Overview of Polarized $^3$He Gas Targets

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- Introduction to spin and polarized $^3$He
- Polarized $^3$He gas targets for high-energy nuclear physics
- Polarized $^3$He for other applications
- Summary

Acknowledgement: some slides provided by my collaborators
some “borrowed” from colleague’s talks on the web
Introduction to Polarized $^3\text{He}$

Spin-Exchange Optical Pumping
Metastability-Exchange Optical Pumping
Asymmetry for Nucleon Spin Measurements

- Double spin symmetries for polarized beam on polarized targets

\[ A = \frac{1}{P_b P_t f} \frac{N^{\uparrow\uparrow} - N^{\downarrow\uparrow}}{N^{\uparrow\uparrow} + N^{\downarrow\downarrow}} \]

- Figure of Merit (FOM) depends on luminosity, beam and target polarization (squared), dilution factor (squared)

\[ FOM = P_b^2 \times P_t^2 \times f^2 \times L \]

\[ L = I \times \rho \left[ \text{cm}^2 \text{ s}^{-1} \right] \]
Polarized Luminosity and Polarization

- **Luminosity**
  - Internal targets (storage ring) \(10^{31}\)
  - Polarized external (fixed) targets
    - Solid (p/d) \(10^{35}\)
    - Gas \((^3\text{He})\) \(10^{36}\) (JLab)

**World highest luminosity/FOM**

- **Polarization** (in high-intensity beam)
  - \(P_{^3\text{He}} > 70\%\) (~60\%) (JLab)
  - \(P_H > 90\%\) (70\%)
  - \(P_D > 70\%\) (40\%)
Polarized $^3$He

- Polarized atomic electrons, then spin exchange with $^3$He nuclei
  - Issue: ground state, two electrons (full shell), opposite spin, can not be polarized (exclusion principle)

- Solutions:
  1) Alkali (Rb) Optical Pumping Spin Exchange
  2) Meta-stability Exchange Optical Pumping
Spin exchange Optical Pumping for $^3$He

Optical Pumping on Rb atom

Spin exchange

Collisional Mixing

$5S_{1/2}$

$795$ nm

$5P_{1/2}$

$\sigma^+$

Zeeman Splitting

$M = -1/2$

$M = +1/2$

$^3$He

Rb
Meta-stability Exchange Optical Pumping

$2^3P_0 \rightarrow \{ \begin{array}{c}
2^3S_1 \\
1^1S_0
\end{array} \} \quad 2^3P_0 \rightarrow \{ \begin{array}{c}
2^3S_1 \\
1^1S_0
\end{array} \} \quad m_F = -3/2 

CP Laser 1083 nm

RF Excitation (~1 ppm)

$\sigma^+$

Equal Probability Decay

Net Polarization

Metastability Exchange

F=1/2

3/2

1/2

-1/2

1/2

-1/2
History/Progress in Polarized $^3$He

- **Spin-Exchange Optical Pumping**
  
  **1960:** Bouchiat/Carver/Varnum (Princeton), PRL 5, 373 (1960)
  
  2.8 atm $^3$He, optically pumped 0.001 mm partial pressure of Rb, \( P = 0.01\% \)
  
  we have observed enhancement of the nuclear polarization by a factor of
  
  \( 10^4 \) above the initial Boltzmann distribution of
  
  \( 10^{-8} \).

  Now: 10 atm $^3$He, Rb-K optical pumping, \( P > 70\% \) (JLab/UVa/W&M...)

- **Meta-stability Exchange Optical Pumping**
  
  **1963:** Colegrove/Schearer/Walters (Texas Instruments), PR, 132, 2561 (1963)
  
  \( \sim 0.001 \text{ atm} \) $^3$He, achieved \( \sim 40\% \) polarization

  The highest polarization measured by nuclear magnetic resonance was \( 40 \pm 5\% \) in a 5 cm-diam Pyrex sphere with the $^3$He gas pressure at 1 mm Hg.

