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High Precision Laser Spectroscopy on ^{12}Be

(Addendum to Proposal INTC-P214 / Experiment IS 449)

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Abstract

We propose to extend the laser spectroscopy measurements of the beryllium isotopic chain as suggested in proposal INTC-P214 (IS 449) up to ^{12}Be. By applying advanced laser techniques and using precision mass shift calculations, the charge radius of ^{12}Be can be determined with a precision of better than 2 %. This nuclear model independent technique allows for evaluation of partially contradictory results from earlier scattering experiments from I. Tanihata and coworkers and recent results from GSI. Furthermore this measurement is a mandatory prerequisite for the later charge radius measurement of ^{14}Be. The proposed measurements will be conducted at the COLLAPS beamline. After a short off-line test beam time, the collection of ^{12}Be data shall be completed in one single run over a period of 18 shifts.

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Second Addendum to Proposal INTC-P214 / Experiment IS 449

Introduction

Some light nuclei close to the neutron and proton drip-line exhibit a strong increase in matter radius compared to the neighbouring nuclides in the isotopic chain [2, 3]. In a semi-classical description these so-called halo-nuclides [4] can be described as a compact core with up to four weakly bound neutrons or protons on far reaching orbits. A large variety of experiments have been conducted to study this nuclear structure phenomenon at the neutron dripline, mainly accelerator based high-energy scattering experiments which allow for a model-based description of the matter distribution and halo-neutron correlations.

Laser spectroscopy can provide complementary information. Optical precision measure-ments of the isotope shift provide model-independent information of the change in the nuclear charge radius along the isotopic chain [8] and therewith yield an insight to the influ–ence of the halo-neutrons on the core nucleus, like recently demonstrated for the two-proton halo candidate ^{17}Ne [9]. For lighter elements the mass shift term dominates the isotope shift but only the field shift part with a contribution in the order of 10^{-4} is sensitive to the change in the nuclear charge radius. Therefore the extraction of charge radii of these elements have just recently become feasible as theoretical calculations of Drake and Yan [7, 11-13] and independently, but in excellent agreement, of Pachucki and Puchalski [10, 14-16], have reached the mandatory precision in the calculation of the mass-dependent contributions.

This enabled a series of accurate laser spectroscopic measurements of the lightest elements up to the neutron dripline. A collaboration of GSI and TRIUMF performed two-photon laser spectroscopy of the complete lithium isotope chain including the two-neutron halo ^{11}Li at GSI [17-19] and ISAC/TRIUMF [20]. Also the complete helium isotope chain including the two-neutron halo ^{6}He as well as the four-neutron halo ^{8}He was studied in atom trap experiments by a group from Argonne National Lab at ATLAS [21] and at Ganil [22]. In all these measurements the charge radii of the halo-nuclei were successfully measured and compared with the non-halo nuclei. In the ISOLDE experiment IS449 our collaboration successfully measured the isotope shifts of the beryllium ions ^{7}Be, ^{9}Be, ^{10}Be and ^{11}Be in 2008 [1]. As suggested in the addendum INTC-P214-add1 we combined the standard collinear laser spectroscopy setup of COLLAPS with state-of-the-art laser techniques developed at GSI and the University of Mainz. A simultaneous excitation in collinear and anti-collinear geometry with two individual laser systems, frequency stabilized to a Doppler-free saturation spectroscopy setup and - for the first time - to a frequency comb, provided the isotope shift of the lightest elements with accuracy of about 1 MHz. Table 1 shows the isotope shift measured at ISOLDE and, extracted from this, the calculated change in charge radii relative to the stable isotope ^{9}Be. Figure 1 shows the behaviour of the charge radius from ^{7}Be to

[11]Be, which was extracted using the absolute charge radius from electron scattering experiments of Jansen *et al.* [6] as reference for [9]Be.

