核物理与化学研究所
INSTITUTE OF NUCLEAR PHYSICS AND CHEMISTRY

Progress in MEOP based ^3He Polarization System

Liangyong Wu (吴良勇)

Institute of Nuclear Physics and Chemistry
China Academy of Engineering Physics

2025/2/27

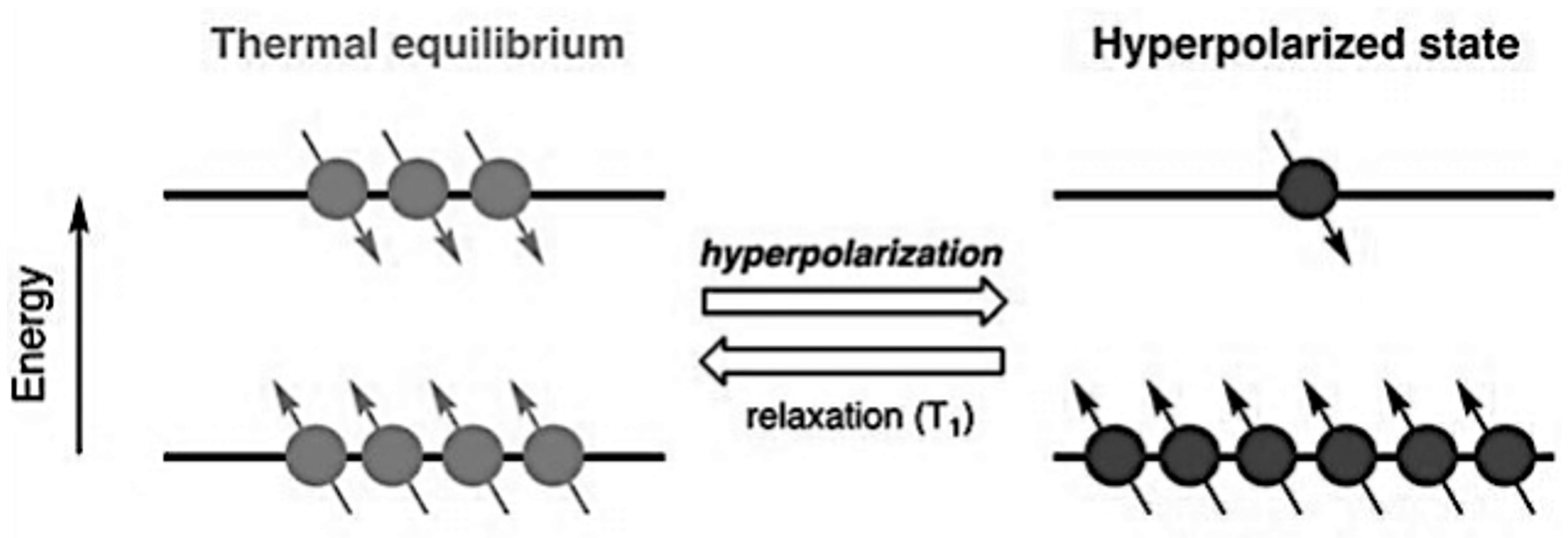
PNCMI 2025 Dongguan

Outline

- Introduction to ^{3}He Polarization
- The Basic Principle of MEOP
- Development of MEOP ^{3}He System
- Summary and Outlook

- Introduction to ^3He Polarization
- The Basic Principle of MEOP
- Development of MEOP 3He System
- Summary and Outlook

^{3}He nuclei spin hyperpolarization

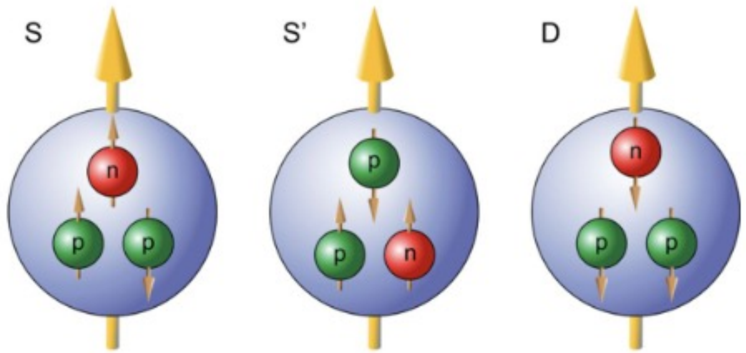


Thermal equilibrium: $P_n = \frac{N_+ - N_-}{N_+ + N_-} \approx 10^{-5}$ Hyperpolarized state: $P_n \approx 10^{-1}$

(For ^{3}He @ T=300 K, B=1 T)

Application in nuclear and neutron physics

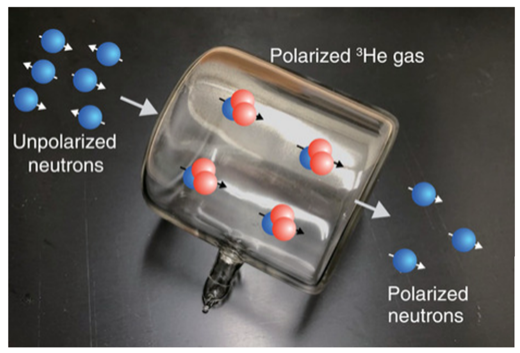
Polarized neutron target

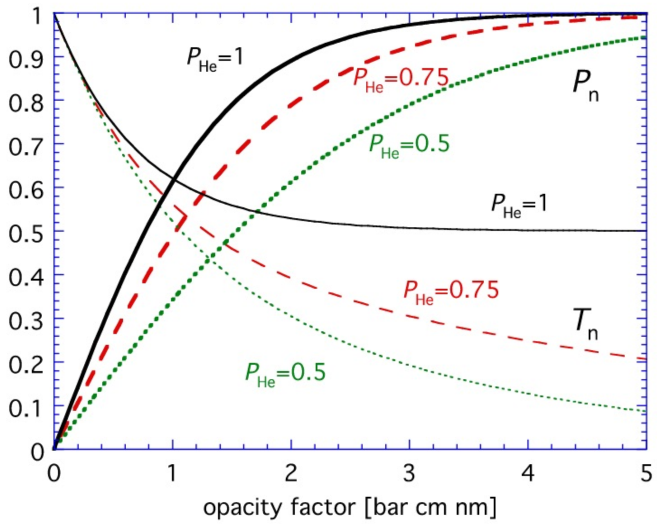


~87% ~8% ~1.5%

~87% of ^{3}He spin is carried by the unpaired neutron.

Neutron spin filter



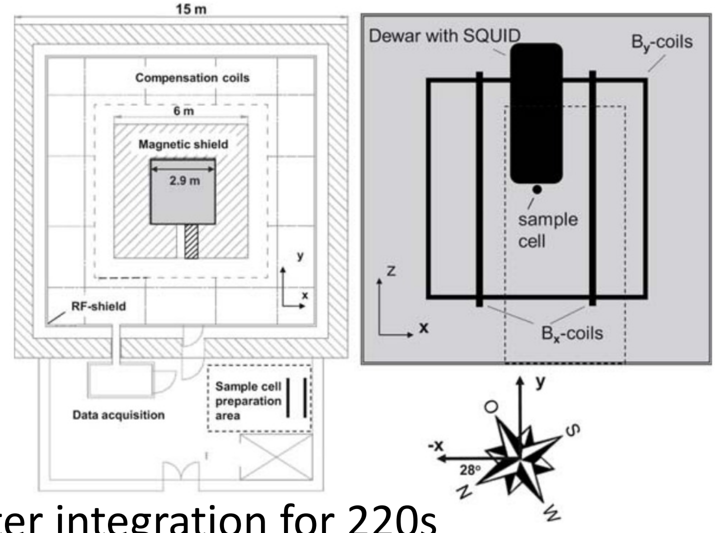


Strong spin-dependent neutron absorption cross-section.

