飛行時間測定による低温ナノ多孔質酸化物材料中のポジトロニウム冷却評価

Evaluation of Positronium Cooling in cold Nano-Porous Oxide Materials by Time-of-flight Measurement

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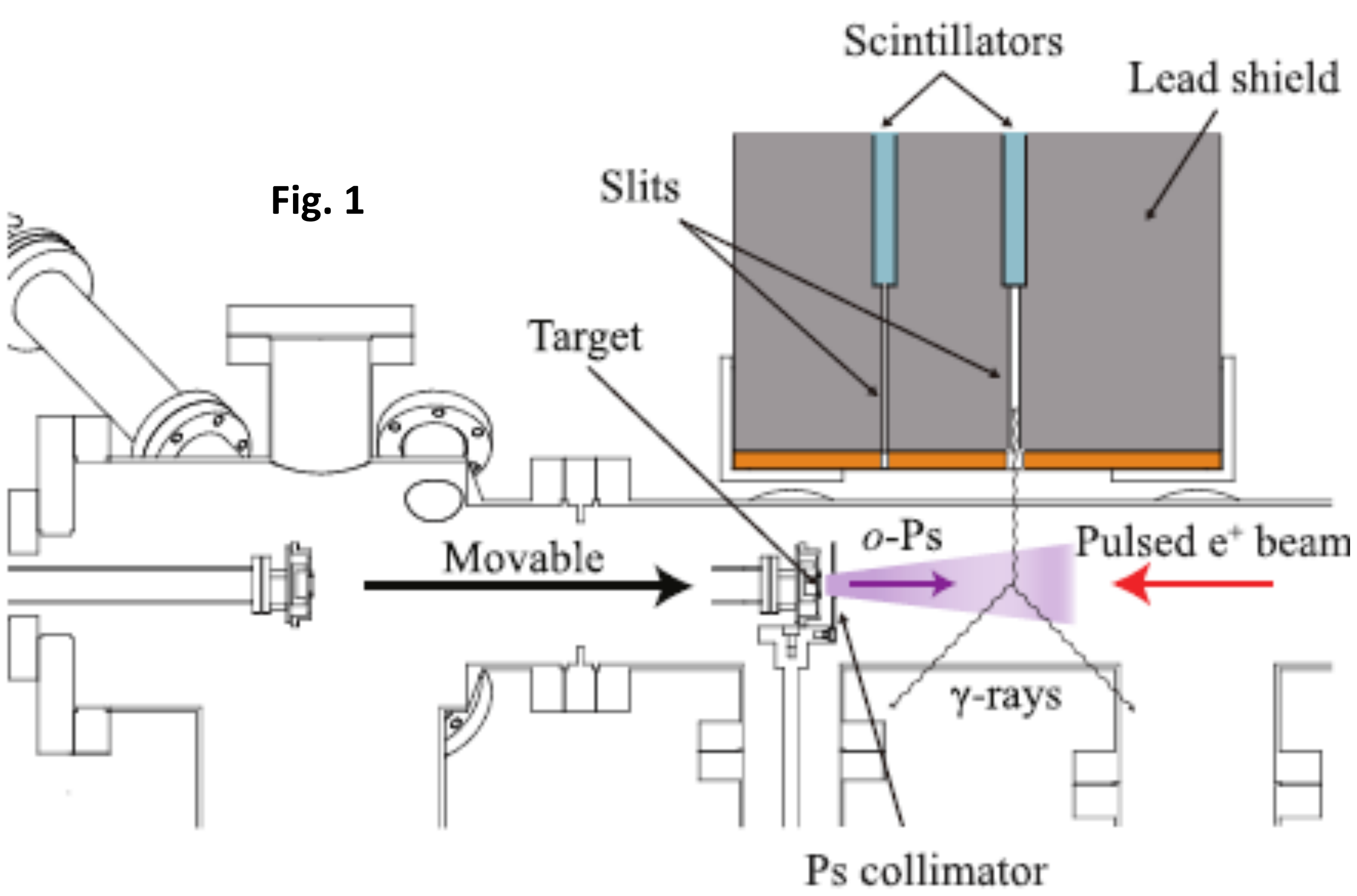
Abstract

