

# Barium autoionization for efficient ion trap loading

Zachary J. Wall<sup>1,\*</sup>, Justin D. Piel<sup>2</sup>, Samuel R. Vizvary<sup>1</sup>, Michael Bareian<sup>1</sup>, Steven Diaz<sup>1</sup>, Elijah Mossman<sup>1</sup>, Anthony Ransford<sup>3</sup>, Chris H. Greene<sup>2</sup>, Eric R. Hudson<sup>1,4,5</sup> and Wesley C. Campbell<sup>1,4,5</sup>

<sup>1</sup>*Department of Physics and Astronomy, University of California Los Angeles, Los Angeles, California 90095, USA*

<sup>2</sup>*Department of Physics and Astronomy, Purdue University, West Lafayette, Indiana 47907, USA*

<sup>3</sup>*Quantinuum, LLC, 303 South Technology Court, Broomfield, Colorado 80021, USA*

<sup>4</sup>*Challenge Institute for Quantum Computation, University of California Los Angeles, Los Angeles, California 90095, USA*

<sup>5</sup>*Center for Quantum Science and Engineering, University of California Los Angeles, Los Angeles, California 90095, USA*



(Received 23 January 2026; accepted 26 May 2026; published 6 July 2026)

We report a theoretical and experimental investigation of autoionizing resonances from the  $5d6p\ ^3D_1^o$  manifold in neutral barium for efficient loading of ion traps. Our calculations predict large resonant cross sections for many narrow autoionizing resonances, but we find experimentally that, for most of these, Doppler broadening during trap loading depresses the effective cross sections that can be achieved in practice. We identify and demonstrate a strong, broad transition at 530.8 nm and show that it furnishes an order-of-magnitude increase in trap loading efficiency compared to other demonstrated resonances.

DOI: [10.1103/c5m6-kt93](https://doi.org/10.1103/c5m6-kt93)

## I. INTRODUCTION

Barium has emerged as a leading trapped-ion qubit due to its visible-wavelength transitions and long-lived ( $\tau \approx 30$  s) metastable  $^2D_{5/2}$  state [1–3]. These features make it a favorable system for implementing the *omg* (optical-metastable-ground) blueprint that utilizes three qubit encodings in a single atom [4,5]. The long-wavelength cooling transition also reduces the rate of surface charging when using integrated photonic systems [6]. Further, the recently introduced synthetic  $^{133}\text{Ba}^+$  isotope incorporates all of these features as well as fast, high-fidelity qubit-state preparation [7–10]. However  $^{133}\text{Ba}^+$  is radioactive and therefore requires working with small quantities that must be loaded efficiently [11]. Even for naturally abundant isotopes, current loading rates can require minutes to populate a moderate-sized processor [1] and will prove infeasible for operating much larger systems. More-efficient loading methods will likely be needed for scaling and may enable wider adoption of trace species that furnish desirable advantages over more-abundant nuclides.

Inspired by the recent work of Greenberg *et al.* [11], we address this challenge by identifying and characterizing autoionizing resonances in neutral barium with the goal of enhancing ion trap loading efficiency. This work provides theoretical calculations and measurements of the cross section of multiple autoionizing resonances from the  $5d6p\ ^3D_1^o$  state. Specifically, we focus on regions of the ionization spectrum between 450 and 454 nm, as well as a broad resonance at 530.8 nm. The 530.8-nm resonance was chosen due to its large predicted cross section and broad spectral width, combined with the availability of high-power lasers at this wavelength. The photoionization schemes considered in this work are summarized in Fig. 1.