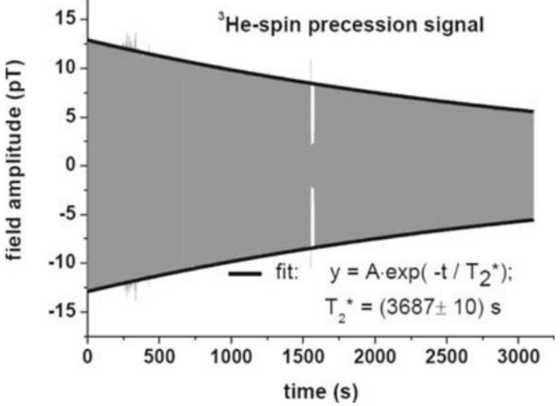
Friar, James Lewis, et al *Physical Review C* 42.6 (1990): 2310.
Gentile, Thomas R., et al. *Reviews of modern physics* 89.4 (2017): 045004.

Magnetic field metrology

Long coherence time enabling long-term measurements

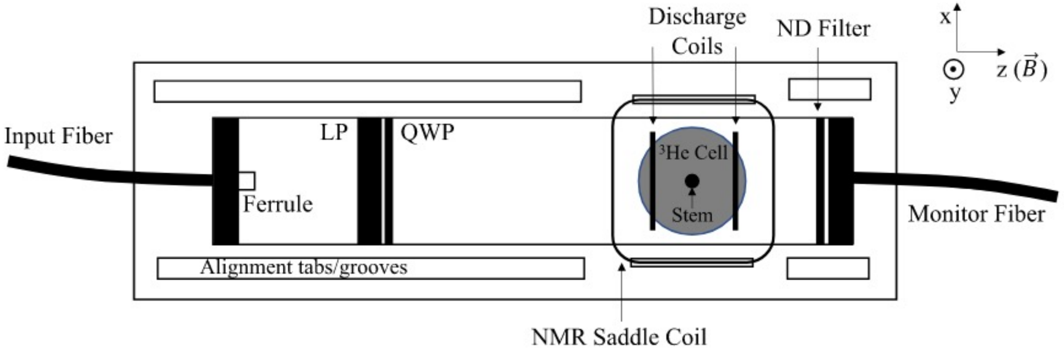


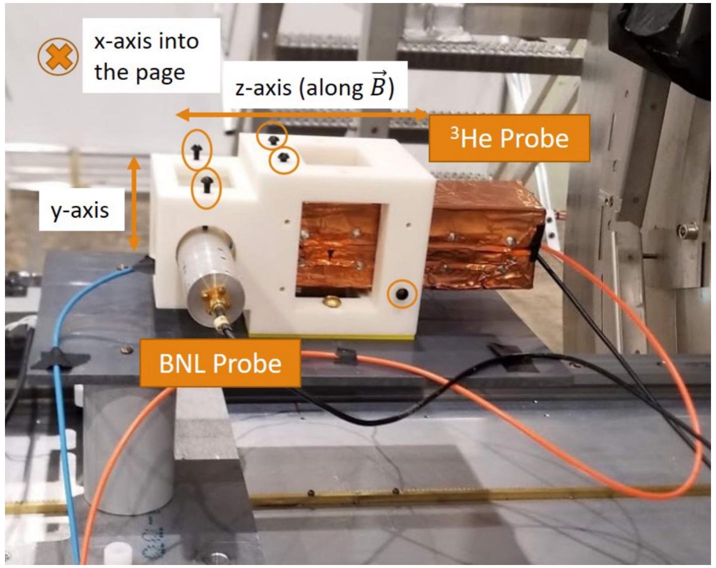
$\delta B \approx fT$ after integration for 220s



Gemmel, C., et al. *The European Physical Journal D* 57 (2010): 303-320

High-field (~T) calibration with a precision of ppb





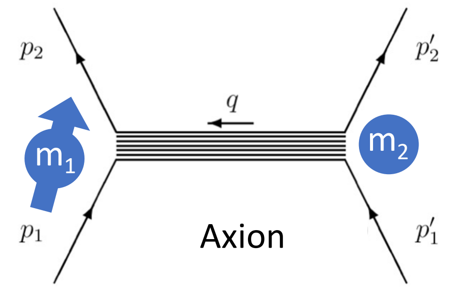
Farooq, Midhat, et al. *Physical Review Letters* 124.22 (2020): 223001.

Tests on fundamental physics

- Electric dipole moments (EDMs) searches
- Lorentz and CPT violation tests
- Exotic spin-dependent interactions

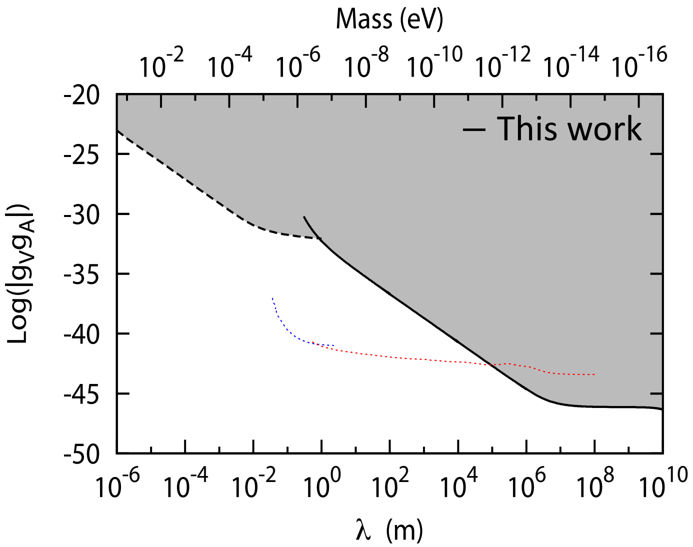
and axion dark matter searches.

$$V_{VA} = \frac{\hbar g_V g_A}{2\pi} \frac{e^{-r/\lambda}}{r} \vec{\sigma} \cdot \vec{v}$$
$$= \hbar \gamma \vec{B}_{VA} \cdot \vec{\sigma}$$

