中国科学院大学
University of Chinese Academy of Sciences

探索里德堡原子：从量子干涉到精密微波场测量

贾凤东
中国科学院大学

2026.6.14

大纲

- 电磁感应透明（EIT）
- 里德堡原子
- 基于里德堡原子的电场测量
- 开源程序 RydIQule
- 里德堡激发的实验技术
- 我们在精密微波场测量中的几项工作

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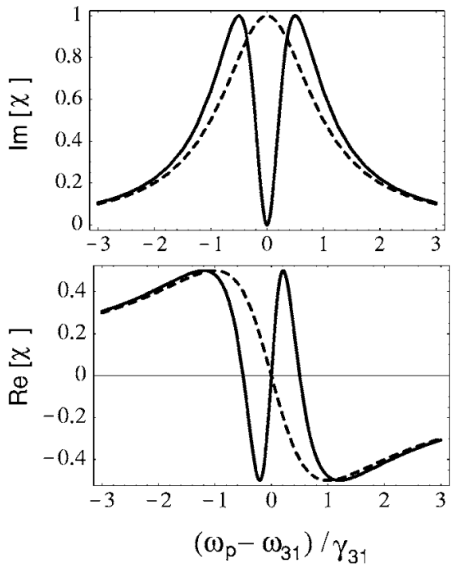
什么是 EIT?

激发路径之间的干涉

Rev. Mod. Phys. 77, 633 (2005).



吸收

折射

FIG. 1. Susceptibility as a function of the frequency ω_p of the applied field relative to the atomic resonance frequency ω_{31}, for a radiatively broadened two-level system with radiative width γ_{31} (dashed line) and an EIT system with resonant coupling field (solid line): top, imaginary part of $\chi^{(1)}$ characterizing absorption; bottom, real part of $\chi^{(1)}$ determining the refractive properties of the medium.

1. |1> → |3>
2. |1> → |3> → |2> → |3>

Λ 型

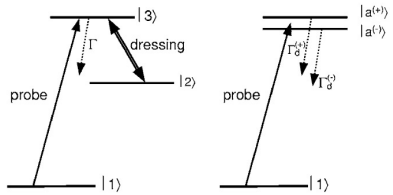


FIG. 4. Interference generated by coherent coupling: left, coherent coupling of a metastable state |2⟩ to an excited state |3⟩ by the dressing laser generates (right) interference of excitation pathways through the doublet of dressed states $|a^{\pm}\rangle$ (Autler-Townes doublet) provided the decay out of state |2⟩ is negligible compared to that of state |3⟩.

左为阶梯型，右为 V 型

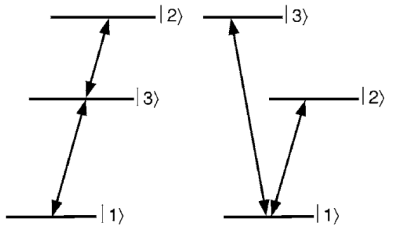


FIG. 6. Ladder (left) and vee-type (right) three-level schemes. These do not show EIT in the strict sense because of the absence of a (meta)stable dark state.

EIT 的重要性在于，它在介质感应透明的光谱区域产生显著增强的非线性极化率，并伴随陡峭色散。

什么是 EIT?

三能级 Λ 型原子的暗态

Λ 型

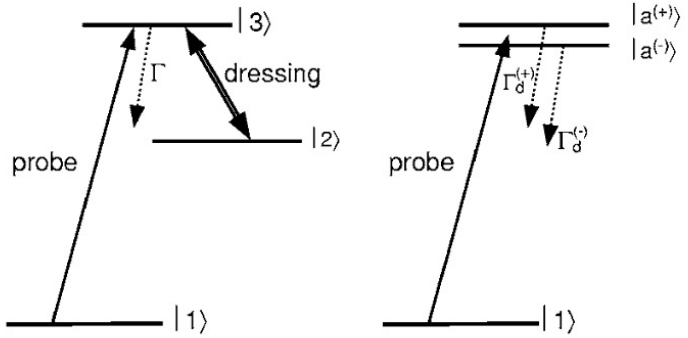


FIG. 4. Interference generated by coherent coupling: left, coherent coupling of a metastable state $|2\rangle$ to an excited state $|3\rangle$ by the dressing laser generates (right) interference of excitation pathways through the doublet of dressed states $|a^{\pm}\rangle$ (Autler-Townes doublet) provided the decay out of state $|2\rangle$ is negligible compared to that of state $|3\rangle$.

$$H_{int} = -\frac{\hbar}{2}\begin{bmatrix} 0 & 0 & \Omega_p \\ 0 & -2(\Delta_1 - \Delta_2) & \Omega_c \\ \Omega_p & \Omega_c & -2\Delta_1 \end{bmatrix}$$

$$\tan\theta = \frac{\Omega_p}{\Omega_c},$$

$$\tan 2\phi = \frac{\sqrt{\Omega_p^2 + \Omega_c^2}}{\Delta}.$$

$$|a^+\rangle = \sin\theta\sin\phi|1\rangle + \cos\phi|3\rangle + \cos\theta\sin\phi|2\rangle,$$

$$|a^0\rangle = \cos\theta|1\rangle - \sin\theta|2\rangle,$$

$$|a^-\rangle = \sin\theta\cos\phi|1\rangle - \sin\phi|3\rangle + \cos\theta\cos\phi|2\rangle.$$

$$\hbar\omega^{\pm} = \frac{\hbar}{2}(\Delta \pm \sqrt{\Delta^2 + \Omega_p^2 + \Omega_c^2}).$$

Rev. Mod. Phys. 77, 633 (2005).

什么是 EIT?

原子动力学与光学响应

$$H_{\text{int}} = -\frac{\hbar}{2}[\Omega_p(t)\hat{\sigma}_{31}e^{i\Delta_1 t} + \Omega_c(t)\hat{\sigma}_{32}e^{i\Delta_2 t} + \text{H.c.}],$$

$$\frac{d\rho}{dt} = \frac{1}{i\hbar}[H_{\text{int}},\rho] + \frac{\Gamma_{31}}{2}[2\hat{\sigma}_{13}\rho\hat{\sigma}_{31} - \hat{\sigma}_{33}\rho - \rho\hat{\sigma}_{33}]$$
$$+ \frac{\Gamma_{32}}{2}[2\hat{\sigma}_{23}\rho\hat{\sigma}_{32} - \hat{\sigma}_{33}\rho - \rho\hat{\sigma}_{33}]$$
$$+ \frac{\gamma_{2\text{deph}}}{2}[2\hat{\sigma}_{22}\rho\hat{\sigma}_{22} - \hat{\sigma}_{22}\rho - \rho\hat{\sigma}_{22}]$$
$$+ \frac{\gamma_{3\text{deph}}}{2}[2\hat{\sigma}_{33}\rho\hat{\sigma}_{33} - \hat{\sigma}_{33}\rho - \rho\hat{\sigma}_{33}],$$

$$\vec{P}(t) = -\sum_i \langle e\boldsymbol{r}_i\rangle/V$$
$$= \frac{N_{\text{atom}}}{V}[\boldsymbol{\mu}_{13}\rho_{31}e^{-i\omega_{31}t} + \boldsymbol{\mu}_{23}\rho_{32}e^{-i\omega_{32}t} + \text{c.c.}].$$

$$\rho_{32} = \frac{i\Omega_c e^{i\Delta_1 t}}{(\gamma_{32} + i2\Delta_2)}\rho_{12},$$

$$\rho_{12} = -\frac{i\Omega_c e^{i\Delta_2 t}}{\gamma_{21} + i2(\Delta_2 - \Delta_1)}\rho_{13},$$

$$\rho_{31} = \frac{i\Omega_p e^{i\Delta_1 t}}{(\gamma_{31} + i2\Delta_1)} + \frac{i\Omega_c e^{i\Delta_2 t}}{(\gamma_{31} + i2\Delta_1)}\rho_{21}.$$

$$\chi^{(1)}(-\omega_p,\omega_p) = \frac{|\mu_{13}|^2\varrho}{\epsilon_0\hbar}$$
$$\times\left[\frac{4\delta(|\Omega_c|^2 - 4\delta\Delta) - 4\Delta\gamma_{21}^2}{||\Omega_c|^2 + (\gamma_{31} + i2\Delta)(\gamma_{21} + i2\delta)|^2}\right.$$
$$\left. + i\frac{8\delta^2\gamma_{31} + 2\gamma_{21}(|\Omega_c|^2 + \gamma_{21}\gamma_{31})}{||\Omega_c|^2 + (\gamma_{31} + i2\Delta)(\gamma_{21} + i2\delta)|^2}\right].$$

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什么是 EIT?

主方程与线性极化率

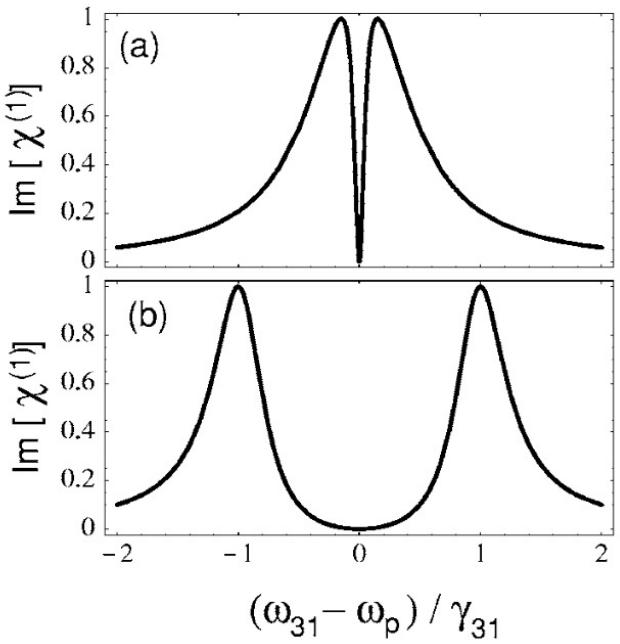

FIG. 7. EIT absorption spectrum for different values of coupling field and $\gamma_{21}=0$: (a) $\Omega_c=0.3\gamma_{31}$; (b) $\Omega_c=2\gamma_{31}$.

Rev. Mod. Phys. 77, 633 (2005).

$$\chi^{(1)}(-\omega_p,\omega_p)=\frac{|\mu_{13}|^2\varrho}{\epsilon_0\hbar}\times\left[\frac{4\delta(|\Omega_c|^2-4\delta\Delta)-4\Delta\gamma_{21}^2}{||\Omega_c|^2+(\gamma_{31}+i2\Delta)(\gamma_{21}+i2\delta)|^2}+i\frac{8\delta^2\gamma_{31}+2\gamma_{21}(|\Omega_c|^2+\gamma_{21}\gamma_{31})}{||\Omega_c|^2+(\gamma_{31}+i2\Delta)(\gamma_{21}+i2\delta)|^2}\right].$$

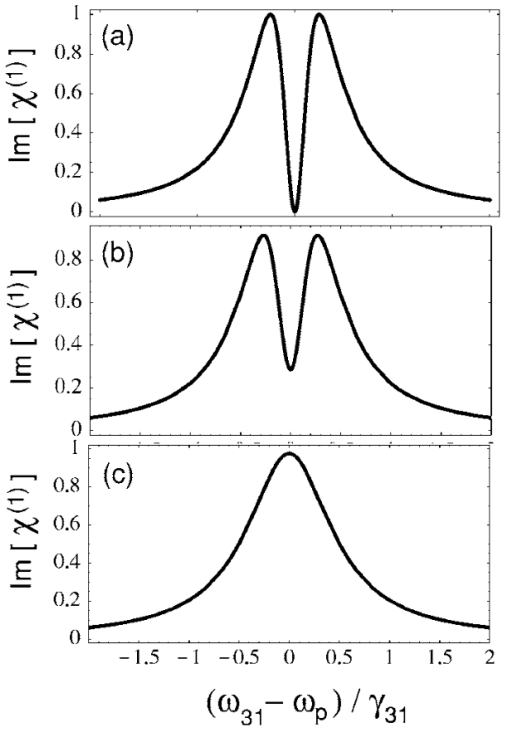

FIG. 10. Absorption spectrum for nonvanishing decay of $|2\rangle$-$|1\rangle$ transition in arbitrary units: (a) $\gamma_{31}=1$, $\gamma_{21}=0$; (b) $\gamma_{31}=1$, $\gamma_{21}=0.1$; (c) $\gamma_{31}=1$, $\gamma_{21}=10$. In all cases $\Omega_c=0.5$.

什么是 EIT?

通过 EIT 介质的透射

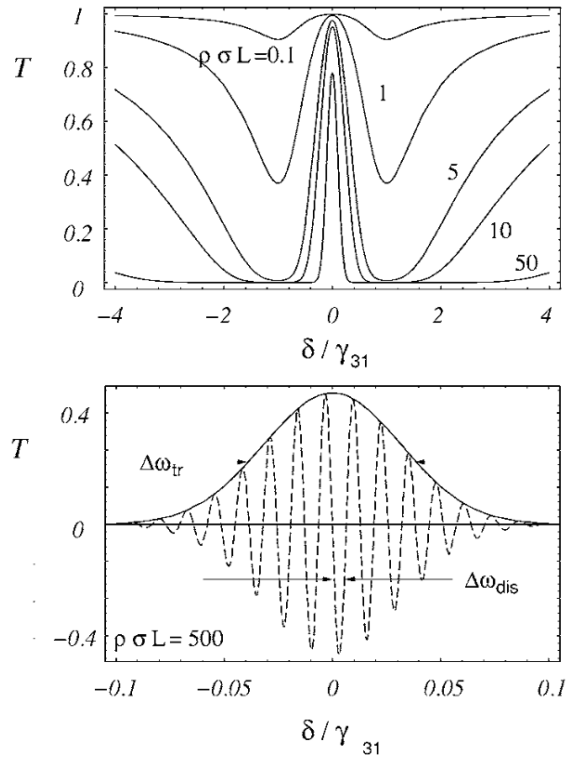

FIG. 11. Transmission spectrum through an EIT medium: top, dependence on density length products $\varrho\sigma z$; bottom, illustration of dispersive width.

Rev. Mod. Phys. 77, 633 (2005).

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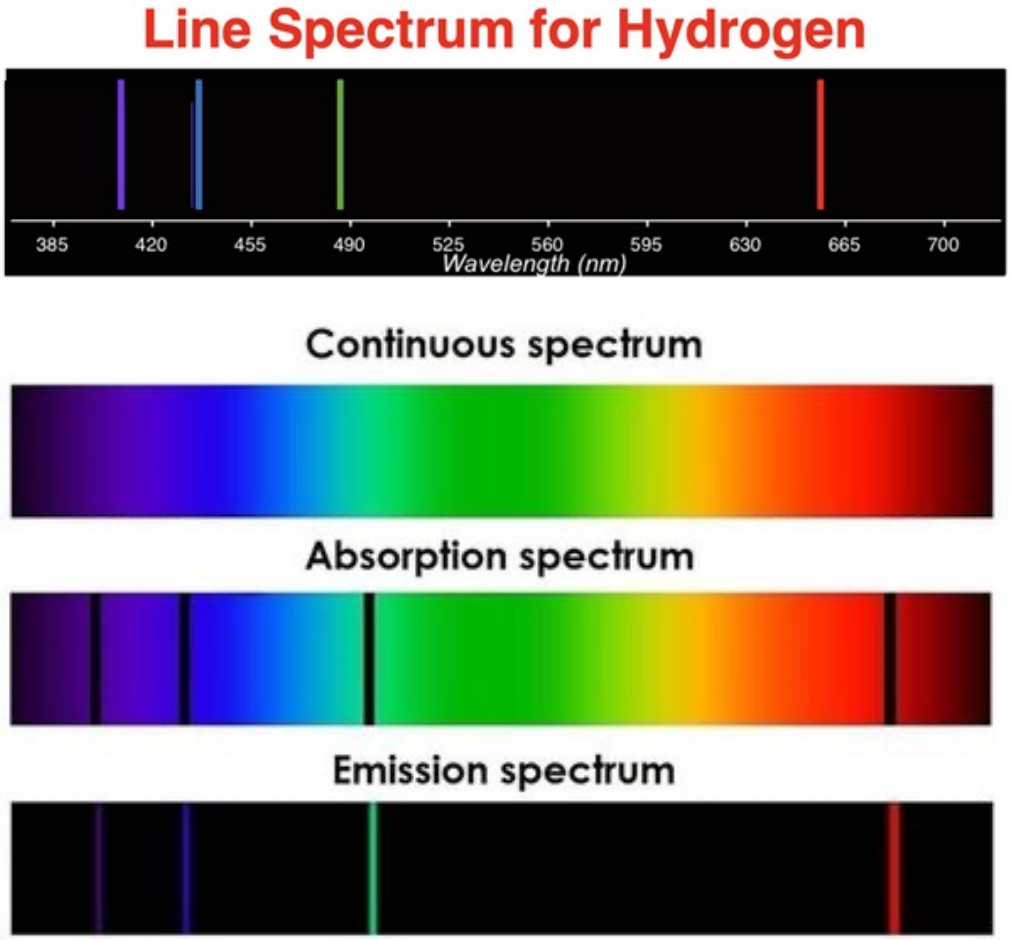
什么是里德堡原子?