Previous studies have measured the cross sections and ion trap loading rates from the  $6s6p\ ^1P_1^o$  [11–14],  $6s6p\ ^3P_1^o$  [15], and  $5d6p\ ^3D_1^o$  [16] states. Here, we provide direct comparison to the most efficient loading rates reported in previous studies and find that the autoionizing transition at 530.8 nm is approximately an order of magnitude more efficient than the 389-nm autoionization scheme reported in Ref. [11]. A key factor that contributes to the utility of this transition is that the second photon absorption exhibits a linear scaling of loading efficiency with laser power up to extremely high intensities, with no visible saturation effect. This is compounded with the practical advantage of high available laser power at this wavelength. The transition wavelength is also comfortably in the visible range, which is expected to suppress trap-charging effects that occur when using ultraviolet photoionization light [17–19]. Finally, the same photoionization laser can also be used for high-fidelity stimulated-Raman gates in  $\text{Ba}^+$  [9].

## II. THEORETICAL METHODS

The theoretical methods used to explore interesting scenarios for creating barium ions from neutrals through two-step photoionization have been well-developed over the past few decades. The present study adopts the techniques of variational *R*-matrix theory integrated with multichannel quantum defect theory, along the lines presented in Refs. [20,21]. The starting point of such calculations for any atom or negative ion with two valence electrons is to first create an accurate model potential energy function  $V_{lj}(r)$  that can be used to describe the interaction of a single electron with the closed-shell ionic core, i.e. for one electron of orbital momentum  $l$  and total individual angular momentum  $j$  in the field of  $\text{Ba}^{++}$ . This potential is radially local, meaning that for each  $l$  and  $j$ , it is an ordinary function of the distance  $r$  between that electron and the nucleus of the closed-shell ion. This potential is optimized to give the energy levels of  $\text{Ba}^+$  as accurately

\*Contact author: [zwall@physics.ucla.edu](mailto:zwall@physics.ucla.edu)

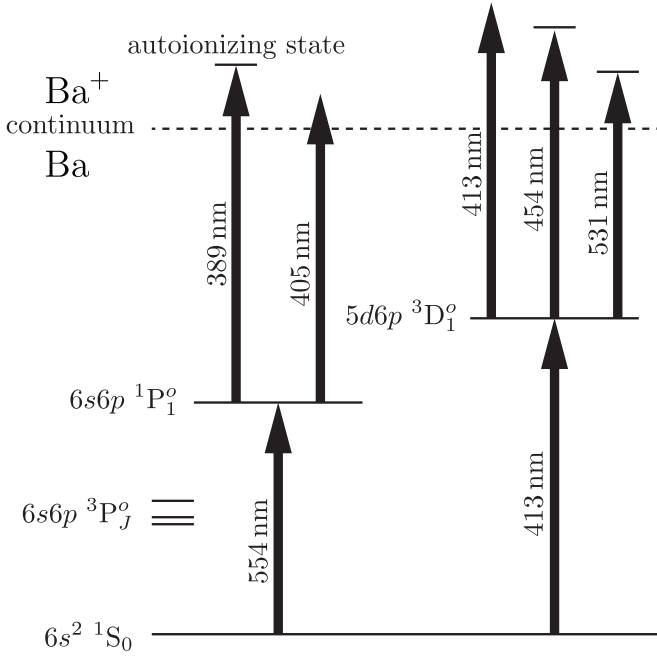


FIG. 1. Level diagram of measured photoionization schemes in this work. The 413 nm + 530.8 nm scheme on the far right is found to be the most efficient for loading barium ions into the trap.

as possible for  $l < 5$ . The physics incorporated in  $V_{lj}(r)$  are primarily the screening effects of the closed-shell electrons of the  $\text{Ba}^{++}$  ion, its polarizability interaction with one electron, and the spin-orbit interaction of that electron in the field of the doubly charged ion. The dielectronic polarization term was not included in the present calculations, consistent with earlier variational eigenchannel  $R$ -matrix studies that obtained good agreement with experiment for photoionization from both the  $6s6p\ ^1P_1^o$  and  $5d6p\ ^3D_1^o$  states in this energy range without this term [14,16,22].

### III. EXPERIMENTAL METHODS

Relative cross sections were experimentally measured by laser ablating a  $\text{BaCl}_2$  target to produce neutral barium in the trap volume and counting the number of loaded ions.

