.1 eV in the case of the GaAs microfabricated trap and the double-needle trap to several eV for the larger traps.

We perform the experiment with either of two ultrafast mode-locked lasers, which are frequency tripled to a central wavelength of 228.9 nm for excitation of the neutral Cd atom [Fig. 1(a)]. The first pulsed laser provides excitation at a 1-ps time scale (psec laser) while the second laser provides excitation at a 100-fs time scale (fsec laser), allowing a study of the photoionization for different pulse durations.

The psec laser pulses are generated by a commercial mode-locked Ti:sapphire laser (Spectra-Physics Tsunami), producing pulse energies up to 12 nJ at 915 nm. A second-harmonic-generation autocorrelator is used to measure the pulse duration of approximately 2 ps. The infrared pulses are frequency doubled in a 12-mm-long lithium borate (LBO) crystal and doubled again in a 10-mm-long β-barium borate (BBO) crystal. Each nonlinear crystal is critically phase matched (angle-tuned) at its corresponding wavelength. The frequency-quadrupled output at λ = 228.9 nm consists of pulses of approximate duration τ ≈ 1 ps with energies up to 60 pJ with a repetition rate of 1/T = 80 MHz. The bandwidth of the psec laser pulses in the ultraviolet is indirectly determined by tuning the same laser to the nearby 2S1/2 – 2P3/2 transition in Cd+ and measuring the trapped ion fluorescence rate. Figure 3 displays the fluorescence level of a single ion from the quadrupled psec laser tuned near this transition at 226.5 nm (fundamental infrared laser center wavelength at 906 nm). The resulting ultraviolet bandwidth of 0.07 nm (400 GHz) is consistent with the autocorrelator measurements extrapolated from the infrared. We expect a very similar spectrum when the laser is tuned to 915 nm and quadrupled to the 1S0 – 1P1 neutral Cd atom resonance at 228.9 nm, verified in Fig. 7 below.

### Table I. Typical atomic species used in laser-cooled ion trapping experiments, with the relevant neutral-atom transition wavelengths from the ground 1S0 state to the 1P1 state and to the single ionization threshold. For each atom, the chosen intermediate excited 1P1 state is near or above the midpoint in the energy separating the ground state and the continuum, making a two-photon ionizing process feasible with a single laser. (Wavelengths for Ca, Sr, and Ba are not the lowest 1P1 state.) The laser setup used in the Cd experiment reported here can be applied to all atomic species listed in the table.

<table>
<thead>
<tr>
<th>Atomic species</th>
<th>λ(1S0 → 1P1) (nm)</th>
<th>λ(1S0 → ∞) (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Be</td>
<td>234.9</td>
<td>133</td>
</tr>
<tr>
<td>Mg</td>
<td>285.3</td>
<td>162</td>
</tr>
<tr>
<td>Ca</td>
<td>272.2</td>
<td>203</td>
</tr>
<tr>
<td>Sr</td>
<td>293.0</td>
<td>218</td>
</tr>
<tr>
<td>Ba</td>
<td>350.2</td>
<td>238</td>
</tr>
<tr>
<td>Zn</td>
<td>213.9</td>
<td>132</td>
</tr>
<tr>
<td>Cd</td>
<td>228.9</td>
<td>138</td>
</tr>
<tr>
<td>Hg</td>
<td>185.0</td>
<td>119</td>
</tr>
<tr>
<td>Yb</td>
<td>398.9</td>
<td>198</td>
</tr>
</tbody>
</table>
case of the trap in Fig. 2

The fsec mode-locked laser is custom built and based largely on the design of Ref. [26]. Typically, mode-locked Ti:sapphire lasers operate in the optimal region of the gain spectrum, near 800 nm. While the design and operation of such lasers is well documented, several important issues arise as the wavelength of the pulsed laser is tuned above 900 nm. A detailed description of the fsec laser cavity and relevant operational issues is provided in Appendix A. The fsec laser typically produces pulse energies of about 6 nJ at 915 nm with a repetition rate of 1/\tau = 86 MHz. This light is frequency doubled in a 7-mm-long LBO crystal and doubled again in a 5-mm-long BBO nonlinear crystal, similar to the psec laser. The frequency-quadrupled output at \lambda = 228.9 nm consists of pulses with energies up to 60 pJ in the trapping region. A spectrum analyzer with a resolution under 1 nm is used to determine the infrared pulse bandwidth of about 6 nm at 915 nm, as shown in Fig. 4. Given the slight dispersion in the doubling crystals, we expect near transform-limited pulses of approximate duration \tau \approx 100 fs at 228.9 nm.

