Scientific experiments of ultra-cold atom and quantum simulation in Chinese Space station

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Outline

1. Introduction to the International Space Ultra-cold Atomic Physics Experiment

2. The scientific missions of the space station's ultra-cold atomic experiment rack

3. The experimental principle of obtaining 100pK temperature

4. Progress of ultra-cold atomic physics rack for Chinese space station

5. Scientific experiments in the ultra-cold atomic laboratory rack

6. Summary
China space station launch

Core module launch April 29, 2021
Core module launch in 2021, Science II module launch in 2022

Experiment module II, Fundamental Physics in microgravity, material science, fluid physics and combustion

SZ Manned spaceship: 2 launches each year

Experiment module I, Space life sciences and biotechnology, Material science.

Core module, Fluid Physics, material Science

Cargo Spaceship: 1 launch each year
Nearly 1,000 domestic experts in various fields have participated in the application task demonstration work.
The overall goal: to build a national-level space laboratory, and strive to make major breakthroughs in science and technology.

Space science research goals: In the key areas of frontier exploration of space science, we will obtain a number of major discoveries with international influence, enter the world's advanced ranks, and improve the overall level of space science in my country.
Scientific experiment platform planning

1. Life Ecological Experiment Platform
2. Biotechnology Experimental Platform
3. Online operation and cryogenic storage platform
4. Fluid physics experiment platform
5. Two-phase system experiment platform
6. Combustion experiment platform
7. High-temperature material science experiment platform
8. Non-container material experiment platform
9. Ultra-cold atomic physics experiment platform
10. High-precision time-frequency system
11. High and microgravity experiment platform
12. Variable gravity experimental platform
13. Modular general experiment platform
14. Science popularization youth scientific experiment platform
Science Capsule II will be launched in 2022
NASA’s Cold Atom Laboratory to Create ‘Coolest Spot in Universe’

Mar 8, 2017 by News Staff / Source

Published in
Featured
Physics
Space Exploration

Tagged as
Bose-Einstein condensate
Cold Atom Laboratory
Dark energy
International Space Station
Matter
NASA

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You Might Like
Extraterrestrials May Be More Like Us than We Think, Say Biologists
Cometary Ice and Organics are Mostly Older than

2018–5–20 launch
Couchbase Server® 5.0
The Database Redefined.

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CAL, developed by NASA’s Jet Propulsion Laboratory (JPL), is in the final stages of assembly, ahead of a ride to space this August on SpaceX CRS-12.

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- At super-low temperatures, atoms behave in surprising ways.
- NASA has never before created or observed this behavior in space.
- A Nobel Prize winner and other scientists will conduct experiments on this behavior using new technology.
- This technology might one day lead to improved sensors, quantum computers, and atomic clocks used in spacecraft navigation.

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Artist’s concept of a magneto-optical trap and atom chip to be used by NASA’s Cold Atom Laboratory aboard the International Space Station. CAL will provide an opportunity to study ultra-cold quantum gases in the microgravity environment of the space station—a frontier in scientific research that is expected to reveal interesting and novel quantum phenomena. Image credit: NASA / JPL-Caltech.
CAL1 5 Flight Investigations and Minor Facility Modifications Needed by PIs

- Zero-G Studies of Few and Many Body Physics (PI E. Cornell)
  - How complexity of the universe evolves from subatomic scale
  - Incorporation of Potassium 39 and a fast tuning magnetic field into CAL instrument
- Atom interferometry will pave the way for definitive space-based tests of Einstein’s Theory of General Relativity (PI N. Bigelow, Co-PI W. Ketterle, Co-I W. Phillips)
  - Holy grail of theoretical physics probing deep into Planck-scale physics
  - Incorporation of Bragg scattering beam for two species atom interferometry

- Microgravity dynamics of bubble-geometry Bose-Einstein condensates (PI Nathan Lundblad)
- Fundamental Interactions for Atom Interferometry with Ultracold Quantum Gases in a Microgravity Environment (PI Jason Williams)
- Development of Atom Interferometry Experiments for the International Space Station's Cold Atom Laboratory (PI Cass Sackett)
CAL (Cold Atom Laboratory) — Design and implementation
CAL Mission Overview

1. Science Definition
   Sept 2012
2. Development
   2012-2017
3. Delivery
   Apr 2017
4. Target Launch
   Aug 2017
5. Mission Operations
   Aug 2017-2020

- **Sequence Control with Ground via TDRSS**
- **Data to MSFC via White Sands**
- **Launch in Pressurized Cargo Vehicle in soft stowage**
- **Docking with ISS**
- **Crew installation into Express Rack**
- **Pressurized Cargo Vehicle: Space-X13**
- **36 month science operations phase ORUs for Mission Life and Science Upgrades**

- **TDRSS**
- **ISS**

- **Science Operations Team at NASA/JPL**

- **Images of equipment and personnel**
Observation of Bose–Einstein condensates in an Earth-orbiting research lab

Quantum mechanics governs the microscopic world, where low mass and momentum...
ESA Space Cold Atom Experiment
MAIUS(I) Rocket - University of Hannover, Germany - January 23, 2017

Atom chip
QUANTUS I – $^{87}$Rb BEC, DKC & Al in $\mu$g

- $10^4$ atoms of $^{87}$Rb
- DKC to $\sim 1$ nK
- asymmetric Mach-Zehnder interferometer

[Physik Journal 05/2013; Müntinga et al., PRL 110, 093602 (2013)]
Fiber laser solution
## Comparison of space cold atom platforms in four countries:

<table>
<thead>
<tr>
<th>Country</th>
<th>United States</th>
<th>Germany</th>
<th>France</th>
<th>China</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Platform</strong></td>
<td>Space station</td>
<td>Drop Tower\Rocket</td>
<td>Parabolic plane</td>
<td>Space station</td>
</tr>
<tr>
<td><strong>Potential well</strong></td>
<td>Atomic chip</td>
<td>Atomic chip</td>
<td>Three-dimensional optical trap</td>
<td>Three-dimensional optical trap</td>
</tr>
<tr>
<td><strong>$^{87}$Rb atomic number</strong></td>
<td>$2 \times 10^5$</td>
<td>QuantusI: $1 \times 10^4$, QuantusII: $4 \times 10^5$</td>
<td>$5 \times 10^5$</td>
<td>$1 \times 10^5$</td>
</tr>
<tr>
<td><strong>$^{41}$K atomic number</strong></td>
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<td></td>
<td></td>
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<tr>
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<td></td>
<td>$1 \times 10^4$</td>
<td></td>
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<tr>
<td><strong>$^{39}$K atomic number</strong></td>
<td></td>
<td></td>
<td>$5 \times 10^4$</td>
<td></td>
</tr>
<tr>
<td><strong>Temperature</strong></td>
<td>100pK</td>
<td>10nK</td>
<td>300nK</td>
<td>100pK</td>
</tr>
<tr>
<td><strong>lifetime</strong></td>
<td>10s</td>
<td>3s</td>
<td>3s</td>
<td>10s</td>
</tr>
<tr>
<td><strong>Deep cooling method</strong></td>
<td>Delta kick cooling</td>
<td>Delta kick cooling</td>
<td>optical trap evaporative cooling</td>
<td>Two-stage cooling</td>
</tr>
<tr>
<td><strong>wavelength</strong></td>
<td>852nm</td>
<td></td>
<td></td>
<td>1064nm</td>
</tr>
<tr>
<td><strong>Dimension</strong></td>
<td>Three-dimensional</td>
<td>None</td>
<td>None</td>
<td>Three-dimensional</td>
</tr>
<tr>
<td><strong>well depth</strong></td>
<td>0-10Er</td>
<td></td>
<td></td>
<td>0-30Er</td>
</tr>
<tr>
<td><strong>Bias magnetic field</strong></td>
<td>0-235Gauss</td>
<td>None</td>
<td>None</td>
<td>0-600Gauss</td>
</tr>
<tr>
<td><strong>Imaging resolution</strong></td>
<td>2um</td>
<td>7um</td>
<td>7um</td>
<td>5.4um</td>
</tr>
<tr>
<td><strong>Degenerate gas preparation</strong></td>
<td>Achieve BEC and Fermi degeneration in the micro-magnetic trap of the atom chip</td>
<td>Obtain $^{87}$Rb, $^{41}$K quantum degenerate gas in the atomic chip micro magnetic trap</td>
<td>Obtain $^{87}$Rb, $^{39}$K quantum degenerate gas in the optical trap</td>
<td>Obtain $^{87}$Rb, $^{39}$K quantum degenerate gas in the optical trap</td>
</tr>
<tr>
<td><strong>Degenerate gas type</strong></td>
<td>Bose-Fermi Mix</td>
<td>Double Bose Deg. Gas</td>
<td>Double Bose Deg. Gas</td>
<td>Bose-Fermi Mix</td>
</tr>
</tbody>
</table>
1. Introduction to the International Space Ultra-cold Atomic Physics Experiment

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6. Summary
China Space Station—Ultra-cold Atomic Physics Experiment Platform
Ultra-cold Atomic Physics Platform Project

The establishment of the ultra-cold atomic physics platform will carry out research on world-class problems and is expected to achieve major basic scientific breakthroughs.

Four types of challenging experiments can be carried out:

I. Quantum states of matter: (1) Ideal quantum gas statistical physics; (2) Quantum magnetism; (3) Quantum new states of matter; (4) Heteronuclear polarized molecules;

II. Celestial body simulation: (5) Acoustic black hole; (6) Bose explosion

III. Quantum computing: (6) Quantum topology;

IV. Frontier exploration category: (7) Quantum measurement theory test; (8) The relationship between quantum mechanics and gravity; (9) Standard model test.
Advantages for Cold Atom Physics in Space

• Low temperature: $10^{-12}$ K (pK, 0.0000000000000K), three order lower than on the earth (nK)

Absolute temp.: 0K=−273.15°C

Room temp.: 300K=26.85°C

• Longer observation time (20s), three order longer than on the earth (20ms),
• Space uniform, no gravity potential.
The Nobel Prize in Physics 1997
"for development of methods to cool and trap atoms with laser light"

Steven Chu
Claude Cohen-Tannoudji
William D. Phillips

Laser cooling

The Nobel Prize in Physics 2001
"for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates"

Eric A. Cornell
Wolfgang Ketterle
Carl E. Wieman

Bose-Einstein Condensation

The Nobel Prize in Physics 2005
"for his contribution to the quantum theory of optical coherence"
"for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique"

Roy J. Glauber
John L. Hall
Theodor W. Hänsch

Precision Measurement based on cold atom

The Nobel Prize in Physics 2012
Serge Haroche, David J. Wineland

Serge Haroche
David J. Wineland

Quantum Manipulation based on cold atom
1. Introduction to the International Space Ultra-cold Atomic Physics Experiment

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6. Summary
Cooling Roadmap for Cooling of Matter

