# Next-Generation Polarized $^3$He Targets for Electron Scattering Experiments

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B.S. in Physics University of Science and Technology of China May 2009

A Dissertation presented to the Graduate Faculty

of the University of Virginia in Candidacy for the Degree of

Doctor of Philosophy

Department of Physics

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Dec, 2016

# Abstract

Historically, $^3$He targets for electron scattering experiments have been polarized through spin-exchange optical pumping (SEOP). Polarized laser light passes its circular polarization to alkali metal vapor, which then transfers its polarization to $^3$He through spin-exchange collisions.

This thesis discusses the basics of SEOP and the polarimetry techniques used in our lab. Narrowband laser and alkali-hybrid SEOP have improved the performance of targets significantly. In alkali-hybrid SEOP, potassium is used together with rubidium for transferring polarization to $^3$He nuclei. We discussed the data collected over many pure-rubidium targets and alkali-hybrid targets. In the course of analyzing the data, we also studied the "X factor" which limits the highest achievable polarization of $^3$He.

Because the experiments planned for the 12GeV era in Jefferson National Laboratory (JLAB) will use much higher electron beam current, we are exploring the possibility of using metal (instead of glass) as the entry points (commonly referred to as "end windows") for future targets. We established the metal composition and developed the techniques to incorporate metal to targets without introducing significant spin-relaxation rates. We have successfully demonstrated that future targets can be constructed with metal end windows and are very close to making such targets.

# Acknowledgements

First and foremost, I'd like to give my thanks to my advisor, Gordon Cates, for supporting me in the past five years in the group. Not only because I have learned a lot about physics from you, but also for your incredible enthusiasm that kept motivating me to push towards earning my degree. I am honored to have worked with you.

I'd like to thank Peter Dolph and Yuan Zheng, who have taught me the basics of spin-exchange optical pumping and $^3$He and alkali polarimetry. Even though the time we spent working together was not long, it laid the very foundation for my work in the following years.

I would like to thank Dr. W. Al Tobias and Dr. Vladimir Nelyubin as well. Al has helped us fill almost every cell we have studied and also taught me the right way to do experiments and the importance of documentation. Vladimir always made sure our experiments could go as smoothly as possible with his laser expertise. We would not have been able to do it without the help from Al and Vladimir.

I also would like to thank all the other graduate students in the group. Maduka Kaluarachchi and Dan Matyas, the two of you made the hours in lab such a joy. I will always miss our talks and of course, the "Young Chicken" we shared at Taste of China. Graduate school was not an easy time for me, I could not have done it without the help from you guys. Sumudu Katugampola and Dave Keder, the two of you are already doing great work, I have no doubt that you will have tremendous amount of success in the future. I look forward to seeing what our lab will be able to achieve because of you.

I'd like to thank the members of my committee: Nilanga Liyanage, Don Crabb, Wilson Miller, for helping me complete the final step towards my degree. I also owe my thanks to my parents and all my friends who have supported me through all these

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years. It means a lot to me knowing that no matter what comes next, I will always have your support.

Last but not least, I would like to thank my girlfriend. Shuangshuang, every bit of success I was able to achieve since I met you was at least partly because of your love and support. You gave me something to hold on to so I could pull myself through a tough time. I would not have been able to move on to the next chapter of my life the same way I did without you.

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# Chapter 1

# Introduction

Nuclear-polarized noble gases have been proven to be very useful in various applications, such as polarized targets for electron scattering experiments [1], magnetic resonance imaging [2] and neutron scattering experiments [3]. Polarized $^3$He has been particularly useful for studying spin-dependent interactions involving neutrons because, to first-order approximation, a $^3$He nucleus has a pair of protons with paired spins and a single neutron that carries most of the nuclear spin. Free neutrons are not used as targets because they decay with a lifetime of about 14 minutes, 42 seconds.

