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EDITED BY
Andrea Bertoldi,
ParisTech Institut d'Optique Graduate School, France

REVIEWED BY
Nassim Zahzam,
Office National d'Études et de Recherches Aérospatiales, France
Guglielmo Tino,
University of Florence, Italy

*CORRESPONDENCE
Xuzong Chen,
xuzongchen@pku.edu.cn

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Deep cooling scheme of quantum degenerate gas and ground experimental verification for chinese space station

Hui Li[1], Jiachen Yu[1], Xiaolong Yuan[1], Biao Wu[1], Yu Xie[2], Lin Li[2], Angang Liang[2], Mingshan Huang[2], Shengjie Jin[1], Wei Xiong[1], Bin Wang[2], Dijun Chen[2], Tang Li[2], Xia Hou[2], Liang Liu[2], Xiaoji Zhou[1], Weibiao Chen[2] and Xuzong Chen[1]*

[1]Institute of Quantum Electronics, School of Electronics, Peking University, Beijing, China, [2]Aerospace Laser Engineering Department, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai, China

The Cold Atom Physics Rack (CAPR) of Chinese space station will be launched at the end of 2022. The important goal of CAPR is to achieve BEC at 100 pk. In order to obtain ultracold atoms in microgravity of space station, we propose a two-stage cooling scheme using all-optical trap with different waist beams. The cold atom cloud obtained by this scheme is composed of condensate and thermal atoms around condensate. The design of our two-stage cooling scheme will effectively reduce the temperature of the thermal atom cloud and the effective temperature generated by the interaction energy of the condensate. The atomic temperature of 5 nk is obtained from the ground test experiment, and the corresponding temperature under the microgravity condition of the space station is theoretically predicted to be less than 100 pk. Taking the advantages of ultracold temperature and long-time detection, many scientific experiments will be arranged. In this paper, the ground test experiments based on ground principle prototype and pre-prototype for CAPR are also introduced.

KEYWORDS

space station, cold atom physics rack, two-stage cooling, picokelvin, microgravity

Introduction

Ultra-low temperature has always been the tireless pursuit of scientists in the field of atomic and molecular physics since the beginning of the last century. The lower the atomic temperature, the more impetus and representative significance for the verification of many physical theories [1–3]. The sensitivity and accuracy of atomic interferometers, gravimeters, and gyroscopes can also achieve an order of magnitude leap in cooler degenerate gases [4–7]. In 1908, Kamerlingh Onnes produced liquid Helium, of which the temperature is below 4.2K [8]. In 1911, he found superconductivity in mercury at 4.1K [9]. The development of laser cooling overwrote the record to micro Kelvin [10, 11]. The success of Bose-Einstein Condensation (BEC) paves the way for lowering temperatures in nano-Kelvin [12–14], and adiabatic release of degenerate gases pushes the limit to sub-nanometer Kelvin [15]. Further atomic deep cooling is limited by gravity. Continuously reducing the depth of the potential well can theoretically obtain lower temperature trapped atoms, but the shallower potential well will not be able to resist the effect of the atom's own gravity, causing the atoms to leak out of the well, resulting in a substantial loss of the number of atoms and a decrease in the collision rate between atoms. Thus the evaporative cooling process tends to be ineffective.

