Precision hyperfine structure spectroscopy of Be isotopes at SLOWRI prototype and prospects of SLOWRI at RIKEN

M. Wada[*,†], A. Takamine[*], K. Okada[**], T. Sonoda[‡], P. Schury[‡], Y. Yamazaki[‡,§], Y. Kanai[‡], T.M. Kojima[‡], A. Yoshida[†], T. Kubo[†], H. Iimura[¶], I. Katayama[‖], S. Ohtani[††], H. Wollnik[‡‡] and H.A. Schuessler[§§]

[*]*Atomic Physics Laboratory, RIKEN, 2-1 Hirosawa, Wako, 351-0198, Japan*
[†]*Nishina Center for Accelerator Based Science, RIKEN, 2-1 Hirosawa, Wako, 351-0198 Japan*
[**]*Department of Physics, Sophia University, 7-1 Kioicho, Chiyoda, Tokyo 102-8554, Japan*
[‡]*Atomic Physics Laboratory, RIKEN, 2-1 Hirosawa, Wako, 351-0198 Japan*
[§]*Graduate School of Arts and Science, University of Tokyo, Meguro, Tokyo 153-8902, Japan*
[¶]*Japan Atomic Energy Agency (JAEA), Tokai, Ibaraki 319-1195, Japan*
[‖]*Institute of Particle and Nuclear Physics, KEK, Tsukuba, Ibaragi 305-0801 Japan*
[††]*ILS, University of Electro-Communications, Chohu, Tokyo 182-8585, Japan*
[‡‡]*II. Physikalisches Institut, Justus-Liebig-Universität Giessem, Giessen, Germany*
[§§]*Department of Physics, Texas A&M University, College Station, TX 77843, USA*

Abstract. Precision atomic spectroscopy experiments for Be isotopes have been carried out at the prototype universal slow RI-beam (SLOWRI) setup at RIKEN. Radioactive Be ions produced at 1 GeV were decelerated and thermlized in an RF-carpet ion guide. The thermalized ions were transferred to an ion trap where laser cooling was used to reduce the ion energy to the order of 1 μeV. Laser microwave double resonance spectroscopy was performed for the hyperfine structure measurements of trapped and laser cooled $^{7}Be^{+}$ and $^{11}Be^{+}$ ions. Measurements of the $S_{1/2} \rightarrow P_{1/2}, P_{3/2}$ transition frequencies of $^{7,9,10,11}Be^{+}$ ions are also in progress. These results are briefly discussed. Future prospects for expanding the capability of SLOWRI is also discussed.

Keywords: radioactive beam, laser spectroscopy, ion trap, gas cell, ion guide
PACS: 21.10.Ky, 27.20.+n, 31.30.Gs, 37.10.Ty, 29.25.Rm, 41.85.Ar, 21.10.Gv, 25.43.+t, 36.10.-k

INTRODUCTION

Laser spectroscopy for unstable nuclei has played important roles in nuclear structure studies [1]. The high sensitivity and precision of these methods allows for not only the identification of elements but also for the determination of the nuclear spin, the nuclear moments, the charge radii, and the magnetization distribution of many short-lived nuclei in a nuclear-model-independent manner. Unfortunately, only a limited number of elements have been investigated so far [2]. This is mainly due to limited availability of slow radioactive ion beams.

A next-generation slow radioactive ion beam facility (SLOWRI) [3], which will provide slow ion beams of high-purity and small emittance for all elements, is being built as one of the principle facilities at the RIKEN RI-beam factory (RIBF). High energy radioactive ion beams from the projectile fragment separator BigRIPS [4] will be thermalized in a large gas catcher cell. The thermal ions in the gas cell will be guided

CP1120, *Perspectives in Nuclear Physics,* edited by S.-C. Jeong, H. Miyatake, Y. Utsuno, H. Ikezoe, T. Motobayashi, and A. Bracco

