



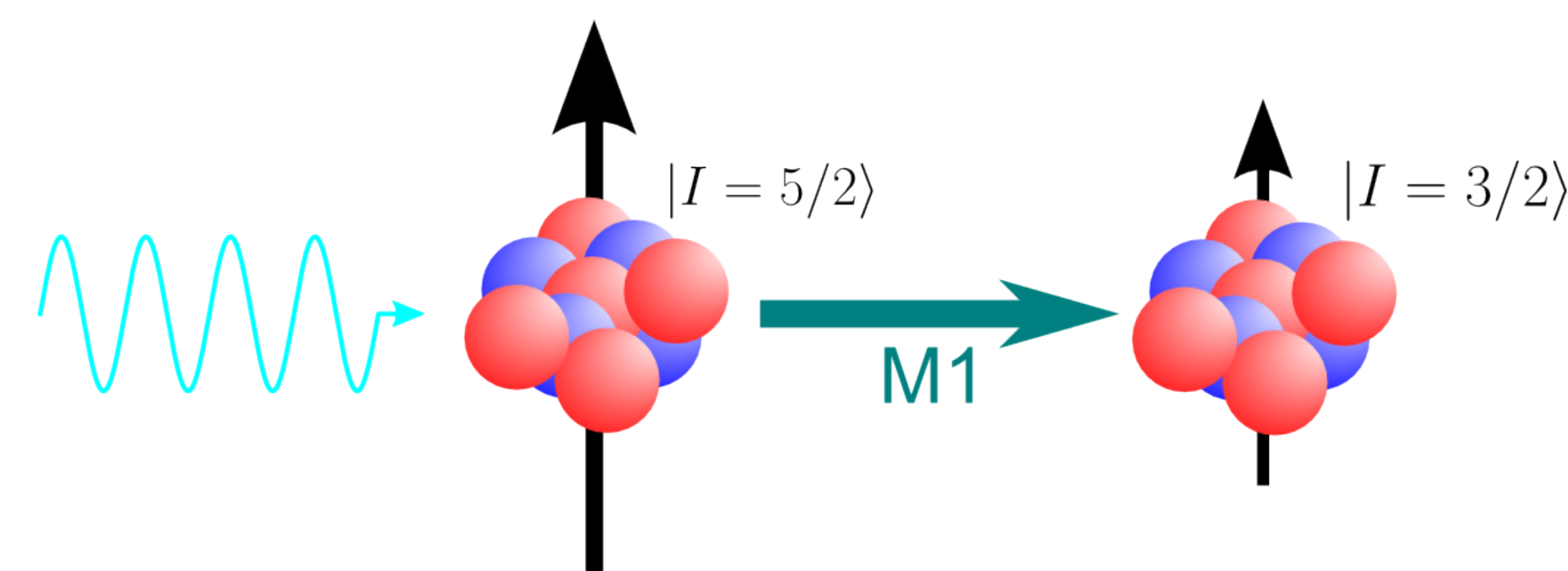
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## Motivation

$^{229}\text{Th}$  has the lowest known nuclear excited state at  $7.6 \pm 0.5$  eV above the ground state [1]. Compared to most nuclear transitions in the keV to MeV range, this is low enough to be accessible to table-top UV lasers. Applications for the  $^{229}\text{Th}$  isomer transition may include:

- Coherent control of nuclei.
- A nuclear clock offering higher precision and accuracy than today's state of the art atomic clocks due to the extremely narrow isomer transition linewidth and the isolation of the nucleus from external fields [2].
- Enhanced sensitivity to temporal variations in the fine structure constant [3, 4].