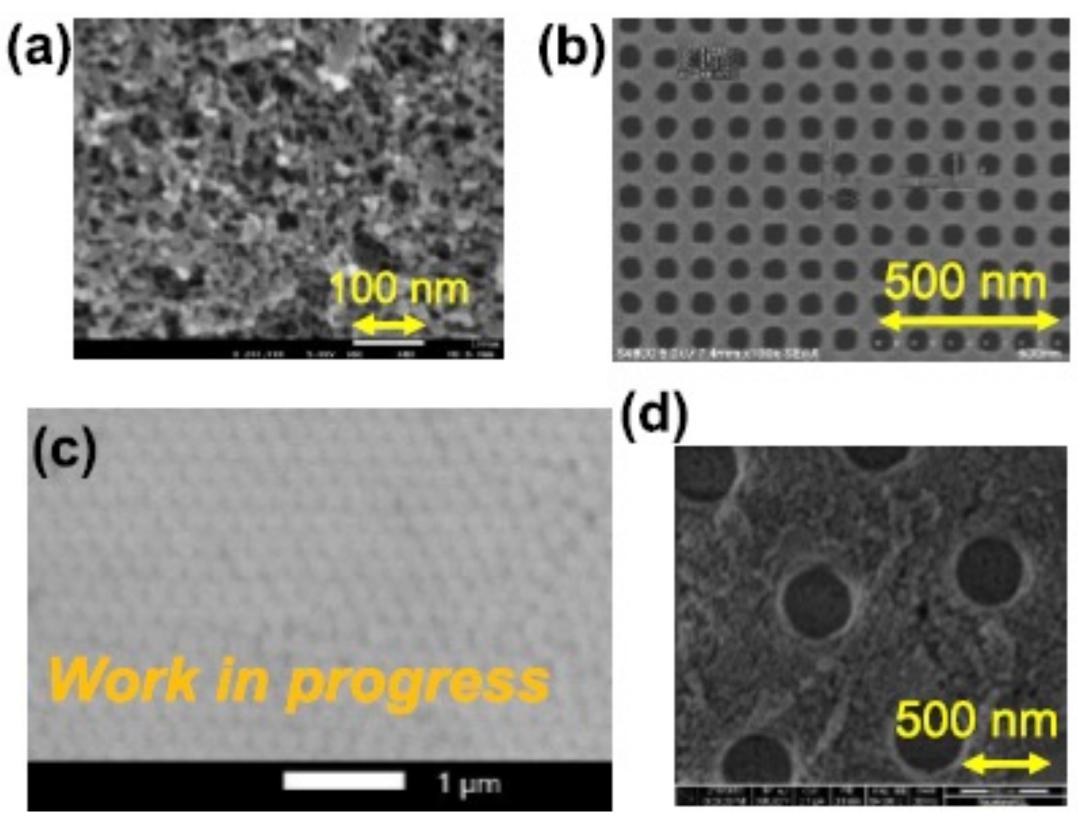
Recent progress in Positronium (Ps) laser cooling—aimed at achieving the Bose-Einstein Condensate (BEC) of Ps—utilizes oxide porous materials like silica (SiO2). These materials are efficient at producing Ps, yet a key challenge is the high energy of Ps generated on these bulk surfaces. Addressing this, porous materials with nano-vacancies have been employed for thermal cooling, but it is necessary to further reduce Ps energy to 0.1 eV or less for efficient Ps laser cooling [1]. Complementing these material advancements, we have integrated a 4K-GM cryocooler into the Ps time-of-flight (TOF) setup to clarify the effect of sample cooling. The expected outcomes include the development of materials for ultra-high-speed Ps laser cooling up to 10 K, below the Ps-BEC transition temperature. This advancement is set to enhance the precision of 1S-2S energy measurements and 1S hyperfine structure (HFS) measurements, contributing to antimatter gravity research and the potential for gamma-ray lasers using Ps-BEC.

Fig. 1



Drawing of the internal setup of the Ps-ToF experiment. The cryocooler is installed on the port to the left of the image and holds the silica aerogel sample [2].