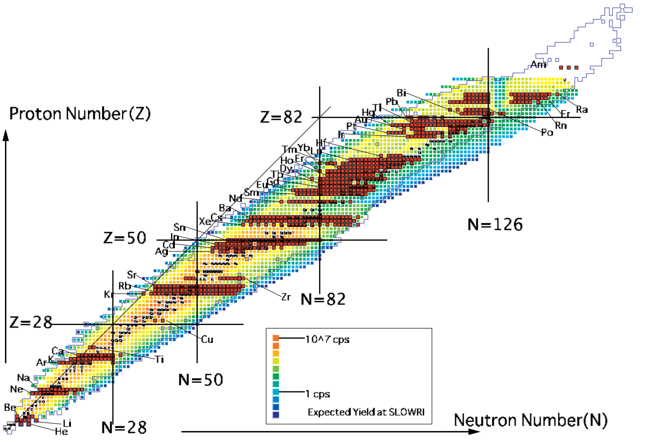

FIGURE 1. Expected nuclides at SLOWRI. The dark boxes indicate nuclei which have been studied with optical spectroscopy [2]

and extracted to a vacuum environment by a combination of DC electric fields and inhomogeneous RF fields (RF carpet ion guide). From there the slow ion beam will be delivered via a mass separator and a switchyard to various devices. These devices might include: an ion trap, a collinear fast beam apparatus and a multi-reflection time of flight mass spectrometer. At SLOWRI, about 3000 nuclides will be available with an intensity of more than 10^{-3} atom per second which should drastically expand the playground for precision atomic spectroscopy (Fig. 1).

A prototype version of SLOWRI has been built and has achieved an overall efficiency of 5% for a 100*A* MeV ^{8}Li ion beam from the present projectile fragment separator RIPS [5]. This prototype facility has been used to conduct laser spectroscopy measurements on trapped radioactive Be isotopes.

SPECTROSCOPY OF BERYLLIUM ISOTOPES

We have developed an online ion trap for precision atomic spectroscopy where unstable Be ions can be stored for extended durations and laser-cooled down to a very low temperature [3, 5, 6, 7]. This is an ideal condition to perform double resonance spectroscopy to determine the absolute optical transition energies, as well as the hyperfine splitting energies, with high accuracies. These measurements allow us to deduce not only the isotope shifts of optical transitions but also the isotope shifts of the hyperfine constant. The former is usually called the *isotope shift*, while the latter is called the hyperfine anomaly or the Bohr-Weisskopf effect [8]. From these two isotope shifts, we can determine the nuclear charge radii and the nuclear magnetization radii. It should be noted that ^{11}Be is considered to have a ^{10}Be core and a valence halo neutron. In a naive picture the charge radius of ^{11}Be is determined by the core size while the magnetization

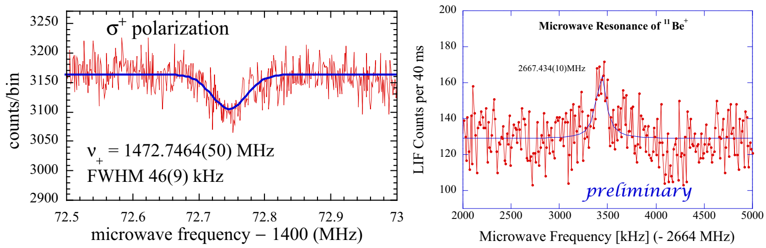

FIGURE 2. Microwave resonance spectra of ^{7}Be$^+$ (left) and ^{11}Be$^+$ (right).

radius is determined by the radius of the extended halo neutron. In this way, we can clearly justify whether the valence neutron is really distributed with a large radius by a reliable pure-optical probe.

Hyperfine structure of Be ion

The ground state hyperfine splittings of ^{7}Be$^+$ and ^{11}Be$^+$ have been measured by laser-microwave double-resonance spectroscopy (Fig. 2) and the magnetic hyperfine constant of ^{7}Be$^+$ was determined to be $A_7 = -742.77228(43)$ MHz [7]. From the hyperfine constant, the nuclear magnetic moment of ^{7}Be was also deduced, within the uncertainty due to the hyperfine anomaly, to be $\mu_I(^7\text{Be}) = -1.39928(1)\mu_\text{N}$. The analysis of ^{11}Be$^+$ measurement is in progress and the result will be reported soon.