Thanks to microgravity, degenerate atomic gases can be cooled to lower temperature than ever before. Germany, France, the United States and China have all carried out cold atom experiments under microgravity conditions. In the QUANTUS project in Germany, Rasel's research team used an atomic chip to realize BEC with atomic kinetic energy of 9 nk in the Bremen drop tower experiment in 2010 [16]. In 2013, they used delta-kick cooling (DKC) method to reduce the atomic temperature to about 1 nk and conducted interference experiments [17]. And in the German MAIUS-1 mission in 2018, they achieved a rubidium BEC of about 1 nk for a longer experimental time under the 6-min microgravity conditions created by the sounding rocket [18]. In France, Bouyer's research team created a microgravity environment by flying the parabolic plane in 2011, using a velocity-selective Raman light pulse carrying two counter-propagating laser fields and cooled the atoms to a temperature of 300 nK in the longitudinal velocity distribution and obtained an improvement in the sensitivity of the interferometer at 0 g [19]. The JPL team of NASA in the United States installed the Cold Atom Laboratory (CAL) experimental module on the International Space Station (ISS) in 2018, using the atom chip to conduct the deep cooling experiment of degenerate gas of rubidium and potassium [20–23]. One of the aim of the CAL is to break the limit of atomic temperature on the ground and realize ultra-low temperature of pK or even fK. Limited by the experimental system and mechanical vibration disturbances in the space station, the current cold atom temperature is on the order of 10 nK. China is scheduled to launch the space station experimental module by the end of 2022, which will be equipped with a Cold Atom Physics Rack (CAPR). The atomic deep cooling adopts the two-stage cooling (TSC) scheme proposed by Peking University [24–27]. In the first stage, atoms undergo the runaway evaporation cooling process in an optical trap formed by two crossed laser beams with narrow beam diameter and high power. In the second stage, low temperatures atoms are loaded into the other optical trap formed by two crossed laser beams with wide waist and weak power. The TSC scheme has been validated to effectively reduce the thermal atomic cloud temperature. The atomic temperature of 5 nk is obtained from the ground verification test, and it is theoretically predicted that the corresponding atomic temperature under the microgravity condition of the space station is less than 100 pk. The project for CAPR includes three stages: ground principle prototype, pre-prototype, formal prototype. We have achieved ground principle prototype, pre-prototype, and completed the test experiments based on pre-prototype.

This article firstly emphasizes the necessity of conducting ultra-cold atomic physics experiments in the microgravity environment. And then introduces the structure, modules, key technologies of ground principle prototype and pre-prototype, as well as ground test experiments for the CAPR on Chinese Space Station. The atomic deep cooling scheme of TSC is introduced through physical principles, theoretical simulation results, ground verification experiments, and the reduction of thermodynamic temperature. Finally, it is concluded that the space station ultra-cold atomic experiment using the two-stage cooling scheme is of great significance to the advancement of atomic and molecular physics research under the conditions of ultra-low temperature and long-term detection.

Cold atom physics rack of chinese space station

Currently, the main factor limiting further temperature reductions is the acceleration of earth's gravity. For DKC cooling and pulsed optical lattice momentum filter, the atoms cannot be trapped by the external potential field during the cooling process, otherwise the external potential field will heat the atomic gas. But the existence of gravitational acceleration will make the atoms leave off the optical trap in the direction of gravity. Therefore, the cooling of the atomic gas by these cooling technologies on the ground only reduces the momentum width of the atomic gas in some dimensions, but does not reduce the average kinetic energy of the atomic gas. Hence, the realization of microgravity conditions is crucial for the reduction of atomic temperature [28], and the long-term gravity-free gradient environment of the space station is very beneficial to the implementation of precise physical experiments.

Chinese space station has been launched in 2021, and the science module II is due to launch in late 2022 with the Cold Atom Physics Rack. The goal of CAPR is to achieve the quantum degenerate gas of picokelvin ultra-low temperature and conduct a series of scientific experiments for quantum simulations and precise verification of physical laws in microgravity conditions on the space station. The CAPR is based on the constraints of external mechanical, electrical, thermal, information, measurement and control resources. Due to the particularity of space station and rocket carrying, CAPR must be small in volume (1.5 cubic meters), light in weight (500 kg) and low in power consumption (1,000 W). There are five units in the miniaturized and highly integrated CAPR system: 1) Physics module; 2) Laser and optics module; 3) Electronics module; 4)

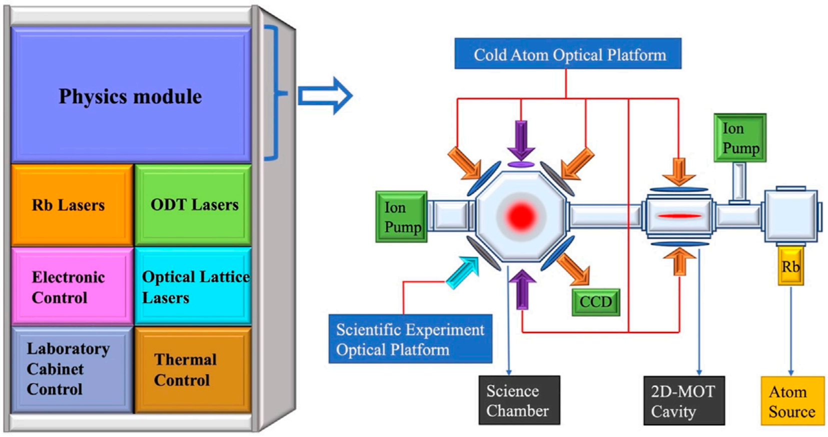

FIGURE 1
The structure of Cold Atom Physics Rack (CAPR) on the Chinese space station. There are five units in the miniaturized and highly integrated CAPR system: (1) Physics module; (2) Laser and optics module; (3) Electronics module; (4) Remote control module; (5) Rack support module.