The layout of the experiment is depicted in Fig. 5 in the case of the trap in Fig. 2(c). The cw cooling laser enters the trapping region with a wave vector that has components along all three principal axes of the ion trap, providing effective Doppler cooling in all three dimensions [27]. The scattered light from the ion(s) is captured by an f/2.1 microscope objective and sent onto an intensified CCD camera. All of the ion traps are loaded from a room-temperature vapor of cadmium, with an estimated partial pressure of about 10^{-9} Pa (10^{-11} torr). This produces a sufficient number of neutrals that traverse the trapping volume for loading, with observed loading rates up to about 10 ions/s. At the same time, this low-level vapor does not compromise the lifetime of the ions in the rf traps through collisions or charge-exchange processes. (We expect the rate of Langevin elastic collisions with background atoms to be about 10^{-3} s^{-1} at this pressure [8].) The bandwidths of the pulsed lasers used in all of the experiments are much larger than the Doppler broadened linewidth of optical transitions in the atomic vapor.

### III. THEORETICAL ION PRODUCTION RATE

In this section, we calculate the expected photoionization rate for a two-photon resonantly assisted ionization process. The result highlights the dependence of the loading rate on controlled experimental parameters such as laser pulse energy and duration, laser beam waist, loading volume, and neutral atom density. (For a similar treatment in the case of a directed atomic beam and continuous-wave photoionization, see Ref. [13].) We solve the optical Bloch equations for the photoionization rate of a single atom excited to an intermediate resonance following Fig. 1(a). We assume the pulsed

<table>
<thead>
<tr>
<th>Trap description</th>
<th>Ring-fork quadrupole</th>
<th>Three-layer linear</th>
<th>GaAs chip linear</th>
<th>Double-needle quadrupole</th>
<th>Four-rod linear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trap depth (eV)</td>
<td>0.8</td>
<td>0.2–5.0</td>
<td>0.08–0.13</td>
<td>0.02–5.0</td>
<td>0.5–2.0</td>
</tr>
<tr>
<td>Trap Size L (\mu m)</td>
<td>500</td>
<td>300</td>
<td>60</td>
<td>45–500</td>
<td>700</td>
</tr>
<tr>
<td>rf drive (MHz)</td>
<td>50</td>
<td>47</td>
<td>16</td>
<td>29</td>
<td>36</td>
</tr>
<tr>
<td>\nu_x (MHz)</td>
<td>0.5</td>
<td>0.6–4.0</td>
<td>0.8–1.0</td>
<td>0.5–10.0</td>
<td>0.25–0.70</td>
</tr>
<tr>
<td>\nu_y (MHz)</td>
<td>0.75</td>
<td>8.1</td>
<td>3.3</td>
<td>0.25–5.0</td>
<td>0.90</td>
</tr>
<tr>
<td>\nu_z (MHz)</td>
<td>1.25</td>
<td>8.3</td>
<td>4.3</td>
<td>0.25–5.0</td>
<td>0.91</td>
</tr>
</tbody>
</table>
laser peak intensity to be in the weak perturbative regime [28], so that no other electronic states are involved in this process.

The laser pulse train consists of individual pulses of approximate duration \( \tau = 100 \) fs or \( \tau = 1 \) ps separated by a pulse period of \( T = 12 \) ns. Each pulse is focused down to peak intensity \( I \) at the position of the atom to be ionized, resonantly coupling the initial ground \( 5S_{1/2} \) electronic state to the intermediate exited \( 5P_{1/2} \) state. The resulting Rabi rotation angle is \( \theta = g \tau \), where the resonant Rabi frequency is \( g = \gamma I / 2 I_{\text{sat}} \approx \gamma \) and \( I_{\text{sat}} \) is the \( 1 \) \( S_{0} \)-\( 1 \) \( P_{1} \) saturation intensity. The same laser pulse is capable of sequentially ionizing the atom with photoionization rate from the \( 1 \) \( P_{1} \) state given by \( \Gamma \sigma / \hbar \omega \), where \( \sigma \) is the \( 1 \) \( P_{1} \) photoionization cross section and \( \omega \) is the laser frequency.

