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Detecting the neutral fluorescence of ^{9}Be

Semester project
Trapped Ion Quantum Information Group

Guglielmo Coloretti
Eidgenössische Technische Hochschule Zürich
M.Sc. in Physics, Autumn Semester 2020/2021
gcoloretti@student.ethz.ch

Supervised by
Prof. Dr. Home Jonathan
MSc. Sägesser Tobias

Abstract

The following report describes the detection of neutral fluorescence of ^{9}Be in the $2s^2\,{}^1S_0 \rightarrow 2s2p\ {}^1P_1$ transition at a wavelength of 234.9 nm. The project is part of a larger experiment, aiming to trap $^{9}Be^{+}$ ions in a Penning trap. In setups working with $^{40}Ca^{+}$, the detection of neutral fluorescence is a routine step when trying to load a new trap, to make sure that a flux of neutral atoms is present. In current experiments in the Trapped Ions Quantum Information (TIQI) group, we do not routinely detect the fluorescence of neutral ^{9}Be atoms. Being unaware of the achievable collection efficiency, we try to find the necessary experimental parameters by detecting neutral fluorescence using an effusive ^{9}Be oven to generate the atom flux. We present a set up which allowed us to achieve its detection. The ability to detect the neutral fluorescence of ^{9}Be is a prerequisite to a follow-up study, where the production of ^{9}Be atoms by pulsed laser ablation is to be characterized.

1 Introduction

$^9Be^+$ ions are commonly used in quantum devices since their particular hyperfine structure offers qubit states which are to first order insensitive to magnetic field fluctuations as well as cycling transitions for cooling. One way of creating them is to produce neutral atoms and then ionize those with photoionization or an electron gun. Frequently, the production of neutral atoms is provided by thermal ovens, which, although able to fulfill this task, present some relevant drawbacks, above all when compared with alternative techniques such as pulsed laser ablation. In fact, effusive ovens require high temperature which gives rise to two major issues: (i) in cryogenic setups, high temperature represents a large heat load and may coat the trap, leading to stray fields (ii) the heating process takes place on a timescale of seconds and once the production of atoms is stopped, the flux is reduced too quickly.

Production of neutral atoms by pulsed laser ablation on the other hand does not have these disadvantages [1]. Ablation uses pulsed lasers which strike a target material and heat a strongly localised region to high temperature, thus inducing the stripping off of atoms and, increasing the energy, also plasma plumes. Furthermore, the high intensity of the lasers used shortens the required time to reach the desired temperature[1] and the flux of atoms can be switched on and off almost immediately. Although ablation has been applied to produce Be atoms and ions before [2, 3, 4], the data on intensity thresholds and velocity distributions remain sparse, which is what we want to know before attempting to trap.

Nevertheless, effusive ovens are an established and robust method to produce a flux of atoms. Hence, as an intermediate step towards characterizing the ablation of Be atoms, we first determine the experimental parameters necessary to detect the fluorescence of ^{9}Be when driving a suitable electronic transition. By performing time-of-flight measurements and taking Doppler shifts into account [5], this can later be used to determine the velocity distribution of atoms produced by ablation of a Be target.

In order to verify that a flux of neutral ^{9}Be atoms is produced, we address the $2s^2\,{}^1S_0 \rightarrow 2s2p^1P_1$ transition of neutral ^{9}Be (Fig. 1) with a laser and attempt to detect the fluorescence light of the excited state relaxing to the electronic ground state. In the case of ^{9}Be, the transition addressed is at 1 276 080 092 MHz (234.9 nm) with a linewidth of 87 MHz [6]. Lasers for generating light directly at this wavelength are not commercially available, so that other techniques are exploited. We use a diode laser to produce 470 nm light and a non-linear crystal in a resonant cavity locked with a Pound-Drever-Hall scheme for frequency-doubling.

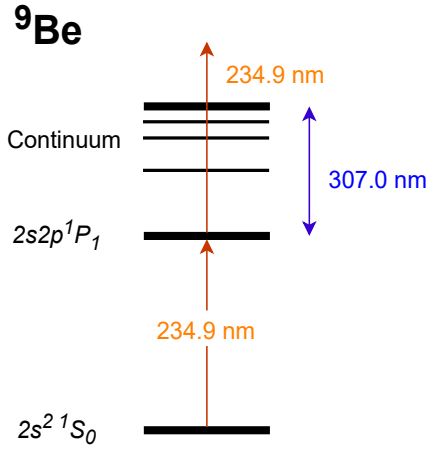

Figure 1: Scheme for the energy levels of ^{9}Be.