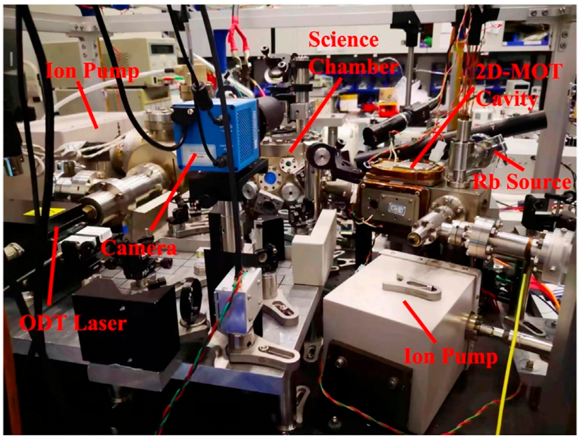

FIGURE 2
Ground principle prototype for CAPR. The purpose of the ground principle prototype is to verify that some technical solutions adopted on CAPR are available.

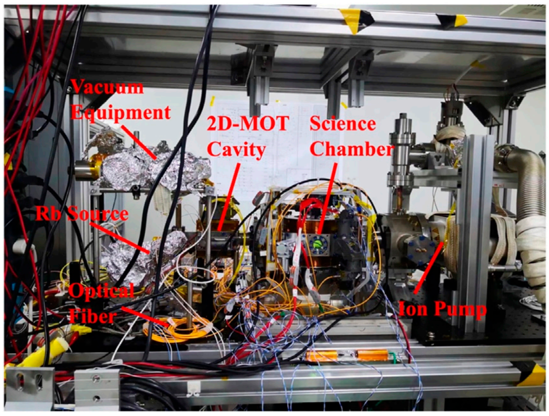

FIGURE 3
Pre-prototype for CAPR (2D-MOT and 3D-MOT parts). The size is almost same of the formal one. All laser transmissions on the pre-prototype use optical fiber, which is different from the space optical path transmission on the ground-based prototype. Various tests are also carried out on the pre-prototype to make reference and backup for the real launched one.

Remote control module; 5) Rack support module. As shown in Figure 1.

Our ground-based verification system for CAPR is a Rb quantum gas system for physical experiments in space microgravity. In order to achieve the goal of miniaturization and low power consumption in the space station, there are several key techniques in the process of preparing Bose-Einstein condensation. High frequency laser phase lock technology is used to produce a tunable frequency-stabilized laser to cool atoms. The tuning range is ±12 GHz (dynamic range 500 MHz). Optical phase lock loop (OPLL) avoids the larger volume and high power consumption of the traditional AOM complex optical path. The complex programmable logic device (CPLD) is used to replace the LabVIEW board card (not available in space) to realize the control of system time sequence. It is just a 10 cm × 10 cm circuit board programmed through a computer, which realize the switch control of shutter driver, AOM driver, magnetic coil driver, laser power variation curve of optical dipole trap, camera trigger and so on. And high current magnetic trap control technology enables a high-current coil to have a current of 500 A and a magnetic field of 600 Gs.

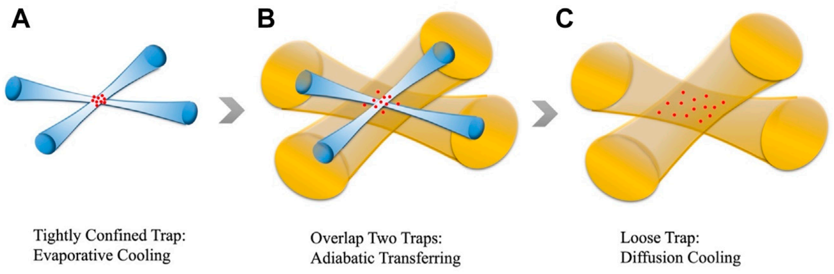

FIGURE 4
Schematic diagram of the experimental process of the two-stage cooling (TSC) scheme. **(A)** Atoms (red dots) trapped in the tightly confined optical dipole trap formed by two thin-waisted crossed beams for evaporative cooling. **(B)** Adiabatic transfer of atoms from the thin-waisted optical trap (blue beams) to the thick-waisted optical trap (yellow beams). **(C)** Atoms are diffusively cooled in the loose optical trap while decreasing the intensity of the thick-waisted beams. After decompression cooling process, the temperature of atoms below 1e-10K is expected to be achieved.