The increasing charge radius from [10]Be to [11]Be can be explained classically in two ways: in the most obvious explanation the increase in charge radius from [10]Be to [11]Be is ascribed to a movement of the [10]Be core and the halo neutron around the centre of mass. The movement of the core leads to a delocalization / smearing out of the protons around the centre of mass which is represented by the increase in charge radius. To explain the observed change in the mean-square charge radius of 0.51 fm^2, the halo-neutron has to orbit at a distance of 7.7 fm relative to the centre of the core inside the [11]Be nucleus. An alternative explanation can be given taking into account that the nucleus of [10]Be is commonly considered to be strongly clustered into two alpha-particles in a distance of about 3.30 fm [23] and two additional neutrons acting as glue between these alpha clusters. Adding a third neutron in [11]Be, increases then the distance between the alpha clusters. Here, an increase by about 10%, i.e. increasing the distance to 3.60 fm, would be sufficient to completely account for the charge radii observed in laser spectroscopy. However, due to the two-body (core + halo neutron) structure of [11]Be, some degree of centre-of-mass motion must be present. Hence, in reality we must expect a mixture of both effects.

In order to estimate how much the core excitation contributes to the total increase in charge radius, we can combine the laser spectroscopic result with results from the one-neutron removal channel in electromagnetic and nuclear inelastic scattering experiments at GSI [24].

Table 1: isotope shift in the D1 line as measured at ISOLDE [1] and calculated mass shift [7] [10]in relation to [9]Be. The resulting change in charge radius is plotted in the third column

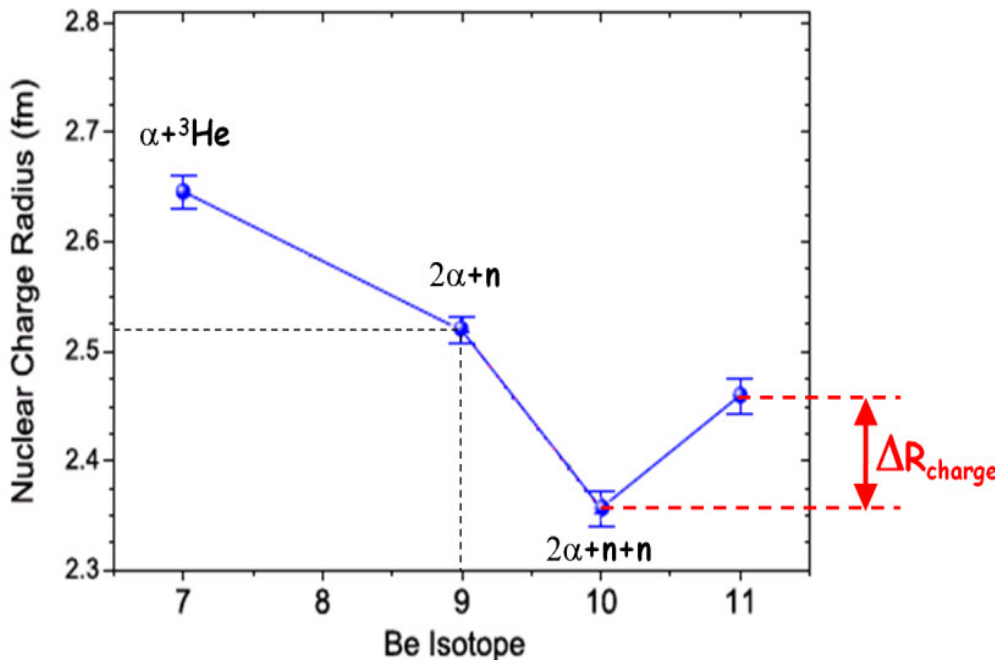|	isotope shift $\delta\nu^{9,A}_{IS}$ / MHz	mass shift $\delta\nu^{9,A}_{MS}$ /MHz	$\delta\langle r_c^2\rangle^{9,A}$ / fm^2
[7]Be	-49236.9(9)	49225.75(4)	0.66(5)
[9]Be	0	0	
[10]Be	17323.8(13)	17310.44(1)	-0.79(8)
[11]Be	31565.0(9)	31560.31(6)	-0.28(5)

Figure 1: Charge radii of the beryllium isotopic chain, referring to electron scattering data [6] as input for [9]Be. Error bars include both the error bar of the laser spectroscopy measurement and of the reference radius.