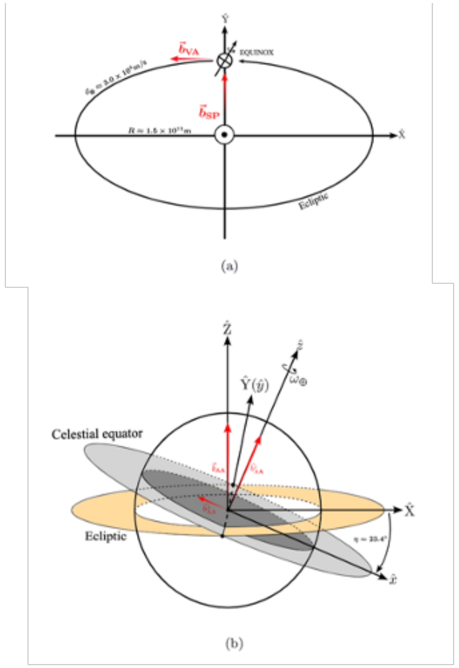


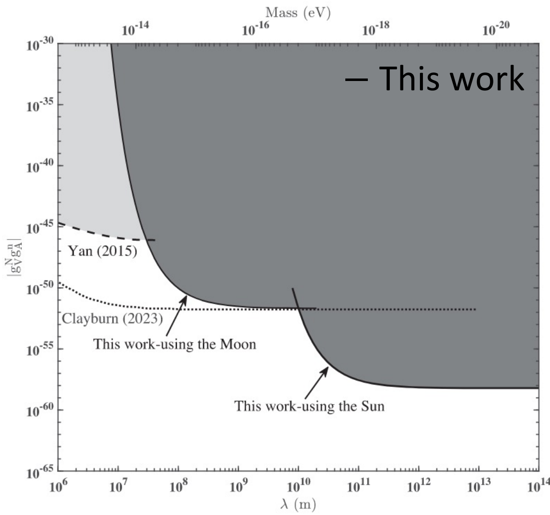
The fluctuated effective magnetic field B_{VA} causes the relaxation of ^{3}He.

$T_1 \approx 347$ hrs[A. K. Petukhov, et. al. PRL 115, 182001 (2015)]



Measuring the effective magnetic field generated by the Sun and Moon using the ^{3}He-^{129}Xe comagnetometer.





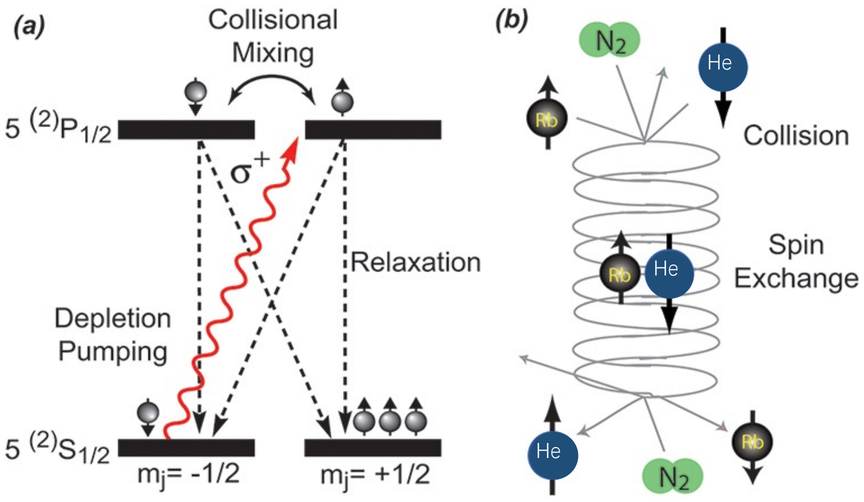
 H.Yan, et. al. Physical Review Letters, 115, 182001 (2015) L. Y. Wu, et. al. Physical Review Letters, 131, 091002 (2023)

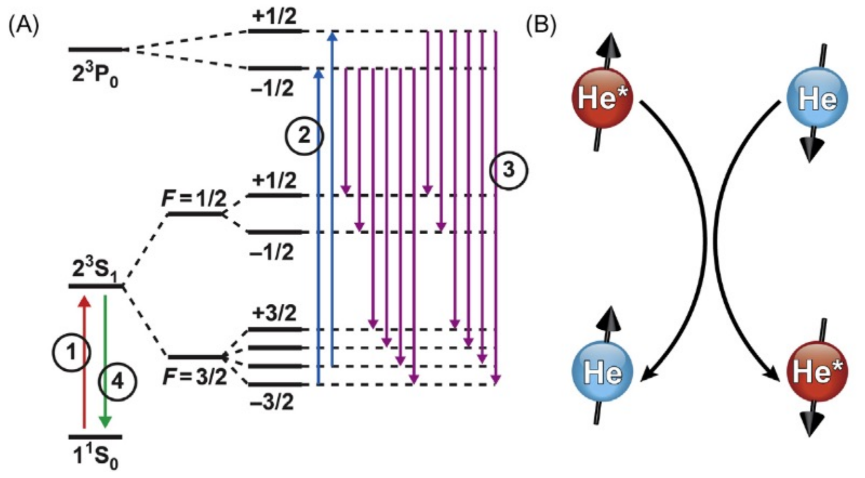
- Introduction to ^3He Polarization
- The Basic Principle of MEOP
- Development of MEOP 3He System
- Summary and Outlook

Indirect approaches of ^{3}He polarization

Spin Exchange Optical Pumping (SEOP)

Metastability-Exchange Optical Pumping (MEOP)





$Rb(\uparrow)+{}^3He(\downarrow) \rightarrow Rb(\downarrow)+{}^3He(\uparrow)$

${}^3He^*(\uparrow)+{}^3He(\downarrow) \rightarrow {}^3He(\uparrow)+{}^3He^*(\downarrow)$

Spin Angular Momentum Transfer: photon→electron →nucleon

Goodson, B. M., et al. *Hyperpolarized and Inert gas MRI*. Academic Press, 2017. 23-46.

Comparison between these two approaches

- SEOP

1960: Bouchiat, M. Ab, et. al. *Physical review letters* 5.8 (1960): 373.

- Slow polarization production (several hours)
- Saturated ^{3}He Polarization (70%-80%)
- High pressure (0.5 to 13 bar)
- Gas cell heating required
- Easy for In-suit polarization
- Successfully applied to polarize

^{21}Ne、^{129}Xe、^{131}Xe

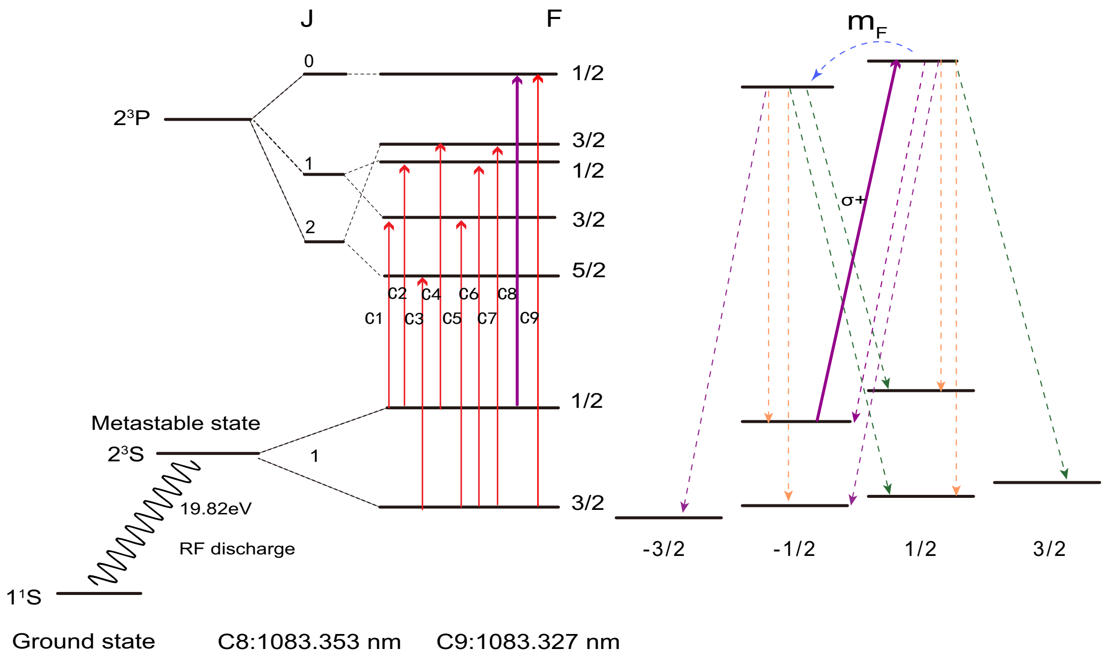
- MEOP

1962: Walters, G. K., et. al. *Physical Review Letters* 8.11 (1962): 439.