Ground test experiments was performed first from the ground principle prototype for CAPR (see Figure 2), which demonstrated that the principle of two-stage cooling is correct and some experimental techniques are available. The pre-prototype for CAPR (see Figure 3) adopts an all-optical scheme, which is almost identical to the launched one in the future. It needs to use the specified components available in aerospace. The following verification experiments were implemented on the pre-prototype. It tested that the techniques and approaches for two-stage cooling and the subsequent experiments are available for the CAPR in microgravity.

Compared with the Cold Atom Laboratory of the US International Space Station, which uses the atom chip and magnetic trap plus microwave cooling, the CAPR on Chinese space station adopts all-optical trap two-stage cooling scheme. Theoretical and ground-based experiments show that our scheme can obtain lower temperature. In addition, the CAPR system is developed to support the research of space ultracold atom physics and carry out quantum simulation experiments. Four fundamental physics experiments based on quantum gas will be implemented on Chinese space station in first 3 years: 1) Quantum Magnetism [29]; [30]; [31]; 2) Exotic material [32]; [33]; 3) Acoustic black hole [34]; 4) Efimov effect [35].

Two-stage cooling scheme

When directly applying evaporation cooling method [36–38] to break through to a lower temperature (pico-Kelvin), a major difficulty is that when the groups of atoms are cooled to a temperature of the order of nK, its internal collision rate per unit time will be greatly reduced. Such a low collision rate is not sufficient to maintain an effective evaporative cooling process. And the longer the cooling process continues, the more atomic number loss is caused by inelastic collisions. Therefore, how to introduce a more efficient mechanism so that the cooling can continue when the atomic gases enter the temperature of the order of nK is a key question. In order to ensure that the temperature of pK magnitude can be reached within an acceptable time, our experimental group proposed the two-stage cross beam cooling method in 2013 [24], and applied it to the ultra-cold atomic physics experiments on Chinese space station launched at the end of 2022.

Here, we deduce the feasibility of the two-stage cooling scheme from physical principles. Without regard to gravity, the potential of the crossed optical dipole trap can be expressed as

$$U(r) = \frac{U_0}{w^2}\left(2z^2 + x^2 + y^2\right) \tag{1}$$

Where w is the waist of the beams, U_0 is the optical trap depth. The far-detuned crossed laser beam traps are approximated as simple harmonic potential traps near the center of the trap. Then, U_0 can be described as

$$U_0 = \frac{3\pi c^2}{\omega_0^3}\frac{\Gamma}{\Delta}\frac{2P}{\pi w^2} = \alpha\frac{P}{w^2} \tag{2}$$

Where $\alpha = \frac{6\pi c^2 \Gamma}{\omega_0^3 \Delta\pi}$, c is the speed of light in vacuum, Γ is the atomic spontaneous emission rate, ω_0 is the atomic center transition frequency, Δ is the detuning difference between the optical dipole trap (ODT) laser frequency and the atomic resonance frequency, and P is the ODT laser power of a single beam.

Taking the x-direction as an example, the potential energy at the center of the simple harmonic trap can be written as

$$E_P(x) = \frac{1}{2}m\omega_x^2 x^2 = U(x) = \frac{U_0}{w^2}x^2 \tag{3}$$

Where m is the mass of the atom, ω_x is the harmonic frequency of the trap in the x direction. From Eqs. 2, 3, we can get trap frequency

$$\omega_x = \sqrt{\frac{2U_0}{mw^2}} = \sqrt{\frac{12c^2\Gamma}{\Delta\omega_0^3 m}}\ \frac{P^{1/2}}{w^2} \tag{4}$$

Similarly, the harmonic trap frequencies in the y and z directions are $\omega_y = \sqrt{\frac{2U_0}{mw^2}}$ and $\omega_z = 2\sqrt{\frac{U_0}{mw^2}}$, respectively.