Fig. 2



SEM photographs of silica nanomaterials. (a) Silica aerogel (b) Nanoprocessing (c) Silica nanoparticles (d) Nanoimprinting

Our project addresses the mystery of why the universe is dominated by matter, presenting challenges that extend beyond the Standard Model of particle physics. Key to solving these challenges is the precise measurement of antimatter gravity using positronium (Ps), a simple atom of an electron and its positron. This involves various experiments, such as measuring Ps-Earth gravity to test antimatter's weak equivalence principle and precisely measuring Ps energy levels to explore matter-antimatter asymmetry. Achieving accurate measurements requires cooling Ps to below 10 K, with laser cooling as a promising method [3].

The experiment utilizes a 4K-GM cryocooler for cooling the Ps-generating materials—silica aerogel in the present work—to test the feasibility of using a cryocooled sample for improving the rate of Ps thermalization. This is performed by measuring the flight time of the Ps emitted from the sample (Figure 1).

Our research seeks efficient Ps generation and emission materials, focusing on oxides like silica with nano-voids (Figure 2). These materials are analyzed to find the best candidates for Ps laser cooling experiments, aiming to optimize our Ps cooling laser system. Figure 3 shows the current setup of the sample holder attached to a cryocooler (shown attached to the experimental chamber in Figure 4) used in the most recent experiments.

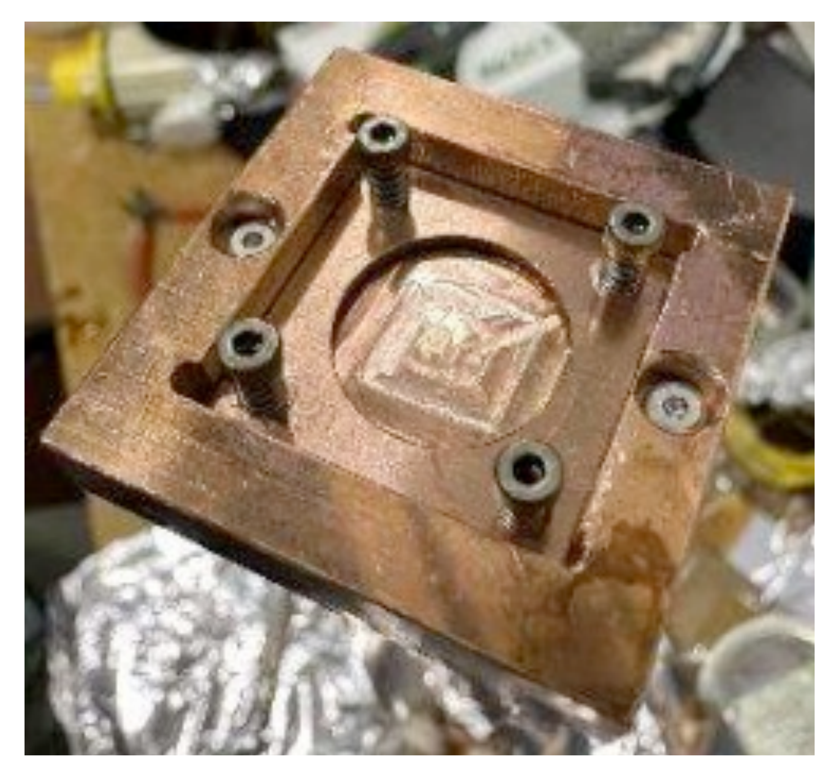


Fig. 3

The sample holder is fixed to the coldhead and contains the silica aerogel sample.

The project's goal is to advance materials that generate low-energy Ps efficiently, using porous materials to reduce Ps energy effectively. We plan to directly measure Ps generation and emission rates and energy distributions across various conditions, identifying the best materials for Ps laser cooling.

Ultimately, this work aims to establish ultrafast Ps laser cooling technology, enhancing precision in fundamental physics measurements and potentially opening new areas in antimatter gravity research. This advancement could significantly impact related fields, increasing the feasibility of Ps-BEC and gamma-ray lasers as future technologies.