A cw laser with intensity \( I_{\text{cw}} \) used for Doppler laser cooling of the eventual ion can also ionize the neutral atom once in the \( 1 \) \( P_{1} \) state, with photoionization rate given by \( \Gamma_{\text{cw}} = I_{\text{cw}} \sigma_{\text{cw}} / \hbar \omega_{\text{cw}} \ll \gamma \), where the cw laser parameters are defined analogously to that of the pulsed laser.

The \( 1 \) \( P_{1} \) spontaneous emission lifetime is usually much shorter than the period between laser pulses \( (T \gg 1/\gamma \gg \tau) \), so the neutral atom returns to the ground \( 1 \) \( S_{0} \) state before the next pulse (unless it has ionized). By integrating the optical Bloch equations for the atomic populations in time (see Appendix B), we can therefore write down the probability \( P_{\text{ion}} \) of ionization per laser pulse period \( T \):

\[
P_{\text{ion}} = 1 - e^{-\Gamma \tau} \left[ 1 + \frac{\Gamma \tau \sin \theta}{\theta} - \frac{\Gamma_{\text{cw}}}{2 \gamma} (1 - \cos \theta) \right].
\]

In this expression, we have assumed that the photoionization rate from the \( 1 \) \( P_{1} \) state is much weaker than the coherent coupling between the \( 1 \) \( S_{0} \) and \( 1 \) \( P_{1} \) states in the atom, or \( \Gamma_{\text{cw}} \ll g \). This is valid for typical atomic systems considered here and for typical (perturbative) laser intensities.

All but the last term in Eq. (1) arise from photoionization from the pulsed laser exclusively, while the last term describes the contribution from the cw laser. For similar average intensities of the cw and pulsed lasers \( (I_{\text{cw}} \approx I = I_{\text{sat}} / T) \) and assuming that the photoionization cross section from the \( 1 \) \( P_{1} \) state is similar for the two processes, we find that the photoionization probability from the pulsed laser alone is roughly \( \gamma T / 2 \) times larger than that from photoionization from the cw laser. In the Cd system considered here \((1/\gamma = 2 \) ns and a \( 1/T = 80 \) MHz laser repetition rate), this amounts to the pulsed laser ionizing the atom about three times faster than the cw laser. In the experiments, the cw laser has a lower average intensity than the pulsed laser, so we neglect the effect of the cw laser on the photoionization calculations for simplicity.

For \( \Gamma \tau / 2 \ll 1 \), the ionization probability per pulse from the pulsed laser alone simplifies to

\[
P_{\text{ion}} = \frac{\Gamma_{\text{sat}}}{2} \left( 1 - \frac{\sin \theta}{\theta} \right) \approx \frac{\theta^{2} \Gamma_{\text{sat}}}{16}.
\]

The above approximation is accurate to within 25% for all Rabi angles \( 0 \leq \theta \leq \pi \). In terms of the laser pulse energy \( \mathcal{E} \)
Since the ionization cross section from the Cd $^1P_1$ state is not known precisely, we use previous measurements in atomic magnesium [12], calcium [10], and barium [29] as guides, because their electronic structure is comparable to Cd. These experiments reported photoionization cross sections from their respective $^1P_1$ states using laser radiation well above the ionization threshold by similar amounts of energy to that considered here. We estimate to an order of magnitude that the Cd $^1P_1$ photoionization cross section is $\sigma \approx 10^{-16}$ cm$^2$ for light at $\lambda = 228.9$ nm. In terms of the laser parameters, we find that the ionization probability per pulse for an atom at the focus of the laser beam is $P_{\text{ion}}^{(0)} = \frac{\sigma \gamma^2 E^2 \tau}{8 \pi^2 \hbar \omega l_{\text{sat}} \rho^3}$, with $E$ in pJ, $\tau$ in ps, and $\rho$ in $\mu m$.