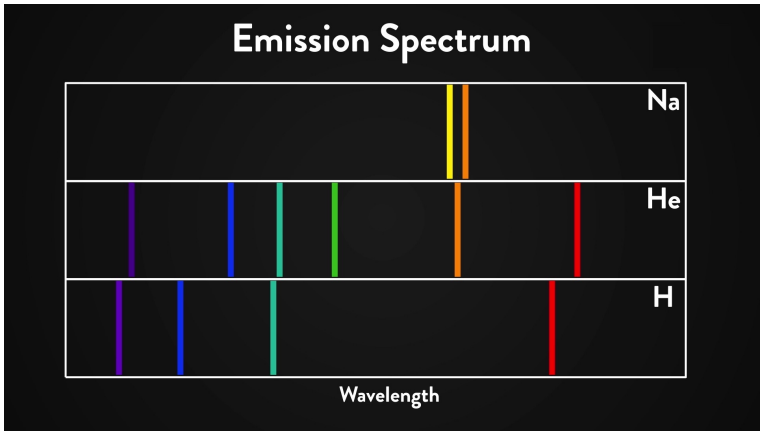
$$\lambda = B\frac{n^2}{n^2-4} \qquad n = 3,4,5,\ldots \qquad E_n = \frac{-R_{\mathrm{H}}}{n^2}$$

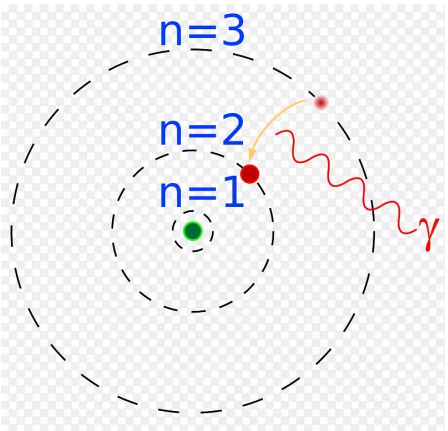
Johann Jacob Balmer
(1825-1898)

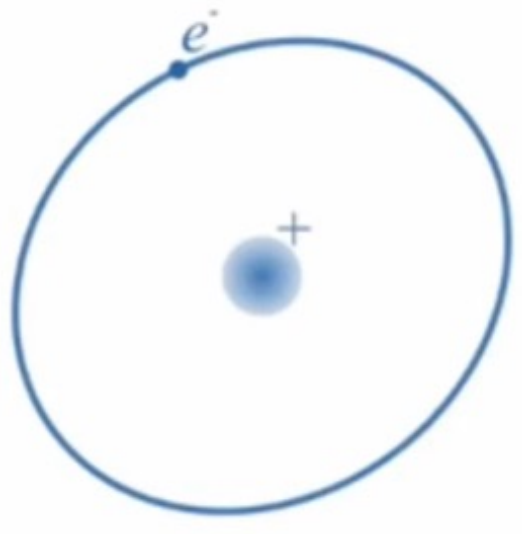
Johannes Robert Rydberg
(1854-1919)

什么是里德堡原子?

Niels Henrik David Bohr
(1885—1962)



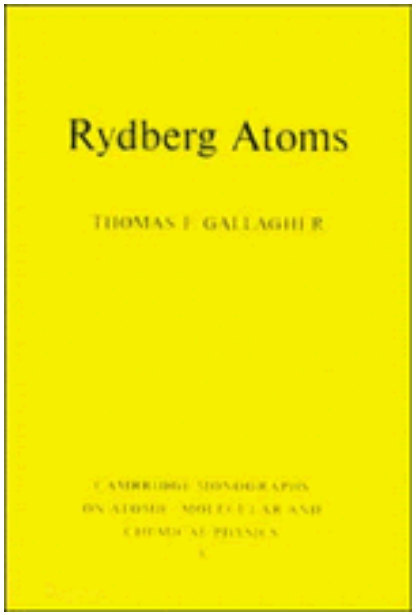


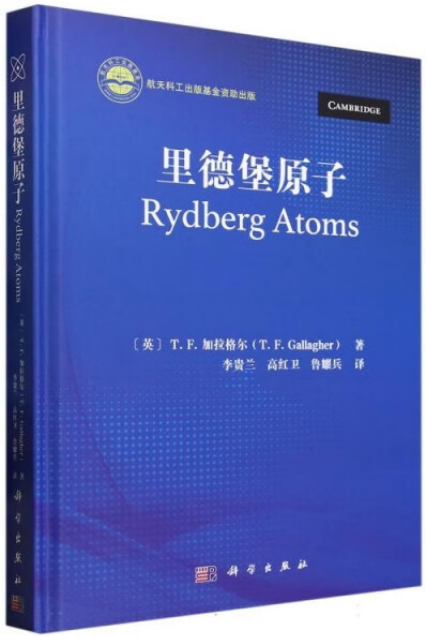


里德堡原子（主量子数 $n \geq 10$）

什么是里德堡原子?

经典著作





With Gallagher T F @2024

Gallagher T F 1994 Rydberg Atoms (Cambridge: Cambridge University Press)

什么是里德堡原子?

University of Chinese Academy of Sciences

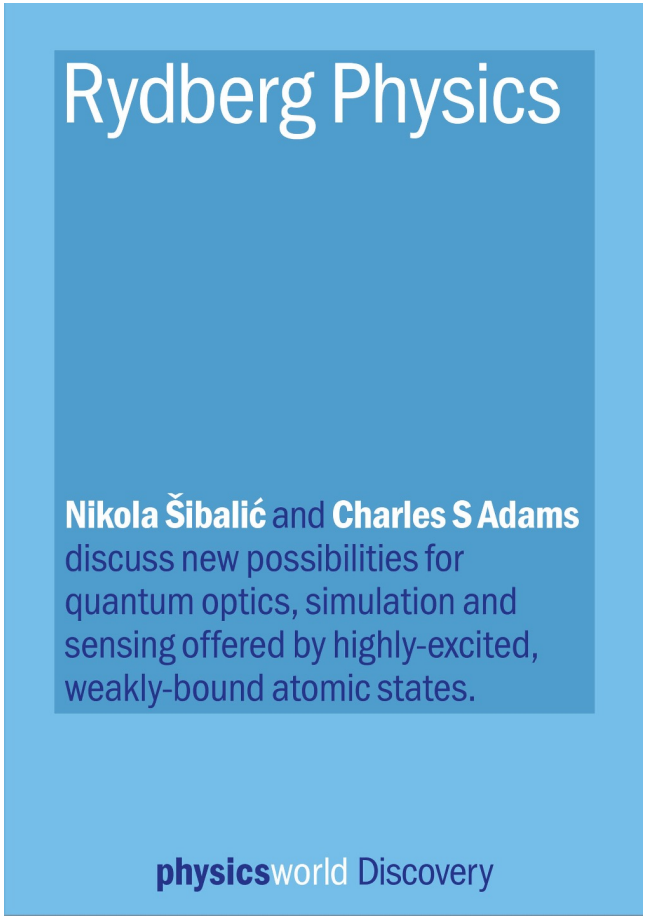
近期综述

Nikola Šibalić

Nikola Šibalić studied theoretical and experimental physics at the University of Belgrade, Faculty of Physics, Serbia. He received his PhD from Durham University, UK, under the supervision of Kevin Weatherill and Charles S Adams. Currently a postdoc, he spends his time between Aarhus University, Denmark, and Institut d'Optique, France, where he continues to explore curiosities of the atom–light interaction, Rydberg states and driven-dissipative many-body dynamics.

Charles S Adams

Charles S Adams studied physics at the University of Oxford and received a PhD on laser physics from the University of Strathclyde in Glasgow, UK. He completed postdoctoral work in Germany and the United States before starting a research group at Durham University in 1995. He is Director of JQC Durham-Newcastle and was awarded the 2014 Institute of Physics Thomson medal for his pioneering work in the field of Rydberg quantum optics.



里德堡原子能做什么?

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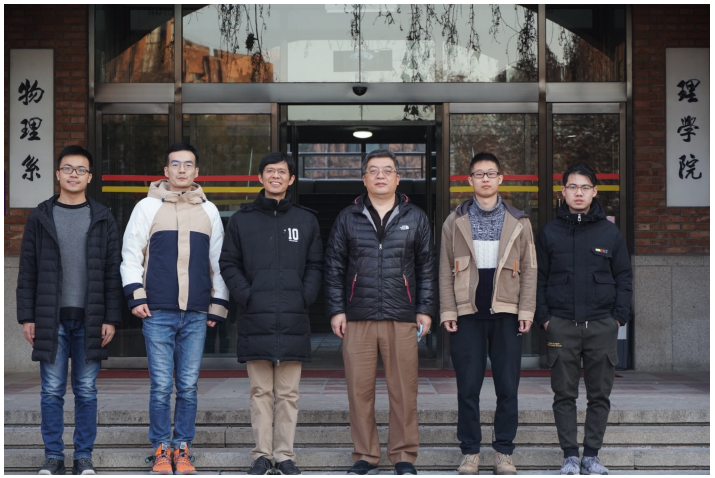
近期综述



Li You(尤力)

Chin. Phys. B Vol. 30, No. 2 (2021) 020305

TOPICAL REVIEW — Quantum computation and quantum simulation

A concise review of Rydberg atom based quantum computation and quantum simulation*

Xiaoling Wu(吴晓凌)[1], Xinhui Liang(梁昕晖)[1], Yaoqi Tian(田曜齐)[2,3], Fan Yang(杨帆)[1,†], Cheng Chen(陈丞)[1], Yong-Chun Liu(刘永椿)[1,4], Meng Khoon Tey(郑盟锟)[1,4], and Li You(尤力)[1,4,5,‡]

Table 1. Scaling with the principle quantum number n for the listed properties of Rydberg atoms.

Properties	Notation	β (scaling n^β)
orbit size	$\langle r \rangle$	2
binding energy	E_n	-2
neighboring level spacing	$E_{n+1} - E_n$	-3
radiative lifetime	τ_0	3
dipole matrix element[a]	$\langle g\|er\|nl \rangle$	$-3/2$
dipole matrix element[b]	$\langle nl\|er\|nl+1 \rangle$	2
polarizability	α	7

[a] g denotes ground state.

[b] dipole matrix elements between neighboring Rydberg states.

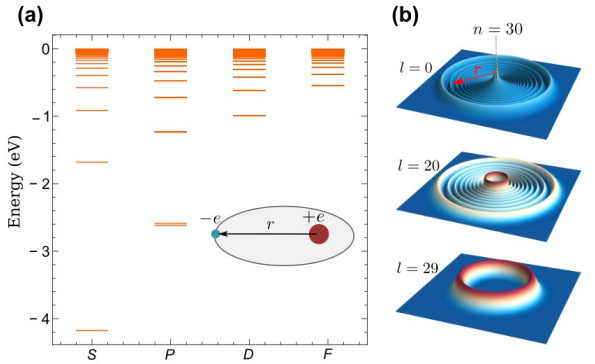


Fig. 1. Energy levels and electron probability density of ^{87}Rb atom. Relevant data and calculations are based on alkali Rydberg calculator (ARC) toolbox.[32] (a) Distribution of energy levels for $5 \le n \le 60$, $0 \le l \le 3$. (b) Density distributions of Rydberg electron in the radial direction $(r|\psi(r)|^2)$. The bottom figure shows that the circular Rydberg atom ($l = n-1$) is highly localized around $n^2 a_0$.

Xiaoling Wu(吴晓凌), Xinhui Liang(梁昕晖), Yaoqi Tian(田曜齐), Fan Yang(杨帆), Cheng Chen(陈丞), Yong-Chun Liu(刘永椿), Meng Khoon Tey(郑盟锟), and Li You(尤力) A concise review of Rydberg atom based quantum computation and quantum simulation 2021 *Chin. Phys. B* 30 020305

里德堡原子能做什么?

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里德堡原子的特点

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polarizability	α	7

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[b] dipole matrix elements between neighboring Rydberg states.

特点:

- 大原子电偶极矩 → 高灵敏度
- 丰富的原子能级 → GHz–THz 载波频率
- 丰富量子自由度编码 → 更高信息容量

可用于量子精密测量、量子计算和量子模拟

大纲

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精确测量微波电场的意义

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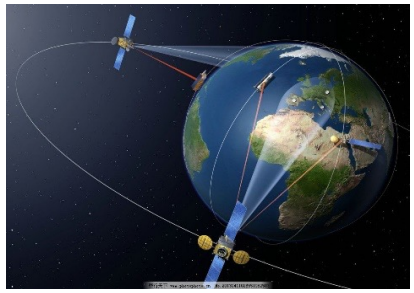
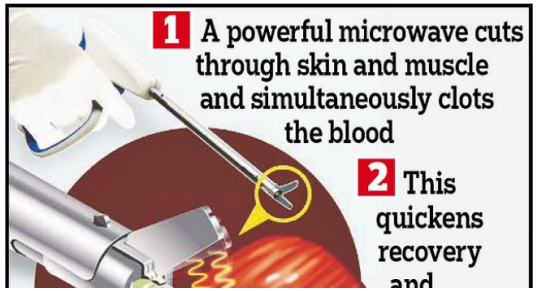
波长：1 mm-1 m 频率：300 GHz-300 MHz

通信
- 卫星；
- 移动无线电；
- 遥测；
- …



医疗
- 诊断；
- 治疗；
- 灭菌；



雷达
- 搜索与救援；
- 机场交通；
- 测速；

材料
- 无损检测；
- 快速加热；
- 选择性加热；

所有应用的基础：
微波电场强度的准确测量

更高灵敏度
更宽带宽

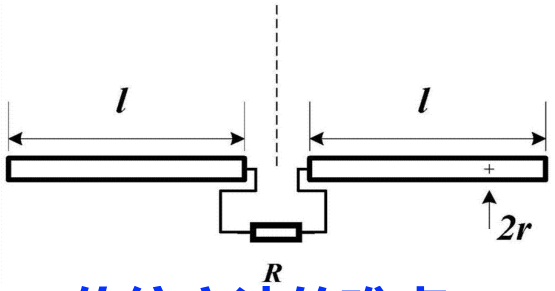
经典天线极限：1 mV/cm

量子极限：小于 1 nV/cm

传统探测与原子传感器

University of Chinese Academy of Sciences

电偶极探头



传统方法的难点：

1. Difficulty in calibration;
2. Accuracy： 4 %;
3. Fre. Range：<100 GHz;
4. Poor spatial： $\lambda/2$;
5. Low limit：1 mV/cm;
6. E Range：5 mV/cm to 10 mV/cm;
7. Interference of metal components
8. Electronic reading, dark current noise;

精密测量：量子计量

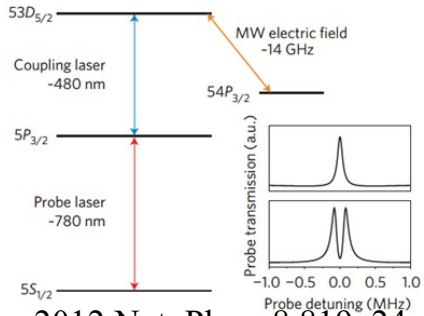
物理 → 量子

量子计量的优势：

- **精度比物理测量高数个数量级；**
- **可溯源至基本物理常数，保证测量目标的准确性；**
- **可在多地点直接复现，避免多级传递造成的误差。**

C.L.Holloway *et al.*, IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, VOL. 62, NO. 12, DECEMBER 2014.
https://arstechnica.com, 2019

原子微波场传感器



2012 Nat. Phys. 8 819–24

原子传感器的优势：

1. Self- calibration, Traceable
2. Accuracy： 1 %;
3. Fre. Range： 50 MHz to 1 THz;
4. Fine spatial： $\lambda/650$;
5. Low limit： 780 pV/cm;
6. E Range:nV/cm to 10 kV/cm;
7. No metal;
8. Optical reading, high efficiency and low noise;

什么是基于里德堡原子的电场测量?

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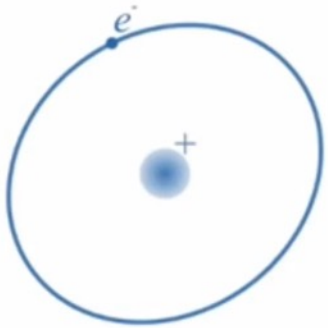
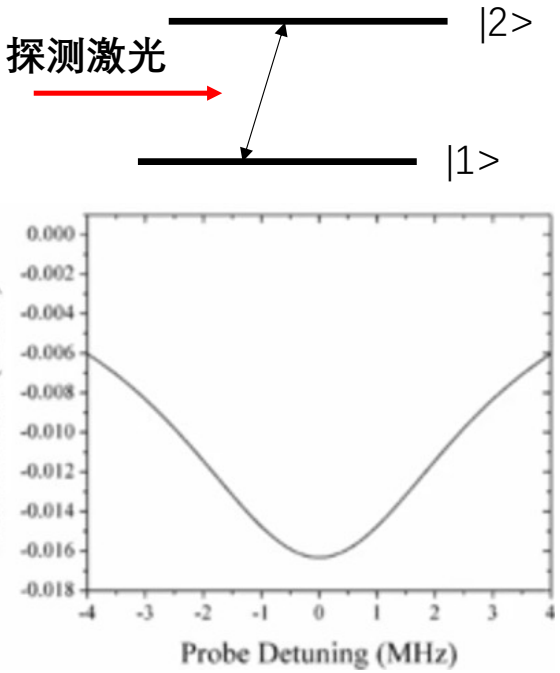
里德堡原子 + **电磁感应透明（EIT）**

- 原子的外层电子被激发到主量子数 n 很大的轨道
- 里德堡态之间的能级间隔位于微波波段
- 相邻里德堡态之间的偶极跃迁矩阵元对微波场很敏感

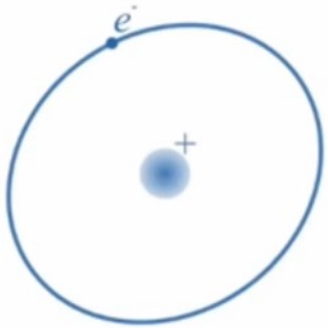


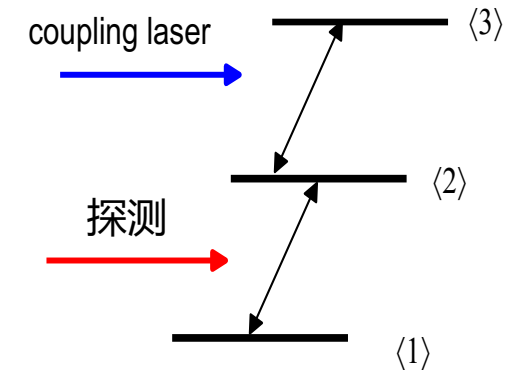


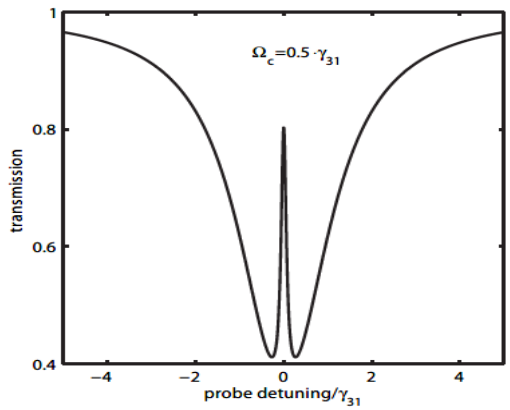
什么是基于里德堡原子的电场测量?

