Next-Generation Polarized ^{3}He Targets for Electron Scattering Experiments

by

© Yunxiao Wang

A thesis submitted to the

School of Graduate Studies

in partial fulfilment of the

requirements for the degree of

Doctor of Philosophy

Department of Physics

University of Virginia

November 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 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.

Contents

List of Tables

List of Figures

Chapter 1

Conclusions

This thesis first discusses the basics of Spin-Exchange Optical Pumping (SEOP) and the polarimetry used to characterize ^{3}He targets. The combination of Spin-Exchange Optical Pumping with hybrid mixture and narrowband laser has improved the polarization of ^{3}He targets from 37% to 70% and significantly reduced the time constant of ^{3}He polarization build-up process. Chapter 4 of the thesis has discussed this development and put extra focus on the measurement of K-^{3}He spin-exchange rate constant and the analysis of the X factor. However, after the 12 GeV upgrade in JLab, the maximum electron beam current is planned to increase to 60 μA, which is 4 times as much as the maximum that was used prior to the upgrade. It is not likely for the traditional pure-glass target design to survive the much higher beam current. Chapter 5 discusses the effort our group made to explore targets incorporating metal and proposes that replacing glass end windows with metal windows will solve the problem without introducing significant spin relaxation. Fig. 1.1 shows the current design of next-generation target for upcoming Super Bigbite G_E^n experiments.

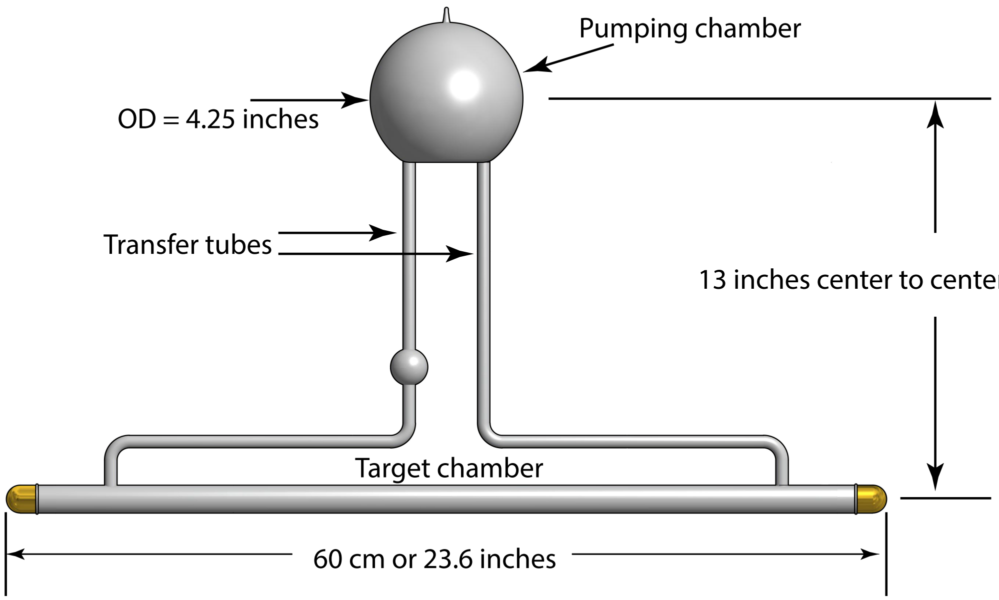

Figure 1.1: Design of next-generation target for upcoming SBS G_E^n experiments.

1.1 Spin Relaxation Introduced by Metal End Windows

Relaxation times measured by pure GE180 target cells and GE180 test cells with metal provide enough data for us extract spin-relaxation rates due to metal surface and calculate the additional relaxation rates that will be introduced by metal end windows. The measured lifetime of ProtovecI, a pure GE180 cell, was 26.52 hr and the measured lifetime of Goldfinger180, a vertical GE180 test cell with gold-coated OFHC copper tube, was 12.4 hr. With the equation $\Gamma_{wall} = \rho S/V$ and the geometric properties of cells, the relaxivity ρ of GE180 and gold surface can be calculated. Assuming the metal end windows have 1" diameter and 1 cm length and using the same value of volume as that of ProtovecI, we can estimate the relaxation rate due to the addition of metal end windows will be 1/98 hr^{-1}. If we double the volume for the upcoming SBS G_E^n experiments to compensate for the higher relaxation rate due to higher electron beam current, the relaxation rate introduced by metal will further drop to 1/196 hr^{-1}. Thus, metal end windows are likely to only cause negligible spin-relaxation rate for the purpose of the experiments planned.