These measurements were averaged over multiple repetitions, typically using 30 shots per data point. Measurements at different wavelengths were interleaved to mitigate slow drifts in ablation conditions, and the ablation laser pulse energy was monitored with a Gentec energy meter and remained stable over the duration of the measurements. We set the experimental cross section equal to the calculated cross section at 413 nm (12 Mb) and scaled all other measured cross sections relative to this value. For context, photoionization from the same  $5d6p\ ^3D_1^o$  intermediate state has also been demonstrated using a 1 + 1 direct ionization scheme at 413 nm + 413 nm [12]. All isotopes of barium that were loaded into the trap were recorded. A 532-nm Nd:YAG, focused to a beam waist of 300  $\mu\text{m}$  with a pulse energy of 0.5 mJ was used for laser ablation. The target was positioned at a distance of 4.3 cm from the trap center. Approximately 500  $\mu\text{W}$  of 413-nm light and a beam waist of 50  $\mu\text{m}$  were used for the first step of photoionization ( $6s^2\ ^1S_0 \rightarrow 5d6p\ ^3D_1^o$ ). This beam was vertically polarized and overlapped with the 493- and 650-nm ion-Doppler-cooling lasers. These were directed through the trap center perpendicular to the direction of the ablation cloud to minimize the Doppler shift. The spectroscopy laser was propagated antiparallel to the 413-nm beam with horizontal polarization.

The ion trap used in this experiment is made up of four, segmented, gold-coated ceramic blades. The ion-to-electrode distance is 200  $\mu\text{m}$  with a trap drive frequency of  $\Omega_{\text{rf}} = 2\pi \times 32.0$  MHz. The radio-frequency voltage is set to an amplitude of 200 V resulting in a secular frequency of  $\omega_{\text{radial}} = 2\pi \times 2.0$  MHz and a radial trap depth of 4.3 eV. Axial confinement is achieved by applying 20 V of static bias to the four outermost electrodes, resulting in an axial secular frequency of  $\omega_{\text{axial}} = 2\pi \times 0.55$  MHz. The trap is housed in a sealed vacuum chamber with a measured pressure of approximately  $2 \times 10^{-10}$  Torr.

### IV. RESULTS AND DISCUSSION

The first photoionization scheme studied in this work begins with a resonant transition at 413 nm from the  $6s^2\ ^1S_0$  state to the  $5d6p\ ^3D_1^o$  state. A second spectroscopy laser is then scanned from 450.5 to 454.8 nm, driving to various au-

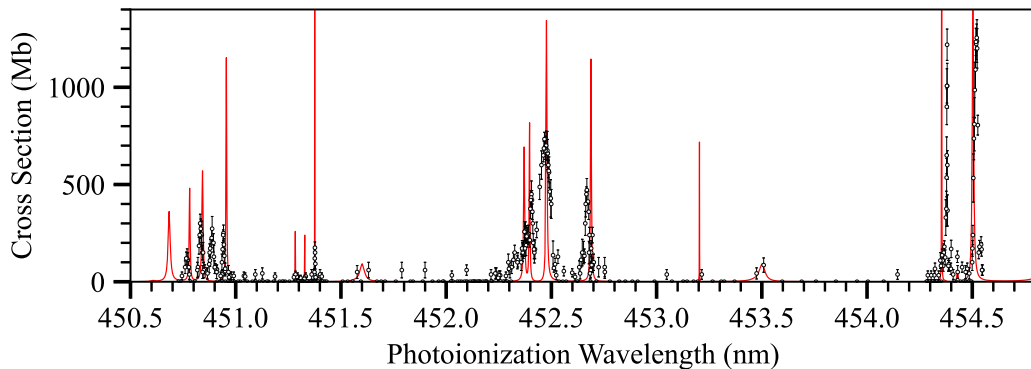


FIG. 2. Spectrum of the autoionizing resonances originating from the  $5d6p\ ^3D_1^o$  state. Data points show the measured cross section, and red lines indicate the theoretical calculations. The calculated peak positions are in reasonable agreement with the measured frequencies, although the peak heights of the narrower resonances exhibit a mismatch.

