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For an investigation concerning the nuclear magnetic moments and their distributions in the nuclei of $^7,^{11}\text{Be}$, an experimental project using laser-microwave double resonance spectroscopy for trapped ions is under progress at INS. Laser cooled ion crystals consisting of a few $^9\text{Be}^+$ ion were observed and the ground state hyperfine splitting of $^9\text{Be}^+$ was measured with a precision of 10^{-5} . Experiments on the unstable isotope ^7Be have been started.

1. Introduction

The nuclear magnetic moments have played an important role in the study of nuclear structure as well as fundamental physics since quite early days. For further understanding of nuclear structure details, it is of importance to investigate the nuclear magnetic moment and its distribution in the nucleus, in particular, for the unstable isotopes. In our project we concentrate on two beryllium isotopes: ^{11}Be and ^7Be .

The magnetic moments of $^7,^{11}\text{Be}$ would be especially interesting because the ground state spin-parity of ^{11}Be is anomalous, the so called Talmi's inversion [1], and ^7Be is the lightest mirror decay nucleus among those nuclei of which magnetic moments are unknown. ^7Be is also one of the key nucleus in the standard solar model [2] in which the ground state magnetic property of ^7Be would be useful to estimate electron and proton capture rates. In this regards, it is surprising that the magnetic moment of ^7Be is still unknown, although the life-time of ^7Be is rather long (53 days) and the production is easy by the $^7\text{Li}(p,n)^7\text{Be}$ reaction. The reason is due to a simple experimental difficulty; the decay mode of ^7Be is 100% electron capture and the γ -decay path is through spin 1/2 state of the daughter nucleus, so that usual β -, γ -NMR cannot be used. Collinear laser spectroscopy is also difficult, because there is no good on-line ion-source for Be and the hyperfine splitting is too small to be measured by the difference of two optical transitions. A possible way is double-resonance hyperfine structure spectroscopy for the laser cooled Be ions in an ion-trap [3].

For a neutron halo nucleus, ^{11}Be , it is understood that the valence neutron is loosely bound and the radial distribution is extended [4]. The distribution of the magnetism should manifest a direct indication of the distribution of such valence neutron. A clear experimental way to investigate the magnetization distribution is to determine the M1 form factor through a measurement of transverse terms in electron scattering [5]. It is, however, not feasible since the luminosity for such scattering experiment too small to get the information. An alternative way is precision spectroscopy of the hyperfine structure. The hyperfine coupling constant A of the M1 term in the atomic hyperfine interaction shows a weak but finite isotope dependence called hyperfine anomaly, the main part of which stems from the finite size of the magnetization distribution in the nucleus (Bohr-Weisskopf effect) [6-8].

We set our first goal to determine the nuclear magnetic moment (μ_I) of ^7Be from the hyperfine constant A , which can be measured precisely by double resonance spectroscopy for trapped ions [3,9]. The accuracy of μ_I is, however, limited by the Bohr-Weisskopf correction. If a more accurate value of μ_I is required for further investigation of the Bohr-Weisskopf effect itself, we have to measure transitions between magnetic sublevels in a strong magnetic field, by which not only A but also μ_I can be determined precisely.

Although the A constant of $^9\text{Be}^+$ has been measured precisely by the NIST group [10], we started with this stable isotope in order to confirm our experimental method. The different points from their experiment are: weak magnetic field and a circular polarized laser are used, and single ion spectroscopy is realized. We have observed a laser cooled ion crystal, or a single ion, of $^9\text{Be}^+$ in our linear trap and measured the ground state hyperfine splitting in a very weak magnetic field. We are now struggling with the first radioactive candidate, ^7Be .

In this paper, the result of ^9Be experiments and the status of ^7Be experiment are reported.

2. Experimental

2.1. Method

The energy diagram of $^9\text{Be}^+$ is shown in Fig. 1. The ground state hyperfine splitting of about 1.25 GHz is the transition which we measured in the present experiment. Since the magnitude of the splitting is rather small compared to the Doppler width of the optical

Figure 1. Energy diagram of $^9\text{Be}^+$ ion.

transition (S-P) at room temperature, we have to apply laser cooling before starting hyperfine spectroscopy. Moreover, since the amount of unstable ions is usually very few, an enhancement in the detection sensitivity by laser cooling is also indispensable. These facts, however, prevent us from using ordinary double resonance technique which has been used in ultra high precision measurements of A constants of several isotopes having large splitting, including a few long-life radioactive species [11]. In their method, the valence electron is pumped out to a state from which no fluorescence are emitted. This does not satisfy one of the laser cooling conditions of continuous excitation-deexcitation cycle.