里德堡原子 + 电磁感应透明（EIT）

- 原子的外层电子被激发到主量子数 n 很大的轨道
- 里德堡态之间的能级间隔位于微波波段
- 相邻里德堡态之间的偶极跃迁矩阵元对微波场很敏感





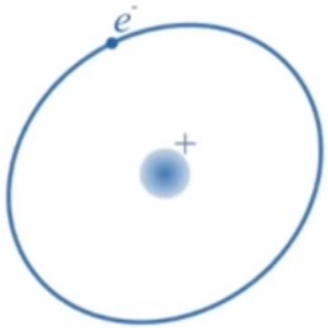


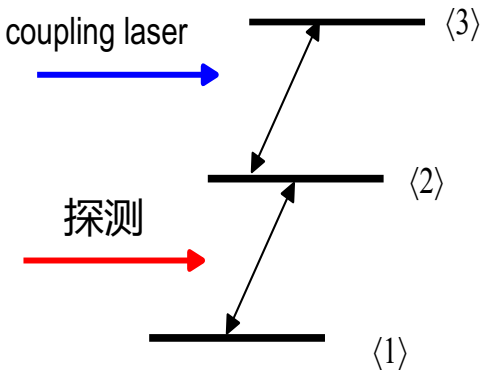
什么是基于里德堡原子的电场测量?

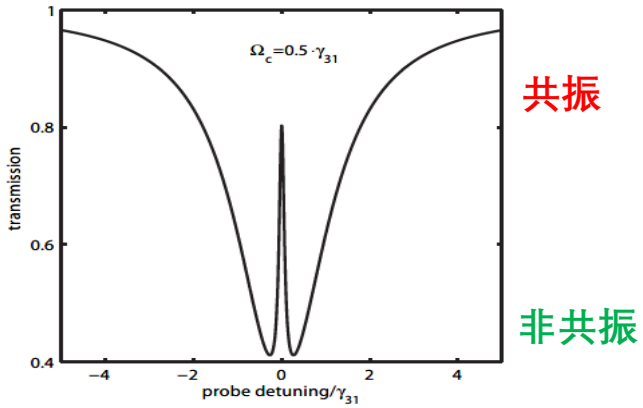
University of Chinese Academy of Sciences

里德堡原子 + 电磁感应透明（EIT）

- 原子的外层电子被激发到主量子数 n 很大的轨道
- 里德堡态之间的能级间隔位于微波波段
- 相邻里德堡态之间的偶极跃迁矩阵元对微波场很敏感



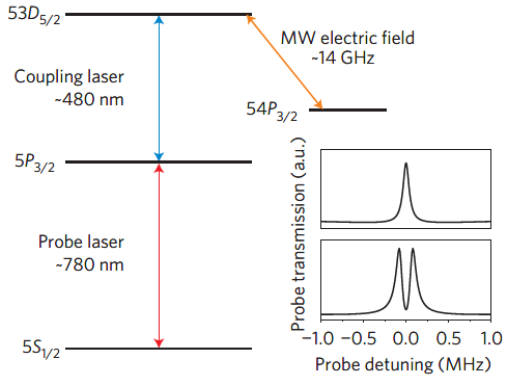




共振

非共振

里德堡原子电场测量



Nature Physics, 2012, 8, 819 – 824

Autler-Townes 劈裂

$$|E_{MW}| = \frac{\hbar}{d_{MW}}\Omega_{MW} = \frac{\hbar}{d_{MW}} D \cdot \Delta f_{MW}$$

$$\hbar\Omega_{\text{on res}} = \wp \langle E \rangle_\tau$$

斯塔克位移

$$\Omega_{\text{off res}} = -\frac{1}{2}\alpha \langle E^2 \rangle_\tau$$

PHYSICAL REVIEW APPLIED 15, 014047 (2021)

基于里德堡原子的电场测量快速发展

综述：

1. Rev. Mod. Phys. **89**, 035002 (2017)
2. IEEE Transactions on Quantum Engineering, **2**, 1-13 (2021)
3. IEEE Aerospace and Electronic Systems Magazine, **35**(4), 48-56 (2020)
4. J. Phys. B: At. Mol. Opt. Phys. **48** 202001 (2015)

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微波通信

1. J. Phys. B: At. Mol. Opt. Phys. **53** 094003 (2020)
2. IEEE Antennas and Propagation Magazine, **63**(3), 63-76 (2020)
3. IEEE Transactions on Antennas and Propagation, **69**(5), 2455-2462 (2020)
4. Appl. Sci. **10**(4), 1346 (2020)
5. Opt. Express **27**, 8848-8857 (2019)
6. AIP Advances **9**, 065110 (2019)
7. Applied Physics Express **12**, 126002 (2019)
8. Appl. Phys. Lett. **112**, 211106 (2018)

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最小可测量值与灵敏度提升

1. Nat. Phys. **8**, 819 (2012)
2. Nat. Phys. **16,** 911 (2020)
3. Phys. Rev. A **103**, 063113 (2021)
4. AIP Advances **11**, 085127 (2021)
5. Appl. Opt. **59**, 8253-8258 (2020)
6. Phys. Rev. A **101**, 053432 (2020)
7. Chin. Phys. B, **29**(3), 033201 (2020)
8. Appl. Sci. **10**(22), 8110 (2020)
9. Opt. Express **25**, 8625-8637 (2017)
10. Sci Rep **7**, 42981 (2017)
11. Applied Physics Letters **108,** 174101 (2016)
12. J. Phys. B:At. Mol. Opt. Phys. **48,** 202001 (2015)
13. **Opt. Express 31, 38165–38178 (2023)**

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最大探测范围

Phys. Rev. Applied **5**, 034003 (2016)

扩展可探测频率范围

1. Phys. Rev. A **104**, 032824 (2021)
2. Appl. Phys. Lett. **105**,024104 (2014)
3. Journal of Applied Physics **123**, 203105 (2018)
4. Phys. Rev. Applied **15**, 014047(2021)
5. Optics Express **30**(8), 13522(2022)
6. IEEE T INSTRUM MEAS. **68**, 2274 (2019)
7. **Phys. Rev. A 107, 043102 (2023)** ☆

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1. Phys. Rev. Applied **16**, 024008 (2021)
2. J. Opt. Soc. Am. B **38**(2) 584-594 (2021)
3. Appl. Phys. Lett. **113**, 073501 (2018)
4. Phys. Rev. Lett. **111**,063001(2013)

里德堡原子混频器

1. Appl. Phys. Lett. **118**, 114001 (2021)
2. J. Phys. B: At. Mol. Opt. Phys. **54** 165501 (2021)
3. Appl. Phys. Lett. **114**, 114101 (2019)
4. AIP Advances **9**, 045030 (2019)

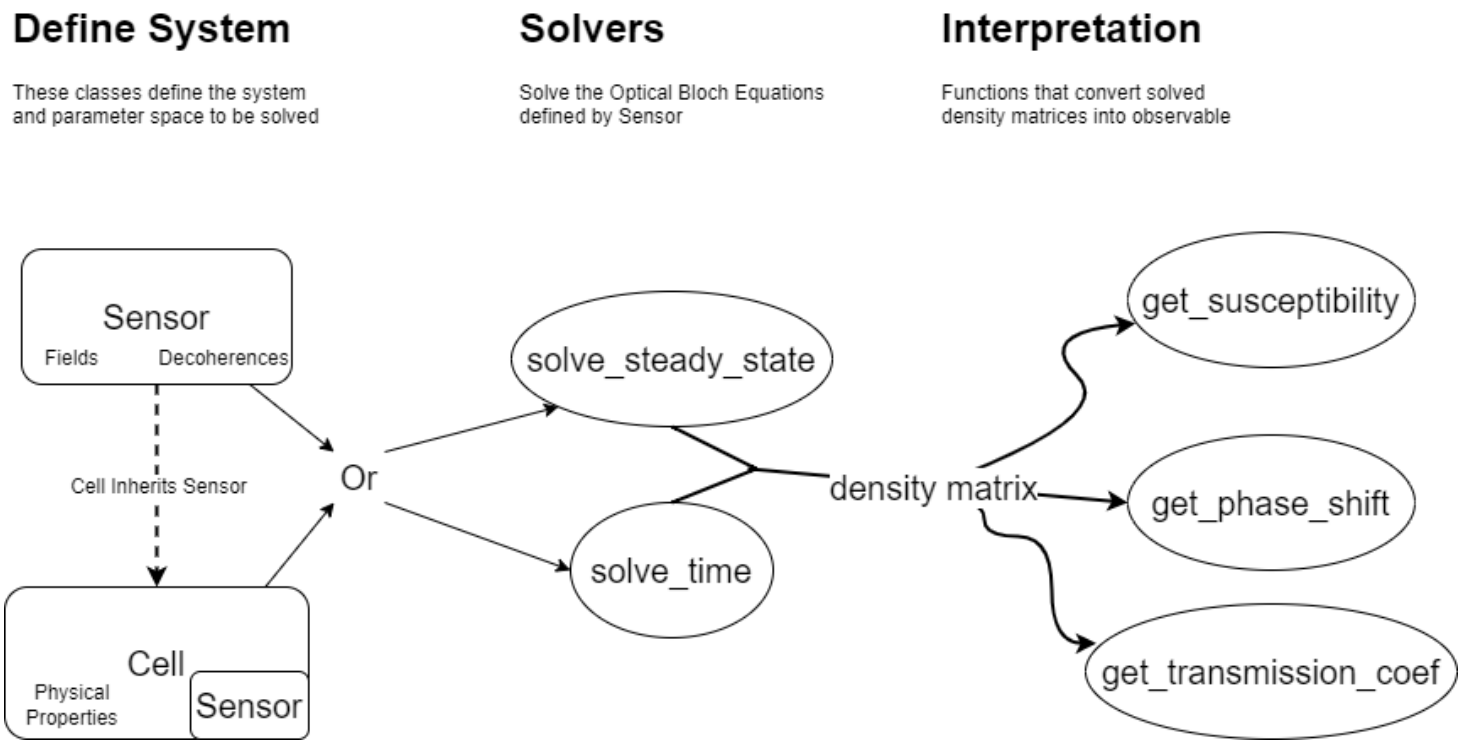
全光学相位灵敏度测量

1. Anderson, D. A. et al., Patent WO 2019/126038 A1 (2019).
2. Chin. Phys. B **31**, 090703 (2022)
3. Opt. Express 31, 10449-10457 (2023)
4. PHYSICAL REVIEW LETTERS 135, 093602 (2025)

大纲

- 电磁感应透明（EIT）
- 里德堡原子
- 基于里德堡原子的电场测量
- 开源程序 RydIQule
- 里德堡激发的实验技术
- 我们在精密微波场测量中的几项工作

什么是 RydIQule?



Miller, B.N.; Meyer, D.H.; Virtanen, T.; O' Brien, C.M.; Cox, K.C. RydIQule: A Graph-Based Paradigm for Modeling Rydberg andAtomic Sensors. Comput. Phys. Commun. 2024, 294, 108952.

https://rydiqule.readthedocs.io/en/stable/overview.html

什么是 RydIQule?

双光子 EIT

```
import datetime
start = datetime.datetime.now()
print('start time:',start)

import numpy as np
import matplotlib.pyplot as plt
import json
from matplotlib.ticker import MultipleLocator
from scipy.optimize import curve_fit
import rydiqule as rq
from rydiqule import A_QState
from rydiqule.sensor_utils import get_rho_ij
import pandas as pd
from tqdm import tqdm
from colorama import Fore, init
from scipy.interpolate import interp1d
from matplotlib import font_manager
#print([f.name for f in font_manager.fontManager.ttflist])
from arc import Wigner6j
init(autoreset=True)
```

什么是 RydIQule?

双光子 EIT

```
atom = "Rb87"
g = A_QState(5, 0, 0.5) #5S1/2
e_1 = A_QState(5, 1, 1.5) #5P3/2
r_1 = A_QState(56, 2, 2.5) #56D5/2
r_2 = A_QState(56, 1, 1.5) #56P3/2

Temperature=300 # K
Rb_Cell = rq.Cell(atom,[g,e_1,r_1,r_2],  cell_length=0.05, beam_diam=0.001,
gamma_transit=2.25,temp=Temperature)

transit_broadening_MHz = 0.5
transit_broadening = 2*np.pi*transit_broadening_MHz
Rb_Cell.add_transit_broadening(transit_broadening)

print(Rb_Cell.states)
print(type(Rb_Cell.states[0]))
print(Rb_Cell.couplings.nodes(data=True))
print(Rb_Cell.couplings.edges(data=True))
print(Rb_Cell.decoherence_matrix())
print(Rb_Cell.couplings.nodes(data="gamma_lifetime"))
print(Rb_Cell.couplings.edges(data="gamma_transition"))
```

什么是 RydIQule?

双光子 EIT

```
detunings_MHz = np.linspace(-100, 100, 2000) # MHz
detunings = 2*np.pi*detunings_MHz

rabi_frequency_p_MHz = 2 # 780 nm Rabi Frequency
rabi_frequency_p = 2*np.pi*rabi_frequency_p_MHz

rabi_frequency_c_MHz = 2 # 480 nm Rabi Frequency
rabi_frequency_c = 2*np.pi*rabi_frequency_c_MHz


rabi_frequency_MW_MHz = 10 # MW Rabi Frequency
rabi_frequency_MW = 2*np.pi*rabi_frequency_MW_MHz

kunit_p = np.array([1,0,0]) # 780 nm k
kunit_c = np.array([-1,0,0]) # 480 nm  k
```

什么是 RydIQule?

University of Chinese Academy of Sciences

双光子 EIT

```
Rb_Cell.add_coupling((g, e_1), rabi_frequency=rabi_frequency_p, detuning=0,
label="probe", kunit=kunit_p)
Rb_Cell.add_coupling((e_1, r_1), rabi_frequency=rabi_frequency_c, detuning=detunings,
label="coupling", kunit=kunit_c)
Rb_Cell.add_coupling((r_2, r_1), rabi_frequency=rabi_frequency_MW, detuning=0,
label="MW")

print(Rb_Cell.couplings.edges(data=True))
print(Rb_Cell)
print(rq.solve_steady_state(Rb_Cell, doppler=True).rho)


rq.draw_diagram(Rb_Cell)


solution = rq.solve_steady_state(Rb_Cell, doppler=True)
print(f"Solution shape: {solution.rho.shape}")
absorption = solution.coupling_coefficient_observable().imag
print(f"Absorption_shape: {absorption.shape}")
```

什么是 RydIQule?