1.2 Structural Strength of Metal End Windows

Glass end windows are not likely to be strong enough to survive the much higher electron beam current. During the 6 GeV era where only 10-15 μA was used, glass windows were already running into risk of blowing up after 4-6 weeks of being exposed to electron beam. If it was solely due to radiation damage, one can expect the glass windows to explode after roughly a week of being used in electron beam of 60 μA, which will be far from enough for the experiments to complete. On the other hand, experience at JLab suggests that even very thin metal windows should still be able to survive the electron beams. Aluminum as thin as 2 mils has been routinely used in JLab without failing. The fact that metal end windows will conduct heat better further suggests that they will be more suitable for experiments planned for the 12 GeV era.

1.3 Overall Design of Future Targets

In addition to the use of metal end windows, the overall design of future targets also differs from that of the previous targets. As shown in Fig. 1.1, the new design uses two transfer tubes for enabling convection as the mechanism to transfer ^{3}He polarization from pumping chamber (PC) to target chamber (TC). Although convection style cell was not discussed in detail in this thesis, it is still worth mentioning again in the conclusion. The higher electron beam current will induce higher spin relaxation which results in higher polarization gradient between PC and TC. By heating one of the transfer tubes, we can drive convection that will replenish ^{3}He polarization in TC at a much higher rate. The convection style cell was already tested to great success in our lab. Together with what we learned from results shown in chapter 4, we will be able to design targets that are well-suited for the upcoming experiments.

1.4 Summary

We have confidence that convection style targets with metal end windows will not only give high ^{3}He polarization in both PC and TC, but also survive the high electron beam currents planned for the future experiments. We are already close to making a target of the final design, tests involving incorporating actual metal windows to targets should still be carried out. Aluminum and Cartridge glass are also potentially good substrates for replacing the OFHC copper used in our tests due to either higher yield strength or higher radiation length, and should also be investigated.

Bibliography

[1] Nuclear relaxation of ^{3}he gas on various solid surfaces. *Canadian Journal of Physics*, 1971.

[2] Physics of practical spin-exchange optical pumping. *PhD thesis, University of Wisconsin-Madison*, 2001.

[3] Spin-exchange optical pumping with alkali-metal vapors. *PhD thesis, University of Wisconsin-Madison*, 2005.

[4] Alkali-hybrid spin-exchange optically-pumped polarized ^{3}he targets used for studying neutron structure. *PhD thesis, University of Virginia*, 2010.

[5] High-performance nuclear-polarized ^{3}He targets for electron scattering based on spin-exchange optical pumping. *PhD thesis, University of Virginia*, 2010.

[6] A. Abragam. *Principles of Nuclear Magnetism.*

[7] M. S. Albert, G. D. Cates, B. Driehuys, W. Happer, B. Saam, C. S. Springer, and A. Wishnia. Biological magnetic resonance imaging using laser-polarized ^{129}xe. *Nature*, 370.

[8] M. Amarian, L. Auerbach, T. Averett, J. Berthot, P. Bertin, W. Bertozzi, T. Black, E. Brash, D. Brown, E. Burtin, J. R. Calarco, G. D. Cates, Z. Chai, J.-P. Chen, S. Choi, E. Chudakov, E. Cisbani, C. W. de Jager, A. Deur, R. DiSalvo, S. Dieterich, P. Djawotho, M. Finn, K. Fissum, H. Fonvieille, S. Frullani, H. Gao, J. Gao, F. Garibaldi, A. Gasparian, S. Gilad, R. Gilman, A. Glamazdin, C. Glashausser, E. Goldberg, J. Gomez, V. Gorbenko, J.-O. Hansen, F. W. Hersman, R. Holmes, G. M. Huber, E. W. Hughes, T. B. Humensky, S. Incerti, M. Iodice, S. Jensen, X. Jiang, C. Jones, G. M. Jones, M. Jones, C. Jutier, A. Ketikyan, I. Kominis, W. Korsch, K. Kramer, K. S. Kumar, G. Kumbartzki, M. Kuss, E. Lakuriqi, G. Laveissiere, J. Lerose, M. Liang, N. Liyanage, G. Lolos, S. Malov, J. Marroncle, K. McCormick, R. McKeown, Z.-E. Meziani, R. Michaels, J. Mitchell, Z. Papandreou, T. Pavlin, G. G. Petratos, D. Pripstein, D. Prout, R. Ransome, Y. Roblin, D. Rowntree, M. Rvachev, F. Sabatie, A. Saha, K. Slifer, P. A. Souder, T. Saito, S. Strauch, R. Suleiman, K. Takahashi, S. Teijiro, L. Todor, H. Tsubota, H. Ueno, G. Urciuoli, R. Van der Meer, P. Vernin, H. Voskanian, B. Wojtsekhowski, F. Xiong, W. Xu, J.-C. Yang, B. Zhang, and P. Zolnierczuk. Q^2 evolution of the generalized gerasimov-drell-hearn integral for the neutron using a ^{3}He target. *Phys. Rev. Lett.*, 89:242301, Nov 2002.

