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Towards high precision measurements of nuclear g-factors for the Be isotopes

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ABSTRACT

We describe the present status of future high-precision measurements of nuclear g-factors utilizing laser-microwave double and laser-microwave-rf triple resonance methods for online-trapped, laser-cooled radioactive beryllium isotope ions. These methods have applicability to other suitably chosen isotopes and for beryllium show promise in deducing the hyperfine anomaly of ^{11}Be with a sufficiently high precision to study the nuclear magnetization distribution of this one-neutron halo nucleus in a nuclear-model-independent manner.

1. Introduction

It is well-known that the nuclear moments and spins of short-lived nuclei have been intensively investigated through hyperfine interactions in a nuclear-model independent manner (see, *e.g.*, [1,2]). Isotope shifts in atomic optical spectral lines enable us to determine the variation of the nuclear charge radii as a function of the neutron number. The magnetic dipole hyperfine anomaly (HFA) gives information on the nuclear magnetization within the nucleus through the Bohr-Weisskopf (BW) [3] effect. The observable magnetic hyperfine structure (HFS) constant A can be represented by

$$A = A_p(1 + \epsilon_{BW}), \tag{1}$$

where A_p denotes the magnetic HFS constant for a point-like nucleus and ϵ_{BW} is so-called the Bohr-Weisskopf effect. With the exception of muonic atoms and hydrogen-like ions, A_p is difficult to precisely calculate. If we take the ratio of A for a pair of isotopes 1 and 2, we calculate the HFA as

$$^1\Delta^2 \simeq \frac{A_1}{g_I^1}\frac{g_I^2}{A_2} - 1, \tag{2}$$

where g_I^i is the nuclear g-factor of isotope i, A_i the HFS constant of isotope i, and $^1\Delta^2 = \epsilon^1_{BW} - \epsilon^2_{BW}$. Here we have taken into account the fact that $\epsilon \ll 1$. It should be noted that to obtain the HFA, which is usually on the order of 0.1–0.01%, independent high-precision measurements of both of g_I and A are required. Consequently HFA values have been determined only for ∼60 nuclides [4] while charge radii have been determined for ∼600 nuclides.

^{11}Be was found to have an exceptionally large matter radius through interaction cross section measurements at medium energies [5]. It is considered to consist of a compact nuclear core of ^{10}Be and one loosely bound, so-called "halo", neutron which is spatially extended. The charge radius of ^{11}Be was determined by isotope shift measurements for the Be isotopic chain with collinear laser spectroscopy at the ISOLDE facility [6] and with trapped ion spectroscopy at RIKEN [7,8]. ^{11}Be showed a 0.1 fm larger charge radius than ^{10}Be, which indirectly supports the picture that the center of the charge distribution is displaced from the center of mass due to the presence of a halo neutron. The halo neutron of ^{11}Be carries most of the nuclear magnetization of the nucleus. If one can determine the magnetization distribution of a nucleus

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through the BW effect, one can directly show the halo structure by optical spectroscopy.

We have worked on the development of an online trap facility located at the prototype of SLOWRI (universal slow RI beam facility) [9] capable of using the highly energetic beryllium isotope ions provided by the RIKEN projectile fragment separator RIPS [10]. The direct measurements of the hyperfine structure constants for the radioactive Be isotope ions, $^7Be^+$ and $^{11}Be^+$, were performed via a laser-microwave double resonance method in weak magnetic fields of $\sim$1 mT for laser-cooled Be^+ ions trapped in a cryogenic linear rf trap [11,12]. The magnetic hyperfine structure constants A_7 and A_{11} of the atomic ground states of $^7Be^+$ and $^{11}Be^+$, respectively, were determined with high-precision and found to be $A_7 = -742.772\,23(43)$ MHz and $A_{11} = -2677.302\,988(72)$ MHz. So far the nuclear magnetic moment of unstable Be isotopes were measured only for ^{11}Be and found to be $\mu_I(^{11}Be) = -1.6816(8)\mu_N$ via the β-NMR method at the ISOLDE facility [13]. Using this value together with the measurement of $\mu_I(^9\mathrm{Be})$ [14] and A-factors of both isotopes [15,12], the HFA could preliminarily be evaluated as $^{11}\Delta^9 = -2.2(4.7) \times 10^{-4}$. However to deduce a statistically significant hyperfine anomaly of the halo nucleus, improving the precision of the value of $\mu_I(^{11}\mathrm{Be})$ by more than one order of magnitude is required. In the following we describe our plan for this high-precision measurement of $\mu_I = g_I I$ for ^{11}Be utilizing laser-microwave double resonance and laser-microwave-rf triple resonance methods for laser-cooled and trapped $^{11}Be^+$ ions. Wineland et al. [15] performed laser-microwave multiple resonance spectroscopy for laser-cooled $^9Be^+$ ions in a Penning trap for application in atomic clocks. For $I > 1/2$, there exists a particular value of the magnetic field strength which makes the nuclear spin flip transition frequency independent of the magnetic field strength to first order, which is called a *clock transition*. Although this is the best condition to determine the nuclear spin flip transition frequencies, such a condition is not present in the case of $^{11}Be^+$. In spite of this Nakamura et al. [16] showed that the g_I/g_J ratio of $^9Be^+$ can be measured with a precision of 10^{-7} without such a special condition from the measurements of both the electron spin flip and the nuclear spin flip transitions in the hyperfine Zeeman splitting utilizing a laser-microwave double and a laser-microwave-rf triple resonance spectroscopy for laser-cooled $^9Be^+$ ions in a combined trap [17]. We will adopt this procedure to measure the g_I factors of the unstable Be isotopes.