Now we can estimate the total rate of ions produced in a loading volume formed by the intersection of the trapping region and the photoionizing laser beam, depicted by the cylinder of radius $\rho$ and length $L \gg \rho$ in Fig. 6. Here $L$ is defined as the linear dimension of the trapping volume along the axis of the laser beam and is assumed to be much smaller than the Rayleigh range $\pi \rho^2 / \lambda$ of the laser beam. We assume that each atom experiences many laser pulses during its trajectory through the loading volume (for room-temperature thermal Cd atoms with mean speed $\bar{v} = 240$ m/s, a typical atom travels about 3 $\mu$m between laser pulses separated by $T = 12$ ns). We expect that the number of ions loaded per pulse should scale as the number of atoms in the loading volume $n_0 \rho^2 L$ times $P_{\text{ion}}^{(0)}$. In Appendix C, a more rigorous calculation of the net flux $\Phi_{\text{ion}}$ of photoionized atoms is performed by averaging over the thermal trajectories of background atoms in the vapor as they traverse the laser pulses. In terms of the background density $n_0$, we find

$$\Phi_{\text{ion}} = \frac{n_0 \rho^2 L P_{\text{ion}}^{(0)}}{8 T} = \frac{\sigma \gamma^2 n_0 \rho^2 L E^2 \tau}{64 \pi^2 \hbar \omega l_{\text{sat}} \rho^3 T^2}. \quad (4)$$

The average photoionization rate over the entire cylindrical loading volume is then

$$R_{\text{ion}} = \Phi_{\text{ion}} (2 \pi \rho L) = \frac{\pi n_0 \rho^2 L P_{\text{ion}}^{(0)}}{4 T} = \frac{\sigma \gamma^2 n_0 \rho L E^2 \tau}{32 \pi \hbar \omega l_{\text{sat}} \rho^3 T^2}. \quad (5)$$

In Ref. [13], similar expressions are derived for the case of a directed atomic beam and continuous-wave photoionization. The above treatment assumes that the ionization probability per pulse for a typical atom is small. If this is not the case, nearly every atom that crosses the laser beam is ionized, and the flux of ionized atoms is then simply $\Phi_{\text{ion}} = n_0 \bar{v} / 4 [30]$. The vapor pressure of Cd metal at room temperature is roughly $10^{-9}$ Pa ($10^{-11}$ torr) [31,32], giving a density of $n_0 = 3 \times 10^5$ atoms/cm$^3$, and we find for the Cd system, $R_{\text{ion}} = 1000 \sigma E^2 (L / \rho^2) (\tau / T)$, with the pulse energy $E$ in pJ and the dimensions $L$ and $\rho$ in $\mu$m. For a $1/T = 80$-MHz laser repetition rate with waist $\rho = 25$ $\mu$m traversing a length $L = 100$ $\mu$m through the trapping volume, we find $R_{\text{ion}} = 0.01 \tau E^2$ s$^{-1}$, with $E$ in pJ and $\tau$ in ps. For 60-pJ pulses, we expect a photoionization rate of approximately $R_{\text{ion}} = 40$ s$^{-1}$ for the psec laser and $R_{\text{ion}} = 4$ s$^{-1}$ for the fsec laser.

The above flux of photoionized atoms can be compared to the total flux of atoms traversing the same region, and the loading efficiency is then

$$\eta = \frac{\Phi_{\text{ion}}}{\Phi_0} = \frac{P_{\text{ion}}^{(0)} \rho}{20 T} = \frac{\sigma \gamma^2 E^2 \tau}{16 \pi^2 \hbar \omega l_{\text{sat}} \rho^3 T^2}. \quad (6)$$

For a photoionizing laser repetition rate of $1/T = 80$ MHz, $\eta = 0.001 \sigma E^2 / \rho^3$, with $E$ in pJ, $\tau$ in ps, and $\rho$ in $\mu$m. For $\tau$ = 1 ps pulses at $E = 60$ pJ focused down to $\rho = 10$ $\mu$m, the efficiency is expected to be $\eta = 0.4\%$, several orders of magnitude larger than electron bombardment ionization efficiency [10]. By increasing the pulse energy to $E = 300$ pJ focused to a waist of $\rho = 10$ $\mu$m, the efficiency of photoionization with the psec laser is expected to approach unity ($P_{\text{ion}}^{(0)} \approx 1$): nearly every atom that traverses the photoionization laser beam within the trap volume should be ionized.