- Fast polarization production (several minutes)
- Saturated ^{3}He Polarization (70%-80%)
- Low pressure (1 mbar)
- Continuous RF discharge
- Need compression for application
- Exclusively applied to polarize Helium

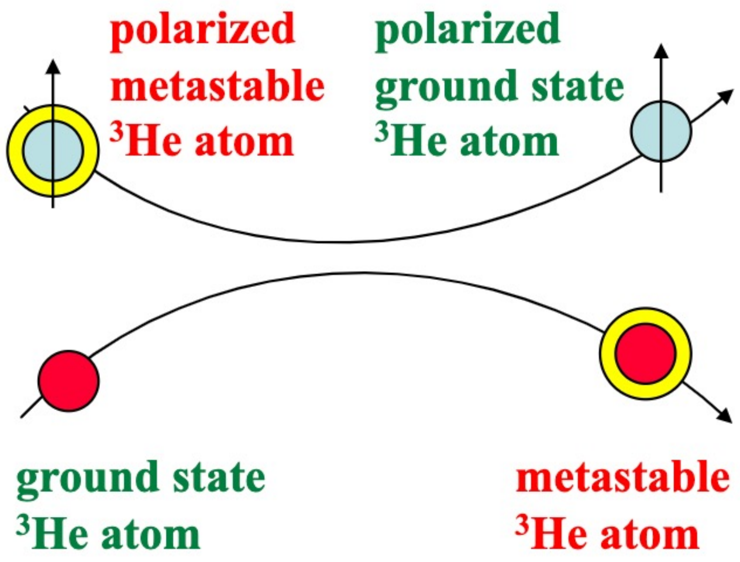
Processes involved in low-field MEOP

- Optical Pumping



1. Striking the atoms into the metastable state by discharge,
2. The metastable state ^3He is polarized by the cycling optical transition between 2^3S-2^3P (e.g., C_8 or C_9 Component).

- Metastability-Exchange Collisions



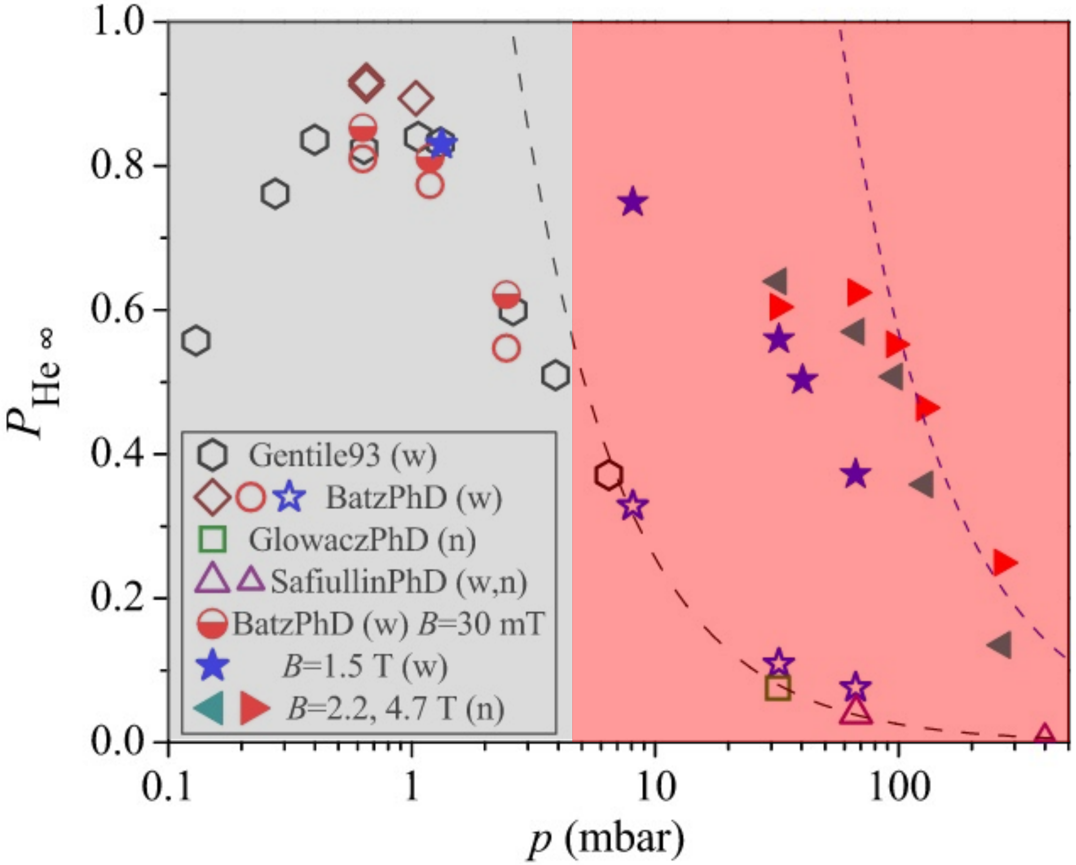
The excitation energy is exchanged in the collisions with nuclear spin unperturbed.

Wang, Yuting, et al. *Science China Physics, Mechanics & Astronomy* 67.7 (2024): 273011.

Recent Advancements in MEOP ^{3}He

Conditions of Efficient MEOP:

- low field (~ mT), low pressure (~ mbar)
- high field (~ T), high pressure (~ 100 mbar)



MEOP ^{3}He without laser

PHYSICAL REVIEW A **98**, 063405 (2018)

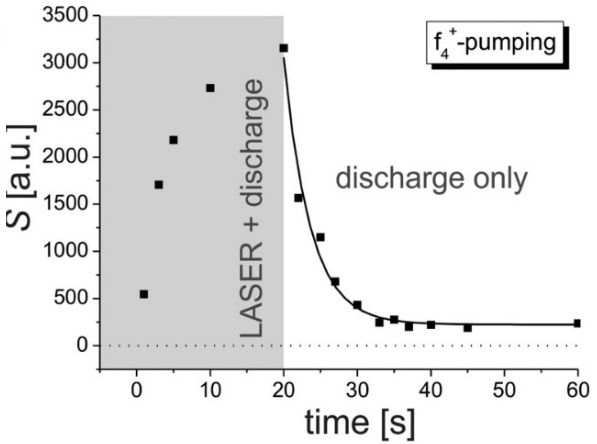
Nuclear hyperpolarization of ^{3}He by magnetized plasmas