To deduce nuclear magnetization radii, we should compare the ratios of the hyperfine constants to the nuclear g-factors for isotopes. For this purpose, nuclear magnetic moments obtained from our recent hyperfine constant measurement can not be used, since this value was obtained by assuming the ratio is a constant for isotopes. The nuclear magnetic moment of ^{11}Be$^+$ has been measured at ISOLDE [9] by the β-NMR (nuclear magnetic resonance) method, however, the accuracy of 5×10^{-4} is not sufficient to see the hyperfine anomaly. It should be noted that ^{7}Be does not emit β-rays, and thereby its nuclear moments elude determination by the β-NMR method.

We have prepared a combined trap for measurements of the Zeeman splittings of the hyperfine structure at high magnetic field strength. The system has already been used to perform measurements of the stable isotope ^{9}Be [10]. With this setup, we can determine both the hyperfine constants and the nuclear g-factors in units of electron's g-factor with high accuracies. We are preparing this setup for online measurements of ^{7}Be$^+$ and ^{11}Be$^+$ ions.

Optical transition energy of Be ion

The optical transition between the ground state of the Be$^+$ ion ($2\,^2S_{1/2}$) and the first excited states ($2\,^2P_{1/2}$, $2\,^2P_{3/2}$) have been measured by optical-optical double resonance spectroscopy [11]. The isotope shift of these transitions for Be$^+$ ions are more than

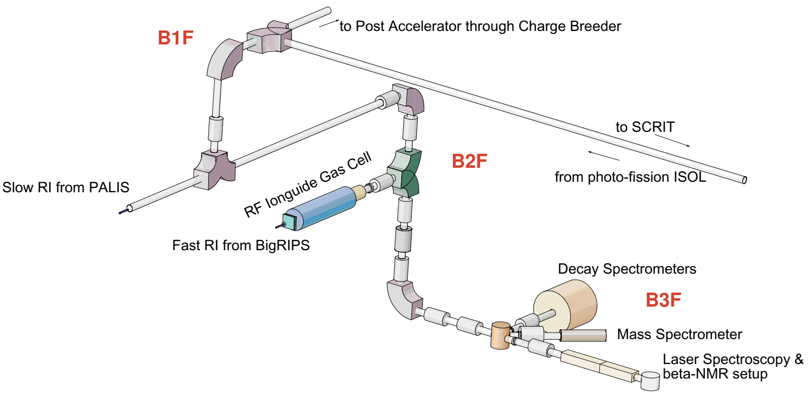

FIGURE 3. Proposed layout of advanced SLOWRI facility.

10 GHz. However the contribution from the charge radius is about 10 MHz while the dominant part is due to the mass dependent effects. Recently the magnitude of the mass dependent part has been theoretically calculated for Be isotopes [12]. With our method the optical transition energies of 1 PHz will be determined with sub-MHz accuracies, which will allow us to deduce nuclear charge radii using the theoretical calculations. Experiments are still underway to improve the accuracy and reliability of the data.

ADVANCED SLOWRI FACILITY

At the SLOWRI facility, fast RI-beams from BigRIPS will be converted to slow RI-beams by the RF-carpet ion guide. It was originally envisioned that these slow ion beams would be used to perform various precision experiments, such as laser spectroscopy, mass measurements [13], β-NMR measurements, decay spectroscopy and so on. Recently, additional functionalities have been suggested to enhance the facility.

