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Proposal to the ISOLDE Committee

Nuclear Charge Radius Measurements of Radioactive Beryllium Isotopes

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Abstract

We propose to measure the nuclear charge radii of the beryllium isotopes ^{7,9,10}Be and the one-neutron halo isotope ^{11}Be using laser spectroscopy of trapped ions. Ions produced at ISOLDE and ionized with the laser ion source will be cooled and bunched in the radio-frequency buncher of the ISOLTRAP experiment and then transferred into a specially designed Paul trap. Here, they will be cooled to temperatures in the mK range employing sympathetic and direct laser cooling. Precision laser spectroscopy of the isotope shift on the cooled ensemble in combination with accurate atomic structure calculations will provide nuclear charge radii with a precision of better than 3%. This will be the first model-independent determination of a one-neutron halo nuclear charge radius.

1. Physics Motivation and Status of Research

More than twenty years ago, I Tanihata et al [1, 2] discovered that some isotopes of the lightest elements close to the neutron drip-line have nuclear matter radii that by far exceed those of their neighbors. The matter radii were extracted from interaction-cross section measurements. The results are shown in Fig. 1. It was soon proposed that these large radii matter are due to weakly bound neutrons, extending far into the classically forbidden range far away from the nuclear core, and the term halo-nuclei was established for such systems [4]. This new form of nuclear matter has been extensively investigated using various techniques from nuclear and atomic physics and many properties were determined (for a review see e.g. [5]).

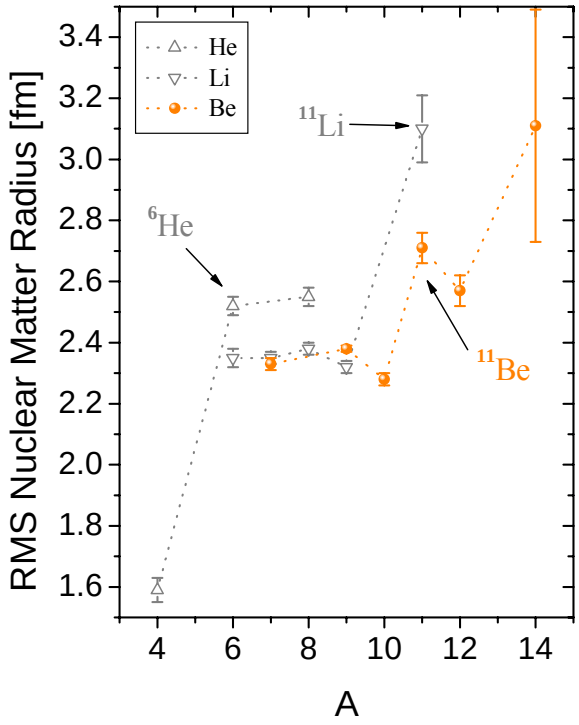

Fig. 1: Nuclear Matter Radii of helium, lithium, and beryllium isotopes [1-3].

However, a model-free direct measurement of the nuclear charge radius was not possible until recently. Based on new and very specialized techniques two groups succeeded in measuring for the first time isotope shifts of radioactive very light nuclei with a precision that is sufficient to extract nuclear charge radii. At the Argonne National Laboratory the charge radius of ^{6}He was obtained from laser spectroscopy on helium atoms confined in a magneto-optical trap [6], while a collaboration from GSI Darmstadt and the University of Tübingen developed a method for high-resolution resonance ionization spectroscopy. They succeeded to measure the charge radii of ^{8,9}Li at GSI [7] and of ^{11}Li [8] at the ISAC mass separator at TRIUMF.

To determine the charge radius from the isotope shift it is necessary to calculate the mass-dependent part of the isotope shift with high accuracy. While this was possible for one- and two-electron systems already since the 1980's, for lithium-like three-electron systems the breakthrough came in 2000 when Z.C. Yan and G.W.F. Drake succeeded in calculating the mass effect in transitions of neutral lithium with a relative uncertainty of better than 5×10^{-6} [9]. These calculations were the prerequisites for the lithium experiments. Similar calculations are in progress for the singly charged beryllium ion, which will be used for the measurement proposed here.