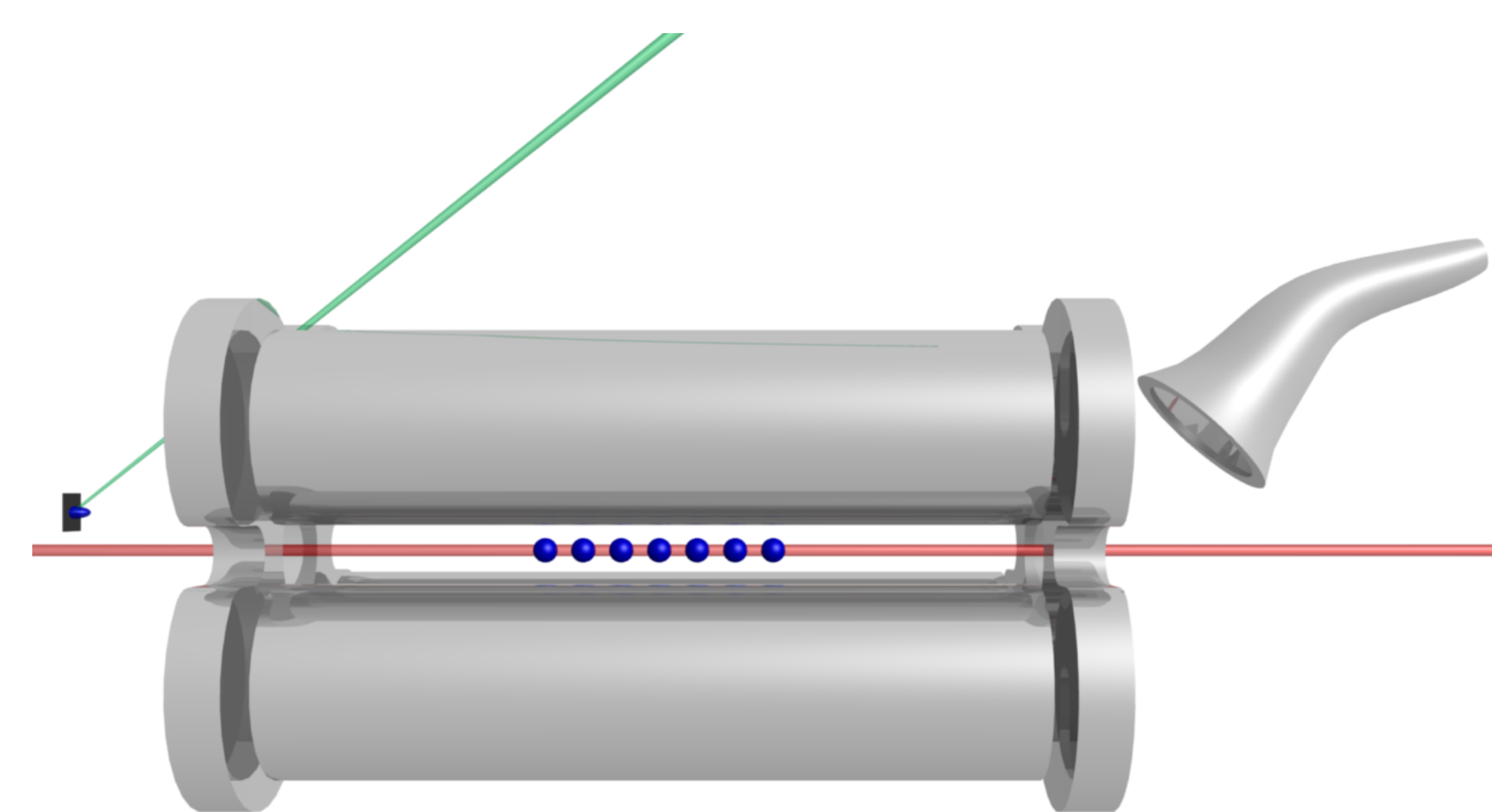
**Figure 1:** An illustration of nuclear laser spectroscopy with a thorium nucleus. In the remarkable case of  $^{229}\text{Th}$ , the photon is in the UV, and the nuclear spin changes from  $I = 5/2$  to  $I = 3/2$  via a M1 transition.

For more on exciting the isomer transition, see M2.00004, "Progress toward a single  $^{229}\text{Th}^{3+}$  ion nuclear optical clock" and [5].

## Chemical Reactions with Thorium

Background gases react readily with  $\text{Th}^{3+}$ , thus limiting the achievable trapping lifetime. Given the great cost of  $^{229}\text{Th}$ , a long trap lifetime is desirable. In order to learn how we can extend this lifetime, we conducted a series of experiments to measure reaction rates and products to determine the primary loss mechanisms.

