EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Letter of Intent to the ISOLDE and Neutron Time-of-Flight Committee

Laser Cooling of Ra ions for Atomic Parity Violation

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Abstract: The observation of weak interactions in atomic systems have played a mayor role in the acceptance of the Standard Model of the electroweak unification. In particular atomic parity violation (APV) is the only route to investigating contribution of the weak interactions at low momentum transfer and ions of the alkaline earth metal Radium offer unique possibilities. In this context we propose to install a Paul trap at the ISOLDE beamline in order to store Ra ions, and perform laser spectroscopic measurements on laser cooled ions on a number of relevant parameters which are crucial for the determination of APV.

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1 Physics Case

The strength of the weak interaction at low momentum transfer has only been determined in one outstanding experiment on an intense cesium atomic beam [1, 2] two decades ago. Several projects are directed towards an improved measurement in Cs, Fr [3], Ba and Ra. This proposal provides a major step into the realization of a quantitative measurement of atomic parity violation in a single trapped Ra^+ ion.
Calculations show that in Ra^+ APV is about 50 times larger than that in atomic Cs [4], where the current most accurate measurement of the weak mixing angle $\sin^2(\Theta_W)$ (Weinberg angle) at low energy has been conducted [1]. The ion Ra^+ renders the possibility for a five-fold improvement in the accuracy of $\sin^2(\Theta_W)$ within 1 week of measurement time. This probes the electroweak running of $\sin^2(\Theta_W)$ with improved sensitivity.
In atomic systems the weak interaction couples to the atomic states by mixing of a photon and a Z^0 boson, both exchanged between electron and nucleus. This causes atomic states to acquire a minute admixture of opposite parity states. These effects are strongly enhanced in heavy atoms and scale significantly stronger than Z^3 [4]. The radioactive Ra^+ ion is the heaviest alkaline earth ion which is available at suitable quantities at the CERN/ISOLDE facility. Therefore, Ra^+ provides a very promising route toward the most precise determination of parity violation at low momentum transfer. Following a proposal by Fortson [5], a single trapped and laser cooled ion is excellently suited to measure APV. The main advantages of a single trapped ion are good control of systematics and long coherence time. An apparatus for such an experiment is currently under development at the Van Swinderen Institute, University of Groningen.

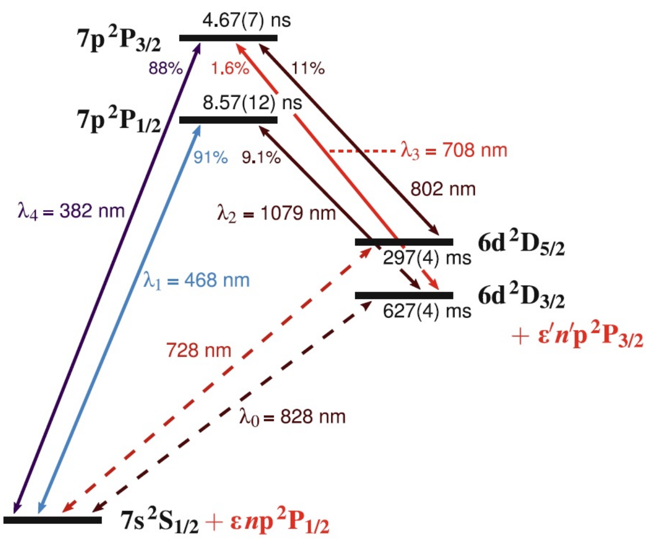

Figure 1: Low lying levels in the Ra^+ ion system. The exchange of a Z^0 boson between the nucleus and an electron in the atomic shell causes mixing of states with opposite parity. Here ϵ and ϵ'denote tiny admixtures of opposite parity states. The wavelengths λ_0 to λ_4 are the transitions accessed in trapped Ra^+ [9, 10]. Calculated lifetimes and branching ratios and wavelengths are taken from [6].

