

Laser-fluence-dependent production of molecular thorium ions in different charge states for trapped-ion experiments

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Thorium ions and molecules, recognized for their distinctive nuclear and atomic attributes, are central to numerous trapped-ion experiments globally. Our study introduces an effective, compact source of thorium atomic and molecular ions produced via laser ablation of microgram-scale, salt-based samples. We thoroughly analyze the variety of ion species and charge states generated at varying laser fluences. Utilizing 10 μg of thorium fluoride crystals and laser fluences between 1.00(5) and 6.75(35) J/cm^2 , we produce thorium molecular ions $^{232}\text{ThF}_x^{n+}$ (with $x = 0-3$ and charge states up to $n = 3$), including ThF^{2+} and ThF^{3+} . These species are particularly relevant for spectroscopy; ThF^{3+} is valuable due to its stable closed-shell configuration, while ThF^{2+} , which is isoelectronic to RaF , offers a unique probe for studying nuclear structure and fundamental symmetries due to its simple electronic structure with a single unpaired electron. Density-functional-theory-based calculations of the electric charge distribution aid in understanding the formation of the observed species. Positive charges are found to be mainly located on the thorium atom, which points to an inhibition of immediate Coulomb explosion, thus supporting the existence of the observed ion species. The simplicity of the method and similarities among the actinide elements suggest that our approach will also be applicable to other actinide species.

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I. INTRODUCTION

The element thorium, particularly the isotope ^{229}Th , is a central focus of recent research due to the exceptionally-low-energy nuclear excited state ^{229m}Th , located above the ground state at 8.355 729 193 198(8) eV [1–3]. The recent excitation from the nuclear ground state via VUV-laser light provides an opportunity for the development of a nuclear clock [4–6] and the investigation of potential temporal variations of fundamental constants [7,8]. Such temporal variations of fundamental constants may arise from galactic ultralight bosonic dark matter or scalar dark matter [9] and can be investigated in thorium ions or molecular ions. In particular, thorium molecular ions exhibit significant sensitivity enhancements to various beyond-the-standard-model phenomena such as electric dipole moments, which are a signature of charge-parity (CP) violation [10–17]. There is a significant interest in thorium molecular ions with the isotope ^{229}Th ,

such as $^{229}\text{ThOH}^+$ and $^{229}\text{ThF}^+$, due to possibly large enhancements of CP violation by nuclear structure via potential octupole deformations [13,15,18].

While thorium monofluoride in the charge state of $1+$ is already at the center of a variety of spectroscopy experiments [19–21], the production of thorium monofluoride and molecular actinide ions in higher charge states has barely been studied. Molecules like ThF^{3+} appear promising in the use of spectroscopy experiments due to a stable closed-electronic-shell configuration [22]. Furthermore, ThF^{2+} is isoelectronic to RaF [22]. RaF has a simple electronic structure with essentially one unpaired electron above energetically well separated closed electronic shells and therefore provides unique opportunities for the investigation of nuclear structure and fundamental symmetries [23–27]. ThF^{2+} could combine the advantages of actinide molecules [28] discussed above with the advantages of RaF and ions, which are comparatively easy to trap and cool.

Laser ablation from a target is one of the most commonly used offline ion-production methods for loading thorium ions into a Paul or Penning trap. Due to the significantly longer half-life of ^{232}Th ($t_{1/2} = 1.4 \times 10^{10}$ yr) compared to, e.g., ^{229}Th ($t_{1/2} = 7.8 \times 10^3$ yr), the specific activity of ^{232}Th is comparatively small, making the handling of larger quantities of material easy. Therefore, typically, experiments of this

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TABLE I. Applied voltages U (in kV) of the ion gun and MCP detector.