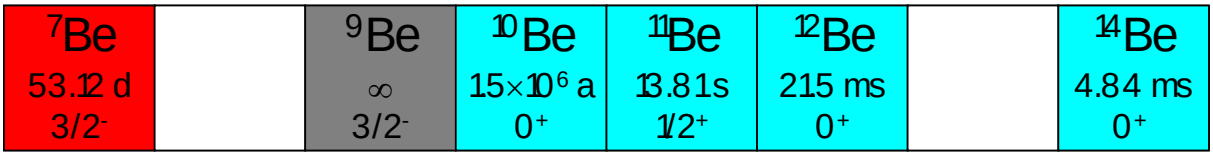

Fig. 2: Beryllium isotopes in the chart of nuclides.

^{11}Be is the archetype of a one-neutron halo and has been the subject of many investigations [10-12]. After the determinations of the charge radii of borromean two-neutron halo systems of first (^{11}Li) and second kind (^{6}He), this would be the first measurement of a model-independent charge radius of a one-neutron halo nucleus. Hence, it should provide information that is complementary to that obtained in the other cases.

Isotope shift measurements of light elements are not only interesting for halo nuclei but are generally considered very important for nuclear theory [13]. Calculations of nuclear structure with the Greens function Monte-Carlo method are available up to mass number $A = 10$ [14, 15]. For these systems the charge radius of the proton r_p is an important part of the overall mean-square charge radius. Hence, the current uncertainty of r_p degrades the ability to test the wave function of light nuclei [13]. As has been pointed out by J. L. Friar, this is a very important point for isotope shift measurements of light nuclei: Measuring the differences in frequencies for a fixed nuclear charge has the advantage that the proton´s intrinsic size cancels. Thus, the comparison to nuclear theory does not suffer from the lack of a precise value for the proton's radius. "Isotope shifts are, therefore, especially »theorist-friendly« measurements, since they are closest to measuring what nuclear theorists actually calculate" [13].

It would be very exciting to extend these measurements to beryllium. Figure 2 shows the relevant part of the nuclear chart. For this element there are two isotopes of particular interest for a charge radius determination: ^{11}Be and ^{7}Be. Additionally, ^{14}Be as a borromean halo nucleus and the intermediate isotope ^{12}Be would also be important, but with their small production rates and short half-lifes (4.84 ms and 23.6 ms, respectively) they will be targeted in a second step, once the method has been established for the "longer-lived" isotopes $^{7\text{-}11}$Be and its limitations concerning half-lifes and production rates are well investigated.

Information on the charge radius of ^{7}Be is of much interest for nuclear astrophysics. Here, relations between astrophysically important low-energy reaction cross-sections and certain size-properties of the involved nuclei are discussed. Examples are the ^{7}Be(p,γ)^{8}B reaction [16, 17] as well as the ^{4}He(^{3}He,γ)^{7}Be reaction [18]. ^{7}Be has a half-life of 53.12 days and would thus even allow an off-line measurement, while the 13.81 s isotope ^{11}Be needs to be measured on-line.

2. Experimental Method

2.1 Optical Isotope Shift

The isotope shift in an electronic transition, i.e. the difference in transition frequencies between two isotopes, has two origins: The difference in nuclear mass influences the exact electron energies due to the nuclear motion around the center of gravity (mass shift, MS), while the spatial extent of the nuclear charge leads to a difference in the binding energy (volume or field shift, FS)

for electrons which have nonzero probability for being inside the nuclear volume. While the mass shift is proportional to

$$\delta\nu_{MS}^{AA'} \propto \frac{M_A - M_{A'}}{M_A \cdot M_{A'}}$$

and thus becomes smaller for heavier elements, the nuclear volume effect increases with Z according to