A. Maul,[1] P. Blümler,[1] P.-J. Nacher,[2] E. Otten,[1] G. Tastevin,[2] and W. Heil[1,*]
[1]*Institute of Physics, University of Mainz, 55128 Mainz, Germany*
[2]*Laboratoire Kastler Brossel, ENS-PSL University, Centre National de la Recherche Scientifique, Sorbonne Université, Collège de France, 24 rue Lhomond, 75005 Paris, France*

(Received 20 June 2018; published 5 December 2018)

Polarization of Atoms in a Magnetized Plasma (PAMP)

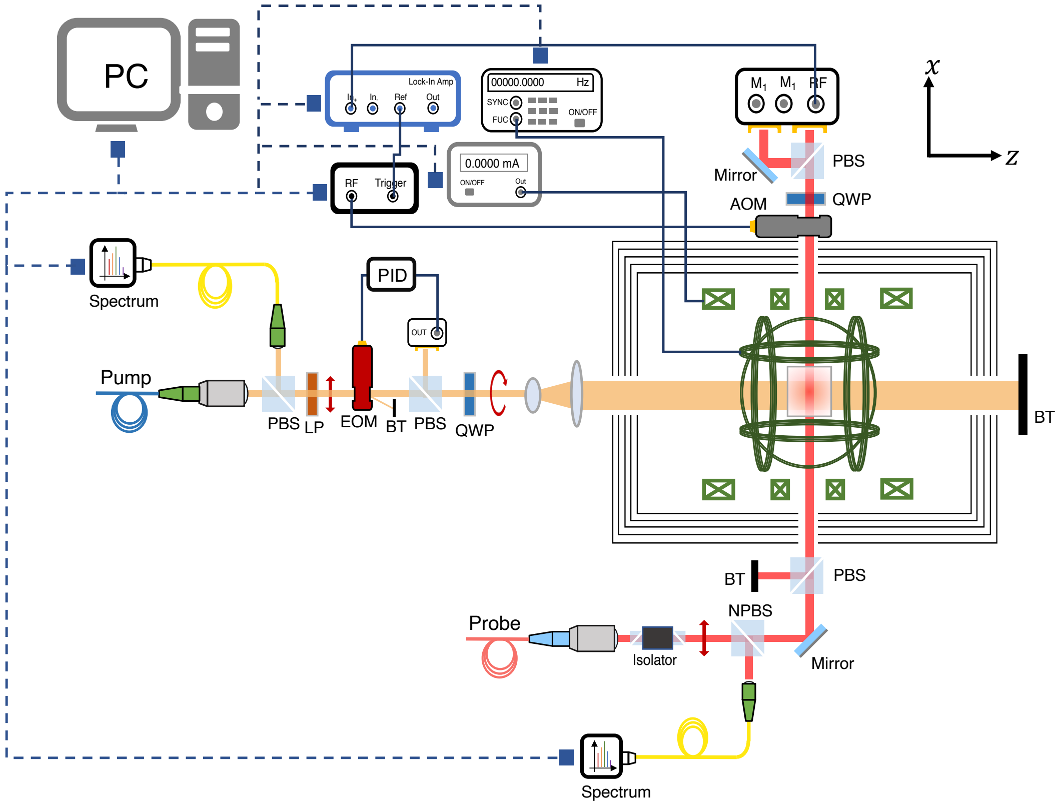
With an rf excitation of 100 MHz and magnetic field B_0=4.7 T, polarizations in the 1 to 9% are achieved in mbar range without laser.



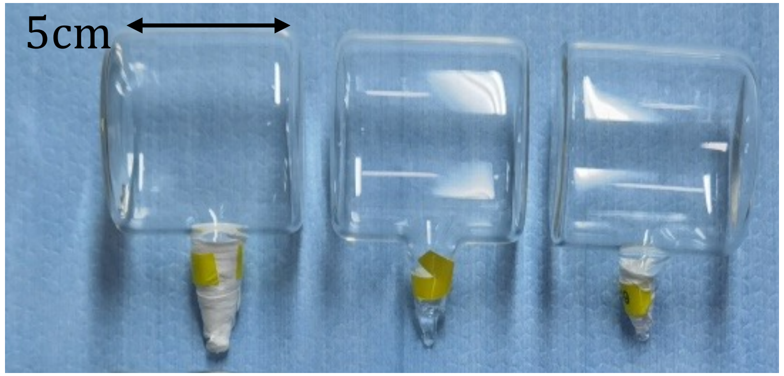
- Introduction to ^{3}He Polarization
- The Basic Principle of MEOP
- Development of MEOP ^{3}He System
- Summary and Outlook

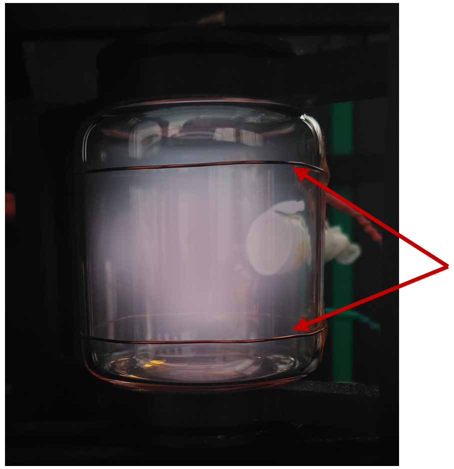
Experimental Setup

Schematic of experimental setup



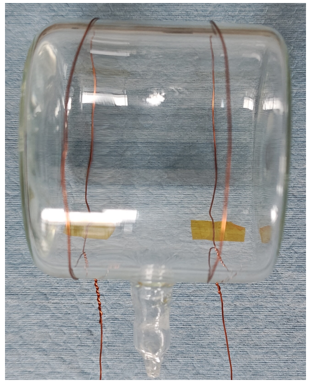
Homemade Duran glass cell



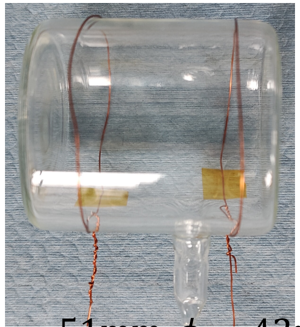


Discharge ring

Homemade GE180 glass cell



($L = 50mm, \phi = 55mm$)



($L = 51mm, \phi = 42mm$)

The guiding magnetic field

The effect of B_0 gradient on the relaxation time

$$\frac{1}{T_1} \approx \frac{8R^4\gamma^2}{175D}(|\nabla B_x|^2 + |\nabla B_y|^2)$$

Low pressure
$$\frac{1}{T_2} \approx \frac{4R^4\gamma^2}{175D}(|\nabla B_x|^2 + |\nabla B_y|^2 + 2|\nabla B_z|^2)$$

Cates, G. D., et. al. *Physical review A* 37.8 (1988): 2877.