Cage anode energy	Extractor extraction	Focus tube		Filament emission	MCP	
		Focus 1	Focus 2		Front end	Back end
1.50	1.16	1.23	0	10 mA	−2.40	0.30

kind start with the ablation of ^{232}Th in different chemical forms (e.g., from metal targets). Laser ablation of ^{232}Th ions was demonstrated in [29–33], as well as in the Trapped And Cooled Thorium Ion spectroscopy via Calcium (TACTiCa) project [34,35]. A challenge of laser ablation of rare and short-lived isotopes such as $^{228,229,230}\text{Th}$ is the very limited availability of material and the larger specific activity, making the handling of larger quantities of material practically impossible. For laser ablation of ^{229}Th , Th-containing salt-based samples have been ablated directly [36,37]. When producing atomic thorium ions, sufficiently high laser power can result in ions attaining charge states higher than $1+$. Laser ablation for thorium ions in the $3+$ charge state was reported by Campbell *et al.* [29,36] and for molecular thorium oxide ions in the $2+$ charge state ($^{232}\text{ThO}^{2+}$) by Li *et al.* [38]. The laser power density plays a decisive role in the ablation process, as it not only influences the production of higher charge states, but also determines the formation of thorium oxide or pure thorium clusters when appropriately optimized [39].

Here we aim at the production of thorium molecular ions and study in detail how to optimize the ablation parameters accordingly for desired production of molecular ion species in different charge states. One method is that preexisting impurities in the thorium foil directly lead to the formation of desired molecules such as thorium oxide (ThO^+) [38,40]. Also, in-flight chemical reactions can be employed, where atomic ions produced during laser ablation interact with a buffer gas [41]. We optimize the laser pulse fluence and directly use target materials that already contain the desired ions, such as using ThF_4 crystals to generate ThF^+ ions. As a result, we show that this mitigates the requirement of buffer-gas mixtures containing carbon tetrafluoride (CF_4) which are introduced during the ablation process to produce singly charged thorium monofluoride (ThF^+) ions [41–43] or larger molecules like ThF_{2-4}^+ [44], thus maintaining UHV conditions during the entire production process. Another asset is that our method is not limited to singly charged molecules [45,46], due to electron capture in the buffer-gas reactions, but we demonstrate the creation of higher charge states. Also, our method is favorable, to produce multiply charged ions ($n+ > 2$) experimentally, as compared to a much more demanding production process of, e.g., triply charged actinide molecules by ion-ion collisions [47].

In this work, we present a novel and practical pulsed laser ablation and ionization source as a tabletop device for producing actinide molecular ions in charge states up to $3+$ as part of the TACTiCa project at Johannes Gutenberg University Mainz, Germany [48]. By varying the laser fluence Ψ , we selectively produce any of several thorium fluoride molecules in different charge states. Quantum chemical calculations of charge distributions in ThF_x^{n+} ions are performed to support understanding of the feasibility of producing multiply

charged molecular thorium fluoride ions. The direct production of exotic molecular ions through the ablation of salt-based samples enables experiments in an ultrahigh-vacuum environment without the need for differential pumping or reliance on gas-phase reactions, targeting for high-precision measurements.

II. METHODOLOGY

A. Experimental setup and calibration of the time-of-flight mass spectrometer

We have built a new time-of-flight (TOF) mass spectrometer to investigate microgram targets ablated by laser light with different fluences to produce molecular actinide-ion species for trapped-ion experiments. Laser ablation is employed to vaporize or directly ionize material from the target material within an ultrahigh-vacuum environment, inside of a modified ion sputter gun (SPECS IQE 12/38) (see Fig. 1). The ion gun consists of a filament or cathode for emitting electrons for electron impact ionization, a repeller to repel the produced electrons, a cage anode to set the starting kinetic energy of the produced ions, an extractor for extraction of the ions and ion optics, and a focus tube and two electrostatic deflectors for manipulating the resulting ion beam (see Fig. 1). After traversing a drift tube, ions are detected by two multichannel plates (MCPs) in combination with a delay-line anode (Reontdek DLD40f). The MCP is operated with a high gain (greater than 10^7), and the delay-line anode system includes a carefully tuned drift region with an optimized potential difference of $+300$ V between the back end of the MCP and the anode wires. Therefore, reliable signal formation of heavy-ion species, such as ThF_3^{n+} , is ensured under these conditions. The flight path of the ions is approximately 1.7 m long. For all experiments and for the calibration of the apparatus, the same experimental parameters of the ion gun and the MCPs were used, which can be found in Table I.

For the ablation of metallic and salt-based targets from a ceramic target holder, the ion gun is modified (see Fig. 1). A Coherent FLARE NX71 515-0.6-2 laser, operating at a wavelength of $\lambda = 515 \pm 5$ nm with a pulse duration of 1.3 ± 0.2 ns and an energy output of $E = 300 \pm 15$ μJ , is employed for laser ablation. The laser's focused beam, with a diameter of 70 ± 7 μm , vaporizes the target material, producing a plasma consisting of ions, neutrals, and electrons.