  Now: \( \sim 1 \text{ atm} \) $^3$He, mass production with MEOP, \( P > 70\% \) (Mainz)
Polarized $^3$He Target @ JLab: 1998-now

Spin-Exchange Optical Pumping

https://hallaweb.jlab.org/wiki/index.php/Hall_A_He3_Polarized_Target
http://hallaweb.jlab.org/equipment/targets/polhe3/polhe3_tgt.html

JLab (J. P. Chen), UVa (G. Cates), W&M (T. Averett), Duke (H. Gao), Temple (Z.E. Meziani), Kentucky (W. Korsch), Caltech(E. Hughes)…
**JLab Polarized $^3$He Target**

- $P = 40-45\%$
- $I = 15\mu A$
- **Diode Laser**
- **Diode Laser**
- **Diode Laser**
- **Photo-Diode for EPR**
- **Helmholtz Coils**
- **Cell: $L = 40\,cm$**
- **windows: $\sim 100\mu m$**
- **NMR RF Drive Coils**

- **3x30W @795nm**
- **$e^-\text{beam}$**
- **$e^-\text{beam}$**
- **Cell**
- **Pickup Coils**

**✓** longitudinal, transverse and vertical

**✓** Luminosity=$10^{36}$ (1/s) (highest in the world) upgrade on the way to $10^{37}$

**✓** High in-beam polarization ~ 60% (>70% no beam)

**✓** Effective polarized neutron target

**✓** 13 completed experiments 8 approved with 12 GeV (A/C)
Figure-of-Merit History for High Lumiosity Polarized $^3$He

Figure of Merit $\equiv (\text{Target Polarization})^2 \times \text{Beam Current}$

SLAC

Jefferson Lab

E142
35% @ few $\mu$A
1990

E154
35% @ few $\mu$A
1992

E94-010
35% @ 10 $\mu$A
1994

E97-110
40% @ 12 $\mu$A
1996

E99-117
40% @ 12 $\mu$A
1998

E02-013
50% @ 8 $\mu$A
2000

E06-010
60% @ 15 $\mu$A
2002

Year
Rb-K Hybrid Optical Pumping for $^3$He

Collisional Mixing

$5P_{1/2}$

795 nm $\sigma^+$

$5S_{1/2}$

$M = -1/2$  $M = +1/2$

Zeeman Splitting
Narrow-width Lasers

With new narrow-width lasers, polarizations > 70%

Left: Blue is current lasers, Red is Comet laser
Right: Absorption spectrum of Rb
Polarimetry

- Two methods: **NMR and EPR**, precision 2-3%
- **NMR** (nuclear magnetic resonance)
  - RF field
  - AFP (adiabatic fast passage) sweep through resonance when target spin flips, induced signal through pickup coils
  - Needs calibration from a known (water calibration)
- **EPR** (electron-paramagnetic resonance)
  - Rb energy level splitting (D2 light) corresponding to main field +/- a small field due to $^3$He polarization
  - Using AFP to flip $^3$He spin. Frequency difference of lights emitted proportional to $^3$He polarization
  - No calibration needed
- Cross checking with elastic asymmetry measurements
EPR and Water NMR

EPR

Water NMR
Ongoing Upgrade for Future Experiments

- 8 approved new experiments at JLab
- Aiming for luminosity $L \sim 10^{37} \text{ cm}^{-2}\text{s}^{-1}$
  - Single transfer tube $\rightarrow$ two transfer tubes allowing convection-driven gas flow
  - Metal target chamber to withstand high beam current
- Pulsed NMR Polarimetry
Other US Polarized $^3$He Facilities

UVa, W&M, Duke, New Hampshire, NIST, Wisconsin, Michigan, …
Polarized $^3$He at UVa (Gordon Cates)/ W&M (Todd Averett)

- Collaborating on JLab polarized $^3$He program
- Produce target cells for JLab experiments
- R&D on upgrade for polarized $^3$He for JLab experiments

- UVa Center for In-vivo Hyperpolarized Gas MR Imaging (2000)
- Both $^3$He and $^{129}$Xe

- $^3$He Spin density MRI

Courtesy of T. Altes et al., University of Virginia

Inhaled Bronchodilator
Asymptomatic Asthmatic

G. Cates’ talk
Polarized $^3$He at Duke (Haiyan Gao)

- Collaborating on JLab polarized $^3$He program
- $^3$He spin structure with High Intensity $\gamma$ Source (HI$\gamma$S)
- Neutron Electric Dipole Moment (EDM)
- Search for Spin-Dependent Short-Range Force (collaboration with Fudan U.)
- Establishing collaboration on polarized $^3$He R&D for at Tsinghua
New Hampshire Center for Xenon Imaging  
(W. Hersman)