In the following, we describe the detection of fluorescence from a flux of neutral ^{9}Be atoms produced by a thermal oven. We describe the experimental setup that was built to achieve this and its parameters, including vacuum and imaging systems.

2 Experimental setup

We built an experimental setup, a sketch of which can be seen in Fig. 2 and Fig. 3 (side view), including a vacuum chamber containing a Be oven, laser delivery and an imaging system for detection of 234.9 nm light.

[1] The process is almost instantaneous, basically just the time required for the atoms to fly the distance to the trap.

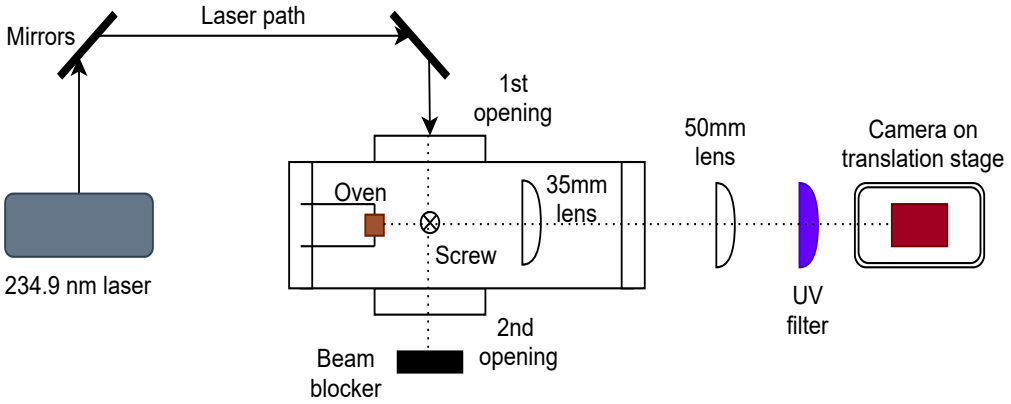

Figure 2: Experimental set up. The vertical (horizontal) dashed line represents the laser path (flux of atoms). The vacuum system, as well as the cables connecting the oven to the power supply, are not shown for the sake of clarity. The screw is placed right below the oven.

2.1 Mechanical arrangement and thermal oven

In order to localize the ^{9}Be atoms and address the flux with the laser, and induce the transition at 234.9 nm, we need to reduce the collision rate the atoms can undergo with other molecules so to free their way on a path as straight as possible. We build a vacuum chamber to accomplish this condition, namely we work in the free molecular flow regime[2]. The oven sits inside the chamber and the transition is driven with a laser pointing close to it through a viewport on one of the openings of the chamber. The chamber is closed with KF40 flanges. The vacuum is obtained with a turbo pump[3] which is able to reach a base pressure of 10^{-6} mbar. Initially, we provided a chamber with a valve to isolate the system from the turbo, since we feared that the flux of atoms could enter the pump and damage it. However, as soon as the valve was closed, the pressure rises up past 10^{-4} mbar within a few seconds. Since the desired experiments would rather take many minutes, the pressure might rise to a level where the path of the atoms is too heavily influenced during measurement. To be more precise, we can give a rough estimate[4] of the mean free path of ^{9}Be: at room temperature, it is around 185 m for a pressure of 10^{-6} mbar and roughly 18 cm for a pressure of 10^{-3} mbar (already on the order of the chamber size). At first, we traced the pressure spike when closing the valve to a possible leak. Testing the chamber with a leak detector[5], we eliminated a small leak due to a scratch on a flange, which nevertheless had no effect on the pressure. To ensure a satisfactory level of vacuum, we decided to conduct the experiment with the valve open and the turbo running[6].

We build a couple of ovens [7], consisting of a filament of Beryllium wound around a tungsten wire. Both ends of the wire are then connected to two different pins of an electrical feed-through on a KF40 flange[7], connected to one opening of the chamber. The oven is connected to a power supply providing the necessary current. The ^{9}Be filament is then heated up via the resistive heating of the tungsten wire. Further, in order to have a flux with

[2] This amounts to the regime in which the free path of a particle is longer than the chamber dimensions.

[3] Pfeiffer HiCube 80 Classic with a pumping speed of 67 L s^{-1}

[4] The formula for the mean free path we use is:

$$\bar{l} = \frac{k_B \cdot T}{\sqrt{2}\pi \cdot p \cdot d_{\mathrm{Be}}^2}$$

where k_B is the Boltzmann constant, T the temperature, p the pressure, d_{Be}^2 the molecular radius.

[5] Helium leak detector Adixen ASM340.

