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Radium Ion Spectroscopy

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Chapter 1

Introduction

1.1 The Standard Model and its Limits

The Standard Model (SM) [1–3] is the theoretical framework which provides a consistent description of three of the four known fundamental interactions in nature, namely the electromagnetic, the weak and the strong interactions [4]. The fourth interaction gravity refuses the quantum field theory approach. The SM is undergoing a continuous development since the past four decades [5] and the SM is known to be the most successful theory in physics. Numerous interesting experiments and measurements have been carried out in this period to discover and to prove different properties of particles and their interactions. Despite its success to describe all experimental observations it is not considered as the ultimate description of nature, because of a lack of explanation for some experimental facts. Such open questions include the masses of the fundamental fermions, the number of particle generations, the large energy difference between electro-weak and grand unification (gauge hierarchy problem), the dominance of matter and antimatter in the universe, and the origin of parity violation. The model has many free parameters that can only be determined experimentally. A number of speculative theoretical extensions to the SM have been suggested in order to explain some of the unanswered questions. Such models include Supersymmetry [6], Technicolor [7], Grand Unified Theory [8], and String Theory [9]. The predictions from such models come either in the form of new possible particles or new possible interactions leading to extended radiative corrections [10]. Those theoretical approaches have no status in physics until they are confirmed by experimental findings. Experimental tests of the SM are therefore motivated to identify the existence of new particles and/or new physical processes that would explain the yet not well understood physical facts observed in nature [11–15].

There are two principally different approaches to test the SM extensions. New particles and interactions can be directly searched for in high energy experiments. The number of facilities to carry out a high energy experiment is limited and the research is done on a large scale of international collaborations. Alternatively, there are precision experiments at lower energies using atomic physics techniques where physical quantities are determined which can be compared to calculations of high accuracy within the established theories and deviations indicate incompleteness of the theory. A significant deviation of the measurement from the calculation leads to an indication of new physics. This approach is complementary to high energy experiments and can probe physics at mass scales well above the direct access to the present and near future generation accelerators.

1.2 Outline of the Thesis

The motivation of the TRIμP (Trapped Radioactive Isotopes: μ-laboratories for fundamental Physics) research program at the Kernfysisch Versneller Instituut (KVI) of the University of Groningen is to test fundamental interactions and symmetries in nature. Through precision experiments experimental signatures of the breaking of discrete symmetries are searched for. Of particular interest are the time reversal symmetry (T) and the parity symmetry (P). The TRIμP facility provides short-lived radioactive isotopes which can be studied as atoms or ions in suitable traps [16–20] (Fig.1.1).

This work is concerned with the development of an experimental setup to carry out a state-of-the-art atomic parity violation (APV) measurement on a single trapped ion. APV in this trapped ion will be measured via a determination of light shift of the Zeeman levels of the low lying ground and metastable states. Such a measurement will yield the weak charge of the radium ion nucleus from which the weak mixing angle will be extracted. This measurement will test the SM in a complementary way to other approaches. A sub-percent accuracy is aimed for comparing it to the high energy physics experiments. In particular, the electroweak mixing angle or the Weinberg angle is aimed for with a sub-percent accuracy or a 5 fold improvement over the best existing measurement which was performed on atomic cesium [22–24]. Recently Ra^+ has been identified to be an excellent candidate for this experiment [25, 26]. Due to the unique atomic