**IV. EXPERIMENTAL RESULTS**

The loading and successful localization of ions in an ion trap through laser cooling is a complex process. Initially, ions are expected to have high kinetic energies of order the trap depth (up to several eV), and laser cooling can follow a...
find the average loading rate for single Cd+ ions is of order $1 \text{s}^{-1}$. The 0.1-nm Doppler width is consistent with the transform limit expected from the measured pulse duration, and allows the excitation and photoionization of atoms in all velocity classes in the background vapor. We do not consider any of these effects when comparing experimental and theoretical photoionization loading rates [35]. The presence of ions already in the trap can also influence the loading process, so for most measurements of loading rate presented below, we simply measure the mean time to load a single ion in a previously empty trap.

In Fig. 7, we plot the observed loading rate of ions in the quadrupole trap of Fig. 2(a) vs the central wavelength of the psec laser (with approximate values $\xi=60 \text{pJ}$, $\tau=1 \text{ps}$, $1/T =80 \text{MHz}$, and $\rho=25 \text{um}$). The photoionization rate traces the spectrum of the psec laser, with peak loading rate near resonance at a central wavelength of 228.9 nm. The 0.1-nm (340-GHz) bandwidth is consistent with the transform limit expected from the measured pulse duration, and allows the excitation and photoionization of atoms in all velocity classes in the background vapor (Doppler width $\nu/\lambda = 1 \text{GHz}$). On resonance (corresponding to $\theta = \pi$ [36]), we find the average loading rate for single Cd+ ions is of order $R_{\text{ion}}=1-10 \text{ s}^{-1}$.

In Fig. 8, the observed loading rate in the linear trap of Fig. 2(b) is plotted as a function of the average power of the fsec pulsed laser. The observed loading rate is consistent with a quadratic scaling in optical power as predicted for $\theta < \pi$ [Eq. (5)]. At the highest pulse energy of about 60 pJ, the loading rate is about 0.1 s$^{-1}$. This is much less than the psec loading rate shown in Fig. 7, due to the shorter pulse duration $\tau$ and the somewhat smaller trapping size $L$ as predicted from Eq. (5). While the observed dependence of loading rate on laser parameters is in rough agreement with theory, the absolute loading rates are about an order of magnitude lower than expected, possibly reflecting the inefficient cooling process discussed above, or overestimates of the effective trap dimension $L$ or the photoionization cross section $\sigma$.

In the smallest ion traps with characteristic size $L = 50 \text{um}$ [GaAs and double-needle traps of Figs. 2(c) and 2(d)], the loading rate is lower than the larger traps using similar photoionizing laser parameters, as expected from Eq. (5). For example, in the GaAs chip trap [23], the loading rate was approximately 0.01 $\text{s}^{-1}$ with the fsec laser at similar energies to that reported above.

In most of the Cd ion traps loaded with pulsed-laser photoionization, the cw Doppler cooling beam has no significant effect on loading: when the pulsed and cw beams are directed into the trap at the same time, the loading rate is observed to be nearly the same as when the lasers are slowly (<1 Hz) alternated in sequence. Figure 9 displays a histogram of the number of ions loaded in a 0.5-s exposure time to the fsec photoionization beam in the four-rod trap [Fig. 2(e)] with and without the simultaneous presence of the cw Doppler-cooling beam, yielding similar average loading rates of $R_{\text{ion}}=1 \text{ s}^{-1}$. However, the linear trap of Fig. 2(b) behaves markedly different than the others. In this trap, the presence of the cw Doppler cooling beam during photoionization is observed to enhance the loading rate by up to an order of magnitude. In addition, by tuning the cw laser near resonance of a particular Cd+ isotope in this trap, we are able to selectively load particular isotopes—a feature that is impossible with the pulsed laser alone, as it has a bandwidth much larger than the $1-5-\text{GHz}$ isotope splittings in Cd. One possible explanation for this behavior is that the linear trap may require a higher level of initial laser cooling for ions to remain confined, perhaps from an abnormally high level of rf micromotion [4].
V. CONCLUSION