[9] P. L. Anthony, R. G. Arnold, H. R. Band, H. Borel, P. E. Bosted, V. Breton, G. D. Cates, T. E. Chupp, F. S. Dietrich, J. Dunne, R. Erbacher, J. Fellbaum, H. Fonvieille, R. Gearhart, R. Holmes, E. W. Hughes, J. R. Johnson, D. Kawall, C. Keppel, S. E. Kuhn, R. M. Lombard-Nelsen, J. Marroncle, T. Maruyama, W. Meyer, Z.-E. Meziani, H. Middleton, J. Morgenstern, N. R. Newbury, G. G.

Petratos, R. Pitthan, R. Prepost, Y. Roblin, S. E. Rock, S. H. Rokni, G. Shapiro, T. Smith, P. A. Souder, M. Spengos, F. Staley, L. M. Stuart, Z. M. Szalata, Y. Terrien, A. K. Thompson, J. L. White, M. Woods, J. Xu, C. C. Young, and G. Zapalac. Determination of the neutron spin structure function. *Phys. Rev. Lett.*, 71:959–962, Aug 1993.

[10] S. Appelt, A. B.-A. Baranga, C. J. Erickson, M. V. Romalis, A. R. Young, and W. Happer. Theory of spin-exchange optical pumping of ^{3}He and ^{129}Xe. *Phys. Rev. A*, 58:1412–1439, Aug 1998.

[11] E. Babcock, B. Chann, T. G. Walker, W. C. Chen, and T. R. Gentile. Limits to the polarization for spin-exchange optical pumping of ^{3}He. *Phys. Rev. Lett.*, 96:083003, Mar 2006.

[12] E. Babcock, I. Nelson, S. Kadlecek, B. Driehuys, L. W. Anderson, F. W. Hersman, and T. G. Walker. Hybrid spin-exchange optical pumping of ^{3}He. *Phys. Rev. Lett.*, 91:123003, Sep 2003.

[13] E. Babcock, I. A. Nelson, S. Kadlecek, and T. G. Walker. ^{3}He polarization-dependent epr frequency shifts of alkali-metal˘^{3}He pairs. *Phys. Rev. A*, 71:013414, Jan 2005.

[14] R. M. Barrer. *Diffusion in and through Solids.*

[15] A. Ben-Amar Baranga, S. Appelt, M. V. Romalis, C. J. Erickson, A. R. Young, G. D. Cates, and W. Happer. Polarization of ^{3}He by spin exchange with optically pumped rb and k vapors. *Phys. Rev. Lett.*, 80:2801–2804, Mar 1998.

[16] F. Bloch. Nuclear induction. *Phys. Rev.*, 70:460–474, Oct 1946.

[17] M. A. Bouchiat, T. R. Carver, and C. M. Varnum. Nuclear polarization in he^3 gas induced by optical pumping and dipolar exchange. *Phys. Rev. Lett.*, 5:373–375, Oct 1960.

[18] G. Breit and I. I. Rabi. Measurement of nuclear spin. *Phys. Rev.*, 38:2082–2083, Dec 1931.

[19] A. C., V. Itkin, and H. M.K. *Candadian Metallurgial Quarterly*, 23, 1984.

[20] P. Callaghan. *Principles of Nuclear Magnetic Resonance Microscopy.*

[21] G. D. Cates. Polarized targets in high energy physics. *Proceedings of the 1993 Summer Institute on Particle Physics: Spin Structure in High Energy Processes (SSI93)*, SLAC-R-444:185–207, 1993.

[22] G. D. Cates, S. R. Schaefer, and W. Happer. Relaxation of spins due to field inhomogeneities in gaseous samples at low magnetic fields and low pressures. *Phys. Rev. A*, 37:2877–2885, Apr 1988.

[23] G. D. Cates, D. J. White, T.-R. Chien, S. R. Schaefer, and W. Happer. Spin relaxation in gases due to inhomogeneous static and oscillating magnetic fields. *Phys. Rev. A*, 38:5092–5106, Nov 1988.

[24] B. Chann, E. Babcock, L. Anderson, T. Walker, W. Chen, T. Smith, A. Thompson, and T. Gentile. Production of highly polarized ^{3}he using spectrally narrowed diode laser array bars. *Journal of applied physcis*, 94:6908–6914.

