Universal Slow RI-Beam Facility at RIKEN RIBF for Laser Spectroscopy of Short-Lived Nuclei


*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
§Department of Physics, Texas A&M University, College Station, TX 77843, USA
¶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
††Institute for Laser Science, University of Electro-Communications, Chofugaoka, Chofu, Tokyo 182-8585, Japan
§§II. Physikalisches Institut, Justus-Liebig-Universität Gießen, Gießen, Germany

Abstract. A universal slow RI-beam facility (SLOWRI) for precision atomic spectroscopy is being built at the RIKEN RI-beam factory. The facility will provide a wide variety of low-energy nuclear ions of all elements produced by projectile fragmentation of high-energy heavy-ion beams and thermalized by an RF-carpet ion guide. At prototype SLOWRI, radioactive Be isotope ions produced at 1 GeV were decelerated and cooled in an ion trap down to 1 μeV by employing laser cooling. The ground state hyperfine structures of \(^{7}\)Be\(^{+}\) and \(^{11}\)Be\(^{+}\) were measured accurately by laser microwave double resonance spectroscopy. 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 aiming at the study of the nuclear charge radii. Other possible experiment at SLOWRI, such as mass spectroscopy, are also discussed.

Keywords: radioactive beam, laser spectroscopy, ion trap, gas cell, ion guide


INTRODUCTION

A next-generation slow radioactive nuclear ion beam facility (SLOWRI) [1], which provides slow, high-purity and small emittance ion beams of all elements is being built as one of the principal facilities at the RIKEN RI-beam factory (RIBF). High energy radioactive ion beams from the projectile fragment separator BigRIPS [2] will be thermalized in a large gas catcher cell. The thermal ions in the gas cell will be guided 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 (Fig. 1). The prototype facility at RIKEN has achieved an overall efficiency of 5% for a 100A MeV $^8$Li ion beam from the present projectile fragment separator RIPS and the dependence of the efficiency on the ion beam intensity was investigated [3].

Recently, our first spectroscopy experiments at the SLOWRI prototype were performed on Be isotopes. Energetic ions of $^{10}$Be and $^7$Be from RIPS were trapped and laser cooled in a linear rf trap and the specific mass shifts of these isotopes were measured for the first time [4]. Subsequently, we measured the ground state hyperfine structure (hfs) of $^7$Be$^+$ [5] and $^{11}$Be$^+$ [6] with high-precision via laser-microwave double resonance spectroscopy.

**LASER SPECTROSCOPY FOR NUCLEAR PHYSICS**

Optical atomic spectroscopy of unstable nuclei has played an important role in nuclear structure studies [7]. Nuclear charge radii and moments for many unstable nuclei were determined model-independently by optical spectroscopy of low energy ion beams or stored ions. The number of nuclides available for investigation by optical spectroscopy has been restricted to about 500 nuclei of about 50 elements [8], mostly limited by low energy radioactive ion beams available at conventional isotope-separator-online (ISOL) facilities. We therefore developed SLOWRI to open up a new frontier. Based on the fast, chemistry-independent method of nuclear fragmentation with in-flight separation, capable of producing any isotope, in the near future more than 4000 unexplored nuclei will be available for study.

**Spectroscopy of Be isotopes**

We have chosen Be isotopes as the first targets of our study. We are particularly interested in $^{11}$Be, a so-called neutron halo nucleus whose valence neutron is expected to have an extended mean radius. We have planned to perform various optical measure-
FIGURE 2. Fluorescence intensity of laser cooled $^7$Be$^+$ ions as a function of the cooling laser frequency scanning from lower to higher frequency. A transition from a broad peak to a sharp peak with a characteristic dip indicates a transition from an ion-cloud to an ion-crystal. The ion temperature was evaluated to be $< 10$ mK from the line width of the sharp peak.

Measurements on the Be isotopes to determine the nuclear charge radii, the valence neutron radii, and the nuclear moments.

Laser cooling is an essential prerequisite for precision optical measurements. Figure 2 shows a typical fluorescence spectrum of laser cooled $^7$Be$^+$ ions, indicating an ion temperature of $< 10$ mK. This is a $10^{15}$-fold reduction in kinetic energy from the relativistic energy at which the nuclei were produced.