University of Chinese Academy of Sciences

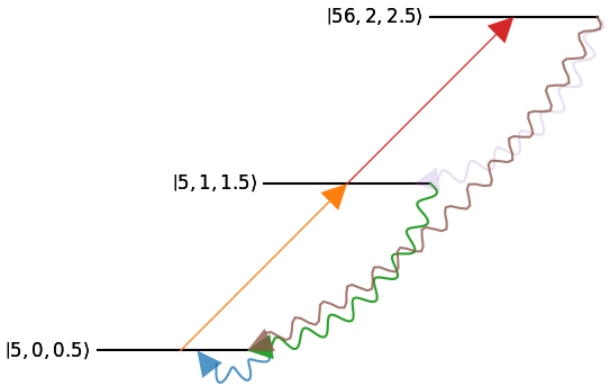
双光子 EIT

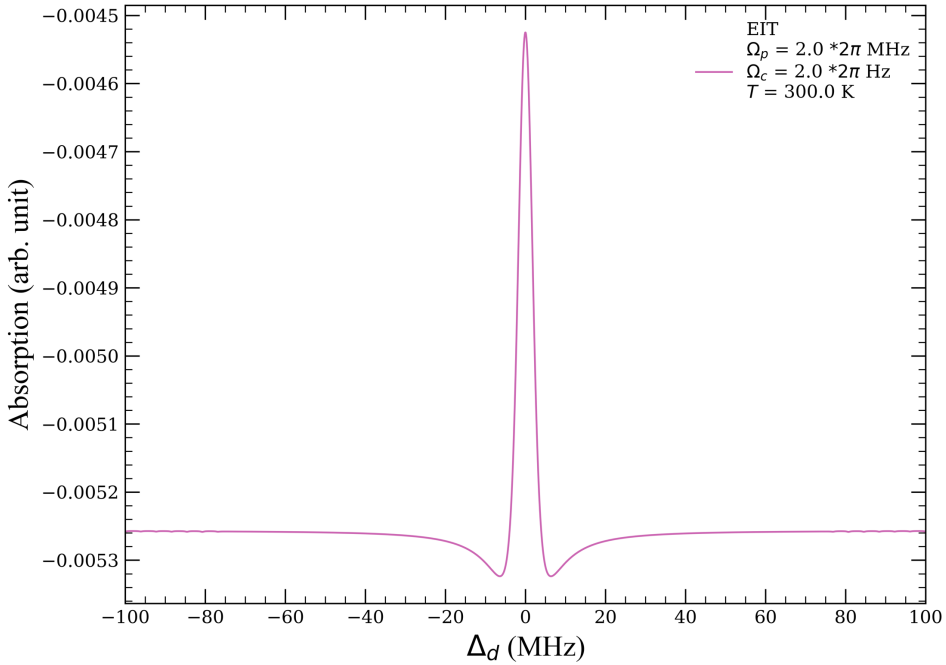
```
plt.figure(3)
fig, ax_1 = plt.subplots(figsize=(8, 6), dpi=600)
plt.plot(detunings_MHz, -absorption, linestyle='-', linewidth=1, color=(0.8, 0.4, 0.7),
         label="EIT\n"
              f"$\Omega_{{p}}$ = {rabi_frequency_p_MHz:.1f} $*2\pi$ MHz\n"
              f"$\Omega_{{c}}$ = {rabi_frequency_c_MHz:.1f} $*2\pi$ Hz\n"
              f"$\Omega_{{MW}}$ = {rabi_frequency_MW_MHz:.1f} $*2\pi$ Hz\n"
              f"$T$ = {Temperature:.1f} K\n"
         )
plt.xlabel(fr'$\Delta_d$ (MHz)', fontsize=16, family='Times New Roman')
plt.ylabel(r'Absorption (arb. unit)', fontsize=16, family='Times New Roman')
plt.legend(loc='upper right', fontsize=10, frameon=False)
plt.xlim(np.min(detunings_MHz), np.max(detunings_MHz))

ax_1.xaxis.set_major_locator(MultipleLocator(20))
plt.savefig(csv_filename[:-4] + ".png", dpi=600, bbox_inches='tight')
plt.show()
```

什么是 RydIQule?

双光子 EIT

rq.draw_diagram(Rb_Cell)

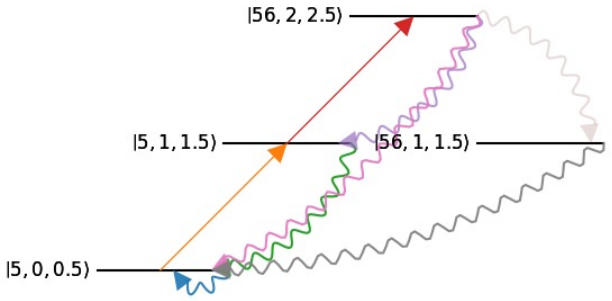


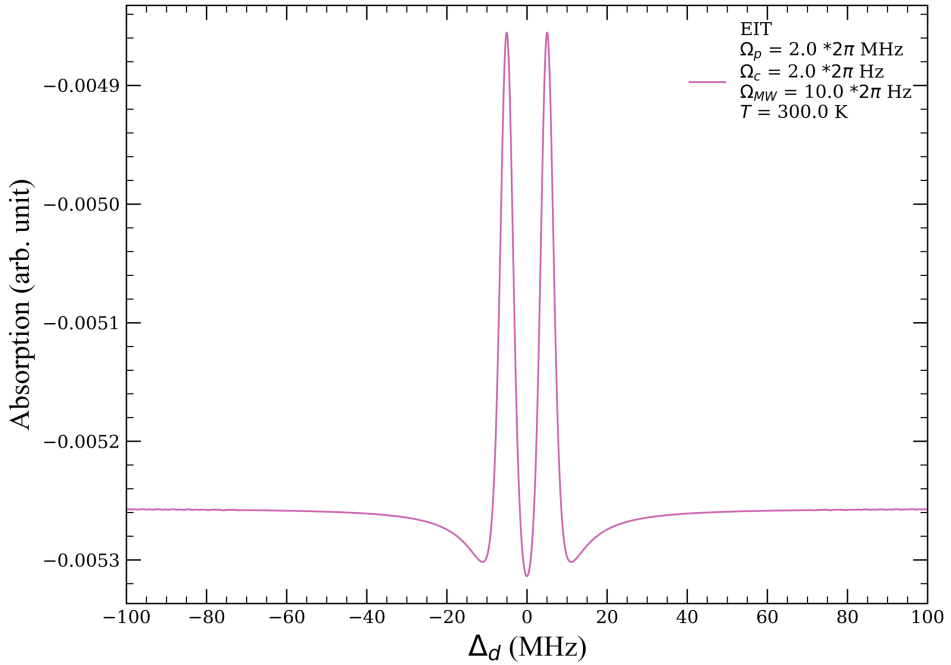


什么是 RydIQule?

双光子 EIT 与 AT 劈裂

rq.draw_diagram(Rb_Cell)



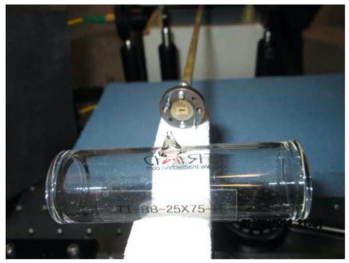


大纲

- 电磁感应透明（EIT）
- 里德堡原子
- 基于里德堡原子的电场测量
- 开源程序 RydIQule
- 里德堡激发的实验技术
- 我们在精密微波场测量中的几项工作

原子样品的选择

（一）气室



(a)

优点：

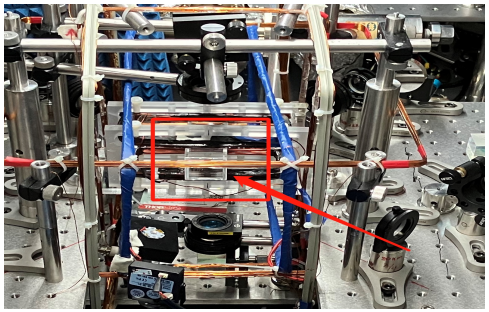
- （1）体积小
- （2）光路相对简单
- （3）原子系统稳定性相对易于控制

缺点：

- （1）多普勒展宽大（500 MHz），EIT 线宽较宽（5 MHz）
- （2）EIT-AT 劈裂线性区间下限较大（3 mV/cm）
- （3）测量结果高度依赖各光场强度

VS

（二）冷原子



优点：

- （1）多普勒展宽小（1 MHz），EIT 线宽窄（0.5 MHz）
- （2）EIT-AT 劈裂线性区间下限较小，理论预测可达 0.1 mV/cm
- （3）理论预测表明，EIT-AT 劈裂对光场强度等参数的依赖显著降低，目前该方向的实验研究仍有限。

缺点：

- （1）光路复杂，需要增加梯度磁场
- （2）实验操作的时序控制复杂，实验周期受限

实验对比！！

（一）气室

- **实验步骤**

（1）调整探测光/耦合光光路
（2）获得 EIT 信号
（3）施加微波以获得 EIT-AT 信号

- 涉及的激光

探测光、耦合光

- 主要难点

（1）控制探测光和耦合光强度的稳定性
（2）消除环境反射微波

（二）冷原子

- **实验步骤**

（1）调整冷却光、再泵浦光、光泵浦光、成像光等激光光路
（2）调整探测光和耦合光光路
（3）使探测光、耦合光与冷原子重合
（4）编写时序控制程序并调试时序控制系统
（5）冷却并俘获冷原子（反复调试时序系统程序和参数）
（6）表征冷原子云
（7）获得 EIT 信号
（8）施加微波以获得 EIT-AT 信号

- 涉及的激光

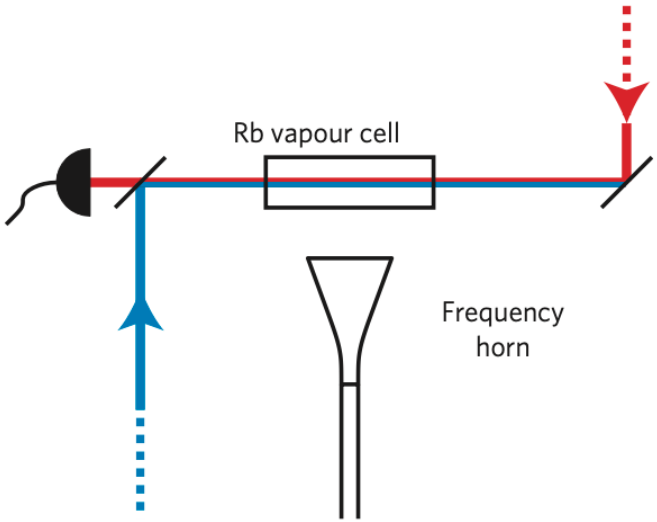
冷却光、再泵浦光、光泵浦光、成像光、探测光、耦合光

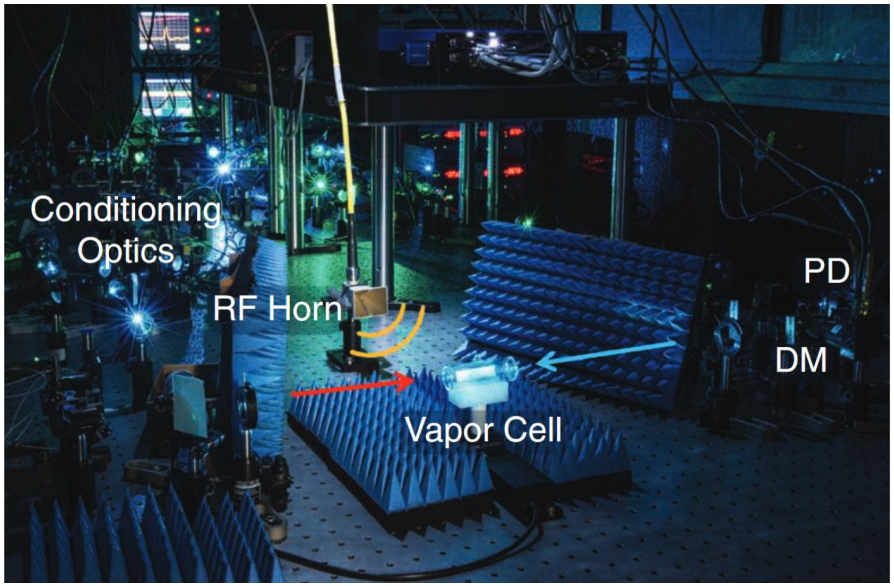
- 主要难点

（1）控制各激光功率的稳定性
（2）调试时序系统
（3）控制冷原子的温度和数量
（4）冷原子成像
（5）控制冷原子云的形状和密度
(6) Elimination of environmental reflected microwaves