To produce ions over a large range in mass-to-charge ratio for calibration purposes we ablated different nonactinide samples. For the production of nonactinide ions and operating at nonionizing laser fluences, electron impact is used for ionization. At nonionizing laser fluences, laser ablation vaporizes the target material and produces neutral species, which are moving towards the cage anode. The neutral species are then ionized by electron impact, stemming from the

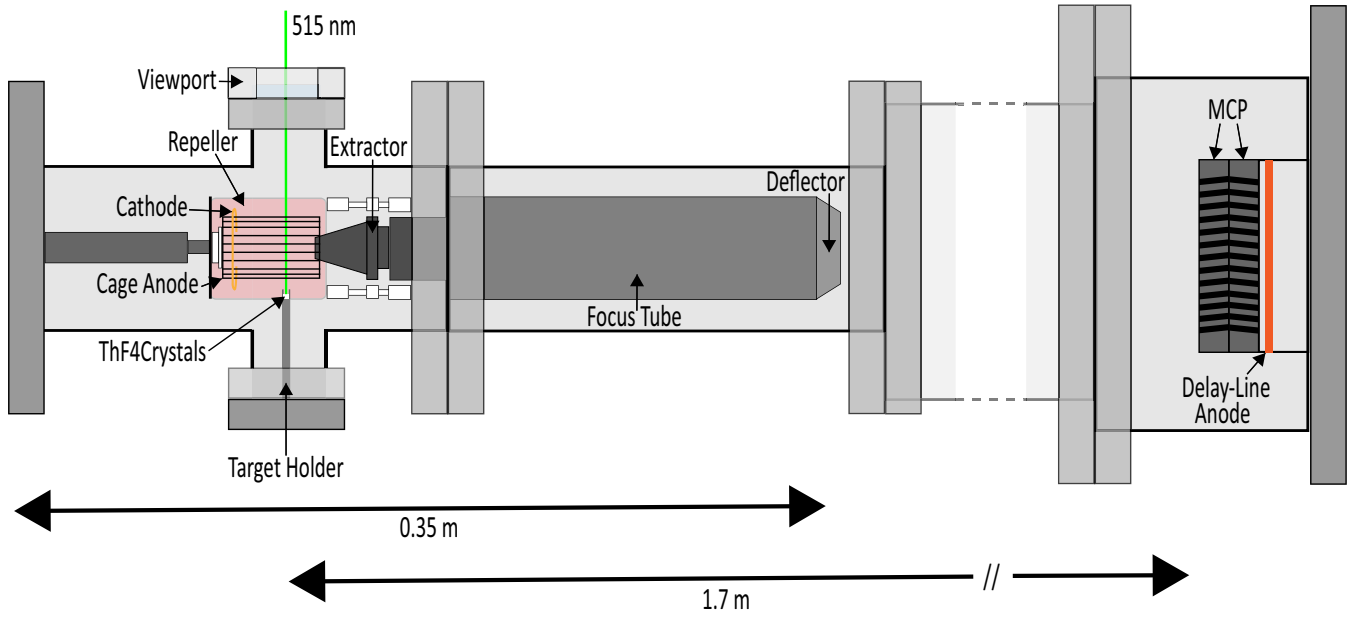


FIG. 1. Schematic of the TOF mass spectrometer, including the modified ion gun (SPECS IQE 12/38), used for salt-based and metallic targets, and two MCPs in combination with a delay-line anode (Reontdek DLD40f) for ion detection (not to scale). The modular setup allows an easy installation of an ion trap between the ion gun and detector.

electron-emitting iridium-coated tungsten cathode, inside the cage anode. The emitted electrons are accelerated to the tungsten cage anode and then repelled by the repeller so that the highest electron density is in the center of the repeller (see Fig. 1). Following ablation and ionization, ions are extracted by the extractor at a voltage of 1.5 kV, for best focus of the ion beam onto the detector. The resulting ion beam is focused into a diameter of 160 μm using the two electrostatic lenses of the focus tube. The ion flight path can be manipulated by two electrostatic defectors, which were not used in the experiments.