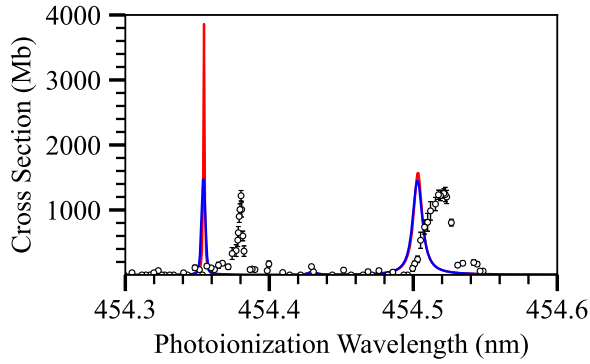


FIG. 3. Autoionization resonances to the  $5d_{3/2}15d_{3/2} J = 2$  state (right) and the  $5d_{3/2}15d_{5/2} J = 1$  state (left). The disagreement in the height of the autoionizing peaks relative to the theoretical calculations (red) is explained by Doppler broadening, as evidenced by the much closer agreement of the cross section produced by convolving the theoretical curve with a Gaussian profile (blue).

tionizing states. The full range of the spectroscopy is shown in Fig. 2.

A key objective of this spectroscopy was to compare the measured resonance structure with the theoretically calculated spectrum. The calculated spectrum provides a useful guide to the locations and relative strengths of the observed features, but quantitative comparison of the peak cross sections requires inclusion of Doppler broadening from the high-temperature ablation plume. This effect is especially important for the narrowest resonances. The plume temperature was estimated from the broadening of the first step  $6s^2 \ ^1S_0 \rightarrow 5d6p \ ^3D_1^o$  transition at 413 nm by fitting the line shape to a Voigt profile and extracting the Gaussian contribution. A Gaussian with a full width at half maximum corresponding to a temperature of 350 K was then convolved with the theoretical autoionization spectrum. Figure 3 shows the two strongest resonances before and after this convolution. Including Doppler broadening yields much closer agreement with the measured peak cross sections, particularly for the narrower resonance. We therefore expect colder atomic sources, such as magneto-optical trap loading, to produce less broadened and correspondingly stronger narrow resonances [23].

After surveying the full theoretical spectrum, taking into account the Doppler broadening effects, a strong resonance driving to the  $5d_{3/2}8d_{5/2} J = 2$  state at 530.8 nm was identified as the ideal peak for photoionization. This transition exhibits the highest cross section of the measured spectrum, and occurs at a wavelength where current laser technology can deliver extremely high power. Precision spectroscopy of this transition was performed with a 1.1 W fiber laser system, shown in Fig. 4. The cross section is experimentally confirmed to be  $(7400 \pm 870)$  Mb, which is consistent with the theoretical calculation within the experimental standard deviation.

To compare the characterized schemes with prior work, we also measured the previously studied pathway consisting of resonant excitation at 554 nm to the  $6s6p \ ^3P_1^o$  state followed by nonresonant ionization at 405 nm. This pathway was included to enable direct comparison with Greenberg *et al.* [11], who reported both the 405-nm scheme and a resonant autoionizing scheme at 389 nm. In the present work, the cross

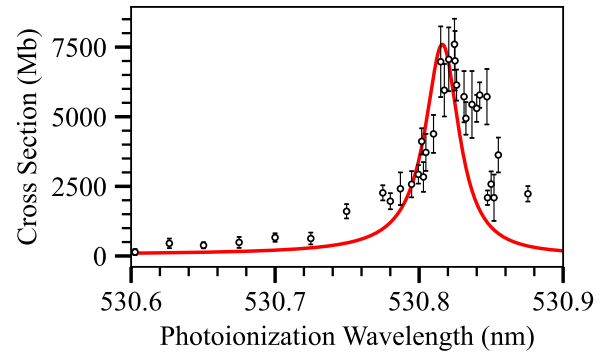


FIG. 4. Spectrum of the autoionizing resonances from the  $5d6p \ ^3D_1^o$  state. The measured spectrum (black points) agrees well with the theoretical prediction (red lines), without the application of additional broadening.