里德堡激发的实验技术

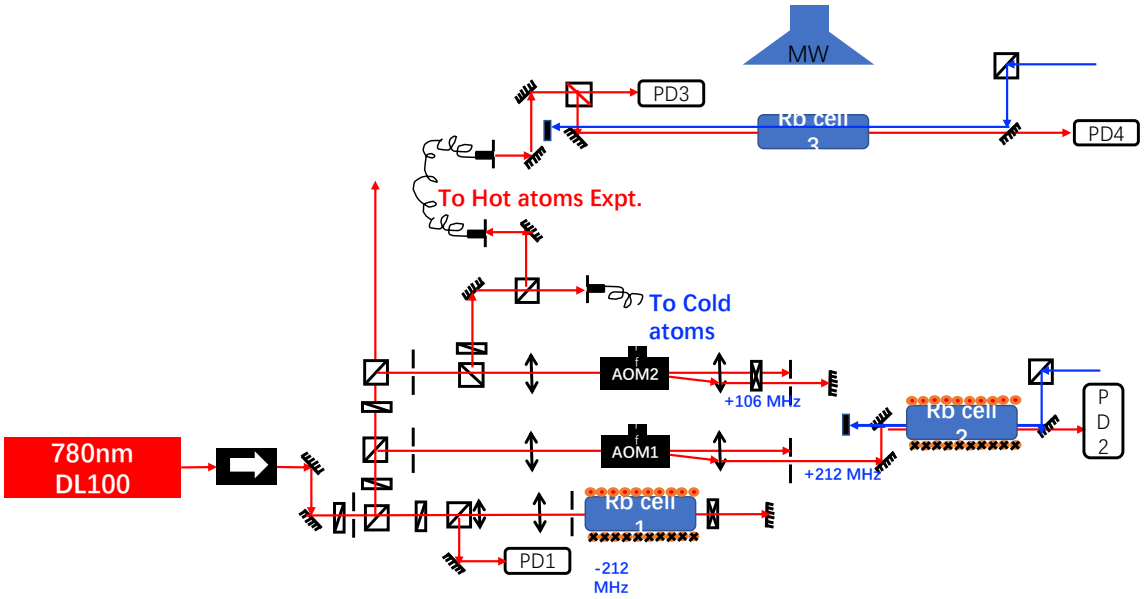
使用气室

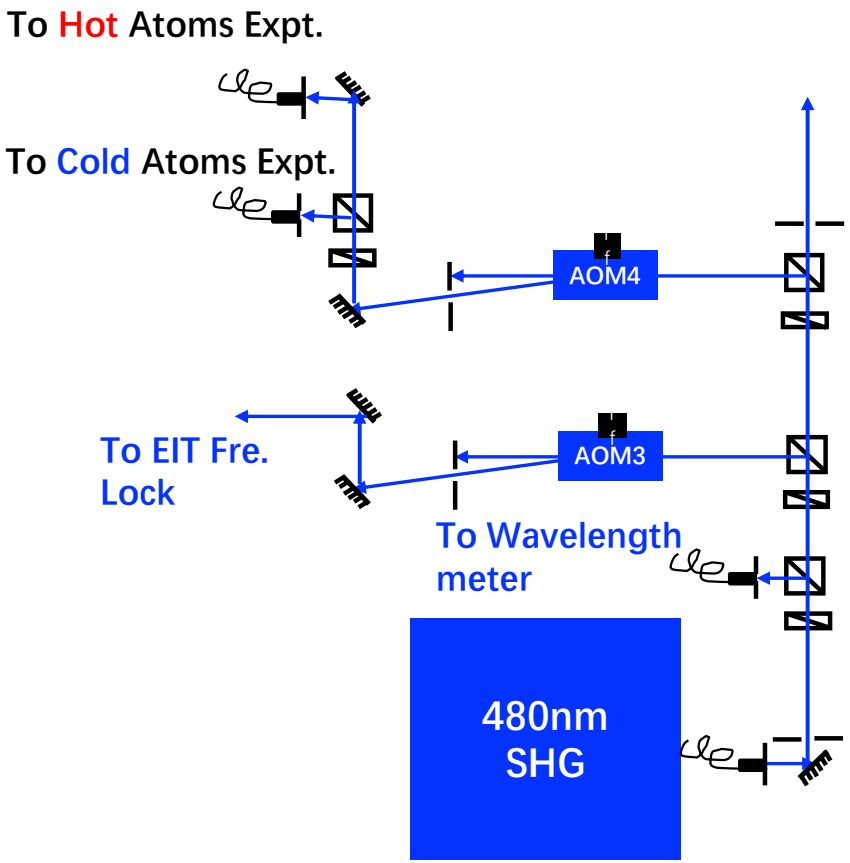




里德堡激发的实验技术

使用气室

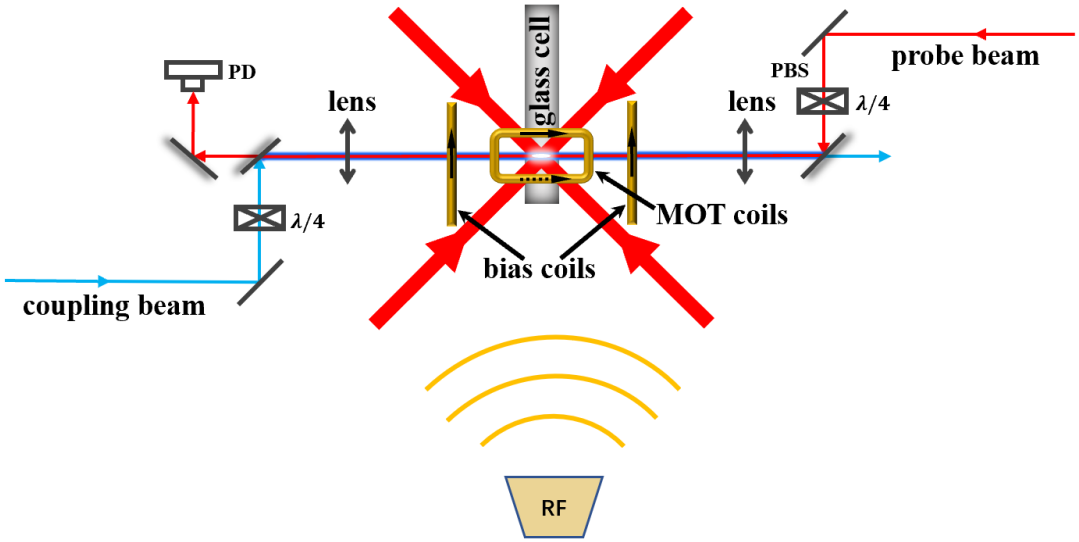




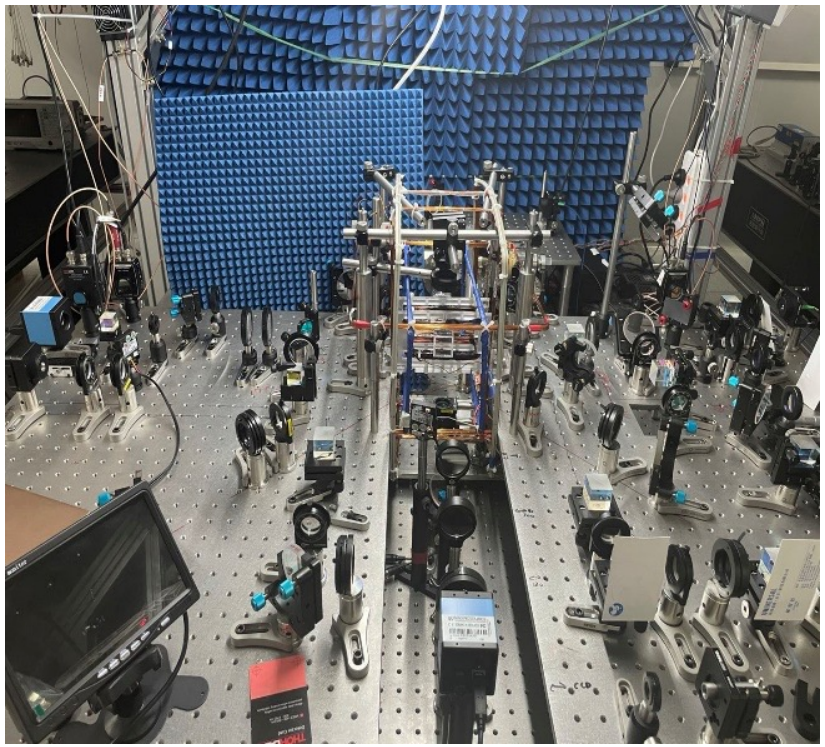
里德堡激发的实验技术

使用冷原子

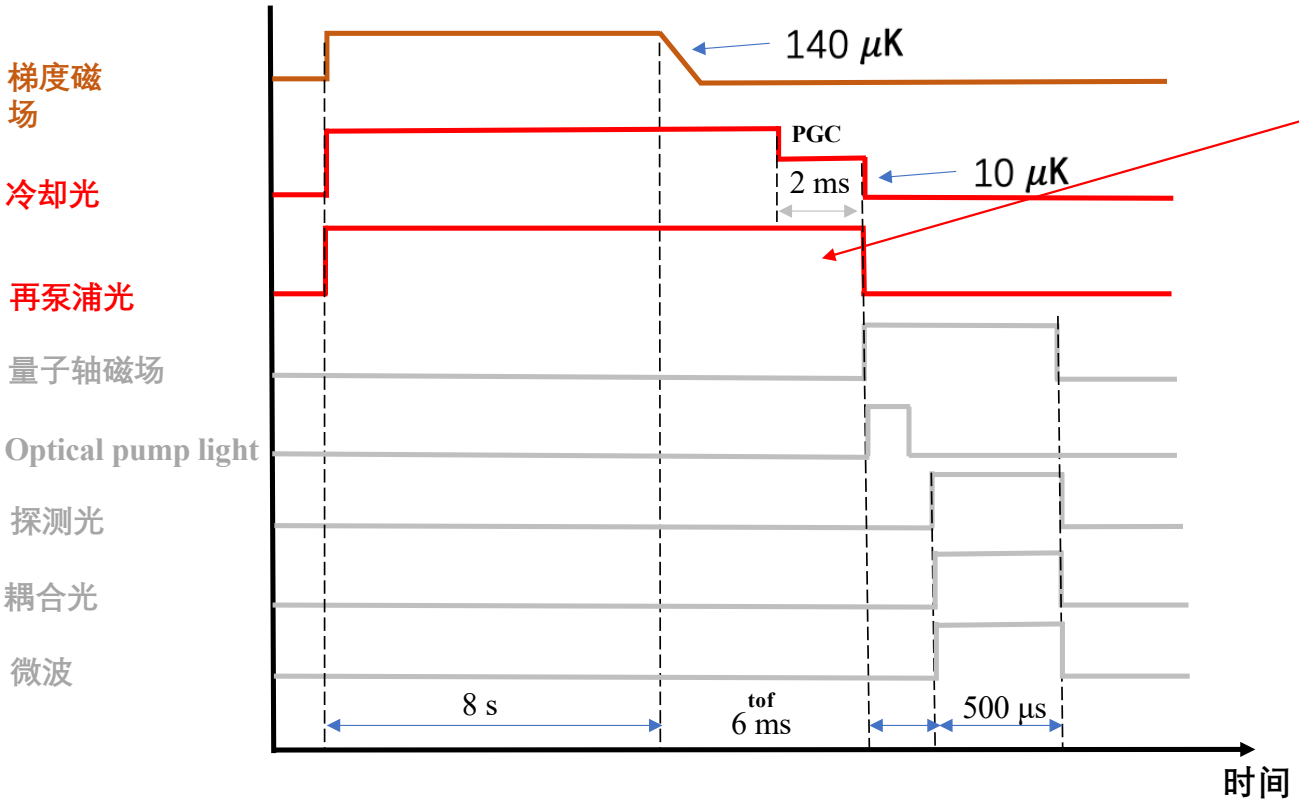
实验装置示意图



实验系统



步骤 1：用 MOT 捕获冷原子，并用 PGC 进一步降低原子温度



实验步骤时序图

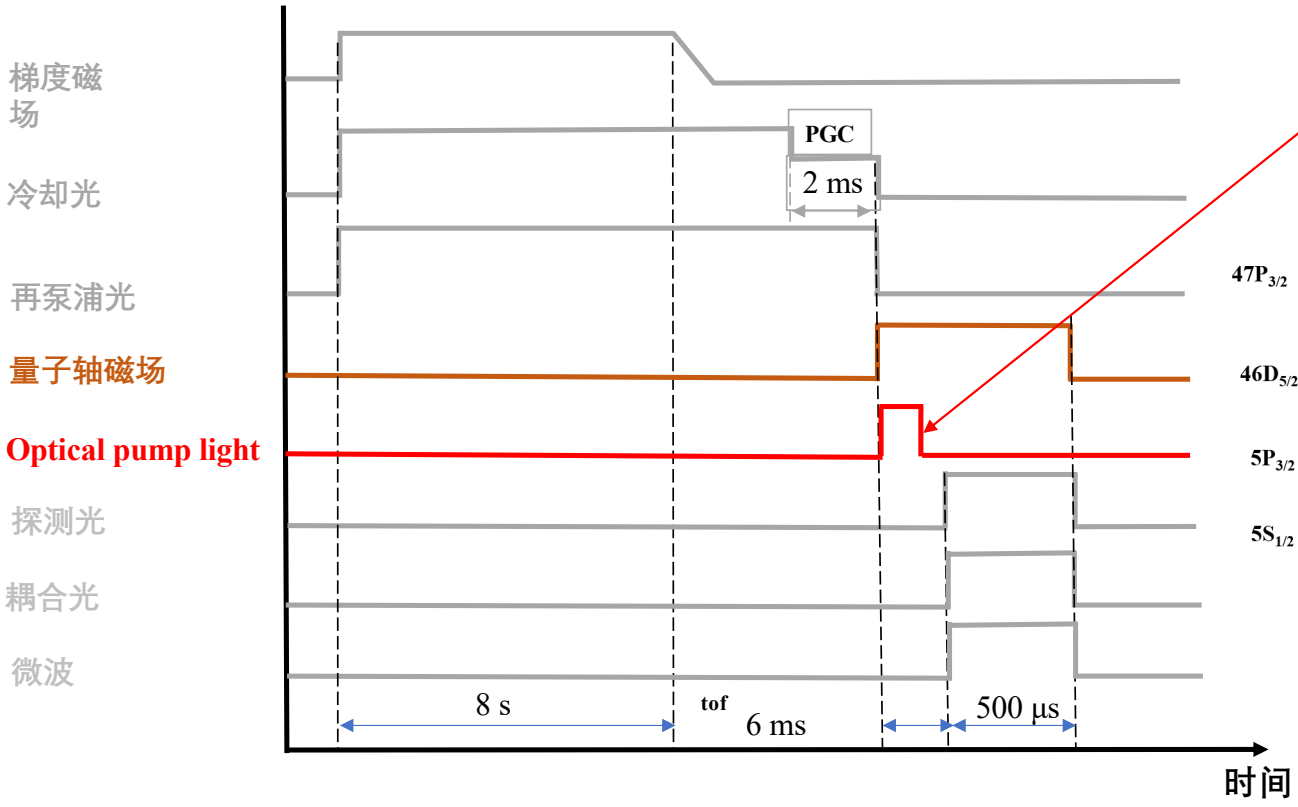
冷原子云准备就绪!