All measurements for nonactinide species were performed with the electron-emitting cathode on. By measuring and analyzing TOF spectra of nonactinide ions, a calibration was obtained (see Fig. 2). Actinide-ion species were assigned according to their mass-to-charge ratio and thus identified. To calibrate the setup, the proportional dependence between flight time and mass-to-charge ratio is used [see Eq. (1)]. This results in the following fit equation, in which a is a proportionality factor and b is a time offset:

$$S_{\text{TOF}} = a\sqrt{\frac{m}{q}} + b. \quad (1)$$

Samples of metallic ^{232}Th , lead, and titanium were used to set calibration points. In addition, carbon, oxygen, and molecular combinations of the two elements were also found in all metallic samples. These points also served as calibration aids for the different spectra. A weighted fit is performed, with the weight of a data point corresponding to the reciprocal quadratic value of the TOF uncertainty. Plotting the TOF against the $\frac{m}{q}$ ratio results in the fit curve shown in Fig. 2.

The resulting fit parameters are $a = 2.892(6) \mu\text{s}/\sqrt{u}$ and $b = 2.72(7) \mu\text{s}$, where b represents the timing offset of the arriving ions. In the following, time-of-flight spectra are

converted into mass-over-charge spectra, with the charge being $q = 1$, with the aid of the determined fit equation as follows:

$$\frac{m}{q} = \left(\frac{S_{\text{TOF}} - b}{a} \right)^2. \quad (2)$$

The mass resolving power R of our time-of-flight spectrometer is obtained as

$$R = \frac{m}{\Delta m} \approx \frac{S_{\text{TOF}}}{2 \Delta S_{\text{TOF}}} \approx 150, \quad (3)$$

where ΔS_{TOF} is defined as the FWHM of the peaks in the TOF spectrum and experimentally determined. Equation (3) is a result of Gaussian error propagation, considering that the mass resolving power is dominated by the widths of the peaks in the TOF spectrum. Experimentally, we find that the mass resolving power also depends on the laser fluence, which was kept at its maximum for Fig. 2. Varying the fluence allowed us obtaining high enough resolution for an unambiguous identification of each species shown in Fig. 3.

For the ablation of thorium fluoride, the target material, consisting of 10 μg of $^{232}\text{ThF}_4$ crystals, is directly synthesized in a notch of a MARCOR ceramic target rod by the reaction of thorium nitrate and hydrofluoric acid. Detailed information about the synthesis and the purity of ThF_4 can be found in the Supplemental Material [49]. Given the smallness of the sample, the approach is directly applicable for the use of exotic thorium isotopes like ^{229}Th or other rare actinide and nonactinide samples. After ablation in combination with direct ionization by the laser, the produced molecular or atomic ions are accelerated by the cage anode and extracted by the extractor by a voltage of 1.5 kV, focused, and detected by the detector.

For producing ions from the ThF_4 target, the electron beam was activated. However, the deactivation of the electron beam

