

# The laser Isotope separation (LIS) methods for the enrichment of $^{48}\text{Ca}$ .

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**Abstract.** Neutrino-less double beta decay measurement is a powerful tool to test the Majorana nature of neutrinos. Among the potential double beta decay nuclei,  $^{48}\text{Ca}$  has the largest Q value (4.3 MeV), we can expect the least background measurement. On the other hand, a smallness of natural abundance of  $^{48}\text{Ca}$  (~0.2%) requires an enrichment to increase the sensitivity to reach interesting regions (Inverted Hierarchy and Normal Hierarchy). We have been studying the laser isotope separation (LIS) methods for the enrichment of  $^{48}\text{Ca}$ , where a narrow band diode laser is used to excite the specific isotope in the calcium vapor beam. For the separation, two methods (deflection and ionization) are employed. In the deflection method, the  $^{48}\text{Ca}$  atoms are deflected by momentum transfers from laser photons by multiple absorption and emission. In the ionization method, an additional dye laser is used to ionize the excited  $^{48}\text{Ca}$ . In this paper, we will report the current status and future prospects of two methods of LIS for the enrichment of  $^{48}\text{Ca}$ .

## 1. Introduction

Many experimental groups are searching for neutrino-less double beta decay ( $0\nu\beta\beta$ ) with the aim of verifying the Majorana property of neutrinos.  $^{48}\text{Ca}$ , an isotope of Ca, has the highest Q value (4.27 MeV) among the  $0\nu\beta\beta$  decay nuclei. This value is much higher than the maximum energies of  $\gamma$ -rays and  $\beta$ -rays from natural radiation, 2.6 MeV and 3.27 MeV, respectively. On the other hand,  $^{48}\text{Ca}$  has a very small natural abundance (0.187%), so it is desirable to concentrate and increase the target nucleus. Since Ca does not contain a gaseous compound at room temperature, the commonly centrifugal method and the gas diffusion method cannot be used, and it makes commercially available  $^{48}\text{Ca}$  expensive. There is an urgent need to develop a  $^{48}\text{Ca}$  enrichment method that can be mass-produced inexpensively for the  $0\nu\beta\beta$  decay search experiment. At Univ. of Fukui, focusing on laser isotope separation, development is continuing.

## 2. Experimental principles of LIS

In laser isotope separation, a target isotope is selectively excited by using a narrowband laser. At this time, concentration is performed by utilizing a slight difference in energy level isotope shift (Figure 1). We have been studying the laser Isotope separation (LIS) methods for the enrichment of  $^{48}\text{Ca}$ , where external cavity diode laser (ECDL) is used to excite  $^{48}\text{Ca}$ . The merit of the method is it can be applied even if the gas compound does not exist at room temperature. The use of atomic beams is a conventional technology that is easy to increase in size, and diode lasers are relatively inexpensive, so the introduction of multiple units has opened the way to mass production.



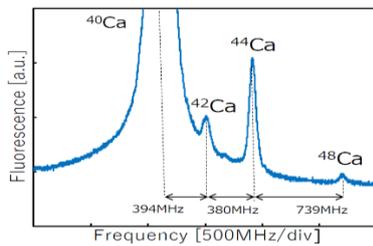


Figure 1. Absorption spectrum of calcium. The isotope shifts are shown in the figure. The peak value of the spectrum corresponds to the abundance ratio of each isotope, 96.941% ( $^{40}\text{Ca}$ ) and 0.187% ( $^{48}\text{Ca}$ ). Isotope separation is performed by utilizing the difference in absorption wavelength between each isotope.

### 3. Experiment Method

We employed two methods (deflection and ionization) for the separation.

Technologies common to the two methods are atomic beam generation and TOF detection field. The atomic beam heats the metallic Ca in an oven and emits it onto the beam vertically upward using a collimator. The TOF detection field consists of electrodes and MCP, and vapor is ionized between the electrodes to analyse and detect ions. The oven and the TOF detection field are in a vacuum chamber. The difference between the two methods is the relationship between laser irradiation and electrodes.

In the deflection method, the vapor is deflected by irradiating the diode laser with the wavelength of  $^{40}\text{Ca}$  (422.6723 nm). The angle of the atomic beam deflected by the diode laser is calculated from the vapor distribution map obtained from the experiment (see Figure 2 and its caption).

In the ionization method, the abundance of each isotope is measured by the TOF spectrum obtained from the experiment (see Figure 3 and its caption).

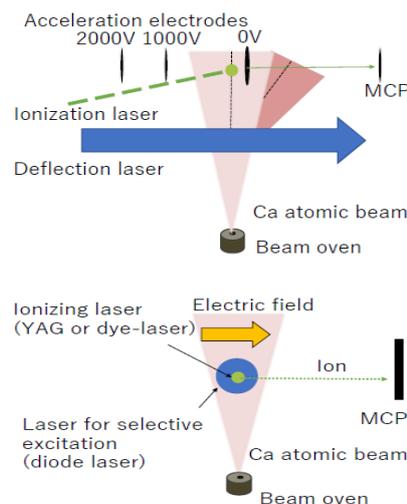


Figure 2. Outline of experiment of deflection method.

In the deflection method, atomic beams are bent by causing momentum transfer by repeating excitation and de-excitation of atoms by several hundred times with photons from a diode laser. In order to verify this principle, a spatial distribution is measured by moving the ionization YAG laser in the x-axis direction at the electrode portion at a distance between the laser irradiation unit and the TOF detection unit.

Figure 3. Outline of experiment of ionization method.

In the ionization method, after selective initial excitation by diode laser light, ionization is performed by absorbing two photons from the dye laser. Therefore, the laser irradiation position is between the electrodes.

## 4. Results

### 4.1. deflection method

Obtained spectra are shown in Figure 4. The spatial difference between the peaks of the two spectra was 4.1 mm which corresponds deflection angle of 12.5 mrad.

Figure 5 shows the result of calculating the recovery rate of  $^{48}\text{Ca}$  in the atomic beam and the concentration of  $^{48}\text{Ca}$  in the recovered metallic Ca using this result.

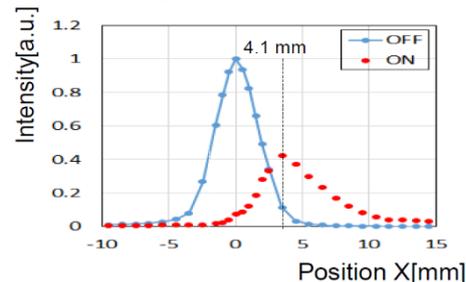


Figure 4. Vapor distributions of  $^{40}\text{Ca}$  when deflection laser is on (red) and off (blue).

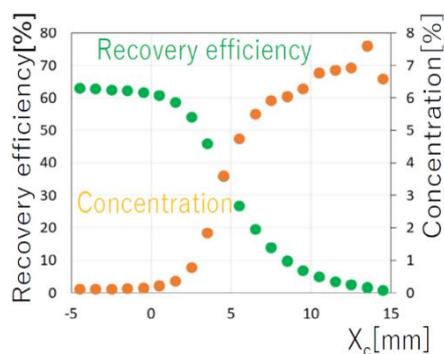


Figure 5. Plot of recovery rate (green) and concentration rate (red) assuming that all atoms on the right can be recovered from a point  $X = X_c$  in Figure 4.

If the  $^{48}\text{Ca}$  vapor distribution is the same as the experimental spectrum, it can be seen that the recovery rate of  $^{48}\text{Ca}$  is 19.6% and the enrichment is 5.5% if the recovery plate is placed at 4.1 mm. In addition, the deflection method enables stable concentration.

#### 4.2. ionization method

Figure 6 shows the TOF spectra obtained in the ionization method. It was found that the enrichment can be increased up to 90% by irradiating the laser with the optimal wavelength and power density for the atomic vapor. Although the concentration rate in the ionization method is higher than that in the deflection method, recovery rate per unit time is lower than that in the deflection method because the dye laser used for concentration is a pulse laser.

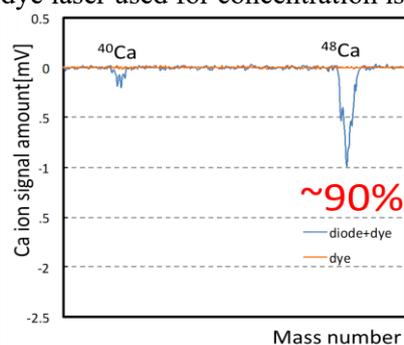


Figure 6. Ca isotope signal that can be confirmed on MPC. The red spectrum is the one when irradiated with only the dye laser, and the blue spectrum is the one when irradiated with the dye laser and diode laser. The area ratio between the  $^{40}\text{Ca}$  and  $^{48}\text{Ca}$  peaks was calculated to obtain the concentration ratio.

### 5. Discussion

From the above experiments, it can be seen that in the deflection method, the concentration is moderate using a CW laser, and the production efficiency per unit time is high.

The ionization method has a high concentration ratio, but the production per unit time is low due to the use of a pulsed laser, but the deflection method requires several hundred to thousand photons to collect one photon. In principle, the ionization method requires only three, so a reduction in cost can be expected by improving the duty factor of pulsed laser.

### 6. Conclusion

We are developing two LIS methods to observe Neutrino-less double beta decay. In the deflection method, the  $^{48}\text{Ca}$  atoms are deflected by momentum transfers from laser photons by multiple absorption and emission. As a result, the deflection method achieved a recovery rate of 19.6% and a concentration level of 5.5% by optimizing the position of the recovery plate. In the ionization method, additional dye laser is used to selectively ionize the  $^{48}\text{Ca}$ . As a result, the ionization method achieved 90% enrichment. In the future, we will improve the total production rate of  $^{48}\text{Ca}$  for mass production.

### References

- [1] Iyoda T., " Study on deflection characteristics of atomic beams in laser isotope separation of Ca ", Master thesis, University of Fukui (2019).
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