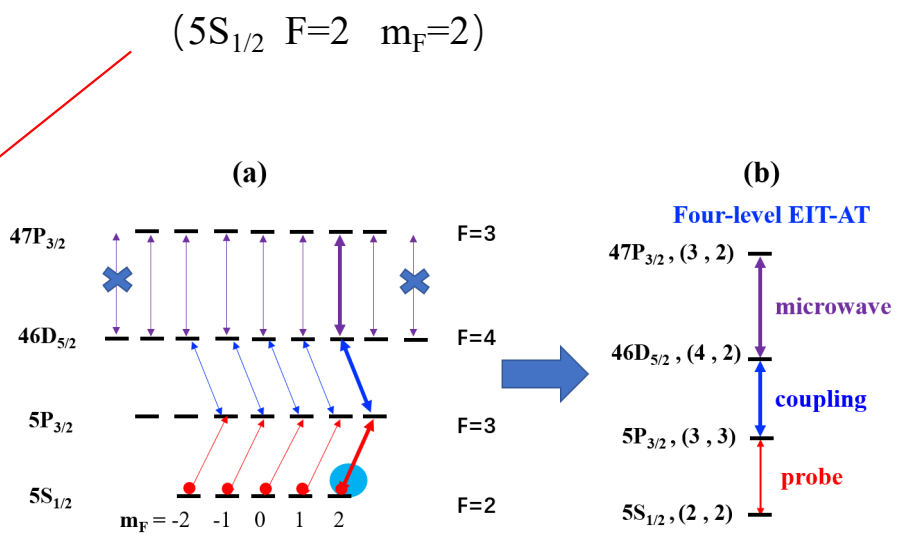
OD: 40

Number: 10^8

Temperature: 10 μK

步骤 2：利用光泵浦将原子泵浦到特定量子态





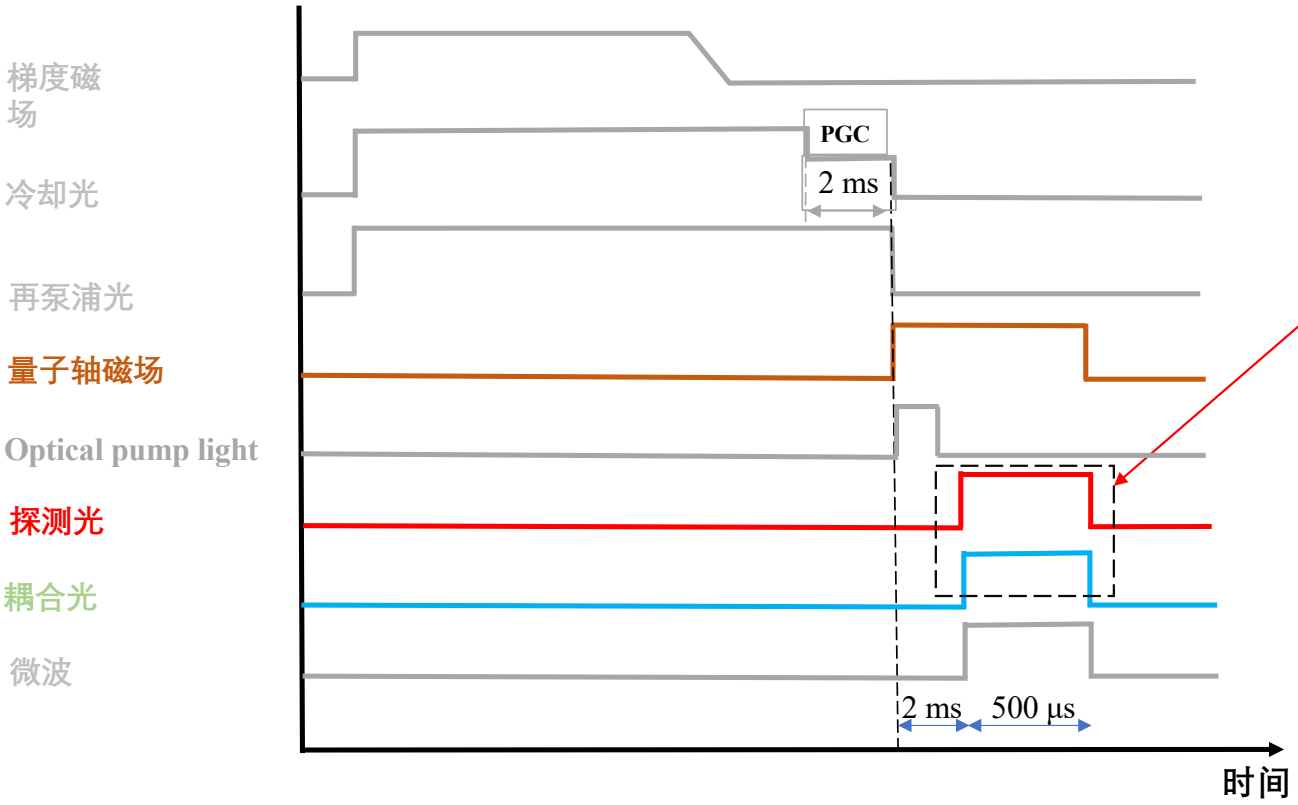
number: 5×10^7

实验步骤时序图

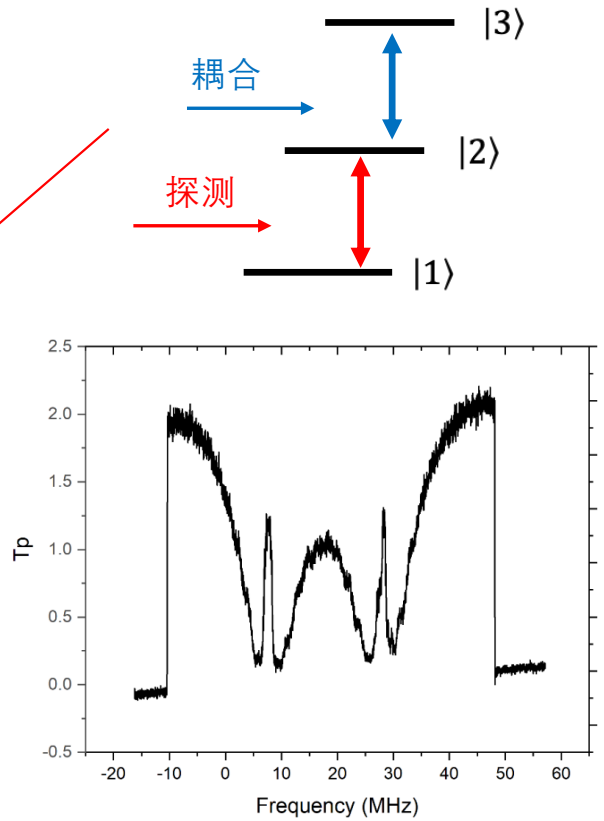
步骤 3：获得冷原子 EIT 光谱

University of Chinese Academy of Sciences

同时打开探测光和耦合光，扫描探测光频率



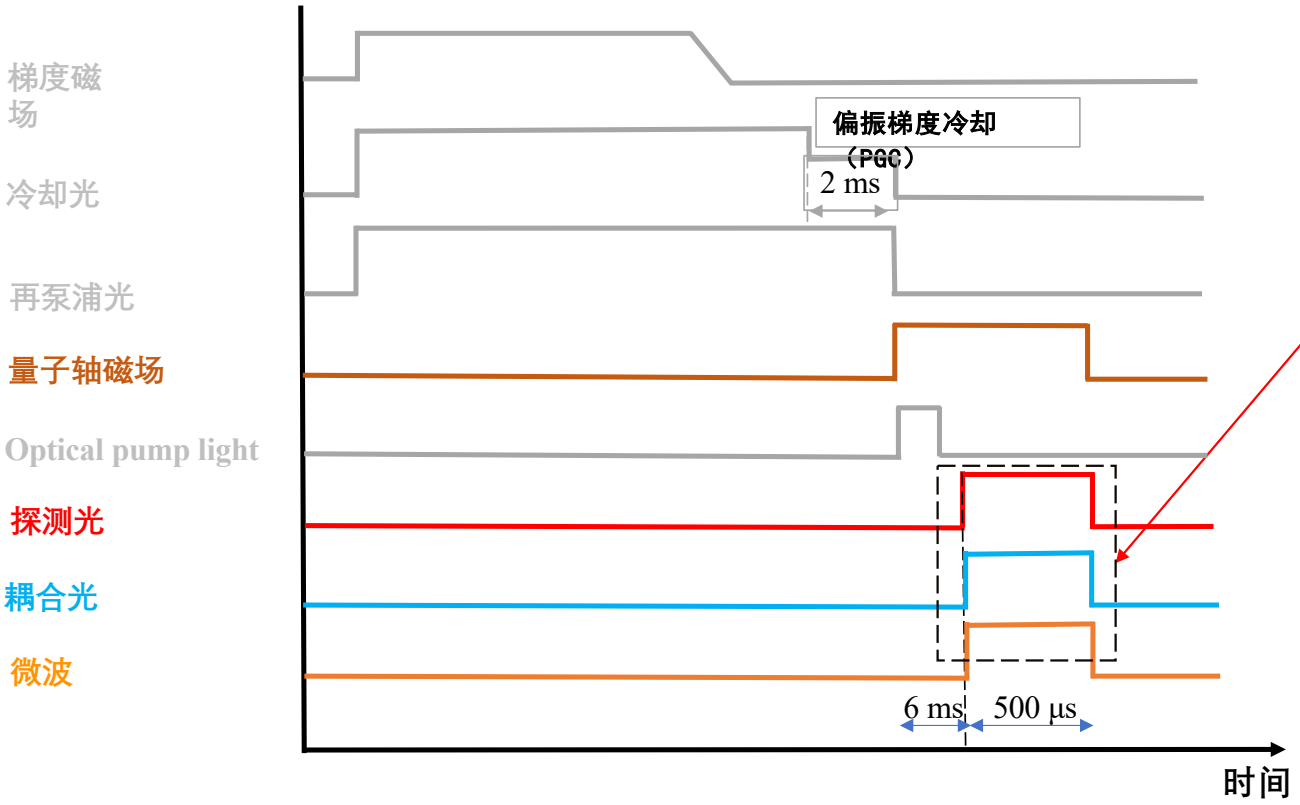
实验步骤时序图



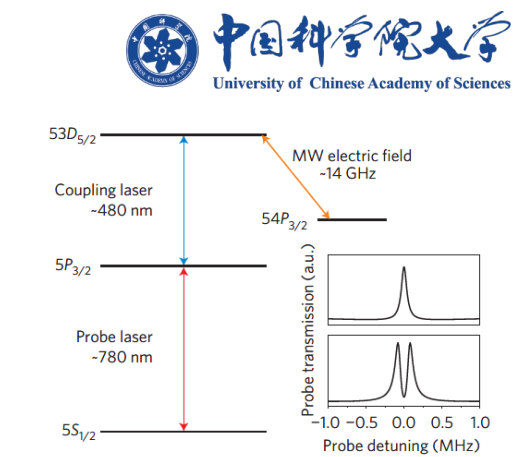
吸收线宽：10 MHz
EIT 线宽：0.5 MHz

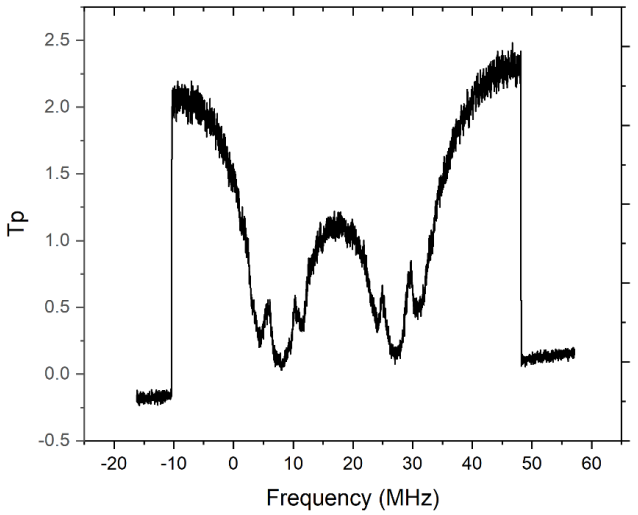
步骤 4：获得冷原子 EIT-AT 劈裂光谱

施加微波电场以获得 EIT-AT 劈裂光谱

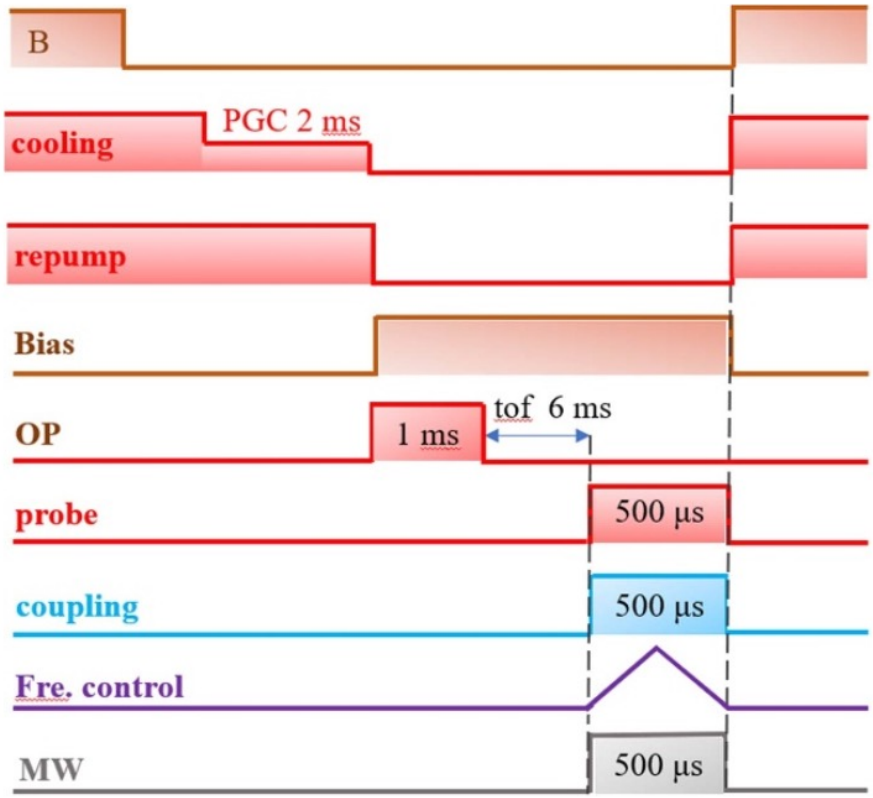


实验步骤时序图





步骤 5：获得冷原子 EIT-AT 劈裂光谱



在冷原子完全扩散前快速重新开启 MOT，可在 200 ms 内重新俘获足够的冷原子，将实验周期从 8 s 缩短到 0.22 s。

大纲

- 电磁感应透明（EIT）
- 里德堡原子
- 基于里德堡原子的电场测量
- 开源程序 RydIQule
- 里德堡激发的实验技术
- 我们在精密微波场测量中的几项工作

常规 EIT-AT 劈裂：不适用于弱场

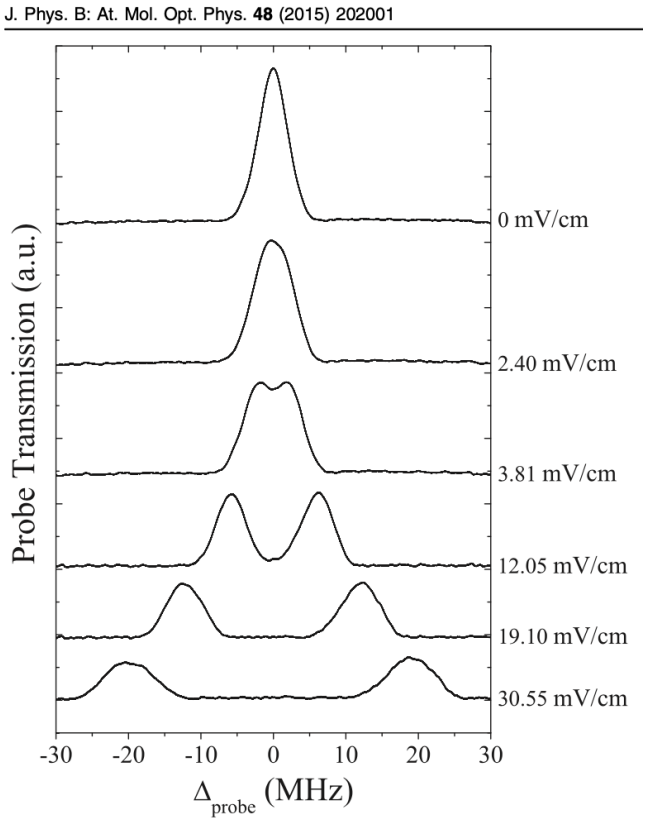


Figure 2. This figure shows experimental probe transmission spectral lineshapes for different RF–FI electric field amplitudes for ^{87}Rb as shown in figure 1 at a frequency of 14.233 GHz [3]. The splitting between the transmission peaks is proportional to the RF–FI electric field amplitude.

常规 EIT-AT 劈裂的下限：

EIT-AT 劈裂间隔 < EIT 线宽

↓

测量结果无法分辨

关键科学问题：如何提高劈裂间隔和分辨率？

J. Phys. B: At. Mol. Opt. Phys. 48 (2015) 202001

关键：如何提高劈裂间隔和分辨率？

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1. 降低残余多普勒展宽

1.1 冷原子

- Phys. Rev. A **101**(5), 053432 (2020)
- J. Phys. B: At., Mol. Opt. Phys. **56**(2), 025501 (2023)

1.2 三光子激发

- Optical and Quantum Sensing and Precision Metrology II, J. Scheuer and S. M. Shahriar, eds., International Society for Optics and Photonics (SPIE, 2022).
- J. Appl. Phys. 134(2), 023101 (2023)

2. 增大 EIT-AT 或色散信号的光谱劈裂间隔

2.1 微波频率失谐法

Appl. Phys. Lett. **108**(17), 174101 (2016)

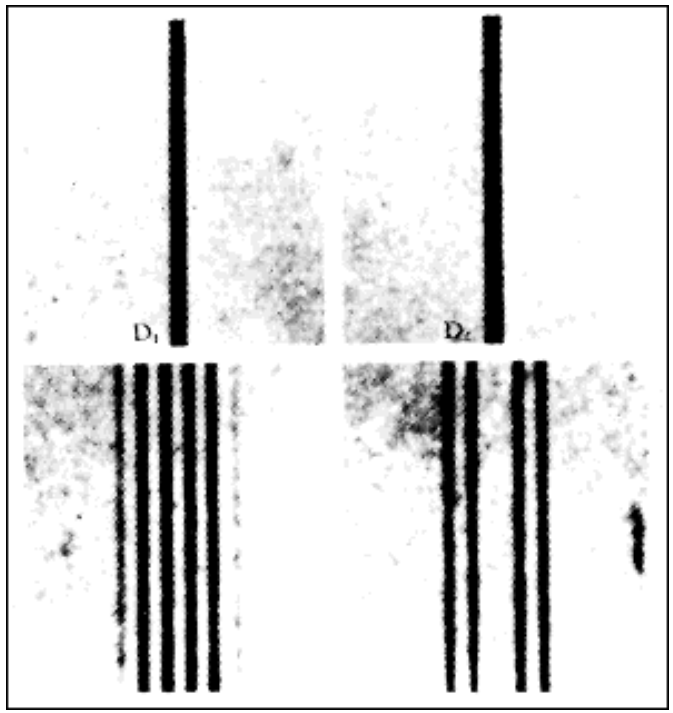
2.2 辅助微波场法

Phys. Rev. A **103**, 063113 (2021), Laser Phys. Lett. **19** 125207(2023)

2.3 微波幅度调制法

AIP Adv. **11**(8), 085127 (2021)

塞曼效应



磁场对里德堡 EIT 或 EIT-AT 有什么影响?

相关文献（按时间顺序）

1. “Splitting of an Electromagnetically Induced Transparency Window of a Cascade System with 133Cs Rydberg Atoms in a Static Magnetic Field,” Shanxia Bao, Wenguang Yang, Hao Zhang, Linjie Zhang, Jianming Zhao, Suotang Jia *Journal of the Physical Society of Japan*, **84,** 104301 (2015) ;
2. ” Polarization spectra of Zeeman sublevels in Rydberg electromagnetically induced transparency,” Bao, Shanxia and Zhang, Hao and Zhou, Jian and Zhang, Linjie and Zhao, Jianming and Xiao, Liantuan and Jia, Suotang *Phys. Rev. A* **94 ,** 043822 (2016);
3. “Direct measurement of excited-state dipole matrix elements using electromagnetically induced transparency in the hyperfine Paschen-Back regime,” Whiting, Daniel J. and Keaveney, James and Adams, Charles S. and Hughes, Ifan G. *Phys. Rev. A* **93 ,** 043854(2016);
4. "Tunable frequency stabilization to Zeeman sublevel transitions between an intermediate state and Rydberg states," Shanxia Bao, Hao Zhang, Jian Zhou, Linjie Zhang1, Jianming Zhao, Liantuan Xiao and Suotang Jia *Laser Phys.* **27 ,** 015701 (2017);
5. "High resolution electromagnetically induced transparency spectroscopy of Rydberg 87Rb atom in a magnetic field," H. Cheng, H. M. Wang, S. S. Zhang, P. P. Xin, J. Luo, and H. P. Liu, *Opt. Express* **25**, 33575-33587 (2017);
6. "Observation of the motional Stark shift in low magnetic fields," Kaiser, Manuel and Grimmel, Jens and Torralbo-Campo, Lara and Mack, Markus and Karlewski, Florian and Jessen, Florian and Schopohl, Nils and Fort\'agh, J\'ozsef *Phys. Rev. A* **96 ,** 043401 (2017);
7. "Paschen-Back effects and Rydberg-state diamagnetism in vapor-cell electromagnetically induced transparency," Ma, L. and Anderson, D. A. and Raithel, G. *Phys. Rev. A* **95,** 061804 (2017);
8. "Electromagnetically induced transparency with Rydberg atoms across the Breit-Rabi regime," J. B. Naber, A. Tauschinsky, H. B. van Linden van den Heuvell, R. J. C. *Spreeuw SciPost Phys.* **2**, 015 (2017);
9. "Interplay between optical pumping and Rydberg EIT in magnetic fields," Linjie Zhang, Shanxia Bao, Hao Zhang, Georg Raithel, Jianming Zhao, Liantuan Xiao, and Suotang Jia, *Opt. Express* **26**, 29931-29944 (2018)
10. “Rydberg electromagnetically induced transparency in a large Hilbert space,” Xue, Yongmei and Hao, Liping and Jiao, Yuechun and Han, Xiaoxuan and Bai, Suying and Zhao, Jianming and Raithel, Georg *Phys. Rev. A* **99,** 053426 (2019);
11. "Frequency stabilization method for transition to a Rydberg state using Zeeman modulation," Fengdong Jia, Jian Zhang, Lei Zhang, Fei Wang, Jiong Mei, Yonghong Yu, Zhiping Zhong, and Feng Xie *Appl. Opt.* **59**, 2108-2113 (2020);
12. "Dispersive microwave electrometry using Zeeman frequency modulation spectroscopy of electromagnetically induced transparency in Rydberg atoms," Fengdong Jia, Yonghong Yu, Xiubin Liu, Xi Zhang, Lei Zhang, Fei Wang, Jiong Mei, Jian Zhang, Feng Xie, and Zhiping Zhong *Appl. Opt.* **59**, 8253-8258 (2020);
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14. "Theoretical Study of Polarized Optical Bistability Due to Rydberg State in a Four-Level Atomic System under External Magnetic Field.," Javanmard, M. *Int J Theor Phys* **60**, 1283–1291 (2021);
15. "Optimizing the Rydberg EIT spectrum in a thermal vapor,"Su H J, Liou J Y, Lin I C, Chen Y H *Opt. Express.* **17**, 30(2):1499-1510 (2022);
16. “Optical-optical double resonance spectroscopy of Rb 5D3/2,5/2 in magnetic fields,” Z.S. Xua, M.H. Caia, S.H. Youa, S.S. Zhanga, H.P. Liua *Spectrochimica Acta Part B: Atomic Spectroscopy* **193**, 106453 (2022);
17. "High resolution spectroscopy of Rb in magnetic field by far-detuning electromagnetically induced transparency," Zi-Shan Xu, Han-Mu Wang, Ming-Hao Cai , Shu-Hang You and Hong-Ping Liu *Chinese Phys. B* **31**, 123201 (2022);
18. "Atom-based sensing technique of microwave electric and magnetic fields via a single rubidium vapor cell," Zhigang Feng, Xiaochi Liu, Yingyun Zhang, Weimin Ruan, Zhenfei Song, and Jifeng Qu, Opt. Express 31, 1692-1704 (2023).