1.1 Radium ions

A central aspect in the exploitation of the intrinsic sensitivity of Ra^+ is the understanding of the atomic structure of the system, which is required for the extraction of Standard Model parameters from a measurement. The required theory of an atomic system with a single valence electron can be treated with sufficient accuracy [6], however, experimental input on nuclear charge radii, isotope shifts, hyperfine structure and metastable state lifetimes are crucial for the evaluation of the uncertainties of atomic structure calculations. Such measurements have been performed in the past and are ongoing. Due to the unique properties of ion trapping and laser cooling highly competitive measurements and additional measurements on otherwise not accessible states can be performed.
In this context some work on radium ions have been performed. The introduction of collinear laser spectroscopy at ISOLDE has provided isotope shifts and hyperfine structure on transitions from the ground state to an accuracy of several MHz [7]. Radium production at TRIμP facility of the University of Groningen with typical rates of a few 100-10^4 Ra ions/s and subsequent loading into a buffergas filled linear Paul trap provided further spectroscopic results [8, 9, 10]. This first trapping and laser spectroscopy of short lived radioactive ions has enabled a number of relevant experimental determination of atomic parameters.
Investigation of the required atomic structure calculations, requires more data on isotope shifts in order to extract the variation of nuclear charge radii and hyperfine structure and metastable state lifetimes. In this context the MuX collaboration at the Paul Scherrer Institute, CH, is investigating the determination of the absolute charge radius of ^{226}Ra [12]. The contribution of nuclear structure on APV has been investigated for a chain of isotopes [11]. Further relevant measurements on the nuclear structure are performed by Coloumb excitation and the determination of octupole deformations [13].
Trapped ions provide access to a number of transitions in the ionic system with a good signal to noise for a small number of trapped ions. Work on single trapped Ba^+ ions is foreseen in order to setup an experimental strategy for the determination of the weak contributions and the study of systematics for such a measurement [14].

2 Ion Trapping and Laser Cooling at ISOLDE

Guided by the successful work at the TRIμP facility, Groningen, The Netherlands, [15] the ISOLDE ion beam of radium isotopes with lifetimes of larger than several seconds will be injected into a radio frequency cooler and buncher [16]. The ion beam properties at ISOLDE are similar to the low energy beam line behind the thermal ionizer at the TRIμP facility where the isotopes 209-214 were available. The radium ions will be cooled by buffer gas collisions. At that stage laser spectroscopy of the laser cooling transitions for the radium ion can be performed and the efficiency of the capturing of radium ions can be determined (Fig. 2). The transitions are observed by photon counting of the resonant fluorescence with a photo-multiplier. The frequency resolution on the laser spectroscopy of the 7S-7P and 6D-7P transitions will be limited by Doppler broadening at this stage. The ions will be extracted into a second linear quadrupole rf-trap in which the buffergas can be removed. In such a trap few ions can be laser cooled, which decreases the

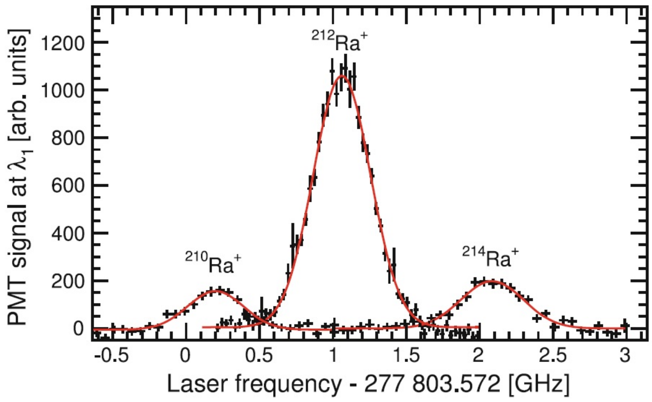

Figure 2: 6d $^2D_{3/2}$ – 7p $^2P_{1/2}$ repump transitions in $^{210,212,214}Ra^+$ at wavelength λ_2 observed in a buffergas cooled ion trap. The solid line represents in each case a fit of a Gaussian lineshape to the data. The absolute laser frequency was determined with a frequency comb [10]. The signal is detected via fluorescence at wavelength λ_1. Labels of the wavelength according to Fig. 1.

spectroscopic linewidth down to the natural linewidth while increasing the signal to noise dramatically. The fitting of the resonant fluorescence with a calculation on the basis of optical Bloch equations permits the determination of all relevant transition frequencies at a level of 100kHz uncertainty (Fig. 3, note the different frequency scale as in Fig. 2), which would be an improvement on isotope shift and hyperfine structure data by more than one order of magnitude for radium isotopes and provides crucial input for high precision cross checks with atomic structure calculations which are of interest e.g. also for the modelling of the structure of super heavy elements.

3 Anticipated Physics Results

The implementation of a Paul trap at an ISOLDE beamline with the capability of laser cooling opens the opportunity to a significant increase in the accuracy of isotope shifts and hyperfine structures for ions, not only radium isotopes, with a lifetime of longer than several seconds. Furthermore, the access to cooled ions permits the observation of many more transitions and the determination of metastable state lifetimes. This is in particular relevant for the case of radium ions in order to provide a solid database of experimental data for testing improved atomic structure calculation and providing crucial input for the analysis of atomic parity violation in this system.

4 Requirements

The experiment requires access to a beam port in order to install a rfq buncher and cooler similar to the one used at the TRIμP facility. Behind the rfq an uhv chamber with a

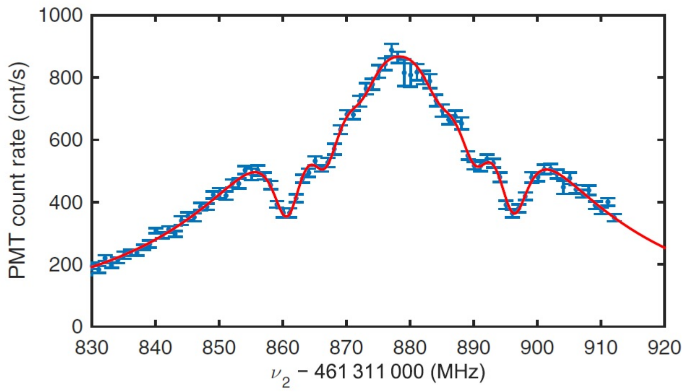

Figure 3: Spectrum of the 5d $^2D_{3/2}$ — 6p $^2P_{1/2}$ transition in a single $^{138}Ba^+$ ion in the presence of two light fields. The solid line corresponds to a fit of the optical Bloch model with the experimental parameters of laser frequencies and polarizations [14]. With this method the transition frequencies for the 5d $^2D_{3/2}$ — 6p $^2P_{1/2}$, 6s $^2S_{1/2}$ — 6p $^2P_{1/2}$ and 6s $^2S_{1/2}$ — 5d $^2D_{3/2}$ can be determined simultaneously.

linear quadrupole trap will be installed. The estimated area is about 3mx5m. The laser light will be delivered by optical fibers in order to minimize the space requirements near the beam line and to place the laser system in a stable environment. The laser system as it was used in the experiment at the TRIμP facility is based solely on diode lasers. The total footprint required on a laser table is about 2.5 m^2. Ideally, the absolute frequency reference for the optical frequencies is provided by an optical frequency comb or secondary frequency standards like molecular tellurium or iodine (see for example [14]). Low energy beams from the ISOLDE facility are well suited for the research. In the initial stage while commissioning the rfq ion trap and the transfer to the linear quadrupole trap in the UHV environment continuous beams of short lived radium isotopes is required for several shifts. We anticipate the use of ion rates of 10^4 ions per second and running with offline beams is desirable. While running the ultra high vacuum trap with laser cooling we will first investigate the longer lived radium isotopes because the storage time of ions in a Paul trap with laser cooling can exceed many hours to days.
Collaboration with other ISOLDE groups operating similar infrastructure regarding laser technology as well as on ion handling is highly desired and presently prepared in discussion with members of the Collaps and the CRIS group.

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