[6] In principle, the turbo could get damaged from too large gas loads. In our set up, this did not happen.

[7] Lewvac KF40-MP-6-NC-CE-SSN.

a well-defined direction instead of a cloud, as well as to protect viewports and other elements in the chamber from getting coated, we insert a collimator[8] which only allows the flux towards the bottom of the chamber (the housing in Fig. 3, Fig. 4). First we tested that the oven is operational and the required current. The first time we ran the experiment we used a value of 2 A for the current and the oven broke after a couple of seconds. In fact, the current turned out to be too high and, more importantly, the current fed through the tungsten wire was driven with a fast change and not slowly brought to 2 A. Further, the oven was quite asymmetric, since one of its ends connected to the tungsten wire was much shorter than the other. It also had only 200 windings due to the Beryllium filament breaking off early during the winding process. We built a better oven, consisting of roughly 400 windings (resistance around 1.6 Ω), and paid attention to rapid changes in the current. We further placed a glass slide inside the chamber, right below the oven (Fig. 5). We then ensured that the second oven was working by seeing it glowing and detecting some ^{9}Be deposit on the glass slide.

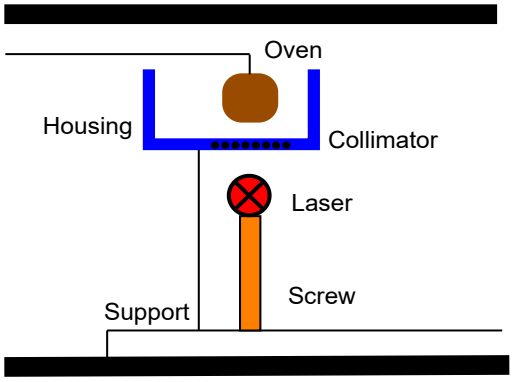

Figure 3: Side view of the part of the chamber where the screw is located. The black dots below the housing represent the holes which serve as collimator.

[8]The collimator we used was, however, a bit rudimentary. It consists of a copper housing with holes drilled over it, shielding the oven. Of course copper is chosen since it is a good material for vacuum, outgassing only weakly. The collimator has been later improved to block much of the light emitted by the hot oven glowing. It then consisted of a cylindrical housing made of Macor glass-ceramic around the oven with holes drilled in the lower part. See Fig. 3, Fig. 4.

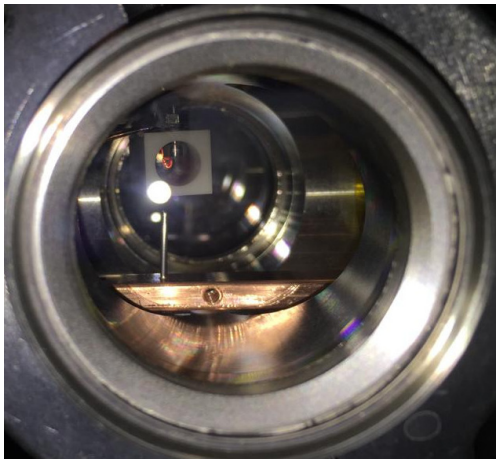

Figure 4: Side view of the chamber. The glowing oven is positioned inside the improved housing (white cylinder), the screw is located just below it.

2.2 Diode laser

To excite the transition, we use a 470 nm diode laser[9], doubling its frequency with a resonant cavity including a nonlinear crystal and reaching a power of 3 mW. The laser path was steered by mirrors to meet the flux as orthogonal as possible and reduce Doppler effects (Fig. 2). In order to align the laser beam to the position in which the flux of atoms is expected to be, we mount a screw and place its tip exactly below the collimator (Fig. 3, Fig. 4). Thus we are able to check the position of the laser beam by shining it through the chamber, and be sure whether it hits the tip of the screw or not with the setting in Fig. 2. The laser enters the chamber via the 1st opening, and its passage above the tip can be checked through the 2nd opening, as denoted with the dashed vertical line. The frequency of the laser is adjusted to the one needed to invoke the desired transition, namely 234.9 nm, by tuning the voltage applied to a piezo actuator that holds a grating in the external cavity of the diode laser.

Note that besides driving the $2s^2\,{}^1S_0 \rightarrow 2s2p^1P_1$ transition, the laser light at 234.9 nm may also photo-ionize a Be atom in the $2s2p^1P_1$ state with a second 234.9 nm photon (see Fig. 1). Nevertheless, the cross section to allow for a subsequent transi-

[9]DLC-DL-SHG PRO (Toptica Photonics).

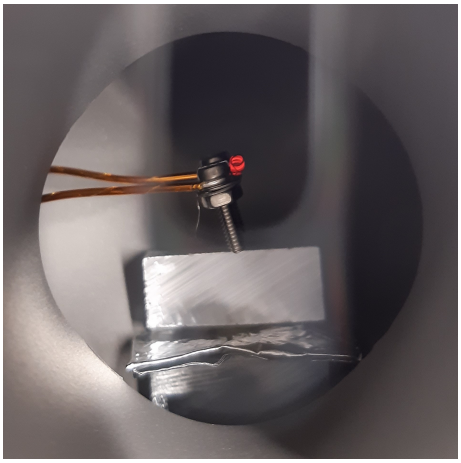

Figure 5: Glowing oven with glass slide for deposit detection.

tion of a ^{9}Be excited level to the continuum is much smaller (about seven orders of magnitude [8]) than the one we are interested in, namely the one that brings the ground state to the first excited level (Fig. 1). Therefore the photoionization happens at a much slower rate, which allows the electron in the $2s2p^1P_1$ state to relax to the ground state, resulting in detectable fluorescence.

Further care needs to be taken, since, although we introduced a collimator, it is very likely that the atoms still have a considerable spread after the collimator. Hence, in order to take account of the Doppler shift at play, we scan the frequency over a range of 20 GHz around the desired frequency. All frequencies are measured with a wavemeter[10].

2.3 Imaging system

We here describe the imaging system adopted to detect 234.9 nm light, of which there have been several iterations during the experiment. At first we used a photomultiplier tube[11] (PMT) which is able to record time-resolved data with high accuracy. In fact, the PMT is able to directly count the number of single photons and thus register more counts in case of a transition. Nevertheless, after initially being unable to detect the fluorescence (see Appendix), we switched to an apparatus yielding a spatially resolved image, namely a cooled sCMOS camera[12] with which we could record the fluorescence. The camera is a somewhat less precise method, since we use it just to visibly detect the fluorescence, not to collect quantitative data, namely reproducing time-resolved data as with a PMT. The camera is mounted on a translation stage which allows to move it in three orthogonal directions (Fig. 2). In fact, the precise position of the cloud of atoms inside the chamber is only partially known, so that we need some freedom to move our imaging system to find the correct spot. In this regard, we use two focusing lenses[13] to image the fluorescence light onto the camera sensor. Since the exact position of the intersection of the flux of atoms with the laser is not precisely known, we put a lens inside the chamber and the second one outside of it, so that we can still move the second lens to adjust the focusing of our system. With the help of a an optical design software[14], we found a good positioning for our purposes, as detailed in Fig. 6. The first lens has also another function: increasing the solid angle[15] from which the light can be collected and thus increasing the collection efficiency[16]. To focus the camera, we exploit again the screw inserted right below of the collimator (see previous paragraph and Fig. 3, Fig. 4): shining the laser right at its tip, it reflects the light and we adjust our imaging system such that we see the tip of the screw with the camera. We further use a dieletric filter[17], to separate the UV signal from the background, such as residual room light or the light emitted from the oven (UV filter in Fig. 2).

[10] High Finesse WS8-10 with 10MHz absolute accuracy after calibration, 400 kHz resolution.

[11] Photon counting heads H10682 Hamamatsu `https://www.hamamatsu.com/resources/pdf/etd/H10682_TPMO1075E.pdf`

[12] pco.edge 4.2 bi UV; resolution: 5120x5120 active pixel; spectral range: 320 nm-1100 nm. `https://www.pco.de/fileadmin/user_upload/pco-product_sheets/DS_PCOEDGE42BI_V104.pdf`

[13] 35 mm UV fused silica plano-convex lens and a 50 mm UV fused silica plano-convex lens. For the correct positioning, see Fig. 6.

[14] Zemax Optical Design Software.

[15] Numerical aperture around $NA = 0.18$.

[16] This is also of help if using a PMT.

[17] UV-Bandpassfilter, 228 nm, 25 nm FWHM, 25 mm diameter.