One is to provide parasitic RI-beams from those nuclei abandoned elsewhere in BigRIPS, such as at the slits of the first focal plane of the fragment separator. This scheme, named PALIS (parasitic RI-beams with resonance laser ionization source) [14], will use a compact gas cell, filled with high pressure Ar gas, located at the slits of BigRIPS. The thermalized nuclei will become neutral atoms and be transported to the exit by gas-flow. The extracted atoms will be re-ionized by resonant laser radiations. Since incoming ions are quickly neutralized by the Ar gas, the space-charge problem in the cell will not occur which will result in a great improvement for the acceptance of the high intensity beam. In this way, wide variety of slow RI-beams will be obtained *everyday* without any *extra operational costs*. It should also be noted that the beam from PALIS can be used for a long period of beam time, because it is *parasitic*, and furthermore, the beam intensity may exceed 10^7 cps. Due to radiation security constraints, the beam intensity after BigRIPS is limited to $< 10^7$ cps, however such a constraint is not applied for the beams at the target area or the first focal plane. As such, very high intensity slow RI-beams could be provided by the PALIS setup.

Other ideas include injecting the slow RI-beams into a post accelerator or the electron scattering experimental SCRIT [15]. The quality of the beams from SLOWRI is equivalent to that for a stable beam accelerator, except for the intensity, and is adequate to re-accelerate up to several MeV per nucleon to perform various nuclear astrophysics experiments. SLOWRI will provide RI-beams of many elements which are not available at ISOL facilities or other RI-beam accelerator facilities. SCRIT is a novel RI-target setup for electron-scttering experiments. Study of nuclear charge-form-factors for a wide variety of RI-beams from SLOWRI, including halo nuclei, is a dream experiment. On the other hand, the SCRIT setup has its own compact fission-ISOL setup which can also be an injector for a post accelerator. The beam transport line is designed to be bi-directional to handle both the beams from SLOWRI to SCRIT and the other way (Fig. 3).

SUMMARY

We have developed a universal slow RI-beam production method. The prototype setup has achieved a high level of performance, providing slow RI-beams of Li and Be isotopes. Precision laser and microwave spectroscopy experiments have been performed for trapped radioactive Be ions at the prototype facility. The proposed slow RI-beam facility at RIKEN RIBF will provide radioactive ion beams of all elements and, with an option of parasitic RI-beam production, PALIS, slow RI-beams will always be available when BigRIPS is in operation. Such slow RI-beams can also be used for post acceleration or a target for electron scattering experiments.

These development works have been carried out at the Nishina Accelerator-Based Science Center of RIKEN. The project was finacially supported by the grant-in-aids of Japan Society for Promotion of Science, and the President fund of RIKEN.

REFERENCES

1. E.W. Otten, in Treatise on heavy-ion science, D.A. Bromley (Ed.), 8, 517 (1989).
2. H.-J. Kluge, and W. Nortershauser, Spectrochim. Acta B 58, 1031 (2003).
3. M. Wada *et al.*, Nucl. Instr. Meth. B 204, 570 (2003).
4. T. Kubo, Nucl. Instr. Meth. **B**204, 97 (2003).
5. A. Takamine *et al.*, Rev. Sci. Inst. 76, 103503 (2005).
6. T. Nakamura *et al.*, Phys. Rev. A 74, 052503 (2006).
7. K. Okada *et al.*, Phys. Rev. Lett. 101, 212502 (2008).
8. A. Bohr and V. F. Weisskopf, Phys. Rev. **77**, (1950) 94.
9. W. Geithner *et al.*, Phys. Rev. Lett. 83, 3792 (1999).
10. T. Nakamura *et al.*, Opt. Comm. 205, 329 (2005).
11. A. Takamine *et al.*, "Isotope shift measurements of $^{11,9,7}Be^{+}$", proceedings of ENAM08 conference, Ryn, Poland, Sept. 2008.
12. Z-C. Yan, D.K. McKenzie, and G.W.F. Drake, Phys. Rev. A54, 1322 (1996).
13. P. H. Schury *et al.*, 'Multi-reflection time-of-flight mass spectrometer for short-lived radioactive nuclei", proceedings of ENAM08 conference, Ryn, Poland, Sept. 2008.
14. T. Sonoda *et al.*, "Restoration of RI-beam from a projectile fragment separator by Laser Ionization gas Catcher", proceedings of the LAP2008 Conference, Nagoya, Japan, Sept. 2008.
15. M. Wakasugi *et al.*, Phys. Rev. Lett. **1**00, 164801 (2008).