section at 405 nm was measured to be  $(72 \pm 3)$  Mb, in good agreement with our calculated value of 76 Mb. The 389-nm autoionizing transition was not measured here; instead, the loading results reported by Greenberg *et al.* [11] are used as an experimental benchmark. Specifically, Greenberg *et al.* [11] reported that the 389-nm scheme was approximately 7 times more efficient for trap loading than the 405-nm nonresonant scheme, whereas the ratio of the corresponding calculated cross sections in our model is approximately 17. No separate theoretical model was presented in Ref. [11].

It is important to consider the practical utility as well as the cross section when comparing the known photoionization pathways. An advantage of the developed 530.8-nm photoionization scheme is the abundance of laser power at this wavelength, which significantly enhances ion trap loading efficiency. This high laser power can be leveraged to linearly increase the loading rate up to an extremely high saturation limit. The saturation limit of this transition was calculated to be  $7.1 \text{ MW/cm}^2$ , owing to the fact that the lifetime of the autoionizing state is on the order of picoseconds. Figure 5 shows the linear relationship between the input laser intensity and the ion loading rate per ablation shot. The 413-nm

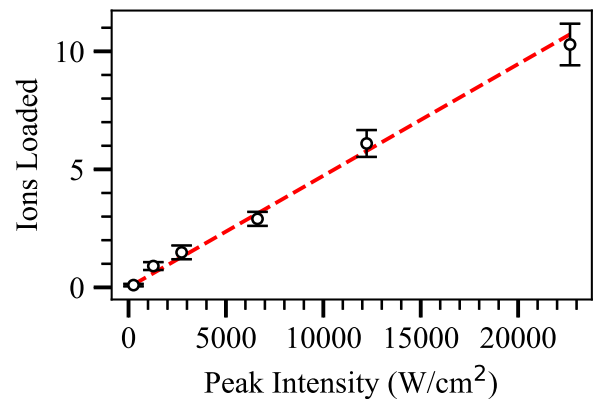


FIG. 5. Average number of ions loaded per ablation shot as a function of the 530.8-nm laser power. The red dashed line shows a linear fit to the data ( $\chi^2/\text{dof} = 1.01$ ), indicating that the loading remains linear over the explored power range with no evidence of saturation.

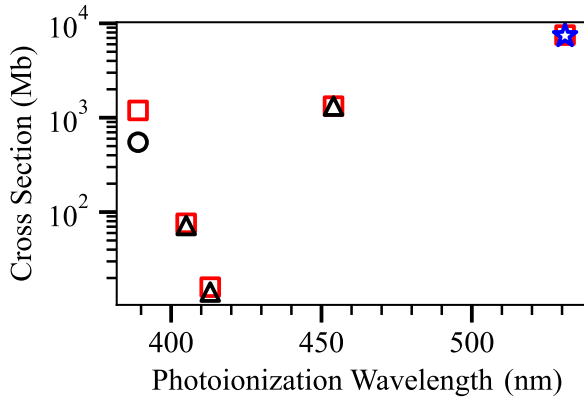


FIG. 6. Comparison of relevant photoionization cross sections. The blue star shows the cross section of the 530.8-nm transition. Black triangles are other measured cross sections in this work, and the black circle is the measured cross section in Ref. [11], driving from the  $6s6p\ ^3P_1^o$  state. Red squares are theoretical calculations from this work.

excitation beam was held fixed throughout the measurements, while the second-step spectroscopy beam power and beam size were held fixed within each spectral scan. We note that at sufficiently high loading rates or ion numbers, deviations from linearity can arise from nonlinear trap-loading dynamics, including effects associated with radio-frequency-induced heating in the ion trap.