A core-halo distance of 6.3(4) fm is extracted from these experiments. Assuming this being the right distance, we can conclude that the missing contribution to the change in the mean square nuclear charge radius can be explained by an increase of the α -α-distance by about 3.3 %. Further combination with results from B(E1) distribution measurements will allow for an even more detailed description of the structure of this one-neutron halo-nucleus as recently suggested by I. Tanihata.

This addendum aims for the extension of our studies of the halo-nuclei within the beryllium isotopic chain to ^{12}Be, which has a production rate of about 1500 ions / µC and is therefore at the very edge of accessibility for collinear laser spectroscopy at ISOLDE.

Physics Motivation

^{12}Be is a spin zero isotope with a half-life of 21.34(23) ms [25]. Like ^{11}Be it has a known intruder *sd*-configuration, due to the disappearance of the *N*=8 magic number within the beryllium isotopic chain. ^{12}Be has a rather high two-neutron separation energy of S_{2n}= 3.76 MeV which does not suggest halo formation on first sight.

^{14}Be is a halo-nucleus and it is commonly accepted to form a ^{12}Be core plus two valence neutrons (like in the case of ^{6}He and ^{11}Li). Nevertheless a configuration with a ^{10}Be core and four halo neutrons (similar like ^{8}He) can currently not be excluded from experimental data. Conclusions about the structure of ^{14}Be from a laser spectroscopic nuclear charge radius measurement can only be drawn if ^{12}Be is measured as well.

The investigation of ^{12}Be has gained new momentum from recent elastic proton scattering experiments. ^{12}Be and ^{14}Be have been investigated in inverse kinematics applying the IKAR detector at GSI. Figure 2 (left) shows the absolute differential cross section for proton elastic scattering on ^{12}Be as a function of the four momentum transfer, taken from the PhD thesis of Stoyanka Ilieva 2008 [5]. The coloured lines represent a variety of fits with varying density
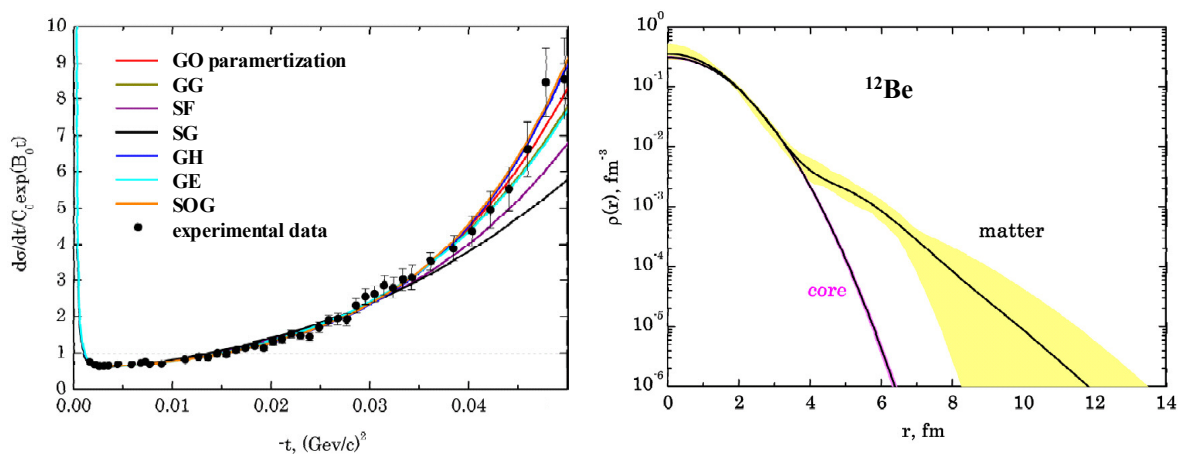