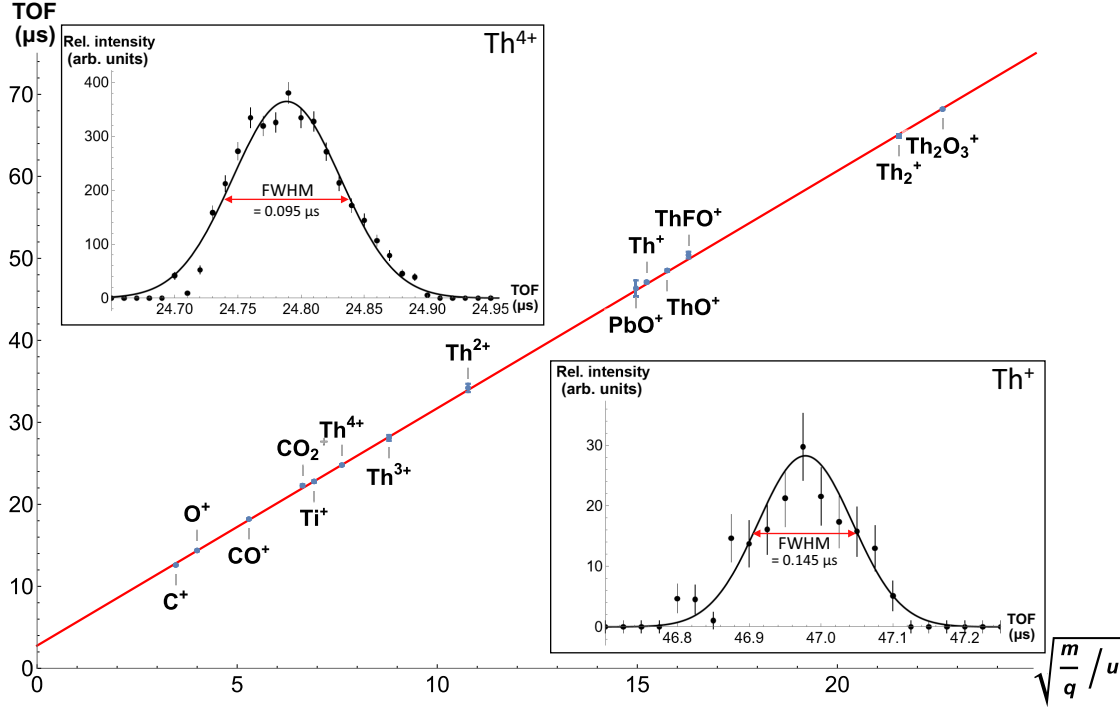


FIG. 2. Calibration fit of different compounds relating the TOF with $\sqrt{m/q}$. The insets show exemplarily the TOF spectra of Th^{4+} and Th^+ .

did not influence the TOF results for actinide-ion species. Apparently, the ionization process of Th ions and molecular ions is fully dominated by the laser pulse induced processes.

B. Quantum chemical calculations of charge distributions in ThF_x^{n+} molecular ions

From previous studies of triply charged uranium monofluoride (UF^{3+}) [47] we expect ThF^{n+} to be stable for $n \leq 3$. Moreover, the thermodynamic stability of similar actinide

monofluoride ion species was theoretically studied before [22,50]. Based on these studies, we assume that additional fluoride atoms carry essentially no positive charge. We expect that ThF_x^{n+} with $x + n \leq 5$ may be (meta)stable and therefore could be observed in the mass spectrum. To support this assumption we computed the charge distribution in the produced molecules. Accurate calculations of the thermodynamic stability of the studied molecules and investigations of their spectroscopic suitability for studies of fundamental physics will be subject of a separate study [51].