Another double resonance method, which was used in the present experiment, satisfy the laser cooling condition. Generally laser cooling of odd isotope ions is not simple, since the presence of the hyperfine splitting causes a leak from the excitation-deexcitation cycle by optical pumping. This problem is overcome by a different pumping scheme using circular polarized laser, which is also a good condition to perform high sensitive double resonance spectroscopy as explained in the following.

The pumping scheme is explained in the case of ^9Be ($I = 3/2$). A circular polarized laser radiation excites the transition from the ground state ($S_{1/2}$) to an excited state ($P_{3/2}$). The states split into hyperfine levels (F) as well as their magnetic sublevels (m_F). Due to the selection rule in the excitation by the $\sigma_+(\sigma_-)$ radiation, only the $\Delta m_F = +1(-1)$ transition is allowed. Thus, the population in the ground state is gradually shifted to higher (lower) m_F states, and, finally, concentrates into the maximum (minimum) state, which is $F = 2$, $m_F = +2(-2)$. Once the electron is pumped into this state, it repeats the cycle of excitation-deexcitation in the transition between $S_{1/2}$, $F = 2$, $m_F = +2(-2)$ and $P_{3/2}$, $F = 3$, $m_F = +3(-3)$. This satisfies the laser cooling condition, and enables us to observe single ions, since one ion emits millions of fluorescence photons per second. If microwave radiation induces the hyperfine transition ($F = 2, m_F = +2(-2)$ to $F = 1, m_F = +1(-1)$), we observe a sudden disappearance of the strong fluorescence radiation.

2.2. Apparatus

A linear RF trap dedicated for an off-line use has been used in the present experiments. The trap electrodes comprise four cylindrical rods (6 mm ϕ) made of oxygen free copper, on which a RF potential (~ 5.3 MHz, ~ 70 V_{pp}) is applied to produce a quadrupole field. The inner diameter of the linear trap is 5.3 mm. In order to give an axial trapping field, the rods were cut into three sections and three different DC offset potentials were applied in superposition with the RF potential. The symmetry axis of the linear trap was inclined about 3 degrees to the laser path, in order to couple the radial motion, which carries most of the kinetic energy of the ions, to the cooling force. A photograph of the trap electrodes mounted on an ICF152 flange is shown in Fig. 2.

The 313 nm UV laser radiation was generated by intracavity frequency doubling from a ring dye laser. Circular polarization was made by a Glan-Taylor prism and a $\lambda/4$ plate. Fluorescence photons were detected by a two dimensional photon counting system, PIAS-TI. Microwaves, which were generated by a precision synthesizer and amplified up to 2 W, were introduced through one of the trap electrodes.

Production of Be ions at the trap was made by a Nd:YAG laser shot (14 mJ at maximum, 6 ns width) on a metallic Be disk, in the case of stable ^9Be , or on a silicon disk in which ^7Be ions were implanted. The target holder, on which the metallic Be disk and the

Figure 2. Photograph of the trap electrode. A pulsed YAG laser irradiates the target which is placed just behind the center section through a slit mounted at the center. The optical path for the fluorescence detection (bottom of this picture) is covered by black sheets.

^7Be implanted Si disk are mounted, is shown in Fig. 3.

A high vacuum of $\sim 3 \times 10^{-9}$ Torr is achieved by an evacuation with a turbo molecular pump (300 ℓ/s) and baking in advance for 1~2 days at about 200 degree Celsius.

Figure 3. Photograph of the target disk holder. A natural Be metal disk and two silicon disks, on which radioactive ^7Be atoms were implanted, are mounted on a turn table.

2.3. Results and discussion

2.3.1. ^9Be experiments

A fluorescence spectrum of $^9\text{Be}^+$ ions plotted as a function of laser frequency is shown in Fig. 4. The sharp asymmetric peak indicates the fact that laser cooling was achieved; and the dip at about 200 MHz lower than the peak frequency shows a phase transition from a cloud state to a crystallized state. If the number of ions in the crystal is very

Figure 4. Fluorescence spectrum as a function of laser frequency.

Figure 5. Image of three ${}^9\text{Be}^+$ ions crystallized in a linear RF trap.

small, we can distinguish each independent ion aligned along the trap axis as shown in Fig. 5.

In principle, microwave resonance for such a single ion is possible, or even better than that for many ions in terms of the homogeneity of the field. The resonance can be detected in a quantum jump phenomena [12]. It is, however, the Be ion crystal in our present trap is very delicate. Fake jumps due to a natural disappearance of ions without microwave resonance were often observed. Figure 6 shows a fluorescence spectrum of a single ${}^9\text{Be}^+$ ion as a function of microwave frequency. A dip around 1263.1 MHz is considered to be the effect of microwave resonance.