Dipole-free Merritt Coil:

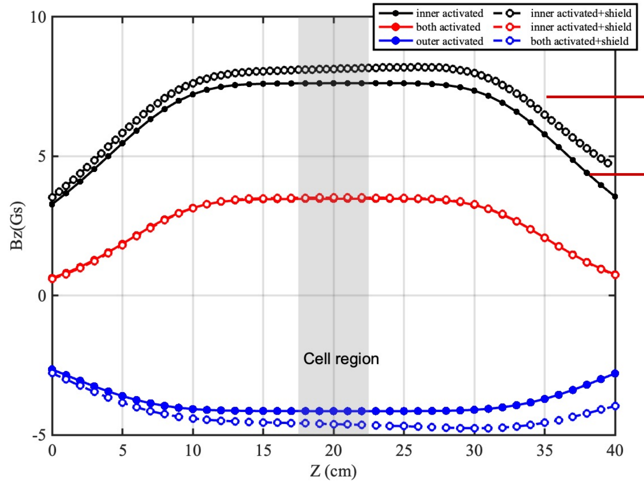
Zero dipole moment outside the coil

Minimize the shielding effect on the field uniformity

Outer coil

Inner coil

The B_z Component along z-axis

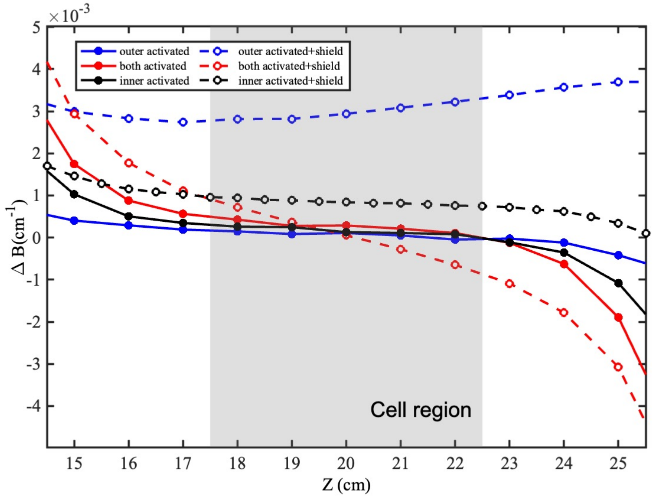


Merritt coil in the shield

Merritt coil without shield

The field of Merritt coil is asymmetry in the shield;

The gradient $\Delta B/B_0$ along z-axis

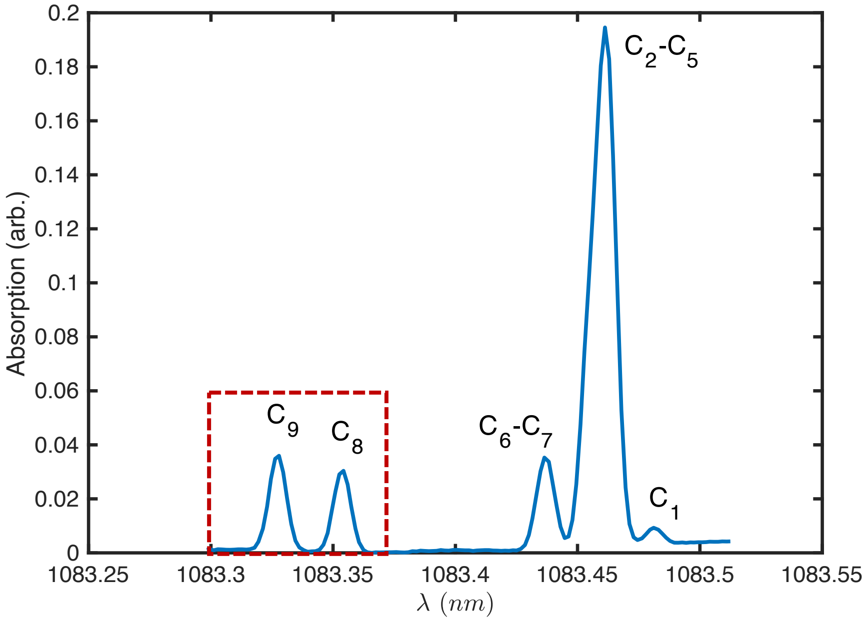


The dipole-free Merritt coil restores symmetry of the field.

Wang, Yuting, et. al. IEEE Trans. Magn. (under review)

Pump Laser

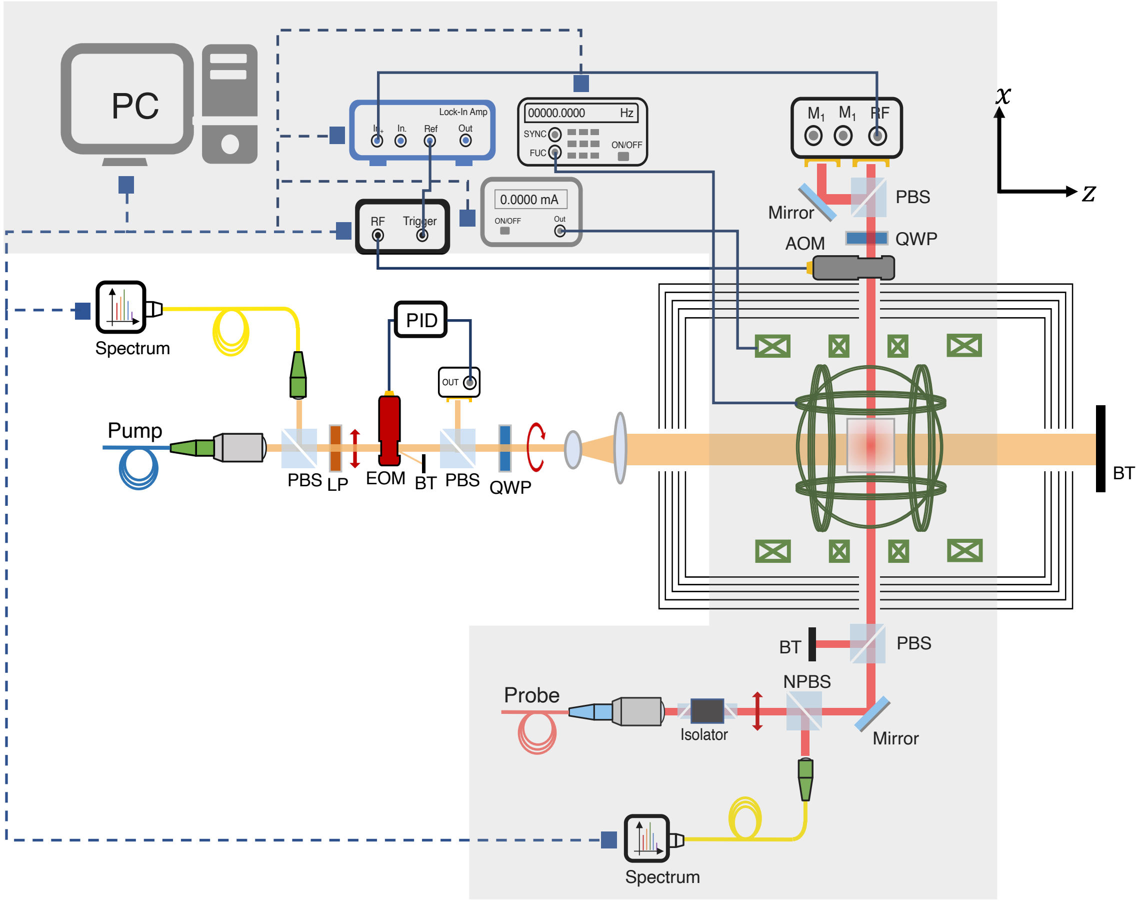
- Pumping laser: Keopsys Ytterbium Laser
- Power: ~2 W
- center wavelength: locked to transition line C_8
- linewidth: 2 GHz (matches the nature linewidth of ^{3}He)



Experimental Spectrum of the 1083nm transition lines

Measurement and acquisition system

Detection Laser: DBR laser with power of about 1mW.