相关文献（分类总结）

磁场下的里德堡 EIT 展现出丰富的光谱信息，并具有提高光谱信噪比的潜力，因此受到广泛关注。

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- 锁频：利用磁场调控里德堡 EIT，实现耦合光频率锁定。Shanxia Bao et al. [Laser Phys. 27, 015701 (2017)] Fengdong Jia et al. [Appl. Opt. 59, 2108-2113 (2020)]

- 偏振效应：研究光场偏振对里德堡 EIT 光谱的影响。Shanxia Bao et al. [Journal of the Physical Society of Japan, 84, 104301 (2015)] [Phys. Rev. A 94, 043822 (2016)] Xue Yongmei et al. [Phys. Rev. A 99, 053426 (2019)]

- 静磁场：研究不同静磁场强度下里德堡能级的线性和非线性变化及相应 EIT 光谱。Ma, L. et al. [Phys. Rev. A 95, 061804 (2017)] Linjie Zhang et al. [Opt. Express 26, 29931-29944 (2018)] J. B. Naber et al. [SciPost Phys. 2, 015 (2017)]

- 光谱强度与分辨率：优化里德堡 EIT 光谱的强度与分辨率。H. Cheng et al. [Opt. Express 25, 33575-33587 (2017)], Su H J et al. [Opt. Express. 17, 30(2):1499-1510 (2022)], Z.S. Xua et al. [Spectrochimica Acta Part B: Atomic Spectroscopy 193, 106453 (2022)] [Chinese Phys. B 31, 123201 (2022)]

  交流磁场：利用交流磁场调制里德堡 EIT 光谱，提高读出区域的信噪比，并进一步结合原子混频器实现相位探测。Fengdong Jia et al. [Appl. Opt. 59, 8253-8258 (2020)] [J. Phys. B: At. Mol. Opt. Phys. 54, 165501 (2021)]

Research Article Vol. 30, No. 2 / 17 Jan 2022 / Optics Express 1499
Optics EXPRESS

Optimizing the Rydberg EIT spectrum in a thermal vapor

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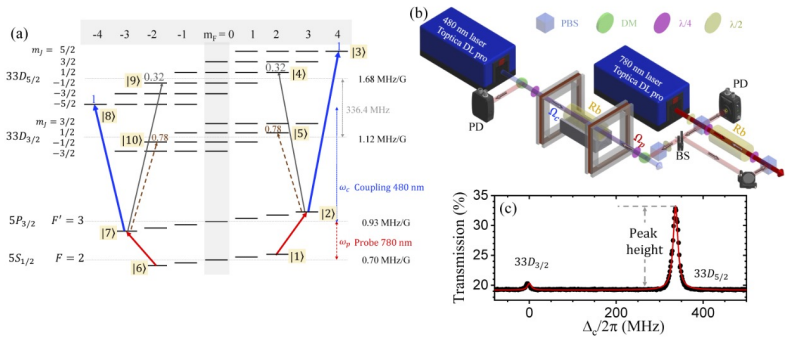

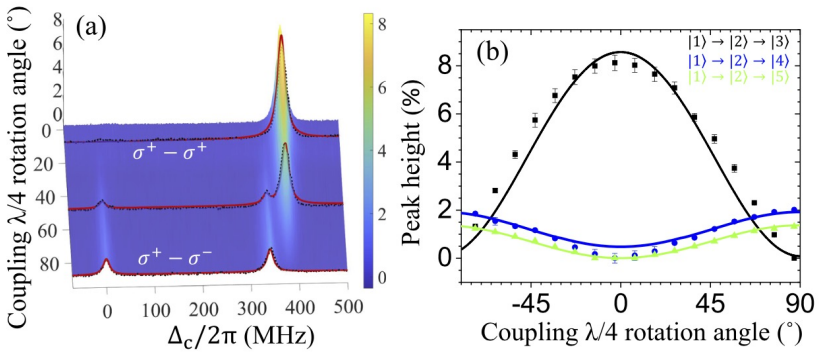

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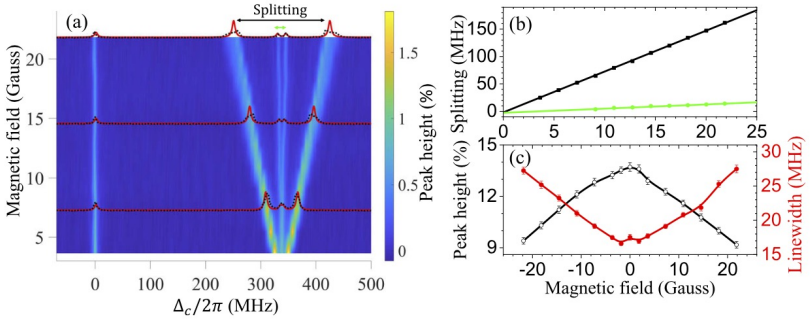

Fig. 3. (a) Rydberg-state EIT evolution along with the magnetic field under a temperature of 27°C. Both the probe and coupling fields are linearly polarized, which is perpendicular to the quantum axis defined by the magnetic field direction. As the applied magnetic field is sufficiently large, e.g. 6 Gauss, the outermost peaks can be completely resolved. In the panel, we also show the spectral lines for 7.3, 15, and 22 Gauss magnetic fields. The four peaks involving $|33D_{5/2}\rangle$ state correspond to the transitions of $|6\rangle \rightarrow |7\rangle \rightarrow |8\rangle$, $|6\rangle \rightarrow |7\rangle \rightarrow |9\rangle$, $|1\rangle \rightarrow |2\rangle \rightarrow |4\rangle$, and $|1\rangle \rightarrow |2\rangle \rightarrow |3\rangle$, from left to right peaks. We take the Zeeman effect and Doppler shifts into account in the simulation, shown as the solid lines. The set parameters are $\alpha = 0.36 \pm 0.02$ according to the baseline transmissions and $\{\Omega_c$ (for CGC=1), $\gamma\} = 2\pi \times \{2.1, 6\}$MHz based on the EIT profiles. (b) The frequency splittings of two main EIT peaks (black squares) and two inner peaks (green circles) versus the magnetic field. The linear fits give the frequency splittings of 7.5 and 0.77 MHz/G. Note that the predicted frequency splitting of $|33D_{3/2}\rangle$ EIT is 0.058 MHz/G, which is magnetic insensitive. (c) The EIT peak height and its relevant EIT linewidth under σ^+-σ^+ polarization configuration and temperature of 51°C. The maximum peak height, as well as the narrowest linewidth, occurred when the magnetic field was around zero.

磁场下的 EIT-AT 劈裂尚未得到详细的定量研究。

静磁场下的实验原理与装置

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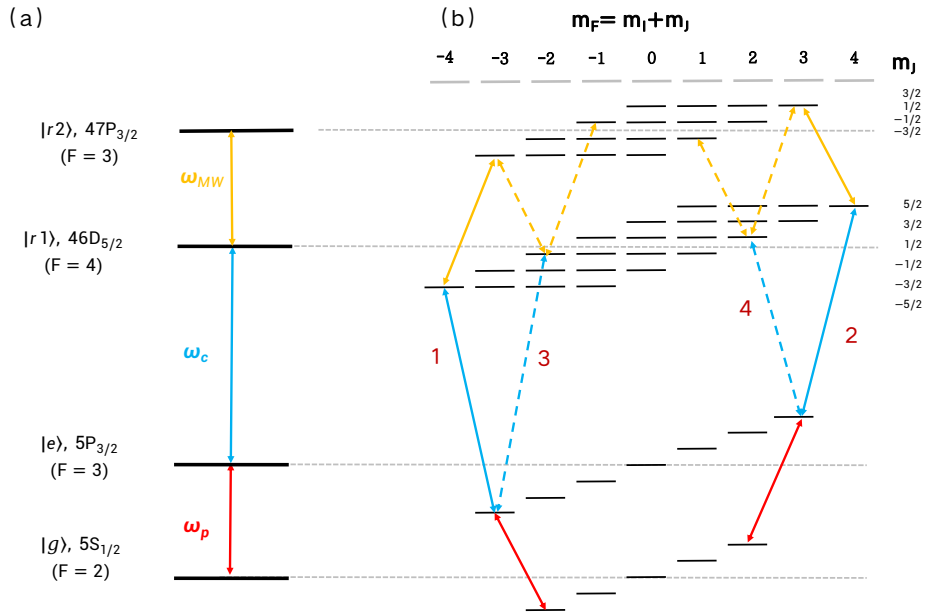
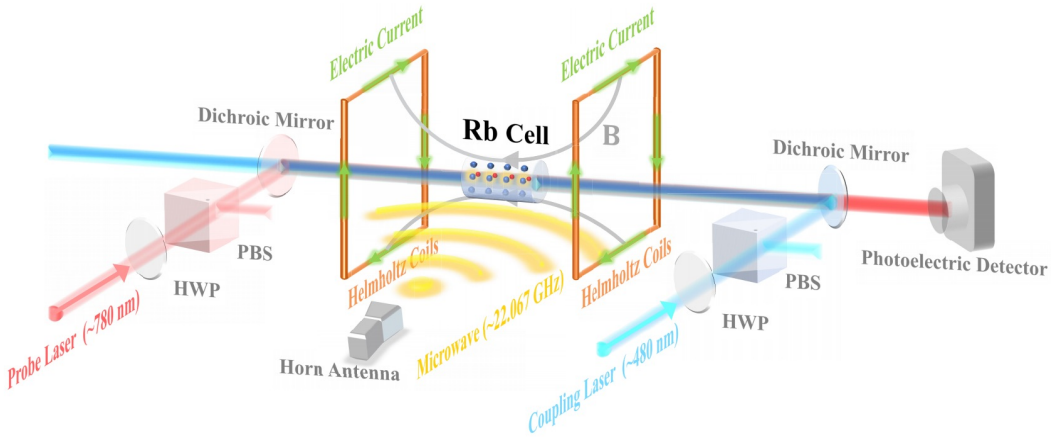
磁场下的能级



实验装置示意图



Xinheng Li, Yue Cui, Fengdong Jia, *Opt. Express* **31**, 38165 (2023)

静磁场下的 EIT 与 EIT-AT 劈裂光谱

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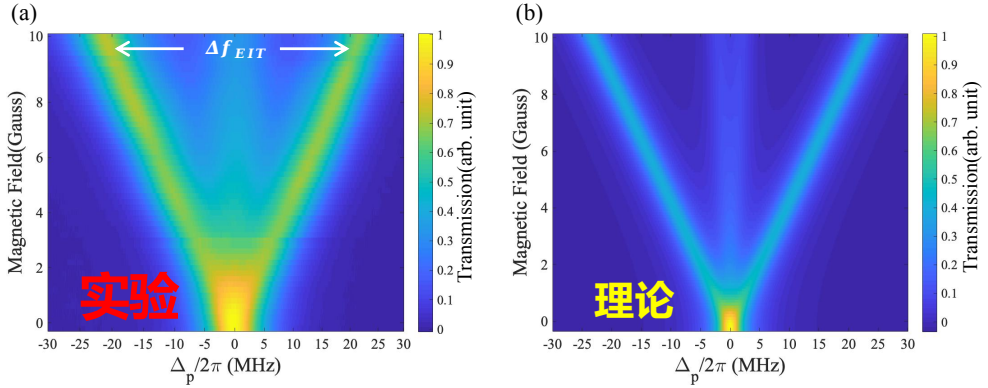
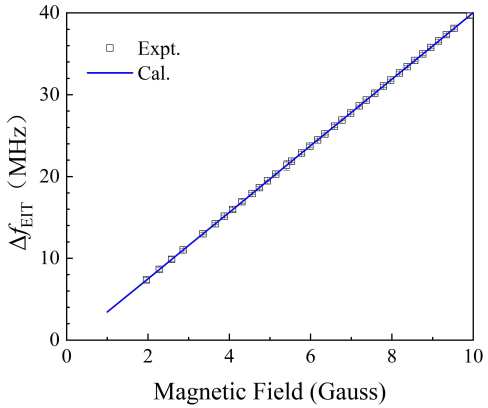
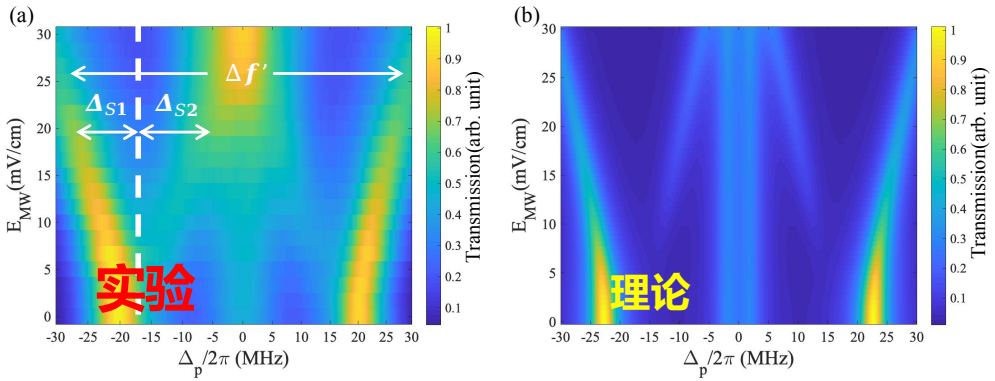
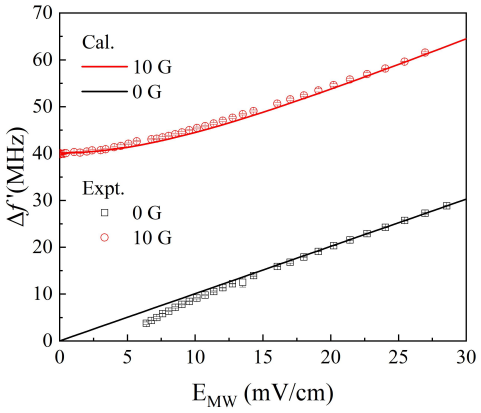
静磁场下的 EIT





静磁场和微波场下的 EIT-AT





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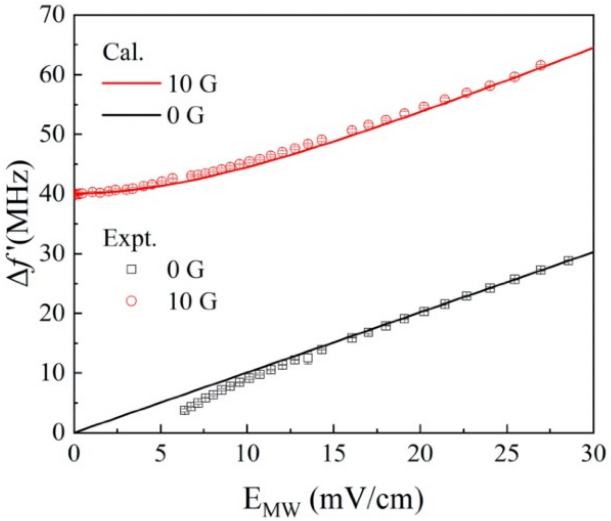
量



$$T(\Delta_c) = exp[-\alpha \frac{\Gamma_e^2(4\gamma^2 + 4\delta^2) + 2\gamma\Omega_c^2\Gamma_e}{(2\gamma\Gamma_e + \Omega_c^2 - 4\Delta_p\delta)^2 + (4\Delta_p\gamma + 2\Gamma_e\delta)^2}]$$

$$\delta = B \times (\Delta_g - \Delta_e + \Delta_{r_1} + \Delta_D) + \frac{\omega_c}{\omega_p}\Delta_p + \Delta_S$$

$$\Delta_g = \frac{\mu_B}{\hbar} g_{F,g} m_F,$$

$$\Delta_e = \frac{\mu_B}{\hbar} g_{F,e} m_{F'},$$

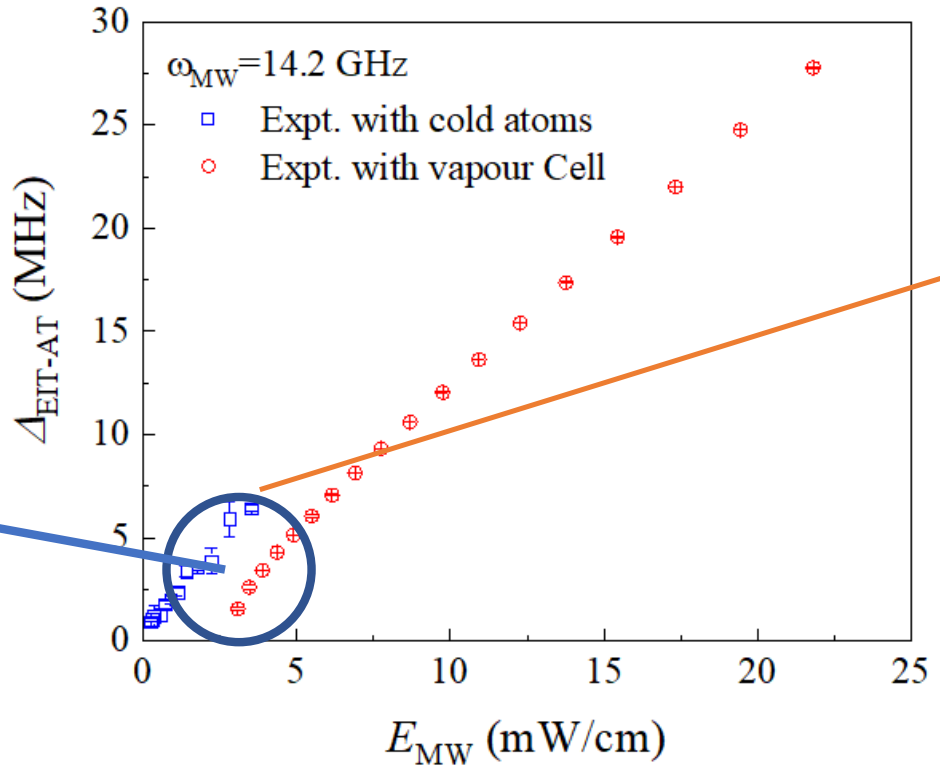
$$\Delta_{r_1} = \frac{\mu_B}{\hbar} g_{J,r_1} m_{r_1}.$$

1. 利用静磁场下观测到的两个最大 |m_F| 态之间的劈裂间隔。
2. 最大 |m_F| 态之间的 Clebsch-Gordan 系数更大。
3. 静磁场引起的微波电场频率失谐会增大 EIT-AT 劈裂间隔

结果：提高劈裂间隔和光谱分辨率，使 EIT-AT 劈裂在弱微波电场下仍然有效！

Xinheng Li, Yue Cui, Fengdong Jia, *Opt. Express* **31**, 38165 (2023)

冷原子与气室中 EIT-AT 劈裂测量结果对比



由于热原子中存在多普勒失配因子 $\lambda p/\lambda c$，测量结果的斜率存在差异

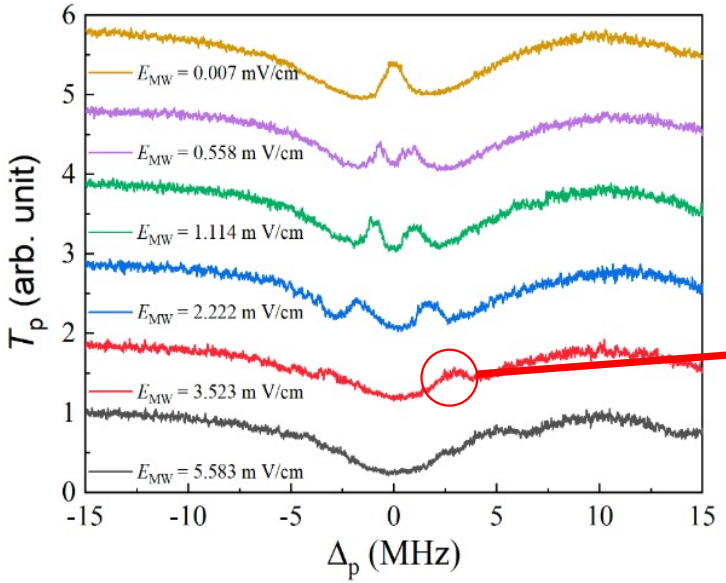
在冷原子中扫描探测光时，微波场较强时 EIT-AT 劈裂线性区的上限会受限

为什么？

- 冷原子中 EIT-AT 劈裂的下限可达 272 μV/cm；
- 与气室中 5 mV/cm 相比，线性区域下限约降低 18 倍。

Fei Zhou, Fengdong Jia, *et al.*, *J. Phys. B: At. Mol. Opt. Phys.* **56** 025501 (2023).

