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INSTITUTE FOR NUCLEAR STUDY
UNIVERSITY OF TOKYO
Tanashi, Tokyo 188
Japan

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AN ION TRAP – LASER EXPERIMENT AT THE INS CYCLOTRON

I. Katayama, M. Wada, J. Tanaka, H. Kawakami, H.A. Schuessler, H. Okada[*1],
T. Nakamura[*1], S. Ohtani[*1], O. Becker[*2], F. Arbes[*2] and G. Werth[*2]

INS, Univ. Tokyo, Midoricho, Tanashi, Tokyo 188
*[*1] Laser Center, Univ. Electro-Communication, Chofu, Tokyo*
*[*2] Phys. Department, Univ. Mainz, Mainz*

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ABSTRACT : A new nuclear instrument which comprises an ion guide behind a recoil mass separator, an RF trap, a Penning trap and a UV laser system is being built to perform a laser-microwave double resonance experiment. Initially the instrument will be used to measure hyperfine anomalies of Ca isotopes produced by a cyclotron beam.

1. Introduction

The advent of high precision lasers together with a Penning trap has made it possible to measure a hyperfine splitting and a Zeeman splitting in the same experiment. This kind of measurements when performed on several odd nuclei of one isotope allows us to study the so-called hyperfine anomaly or Bohr-Weisskopf effect[1]. Historically the measurements were carried out mostly for stable nuclei and so far only for few long lived radioactive nuclei. This is because the experiments were performed in laboratories where an accelerator was not available. We have proposed the application of this method to short-lived unstable nuclei. The first objects for the present study were chosen to be the odd Ca nuclei for the two reasons. Firstly, the element Ca has many odd isotopes, ^{39}Ca to ^{51}Ca which are good candidates for a double resonance experiment. The study of Bohr-Weisskopf effects for these nuclei will provide information on the structure of the ground states of these nuclei, especially of the valence neutrons. Secondly, lasers in the proper wave length range are available which can induce the resonance fluorescence of the Ca^+ ions.

This paper reports the present status of the experiment with an emphasis on the laser system, the ion traps and a trapping device for unstable nuclear beams.

2. HFS anomaly

The hyperfine structure (hfs) constant A is given as

$$A = [\mu_I \overline{B(0)} / IJ] (1+\varepsilon) \qquad (1),$$

where μ_I is the nuclear magnetic dipole moment, $\overline{B(0)}$ is the time-averaged magnetic field at the site of the nucleus generated by the orbital electrons, I and J are the total angular momenta of the

electrons and the nucleus and ε is called the Bohr-Weisskopf correction which describes the extent of the deviation of the nuclear magnetism from that of a point nucleus. If we can measure the A constant and the μ_I very precisely and calculate B(r) accurately enough, it will be possible to determine ε, which will be compared with nuclear model predictions. There has been tremendelous progress in atomic physics since the work of Bohr-Weisskopf, it is still, however, not easy to provide accurate B(r) for all atoms. So one does think of another way where B(r) does not come into play explicitly. As B(r) stays the same among the different isotopes and isomers, the hyperfine anomaly $^1\Delta^2$ defined in the following is normally used.

$$^1\Delta^2 = (A^1g^2 / A^2g^1) - 1 \cong \varepsilon_1 - \varepsilon_2 \qquad (4),$$

where g is nuclear magnetic g_I factor and suffices 1, 2 are to differentiate isotopes or isomers to be compared. The magnitude of the hyperfine anomaly is around10^{-3} in the maximum situations for the case of proton odd nuclei. Therefore, to say something about $^1\Delta^2$, it is necessary to determine the A factors and the g_I factors with accuracies of better than 10^{-6}. This is the reason why we need a high precision measurement.

3. HFS spectroscopy using ion traps

We are aiming at measuring the hyperfine anomalies of the Ca isotopes, i.e., ^{39}Ca ($T_{1/2}$= 860ms), ^{41}Ca (1x10^5y), ^{43}Ca (stable), ^{45}Ca (163d), ^{47}Ca (4.5d), ^{49}Ca (8.7m), and ^{51}Ca (10s), The ^{39,41}Ca isotopes are accessible using cyclotron beams, on the other hand we need reactors or high energy proton beams to produce the $^{45\text{-}51}$Ca isotopes. In this section we will describe the case of ^{43}Ca which is the first study undertaken at the Laser Center of the Electro-Communication University as preparation work.