• Functional Lung Imaging  
• Low-field and ultra-low-field imaging  
• Functional dissolved-state imaging  
• Biomedical imaging simulations  
• Also R&D on polarize 3He  

(Xemed LLC)
Polarized $^3\text{He} @ \text{NIST and Wisconsin}$

- NIST, SEOP polarized $^3\text{He}$ as Neutron Spin Filter for material science experiments with neutron scattering

- Wisconsin: R&D on SEOP polarized $^3\text{He}$ to improve performance
  - Search for Axion-like Particles using dual-species NMR $^{129}\text{Xe}$ and $^{131}\text{Xe}$
  - Optically pumped alkali magnetometers for biomedical applications
**Polarized $^3$He at Michigan** (T. Chupp)

- R&D on SEOP polarized $^3$He
- Nuclear physics (neutron spin structure)
- Fundamental Physics with Neutron
- Atomic EDM

**Polarized $^3$He Beam Source R&D for EIC @ MIT** (R. Milner)

- Based on MEOP
- Doubly ionization $^3$He++ for injection
- Goal: ~70% @ 30G 1 torr
- Transfer $\sim 10^{-14}$ $^3$He/s to EBIS @ 5T & 10$^{-7}$ torr
- Deliver $1.5 \times 10^{11}$ $^3$He++ per 20 µs pulse

RHIC’s Electron Beam Ion Source
Polarized $^3$He Facility in Europe
Mainz (W. Heil et al.), …

Meta-Stability Exchange Optical Pumping
Current $^3$He Polarizing Facility in Mainz

- $P=75-78\%$ @ 1 bar-liter/Hour for fundamental science
- $P\approx 65\%$ @ 2-3 bar-liter/Hour for medical application
- "Polarized Helium Lung Imaging Network"
- "Magnetic Resonance Imaging for Diagnosis and Monitoring of COPD and Asthma"
Applications of Polarized $^3$He @ Mainz

- **Fundamental applications**
  - Symmetry test He3/Xe-129
  - Search for new short-rang force (axion-like)
  - Search for Electric Dipole Moment of Xe-129
  - Accurate measurements of high magnetic field
  - Medium energy physics: neutron form factor, GDH sum rule
  - F. Allmendinger’s talk

- **Fundamental physics with cold and ultracold neutrons**
  - angular correlation of beta-particle and neutrino in beta-decay
  - Neutron lifetime

- **Medical Applications**
  - MRI of the lung with $^3$He and $^{129}$Xe

- K. Tullney’s talk
Polarized $^3$He Facilities in Asai

Japan, Korea, China (Lanzhou, Tsinghua, …)
Polarized $^3$He in Japan: Neutron Spin Filter

- Japan: SEOP polarized $^3$He as Neutron Spin Filter
- Developed for the pulsed neutron beam at J-PARC BL10 beamline

Figure 3. (a) Wavelength dependence of the transmitted neutron beam intensity for the NSF with polarized and depolarised $^3$He gas. (b) Calculated neutron polarization. (c) Pumping time dependence of the $^3$He gas polarization measured during in-situ SEOP.
Polarized $^3$He @ Lanzhou Univ.

B. Hu, Y. Zhang, et al.

- clean room
- gas filling system
- SEOP
- Obtained 1st polarization
- NMR (3He and water)
- EPR (commissioning)
Polarized $^3$He Lab at Tsinghua for fundamental symmetry studies

H. Gao et al.
Summary

- Spin and polarization: amazing phenomenon with broad applications
- Introduction to polarized $^3$He: SEOP and MEOP, tremendous progress
- Polarized $^3$He: critical for neutron spin structure study, wide range of fundamental physics, medical imaging and other applications
- JLab: SEOP, neutron and $^3$He spin physics
  Highest polarized luminosity and highest FOM
  Future: improve luminosity by one order of magnitude
- Polarized $^3$He groups in USA, Europe and Asia
- Pioneering work just started in China (Lanzhou/Hefei, Tsinghua, …)
- Useful tool for spin physics and great potential for applications