Figure 6. Microwave resonance on a single ${}^9\text{Be}^+$ ion.

The origins of the fake disappearance would be ion losses due to a leak from the optical pumping cycle, or ion heating due to a so called RF heating. The RF heating of ions may be triggered by collisions with residual gas molecules. In order to avoid this RF heating problem, the RF potential at the central region must be decreased. Use of multipole (6- or more) linear RF trap would be a solution; in which relatively weak RF field is present

at the central region while keeping the total potential depth.

We have also observed a microwave resonance in a cloud state of ${}^9\text{Be}^+$ ions; the number of which was about 100 ions. In their spectra, the resonance dip was not a discrete jump but a Gaussian one. A precision of 4×10^{-6} for the transition frequency was obtained from a Gaussian dip of 250 kHz FWHM [9]. The present precision is not as high as expected; it would be due to short coherent time and power broadening. In order to improve the precision, some modification in the measurement scheme have been made. A fast rotating laser beam chopper with a high duty ratio of $\geq 95\%$ was introduced to achieve a long coherent time of ≥ 10 ms without losing sufficient cooling excitation.

Figure 7. Microwave resonance spectrum of a ground state hyperfine transition of ${}^9\text{Be}^+$ ($F = 2, m_F = +2 \rightarrow (1, +1)$) at about 0.5 mT.

A slow pulsed method was also tested. In this method, laser radiation was blocked when microwaves were supplied for ~ 100 ms after a sufficient cooling period of ~ 400 ms; then the fluorescence intensity integrated for a period of ~ 100 ms after the microwave irradiation, was plotted as a function of the microwave frequency (Fig. 7). A narrower width of about 100 kHz was obtained but the precision of the transition frequency was 2×10^{-5} due to lack of statistics in this measurement. The polarization of the laser radiation was σ_+ , and an external magnetic field of ~ 0.5 mT was applied collinear to the laser beam. The hyperfine splitting constant A can be obtained according to the Breit-Rabi formula in combination with the opposite polarization measurement in the same magnetic field.

2.3.2. Status of ${}^7\text{Be}$ experiment

The first radioactive species, ${}^7\text{Be}$, was prepared in an implanted form. Since the half-life of ${}^7\text{Be}$ is rather long, we can use the same off-line trap and experimental method as that for the stable ${}^9\text{Be}$. A collimated 30-MeV proton beam from INS cyclotron irradiated a relatively thick LiF target (400 mg/cm^2). A part of ${}^7\text{Be}$ produced in a reaction of ${}^7\text{Li}(p, n){}^7\text{Be}$ were recoiled out from the target and implanted on a surface of $2 \text{ mm}\phi$ of a

silicon disk. Approximately 10^{11} atoms of ^7Be were accumulated on a surface (the mean depth was $\sim 3\mu\text{m}$) of the disk.

A peak in a fluorescence spectrum was observed in the first trial. The peak frequency was about 6 GHz lower than that of ^9Be . It is not confirmed yet whether the signal was really from $^7\text{Be}^+$ ions, since the signal was observed only a few times in a series of experiment.

The YAG laser ablation method for implanted samples in a target has been tested already in other experiment for Ca ions [3]. Approximately similar surface density of Ca ions were implanted on a Be disk. The disk has been used to produce Ca ions in a trap for more than a thousand times of filling. The combination of Ca species and Be disk would be good, since Be is lighter than Ca and the boiling point of Be is much higher than that of Ca, while the condition do not hold in the combination of Be species and Si disk. We plan to use other disk materials such as Mo, W, or Ta, even though their mass is much heavier but they are highly refractive.

3. Summary

The experimental technique of trapping, laser cooling and hyperfine spectroscopy for a small amount of Be ions has been established in our setup.

The present precision is not as high as other double resonance experiments. It is, however, sufficient for the present purpose of the first determination of the nuclear magnetic moment of ^7Be from the hyperfine constant A . For more precise measurements, we are now preparing a superconducting Helmholtz magnet.

An experiment for the first radioactive species of ^7Be was started, but the fluorescence signal is not confirmed yet. It would be cleared within a few months.

For a challenging experiment of a short lived beryllium isotope, ^{11}Be , we have been developing a new technique to accumulate energetic ions from a recoil mass separator [13,14]. The on-line trap and the present spectroscopic method will be combined in the near future for the investigation of the most interesting object, ^{11}Be .

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