Figure 2: Plot from elastic proton scattering on ^{12}Be taken from the PhD thesis of Stoyanka Ilieva [5], GSI. *Left:* experimental absolute differential cross section as a function of the four momentum transfer "-t" compared with fitted cross sections of different density parameter sets. *Right:* Resulting averaged density distribution of ^{12}Be taking the mean of the GG, GH, GO and SOG parameterizations and summing the individual error-bands.

parameterizations. The standard distribution functions for a "classical" compact nucleus, like the Single Gaussian (SG, black line) as well as the Symmetrised Fermi (SF, purple line) distributions, cannot describe the measured data at higher momentum, while typical halo-distribution functions like Gauß-Halo (GH) can be fitted very well to the data. Averaging over the Gauß-Gauß- (GG), Gauß-Halo- (GH), Gauß-Oscillator (GO) and Sum-of-Gauß-parameterization (SOG) an averaged matter radius of R_{matter} =2.82(12) fm was deduced, which furthermore could be divided into an R_{core}=2.18(10) fm and a halo radius of R_{halo}=5.51(32) fm. In figure 2 (right) the calculated averaged total density distribution extracted from the new scattering data is plotted as black line; the purple line represents the contribution of the core of ^{12}Be. From these elastic scattering data a halo-character of ^{12}Be was concluded despite its comparably large two-neutron separation energy.

In earlier measurements from Tanihata and co-workers [26] no evidence for a halo-structure has been observed. Depending on the parameterization, a total matter radius of R_{matter} =2.57(5) fm or R_{matter} =2.59(6) fm [26] was extracted, which is about 10 % smaller than the recent result. Furthermore, theory can to a certain extent model these earlier measurements, but neither the few-body calculation approach nor fermionic molecular dynamics are able to describe the new GSI data up to now. A laser spectroscopic measurement of the charge radius of ^{12}Be will help to differentiate between the results of these measurements and indicate whether ^{12}Be is a halo nucleus. In the latter case, ^{12}Be would represent the first non-Borromean two-neutron halo nuclide, since removing one neutron will result in the bound nucleus ^{11}Be.

Similar to ^{12}Be, the elastic proton scattering at GSI was conducted for ^{14}Be as well and the experimental data was compiled the same way. The result of the extracted matter distribution is shown as black line in figure 3, taken again from the PhD thesis of S. Ilieva [5]. The green line represents the interpolated ^{12}Be-core contribution if the nucleus is described as a ^{12}Be+2n-system. For better visibility the matter radius of the unbound ^{12}Be from figure 2 has been superimposed as red line in figure 3. A comparison between the red and the green line indicate that the free ^{12}Be and the core of ^{14}Be have a different structure. ^{12}Be exhibits a more extended structure which might be attributed to a large $1s_{1/2}^2$ contribution of the free
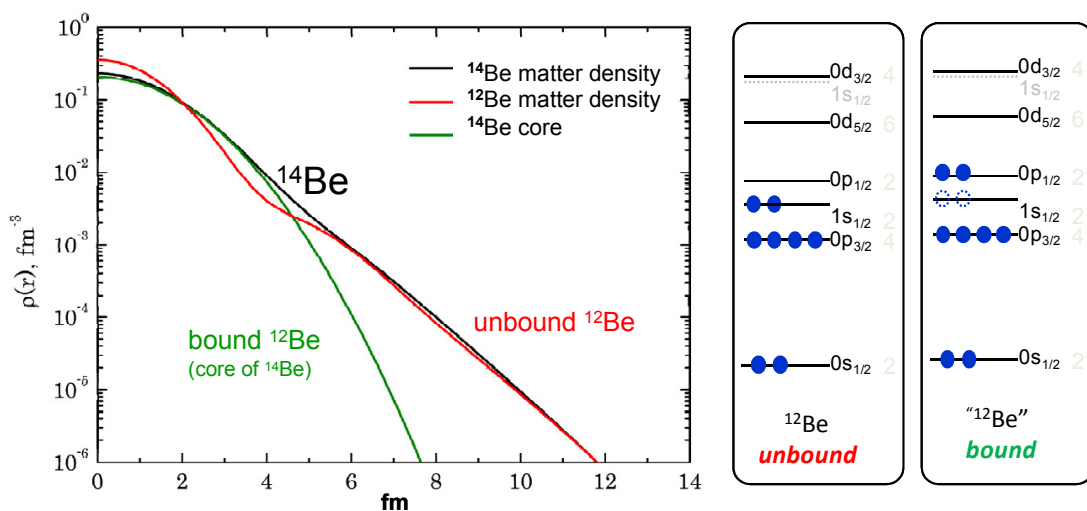