Hyperfine structure of Be isotopes

$^7$Be is a unique nucleus whose nuclear moments elude determination via $\beta$-$\gamma$-NMR, since no $\beta$-rays are emitted and $\gamma$-rays are isotropically emitted. Measurements of the magnetic sublevels of the hfs in a high magnetic field is the most accurate way to determine the nuclear moments, as we have shown in a measurement of $^9$Be$^+$ [9]. The magnetic moment of $^{11}$Be was measured by $\beta$-NMR [10], however the accuracy of $4 \times 10^{-4}$ is not sufficient for our purpose. Comparisons of the ratios of the nuclear magnetic moment to the hyperfine constant $A$ enable us to deduce the Bohr-Weisskopf effect which stems from the different distribution of the magnetism in a nucleus. The effect can be a unique probe to determine the mean radius of the valence neutron of the halo nuclei by pure electro-magnetic interaction [11]. Thus far, we have measured the hfs under a weak magnetic field to determine the hfs constant $A$. Figure 3 is a microwave resonance spectrum of $^7$Be$^+$ and $^{11}$Be$^+$. The analyses of the measurements of the hfs constant for $^7$Be$^+$ and $^{11}$Be$^+$ are in progress; the results will be published soon [5, 6]. An experiment for accurate determination of the nuclear magnetic moments of these unstable Be isotopes is under preparation.
Isotope shift of Be isotopes

Nuclear charge radii of halo nuclei have seen great interest since discovery of the neutron-halo in $^{11}$Li [12]. Thanks to the modern atomic theory [16] and high precision laser spectroscopy, charge radii of light nuclei has been determined for He [13, 14] and Li [15] isotopes. We worked on the measurement of Be isotopes using ion-trap, laser-cooling and laser-laser double resonance spectroscopy, which is the most accurate method to determine atomic transition frequencies today.

We measured the $S_{1/2} \rightarrow P_{1/2}$ and $S_{1/2} \rightarrow P_{3/2}$ transitions of Be isotopes by laser-laser double resonance method. A cooling laser repeats excitation/de-excitation cycles for many times and optical pumping and low temperature conditions are achieved simultaneously. During the period of cooling laser off, a weak resonant probe laser ignites a population shift. Then, the resonance is detected by the fluorescence intensity during the subsequent cooling cycle. In this way, the probe transitions can be measured without any shifts or broadening. So far we measured these transitions for $^{9,11}$Be$^+$ ions with relative accuracies of $\approx 10^{-10}$. Careful evaluations for the measured frequencies are in progress in terms of the magnetic field dependence and the identification of magnetic sublevels.

MASS MEASUREMENTS

The atomic mass is a fundamental quantity of a nucleus and various mass spectrometers were used to measure the atomic masses including unstable nuclei since early days. We developed a multi-reflection time-of-flight mass spectrograph [17] aiming at precision mass measurements of short-lived nuclei. With a small prototype setup, we achieved a high mass resolving power of 200,000 with a short measurement period of 7 ms [18]. A design of full-scale spectrograph is in progress and a development of stable and precision high voltage supplies is also underway. We found that the performance of MRTOF especially for very short-lived nuclei, say $T_{1/2} < 100$ ms, outperforms the well-known Penning trap mass spectrometer (Fig. 4) [19].
At SLOWRI, not only laser spectroscopy for trapped ions or mass measurements but also many other experiments will be performed. A collinear fast beam apparatus for laser spectroscopy was tested off-line and a precision measurement of the absolute frequency of the metastable Ar\(^+\) using a frequency comb and two lasers, parallel and anti-parallel, was demonstrated [20]. It will be used for studying the charge radii of many isotopes which are not available at ordinary ISOL facilities. Since SLOWRI will provide high purity RI-ions at low energy, it has great advantage also for decay spectroscopy experiment, especially for \(\beta, \gamma\) and delayed-particle spectroscopy which will determine the half-lives, the \(Q\)-values, the branching ratio and so on with a high reliability. A \(\beta\)-NMR apparatus coupled to the collinear beam setup will allow us to measure nuclear moments. A possibility of post acceleration of the beams from SLOWRI for nuclear astrophysical interest is also under discussion.

A big problem of the new accelerator facility of RIKEN, RIBF, is that only a single experiment can run with the beam from the fragment separator BigRIPS. Although projectile fragmentation reactions from a single primary beam produce more than a thousand nuclei at the same time, only a single nucleus can be used for experiments. We proposed a novel scheme to rescue those nuclei dumped elsewhere in the separator for parasitic production of slow RI-beams using a compact gas cacher cell and resonant laser ionization method [21]. This scheme will provide slow RI-beams everyday without extra operation cost.

**FIGURE 4.** Comparison of minimum half-life for which a mass resolving power of \(R = 200,000\) can be achieved by a Penning trap mass spectrometer (PTMS) and a MRTOF mass spectrograph (MRTOF).

**PROSPECTS OF SLOWRI**
ACKNOWLEDGMENTS

The authors acknowledge the contribution of the crew of the RIKEN Nishina Center for Accelerator-based Science for their contribution to our on-line experiments. This work was supported by the Grants-in-Aid for Scientific Research from the Japan Society for the Promotion Science, by the President’s Special Grant of RIKEN, and by the Welch Foundation grant No.1546.

REFERENCES

6. M. Wada et al., to be submitted.
20. V. Lioubimov et al, these proceedings.
21. T. Sonoda et al, these proceedings.