We have demonstrated efficient photoionization loading of Cd\(^+\) ions into a variety of rf ion traps using frequency-quadrupled Ti:S mode-locked pulsed lasers. The laser pulses resonantly promote neutral Cd atoms to an intermediate excited state that subsequently photoionizes. Observed loading rates over 1 ion/s are within an order of magnitude of the expected photoionization rate derived from a simple theoretical model of the photoionization process, and the dependence on laser parameters and trap volume agree with theory. Because the pulses are broadband, all velocity classes of atoms can be photoionized, leading to a very efficient loading technique. With slightly increased pulse energies and tighter focusing, we expect that ultrafast laser pulses could successfully load every atom that traverses the laser beam within a typical trapping volume. This may allow ion trap electrodes to be cleaner than in previous systems, with lower pressures in the trapping region.

ACKNOWLEDGMENTS

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APPENDIX A: DESCRIPTION OF LONG-WAVELENGTH MODE-LOCKED Ti:SAPPHIRE LASER

The mode-locked Ti:sapphire laser is very useful for photoionization loading of trapped ions because of its large tuning range (650–1150 nm). Moreover, with ultrafast pulses in the range 10–100 fs, it is easy to up-convert to blue or ultraviolet wavelengths needed for nearly any of the popu-
There is an excellent description for this type of cavity when operating a wavelength around 800 nm in Ref. [26]. However, when operating at much longer wavelengths, there are a few additional issues. When the laser oscillates at wavelengths longer than about 900 nm, we observe that heating of the crystal from the pump laser can prevent the laser from mode locking. We find that by providing good thermal contact between the crystal and its metallic housing and water cooling the Ti:sapphire crystal assembly eliminates this problem [38]. In addition, at longer wavelengths, there is a potential problem with the absorption of water vapor in the air, that can lower the gain of the laser to below threshold, especially in the 925–960-nm-range.

A final critical issue concerns the proper choice of optical coating. It is known that care must be taken in making sure that cavity mirrors have matched coatings—both curved mirrors are especially sensitive to this requirement [39]. Even if all of the mirrors are from the same coating run, one of them can still prevent proper mode locking. This is not well understood, and our experience is that repeated replacement of seemingly identical optical components appears to make a difference [39]. Ultrafast Ti:sapphire lasers operating at any wavelength are sensitive to the subtle details of mirror coatings, but this appears to be even more critical when the laser is tuned to the longer wavelength range where the gain is significantly lower.

APPENDIX B: PROBABILITY OF RESONANTLY ASSISTED PHOTOIONIZATION PER PULSE

In this appendix, we determine the probability of photoionization of an atom illuminated with an ultrafast laser pulse that promotes an atomic electron from a ground state through an intermediate atomic resonance and to the continuum, following Fig. 11. For simplicity, the laser pulse is described by a square wave profile of duration \( \tau \) and peak intensity \( I \) and is in the weak perturbative regime where no other atomic levels contribute to the photoionization [28].

We consider an atom initially in the \( 1^{1}S_{0} \) electronic ground state coupled to an intermediate exited \( 1^{1}P_{1} \) state (radiative linewidth \( \gamma \)) with Rabi frequency \( g = \sqrt{\gamma/\hbar I} \), \( I \) is the saturation intensity for this transition. The Rabi angle accumulated during the pulse is \( \theta = g \tau \). The photons in the same laser pulse have enough energy to sequentially ionize the atom with photoionization rate from the \( 1^{1}P_{1} \) state given by \( \Gamma = \theta^2/\hbar \omega_c \), \( \omega_c \) is the \( 1^{1}P_{1} \) photoionization cross section and \( \omega_c \) is the laser frequency. In addition, a cw laser with intensity \( I_{\text{cw}} \) used for laser cooling of the eventual ion can also ionize the neutral atom once in the \( 1^{1}P_{1} \) state, with photoionization rate given by \( \Gamma_{\text{cw}} = I_{\text{cw}} \sigma_{\text{cw}} / \hbar \omega_{\text{cw}} \), \( \sigma_{\text{cw}} \) is the cw laser parameters are defined analogously to that of the pulsed laser. The Bloch equations describing the populations \( \Pi_s \), \( \Pi_P \), and \( \Pi_{\text{ion}} \) of the ground \( S \) state, intermediate excited \( P \) state, and photoionized state, respectively, can be written