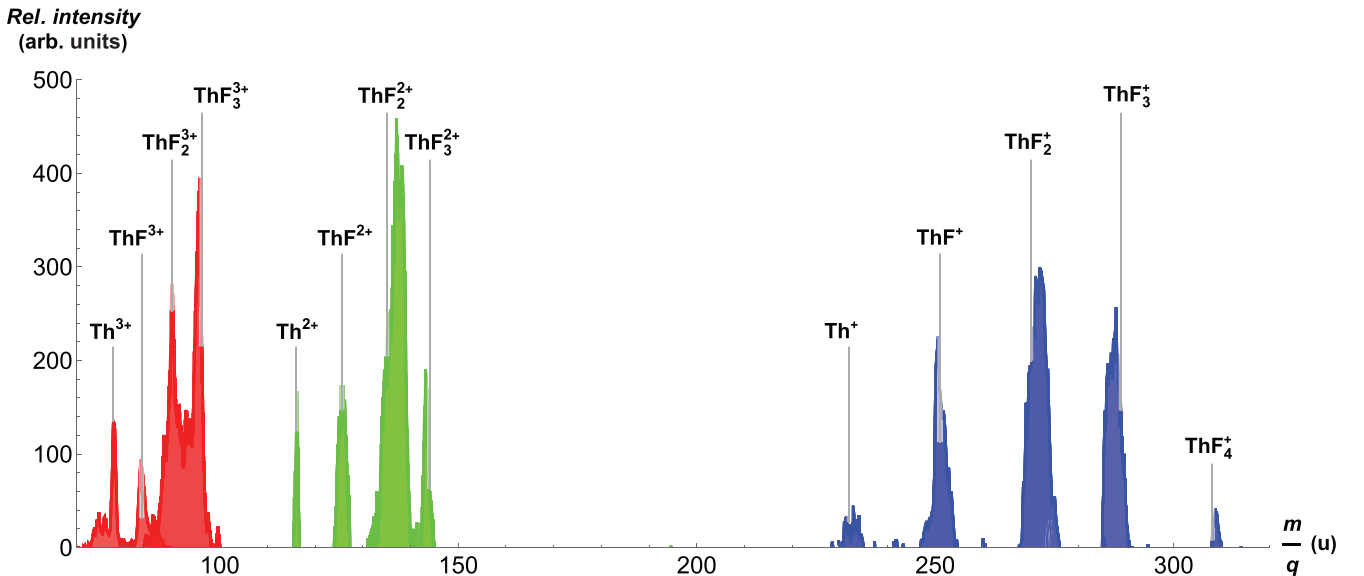


FIG. 3. Spectra of measured atomic and molecular Th ions in charge states 1+ (blue), 2+ (green), and 3+ (red). Nine individual spectra recorded at the fluences listed in Table III are summed.

All density-functional-theory-based calculations were performed with a modified version [22,52] of a two-component program [53] based on Turbomole [54]. We employed the exchange correlation functional by Perdew, Burke, and Ernzerhof [55] in a hybrid version with 50% Fock exchange (PBE50) [56]. All calculations were performed within a quasirelativistic complex generalized Kohn-Sham framework including relativistic effects on the two-component zeroth-order regular approximation (2CZORA) level. The 2CZORA was employed with a damped model potential to alleviate the gauge dependence [57,58]. The Hilbert space was sampled with atom-centered Gaussian basis functions using the core-valence basis set of triple- ζ quality by Dyall (dyall.cv3z) [59,60]. The nuclear charge density distribution was modeled as a normalized spherical Gaussian $\rho_K(\vec{r}) = \frac{\zeta_K^{3/2}}{\pi^{3/2}} e^{-\zeta_K|\vec{r}-\vec{r}_K|^2}$, with $\zeta_K = \frac{3}{2r_{\text{nuc},K}^2}$. The root-mean-square radius $r_{\text{nuc},K}$ was chosen as suggested by Visscher and Dyall by employing the isotopes ^{19}F and ^{232}Th [61]. Electronic densities were converged until the change of the total energy between two consecutive cycles in the self-consistent-field procedure was below $10^{-10} E_h$. Molecular structures were optimized until the change of the norm of the gradient with respect to nuclear displacements was below $10^{-3} E_h/a_0$ and the change of the total energy was below $10^{-6} E_h$. Obtained molecular structure parameters are provided in the Supplemental Material [49]. The supposedly lowest-lying electronic states were found using the closed-shell species ThF^{3+} , ThF_2^{2+} , and ThF_3^{+} as starting points and adding or removing sequentially electrons. This method does not guarantee finding the global minimum, and therefore energetically lower-lying electronic states may exist on the level of 2CZORA-PBE50/dyall.cv3z. However, we do not expect an essential change in the charge distribution in potential energetically lower-lying states. For reproducibility, the obtained electronic states were characterized by computing the reduced total electronic angular momentum $\vec{J}_e = \vec{L} + \vec{S}$, where $\vec{L}$ and $\vec{S}$ are the electronic orbital and spin angular momenta, respectively. In addition, we computed the expectation value of $\hat{S}^2$, $S(S+1)$. Although L_z , S_z , and S are not good quantum numbers in a relativistic framework, they can be used to estimate the composition of the spin symmetry-broken determinant from configuration state functions of nonrelativistic symmetry (see also Refs. [22,50]). Angular momenta of the computed states of ThF_x^{n+} molecules are listed in the Supplemental Material [49]. For nonlinear molecules, the direction of $\vec{J}_e$ is arbitrary and we report only the length of the angular momentum vector. Linear molecules were oriented with the molecular axis aligned to the z axis. The total angular momentum of diatomic molecules was aligned essentially to the z axis as well. Therefore, for diatomic molecules $\Omega = |\vec{J}_e|$ and analogously for other angular momenta. For the optimized electronic states, we computed the distribution of electrons over the nuclei using a simple Mulliken population analysis.

III. RESULTS AND DISCUSSION

The experiments revealed the formation of various charged species of thorium fluoride from laser ablation. As depicted in Fig. 3, we observed that the mass-over-charge ratios of these ions suggest the presence of both atomic and molecular

thorium ions as $^{232}\text{ThF}_x^{n+}$, with $x = 0-3$ and ionization states up to $n = 3+$ (see Table III). A general trend is seen, that tri- and tetratomic molecular ions have a higher relative intensity compared to mono- and diatomic ions, with the highest relative intensity at ThF_2^{2+} . Through ablation of the thorium fluoride target by varying the laser power in combination with different laser spot sizes, it was possible to determine the optimum fluence ranges. The optimum fluence range in which the respective ion species achieves the highest intensity relative to all the observed species can be found in Table III.