2. Experimental procedure

The HFS states of the $2s\,^2S_{1/2}$ ground state of the $^{11}Be^+$ ion split in the magnetic field as shown in Fig. 1. The $^{11}Be^+$ ion can be laser-cooled by irradiation with circular-polarized laser radiation at 313 nm, resonant to the $2s\,^2S_{1/2} \rightarrow 2p\,^2P_{3/2}$ transition, which leads to optical pumping into a maximum or a minimum magnetic sublevel (m_J, m_I) and the observation of strong laser-induced-fluorescence (LIF). When σ^+-polarized laser radiation is used, most of the ions will be pumped in the $(m_J, m_I) = (+1/2, +1/2)$ state. Microwave radiation resonant to the $(m_J, m_I) = (+1/2, +1/2) \rightarrow (-1/2, +1/2)$ transition ν_{e1} $(\Delta m_J = -1)$ will induce the electron spin flip transition, decreasing the LIF signal since ions will be depopulated from the cycling transition. In order to avoid a light shift [18], the laser and the microwave must alternately irradiate the ions during the electron spin flip transition measurement.

For measurements of the nuclear spin flip transition ν_{n1}, a prerequisite is to populate ions into both $(+1/2, +1/2)$ and $(-1/2, +1/2)$ states with irradiation by both σ^+-polarized laser light and microwave radiation ν_{e1}. An additional rf radiation induces $(-1/2, +1/2) \rightarrow (-1/2, -1/2)$ transition ν_{n1} $(\Delta m_I = -1)$, causing a decrease in the observed LIF signal. The other electron

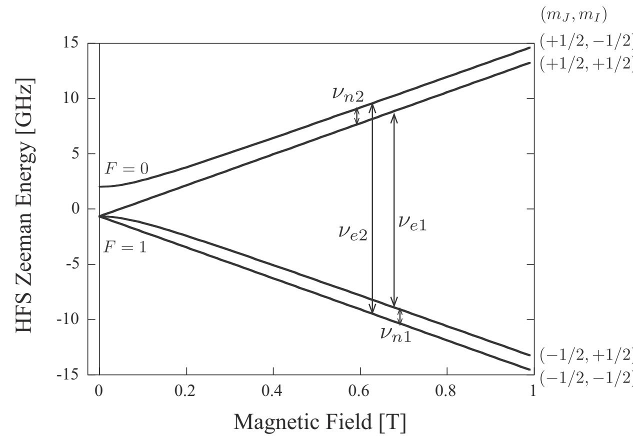

Fig. 1. Zeeman Splitting of the $2s\,^2S_{1/2}$ ground state of the $^{11}Be^+$ ion as a function of magnetic field strength.

flip transition ν_{e2} $(\Delta m_J = +1)$ and nuclear flip transition ν_{n2} $(\Delta m_I = +1)$ frequencies can be measured in a similar way with a σ^--polarized laser radiation. From the sets of transition frequencies ν_e and ν_n, we will simultaneously obtain the HFS constant A and the g-factor ratio $\gamma = g'_I/g_J$ from the fitting to the Breit-Rabi formula, where g'_I is the nuclear g-factor in units of the Bohr magneton μ_B, given as $g'_I = g_I\mu_N/\mu_B$.