- Surface of sun
  - H.K. Onnes, 1908, 1919

- Liquid Nitrogen
  - Bardeen, 1950, 1972

- Liquid $^4$He, superfluidity, superconductivity
  - D. Lee et al., 1970, 1996

- $^3$He superfluidity, Doppler cooling, MOT
  - S. Chu et al., 1980, 1997

- Sisyphus cooling
  - Cornel, et al., 1995, 2001

- Subrecoil cooling, evaporative cooling, BEC

- Space station
## Comparison of cooling methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Material</th>
<th>Principle</th>
<th>Loading Method</th>
<th>Speed</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser cooling</td>
<td>Gas: atoms and molecules</td>
<td>Laser radiation pressure</td>
<td>Magnetic field + laser</td>
<td>Fast</td>
<td>$10^{-6}$ K µK</td>
</tr>
<tr>
<td>Evaporative cooling</td>
<td>Gas: atom and molecule</td>
<td>Evaporation + collision</td>
<td>Magneto-optical or laser</td>
<td>Fast</td>
<td>$10^{-9}$ K nK</td>
</tr>
<tr>
<td>Cryogenic cooling</td>
<td>Liquid, solid</td>
<td>Collision, Container loading</td>
<td>Container loading</td>
<td>Slow</td>
<td>$10^{-3}$ K mK</td>
</tr>
</tbody>
</table>
Doppler laser cooling
Principle for laser cooling

absorption: $\hbar \omega + K v = \hbar \omega_0$

emission: $\hbar \omega_0$

The frequency of absorbing photons: $\omega$

Less than

The frequency of photons radiated by atoms: $\omega_0$
The laser cools the temperature of atoms down.

The momentum change of one photon absorbed by an atom:

\[ \Delta Mv = \hbar k \]

Atomic momentum change:

\[ \Delta \nu = \frac{\hbar k}{M} \approx 3\text{cm/s} \]

Spontaneous emission rate:

\[ \Gamma = 10^8 / \text{s} \]
Laser cooling: high-efficiency cooling

Acceleration:

\[ a = \frac{\Delta v}{\tau} \]
\[ = \frac{3 \times 10^{-2}}{10^{-8}} \]
\[ = 3 \times 10^6 \text{ m/s}^2 \]
\[ = 3 \times 10^5 \text{ g} \]

From 300K to 300uK
Decrease by 6 orders of magnitude!

Cool the speed of the atom from 1000m/s to 0,
It takes 300,000 jumps and only 3ms!

Actual temperature: 100\( \mu \text{K} \)–0.0001K
Evaporative cooling
Principle of evaporative cooling:

Traditional evaporative cooling technology

Bose-Einstein Condensation (BEC)
Forced evaporative cooling
Bose-Einstein Condensation (BEC)

Temperature up to 50 nanoKelvin

$-0.000000005k$
Bose-Einstein Condensation

Atoms and molecules

\[
 n(\varepsilon) = \frac{1}{e^{\frac{\varepsilon - \mu}{k_B T}} - 1}
\]

Black-Body Radiation

“Photons”

Predication in 1924, Bose and Einstein

1995

Max Planck

Satyendra Nath Bose
The fifth state of matter

De Broglie wavelength

$$\lambda_{dB} = \frac{h}{\sqrt{2\pi MK_B T}}$$

Some very cold atoms

$T > T_c, \lambda_D < \lambda_a$

Some atoms in a BEC condensate

$T < T_c, \lambda_D > \lambda_a$
The effect of gravity on temperature

\[ E = -mgz + \frac{1}{2} m \omega^2 z^2 \]
Phase transition temperature:

\[ T_c = 0.94 \frac{\hbar}{k} \omega N^{1/3} = \omega (nk) \]

Critical temperature in different traps

\[ \omega = 100\text{Hz}, \quad T_c = 100nk \quad \text{ground} \]
\[ \omega = 0.001\text{Hz}, \quad T_c = 1pK \quad \text{space} \]

Collision rate:

\[ r \propto \omega \]

\[ T_c \to pK \quad \text{needs 1000s} \]
Two-stage evaporative cooling (TSC) theory in microgravity environment

The emergence of picokelvin physics, Xuzong Chen and Bo Fan, Rep. Prog. Phys. 83, 076401 (31pp), (2020)
Break through the ground limit and get a theoretical prediction of pK-level temperature

(A) The relationship between rubidium 87 atomic gas temperature and time

(b) The relationship between rubidium 87 atomic number and time

Within 15 seconds, the atom can theoretically be cooled to 7pK
Cooling methods in Germany and the United States: pulse impulse cooling

DKC (Delta Kick cooling), (DKC)


QUANTUS $^87$Rb BEC, DKC & Al in $\mu$g

- $10^4$ atoms of $^87$Rb
- DKC to $\sim 1$ nK
- asymmetric Mach-Zehnder interferometer

[Physik Journal 05/2013; Müntinga et al., PRL 110, 093602 (2013)]
Simulation comparison of two cooling methods in microgravity environment

TSC cooling method and pulse impulse cooling method (DKC) comparison

<table>
<thead>
<tr>
<th>物理量</th>
<th>TSCBC</th>
<th>DKC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{fb}$</td>
<td>7pK</td>
<td>75pK</td>
</tr>
<tr>
<td>$t_{fb}$</td>
<td>10s</td>
<td>0.1s</td>
</tr>
<tr>
<td>$r_{fb}$</td>
<td>300μm</td>
<td>100μm</td>
</tr>
<tr>
<td>PSD$_{fb}$</td>
<td>3.70</td>
<td>3.57</td>
</tr>
<tr>
<td>$(\Delta P/P)_{fb}$</td>
<td>$10^{-3}$</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>$T_k$</td>
<td>51.2</td>
<td>388</td>
</tr>
<tr>
<td>$t_g$</td>
<td>10s</td>
<td>5s</td>
</tr>
</tbody>
</table>

- It can be preliminarily drawn that, compared with the two cooling methods, the two-step cross-cooling method can obtain a lower temperature of 7pK (pulse impact method 75pK), but the pulse impact method requires a shorter time for continuous preparation of cold atoms, about 5.1s (two-step cross cooling for 15s).
Analysis of the influence of gravity on two cooling methods

<table>
<thead>
<tr>
<th>g</th>
<th>$10^0$</th>
<th>$10^{-1}$</th>
<th>$10^{-2}$</th>
<th>$10^{-3}$</th>
<th>$10^{-4}$</th>
<th>$10^{-5}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>5.2nk</td>
<td>770pK</td>
<td>91pK</td>
<td>25pK</td>
<td>7.2pK</td>
<td>7pK</td>
</tr>
</tbody>
</table>

The influence of gravity on two-stage optical trap evaporative cooling (TSCBC)

<table>
<thead>
<tr>
<th>g</th>
<th>$10^0$</th>
<th>$10^{-1}$</th>
<th>$10^{-2}$</th>
<th>$10^{-3}$</th>
<th>$10^{-4}$</th>
<th>$10^{-5}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>112nK</td>
<td>14nK</td>
<td>2.2nK</td>
<td>601pK</td>
<td>76pK</td>
<td>70pK</td>
</tr>
</tbody>
</table>

The effect of gravity on pulse impact cooling (DKC)

The yellow highlight is the gravitational condition for two methods to reach a temperature of the order of 100pK.