In Fig. 3, the gray vertical lines show the calculated $\frac{m}{q}$ positions of the respective ions based on the calibration curve. The experimental peaks were identified by their centers. These lie on the calculated masses within the experimental uncertainty. Minor deviations between the expected and observed peak positions may arise from detector saturation effects [62,63], particularly for intense and closely spaced peaks. However, the purity of the crystals was confirmed by additional analysis, which excludes foreign ions (see [49]).

We conjecture that the ability to produce thorium molecular ions in higher charge states is primarily attributable to (i) the fact that the initial three ionization energies of the thorium atom (6.30, 12.10, and 18.32 eV [64]) are lower than the dissociation energy of actinide fluoride bonds [22,65,66] and (ii) the charge being predominantly localized on the central thorium atom, which inhibits a Coulomb explosion. Both factors combined allow the central thorium atom to be ionized before dissociation of the Th-F bond occurs. To support assumption (ii) we computed Mulliken partial charges of ThF_x^{n+} ions as detailed in Sec. II B. The results are shown in Table II. These partial charges suggest that the charge of ThF_x^{n+} , with $x + n < 5$, is almost exclusively located at Th with the fluorine atoms being neutral or bearing slight negative charges. The calculations indicate that in ThF_2^{3+} , ThF_3^{2+} , and ThF_3^{3+} a small fraction of the charge may be moved to one of the fluorine atoms. This could be explained by the removal of an electron from a Th-F bond which is in line with elongated Th-F bonds for these species (see the table in the Supplemental Material [49]). However, the charge on the fluorine atoms seems to be small enough to inhibit immediate Coulomb explosion of these molecular species. A quantitative discussion of the thermodynamic stability of the observed

TABLE II. Mulliken partial charges of ThF_x^{n+} with $x, n = 1, 2, 3$ molecular ions computed at the level of 2CZORA-PBE50/dyall.cv3z for the optimized electronic states (see Sec. II B and Supplemental Material for details [49]).

Molecule	δ_{Th}/e	δ_{F1}/e	δ_{F2}/e	δ_{F3}/e
ThF^{+}	+1.31	-0.31		
ThF^{2+}	+2.21	-0.21		
ThF^{3+}	+3.00	0.00		
ThF_2^{+}	+1.64	-0.32	-0.32	
ThF_2^{2+}	+2.37	-0.19	-0.19	
ThF_2^{3+}	+2.79	+0.23	-0.02	
ThF_3^{+}	+2.02	-0.34	-0.34	-0.34
ThF_3^{2+}	+2.28	+0.10	-0.19	-0.19
ThF_3^{3+}	+2.59	+0.23	+0.23	-0.04

TABLE III. Production of atomic and fluoride-containing Th ions in charge states 1+ to 3+. The table shows the fluence Ψ (in J cm^{-2}) ranges in which the respective species dominates.

Ion species	3+	2+	1+
Th	6.75 ± 0.35	4.00 ± 0.20	2.80 ± 0.15
ThF	5.20 ± 0.30	2.40 ± 0.25	1.40 ± 0.05
ThF ₂	1.60 ± 0.05	1.50 ± 0.05	1.40 ± 0.05
ThF ₃	1.60 ± 0.05	1.50 ± 0.05	1.00 ± 0.05
ThF ₄			2.80 ± 0.15

species requires calculating energies of all possible dissociation channels or potential energy curves for all ThF_x^{n+} , which will be provided in a separate work [51].