The Zeeman splitting energy shifts of a $J = 1/2$ state atom with a nuclear spin I are described by the Breit-Rabi formula:

$$E(m_J, m_I, b) = -\frac{1}{4}A - (m_J + m_I)\gamma b + m_J \times \sqrt{A^2\left(I + \frac{1}{2}\right)^2 + 2A(m_J + m_I)(\gamma - 1)b + (1 - \gamma)^2 b^2} \quad (3)$$

where the magnetic field strength B_0 is expressed in terms of the Larmor precession energy of the valence electron as $b = g_J\mu_B B_0/h$ and the nuclear-to-atomic g-factor ratio as $\gamma = g'_I/g_J$. The electron and nuclear spin flip transition frequencies mentioned above are straightforwardly calculated from Eq. 3. The sensitivity of the frequencies to variations in b, A, and γ is described by

$$\frac{\Delta\nu}{\nu} = c_b\frac{\Delta b}{b} + c_A\frac{\Delta A}{A} + c_\gamma\frac{\Delta\gamma}{\gamma} \quad (4)$$

where $c_X \equiv (X/\nu)(\partial\nu/\partial X)$. The coefficients c_b, c_A and c_γ can be analytically derived from Eq. (3). It is straightforward to find the contri-

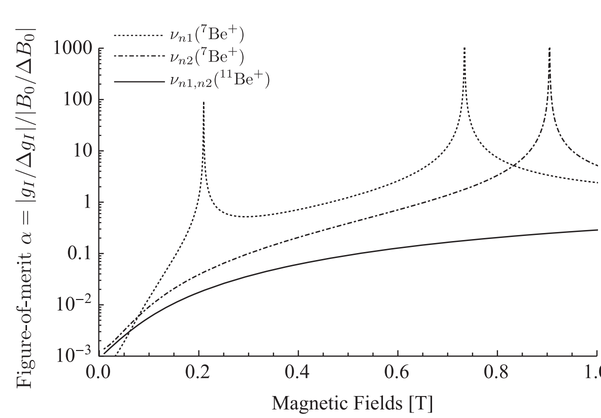

Fig. 2. Figure-of-merit $\alpha = |g_I/\Delta g_I|/|B_0/\Delta B_0|$ of the nuclear spin flip transitions ν_{n1} and ν_{n2} for $^7Be^+$ and $^{11}Be^+$.

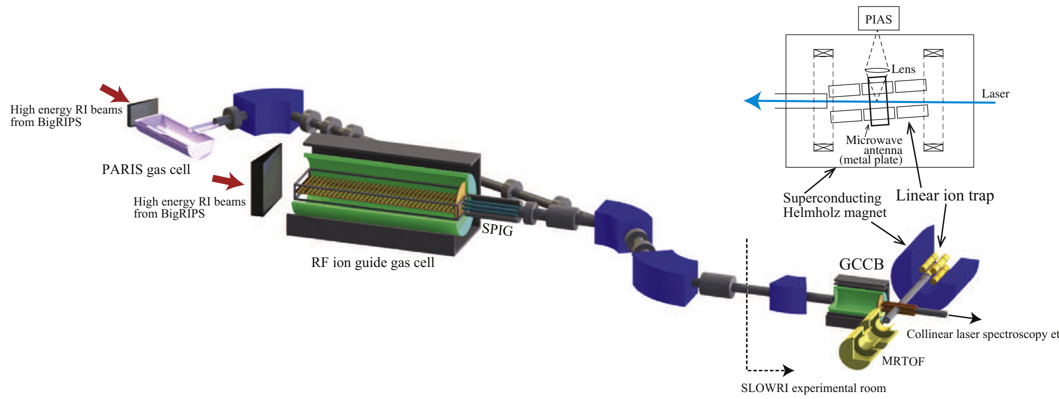

Fig. 3. Sketch of the overview of the SLOWRI facility. The continuous 30 keV ion beams will be cooled and bunched in the GCCB and then transferred into the linear ion trap where the proposed experiment will be conducted. The inset shows the cross section of the ion trap setup for more details. The resonant rf radiation will be irradiated on the trapped ions by the trap electrodes while the microwave is applied by a metal plate antenna. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