## V. CONCLUSION

In summary, two autoionization pathways with high cross sections have been measured. Scheme 1, utilizing the autoionizing 454-nm transition, demonstrates a method that is roughly equal in photoionization efficiency and available laser power to the previously reported 389-nm autoionization

scheme. Scheme 2 drives the resonant 530.8-nm transition and shows approximately an order-of-magnitude increase in cross section over the 389-nm scheme. A comparison of the cross sections of all relevant photoionization pathways considered in this work is shown in Fig. 6. The higher cross section of Scheme 2 is coupled with the practical advantage of multiple orders of magnitude of increased available laser power, which directly translates to higher ionization rates. Additionally, the 530.8-nm transition, being in the visible spectrum, mitigates anomalous charging effects that are commonly observed with ultraviolet photoionization lasers. These capabilities are especially valuable for loading radioactive isotopes like  $^{133}\text{Ba}^+$ , where maximizing ion yield is essential for overcoming material scarcity and radioactivity constraints. By leveraging this transition, future ion trap experiments can achieve significantly faster and more reliable ion loading, reducing downtime and improving scalability for quantum technologies.

## ACKNOWLEDGMENTS

This work was supported in part by the Army Research Office under Grant No. W911NF-20-1-0037 and the National Science Foundation under Grants No. PHY-2207985, No. PHY-2207546, and No. OMA-2016245. The theory work at Purdue University by C.H.G. and J.D.P. was supported in part by the Air Force Office of Scientific Research Multidisciplinary University Research Initiative under Grant No. FA9550-20-1-0323. We thank Quantinuum for supplying the 554-nm laser used in this work.

## DATA AVAILABILITY

The data that support the findings of this article are openly available [24].

- 
- [1] S. A. Moses *et al.*, A race-track trapped-ion quantum processor, *Phys. Rev. X* **13**, 041052 (2023).
  - [2] Z. Mehdi, V. D. Vaidya, I. Savill-Brown, P. Grosser, A. K. Ratcliffe, H. Liu, S. A. Haine, J. J. Hope, and C. R. Viteri, Fast mixed-species quantum logic gates for trapped-ion quantum networks, *Phys. Rev. A* **112**, L050601 (2025).
  - [3] A. Ransford, M. S. Allman, J. Arkinstall, J. P. Campora III, *et al.*, A 98-qubit trapped-ion quantum computer with all-to-all connectivity, *Nature* **655**, 81 (2026).
  - [4] D. T. C. Allcock, W. C. Campbell, J. Chiaverini, I. L. Chuang, E. R. Hudson, I. D. Moore, A. Ransford, C. Roman, J. M. Sage, and D. J. Wineland, *omg* blueprint for trapped ion quantum computing with metastable states, *Appl. Phys. Lett.* **119**, 214002 (2021).
  - [5] H.-X. Yang, J.-Y. Ma, Y.-K. Wu, Y. Wang, M.-M. Cao, W.-X. Guo, Y.-Y. Huang, L. Feng, Z.-C. Zhou, and L.-M. Duan, Realizing coherently convertible dual-type qubits with the same ion species, *Nat. Phys.* **18**, 1058 (2022).
  - [6] C. Mordini, A. Ricci Vasquez, Y. Motohashi, M. Müller, M. Malinowski, C. Zhang, K. K. Mehta, D. Kienzler, and J. P. Home, Multizone trapped-ion qubit control in an integrated photonics QCCD device, *Phys. Rev. X* **15**, 011040 (2025).
  - [7] J. E. Christensen, D. Hucul, E. R. Hudson, and W. C. Campbell, High-fidelity manipulation of a qubit enabled by a manufactured nucleus, *npj Quantum Inf.* **6**, 35 (2020).
  - [8] D. Hucul, J. E. Christensen, E. R. Hudson, and W. C. Campbell, Spectroscopy of a synthetic trapped ion qubit, *Phys. Rev. Lett.* **119**, 100501 (2017).
  - [9] M. J. Boguslawski, Z. J. Wall, S. R. Vizvary, I. D. Moore, M. Bareian, D. T. C. Allcock, D. J. Wineland, E. R. Hudson, and W. C. Campbell, Raman scattering errors in stimulated-Raman-induced logic gates in  $^{133}\text{Ba}^+$ , *Phys. Rev. Lett.* **131**, 063001 (2023).
  - [10] S. R. Vizvary, Z. J. Wall, M. J. Boguslawski, M. Bareian, A. Derevianko, W. C. Campbell, and E. R. Hudson, Eliminating qubit-type cross-talk in the *omg* protocol, *Phys. Rev. Lett.* **132**, 263201 (2024).
  - [11] P. J. L. N. Greenberg, B. M. White, and C. Senko, Trapping  $\text{Ba}^+$  with seven-fold enhanced efficiency utilizing an