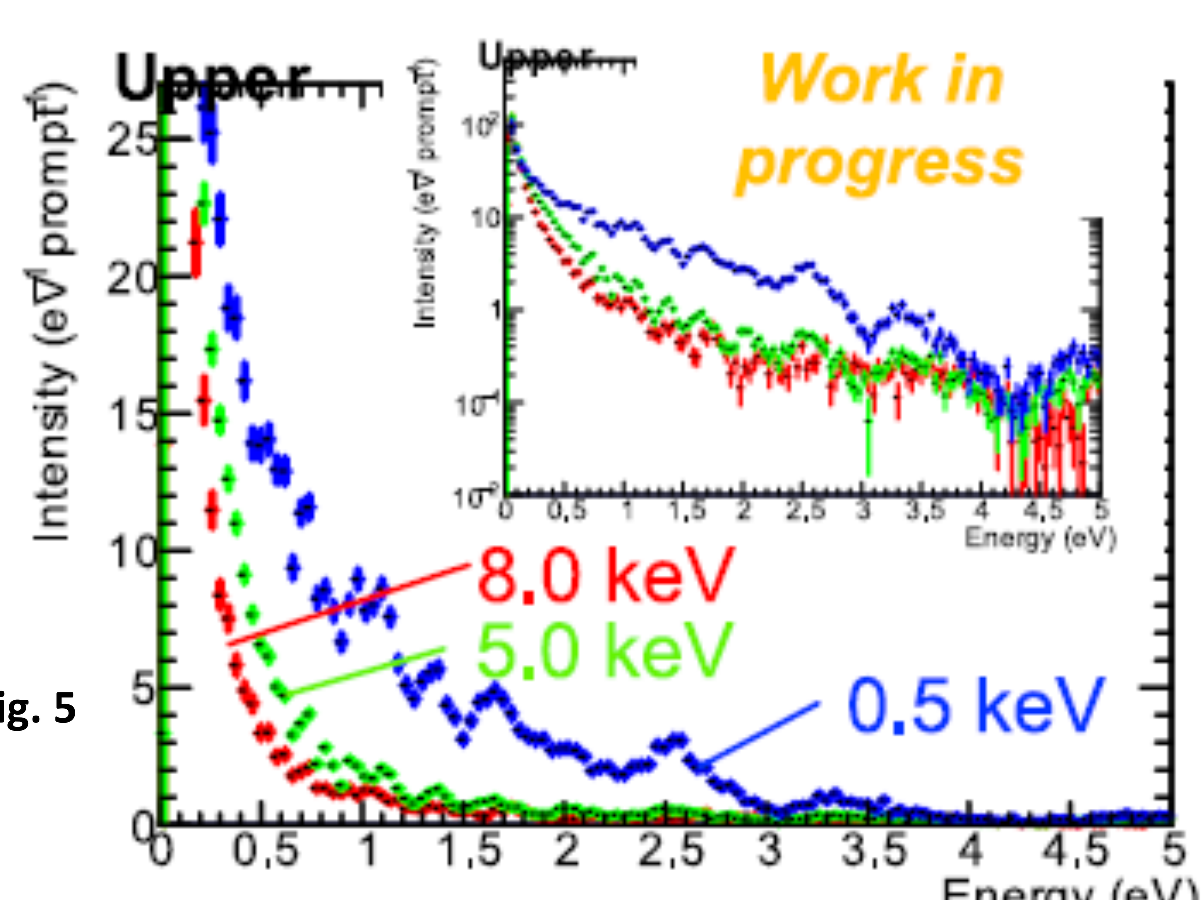


Fig. 5

Ps-TOF measurements on room temperature silica aerogel (from Ishida, et al., presented at the 2022 fall meeting of the Physical Society of Japan)