Comparison of different techniques in optical trap for generating picokelvin 3D atom cloud in microgravity, Hepeng Yao, Tian Luan, Chen Li, Yin Zhang, Zhaoyuan Ma, Xuzong Chen, *Optics Communications*, 359 (2016) 123–128
Ground cooling experiment verification system

System composition:
- vacuum
- Ion pump
- Imaging system
- Atomic source
- Two-dimensional magneto-optical trap
- Magnetic field coil
- Scientific chamber
Evaporative cooling experiment program

Two Stage Cross Beam Cooling, TSCBC

Luminous flux diameter: 60um, wavelength: 1064nm.

Luminous flux diameter: 3mm, wavelength: 1064nm
**Principle prototype preparation degenerate gas results**

- **750nK**
  - $N=5.85 \times 10^5$
  - $T=750nK$
  - $\eta=0\%$
  - $PSD=9.13 \times 10^{-2}$

- **390nK**
  - $N=5.09 \times 10^5$
  - $T=390nK$
  - $\eta=16\%$
  - $PSD=4.88 \times 10^{-1}$

- **190nK**
  - $N=2.5 \times 10^5$
  - $T=190nK$
  - $\eta=51\%$
  - $PSD=6.34 \times 10^{-1}$

- **75nK**
  - $N=2 \times 10^5$
  - $T=75nK$
  - $\eta=78\%$
  - $PSD=1.5 \times 10^{0}$

---

**全光阱**

87Rb

原子

BEC

的制备

Principle prototype preparation degenerate gas results
Experimental design of cooling of two-stage optical well on the ground

Limitation analysis of evaporative cooling on the ground

The side effects of magnetic suspension balance gravity

\[ U_B(x, y, z) = \mu_B B'_z \sqrt{\frac{x^2}{4} + \frac{y^2}{4} + \left(z - \frac{B_z}{B'_z}\right)^2} \]

The compensate magnetic field compensates for the limitation of lateral binding

\[ \omega_x = \omega_y = \sqrt{\frac{\partial^2 U_B(x, y, z)/\partial x^2}{m}} \]

\[ = \frac{B'^2_z}{4mB_z} \]

Limitation of magnetic field noise

\[ \mu_B \Delta B = 1 \text{Er} = \frac{h^2 k^2}{2m} \]

\[ \Delta B \approx 10 \text{ mG} \]

\[ \Delta T \approx 3 \text{ nK} \]

\[ \omega_0 \approx 700 \text{ Hz} \]

The magnetic field noise has a great influence!
Results for two stages cooling


1. Levitation: using gradient magnetic field
   30.5G/cm for |1,-1>
2. Adiabatic expansion of optical trap
(1) after trap being turned off:

- $\omega^2 t_1 t_2 = 1$
- $t_1 t_2 = 1/\omega^2 = 1/(4\pi^2 \times 10 \times 10)$

- 0.01Hz T=7pK $t_1 = 10s$ $t_2 = 20s$
- 0.1Hz T=0.07nK $t_1 = 1s$ $t_2 = 2s$
- 1Hz T=0.7nK $t_1 = 100ms$ $t_2 = 200ms$
- 10Hz T=7nK $t_1 = 10ms$ $t_2 = 20ms$
- 100Hz T=70nK $t_1 = 1ms$ $t_2 = 2ms$
- 1000Hz T=700nK $t_1 = 0.1ms$ $t_2 = 0.2ms$
- 10000Hz T=7uK $t_1 = 10us$ $t_2 = 20us$
- 100000Hz T=70uK $t_1 = 1us$ $t_2 = 2us$

\[ \omega^2 t_1 t_2 = 1 \]
\[ v = 0 \]
Ground pulse impulse cooling test results

- 温度测量结果：
  \( t_1 = 9 \text{ ms}, 33.6\text{nK} \)
  \( t_1 = 29 \text{ ms}, 23.3\text{nK} \)
Experimental results of ground DKC

The results of Delta kick cooling (DKC) are as follows

Temperature measurement

$t_1=9\text{ ms, }33.6\text{nK}$

$t_1=29\text{ ms, }23.3\text{nK}$
The new challenge of space station cooling: the impact of vibration on cooling
Deep cooling technology under spatial vibration conditions

- The method of this numerical simulation adopts the "direct Monte Carlo simulation" or DSMC method.
- The DSMC method is derived from the numerical simulation of fluid problems and is usually used in aeronautical engineering. It can handle the dynamic evolution of large particle systems. We use this method to simulate the cooling process of the boson ultra-cold gas system until the quantum phase transition occurs.
- This numerical simulation can give key physical parameters such as temperature, particle number, number density, phase space density, etc. of the total cooling process.
- The impact of mechanical vibration is a typical forced vibration problem, which specifically belongs to Base exited Forced Vibration.
- We study the cooling problem under single-frequency continuous vibration. Second, study the vibration problem under the vibration acceleration spectrum of the International Space Station.
Numerical simulation of vibration heating process

\[ E \sim \left( \frac{a}{\omega} \right)^2 \]

\[ A(\mu m) \]

\[ f(\text{Hz}) \]

\[ f(\text{Hz}) \]

\[ \text{Temperature (\degree K)} \]