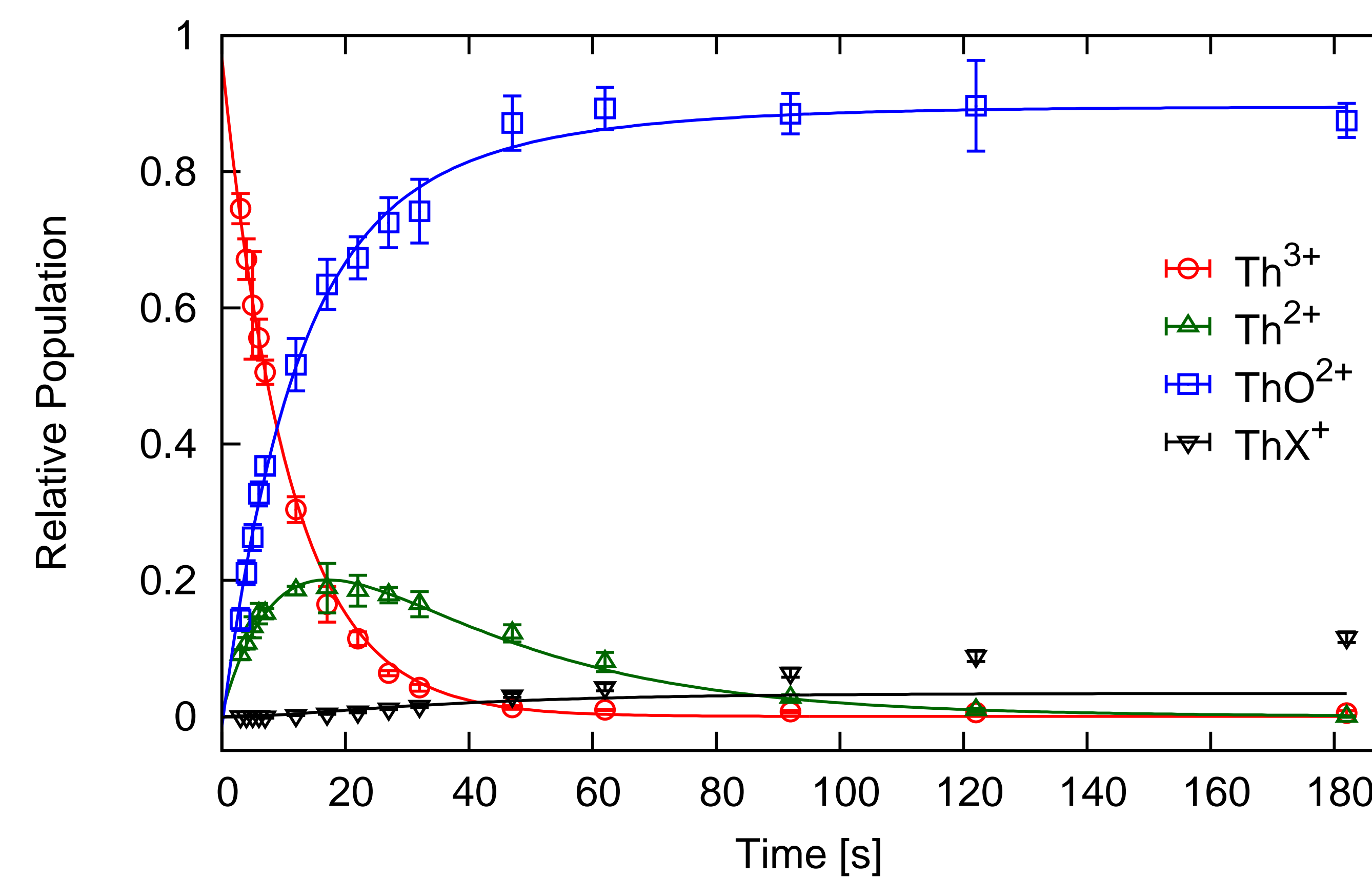
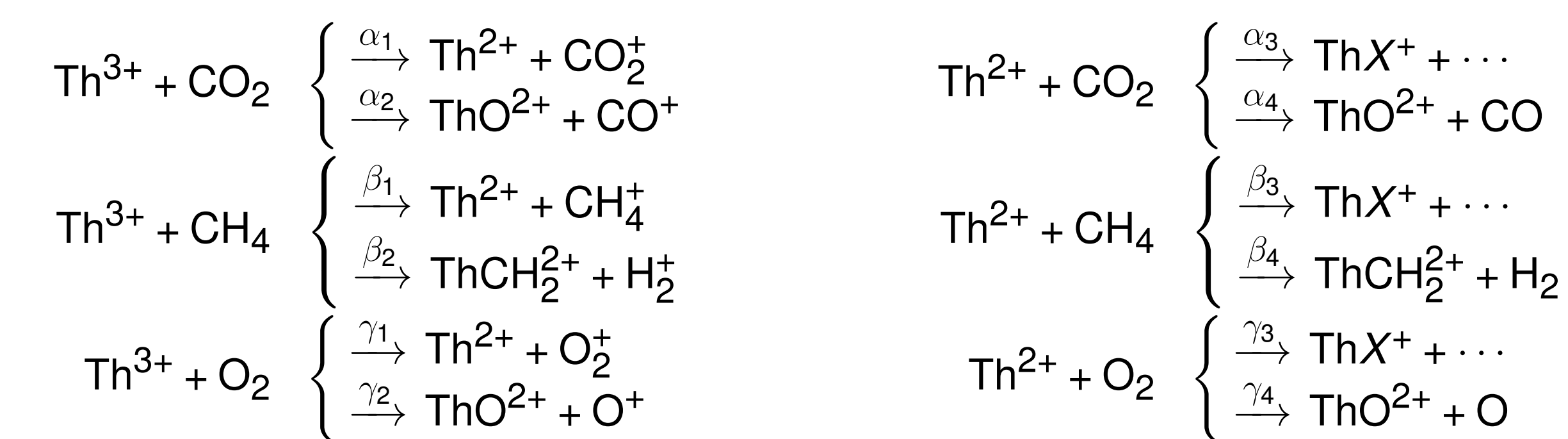
**Figure 2:** An illustration of the Paul trap used to measure reaction rates and products. Ions are produced by laser ablation (left), trapped for a variable amount of time, and then released out the back end cap where they can be detected with a channel electron multiplier (right).