## 1.1  Motivation and Approved JLab Experiments

The neutron electromagnetic form factors, $G_E^n$ and $G_M^n$ play essential roles for understanding nucleon structure. At non-relativistic energies, they are the Fourier transforms of the electric charge and magnetic moment distributions. Even at relativistic energies, the elastic form factors provide unique information on the transverse structure of the nucleon [4, 5]. Double-polarization experiments on the proton showed that the ratio $G_E^p/G_M^p$ declines linearly as $Q^2$ increases, in sharp contrast to expec-

tations [6]. These measurements caused a resurgence of interest in nucleon structure, and shed light on the importance of quark orbital angular momentum. More recent double-polarization experiments measured the neutron electric form factor $G_E^n$ up to a $Q^2$ of $3.4\,\mathrm{GeV}^2$ (E02-013) [7], and showed behavior that was generally consistent with models that described well the earlier proton results. The neutron results, when combined with the proton results, made it possible to extract the form factors for the individual up- and down-quark flavors [8]. Significantly different $Q^2$ dependence was seen for the up- and down-quarks, a difference that some theorists have interpreted as evidence for the importance of diquark correlations.

The multiple surprises that have emerged from the study of nucleon elastic form factors at Jefferson Laboratory have underscored the value of performing such studies at high values of $Q^2$. For the neutron, predictions for the behavior of the ratio of the electric and magnetic elastic form factors, $G_E^n/G_M^n$, vary significantly from one model or calculation to another. A particularly compelling example, based on the Dyson-Schwinger Equation (DSE) formalism, predicts a dramatic turnover and zero crossing in the vicinity of $Q^2 = 10\,\mathrm{GeV}^2$ [9]. The verification of this prediction would have profound impact on our understanding of nucleon structure. An important part of the future program at JLab to explore the high-$Q^2$ behavior of the elastic nucleon form factors is the Super Bigbite Spectrometer (SBS) program. The SBS experiment to measure $G_E^n/G_M^n$ up to $Q^2 = 10\,\mathrm{GeV}^2$, E12-09-016, is a major motivating factor for the work described in this thesis. The count rate associated with the elastic form factors drops off very quickly with increasing $Q^2$. This in turn puts pressure on all aspects of the experiment to achieve adequate statistics, including running the polarized $^3$He target at high luminosity.

Another important issue in understanding nucleon structure is the spin structure associated with the quarks. Polarized deep inelastic scattering provides a window

in the spin carried by the quarks, and a particularly useful observable is the spin asymmetry $A_1^n$, the that describes the spin depence of the virtual photo absorption cross section. It is particularly useful to measure $A_1^n$ at high values of Bjorken $x$, where several predictions exist. Both constituent quark models and perturbative QCD predict that $A_1^n \to 1$ as $x_{\text{Bj}} \to 1$, but it is also the case that count rates drop quickly toward high values of $x_{\text{Bj}}$. Two experiments are currently approved at JLab that will measure $A_1^n$ up values of $x_{\text{Bj}}$ in excess of 0.7; they are E12-06-122 in Hall A, and E12-06-110 in Hall C. Both of these experiments will require a polarized $^3$He target capable of running at high luminosity and thus depend critically on the work describe here.

## 1.2   Overview of Recent Target Development

An early use of polarized $^3$He targets in electron scattering experiments was at the Stanford Linear Accelerator Center (SLAC) in the year of 1992. The experiment was known as E142 and investigated the spin structure of neutrons [1]. Recent experiments were conducted at Jefferson Laboratory (JLAB) in Newport News, Virginia, such as the aforementioned E02-013, also known as "Measurement of the Neutron Electric Form Factor $G_E^n$ at High $Q^2$". Experiments that investigated single-spin asymmetries [10] also included E06-10, E06-014 and E05-015.

The $^3$He targets used in these experiments were polarized with the technique of Spin-Exchange Optical Pumping (SEOP). Fig. 1.1 shows schematically a typical target, also referred to as a "target cell". These cells were made of GE180 glass and used a two-chambered design. The top chamber, known as the pumping chamber, is where $^3$He is polarized through SEOP. The bottom chamber, known as the target chamber, is where electron scattering occurs. The two ends of the target chamber