$$\delta\nu_{FS} \propto \frac{Z}{\sqrt[3]{A}}.$$

For heavy elements the isotope shift is therefore dominated by the volume shift, but for light elements the volume shift is only a tiny fraction of the mass shift. For example, in helium, lithium and beryllium transitions, the field shift contributes only approximately 1 MHz, while the mass shift is several 10 GHz. Separation of the two effects can only be achieved if the mass shift in the electronic transition can be reliably calculated with an accuracy of 10^{-5} or better. To reach this accuracy, relativistic and quantum electrodynamical corrections have to be considered. Such calculations have been demonstrated for the three-electron system lithium a few years ago [9, 19, 20].

The Be^+ ion is also a three-electron system and can be calculated with the techniques already developed for the case of lithium. Such calculations are currently performed by G.W.F. Drake and Z.-C. Yan. For the atomic system, there has been considerable progress towards high-accuracy calculations. Recently, K. Pachucki and J. Komasa reported on a complete calculation of relativistic and quantum electrodynamics corrections of order α^2 Ry and α^3 Ry for the ground state of the beryllium atom and its positive ion [21]. J. S. Sims and H. A. Hagstrom discussed recursive techniques to solve the most difficult integral arising in Hylleraas-configuration interaction calculations – the three-electron triangle integral [22]. Even though it seems conceivable that the required accuracy will soon be reached, our proposal is independent on these calculations since we will measure the isotope shift in beryllium ions.

With these calculations, the nuclear volume shift can be calculated according to

$$\delta\nu_{FS} = \delta\nu_{IS}^{\mathrm{Exp}} - \delta\nu_{MS}^{\mathrm{Theorie}}.$$

Using the well-known nuclear charge radius dependence of the field shift

$$\delta\nu_{FS} = \frac{2\pi}{3}\Delta\left|\Psi(0)\right|^2 \cdot \delta\left\langle r_c^2\right\rangle,$$

with the change of electron probability at the nucleus $\Delta\left|\Psi(0)\right|^2$ in the transition (calculable from atomic theory) and the change in the root-mean-square nuclear charge radius $\delta\left\langle r_c^2\right\rangle$ between the isotopes, one can obtain the expression for the nuclear charge radius of the isotope A'

$$\delta\left\langle r_c^2\right\rangle^{A'} = \delta\left\langle r_c^2\right\rangle^{A} + \frac{\delta\nu_{IS}^{\mathrm{Exp}} - \delta\nu_{MS}^{\mathrm{Theorie}}}{\frac{2\pi}{3}\Delta\left|\Psi(0)\right|^2}.$$

provided that the nuclear charge radius of a reference isotope A is known. In the beryllium case the charge radius of the stable isotope ^{9}Be has been determined with electron scattering ($r_c = 2.50\pm0.09$ fm and 2.519 ± 0.012 fm [23, 24]) and via spectroscopy on muonic atoms ($r_c = 2{,}39\pm0.17$ fm [25]). All values are in reasonable agreement.