Fig. 1 shows the magnetic sublevels of a $^{43}Ca^+$ ion in a weak magnetic field. There are two metastable D states which are a nuisance for laser excitation of the ground state $S_{1/2}$ to the excited state $P_{3/2}$. In order to solve the problem, we use two diode lasers at 854nm ad 850nm to excite the atoms in D states back to P state. UV laser light at λ = 393nm with σ^- polarization is used to excite atoms from the $^2S_{1/2}$, F=4, m_F=-4 to the $^2P_{3/2}$, F=5, m_F=-5. The laser frequency is slightly shifted to

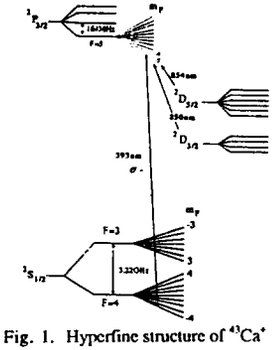

Fig. 1. Hyperfine structure of $^{43}Ca^+$ in a weak magnetic field.

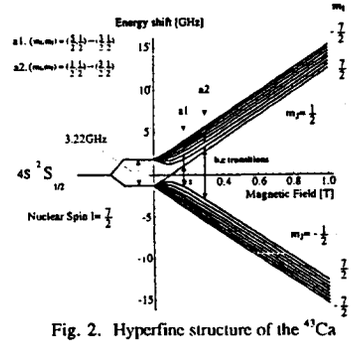

Fig. 2. Hyperfine structure of the ^{43}Ca ground state in a strong field.

lower values from the center so that the laser cooling is effected. At first the ions stored in an RF trap are at the temperature of several thousand degree Kelvin. This results in a large Doppler broadening of the fluorescence spectrum. This broadening enables the ions, which have a distribution over different m-sub levels of the F=4 state, to be also excited to the $P_{3/2}$ state. Due to the selection rule for σ- light, the Δm_F=-1 transition is only allowed from $S_{1/2}$ to $P_{3/2}$ states. As a conséquence of continuous laser excitation, the population of the lower m_F states in the F=4 increases and finally we have optical pumping of the F=4, m_F=-4 state. Now we can observe the fluorenscence due to recycling between S and P states. It should be also emphasized that the ^{43}Ca nuclei are now polarized. As a next step, we will proceed to apply a micro wave frequency to excite the state $^2S_{1/2}$, F=4, m_F=4 to $^2S_{1/2}$, F=3, m_F=-3 in F=4 state. The resonance is observed as a decrease in the laser fluorescence. If a single ion is stored in the trap, we will see the stop of the fluorescence, which is a quantum jump effect. The way to observe the resonance mentioned above is called a shelving method. We will repeat a similar procedure to excite the state $^2S_{1/2}$, F=4, m_F=4 to $^2P_{3/2}$, F=5, m_F=5 with σ$^+$ polarized laser light. This will give us the frequency of $^2S_{1/2}$, F=4; m_F=-4 to $^2P_{1/2}$, F=3, m_F=3 transition. In a weak magnetic field, the magnetic sublevels split symmetrically. Therefore, the mean value of these two microwave frequencies gives us the A factor of ^{43}Ca.

This autumn a superconducting magnet becomes available, and we will use it to implement a Penning trap. The ions in the RF trap are then transferred to the Penning trap. The atomic levels of the $^{43}Ca^+$ ions in the strong field are shown in fig.2. The $^{43}Ca^+$ ions are in either one of the states (m_I, m_F) = (7/2, 1/2) or (-7/2, -1/2), which are selected by the polarization of the laser light. For the precise measurement of the g_I factors, we will use the so-called clock transition. Namely at a certain magnetic field strenght, the frequency of the transition becomes insensitive to a small change in the magnetic field. It is also important that the transition frequency should depend strongly on the strength of the nuclear magnetic moment. With these two factors in mind, candidates of the transition to be measured are chosen and shown in fig.2. They are both clock-transitions.

4. Experimental apparatus.

In order to develop the total system in a timely manner, we are working in two places. At the Laser Center, the preparation of laser system and an experiment of a laser-microwave double resonance for the $^{43}Ca^+$ are just undertaken. On the other hand at INS, the scheme to trap radio-active nuclei in ion traps is being developed.

4.1 Laser and ion-trap system.

Fig. 3 shows the present experimental set-up for trapping stable Ca ions. For the laser cooling of Ca^+ ions, a piece of natural Ca metal is laser-ablated using a YAG laser. For the $^{43}Ca^+$ experiment, a thin plate of Be in which $^{43}Ca^+$ ions were implanted is to be used.

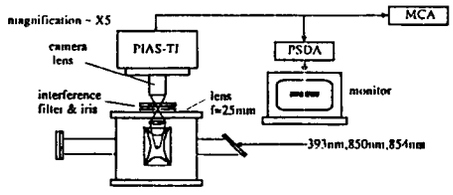

Fig. 3. Trapping stable Ca^+ ions.

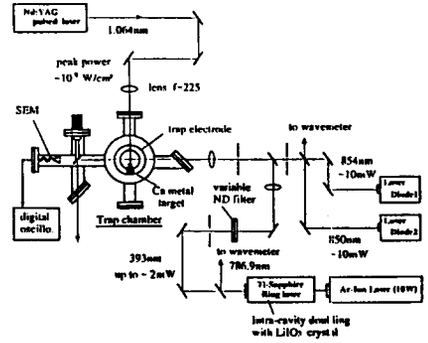

Fig. 4. The laser system for Ca isotopes.

The UV light of 393nm is generated by a non-linear crystal of $LiIO_3$ placed inside the cavity of a Ti-Saphire laser (Intra-cavity doubling). We have obtained about 2 mW of power at 393nm. Fig. 4 shows the laser-system for the Ca experiment. Two infra-red (IR) diode lasers are also required to excite and pump out the ions from the two metastable D states. The wave length of the UV laser is adjusted by measuring the absorption of the laser light in Ca discharge tube. For the IR lasers the same discharge tube is used. An absolute wave length calibration is carried out by observing the opto-galvano signals. The fluorescence is detected by a position sensitive photon counting device (PIAS, Hamamatsu product). The optical lens system for the fluorescent light has a magnification of five and has a interference filter to only detect 393nm.

4.2 The trapping scheme for unstable nuclear ions.

The ion trapping system which has been developed at INS is shown in fig. 5[2,3]. The system consists of (1) GARIS (a gas-filled recoil isotope separator) to separate the recoiling reaction product, (2) an ion guide-gas cell followed by an RF sextuple ion beam guide (SPIG) to stop the ions injected from the separator when keeping them in singly charged state, to extract them from the

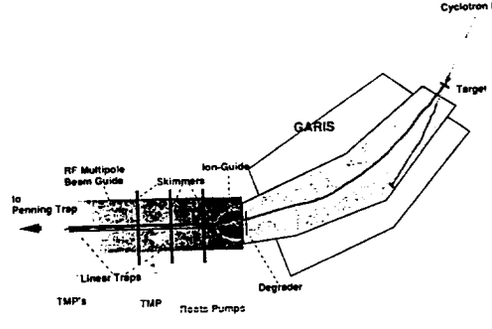

Fig. 5.
Schematic lay-out of the INS on-line ion trap system [from ref.[3]].

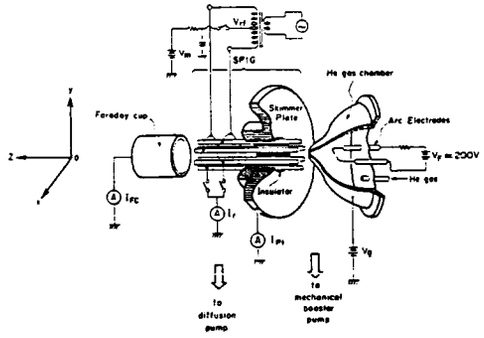

Fig. 6.
Lay-out of the ion guide and SPIG system for the test experiment. The aperture of the SPIG is 2.5mm, the RF frequency of is 4.7 MH_z and the voltage is 60V. [from ref.[4]].

cell with a very low beam energy and to transport them to an ion trap in a high vacuum, (3) a linear ion trap to perform laser cooling and (4) a Penning trap to perform laser spectroscopy for the nuclear magnetic moment measurement. The latter (3) and (4) are those which are being tested at the Laser Center. At INS, we have developed a new focussing and cooling device called a SPIG[4], which is schematically shown in fig.6. Further improvements of the SPIG are now ongoing.

5. Status of the laser experiment.

5.1 Counting of the number of stored ions.

We have developed a new method to count the number of ions stored in the RF trap. The method is rather simple but has not been reported up to now. In this method one of the IR laser, e.g., the one for $D_{5/2}$ state, is detuned from the resonance, while the other IR laser and the UV laser are on resonance. After the irradiation of the laser light for a while, all the ions are excited to the $D_{5/2}$ state, which means that the fluorescence stops. Then the detuned IR laser is suddenly set on resonance, which leads to the observation of the fluorescence. The strength of the fluorescent photons gives us the number of ions. Our detection efficiency is estimated to be around $4x10^{-5}$. Observation of 49 counts when repeating the measurement 100 times yields a number of around $1.2x10^4$ ions in the trap. It should be noted that the method can only be applied in the absence of the pile-up effect in the photon detector.

5.2 Laser cooling of the trapped ions.

Fig.7 shows a time spectrum of the fluorescence. At the beginning, the number of ions is too large to be laser-cooled. After a certain time, the number of ions becomes adequate enough for the laser cooling, which explains the increase of the flourescence. The flat part in the figure just corresponds to the equilibrium between the laser cooling and rf and/or collision heating. This flat part decays with a time constant of 30min. The life time is limited by the slight instability of the IR lasers. Laser cooling works in two ways., i.e., cooling of the ion motions in momentum space and physical space. The spectra in fig.8 were taken by the PIAS system. They clearly show the laser cooling effect in physical space. From the left spectrum, which was taken before laser cooling, we found the laser was focused with the size of 500μm in diameter. From the right spectrum, we conclude that the ions were cooled to the size of 300μm in diameter.

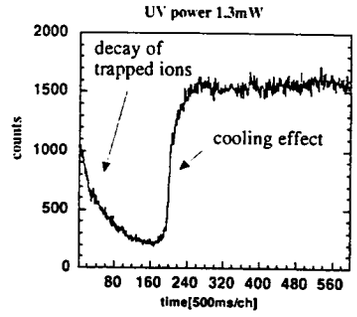

Fig. 7.
Flourescence from trapped ions as a function of time. The UV laser light was detuned-200 MHg from the center.

Next is the observation of the cooling effect in momentum space. Fig.9 shows the fluorescence yield as a function of the UV light frequency. As mentioned before the temperature of the ions before the cooling is around 2000°k, which corresponds 4GHz in the FWHM. The scanning was done from the lower to the higher frequencies. When the frequency exceeds the line center, the laser works as heating, which explains the sudden loss of ions at higher frequencies. In order to see the temperature of the ions after laser cooling, one of the IR lasers was scanned 100 times over 1.2 GHz. The result shows that the temperature is about 64K. To improve the cooling effect further, we must decrease the number of ions. Soon we will come then to the double resonce phase.

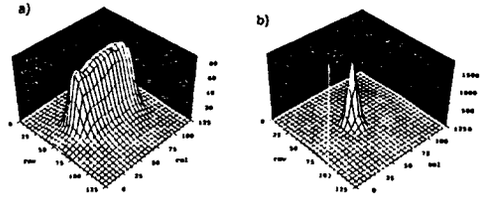

Fig. 8. Spatial distribution of the UV flourescence from trapped ions. a) not cooled ions, b) cooled ions

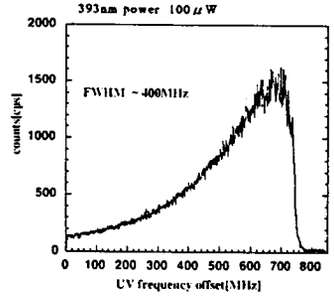

Fig. 9. Flourescence spectrum of trapped Ca^+ as a function of UV laser frequency.

6. Conclusion

The status of the laser-microwave resonance experiment for Ca isotopes is reported. The experiment is intended to exploit the system to measure the Bohr-Weisskopf effect for a wide range of unstable nuclei. The lasers and ion trap are now tested for the stable isotope ^{43}Ca. A new trapping scheme for unstable Ca ions has been also developed. In the near future we will start the double resonance experiment for the unstable ^{39}Ca and ^{41}Ca isotopes.

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