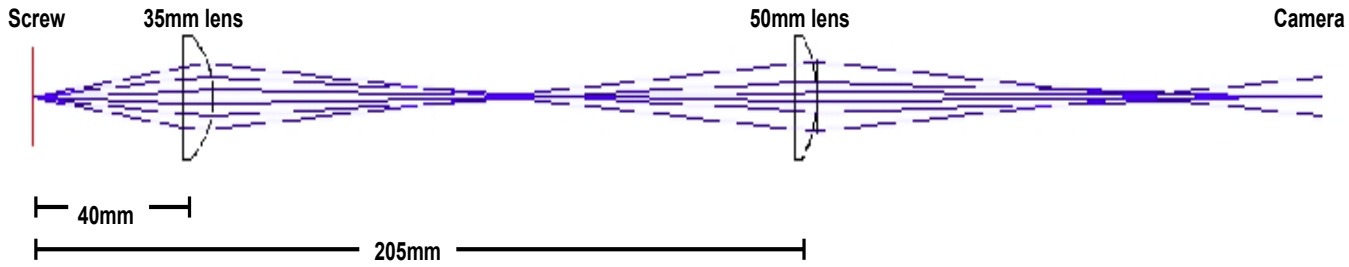

Figure 6: On the left: 35mm lens inside the chamber, at 40mm from the tip of the screw; on the right: 50mm lens, at 205mm from the tip of the screw.

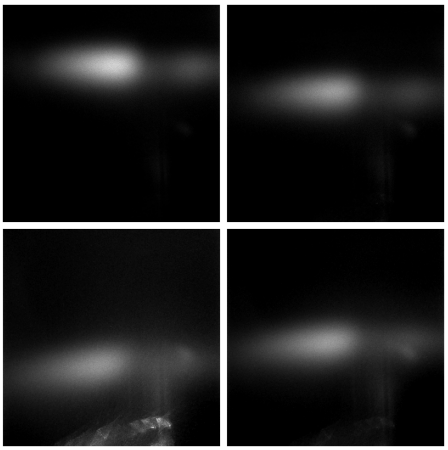

Figure 7: Detection of neutral fluorescence of ^{9}Be. The four pictures represent the signal while moving the laser up and down. The bright spot moves accordingly.

This filter is able to clear up the background noise, although its transmission is only 25% in the target range of 235 nm.

Shortly after the time for this semester project ended, the neutral fluorescence was successfully detected [9] with a oven current of 1.16 A, a 234.9 nm laser power of about 3 mW and a beam diameter of 1.2 mm [10], as shown in Fig. 7. It was crucial to increase the oven current sufficiently: at 1 A little fluorescence light could be detected while it was clearly visible at a current of 1.16 A. The resulting intensity is 2.65 mW/mm^2, or 0.3 times the saturation intensity of this Be transition of 8.9 mW/mm^2 [11]. Fluorescence light was detected right below the oven and just where the laser pointed. To be sure the wanted transition was hit, it has been checked that when the laser beam was moved, also the fluorescing region on the camera moved accordingly. Further, when the laser frequency was detuned away, the signal disappeared.

3 Conclusions

We successfully detected the neutral fluorescence of ^{9}Be. The source of ^{9}Be is provided by an effusive oven made of 400 windings of a ^{9}Be filament, which produces a flux of atoms with the help of a collimator. The flux of atoms is illuminated with a laser at a frequency 234.9 nm and the fluorescence signal collected with an sCMOS camera. Our project serves as a preliminary step towards characterising pulsed laser ablation of Be. In the future the project will continue replacing the effusive oven procedure with the ablation of ^{9}Be target as a source of atoms.

4 Appendix

The first imaging system adopted was a PMT, as discussed in section 2.3, later substituted with a sCMOS camera. We describe here the problems met in using the PMT as imaging system. We arranged a mechanical arm to fix the PMT above an opening of the vaccum chamber and point it at the oven without any lenses present. In this way, the PMT should be able to detect a spike in the count of photons if any transition in the Beryllium atoms happens. We shielded the whole apparatus with light shielding cloths and tapes and reached a

background counts of nearly zero. Nevertheless, we were not able to detect any spike in the counts. We previously measured the counts coming from each contribution of the single sources, namely the background of the laboratory, the oven and the PI laser. We then detected the overall counts and removed the backgrounds. We did not register any sign of fluorescence but only the a change in background counts corresponding to the laser power fluctuation while scanning of the frequency of the diode laser over 10 GHz.

The reasons why we were not able to detect the neutral fluorescence with the PMT could be several and along the experiment we tried to face each of them improving our set up: (i) the signal is too low - hence the problem is fundamental, we cannot be sure about it; (ii) the laser beam does not hit the flux of atoms - we included the needle to make sure where the laser pointed; (iii) the flux of atoms is inexistent or not dense enough - we put the glass slide in the chamber and detected a coating; (iv) the fraction of emitted photons hitting the PMT is too low - we included the lens system to focus the photons on the PMT as well as the UV filter to screen the light not coming from the desired transition; (v) the frequency is wrong - we needed to scan the laser enough to find the real transition.

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