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## Laser cooling, trapping and spectroscopy of calcium isotopes

Mollema, Albert Kornelis

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# Chapter 1

## Introduction

In 1975, Hänsch and Schawlow were amongst the first to realize that laser light could be used to slow down and eventually trap neutral atoms [1]. Throughout the 1980's, important experimental realizations of their ideas were demonstrated. In 1982 Philips and Metcalf built the first so called Zeeman slower, a device to slow down atom beams using laser light and a magnetic field that changes in strength along the direction of the atomic beam [2]. In 1987 another milestone was reached: Raab et al. demonstrated the first magneto-optical trap (MOT). In a MOT atoms can be trapped using red detuned, circularly polarized laser light together with a quadrupole magnetic field [3]. Ever since, the MOT scheme has been applied in many fields of physics, e.g. optical frequency standards [4, 5], charge exchange processes [6], cold and ultra cold collisions [7, 8], experimental  $\beta$ -decay studies [9] and ultra sensitive trace analysis [10, 11]. Besides that, it paved the way to the first experimental realization of Bose-Einstein condensation (BEC) [12, 13].

The first laser cooling and trapping experiments were performed with Na. Later on, also other alkaline elements (Li, K, Rb and Cs) were cooled and trapped [14, 15]. Initially, little work was done on alkaline-earth elements like Mg, Sr and Ca. However, in contrast to alkaline elements, even isotopes of alkaline earth elements do not possess nuclear spin, and therefore do not have hyperfine structure in the ground and excited states. Moreover, the  $^1S_0 - ^1P_1$  resonance transition, which is very suitable for laser cooling, is in the case of the elements Mg, Sr and Ca an almost ideal two-level system, which makes these elements interesting systems to test predictions of Doppler temperature limits achievable by laser cooling [16, 17]. Odd alkaline-earth isotopes, on the other hand, do possess nuclear spin and therefore hyperfine structure. This may lead to a different trapping behavior resulting for example in lower temperatures of the odd isotopes, as has been shown for  $^{87}\text{Sr}$  [18, 19].

This thesis focusses on Ca. Ca is chosen because of our investigations on the possibilities of using atom trap trace analysis [10] to observe the very rare  $^{41}\text{Ca}$  isotope in natural samples (at abundances as low as  $10^{-14}$ ) [11, 20, 21]. In addition, short-lived  $^{39}\text{Ca}$  isotopes are candidates for  $\beta$ -decay studies searching for physics beyond the standard

model of particle physics [22, 23]. The most abundant natural odd isotope of calcium is  $^{43}\text{Ca}$ . In this thesis, this isotope is therefore chosen to compare its trapping dynamics with that of the even isotopes of Ca.

## 1.1 ATTA: atom trap trace analysis

Atom trap trace analysis (ATTA) is an experimental method pioneered by the group of Z.-T. Lu at Argonne National Laboratory, USA, and very successfully applied to the isotope separation of rare Kr isotopes [10, 24]. ATTA experiments combine various laser cooling and trapping techniques, each of which is isotope selective. Using laser cooling and trapping techniques has the major advantage that no ionization processes are needed to apply the method. Moreover, since it deals with a specific atomic transition, the method is not sensitive for isomers of the isotope of interest.

The mechanism of isotope selection is the repeated excitation by laser light of an electronic transition of the neutral atom, in our case Ca. Due to the isotope shift, the scattering rate resulting from laser light of a fixed frequency is different for each isotope. Two key-properties for the application of ATTA are the isotope shift and the natural linewidth of the transition used. In the case of Ca, the average isotope shift for every adjacent isotope (in the range from 40-48) is about 190 MHz. The natural linewidth for the utilized  $^1S_0 - ^1P_1$  transition is 34.6 MHz. The ratio between the two is sufficiently large to make isotope selection by repetitive laser pumping feasible. In order to suppress Doppler broadening of the transition, the atoms need to be cooled to very low temperatures. In a MOT temperatures in the mK range can be reached routinely and a MOT therefore forms the central part of ATTA setups. The fluorescence light of the trapped atoms is collected and detected and this way the relative abundance of the isotopes can be determined.

For any specific isotope, the final sensitivity that can be reached in an ATTA experiment is limited either by the background of the other isotopes or by the loading rate of the MOT. The previous work by Hoekstra et al. on Ca [11, 20] has shown that if the atomic calcium beam by which the trap is loaded is carefully prepared, isotope selectivity is not the limiting factor. The loading rate, on the other hand, is. The loading rate is directly connected to the transport efficiency of the setup, i.e. the ratio between the number of atoms introduced into the setup and the number of atoms eventually trapped in the MOT. In this thesis, possible solutions to this problem are explored.