[25] B. Chann, E. Babcock, L. W. Anderson, and T. G. Walker. Measurements of ^{3}He spin-exchange rates. *Phys. Rev. A*, 66:032703, Sep 2002.

[26] W. C. Chen, T. R. Gentile, T. G. Walker, and E. Babcock. Spin-exchange optical pumping of ^{3}He with rb-k mixtures and pure k. *Phys. Rev. A*, 75:013416, Jan 2007.

[27] T. E. Chupp, M. E. Wagshul, K. P. Coulter, A. B. McDonald, and W. Happer. Polarized, high-density, gaseous ^{3}He targets. *Phys. Rev. C*, 36:2244–2251, Dec 1987.

[28] F. D. Colegrove, L. D. Schearer, and G. K. Walters. Polarization of he^3 gas by optical pumping. *Phys. Rev.*, 132:2561–2572, Dec 1963.

[29] K. Coulter, A. McDonald, W. Happer, T. Chupp, and M. Wagshul. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 270:90–94, 1988.

[30] I. Delstar Metal Finishing. *https://www.delstar.com/electropolishing.*

[31] A. Deninger, W. Heil, W. E. Otten, M. Wolf, K. R. Kremer, and A. Simon. Paramagnetic relaxation of spin polarized 3he at coated glass walls. *The European Physical Journal D - Atomic, Molecular, Optical and Plasma Physics*, 38(3):439–443, 2006.

[32] P. A. M. Dolph, J. Singh, T. Averett, A. Kelleher, K. E. Mooney, V. Nelyubin, W. A. Tobias, B. Wojtsekhowski, and G. D. Cates. Gas dynamics in high-

luminosity polarized ^{3}he targets using diffusion and convection. *Phys. Rev. C*, 84:065201, Dec 2011.

[33] W. A. Fitzsimmons, L. L. Tankersley, and G. K. Walters. Nature of surface-induced nuclear-spin relaxation of gaseous he^3. *Phys. Rev.*, 179:156–165, Mar 1969.

[34] J. Frenkel. *Kinetic Theory of Liquids*.

[35] R. L. Gamblin and T. R. Carver. Polarization and relaxation processes in he^3 gas. *Phys. Rev.*, 138:A946–A960, May 1965.

[36] L. E. Glass. *http://www.larsonelectronicglass.com*.

[37] W. Happer, G. Cates, M. Romalis, and C. Erickson. U.s. patent no. 6318092. 2001.

[38] W. Heil, H. Humblot, E. Otten, M. Schafer, R. Sarkau, and M. Leduc. Very long nuclear relaxation times of spin-polarized ^{3}he in metal coated cells. *Phys. Rev. A*, 201:337–343, May 1995.

[39] W. G. Houskeeper. The art of sealing base metals through glass. *Transactions of the American Institute of Electrical Engineers*, XLII:870–877, 1923.

[40] M. F. Hsu, G. D. Cates, I. Kominis, I. A. Aksay, and D. M. Dabbs. Sol-gel coated glass cells for spin-exchange polarized 3he. *Applied Physics Letters*, 77(13):2069–2071, 2000.

[41] M. G. Huber, M. Arif, T. C. Black, W. C. Chen, T. R. Gentile, D. S. Hussey, D. A. Pushin, F. E. Wietfeldt, and L. Yang. Precision measurement of the n-^{3}he incoherent scattering length using neutron interferometry. 102, 2009.

[42] E. T. Inc. *http://www.epner.com.*

[43] J. Jackson. *Classical Electrodynamics.*

[44] C. Kittel. *Introduction to Solid State Physics.*

[45] J. Korringa. Nuclear magnetic relaxation and resonance line shift in metals. *Physica*, 16, 1950.

[46] B. Larson, O. Hausser, P. P. J. Delheij, D. M. Whittal, and D. Thiessen. Optical pumping of rb in the presence of high-pressure ^{3}He buffer gas. *Phys. Rev. A*, 44:3108–3118, Sep 1991.

[47] D. Matyas. Characterizing ^{3}he nuclear spin relaxation in vessels of glass and metal. *Master thesis, University of Virginia*, 2016.

[48] E. Merzbacher. *Quantum Mechanics.* 1998.

[49] N. R. Newbury, A. S. Barton, P. Bogorad, G. D. Cates, M. Gatzke, B. Saam, L. Han, R. Holmes, P. A. Souder, J. Xu, and D. Benton. Laser polarized muonic helium. *Phys. Rev. Lett.*, 67:3219–3222, Dec 1991.

[50] N. R. Newbury, A. S. Barton, G. D. Cates, W. Happer, and H. Middleton. Gaseous $^3-^3$he magnetic dipolar spin relaxation. *Phys. