

Optimization of the Atomic Beam System for Laser Isotope Separation of ^{48}Ca

Rei TANAKA¹, Izumi OGAWA¹, Hideaki NIKI^{1, 2}, Masashi TOZAWA¹, Saori UMEHARA², Anawat RITTIRONG², Kenji MISHIMA², Sei YOSHIDA³, Shigeki TOKITA⁴, Masahiro UEMUKAI⁵, Noriaki MIYANAGA⁶

(¹Fac. of Engineering, Univ. of Fukui, ²RCNP, The Univ. of Osaka, ³Fac. of Science, The Univ. of Osaka, ⁴ICR, Kyoto Univ., ⁵Grad. Sch. of Eng. Sci. The Univ. of Osaka, ⁶Inst. for Laser Technol.)

For details on laser isotope separation, please refer to Anawat's poster and Mishima's talk.

Target: Mass production of ^{48}Ca by laser isotope separation

- Proof of principle has been demonstrated
- Collaborative development by CANDLES

Isotope enrichment of ^{48}Ca

- Liquid extraction using crown ethers
- Liquid centrifugation
- Laser isotope separation**

Characteristics of ^{48}Ca

- The highest Q-value(4.27 MeV)
- Low natural abundance (0.187 %)

Observation of $0\nu\beta\beta$

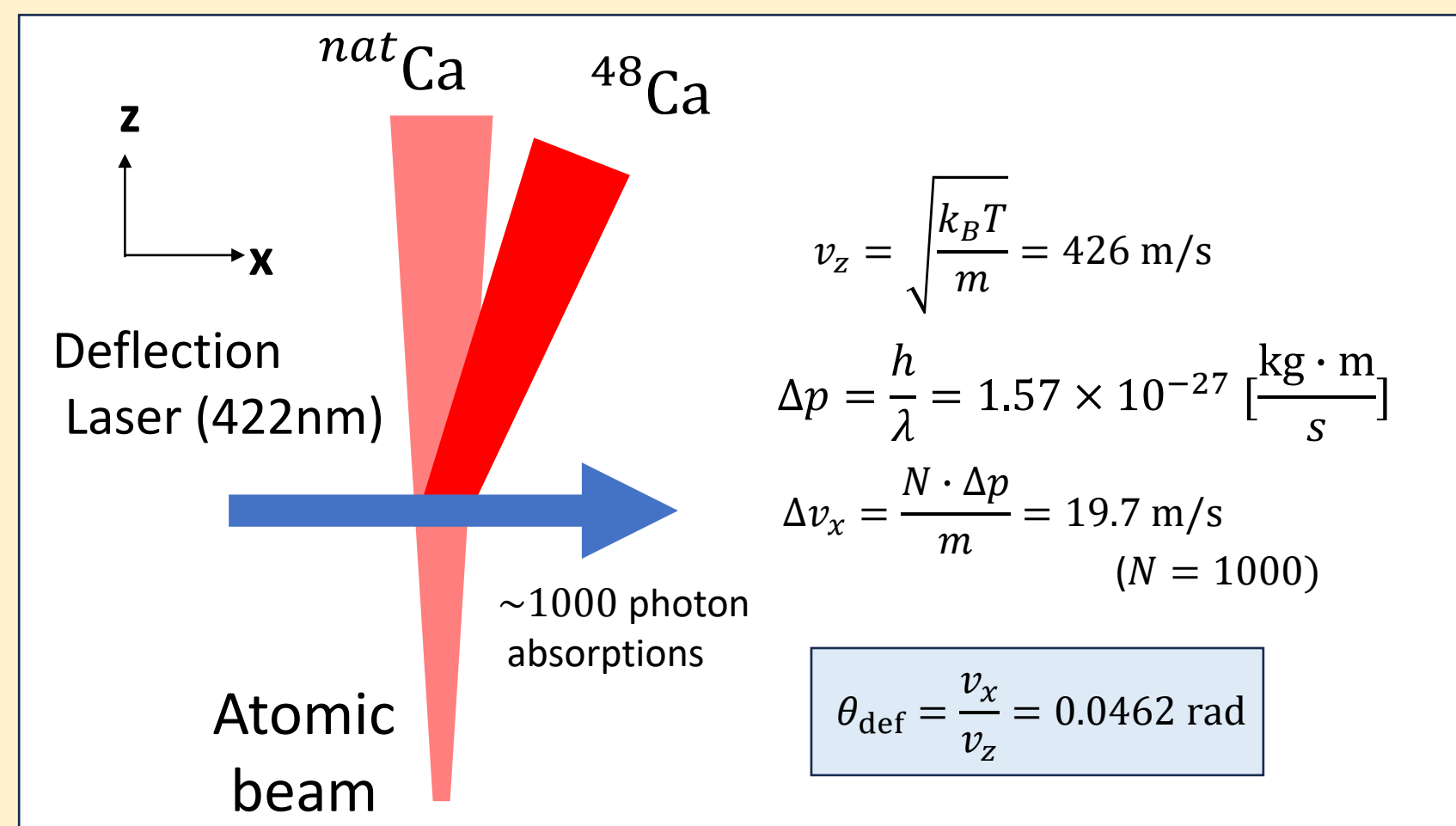
- Proof of the Majorana nature of neutrinos
- Ultra-rare nuclear decay process

Laser Isotope Separation

Selective absorption/emission of ^{48}Ca

Momentum transfer by multiple photon-absorption

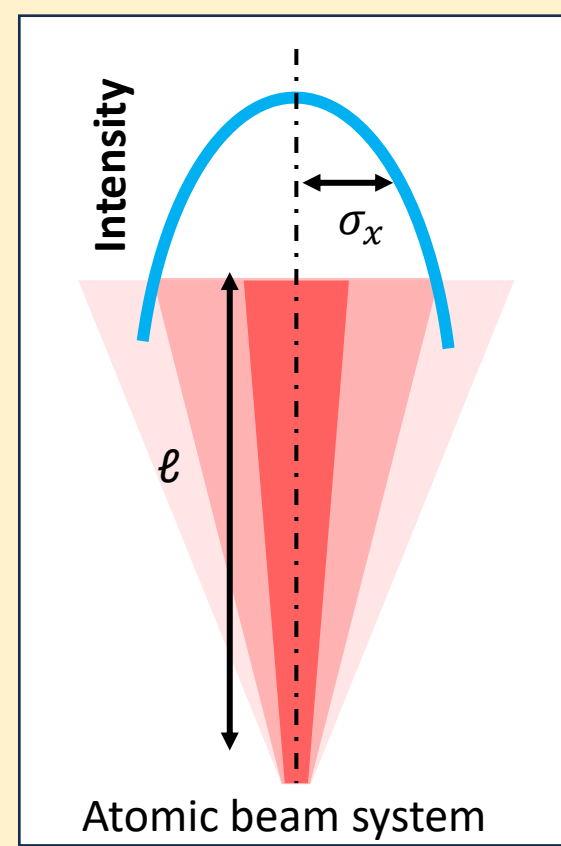
Isotope separation



Atomic Beam Divergence

- Atomic beam divergence reduces separation efficiency.
- Atomic beam divergence

$$\theta_{\text{div}} = \arctan\left(\frac{\sigma_x}{\ell}\right)$$

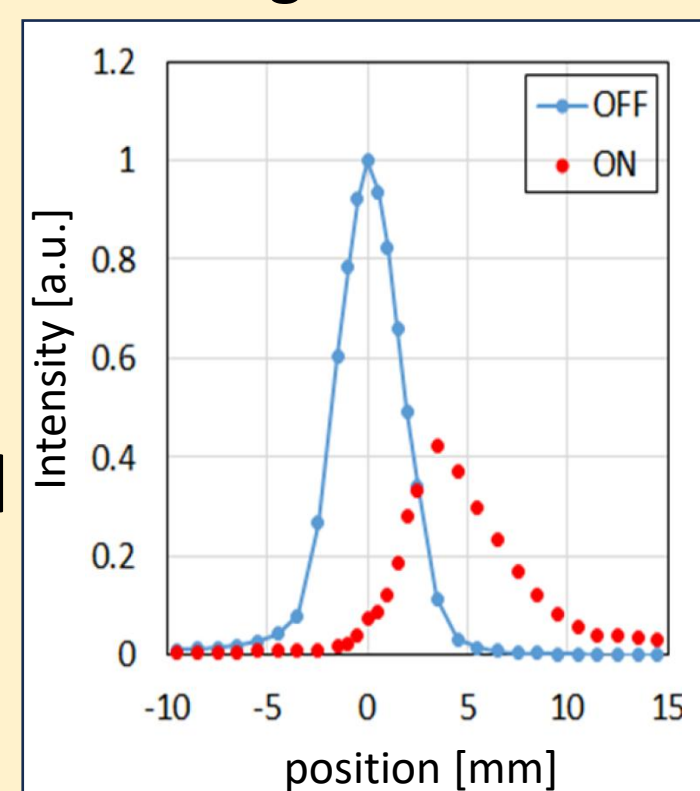


K. Matsuoka, H. Niki, I. Ogawa, Y. Shinki, Y. Kawashima, K. Matsumura, J. Phys.: Conf. Ser. 1468, 012199 (2020).

Proof of Principle

Spatial distributions of Ca with/without the deflection laser tuned to the ^{40}Ca absorption wavelength

$$\theta_{\text{def}} = 0.0127 \text{ rad}$$



Direct Simulation Monte Carlo (DSMC)

Simulation Features

Gas flow in the collimator must be treated as a rarefied gas flow because $K_n > 1$.

The commercially available simulation software DSMC-Neutrals, specialized in rarefied gas flows and using Monte Carlo and finite element methods, was used.

Simulation Parameters

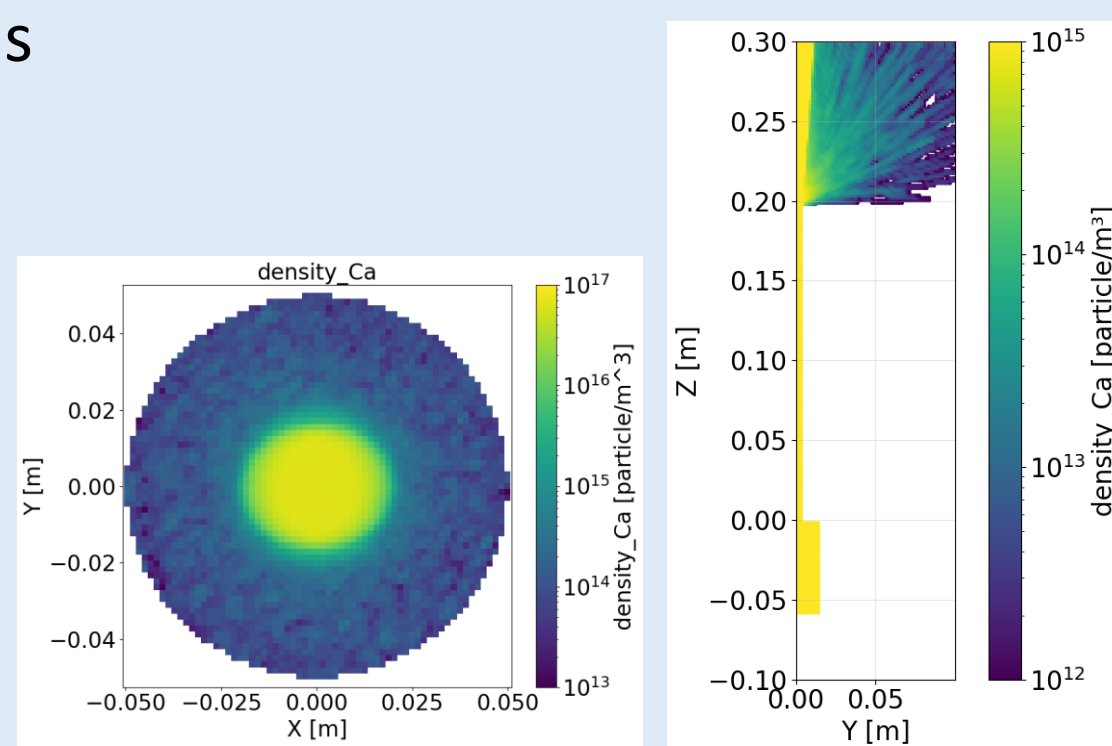
- We show how the experimental parameters of the atomic beam system correspond to the simulation parameters.

ABS

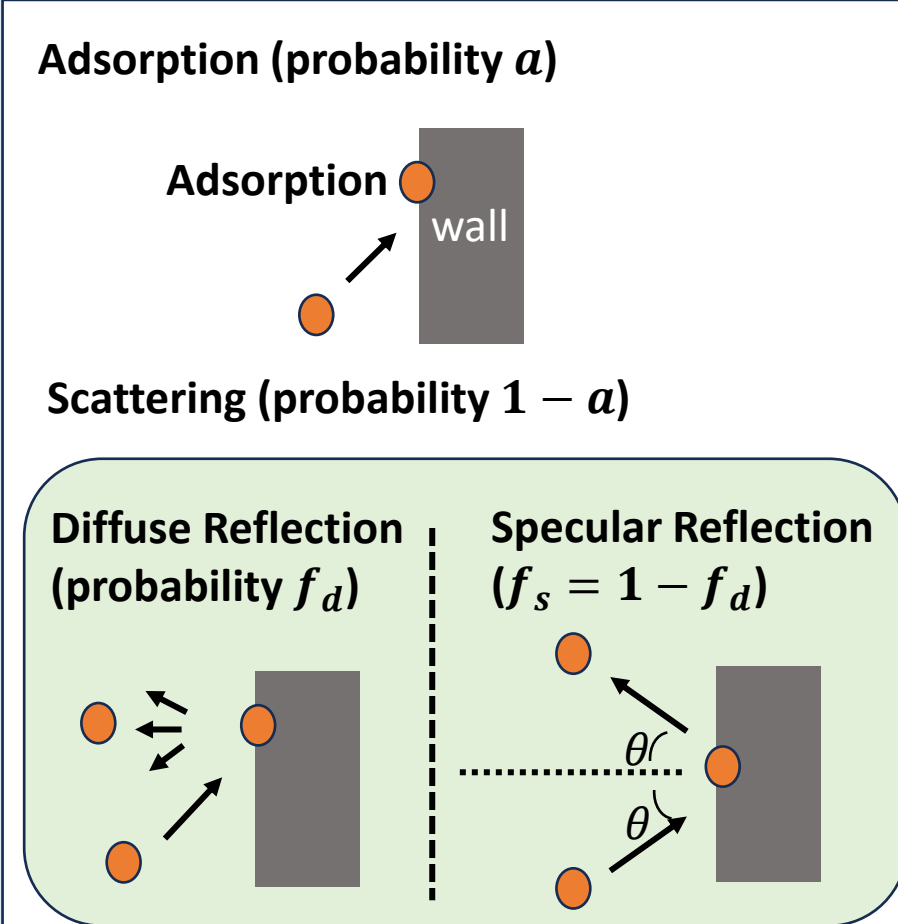
- | | |
|-------------|--|
| Temperature | • Wall temperature (T_w)
• Evaporation rate (J_{Ca}) |
| Shape | • Geometry |
| Material | • Adsorption coefficient (α)
• Accommodation coefficient (f_d) |

Knudsen number

$$K_n = \frac{\lambda}{L} = \frac{k_B T}{\sqrt{2} \pi \sigma^2 P L}$$



Ca Distribution in the Simulation



Atomic Beam System (ABS)

Requirements for Atomic Beam Characteristics

(1) High intensity

Initial target: 0.05 mol/year
→ Readily achievable at 600 °C
($\alpha_v = 9.07 \times 10^{-4} \text{ kg/m}^2 \cdot \text{s}$)

R. Yuhaku, Master's Thesis, Univ. of Fukui (2024).

(2) Small atomic beam divergence

Simulation study using Geant4
 $\theta \leq 0.009 \text{ rad}$

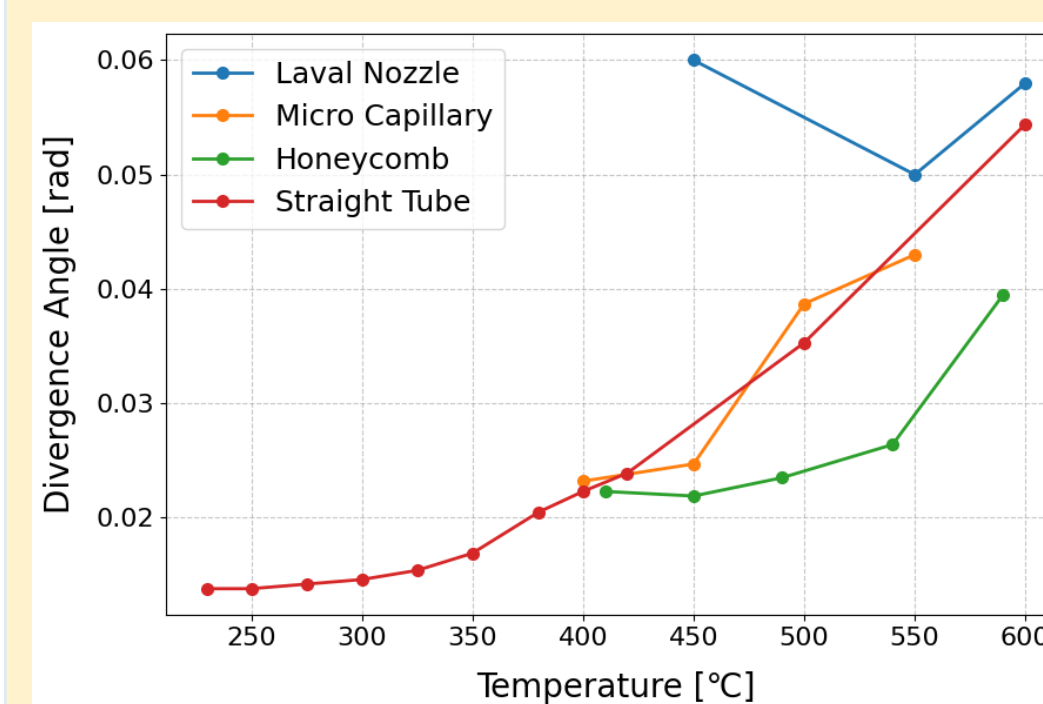
(Separation efficiency: 5%, Recovery rate: 20%)

J. Nakajima, Master's Thesis, Univ. of Fukui (2024).

Parameters to Optimize ABS

We experimentally investigated the effects of parameters on atomic beam divergence and intensity.

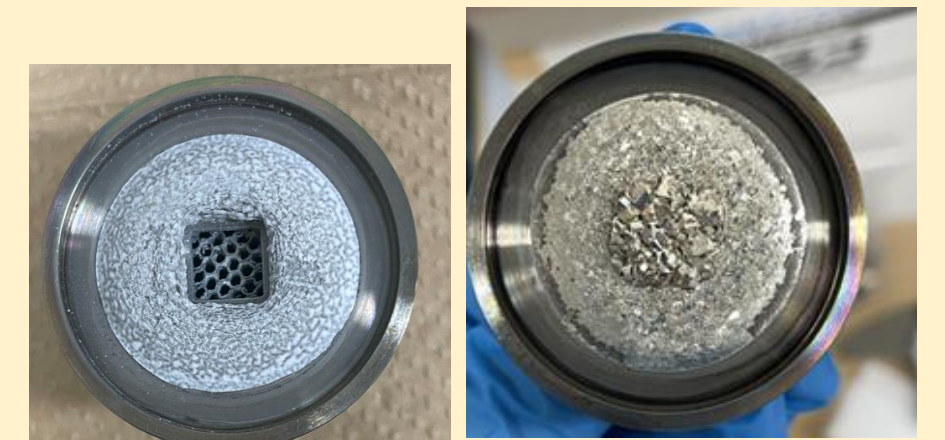
Parts	Parameters	
Oven	Temperature	150-600°C
Collimator	Shape	Straight Tube, Laval Nozzle
	Material	SUS, Al_2O_3 , Carbon



R. Yuhaku, Master's Thesis, Univ. of Fukui (2024).

- Temperature and shape affect atomic beam divergence
- Material affects the amount of Ca deposition on the collimator, causing Ca clogging.

➡ Optimization of parameters using simulations



Ca clogging

Simulation Setup

First step: Investigated the relationship between simulation parameters and atomic beam divergence and intensity.

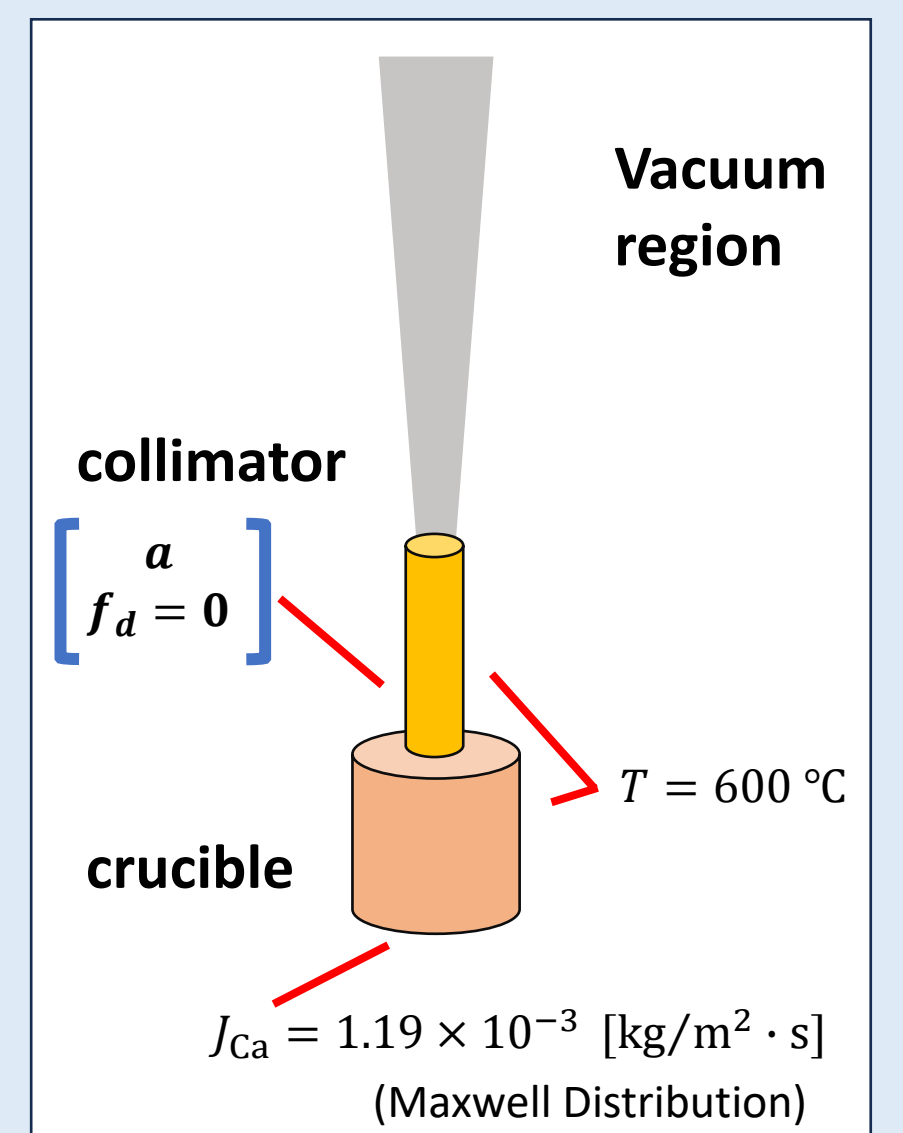
➡ Focus: Collimator geometry and material

Study 1 : Effect of Collimator Geometry

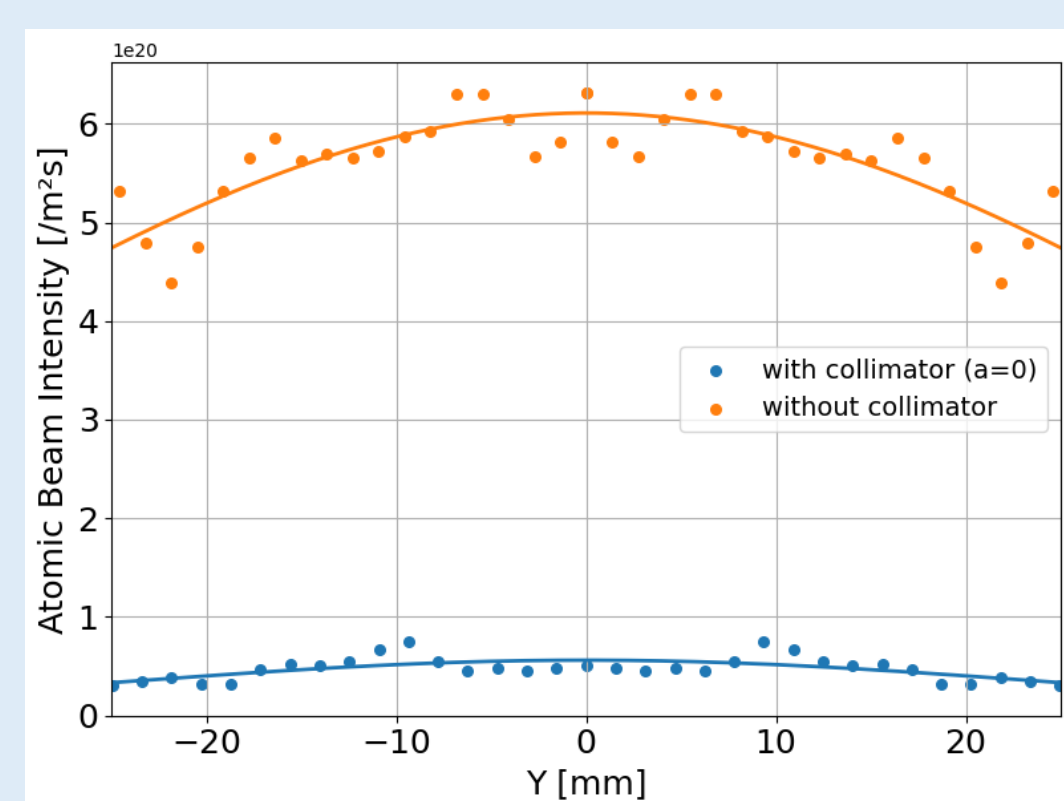
The collimation effect of geometry was evaluated by comparing the cases without a collimator and with a collimator ($\alpha = 0$), excluding material effects.

Study 2 : Effect of Collimator Material

An increase in adsorption coefficient α is expected to reduce the divergence angle. The dependence of the divergence angle and beam intensity on adsorption coefficient α was evaluated.



Simulation Results study1



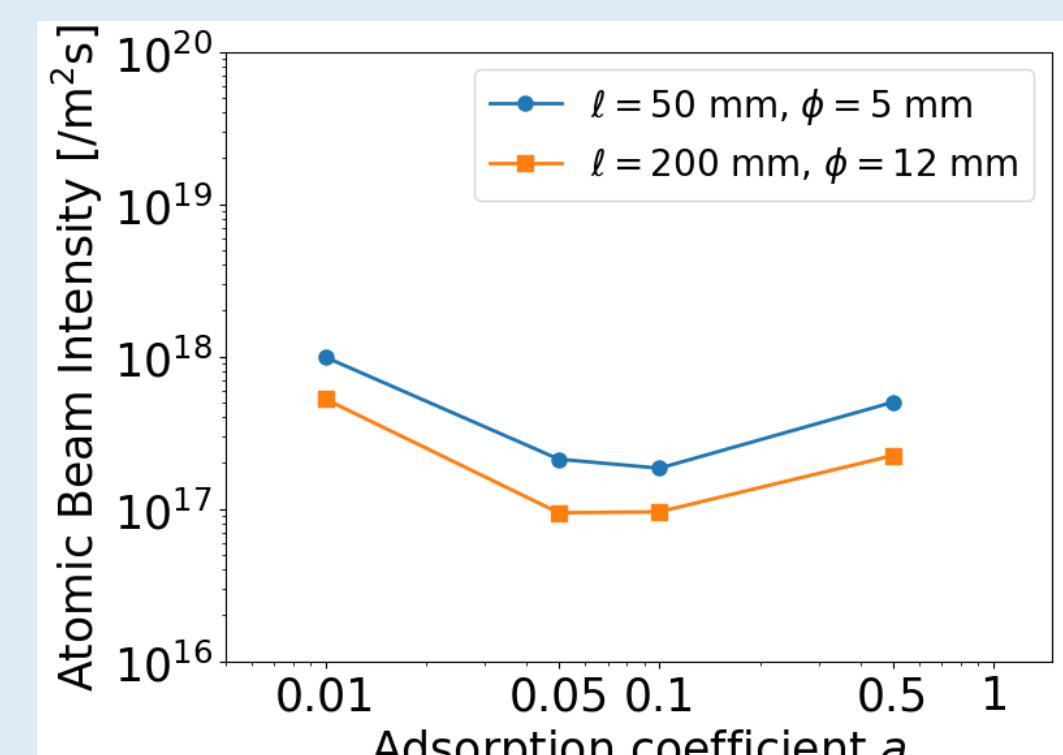
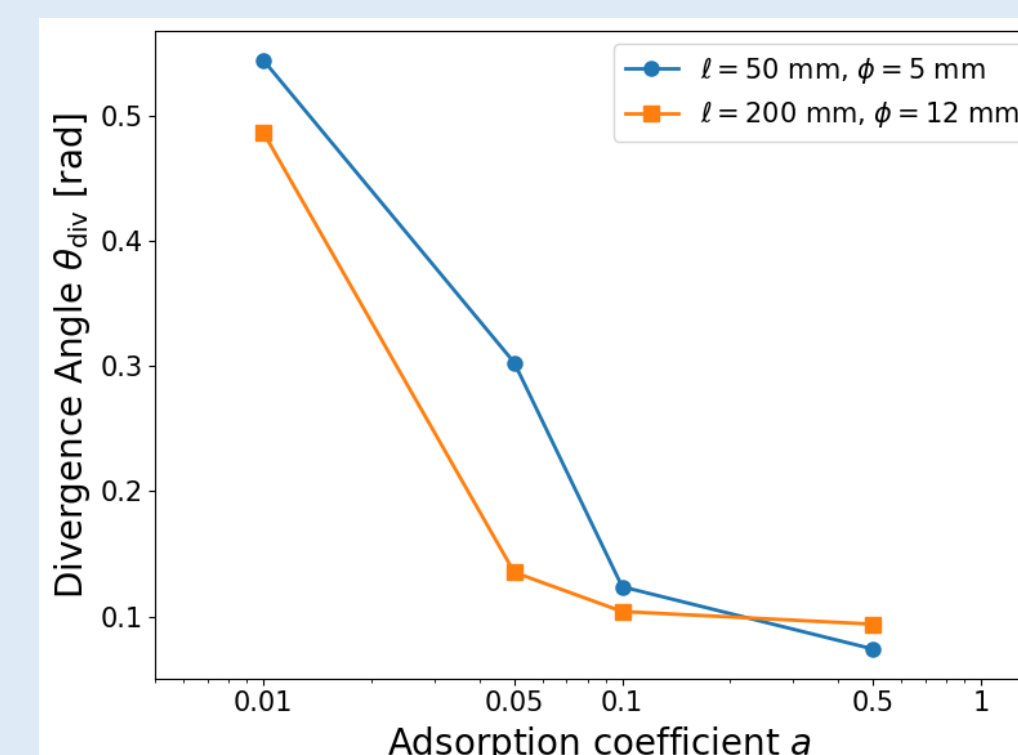
With collimator ($\alpha = 0$) :
 $\sigma = 24.47 \text{ mm}$, $\theta_{\text{div}} = 0.24 \text{ rad}$

Without collimator :
 $\sigma = 35.12 \text{ mm}$, $\theta_{\text{div}} = 0.34 \text{ rad}$

We confirmed that the collimator reduced atomic beam divergence. However, the divergence was not sufficiently reduced.

➡ Study2 (Material)

study2



A decreasing trend in atomic beam divergence was observed with increasing α . In contrast, no clear trend was observed between beam intensity and α . However, the atomic beam divergence remains insufficient. Selecting a material with an appropriate α (f_d) is expected to reduce atomic beam divergence.

Summary

- Developed an atomic beam system for laser isotope separation, motivated by the investigation of the Majorana nature of neutrinos.
 - ➡ An atomic beam with small divergence and sufficient intensity is required.
- Previous studies have shown that the temperature and shape of the atomic beam system affect atomic beam characteristics.
- This study investigated the effects of shape and material on atomic beam characteristics through simulations.
 - We confirmed that the collimator reduced atomic beam divergence. However, the reduction was insufficient to achieve the target divergence angle, indicating that material optimization is also necessary.
 - Selecting a material with an appropriate α (f_d) is expected to reduce atomic beam divergence.