\[
\frac{d\Pi_s}{dt} = -g(t)C + \gamma \Pi_P, \quad (B1a)
\]

\[
\frac{d\Pi_P}{dt} = (\Gamma + \Gamma_{\text{cw}} + \gamma) \Pi_P, \quad (B1b)
\]

\[
\frac{d\Pi_{\text{ion}}}{dt} = (\Gamma + \Gamma_{\text{cw}}) \Pi_P, \quad (B1c)
\]

\[
\frac{dC}{dt} = -\frac{g(t)}{2}(\Pi_P - \Pi_s) - \frac{\Gamma}{2} C, \quad (B1d)
\]

where \( C \) is the coherence between the \( S \) and \( P \) electronic states and the \( S-P \) Rabi frequency for the laser pulse is \( g(t) = g \) for \( 0 \leq t < \tau \) and \( g(t) = 0 \) for \( \tau \leq t < T \). The \( 1^{1}P_{1} \) spontaneous emission lifetime is usually much shorter than the laser pulse period \( T \gg 1/\gamma \), so the neutral atom returns to the ground \( 1^{1}S_{0} \) state before the next pulse (unless it has ionized). The probability \( P_{\text{ion}} \) of ionization per laser pulse period \( T \) can then be identified as the value of \( \Pi_{\text{ion}}(t=T) \) by integrating the above Bloch equations over the time span \( 0 \leq t < T \), under the initial condition \( \Pi_{s}(t=0) = 1 \):

\[
P_{\text{ion}} = 1 - e^{-\Gamma \tau/2} \left( 1 + \frac{\Gamma \sin \theta}{2 \gamma} - \frac{\Gamma_{\text{cw}}}{2 \gamma} (1 - \cos \theta) \right), \quad (B2)
\]

where \( x = \Gamma \tau/2 \). In the weak pulse limit considered here, the \( S-P \) Rabi frequency is much larger than the photoionization rate from the \( P \) state \( (g \gg \Gamma) \), thus \( \theta \gg x \) and the above equation simplifies to

\[
P_{\text{ion}} = 1 - e^{-\Gamma \tau} \left[ 1 + \frac{\Gamma \sin \theta}{2 \gamma} - \frac{\Gamma_{\text{cw}}}{2 \gamma} (1 - \cos \theta) \right]. \quad (B3)
EFFICIENT PHOTOIONIZATION LOADING OF TRAPPED…

APPENDIX C: THE FLUX OF PHOTOIONIZED ATOMS FROM A VAPOR

Here, we calculate the average flux of atoms expected to photoionize within the trapping volume. The photoionizing laser consists of ultrafast pulses separated by period $T$ that are focused to a Gaussian transverse waist of $\rho$. The trap dimension $L \gg \rho$ is defined as the linear dimension of the trapping volume along the laser beam, and is assumed to be much smaller than the axial Rayleigh range of the laser beam. The relevant loading volume is thus a cylindrical shape of radius $\rho$ and length $L$ as shown in Figs. 6 and 12.

Given the probability per pulse $P_{\text{ion}}^{(0)}$ of ionizing a neutral Cd atom at rest in the focus of the Gaussian beam [Eq. (3)], we now consider the probability of photoionization for an atom that pierces the cylindrical loading volume at a radial distance $\rho$ from the laser axis. The atom has speed $v$, polar (azimuthal) angle $\theta'$ ($\phi'$) with respect to the normal of the cylindrical surface, as drawn in Fig. 12. This atom experiences a Gaussian laser beam profile along its trajectory, and the resulting probability of photoionization for a single laser pulse is proportional to the squared intensity,

$$P_{\text{ion}}(\theta', \phi') = P_{\text{ion}}^{(0)}(\theta', \phi') e^{-4(\xi_0)^2 w(\theta', \phi')^2},$$  \hspace{1cm} (C1)

where the peak photoionization probability $P_{\text{ion}}^{(0)}(\theta', \phi')$ and the effective laser beam waist $w(\theta', \phi')$ along the atom’s trajectory $\xi(t)$ are

$$P_{\text{ion}}^{(0)}(\theta', \phi') = P_{\text{ion}}^{(0)} \exp \left( -\frac{4 \sin^2 \theta' \sin^2 \phi'}{1 - \sin^2 \theta' \cos^2 \phi'} \right)$$  \hspace{1cm} (C2)

and

$$w(\theta', \phi') = \frac{\rho}{\sqrt{1 - \sin^2 \theta' \cos^2 \phi'}}.$$  \hspace{1cm} (C3)