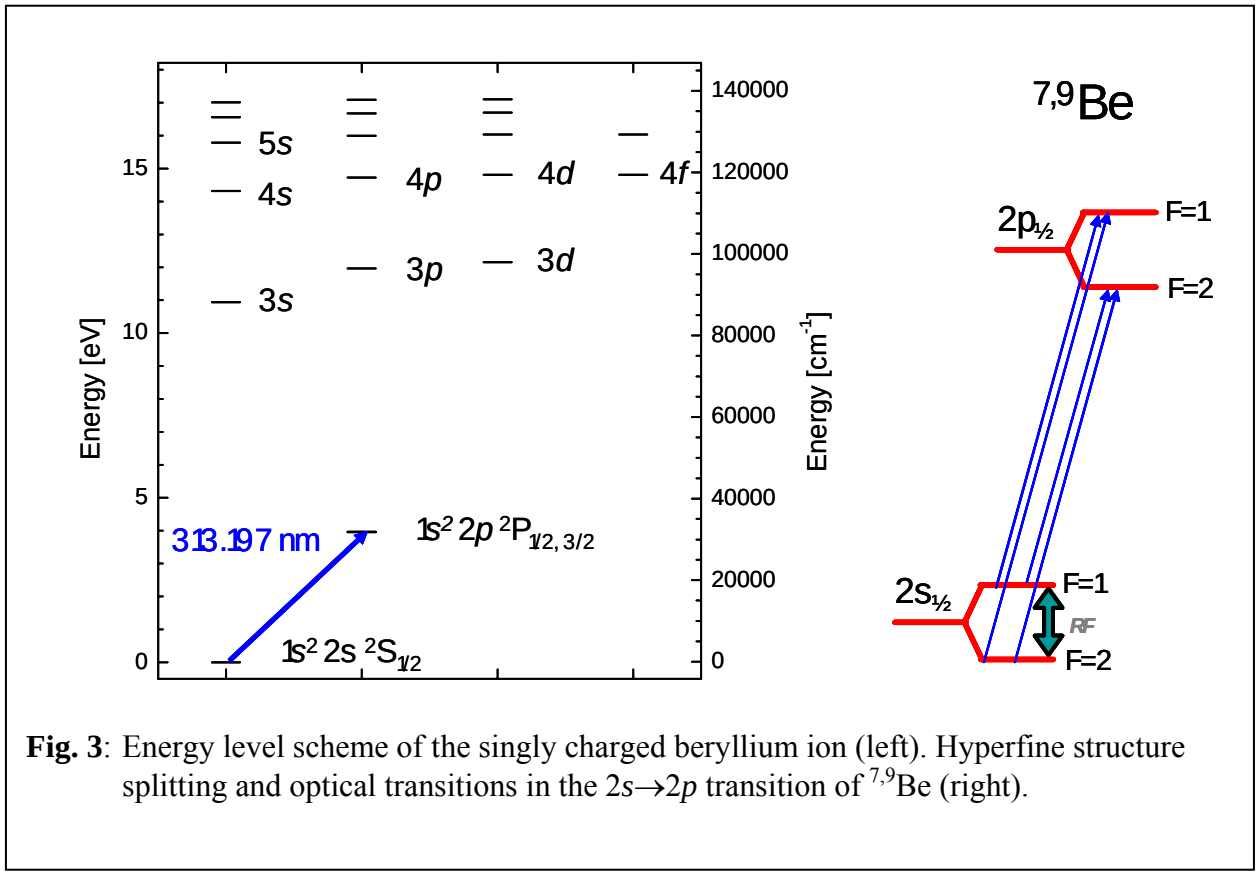

Fig. 3: Energy level scheme of the singly charged beryllium ion (left). Hyperfine structure splitting and optical transitions in the $2s \rightarrow 2p$ transition of ^{7,9}Be (right).

2.2. Be^+ Ionic Level Structure and Laser Excitation Scheme

Figure 3 shows the lowest lying levels of the beryllium ion. It is obvious that only the $2s \rightarrow 2p$ transition is accessible with (frequency-doubled) continuous wave (cw) lasers, all other transitions out of the ground state (even the $2s \rightarrow 3s$ two-photon transition) are far in the vacuum-UV. The fine structure splitting leads to two possible transitions, $2s_{1/2} \rightarrow 2p_{1/2}$ and $2s_{1/2} \rightarrow 2p_{3/2}$, but the nuclear spin of the odd beryllium isotopes results in a hyperfine structure splitting that is only resolved in the $2s_{1/2} \rightarrow 2p_{1/2}$ transition. The natural linewidth is given by the lifetime of the 2p level (τ= 8.1(4) ns [26]) and leads to a FWHM of 20 MHz. Thus, the line center has to be determined to an accuracy of better than 1% (200 kHz) to extract meaningful values of nuclear charge radii.