Figure 3: Averaged density distribution of ^{14}Be (black line) modelled from elastic proton scattering data by Ilieva [5]. In green: core density of ^{14}Be in comparison to the total matter distribution of an unbound ^{12}Be core (red line).

[12]Be ground state. In relation to the free [12]Be nucleus, the interpolated density distribution of the [12]Be core in [14]Be (green line) is more compact, which might be explained by the two last neutrons "occupying the next *p*-shell which is the available one" [5], as depicted in figure 3 (right). In this simplified picture, the two halo-neutrons of [14]Be would have a large admixture from the $1s_{1/2}$ state, like in the case of the free [12]Be, to which also the identical halo radius in table 2 might give a hint.

Table 2: Total matter radii of [12]Be and [14]Be and extracted radii of the core and the halo [5].

	[12]Be / fm	[14]Be / fm
R_{matter}	2.82 (12)	3.11 (14)
R_{core}	2.18 (10)	2.65 (12)
R_{halo}	5.40 (37)	5.41 (32)

Hence, already for a full description of the free [12]Be nucleus, there is no converging consensus for the contributions of the $\nu\,(1s_{1/2})^2$, $\nu\,(0p_{1/2})^2$ states to the ground state in the various theoretical models. Recently, even a strong admixture of the intruder $\nu\,(0d_{5/2})^2$ has been proven experimentally [27]. Again, an experimental measurement of the [12]Be charge radius by laser spectroscopy can provide a model-independent observable, on which the various theoretical descriptions with its differing admixtures of contributions to the ground state can be tested and evaluated.

Experimental Design

The experimental design consists of two main components which will be mostly identical as described in addendum-1 to IS449. The beamline applied for the measurement will be the standard COLLAPS beamline [28, 29] in the optical detection version. The laser system of COLLAPS will be replaced by a laser system that has been developed at GSI and at the University of Mainz [30].

The heart of this system are two continuous-wave ring dye lasers which are frequency stabilized to various iodine lines by Doppler-free frequency modulation (FM) saturation spectroscopy and a state-of-the-art fibre-laser-based frequency comb, respectively. Thus, the laser frequencies can be fixed in frequency within a few ten kHz for the duration of the complete measurement campaign, which enables us to control the laser frequencies and therewith isotope shifts of the individual isotopes with a precision of about 1 MHz including all statistical and systematic uncertainties of the experiment. In order to increase the precision of the absolute frequency determination it is planned to upgrade the laser system by a GPS satellite receiver as frequency reference for the frequency comb. Therefore the installation of a compact GPS antenna from University Mainz outside building 507 will be required.