\[ \text{Time (s)} \]
Numerical simulation of vibration heating process

(a) final temperatures

(b) final number of atoms

<table>
<thead>
<tr>
<th>频率 (Hz)</th>
<th>概率 (%) @1X</th>
<th>概率 (%) @0.1X</th>
<th>概率 (%) @0.01X</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1 ~ 0.9</td>
<td>27</td>
<td>29</td>
<td>22</td>
</tr>
<tr>
<td>1 ~ 10</td>
<td>27</td>
<td>21</td>
<td>7</td>
</tr>
<tr>
<td>11 ~ 20</td>
<td>27</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>21 ~ 30</td>
<td>27</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>31 ~ 40</td>
<td>25</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>41 ~ 50</td>
<td>10</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>51 ~ 60</td>
<td>11</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>61 ~ 70</td>
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<td>1</td>
<td>0</td>
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<tr>
<td>71 ~ 80</td>
<td>6</td>
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<td>0</td>
</tr>
<tr>
<td>81 ~ 90</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>91 ~ 100</td>
<td>7</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>101 ~ 200</td>
<td>&lt;2</td>
<td>&lt;2</td>
<td>0</td>
</tr>
</tbody>
</table>

a ‘1X’ 为国际空间站 (ISS) 振动谱
b ‘0.1X’ 为 0.1 倍的国际空间站 (ISS) 振动谱
c ‘0.01X’ 为 0.01 倍的国际空间站 (ISS) 振动谱
Numerical simulation of vibration heating process

(a) 5Hz振动，0.157×10^3个原子；(b) 65 Hz振动，1.369×10^5个原子，温度为T = 29 nK的BEC；
Outline

1. Introduction to the International Space Ultra-cold Atomic Physics Experiment

2. The scientific goals of the space station's ultra-cold atomic experiment rack

3. The experimental principle of obtaining 100pK temperature

4. Progress of ultra-cold atomic experiment rack for space station

5. Scientific experiments in the ultra-cold atomic laboratory rack

6. Summary
Peking University is an institution of scientific PI, one of the pioneers of cold atom in China.
Magneto-Optical Trap of Cesium Atoms *

GAN Jian-hua, LI Yi-min, CHEN Xu-zong, LIU Hai-feng†,
YANG Dong-hai, WANG Yi-qiu
Department of Electronics, Peking University, Beijing 100871
†Permanent address: Shaanxi Astronomical Observatory,
Chinese Academy of Sciences, Lintong 710600

(Received 24 April 1996)

We have trapped a cold sample of cesium atoms in a magneto-optical trap. The damped harmonic force of magneto-optical trap was used to capture and trap the cesium atoms directly from

PHYSICAL REVIEW A 73, 013624 (2006)

Population oscillation of the multicomponent spinor Bose-Einstein condensate induced by nonadiabatic transitions

Xiuquan Ma, Lin Xia, Fang Yang, Xiaoji Zhou, Yiqiu Wang, Hong Guo,* and Xuzong Chen†
Key Laboratory for Quantum Information and Measurements, Ministry of Education, School of Electronics Engineering and Computer Science, Peking University, Beijing 100871, Peoples Republic of China
(Received 1 October 2005; published 24 January 2006)

The generation of the population oscillation of the multicomponent spinor Bose-Einstein condensate is demonstrated in this paper. We observe and examine the nonsynchronous decreasing processes of the magnetic fields generated between quadrupole coils and Ioffe coils during the switch-off of the quadrupole-Ioffe-configuration trap, which is considered to induce a nonadiabatic transition. Starting from the two-level

First cesium MOT in china

First atom laser and first BEC paper published in international journal in china
Ground prototype of space ultra-cold atomic experiment system

**Experimental System-B**

- Normal working vacuum pressure: <3X10⁻⁹Pa
- Experiment content:
  - Rubidium atom degenerate gas experiment, potassium atom degenerate gas experiment, ground scientific experiment verification, vacuum holding experiment without power supply
Prototype of space ultra-cold atomic experiment system

Nobel Prize winner Wolfgang Ketterle visited the prototype of the space ultra-cold atomic experiment system
August 3, 2016
Shanghai Institute of Optics and Fine Mechanics is institution of Project PI, the pioneer of cold atom in china
First laser cooling paper and temperature lower than Doppler limit

Evidence for a Bose–Einstein Condensate in Dilute Rb Gas by Absorption Image in a Quadrupole and Ioffe Configuration Trap

WANG Yu-Zhu, ZHOU Shu-Yu, LONG Quan, ZHOU Shan-Yu, FU Hai-Xiang
Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800

(Received 21 February 2003)
Introduction of ultra-cold atomic experiment rack

- **Advance**: to ensure that the space ultra-cold atomic platform established represents the international advanced level and meets the goals of forward-looking scientific experiments.

- **Safety**: Fully consider the safety of the space station and the safety of astronauts;

- **Scalability**: The platform adopts a modular design, the size of each module meets the specifications of the experimental cabinet, and the communication and power supply adopt the standard of the experimental cabinet, which is versatile and expandable, and is easier to replace and upgrade to meet the needs of future space science experiments.
System composition of ultra-cold atomic physics rack (CAPR)

Ultra-cold atomic experiment cabinet

Ultra-cold atomic physics experiment platform

Physical subsystem

Experimental electronics

Laser light source

Supporting system

Laboratory cabinet electronics

Experimental cabinet thermal control

Experiment cabinet

System composition of ultra-cold atomic physics rack (CAPR)
Physical Unit

- NEXTtoor ND500-5
- Agilent 20L ION PUMP
- ST171*8 B Shelter
- Science Chamber 2D-MOT
- GAMMA 3L ION PUMP
- Atomic source
- Microwave source
- Optical platform
Test of the system by the team of Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, and Peking University
Key technology (1): all-fiber laser technology
Key technology (2): high frequency laser phase lock technology