测量上限受限原因分析



吸收线宽因多普勒效应而不同：

- 冷原子（10 MHz）
- 室温气室（500 MHz）

冷原子中存在 10 MHz 吸收线宽的吸收峰；当劈裂峰超出吸收峰范围时将无法观测！

扫描探测光频率 → **耦合光频率固定** → 透明峰只出现在探测光共振附近 → 共振点移出吸收峰

微波强度增加

扫描耦合光频率 → **探测光频率固定** → 探测光始终处于共振并被吸收 → 透明峰始终存在

微波强度增加

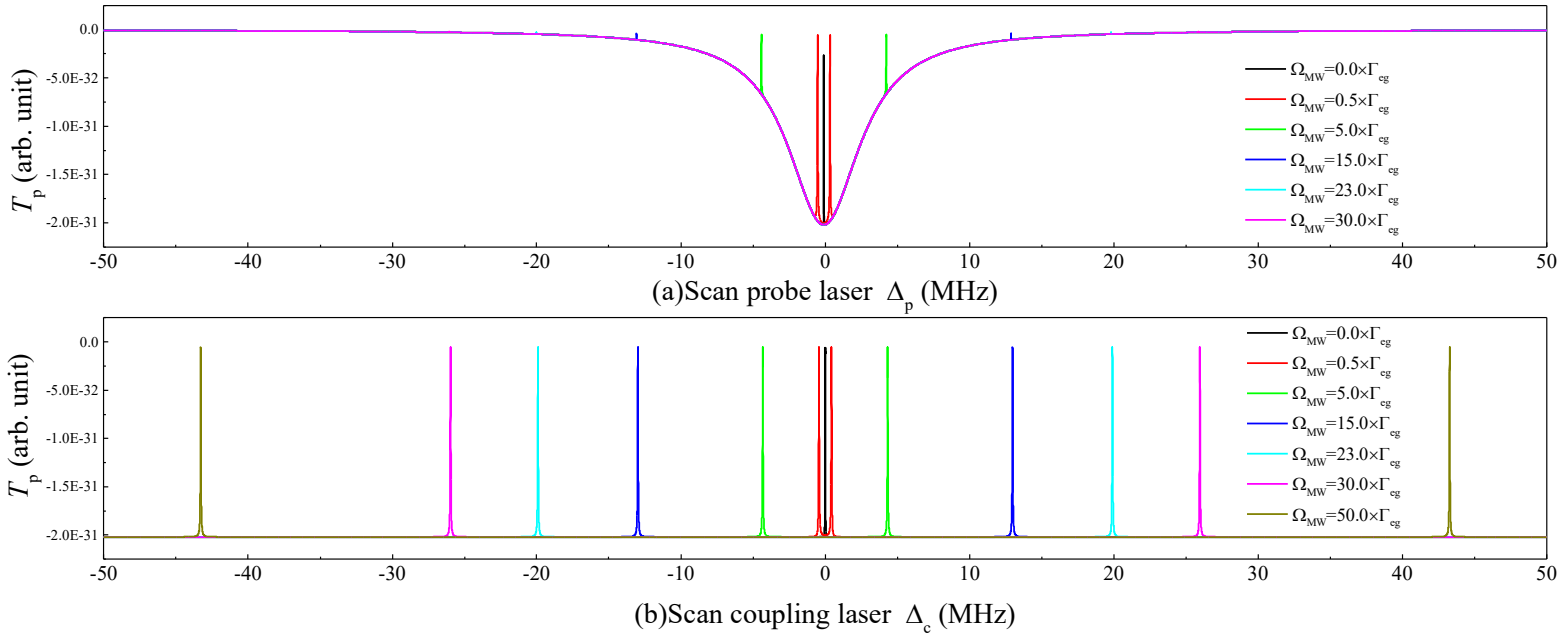
Fei Zhou, Fengdong Jia, *et al.*,, *J. Phys. B: At. Mol. Opt. Phys.* **56** 025501 (2023).

扫描探测光频率的计算结果或扫描耦合光频率

扫描探测光频率

VS

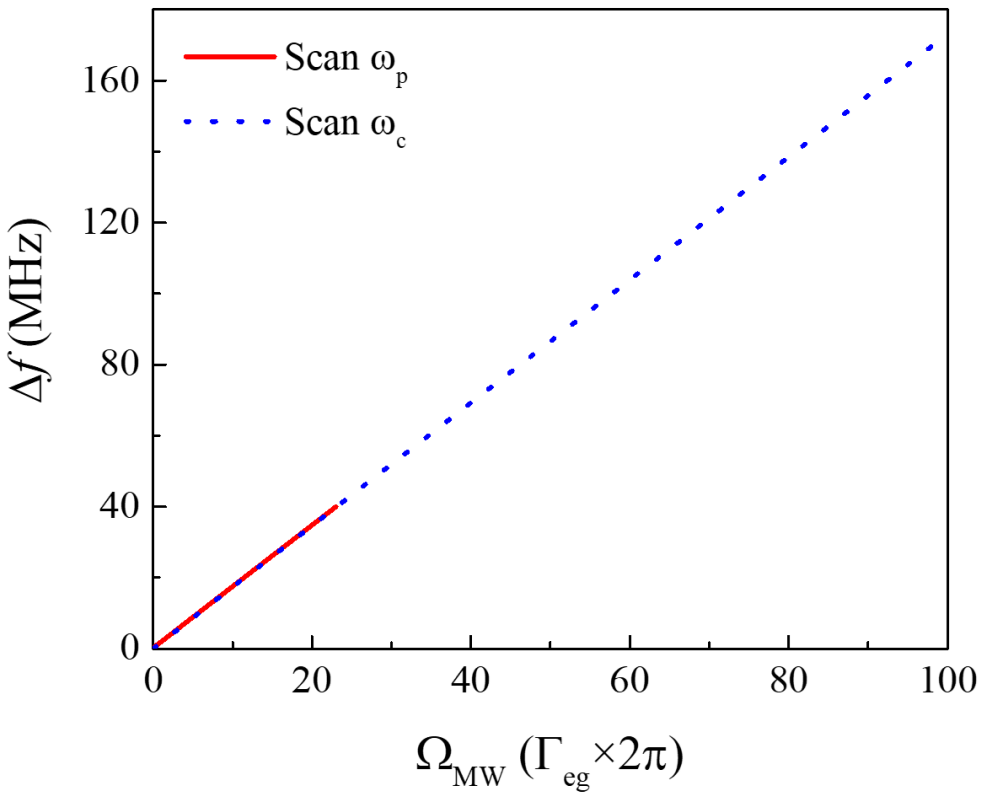
扫描耦合光频率



扫描探测光时，当微波场强增大到一定程度，EIT-AT 劈裂峰会超出冷原子吸收峰范围而无法观测。

扫描耦合光频率时，不受吸收峰线宽限制，计算结果与理论预期吻合良好

两种扫描方法计算结果的详细比较



1. 微波电场强度与 EIT-AT 劈裂间隔之间存在线性关系

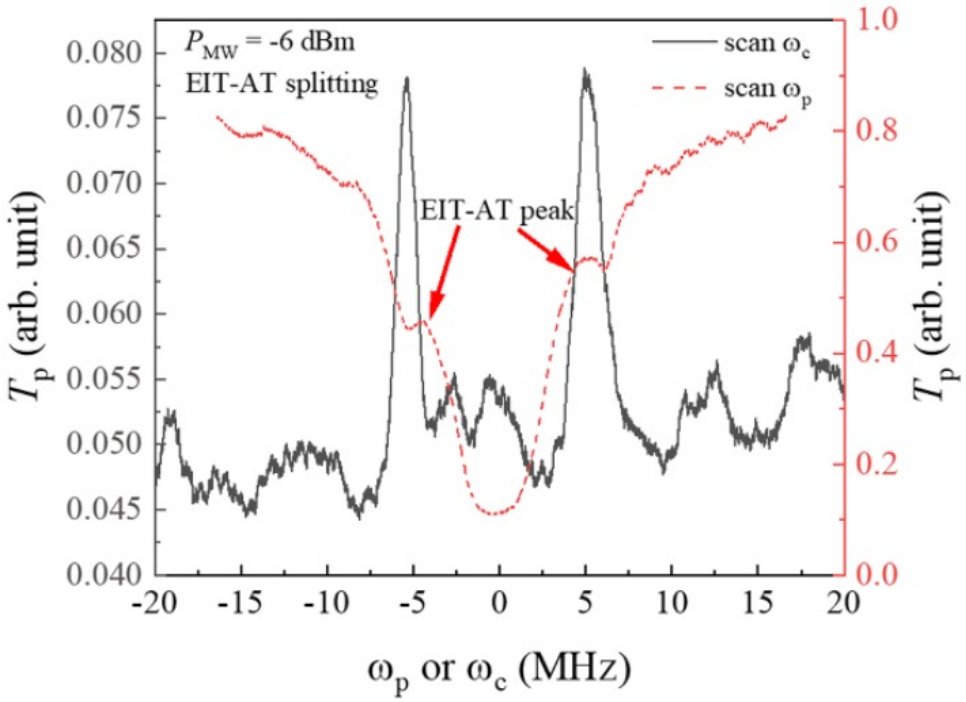
2. 两者可测量的微波电场强度下限相同

3. 扫描耦合光频率得到的最大微波电场强度更大

实验

1. 将耦合光光路改为双程 AOM 移频光路
2. 调整耦合光功率以满足所需值并控制其稳定性
3. 修改时序程序，将耦合光改为扫描模式

相同微波电场强度下两种扫描方法的 EIT-AT 光谱对比



在相同微波电场强度下，通过扫描探测光频率和扫描耦合光频率得到的 EIT-AT 劈裂峰间隔相同。

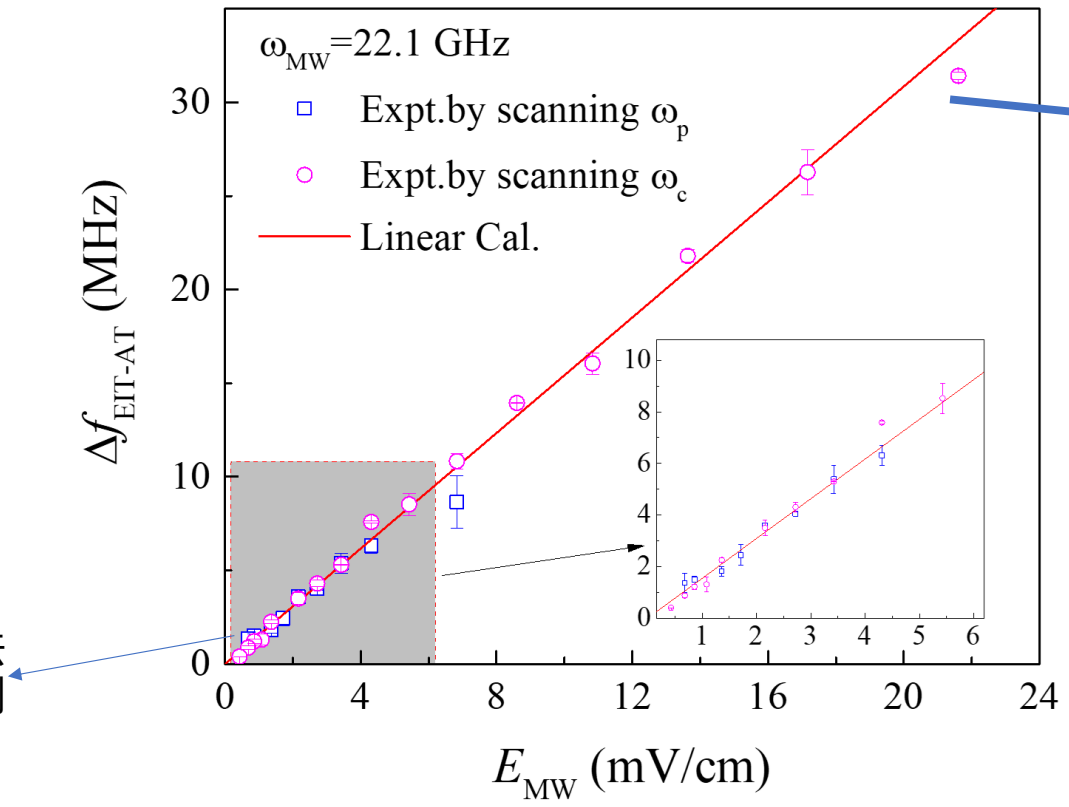
实验系统可靠，并与理论预测一致。

Fei Zhou, Fengdong Jia, *et al.*,, *J. Phys. B: At. Mol. Opt. Phys.* **56** 025501 (2023).

不同微波电场强度下两种扫描方法的测量结果对比

中国科学院大学 University of Chinese Academy of Sciences

总体结果



两种扫描方法具有相同的测量下限

扫描耦合光频率测量的线性范围上限为 21.6 mV/cm。这是扫描探测光频率时 6.8 mV/cm 线性范围上限的三倍。
该上限受我们的耦合光 AOM 限制。

Fei Zhou, Fengdong Jia, *et al.*, *J. Phys. B: At. Mol. Opt. Phys.* **56** 025501 (2023).

Acta Physica Sinica

基于磁光阱荧光损失谱的微波电场测量 *

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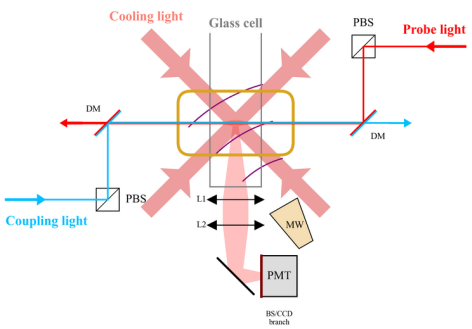
本文利用冷铷原子样品，在无需关闭磁光阱（MOT）的条件下，通过 MOT 荧光损失谱方法

MOT fluorescence-loss microwave electrometry

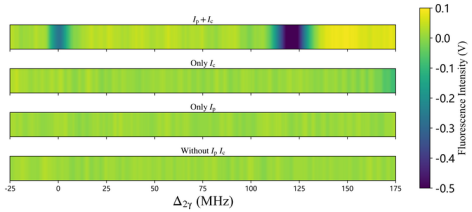
continuous cold-atom readout | ~6 MHz linewidth | calibrated Autler-Townes response

(a) Continuous MOT



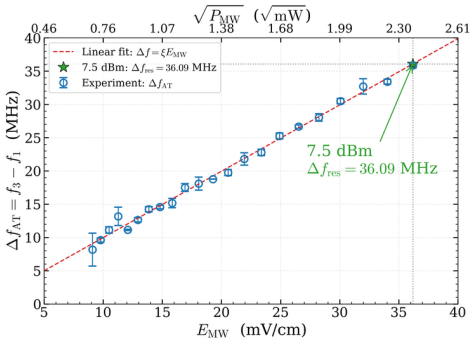
2D+ cold 87Rb cloud; 780/480 nm beams and PMT fluorescence readout.

(b) Loss readout



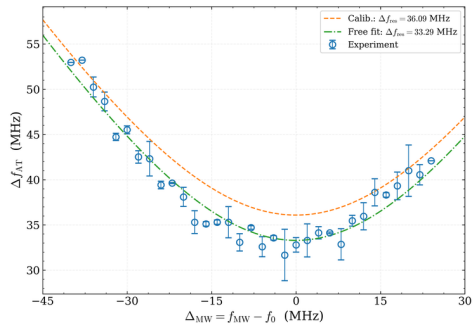
Two-photon Rydberg resonance opens a fluorescence-loss channel.

(c) MW-field scale



Resonant AT splitting is linear in E_MW; Delta f_res = 36.09 MHz.

(d) Detuned response



Peak separation follows the detuned AT model for frequency inference.

Key result: continuous MOT operation enables cold-atom MW sensing with narrow fluorescence-loss spectra

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感谢聆听！！

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希望我们一起能把微波电场的量子传感做得更好，为精密测量和应用作出贡献。

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谢谢!

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