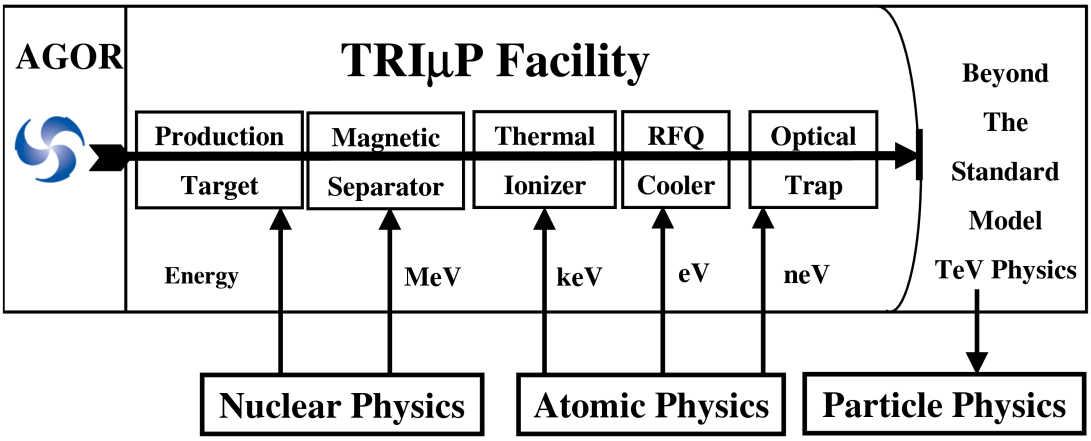

Fig. 1.1: Conceptual view of the TRIμP facility and the TRIμP research program. Radioactive ion beams are produced in nuclear reactions with the beam from the AGOR cyclotron and the production target. A magnetic separator is used to select isotopes of interest. A thermal ionizer and a radio frequency quadrupole cooler convert the high energetic particles to ion or atom beams at thermal energies. Optical traps provide the experimental environment to store and perform high precision measurements with the goal to search for physics beyond the SM [21].

and nuclear structure, sensitivity to the parity violating weak interaction effects in this alkali like system is strongly enhanced. To exploit this enhancement an experiment is being developed within the TRIμP research program at KVI. APV experiments probe the electroweak interaction as described in the SM of particle physics. The agreement with the SM on parity violation could reveal the existence of new physics beyond the SM and guide model building [27,28]. As an example, the current agreement between the cesium measurement and the SM provides a lower mass limit on an additional Z' boson at 1.3 TeV/C^2 [29].

The thesis describes the necessary steps towards a new APV measurement in a new system Ra$^+$ (Fig. 1.2). In the framework of this thesis, a setup for this experiment has been developed based on the requirements of the measurement. Some of the experimental parameters have been investigated by several measurements. The planned parity violation experiment is technically challenging and a long-term project in scope. The first step is the production of radium at the TRIμP facility at KVI. The produced high energetic radium isotopes are thermalized to singly charged ions. The ions are trapped and cooled in a linear Paul trap where precision laser spectroscopy is performed to search for essential

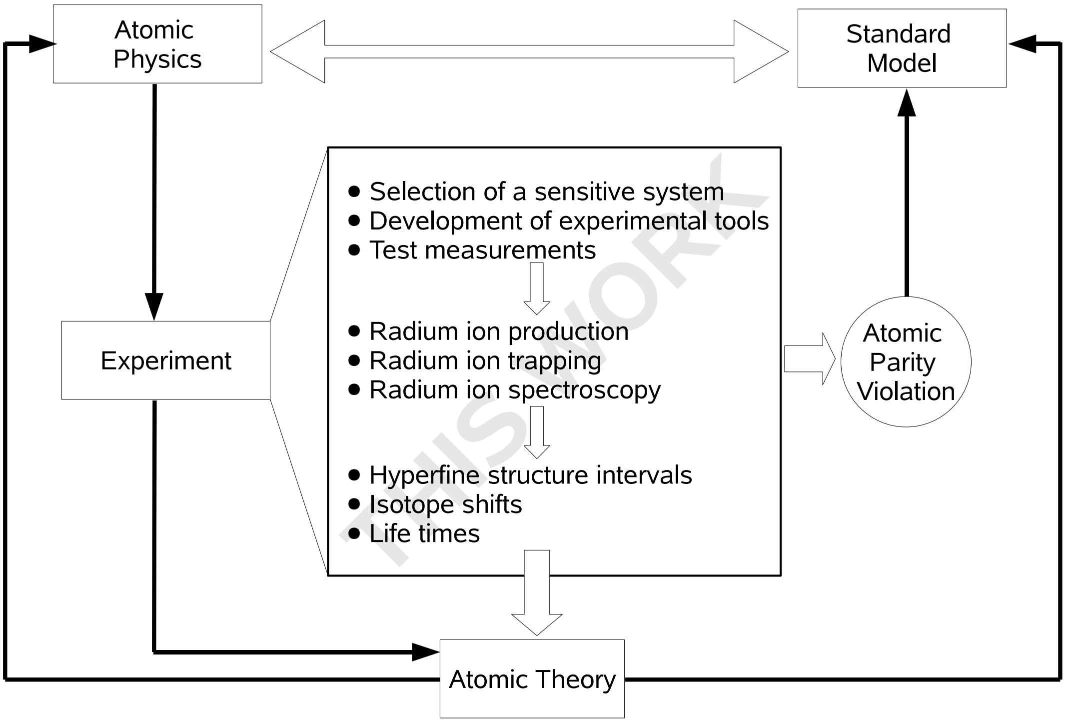

Fig. 1.2: Depiction of the layout of this thesis. Atomic physics techniques are used to precisely measure atomic parity violation enabling a low energy test of the Standard Model. On one hand atomic theory is indispensable to interpret the experimental results and on the other hand the required atomic theory needs experimental input. This work is concerned with the development of necessary experimental tools and leads to important physics results that are required to test the atomic theory.

atomic, nuclear and spectroscopic properties in this system which are scarce in literature. This work provides indispensable building blocks for the parity violation measurement in the radium system. It is at the overlap of many different fields in experimental and theoretical physics.