- In the process of laser cooling atoms, a tunable frequency-stabilized laser is required.
- Traditional AOM + Double Pass method: complex optical path, large volume, high power consumption.
- The new system uses beat frequency locking.
- The circuit is realized based on CPLD: highly integrated, PCB area is only 6cm × 6cm.
- The beat frequency signal line width is 22MHz, and the lock frequency is set to red detune 6.57GHz.
- The frequency lock and phase lock modules cooperate with each other to complete the laser lock, and the lock line width is 10MHz.
- Tuning range ±12GHz, dynamic range 500MHz.
Key technology (3): laser power stabilization and laser phase lock

\[ \phi = 0 \]

\[ \phi = \pi \]
Key technology (4): CPLD/FPGA control circuit

CPLD/FPGA
Control block diagram

- Shutter Driver
- AOM Driver
- Magnetic Coil Driver
- DAC
- DDS
- Camera Trigger

- Magnetic Coil for Precooling Chamber
  - Guide Coil
  - Compensate Coil
- Magnetic Coil for Science Chamber
  - Optical Dipole Trap
- RF Coil
- Laser Frequency

Computer → CPLD main control board → CPLD main control board → ... → Vacuum Chamber
Key technology (5): high current magnetic trap control technology

磁场：600Gs
电流：500A
A three-dimensional light lattice can be formed by adding a third pair of lights in the vertical direction.
(6) The key technology of scientific experiment: optical lattice technology
1. Introduction to the International Space Ultra-cold Atomic Physics Experiment

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Famous scientific experiments on the International Space Station —— Measurement of critical phase transition characteristics of $^4$He between the space station and the ground

$$\hat{H} = \sum_i \left[ -\frac{\hbar^2}{2m_i} \Delta_i + U_i(z) + V_i(x, y, z) \right]$$

$^4$He superfluid lambda transition in earth gravity


$^4$He superfluid lambda transition in microgravity in ISS

Wilson proposed the renormalization group theory:

- Consider the fluctuations in the phase change region
- Remove the high-energy mode integrals, leaving the low-energy mode

The critical exponents obtained by the renormalization group method agree well with the experiments!

\[ Z = \int D[\phi] e^{-S_{\Lambda_0} - S_1} = \int D[\phi^-] \int D[\phi^+] e^{-S_{\Lambda_0} - S_1} \]

\[ S_{\Lambda_0} [\phi] = \frac{1}{2} \int_{\vec{k}} \left[ r_0 + c_0 \vec{k}^2 \right] \phi(-\vec{k}) \phi(\vec{k}) \]

\[ S_1 = \frac{n_0}{4!} \int_{\vec{k}_1} \int_{\vec{k}_4} \delta(\vec{k}_1 + \ldots + \vec{k}_4) \phi(\vec{k}_1) \phi(\vec{k}_2) \phi(\vec{k}_3) \phi(\vec{k}_4) \]

Cutoff

\[ |\vec{k}| < \Lambda_0 \]

\[ \xi = e^l \]
The critical index of critical behavior is compared with experimental results.

### TABLE I. Comparison of predicted and observed values of universal quantities near the lambda point.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Predicted</th>
<th>Reference</th>
<th>Observed</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>$-0.01126\pm0.0010$</td>
<td>7</td>
<td>$\sim-0.022\pm0.006$</td>
<td>15, 16, 17</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>$-0.0146\pm0.0008$</td>
<td>8</td>
<td>$-0.0105\pm0.00038$</td>
<td>10, 11</td>
</tr>
<tr>
<td>$\xi$</td>
<td>0.67155\pm0.00027</td>
<td>8</td>
<td>0.6705\pm0.0006</td>
<td>18</td>
</tr>
<tr>
<td>$3\xi+\alpha-2$</td>
<td>0(exact)</td>
<td>20</td>
<td>$-0.0012\pm0.0027$</td>
<td>5, 18</td>
</tr>
<tr>
<td>$\Delta$</td>
<td>0.529\pm0.009</td>
<td>25</td>
<td>0.5\pm0.1</td>
<td>22</td>
</tr>
<tr>
<td>$P$</td>
<td>4.433\pm0.077</td>
<td>9</td>
<td>4.2\pm0.1</td>
<td>23</td>
</tr>
<tr>
<td>$a_c^+/a_c^-$</td>
<td>1.6\pm1.0</td>
<td>24</td>
<td>1.0\pm0.3</td>
<td>23</td>
</tr>
<tr>
<td>$a_c^-/\alpha a$</td>
<td>3.4\pm0.1</td>
<td>24</td>
<td>4.1\pm0.2</td>
<td>23</td>
</tr>
</tbody>
</table>

\[
C_p \sim |t|^{-\alpha} \quad \xi \sim |t|^{-\nu} \quad t = \frac{T-T_c}{T_c}
\]

\[
\alpha = \frac{1}{2} - \frac{3\tau}{10} - 0.1297777778\tau^2 - 0.039547352\tau^3 - 0.02432025\tau^4 - 0.00324983\tau^5 - 0.0121092\tau^6
\]

PHYSICAL REVIEW B 68, 174518 (2003)
Comparison of He\(^4\) and Bose gas

(1) Multi-body interaction system
(2) H4 Bose system, H3 Fermi system,
(3) 87Rb Bose, 40K Fermi system;
(4) superfluid T<Tc
(5) \(\lambda\) phase change
(6) critical temperature: Tc;
Quantum simulation experiments based on ultra-cold atoms optical lattices

2001 Nobel Prize winner Wolfgang Ketterle: "Quantum simulation of quantum gases in optical lattices can help people understand the properties of matter on a larger scale. Usually, the distance between atoms is on the order of nanometers. On the order of micrometers, this makes it easier to prepare and observe microscopic substances."