The critical temperature of atoms is directly related to the potential trap frequency, which can be obtained from the following equation

$$k_B T_c \approx 0.94\hbar\bar{\omega}N^{1/3} \tag{5}$$

Where k_B is the Boltzmann constant, $\hbar = \frac{h}{2\pi}$ is the reduced Planck constant, $\bar{\omega} = (\omega_x\omega_y\omega_z)^{1/3}$ is the mean frequency of three-dimensional harmonic oscillatory traps, N is the number of atoms.

The relationship between the ground state atomic ratio and temperature is $\frac{T}{T_c} = (1 - \frac{N_0}{N})^{1/3}$, where T_c is the critical temperature and N_0 is the number of atoms in the ground state, or at the state of Bose-Einstein Condensation. From the above formulas, we can get the relationship between the temperature of atomic cloud and ODT laser power and waist width:

$$\begin{aligned} k_B T &= k_B T_c\left(1 - \frac{N_0}{N}\right)^{1/3} \\ &= 0.94\hbar\bar{\omega}(N - N_0)^{1/3} = 0.94\,\hbar\,(N - N_0)^{1/3}\sqrt{\frac{12c^2\Gamma}{\Delta\omega_0^3 m}}\ \frac{P^{1/2}}{w^2} \end{aligned} \tag{6}$$

From Eq. 6, we can get that the atomic temperature is proportional to the root square of the laser power and inversely proportional to the square of the beam waist size. The reduction of ODT laser power P corresponds to the well-known all-optical trap evaporative cooling. Since the exponent of w is larger than the exponent power of P, the effect of increasing the laser waist w on reducing the atomic temperature is more significant. When the laser power continues to decrease until the cooling effect of evaporative cooling is not obvious, increasing the beam waist size will further reduce the temperature of atomic cloud.

The experimental process of the two-stage cooling scheme is shown in Figure 4. First, the atoms of micro-Kelvin temperature are loaded into the tightly confined optical dipole trap formed by two thin-waisted crossed beams. Atoms undergo the runaway evaporation cooling process with decreasing laser intensity. In the first stage the atoms will be cooled to tens of nanokelvin temperature in about 5 s. Next, overlap the loose optical dipole trap consisting of a pair of thick-waisted intersecting beams. With the continuous weakening of the laser intensity of the thin-waisted optical trap and the continuous increase of the intensity of the thick-waisted optical trap, the atoms undergo adiabatic transfer in these two optical traps. Afterwards, continuously reducing the intensity of the thick-waisted beams, the atoms are diffusively cooled in the loose trap to the picokelvin temperature. A deeply cooled quantum degenerate gas is thus formed.

Ground experimental verification

In order to provide reference and verification for the space station experiment, we did a series of tests on the ground. Figure 5 shows the illustrations of experimental parameter settings for the TSC scheme in the ground verification experiments towards Chinese space station.

In the experiment, we used a pair of 1,064 nm far-detuned lasers with the waist radius of 30 μm to form an optical dipole trap, which trapped the ^{87}Rb atoms. The initial power of a single laser beam is 5 W, and the intensity is ramped down to 23 mW in 5,700 m by the exponential curve

$$P(t) = P_0\left(1 + \frac{t}{\tau}\right)^{-\beta}, \tag{7}$$

Where P_0 is the initial laser power, τ and β are the characteristic parameters associated with the ramping curve. This process reduces the depth of the optical dipole trap gradually in order to allow the atoms to undergo runaway evaporation cooling. After the atomic clouds are cooled in the thin-waisted optical trap in the first stage, the BEC with an atomic number of 6.75×10^4 and a temperature of 74 nk is formed (see Figure 6A). Then, the laser power of the thin-waisted optical trap is kept unchanged for the next 200 m, during which the thick-waisted optical trap laser is turned on for adiabatic loading to the maximum power of 200 mW and the waist width of each beam is 300 μm. At the same time, the lifting magnetic field is gradually turned on at this stage in order to counteract the effect of the gravitational field in the subsequent decompression cooling. After that, the laser power of the thin-waisted optical trap was gradually turned off, and the laser intensity is slowly decreased from 23 to 7 mW within 400 m. During this period, the thick-waisted optical trap first kept the laser power value unchanged for 50 m, and then reduced the laser power to 74 mW at the next 350 mW according to Eq. 7 by setting different parameters. In the meantime, after holding the value of the lifting magnetic field unchanged for 50 m, the gradient of the magnetic field is slowly decreased in a linear form for 300 m, and remains unchanged for the last 50 m. To minimize the effects of ground gravity, we use gradient magnetic fields to lift the atoms. But after many experiments, we found that when the second-stage potential well is shallow, the gradient magnetic field will heat the atoms. So in the later stage we gradually weaken the gradient of the magnetic field. At the end, after 20 m of TOF (time-of-flight), the equivalent temperature of BEC energy is measured to be 5 nk, and the number of ^{87}Rb atoms is 2.81×10^4. The image of BEC after deep cooling in the ground verification experiments are shown in the insert of Figure 7.

