Overview of Polarized $^3$He Gas Targets

Jian-ping Chen(陈剑平), Jefferson Lab
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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 $^3$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 ($^3$He) $10^{36}$ (JLab)

World highest luminosity/FOM

- Polarization (in high intensity beam)
  $P_{^3$He} > 70\%$ ($\sim 60\%$) (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, cannot be polarized (exclusion principle)

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

Optical Pumping on Rb atom

Spin exchange

Collisional Mixing

5P$_{1/2}$

795 nm

$\sigma^+$

1/2

Zeeman Splitting

5S$_{1/2}$

$M = -1/2$

$M = +1/2$

$^3\text{He}$

Rb
Meta-stability Exchange Optical Pumping

\[ 2^3P_0 \]

CP Laser 1083 nm

\[ 2^3S_1 \] \{ \\
\[1/2\] \[3/2\]

RF Excitation (~1 ppm)

\[ 1^1S_0 \]

\[ F=1/2 \]

\[ m_F = -3/2 \]

\[ -1/2 \] \[ 1/2 \] \[ 3/2 \]

\[ \sigma^+ \]

Equal Probability Decay

Net Polarization

Metastability Exchange
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/Scheerer/Walters (Texas Instruments), PR, 132, 2561 (1963)
  
  $\sim 0.001$ 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: $\sim 1$ 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

- $P = 40\text{--}45\%$
  - $@\ I = 15\ \mu A$

- Longitudinal, transverse and vertical
- Luminosity =$10^{36} \ \text{(1/s)}$
  - (highest in the world)
  - Upgrade on the way to $10^{37}$
- High in-beam polarization
  - $\sim 60\%$ ($>70\%$ 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**
  - E142: 35% @ few µA
  - E154: 35% @ few µA

- **Jefferson Lab**
  - E94-010: 35% @ 10 µA
  - E99-117: 40% @ 12 µA
  - E97-110: 40% @ 12 µA
  - E02-013: 50% @ 8 µA
  - E06-010: 60% @ 15 µA

Year:
- 1990
- 1992
- 1994
- 1996
- 1998
- 2000
- 2002
- 2004
- 2006
- 2008
- 2010
Rb-K Hybrid Optical Pumping for $^3$He
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
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
Polarized $^3$He at Duke (Haiyan Gao)

- Collaborating on JLab polarized $^3$He program
- $^3$He spin structure with High Intensity $\gamma$ Source (HIGS)
- 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

Medium Energy Physics Group

Triangle Universities Nuclear Laboratory
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 $^3$He @ NIST and Wisconsin

- NIST, SEOP polarized $^3$He as Neutron Spin Filter for material science experiments with neutron scattering
- Wisconsin: R&D on SEOP polarized $^3$He to improve performance
- Search for Axion-like Particles using dual-species NMR $^{129}$Xe and $^{131}$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: $\approx 70\%$ @ 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 $\mu$s pulse

J. Maxwell’s talk

[Diagram of RHIC’s Electron Beam Ion Source]
Polarized $^3$He Facility in Europe Mainz (W. Heil et al.), ...
Current $^3$He Polarizing Facility in Mainz

- $P=75-78\%$ @ 1 bar-liter/Hour for fundamental science
- $P\sim 65\%$ @ 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

- **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

F. Allmendinger’s talk

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 3He as Neutron Spin Filter
- Developed for the pulsed neutron beam at J-PARC BL10 beamline

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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 1\textsuperscript{st} polarization
- NMR (3He and water)
- EPR (commissioning)
Summary

- Spin and polarization: amazing phenomenon with broad applications
- Introduction to polarized $^3\text{He}$: SEOP and MEOP, tremendous progress
- Polarized $^3\text{He}$: critical for neutron spin structure study, wide range of fundamental physics, medical imaging and other applications
- JLab: SEOP, neutron and $^3\text{He}$ spin physics
  - Highest polarized luminosity and highest FOM
  - Future: improve luminosity by one order of magnitude
- Polarized $^3\text{He}$ 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