Application prospects: precision quantum measurement, quantum sensors, quantum computers, quantum multi-body physics

Optical lattices

- Control geometric configuration: potential barrier $V(r)$
- Control microscopic parameters: $J$, $U$
- Clean: no impurities, no phonons
- Ingredients: Fermi, Bose, Molecule

Theoretical model

$$\hat{H}_{\text{model}} = -J \sum_{\text{link}} \hat{a}^\dagger_j \hat{a}_j + 1 + U \sum_{\text{sites}} \hat{a}^\dagger_j \hat{a}^\dagger_j \hat{a}_j \hat{a}_j + \text{ingredient} \ldots$$

Lattice

- High temperature superconductor
- Graphene
- Topological insulators
- Topological superfluid
- Weir Semimetal
Quantum simulation

(1) Multi-body system;  
(2) Periodic  
(3) Bose-Hubbard model

\[ \hat{H} = -J \sum_{\langle i,j \rangle} \hat{a}_i^\dagger \hat{a}_j + \sum_i \varepsilon_i \hat{a}_i^\dagger \hat{a}_i + \frac{1}{2} U \sum_i \hat{a}_i^\dagger \hat{a}_i \hat{a}_i \hat{a}_i \]

\[ = -J \sum_{\langle i,j \rangle} \hat{a}_i^\dagger \hat{a}_j + \sum_i (\varepsilon_i - \mu) \hat{n}_i + \frac{1}{2} U \sum_i \hat{n}_i (\hat{n}_i - 1) \]
Optical lattice and quantum simulation

**Bose-Hubbard Model: SF-MI transition**

- **1998**: P. Zoller (Innsbruck)
- **2002**: I. Bloch (Max Planck)
- **2010**: S. Kuhr (Strathclyde)
- **2010**: M. Reiner (Harvard)

Science (2010)

**Fermi-Hubbard Model: Antiferomagnetism**

\[
\hat{H} = -J \sum_{\langle i, j \rangle \sigma} \hat{c}^\dagger_{i \sigma} \hat{c}_{j \sigma} + U \sum_i \hat{n}_{i \uparrow} \hat{n}_{i \downarrow} - \mu \sum_i \hat{n}_i
\]


- **2015**: R. G. Hulet (Rice University)
- **2016**: M. Zwierlein (MIT)

**KT- transition**

- **1972**: D. J. Thouless (Univ of Washington)
- **1972**: J. M. Kosterlitz (Brown Univ)
- **2006**: Jean Dalibard (COF)


**Haldane Model**

\[
\hat{H} = \sum_{\langle i, j \rangle} t_{ij} \hat{c}^\dagger_{i \uparrow} \hat{c}_{j \uparrow} + \sum_{\langle\langle ij \rangle\rangle} e^{\delta_{ij}} t_{ij} \hat{c}^\dagger_{i \downarrow} \hat{c}_{j \downarrow} + \Delta_{AB} \sum_{\langle i \in A \rangle} \hat{c}^\dagger_{i \uparrow} \hat{c}_j
\]

Nature (2014)

- **1988**: D. Haldane (Princeton)
- **2014**: T. Esslinger (ETH)
6.2 Quantum simulations, and artificial states of matter

In our discussion of the KT phase transition, we stressed universality, meaning that the same model Hamiltonian describes critical phenomena in very different physical systems. This universality is however to a very small critical region in the vicinity of the transition temperature. There is however another strategy that allows the use of the same Hamiltonian for different systems in wider parameter ranges. The basic idea goes back to Feynman, who pointed out that one could hope to solve very hard quantum problems by designing a quantum simulator.

Such a simulator is itself a quantum system with many degrees of freedom, but it should be well controlled and designed to embody the important aspects of the physical system one is attempting to simulate. More precisely, this means having the correct degrees of freedom and the correct interactions. Cold atomic gases have turned out to provide a perfect platform for obtaining this [11]. An important tool in these experiments is the optical lattices that are formed as an interference pattern by intersecting laser beams.

An example of this is the observation of the KT-transition in a layered Bose-Einstein condensate of $^{87}\text{Rb}$ atoms. At low temperatures one observes coherence effects characteristic of the phase with power law correlations, and at higher temperatures one sees free vortices [20].

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Scientific Background on the Nobel Prize in Physics 2016

TOPLOGICAL PHASE TRANSITIONS AND TOPOLOGICAL PHASES OF MATTER

compiled by the Class for Physics of the Royal Swedish Academy of Sciences

In a 2014 experiment, the group led by Immanuel Bloch managed to design a lattice with topologically non-trivial bands, similar to the ones studied in the famous paper by Thouless et al. [51]. These bands were then populated by a gas of cold bosonic $^{87}\text{Rb}$ atoms, and using an intricate measuring procedure, they could experimentally determine the Chern number for the lowest band to $C_1^{\text{exp}} = 0.99(5)$ [3].

Also in 2014, the group led by Tilman Esslinger made an experiment with cold $^{40}\text{K}$ atoms in an optical lattice to simulate the precise model proposed by Haldane in 1988 [29]. This shows that reality sometimes surpasses dreams. At the end of his paper Haldane wrote: “While the particular model presented here, is unlikely to be directly physically realizable, it indicates …”. What he could not imagine was that 25 years later, new experimental techniques would make it possible to create an artificial state of matter that would indeed provide that “unlikely” realization.

---

The Nobel Prize in Physics 2016

David J. Thouless
Prize share: 1/2

F. Duncan M. Haldane
Prize share: 1/4

J. Michael Kosterlitz
Prize share: 1/4
Advantages of space quantum simulation platform

Bose–Hubble Model

\[ H = -J \sum_{\langle ij \rangle} a_i^\dagger a_j + \frac{U}{2} \sum_i n_i(n_i - 1) + \sum_i W_i n_i \]

(1) Theoretical simulation of the Bose Hubble model
(2) Gutzwiller mean field theory;
(3) Quantum model Carlo simulation;
(4) Calculation of renormalization group.