butions from the quantities b, A, γ to ν_e or ν_n. For the precise determination of γ, the magnetic field strength where $|c_b^n|$ is small and $|c_\gamma^n|$ is large is an optimum condition. At the *clock* transition condition$|c_b^n|$ becomes zero. The condition is estimated to be realized at $B_0 \simeq 0.20964$ T and 0.73385 T for $\nu_{n1}(^7\text{Be})$ and $B_0 \simeq 0.90464$ T for $\nu_{n2}(^7\text{Be})$. In the case of $^{11}\text{Be}^+$, we will measure the transition frequencies at an arbitrary high magnetic field. If we calculate a figure-of-merit α defined as $\alpha = |c_\gamma^n|/|c_b^n| = |g_I/\Delta g_I|/|B_0/\Delta B_0|$ analogous to Ref. [16], it is found that α for ^{11}Be monotonically increases as a function of B_0 and approaches to one in the high magnetic field limit. The figures-of-merit α for ν_{n1} and ν_{n2} of $^{11}\text{Be}^+$ as well as $^7\text{Be}^+$ are plotted in Fig. 2. When we take $B_0 = 0.5$ T and assume the homogeneity of the magnetic field $|\Delta B_0/B_0|$ of 10^{-7} over the ion cloud, since $\alpha \simeq 0.1$, a precision of 10^{-6} is expected for $|\Delta g_I/g_I|$, which is sufficient to deduce the BW effect. This requires ν_n and ν_e to be measured with precisions of 10^{-8} and 10^{-7}, respectively. In the demonstration for $^9\text{Be}^+$ ions in Ref. [16], the precisions of 10^{-9} and 10^{-8} were achieved forν_n and ν_e measurements, respectively, in a magnetic field of ~0.47 T which is outside the clock transition condition.

In this way, the nuclear g-factor g_I of ^{11}Be is expected to be obtained with sufficient precision to deduce a statistically significant BW effect to study the halo neutron distribution of ^{11}Be. This method is also essential for determining the nuclear g-factor of ^{7}Be which cannot be accessed by the β-NMR method.

3. Experimental setup

The experiments are planned to be performed at the SLOWRI facility [19,20] at the RIKEN RIBF. The radioactive Be isotope ion beams will be produced and separated at BigRIPS [21], a gas cell will efficiently convert them to slow beams, which will be transported with an energy of 30 keV through the SLOWRI beamline and mass-separated by dipole magnets. A schematic overview of the SLOWRI facility is shown in Fig. 3. The slow RI beams both from the PALIS (parastic RI-beams by laser-ion source) [22] gas cell and the RF ion guide gas cell can be delivered to the SLOWRI experimental room. The continuous 30 keV ion beams will be efficiently cooled and bunched in the gas-cell beam cooler-buncher (GCCB) [23] and the ion bunch will be delivered into the linear ion trap as well as into various high precision experimental devices such as an MRTOF mass spectrograph [24]. The GCCB system will be a key apparatus for high precision experiments that are planned at the SLOWRI facility. The linear ion trap will be installed inside a liquid-He-cooled superconducting Helmholz magnet (Cryomagnetics Inc., split pair) which produces a magnetic field up to 1 T. The trap will be operated in the unbalanced mode where an rf signal for ion trapping is applied only to one pair of the trap electrodes. The rf signal to induce the transition between the hyperfine substates is applied to the ground side of the electrodes. The resonant microwave radiation will be irradiated from the metal plate antenna located close to the ion trap. The LIF signal from the trapped ions will be detected by a two-dimensional photon counting system (PIAS, Hamamatsu) through an achromatic lens.

We plan to prepare an all solid-state narrowband laser system as the light source for the laser cooling of the Be^+ ions for high stability operation. The system will consist of an external-cavity diode laser ($\lambda = 939$ nm), which will be followed by a tapered amplifier for amplification up to ~2 W, a second harmonic generator with a BiB_3O_6 crystal to produce 470 nm laser light, and a sum frequency generator with a BBO crystal to produce 313 nm laser light from the 939 nm and 470 nm laser radiations. The output power of the 313 nm laser light is expected to be ~5 mW. A part of the fundamental laser light will be delivered to a frequency comb and the frequency will be stabilized by a femtosecond frequency comb (Menlo Systems FC1500) using frequency offset locking [25].

4. Conclusions and outlook

We have already determined the HFS constants of $^{7,11}\text{Be}^+$ with high precisions. In order to determine the hyperfine anomalies for ^{7,11}Be, the nuclear g-factor of ^{7,11}Be will be determined with high-precision in a nuclear-model-independent manner from the measurements of both the electron spin flip and the nuclear spin flip transitions in the Zeeman splitting in a strong magnetic field. The expected precisions for g_I of ^{7,11}Be were evaluated from the calculations of the sensitivities of the resonance frequencies to the variations in the magnetic fields, HFS constants, and g-factor ratios in these measurements. In the event of the accomplishment of these measurements, the magnetization radius of the neutron halo nucleus ^{11}Be will be deduced to clearly reveal the halo nucleus structure by the combination of the experimental result of $^{11}\Delta^9$ and a theoretical investigation with modern atomic physics models such as adopted by Puchalski and Pachucki [26] for ^{9}Be.

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