## 1.2 ATTA applications for $^{41}\text{Ca}$

$^{41}\text{Ca}$  has two unique properties that makes it in principle suitable for a range of applications. The abundance of  $^{41}\text{Ca}$  as compared to  $^{40}\text{Ca}$ , the latter making up for some 97% of all Ca occurring on earth, is in the order of  $10^{-15}$ . On Earth,  $^{41}\text{Ca}$  is predominantly produced via slow neutron capture on to  $^{40}\text{Ca}$ . The half life of  $^{41}\text{Ca}$  is 104,000 years [25]. From the cross section of the neutron capture reaction together with the

neutron flux on Earth and the life time of  $^{41}\text{Ca}$ , the equilibrium abundance of  $^{41}\text{Ca}$  at the surface of the Earth can be calculated to be  $\sim 8 \times 10^{-15}$  [26].

Its low abundance makes  $^{41}\text{Ca}$  an attractive isotope to be used as a tracer in biomedical research instead of the radioactive isotopes of Ca, i.e.,  $^{45}\text{Ca}$ ,  $^{47}\text{Ca}$  [27, 28]. It could be used to monitor the bone loss and retention rates of human subjects in both research and diagnosis of osteoporosis [11].

The half life of  $^{41}\text{Ca}$  of 104,000 years [25] makes it a suitable isotope for the development of radiocalcium dating [29, 30]. Due to its long half life,  $^{41}\text{Ca}$ -dating has the potential to date calcium containing materials to earlier times than is possible with  $^{14}\text{C}$ , which has a half life of 5730 years.  $^{41}\text{Ca}$ -dating would open the way to date middle and late pleistocene bone material which would help to clarify uncertainties about chronological relationships among important fossil hominids for a time period during which major events in hominid biological and cultural evolution took place.

### 1.3 Other ultra sensitive trace analysis methods applied to $^{41}\text{Ca}$

While ATTA uses neutral isotopes, the other ultra sensitive trace analysis methods are based on detecting atoms in their ionic state.

#### 1.3.1 AMS

Accelerator mass spectrometry (AMS) uses magnetic and electrostatic spectrometry [31] to determine the abundance of the isotope of interest. Examples of application of AMS for  $^{41}\text{Ca}$  can be found in Refs [29, 32, 33]. The main drawback of AMS is the fact that a lot of chemistry is needed for proper sample preparation in order to circumvent the  $^{41}\text{K}$  isobar contamination in the case of  $^{41}\text{Ca}$  studies. Wallner et al. [33] nevertheless managed to measure abundances of  $^{41}\text{Ca}$  as low as  $2 \times 10^{-15}$ .

#### 1.3.2 RIMS

Another technique to determine the fractions of rare isotopes is resonance ionization mass spectrometry (RIMS) [34]. The main isotope selective process is the multi-step resonant excitation/ionization of the isotope of interest, followed by the detection of the ions using a quadrupole mass spectrometer. For  $^{41}\text{Ca}$ , the sensitivity limit of RIMS currently is  $\sim 10^{-11}$  due to background arising from photoinduced Ca dimers and Ca hybrids, surface ionized  $^{41}\text{K}$  and detector dark counts [24, 35].

## 1.4 Outline of this thesis

- In Chapter 2 an overview of the relevant fundamental concepts of laser cooling and trapping is given, together with a brief description of the structure of the relevant aspects of the calcium atom.

- In Chapter 3 the Al<sup>41</sup>Catraz setup is described. A description of the vacuum system, laser system, optics, oven, Zeeman slower, MOT and the detection system is given.
- In Chapter 4 a newly developed spectroscopy technique (LiPS: light pressure induced spectroscopy) is described. LiPS is an easy to apply technique that can be used to perform spectroscopy on atomic beams. During the experiments described in this thesis, LiPS was used as a tool to frequency stabilize the laser system.
- In Chapter 5 experiments done to characterize the Zeeman slower are presented. The velocity distributions of atoms leaving the Zeeman slower are measured as a function of the Zeeman slower parameters laser detuning, laser power, and magnetic field. Furthermore, measurements performed in order to find optimal parameters for the deflection section are presented.
- In Chapter 6 the trap dynamics of even and odd isotopes of Ca trapped in the MOT are investigated. Temperature measurements of atoms trapped in the MOT are compared with recent models. Also the trapping time of atoms in the MOT, i.e. the time atoms spend in the trap is studied and compared to a rate equation model we developed to understand the Ca trapping behaviour.