The net photoionization probability accumulated along the atom’s trajectory is then

$$P_{\text{net}}(v, \theta', \phi') = 1 - \prod_{j=0}^{+\infty} \left[ 1 - P_{\text{ion}}^{(0)}(\theta', \phi') e^{-4(\xi_j)^2 w(\theta', \phi')^2} \right].$$  \hspace{1cm} (C4)

where $\xi_j = j \theta T + \xi_0$ is the position of the atom at the $j$th laser pulse and $\xi_0$ is the position of the atom for a particular pulse. The above product is safely taken to $\pm \infty$ because the probability of photoionizing an atom is negligible outside of the laser beam where $\xi_j \gg w(\theta', \phi')$. For $P_{\text{ion}}(\theta', \phi') \ll 1$, the above product simplifies to

$$P_{\text{net}}(v, \theta', \phi') = P_{\text{ion}}^{(0)}(\theta', \phi') \sum_{j=0}^{+\infty} e^{-4(\xi_j)^2 w(\theta', \phi')^2}.$$  \hspace{1cm} (C5a)

$$P_{\text{ion}}^{(0)}(\theta', \phi') = \frac{\int_{-\infty}^{+\infty} \frac{d\xi}{v T} e^{-4(\xi)^2 w(\theta', \phi')^2}}{4 \int_{-\infty}^{+\infty} \frac{d\xi}{v T}}.$$  \hspace{1cm} (C5b)

The conversion to an integral in Eq. (C5b) presumes that the atom experiences many laser pulses as it moves through the beam ($vt < \rho$). For thermal Cd atoms of mean speed $\bar{v} \approx 240 \text{ m/s}$ and a laser repetition rate of $1/T = 80 \text{ MHz}$, a typical atom moves $\bar{V}T \approx 3 \mu\text{m}$ between pulses, which is much smaller than a typical beam waist.

We can now calculate the flux of photoionized atoms by averaging $P_{\text{net}}(v, \theta', \phi') n(v)v \cos \theta'$ over the thermal density distribution $n(v)$ of atomic speeds $v$ in the hemisphere represented by $\theta' \in (0, \pi/2)$ and $\phi' \in (0, 2\pi)$. The density distribution is

$$n(v) = n_0 \left( \frac{m}{2\pi k_B T_v} \right)^{3/2} \exp \left( -\frac{mv^2}{2k_B T_v} \right),$$  \hspace{1cm} (C6)

where $n_0$ is the uniform density of atoms in the vapor, $T_v$ is the vapor temperature, $k_B$ is Boltzmann’s constant, and $m$ is the atomic mass [30]. The net flux of ions is then

$$\Phi_{\text{ion}} = \int_0^{+\infty} v^2 dv \int_0^{2\pi} d\phi' \int_0^{\pi/2} \sin \theta' d\theta' P_{\text{net}}(v, \theta', \phi') \times n(v) v \cos \theta'$$  \hspace{1cm} (C7a)

$$= P_{\text{ion}}^{(0)} \left( \frac{\pi \rho}{4 T} \int_0^{+\infty} v^2 n(v) dv \int_0^{2\pi} d\phi' \int_0^{\pi/2} \sin \theta' \cos \theta' d\theta' \right) \times \left( \frac{\sin \theta' \cos \theta'}{\sqrt{1 - \sin^2 \theta' \cos^2 \phi'}} \right) \times \left( \exp \left( -\frac{4 \sin^2 \theta' \sin^2 \phi'}{1 - \sin^2 \theta' \cos^2 \phi'} \right) \right)^{1/2}$$  \hspace{1cm} (C7b)

$$= P_{\text{ion}}^{(0)} \left( \frac{n_0 \bar{v}}{8T} \right)^{3/2}.$$  \hspace{1cm} (C7c)
[16] A. Sinclair (private communication).


See, for example, F. Reif, Fundamentals of Statistical and Thermal Physics (McGraw-Hill, New York, 1965).