where electron beam enters and exits are known as the "end windows". Great effort has been made in our lab to develop this generation of cells. Alkali-hybrid SEOP together with narrowband laser diode arrays have increased the $^3$He polarization from 37% to 70%. Among other things, we also carefully studied an additional spin relaxation mechanism that limits the maximum achievable $^3$He polarization, which is referred to as the "X Factor". Analysis of data accumulated through developing this generation of target cells were thoroughly discussed in Ref. [11], part of which will be presented in chapter 4.
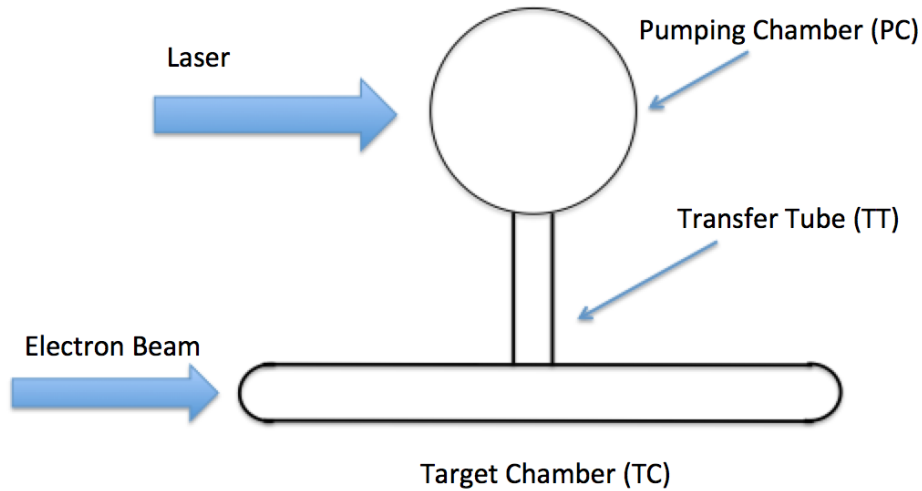


**Figure 1.1:** A schematic representation of a target cell. The dimensions of different parts of the cell are not to scale.

## 1.3 New Generation Target Cells

The future experiments planned during the 12GeV era after the upgrade will be much more demanding in terms of target cell performance. In particular, there is a desire

to run experiments with higher luminosity where luminosity is the product of gas density in the target, interaction length and beam current. Increased luminosity will lead to more interactions that depolarize the target. We have designed and tested a new style cell that utilizes convection instead of diffusion to increase the rate at which the polarization in the target chamber is replenished by polarized gas from pumping chamber [12]. We have obtained over 50% polarization with controllable convection speed so far.

An additional problem that comes with higher beam current is that the glass end windows of traditional design are not likely to survive the experiments. Our group started exploring the option of using metal end windows since eight years ago. Fig 1.2 shows an example configuration of such a target. The first problem to solve is to find out the correct material and the proper technique to incorporate metal without introducing significant spin relaxation and still being able to hold high pressure gas (12 atm) inside. This is a brand new technique that may have a profound impact on future cell designs once fully developed. Although no metal end windows have been tested so far, through carefully examining multiple glass cells with different kinds metal tubes (much larger in area compared to the end windows that will be used in JLAB experiments) attached, we have developed a reliable way of incorporating metal to target cells without introducing significant spin relaxation rates. We believe the next generation target cells used in the 12GeV era will be able to utilize metal end windows. In our test cells, the metals tubes were connected to Pyrex glass with Houskeeper seals [13] and stayed intact through high pressure tests. After exploring options such as pure copper, gold coated copper, titanium, stainless steel, gold coated titanium, we have established that electroplating gold on copper substrate yields the best result so far. We have achieved a 15.6 h relaxation time with a Pyrex cell that had a 5" long by 1" gold coated copper tube attached horizontally. The additional

**Figure 1.2:** A diagram of convection style target cell with metal end windows.

relaxation rate introduced by the metal surface is proportional to the area of the gold surface. By comparing relaxation rates of test metal cells with pure-glass control cells, the relaxation rate due to the gold surface was extrapolated. With this result, we believe the relaxation rate introduced by small metal windows in a target will be less than $1/130.6$ hr$^{-1}$. To the best of our knowledge, our group was the first to have proved the potential of incorporating metal to target cells in the presence of alkali vapor.

## 1.4 Structure of This Thesis

This thesis focuses on both discussion on the development of high-performance polarized 3He targets that utilize spin-exchange optical pumping (SEOP) and the development of future target cells that incorporate metal end windows. Chapter 2 gives a general description of SEOP. Chapter 3 introduces polarimetry techniques used in our lab for target cell characterization. Chapter 4 discusses the result collected in our lab from the over-a-decade development of $^3$He target cells, in which the spin-

exchange rate constant for K and $^3$He is calculated and the so-called "X Factor" is studied. Chapter 5 presents the development process of target cells with metal parts that aims to incorporate metal end windows to future cells for the 12 GeV era experiments. Chapter 6 summarizes this thesis and suggests future directions.

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