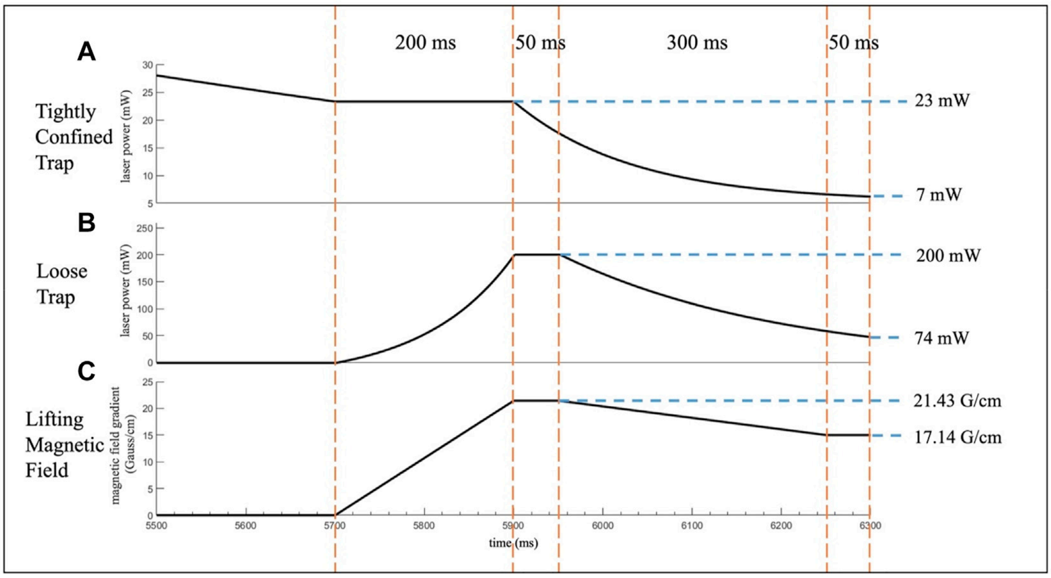

FIGURE 5
Experimental parameter settings for the two-stage cooling scheme in the ground verification experiments towards Chinese space station. Illustrations **(A,B)** show the variation of laser power with time for the thin-waisted ODT and the thick-waisted ODT, respectively, during the implementation of the TSC scheme. **(C)** The gradient of the lifting magnetic field (compensating for gravitational effects) changes as the experiment progresses.