The red light of the two dye lasers is frequency doubled in two second harmonic generators to a wavelength of 313 nm in order to perform spectroscopy on the atomic $2s_{1/2} \rightarrow 2p_{1/2}$ transition in the beryllium ion. These blue laser beams are then coupled in collinear and anti-collinear geometry into the COLLAPS beamline and overlapped with the ion beam. Two fast shutters will block either one of the laser beams in order to perform collinear and anti-collinear spectroscopy in fast sequence. Careful studies with [10]Be will be carried out to reduce systematic uncertainties induced by multi photon-absorption recoil.

Table 3: Yield of the beryllium isotopes at ISOLDE, taken from the ISOLDE yields tables. Added in red: the measured yield of ^{11}Be at the end of the COLLAPS beam line during the ^{11}Be COLLAPS beam time in June 2008, applying for the first time the new upgraded RILIS laser ion source.

Isotope	Yield /μC		Energy /GeV	Target	Ion Source
^{7}Be	1.4E+10	PSB	1.4	UC$_x$	RILIS
^{10}Be	6.0E+09	PSB	1.4	UC$_x$	RILIS
^{11}Be _our run:_	7.0E+06 2.7E+07	PSB	1.4	UC$_x$	RILIS new RILIS
^{12}Be	1.5E+03	PSB	1.4	UC$_x$	RILIS
^{12}Be	7.0E+03	PSB	1.4	thin Ta foil	RILIS

Table 3 shows the yields of beryllium according to the ISOLDE database. The actual yield observed in the measurement run in June 2008 is added in red. From this it becomes obvious, that we benefited from a 3.8-fold higher yield than previously documented which might be due to the first application of the new improved RILIS laser system. Independent of this, a laser spectroscopy experiment with in the order 10^3-10^4 ions, as to be expected for ^{12}Be is not feasible with the standard classical pure optical detection. In April 2009 we therefore requested a preparatory off-line test beam time, to test the feasibility of beryllium laser spectroscopy in combination with bunched ion beams from ISCOOL [31].

Within the rather short period of a single day, we observed a variety of critical parameters like gas pressure, ion flux into the RFQ, and others, which influenced the laser resonance position and which seem to be difficult to keep stable and controlled for the duration of the isotope shift measurements. The main argument, which leads our collaboration to a decision against the usage of ISCOOL for a possible beryllium run, was its transmission for beryllium. Even after thoroughly tuning the ion beam into ISCOOL and the RFQ structure of ISCOOL
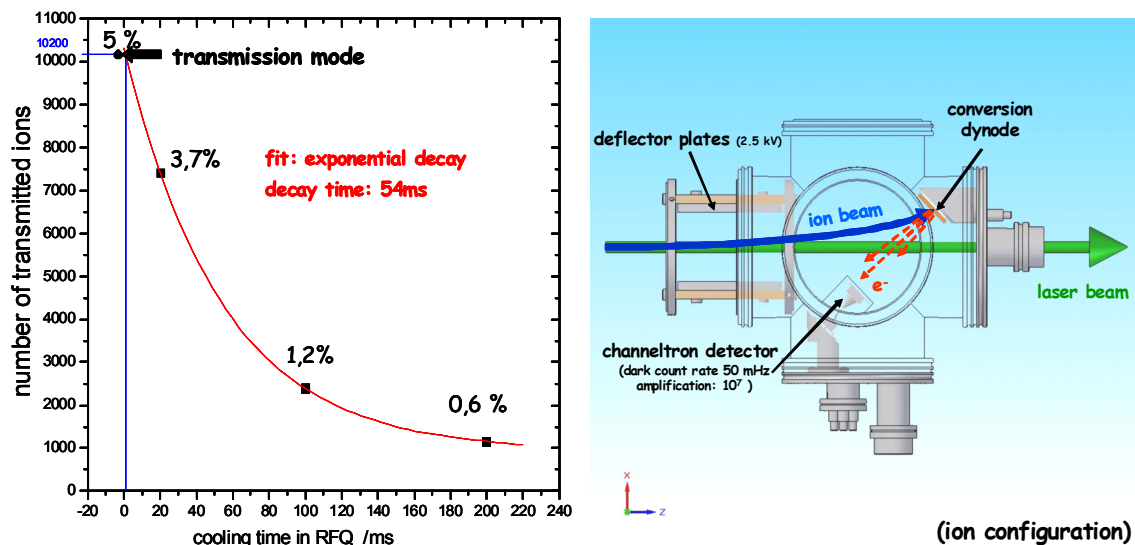