Ultra-low temperature provides new possibilities for precision quantum simulation
Advantages of space quantum simulation platform

Low temperature: 100pK, long observation time: 10s.

Review

The emergence of picokelvin physics

Xuzong Chen and Bo Fan

Institute of Quantum Electronics, Department of Electronics, School of Electronics Engineering and Computer Science, Peking University, Beijing 100871, People’s Republic of China

E-mail: xuzongchen@pku.edu.cn

Table 2. Parameters with relative energy (temperature).a

<table>
<thead>
<tr>
<th>Optical trap depth $U_0$</th>
<th>10$E_r$</th>
<th>15$E_r$</th>
<th>20$E_r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T$ (tunneling)</td>
<td>0.02$E_r = 2.2 k_B$ nK</td>
<td>0.007$E_r = 0.7 k_B$ nK</td>
<td>0.003$E_r = 0.3 k_B$ nK</td>
</tr>
<tr>
<td>$U$ (interaction)</td>
<td>0.28$E_r = 27 k_B$ nK</td>
<td>0.38$E_r = 37 k_B$ nK</td>
<td>0.47$E_r = 46 k_B$ nK</td>
</tr>
<tr>
<td>$J = \frac{42}{\Delta}$ (tunneling in Heisenberg model)</td>
<td>0.007$E_r = 0.7 k_B$ nK</td>
<td>$5.8 \times 10^{-4}$ $E_r = 0.056 k_B$ nK</td>
<td>$6.6 \times 10^{-5}$ $E_r = 0.006 k_B$ nK</td>
</tr>
</tbody>
</table>
Advantages of space quantum simulation platform

Higgs Mode disappears, $T>J$

5.8 to 15 nK

Provides a new way for quantum simulation precision measurement
Experiments for construction period

- **Quantum simulation category:**
  - Quantum magnetism \((^87\text{Rb})\);
  - Quantum new state of matter \((^87\text{Rb})\);
  - Effimov effect \((^87\text{Rb}+^{40}\text{K})\);

- **Black hole exploration category:**
  - Acoustic black hole \((^87\text{Rb})\).

After two and three rounds of discussions, the four scientific experiment schemes, key technology design, optical path design, timing design, and acceptance of experimental results were basically determined, and the input conditions for the four experiments were determined together with the Shanghai Institute of Optics and Mechanics.
Experiment 1: Quantum Magnetism

Liu Wuming, Institute of Physics, Chinese Academy of Sciences

https://physics.aps.org/articles/v11/131
Experiment 2: Novel Quantum State

Zhou Xiaoji, Peking University,

https://www.nature.com/articles/nmat4604, Genevieve Martin, Oak Ridge National Laboratory
Kagome lattice magnetic quantum simulation

![Graphical representation of the Kagome lattice and related quantum simulation concepts.](image_url)
Experiment 3: Acoustic Black Hole

Lv Baolong, Wuhan Institute of Precision Measurement Science and Technology Innovation, CAS

The creation of acoustic black holes
Experiment 4: Efimov effect

Zhou Shuyu, Shanghai Institute of Precision Optics and Mechanics,

Rb–K heteronuclear Effimov effect
On-orbit experiment

Four types of experiments are planned (January 2023–December 2032): (1) Quantum simulation; (2) Quantum new state of matter; (3) Test of basic physical theories; (4) Dark matter, Higgs model Wait for measurement.

- The first category: quantum simulation
  - Highly excited state new optical lattice phase transition (87Rb)
  - Quantum Hall effect on the “Haldane sphere” of cold atoms in space (87Rb)
  - Research on Super Solid State and Topological Super Solid State (87Rb)
  - Quantum simulation of spin polarization induced by chiral structure (87Rb)
  - Three-dimensional Anderson localization (87Rb)

- The second category: quantum state of matter
  - Preparation and detection of Majorana fermions in cold 40K atoms (40K)
  - Deep degeneracy of ultra-cold Bose–Fermi mixed gas (87Rb+40K)
  - Study on Excitation Properties of Cold Atomic Element under Special Shape External Potential (87Rb)
  - Excellent fluid physics research under microgravity conditions: shock waves and turbulence under quantum viscous forces (87Rb)
The third category: precise examination of physical theories

- The precise inspection of the renormalization group of the ideal optical lattice quantum phase transition (87Rb)
- Research and application of one-dimensional quantum system under microgravity conditions (Yang-Bax equation test) (87Rb)
- Test General Relativity Based on the Gravitational Electromagnetic Effect of Space Cold Atoms (87Rb)

The fourth category: dark matter, Higgs mode, etc. measurement

- Develop coherent matter wave optics and interferometer (measurement of dark matter gauge field and density distribution) in a microgravity environment (87Rb)
- Ideal optical lattice Higgs-type excitation measurement (87Rb)
- pK BEC interferometer (UFF/WEP test) (87Rb)
- Quantum simulation based on complex cold atom optical lattice and its microgravity precision measurement (derived gauge field in curved space and its physical effects) (87Rb)
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6. Summary
Conclusion

- Excellent ultra-cold atomic physics experiments require extreme conditions of microgravity, and the space ultra-cold atomic experiment cabinet will become an ideal platform to provide such extreme conditions.
- Space ultra-cold atomic physics is an important result of the combination of basic research and aerospace engineering, and it is also a good opportunity for the simultaneous development of Chinese aerospace science and technology with the world's aerospace science and technology.
- The ultra-cold atomic physics experimental platform is currently the most complex scientific research system on the space station. The successful development has played an important role in promoting the development of Chinese aerospace science and ultra-cold atomic physics.
- The team of scientists in China’s ultra-cold atomic physics experiments has matured and will show our important role in the future international ultra-cold atomic physics and space science experiments.
Thanks to colleagues of Shanghai Institute of Optics and Fine Mechanics, CAS,

Thank the colleagues of the cold atom science for space,

Thank all the friends of the world for their support!

http://iqenew.pku.edu.cn