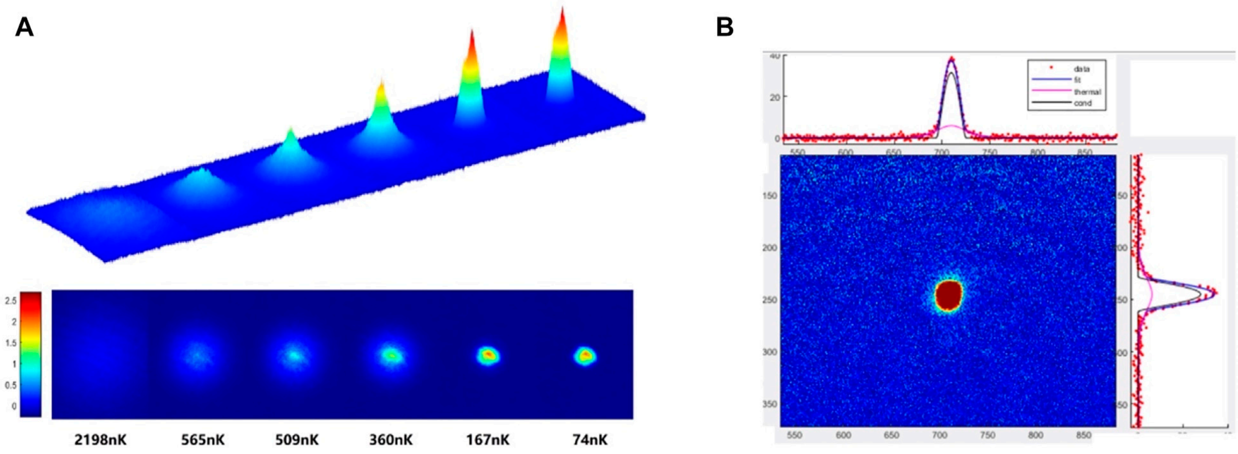

FIGURE 6
(A) First stage cooling with tight crossed beam trap. The temperature of BEC reached to 74 nK; **(B)** Second stage cooling with loose crossed beam trap. The temperature of BEC reached to 5 nK. Corresponding 100 pK in the microgravity.

Our group has previously performed multiple numerical simulations using the direct simulation Monte Carlo (DSMC) method [25, 39]. The simulation results theoretically confirm that the atomic temperature can be reduced to 100 pK when the TSC process is carried out for about 7.3 s in the microgravity on the space station [39]. This includes 5 s of evaporative cooling in the first stage and about 2.3 s of adiabatic diffusion cooling in the second stage. Simultaneously, the numerical simulation results show that if the CAPR on the Chinese space station are isolated from vibration, the temperature of quantum gas can be below

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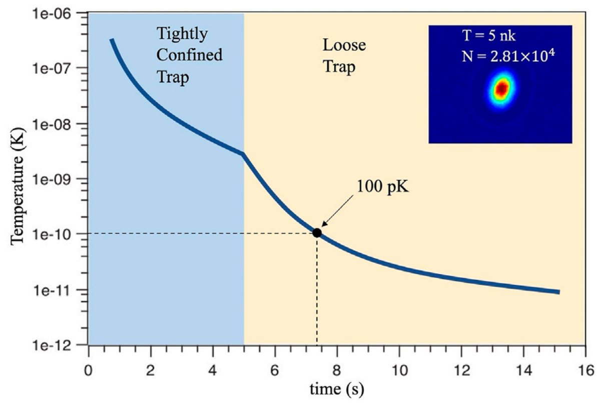

FIGURE 7
The schematic diagram of the numerical simulation results of TSC scheme. It is theoretically confirmed that the atomic temperature can be reduced to 100 pK when the TSC process is proceeded around 7.3 s in microgravity on the space station [39]. The insert shows the image of BEC after deep cooling in the ground verification experiments. The equivalent temperature of BEC is T = 5 pK and the number of ^{87}Rb atoms is $n = 2.81 \times 10^4$.

10 pK around 15 s [39]. The schematic diagram of simulation results of TSC scheme is shown in Figure 7.

Conclusion

Mankind is making continuous efforts in the pursuit of low temperature. From the preparation of liquid helium to cold atomic gases, the level of low temperature continued to improve from K (liquid helium) to 1×10^{-3} K (magneto-optical trap), 1×10^{-6}K (molasses), 1×10^{-9} K (quantum degenerate gas), and possibly even 1×10^{-12} K (deeply cooled quantum gas). Further cooling is a key area of competition. It has been widely recognized in the international physics community that ultra-cold atomic experiments in microgravity can achieve this goal. The purpose of the Cold Atom Physics Rack on Chinese space station is to achieve ultra-low temperature Bose-Einstein Condensation on the scale of pico-Kelvin (pK) and carry out a series of physical experiments. Two-stage cooling is proved to be a reliable and operational solution that can meet the requirements of physical experiments towards CAPR. Cold atoms of 5 nK on the ground have been obtained in verification experiments, and the equivalent temperature will be less than 100 pK in the microgravity environment of the space station in the future. Ultracold atoms in space are about to open up new avenues for quantum simulation and precision measurements.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

HL, JY, XY, BW, YX, LL, AL, MH, SJ, WX, BW, DC, TL, XH, LL, XZ, WC, and XC participated in the construction of prototypes. XC, WX, and WC directed the research. HL and BW performed the experiments and measured experimental data. LL, AL, MH, and SJ assisted the experiments. JY and XY contributed to the analysis of data. YX contributed to the numerical simulation. HL wrote the manuscript. XC revised the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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