2.3. Production and Transfer of Radioactive Beryllium Ions

All radioactive beryllium isotopes shown in Fig. 2 can be produced at ISOLDE. Applying the laser ion source, yields of more than 10^6 ions/s of the halo isotope ^{11}Be have been delivered to laser spectroscopy experiments previously [11] and much higher yields can be expected for the lighter radioactive isotopes. To take maximum advantage of the existing ISOLDE infrastructure we are collaborating with the ISOLTRAP team and will use their existing radio frequency quadrupole (RFQ) cooler and buncher device as shown in Fig. 4 [27]. This has the advantage that pre-cooled bunches with a well defined time structure and bunch energy will be delivered to our Paul trap set-up. Since the energy of the ion bunch ejected out of the ISOLTRAP cooler can be decreased to a few 100 eV with the pulsed drift tube integrated in the beam transport between the

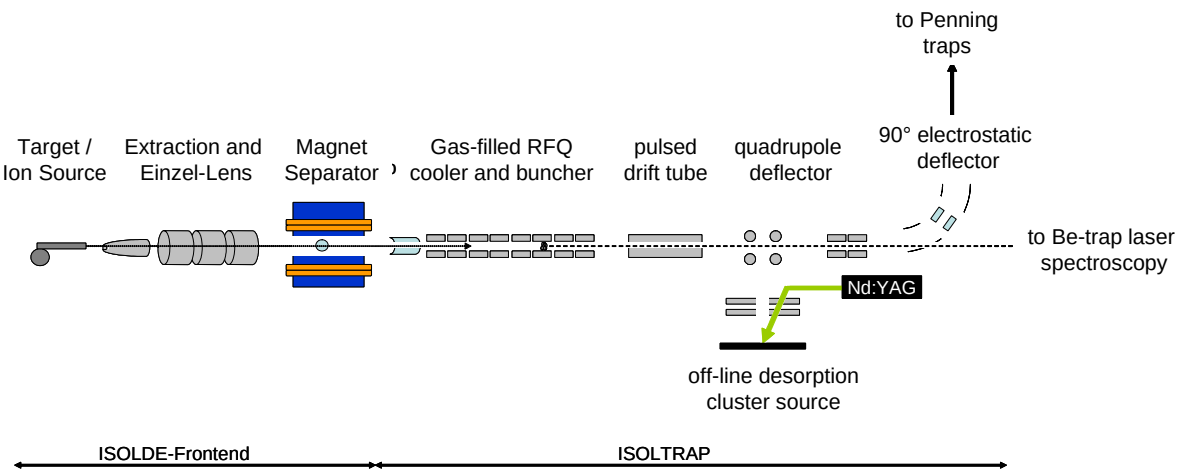

Fig. 4: ISOLDE front-end and ISOLTRAP beamline to be used for beryllium laser spectroscopy (not to scale drawing).

RFQ structure and the ISOLTRAP deflector cube, stopping of the ions can be easily achieved either with a second fast drift tube at low voltages or by floating the trap set-up to a relatively small offset voltage. Since we can tolerate some losses in transfer efficiency due to the relatively high production rates and the small number of ions needed for spectroscopy – in the ideal case we will work with a single ion in the trap – this approach should be sufficient.

Together with the ISOLTRAP collaboration a few test experiments will be performed during this year to investigate the ion beam structure and emittance that can be delivered to our experiment.