- autoionizing resonance, *Quantum Sci. Technol.* **9**, 035023 (2024).
- [12] G. Leschhorn, T. Hasegawa, and T. Schaetz, Efficient photoionization for barium ion trapping using a dipole-allowed resonant two-photon transition, *Appl. Phys. B* **108**, 159 (2012).
- [13] B. M. White, P. J. Low, Y. de Sereville, M. L. Day, N. Greenberg, R. Rademacher, and C. Senko, Isotope-selective laser ablation ion-trap loading of  $^{137}\text{Ba}^+$  using a  $\text{BaCl}_2$  target, *Phys. Rev. A* **105**, 033102 (2022).
- [14] D. J. Armstrong, R. P. Wood, and C. H. Greene, Photoionization of the  $5d6p\ ^3D_1$  state of barium, *Phys. Rev. A* **47**, 1981 (1993).
- [15] A. V. Steele, L. R. Churchill, P. F. Griffin, and M. S. Chapman, Photoionization and photoelectric loading of barium ion traps, *Phys. Rev. A* **75**, 053404 (2007).
- [16] R. P. Wood, C. H. Greene, and D. Armstrong, Photoionization of the barium  $6s6p\ ^1P^\circ_1$  state: Comparison of theory and experiment including hyperfine-depolarization effects, *Phys. Rev. A* **47**, 229 (1993).
- [17] M. Harlander, M. Brownnutt, W. Hänsel, and R. Blatt, Trapped-ion probing of light-induced charging effects on dielectrics, *New J. Phys.* **12**, 093035 (2010).
- [18] D. M. Lucas, A. Ramos, J. P. Home, M. J. McDonnell, S. Nakayama, J.-P. Stacey, S. C. Webster, D. N. Stacey, and A. M. Steane, Isotope-selective photoionization for calcium ion trapping, *Phys. Rev. A* **69**, 012711 (2004).
- [19] M. Qiao, Y. Wang, Z. Cai, B. Du, P. Wang, C. Luan, W. Chen, H.-R. Noh, and K. Kim, Double-electromagnetically-induced-transparency ground-state cooling of stationary two-dimensional ion crystals, *Phys. Rev. Lett.* **126**, 023604 (2021).
- [20] M. Aymar, C. H. Greene, and E. Luc-Koenig, Multichannel Rydberg spectroscopy of complex atoms, *Rev. Mod. Phys.* **68**, 1015 (1996).
- [21] P. C. M. Aymar and A. E. Himdy, Multichannel quantum defect analysis of the autoionized even-parity spectrum of neutral barium below the  $5d\ ^2D_3/2$  limit, *Phys. Scr.* **27**, 183 (1983).
- [22] C. H. Greene and M. Aymar, Spin-orbit effects in the heavy alkaline-earth atoms, *Phys. Rev. A* **44**, 1773 (1991).
- [23] J. Johansen, B. Estey, M. Rowe, and A. Ransford, in *2022 IEEE International Conference on Quantum Computing and Engineering (QCE)* (IEEE, New York, 2022), pp. 299–303.
- [24] Z. J. Wall, J. D. Piel, S. R. Vizvary, M. Bareian, S. Diaz, E. Mossman, A. Ransford, C. H. Greene, E. R. Hudson, and W. C. Campbell, Autoionization Data, Zenodo, 2026, doi:10.5281/zenodo.20804794.