In Fig. 3 we examine the $\frac{m}{q}$ of approximately 77, where both Th^{3+} and ThF_4^{4+} could be identified as the produced species. Compared to observations of the formation of ThF_2^{2+} at a fluence of 2.40 J cm^{-2} , Th^{3+} is formed as a result of the complete dissociation of all bonds. This is underlined within the fluence range of $2.80\text{--}4.00 \text{ J cm}^{-2}$ resulting in Th^+ and Th^{2+} (see Table III), while no ThF_4^{2+} could be observed at a fluence of 2.40 J cm^{-2} . The trend of bond dissociation with laser fluence ranging from 2.00 to 6.75 J cm^{-2} is more likely to occur before leading to higher charge stages. In contrast, the process of bond dissociation is less dominant in the range from 1.00 to 2.00 J cm^{-2} , and reaching molecular ions in higher charge states does not necessitate significant increases in fluence, unlike for atomic thorium ions. This is particularly relevant as the thorium fluoride sample does not exhibit a perfect crystal structure, caused by the chemical synthesis reaction chosen, resulting in the production of ThF_x^{n+} instead of ThF_4^{n+} (both $n = 1\text{--}3$) after ablation. A crystallographically grown thorium fluoride crystal will probably have a smaller defect density. A direct statement about the dissociation process by analyzing the peak shape cannot be made, due to the extraction of the ions. Although dissociation processes could in principle lead to kinetic energy release and peak broadening, the use of lateral extraction at 1.5 kV significantly suppresses energy-dependent TOF spread for energies as they emerge from dissociation processes. All observed peaks exhibit Gaussian shapes without discernible asymmetries.

The formation of atomic thorium (Th^{n+}) and thorium monofluoride (ThF^{n+}) ions is significantly influenced by the application of a laser fluence above 2.00 J cm^{-2} . The relative intensities of the signals are comparably low for tri- and tetratomic ion species. During the ion production, a substantial ion loss occurs due to the ablation process itself at fluences above 2.00 J cm^{-2} , which leads to ion absorption by the walls of the sample holder or other parts of the apparatus leading to low relative intensities. In contrast, at fluences below 2.00 J cm^{-2} , the ablated ions are concentrated in a smaller plasma volume, leading to higher intensities.

The range of $2.00\text{--}3.00 \text{ J cm}^{-2}$ represents the threshold between the processes of direct ionization and bond dissociation. This is demonstrated by the simultaneous laser-induced production of Th^+ and ThF_4^+ . In this scenario, the majority of the energy goes into bond dissociation, while the residual

energy facilitates production of ThF_4^+ . These observations highlight the complex interplay between direct ionization, vaporization, and bond dissociation in the production of various ionic species. This indicates that different ionic species require distinct conditions for effective ionization, potentially affecting the overall efficiency and selectivity of the ion generation process.

The MCP detection efficiency depends on the ion impact velocity, which scales as $v \propto \sqrt{q/m}$. Heavier ions with lower charge states (e.g., ThF_3^+) have lower velocities than lighter or more highly charged species (e.g., ThF_3^{3+}), which results in a reduced detection efficiency. Experimental studies have shown that MCP detection efficiency can vary by up to a factor of 2 for ions whose impact velocities differ by a factor of $\sqrt{3}$ [67–69]. While this may influence the absolute intensity ratios between ions of different charge states, it does not affect species identification or the interpretation of relative production trends within a given charge state.

Further investigation is needed to determine if production of higher charge states than 3+ in molecular thorium ions is possible or if Coulomb repulsion precludes the formation of such ions.

IV. OUTLOOK FOR FURTHER WORK

Direct laser ablation of thorium fluoride crystals effectively generates atomic thorium ions and thorium fluoride ions in charge states up to 3+. This newly designed tabletop TOF source can be used to load atomic and molecular ions of thorium with chosen charge states into ion traps due to its modularity (see Fig. 1).

These experiments highlight the potential of microgram thorium fluoride crystals as laser ablation targets for applications in the exploration of physics beyond the standard model (BSM). While ^{232}Th was used in this work due to its availability and long half-life, this method can be adapted to more rare isotopes such as ^{228}Th , ^{229}Th , and ^{230}Th , through microgram-scale synthesis techniques.

This approach can likely be extended to the production of other actinide molecules AnF_x^{n+} , where the dissociation energy of the actinide fluoride bond is higher than the ionization energy of the actinide atom and also where the charge would similarly reside on the central actinide atom [22]. Several molecules of these type are also relevant to BSM physics [28], highlighting the potential for broader applicability and paving the way for future studies and technological advancements in this area.

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(original draft); D.R., resources and writing (review and editing); F.S.-K., funding acquisition, supervision, and writing (review and editing); A.T., investigation and writing (review and editing); and L.v.d.W., resources and writing (review and editing).

DATA AVAILABILITY

The data supporting this study's findings are available within the article.

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