Figure 4: _Left:_ Transmission rate of incident beryllium ion beam through ISCOOL as a function of cooling and storage time, measured during an off-line beamtime in April 2009. _Right:_ Ion detection chamber of the ion-photon detection unit.

itself, only 5 % of the incident ion beam was transmitted in the transmissive mode, which reduced down to even 1.2 % when the ions were stored and cooled for 100 ms inside ISCOOL, as shown in figure 4 (left). The high loss rate of incident ions can be attributed to rf-heating effects due to the low mass difference of the helium buffer gas to the beryllium ions. Here more long-term technical developments and detailed tests with heavier buffer, e.g. Argon, and gas purities would be required.

Instead of bunched ion beams an ion-photon coincidence will be applied for spectroscopy of ^{12}Be, where only these photon events will be counted which are correlated by a fixed delay to the detection of an ion by a channeltron detector at the end of the COLLAPS beam line. A corresponding coincidence unit, as shown in figure 4 (right), is under development and will be tested beforehand at the TRIGA-Laser beam line at the University of Mainz. Assuming the ^{12}Be production rate given in the ISOLDE yield tables, a background suppression in the optical detection of up to a factor 8000 can be achieved. Nevertheless, the low yield makes it very demanding to collect sufficient statistic for a precise charge radius determination. In order to determine the charge radius of ^{12}Be with a meaningful precision of at least 2 MHz we need about 5 days (15 shifts) continuous collection of scans using every second pulse of the booster's super cycle. For referencing these measurements with earlier measurements we furthermore will apply reference isotope shift measurements of ^{9}Be to ^{10}Be. Additionally we will shortly test the systematic influence of repetitive photon recoil on the ^{10}Be line position (which can be tested only on-line) applying fast optical shutters, which for technical reasons could not be tested during the previous beryllium run. This, together with short reference measurement of ^{10}Be in regular intervals in between the collection of ^{12}Be statistics, will request in total about 3 shifts additional to the pure collection time for ^{12}Be.

Beam time Request

Because of the complexity of the laser system and the required sensitivity of the coincidence setup and in order to assure the required precision for the experiments, we request three days (9 shifts) off-line beam time in advance of the later on-line run, which should not be separated by less than 3 weeks and not more than 6 weeks.

For the on-line charge radius measurement of ^{12}Be we request 18 shifts with every second pulse of the super cycle and maximum proton intensity on the target. For the collection of the ^{12}Be data, a constant yield over the entire beam time period of 6 days has to be provided. Therefore and due to the required stability under the above mentioned high proton intensity on the target, a UC_x target shall be applied.

For both runs, off-line preparation and on-line measurement, the application of the RILIS laser ion source is mandatory.

Appendix

As with these measurements we can also determine the ion beam energy, we would offer to repeat last year's high voltage recalibration with a high precision voltage divider build by the group of Christian Weinheimer (University Münster) which has been calibrated at the Physikalisch Technische Bundesanstalt (PTB) in Braunschweig, Germany. This way we could provide information on the aging effects of the ISOLDE ion source voltage power

supplies. Furthermore this provides the possibility to compare the voltage deviation and stability of the ASTEC power supplies with the new Heinzinger power supply of ISOLDE.

For the accomplishment of these measurements access to the ISOLDE high voltage power supplies has to be provided for about 12 hours. As the measurements have to be performed in the high voltage power supplies room, no protons should be delivered to any of the target stations, like during a target change or off-line period for example.

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