1. Optical polarimetry:

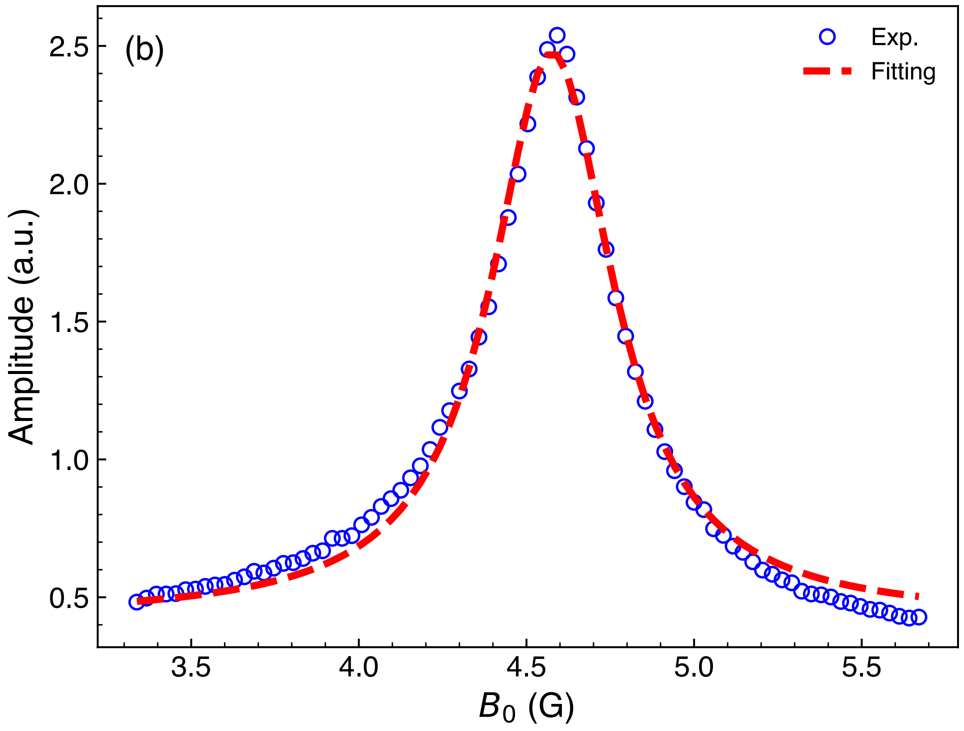
The wavelength of the laser is set to the transition line C_9; the power is modulated by an optical chopper and the absorption signal is extracted by lock-in method.

2. Magnetic resonance:

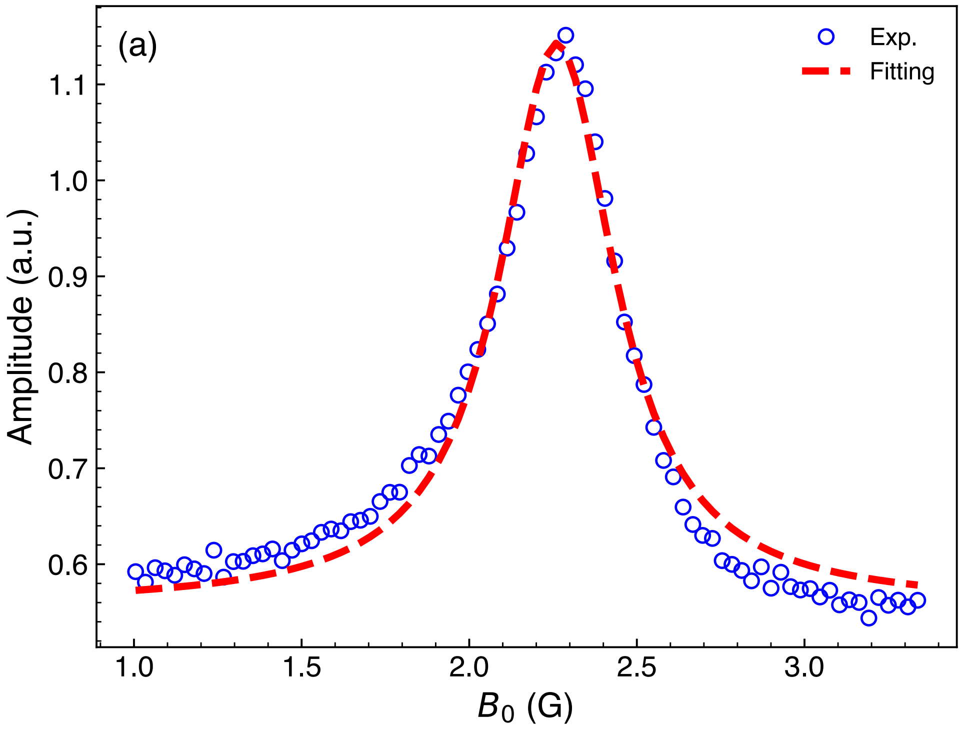
The wavelength of the laser is detuned, and the Faraday rotation signal is detected via homodyne detection.