2.4 Location of the Experimental Set-up at ISOLDE

We plan to install our vacuum chamber beneath the ISOLTRAP tower inside the small laser cabinet. Space should be sufficient to house the small vacuum chamber and two set-ups for frequency doubling in order to produce the 313 nm light for the beryllium ion resonance transition. A few hundred milliwatts of the 626 nm fundamental will be delivered to this place via a photonic crystal fiber (LMA = Large Mode Area fiber) that has been demonstrated to transport up to 1 W of laser light without limitations due to non-linear effects. An ideal place to install the dye lasers for generation of the fundamental and the optical frequency comb that will be used for laser stabilization, would be the laser laboratory that is currently used by the COMPLIS collaboration. The length of our existing fiber fits almost exactly to the distance between this laboratory and the ISOLTRAP set-up. Moreover, it will provide the infrastructure for low-noise laser operation, a thermally stabilized environment, and sufficient space for laser set-up and some data acquisition electronics. A sketch of a possible installation is shown in Fig. 5

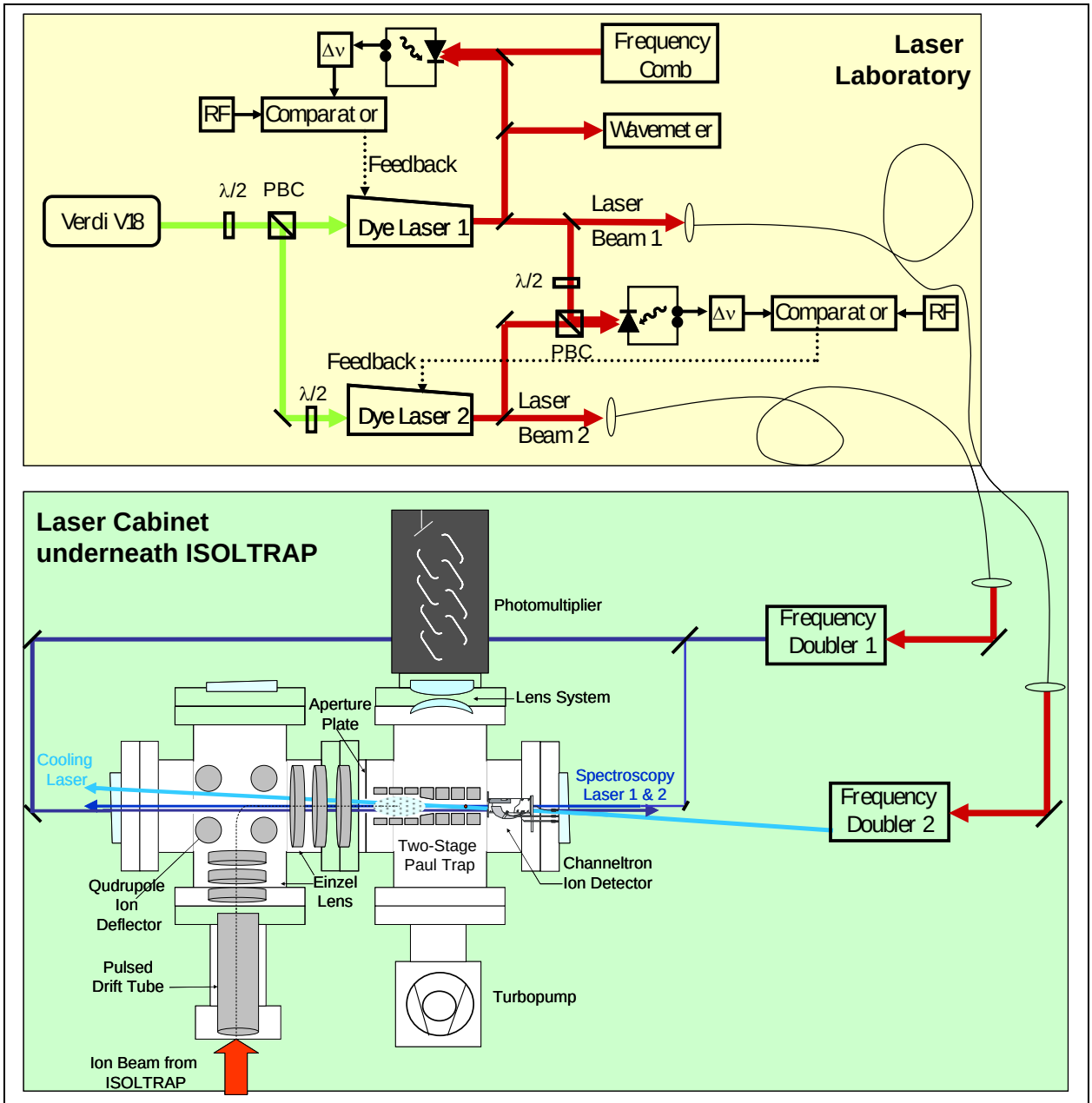

Fig. 5: Experimental set-up and possible arrangement at ISOLDE.