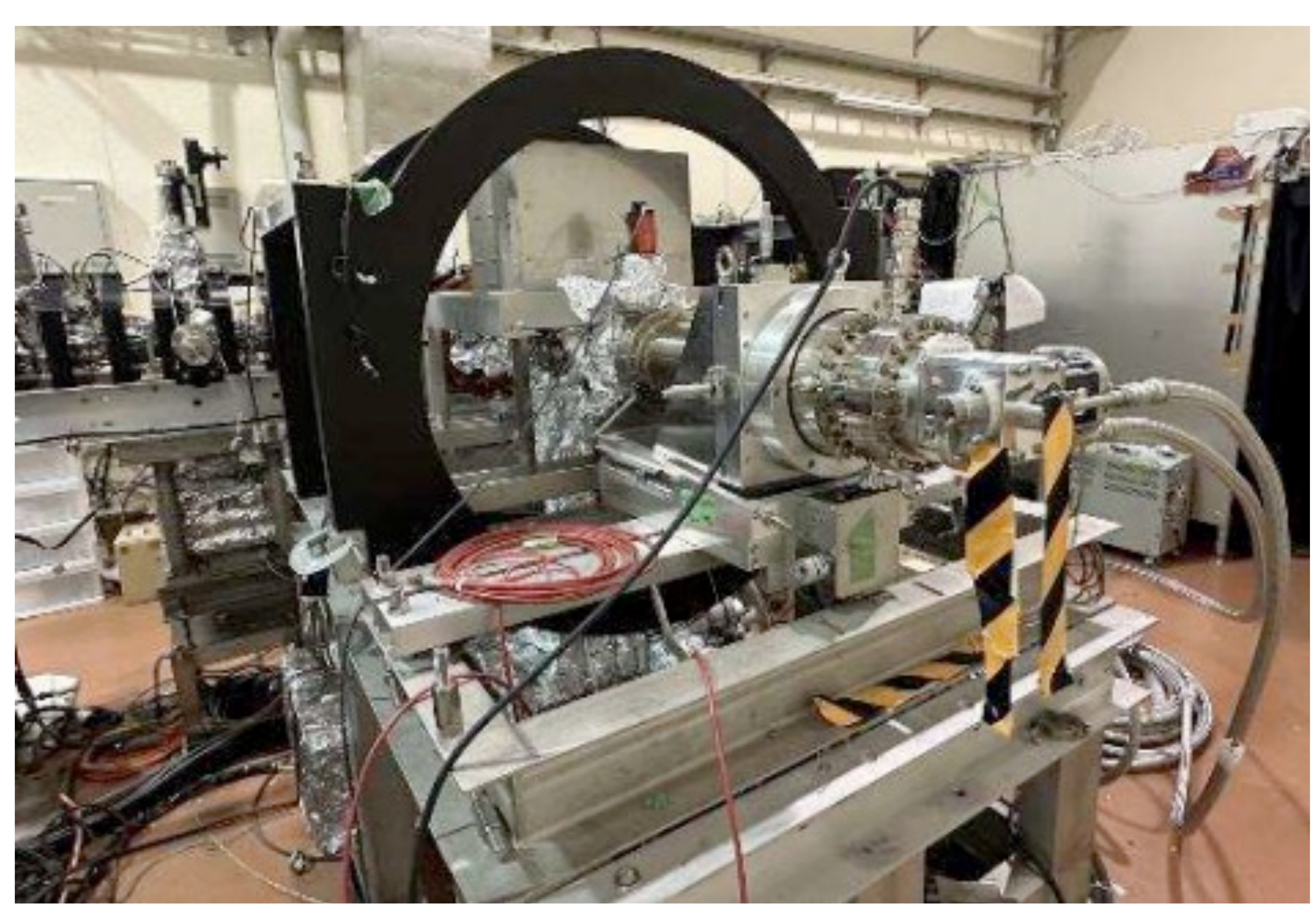


Fig. 4

The experimental setup at KEK-SPF. The cryocooler can be seen in the foreground of the image attached to the sample chamber.

References

[1] K. Shu et al.、 J. Phys. B: At. Mol. Opt. Phys. 49 (2016) 104001.
[2] S. Iida, K. Wada, I. Mochizuki, T. Tachibana, T. Yamashita, T. Hyodo and Y. Nagashima, J. Phys.: Condens. Matter 28 (2016) 475002.
[3] Shu, K., et al., Laser cooling of positronium. arXiv:2310.08761 (2023).

Acknowledgements

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