Magnetic resonance of the metastable states

$F = 1/2$



$F = 3/2$

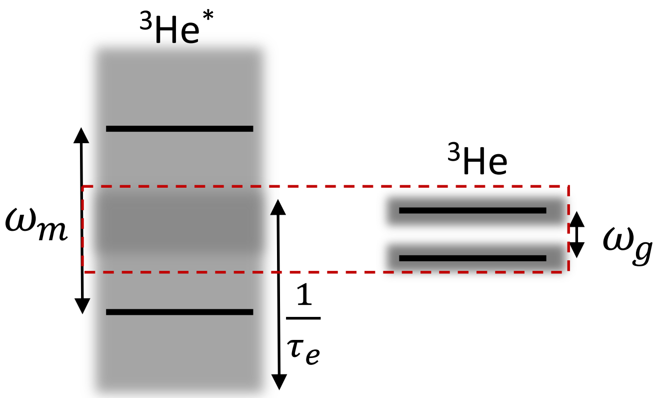


The metastability-exchange collisions rate derived are

$$1/\tau_e = 1.02 \pm 0.02 \times 10^6\ s^{-1}$$

Magnetic Resonance Measurement

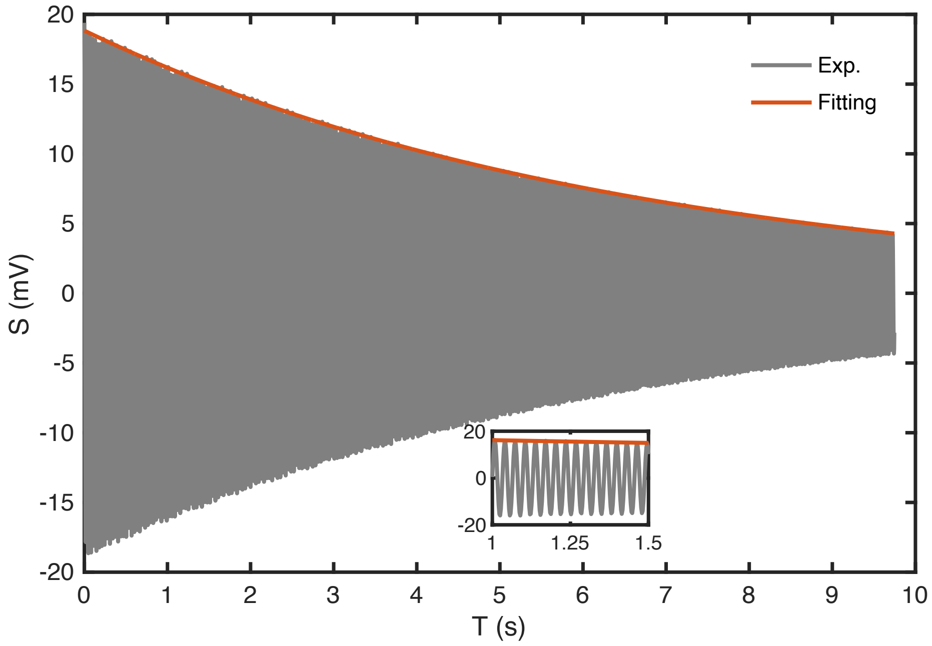
The coherence of the ground state is transferred to the metastable state by metastability-exchange collisions.



If ($\omega_m \ll \frac{1}{\tau_e}$), the metastable state and ground state is coupled.

Optical Detection of NMR

Magnetic resonance of the ground state



Optical detected FID Signal

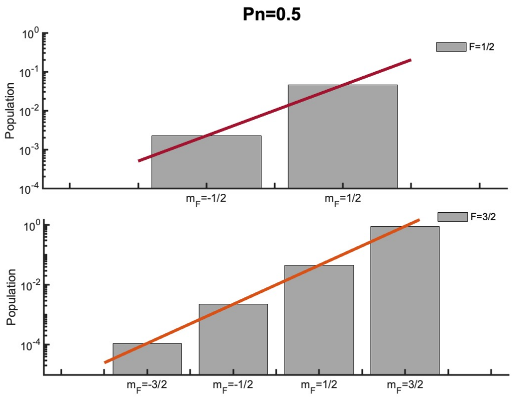
Larmor frequency $\omega_0 = 30.7429 \pm 0.00002$ Hz
Transverse relaxation time $T_2 = 6.58 \pm 0.01\ s$

Optical Polarimetry

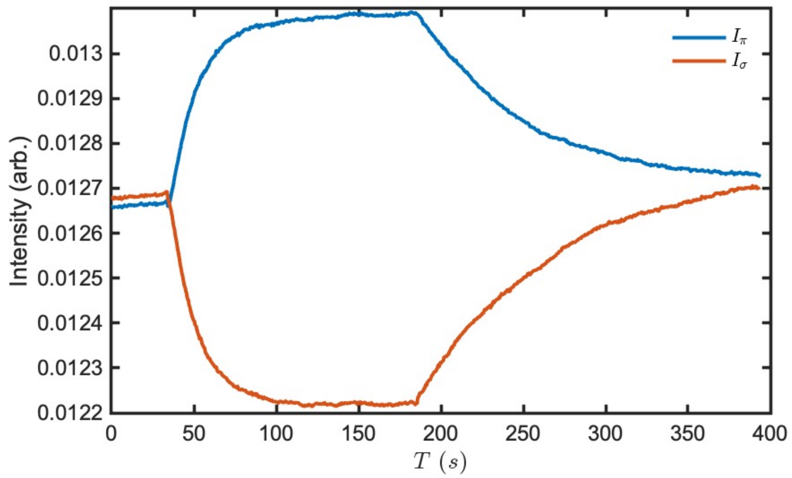
A spin-temperature distribution of the metastable state is decided by the ground ^{3}He polarization.

$$N_{m_F} \propto e^{\beta m_F},\ \ \beta = \ln \frac{1+P_n}{1-P_n}$$

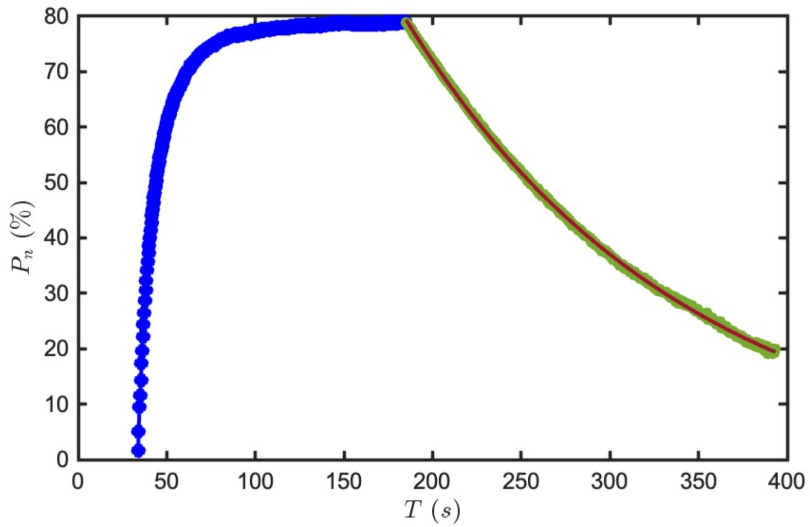
$$P_n = \sqrt{\frac{1 - A_\pi / A_\sigma}{1 + 2A_\pi / A_\sigma}}$$



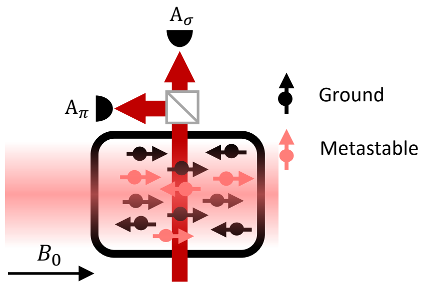
Spin-temperature distribution

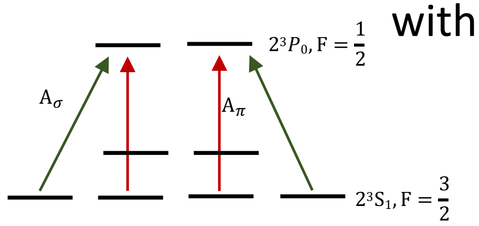


The absorption of the probe light with different polarization



The polarization buildup and decay





Saturated Polarization $P_n = 79 \pm 1\ \%$

Longitudinal relaxation time $T_1 = 158 \pm 2\ s$

- Introduction to ^3He Polarization
- The Basic Principle of MEOP
- Development of MEOP 3He System
- Summary and Outlook

Summary

- Summary

(1). Applications of polarized ^{3}He, particularly in fundamental physics

(2). The basic of the MEOP

(4). Progress in developing the low-field MEOP ^{3}He system, including

a. A dipole-free coil system for obtaining uniform field in the shield,
b. The magnetic resonance measurement in the system,
c. Optical polarimetry of the nuclear polarization.

- Outlook

The metastability exchange collisions may be harnessed to squeeze the noble gas nuclear spin.

A. Serafin, et. al. Physical review letters, 127, 013601 (2021)

Thanks for watching

Acknowledgements

PhD supervisor:

Haiyang Yan

Coauthors:

Yuting Wang,

Siyu Cheng