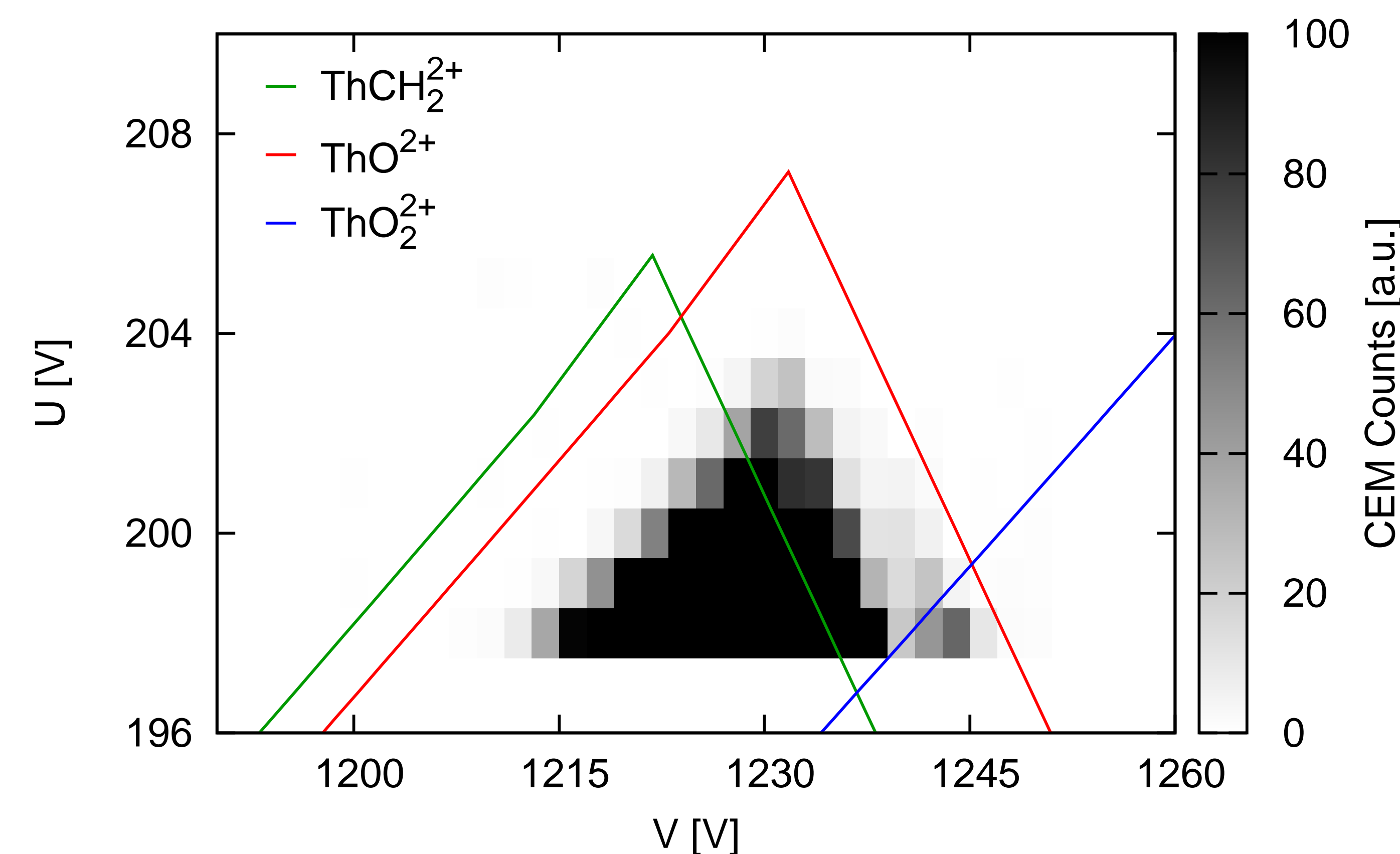
By using the mass selective capabilities of ion traps, we have investigated reaction rates of  $\text{Th}^{3+}$  and various gases to determine what ultimately limits ion lifetime. We found [6]:

- $\text{H}_2$ , Ar, He, Ne, and  $\text{N}_2$  have negligible reaction rates.
- $\text{O}_2$ ,  $\text{CO}_2$ , and  $\text{CH}_4$  are highly reactive.

Reaction pathways for highly reactive gases are



**Figure 4:** Evolution of trap contents over time in the presence of  $10^{-4}$  torr of helium and  $2 \times 10^{-8}$  torr of  $\text{CO}_2$ .  $\text{Th}^{3+}$  ions are loaded into the trap in the presence of He and  $\text{CO}_2$ . After a set time, mass selection is performed to remove all but a specific reaction product which is released from the trap and detected with a channel electron multiplier (CEM). Data are fit to rate equations given below.  $\text{ThX}^+$  represents any ions with  $m/Z > 156$  amu since RF amplitude limitations prevented further differentiation of reaction products.



**Figure 5:** Mass resolution of the trap following reactions between  $\text{Th}^{3+}$  and  $\text{CO}_2$ . Each curve represents the cutoff between stability (below the curves) and instability (above the curves) for three different  $m/Z$ .

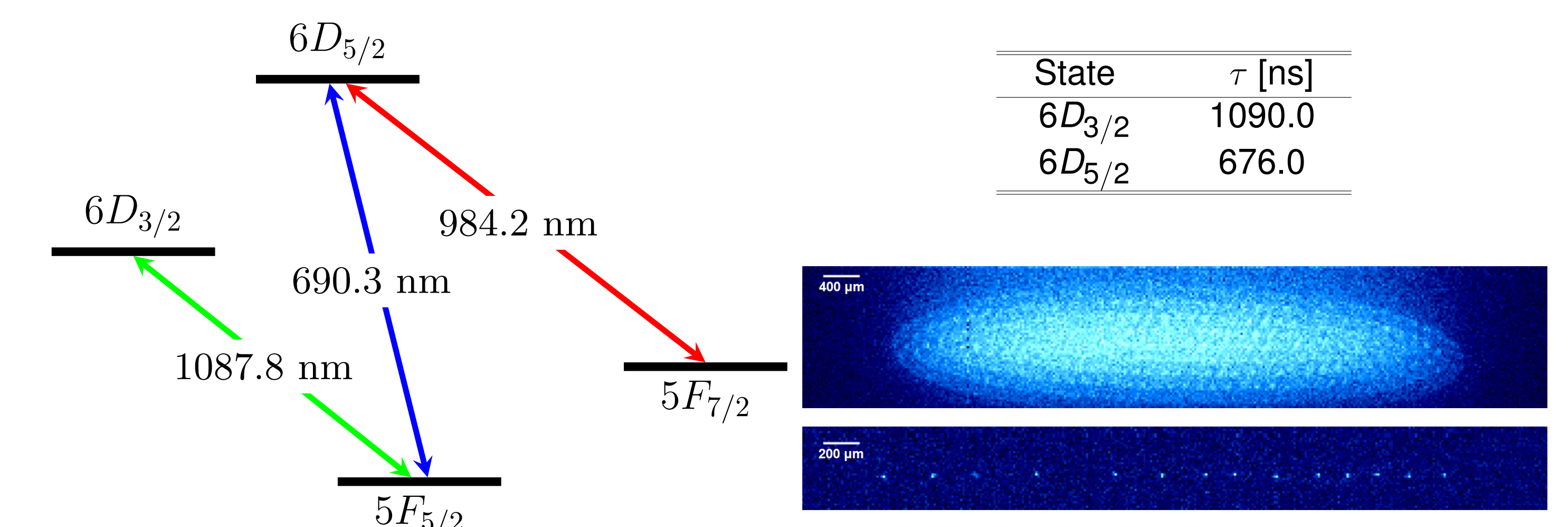
The reaction dynamics are well described by a series of simple rate equations. Rate equations for  $\text{Th}^{3+}$  in the presence of  $\text{CO}_2$  are given below (left), and branching ratios for observed reactions are also listed (right).

$$\begin{aligned} \frac{d}{dt} n(\text{Th}^{3+}) &= -k_1 n(\text{Th}^{3+}) \\ \frac{d}{dt} n(\text{Th}^{2+}) &= -k_2 n(\text{Th}^{2+}) + \alpha_1 k_1 n(\text{Th}^{3+}) \\ \frac{d}{dt} n(\text{ThO}^{2+}) &= \alpha_2 k_1 n(\text{Th}^{3+}) + \alpha_4 k_2 n(\text{Th}^{2+}) \\ \frac{d}{dt} n(\text{ThX}^+) &= \alpha_3 k_2 n(\text{Th}^{2+}) \end{aligned}$$

Branching Ratio	$\text{CO}_2$	$\text{CH}_4$	$\text{O}_2$
$[\alpha, \beta, \gamma]_1$	0.36	0.89	1.0
$[\alpha, \beta, \gamma]_2$	0.78	0.0	0.09
$[\alpha, \beta, \gamma]_3$	0.10	0.0	0.08
$[\alpha, \beta, \gamma]_4$	0.44	0.94	0.83

## $\text{Th}^{3+}$ Excited State Lifetimes

$\text{Th}^{3+}$  presents a convenient level structure consisting of a closed two level system we use for laser cooling and a three level  $\Lambda$  system we use for fluorescence detection. The excited state lifetimes of these two systems have been calculated [7], but not yet measured. We plan to measure the  $6D_{3/2}$  and  $6D_{5/2}$  excited state lifetimes using laser cooled  $^{232}\text{Th}^{3+}$  ions.



**Figure 6:** (Left)  $\text{Th}^{3+}$  levels used for fluorescence and laser cooling. (Top right) Calculated lifetimes of the 6D states [7]. (Bottom right) Laser cooled  $^{232}\text{Th}^{3+}$  [8].

## Summary

- We have investigated the chemical reactions responsible for limiting the trap lifetime of  $\text{Th}^{3+}$  ions.
- We plan to measure excited state lifetimes for the  $6D_{5/2}$  and  $6D_{3/2}$  states of  $\text{Th}^{3+}$ .

## References

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