2.5 Cooling and Spectroscopy in the Paul Trap

We are currently investigating an optimized trap geometry to stop and efficiently cool the delivered beryllium ions. We will use a novel trap design that allows us to combine two linear segmented Paul traps with different sizes but driven by the same RF frequencies. A first trap with a high acceptance will be used to efficiently catch ions delivered from the RFQ cooler and buncher. For quick cooling, a cloud of laser-cooled calcium ions will be prepared inside this trap and the relatively "hot" beryllium ions from the ISOLTRAP cooler and buncher implanted into this cloud. Via Coulomb interaction the energy will be transferred from the beryllium to the calcium ions and dissipated away by laser cooling. Spatial separation between the calcium and

beryllium ions can be obtained via the light pressure that the resonant (calcium) ions experience from the cooling laser. Only the isolated and pre-cooled beryllium ions will then be transferred into the second trap, which has a smaller radius but the same RF frequency and amplitude and thus a tighter confinement of the ions onto the trap axis.

Once the ions are transferred into this measurement trap, they will be further cooled and located very close to the center axis of the trap. This has the advantage that the ions micro-motion will not be driven by the RF frequency field and therefore the ions stay cool. Now the spectroscopy laser will be turned on and the cooling laser turned off. For a few microseconds, short enough that the ions are not considerably heated, fluorescence from the spectroscopy laser is collected and then the cooling laser is turned on again to dissipate all energy transferred into the system. This cycling is repeated until all ions transferred into the trap are lost.

In order to avoid optical pumping into dark states, an RF frequency will be coupled to the ion cloud in order to mix the two hyperfine states of the 2s level as indicated in Fig. 3(b). With these procedures we should be able to reach a transition linewidth close to the natural linewidth. The statistical uncertainty to determine the center of a 20 MHz wide line to an accuracy of approximately 1% of the linewidth should be easily reachable, considering the rather high yields and relatively long half-lifes of the beryllium isotopes up to the one-neutron halo ^{11}Be.

In a number of studies we want to investigate systematic effects of the number of ions inside the trap, the cycling lengths and other parameters onto the exact resonance positions. These investigations will be performed off-line at the Nuclear Chemistry Department at the University of Mainz before the whole equipment is being moved to and installed at ISOLDE.

3. Beam Time Request

We would like to ask for a beamtime in fall 2006 with stable beryllium ^{9}Be to test the extraction and transport efficiency of ions from the RFQ cooler and buncher to our set-up. After installation of the set-up, first test experiments can be performed with stable beryllium ions produced in the cluster ion source of the ISOLTRAP experiment. According to our time schedule we anticipate to be ready for on-line measurements at ISOLDE in 2008 and want to start with measurements on ^{7,9,10}Be. We estimate that one week of beamtime would be sufficient to study these isotopes and to perform also a first short test with ^{11}Be. Based on our experience during this run, we will estimate the required beamtime for a ^{11}Be measurement and will apply for beamtime in an addendum of this proposal. The beam time request is given in Table 1.

Table 1: Beam Time Request

Nuclides	Field of interest	No. of shifts	Ion Source	Target
^{9}Be	Halo	8	RILIS	-
8 stable beam shifts for test measurements				
^{7,9,10,11}Be	Halo	18	RILIS	UC
18 radioactive beam shifts for charge radius measurements of ^{7,9,10}Be, including a short test with ^{11}Be				

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