This thesis is organized as follows.

- We start with a description of violation of parity symmetry in an atomic system. The experimental effort is placed into context with worldwide parity violation research. The principle of measurement of parity violation in general is also discussed.

- We describe the general requirements of an atomic system to be a potential candidate for this experiment. We compare Ra^+ with other candidates (Ba^+, Yb^+, Fr and Cs). The observable for APV is presented.

- The tools that have been developed are introduced. The TRIμP facility is discussed with an emphasis on the operation of different components of the facility for radium production. The experimental results of radium isotope production are presented and discussed. Special attention has been given to ion traps which are dedicated to this experiment. The laser systems are described extensively with emphasis given to frequency calibration.

- The results from the measurements of hyperfine structure, isotope shift and lifetime are presented. Data analysis and interpretation of the results are discussed with emphasis given to isotope shifts.

- We summarise the results of radium isotope production and the results of laser spectroscopy. The importance of the results towards the planned APV experiment is discussed.

- We conclude with an outlook. The principle of measurement of differential light shift by RF spectroscopy using shelving technique is discussed. The current status of the experiment and an overview of short-term plans are presented.

Ra^+ is the heaviest alkaline-earth ion for which a high precision measurement of atomic parity violation can be carried out. At the same time one can expect that the achievable precision depends on a precise atomic description of this system. The sensitivity to parity violating effects in this alkali like system is 50 times higher than in cesium where the best such measurements have been performed till date [22, 23, 29, 30]. The energy levels of Ra^+ which are relevant for this work are shown in Fig. 1.3. It is a particular advantage of Ra^+ that all transitions relevant for an APV measurement are accessible with commercially available cost effective diode laser systems.

The concept for an APV experiment based on a single ion has been worked out for Ba^+ [31–33]. However, the relative strength of the APV signal is 20 times larger for Ra^+ [26] and an experiment to exploit this enhancement is currently developed within the TRIμP research program at KVI. The experiment aims at a 5 fold improved measurement of the weak mixing angle over the sole best APV result in atomic cesium.

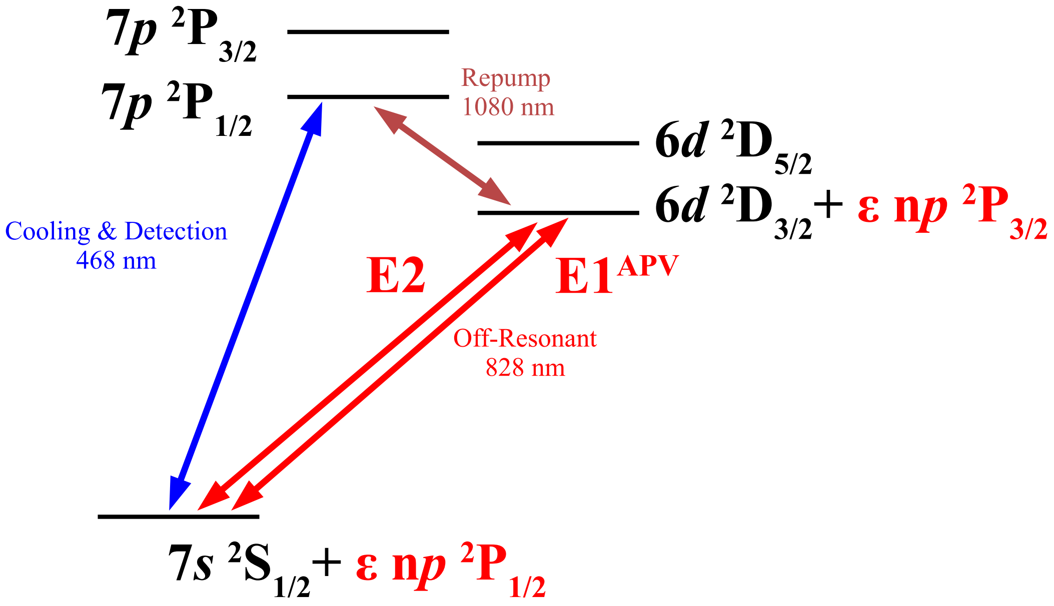

Fig. 1.3: Level diagram of Ra^+ with emphasis given to the admixture of P states with the low lying S and D states.

A parity violation experiment requires a good study of possible systematic effects. This work developed the principle and realization of production of short-lived radium isotopes, the subsequent trapping and laser spectroscopy in a linear Paul trap. The next steps towards trapping and cooling of a single ion is underway.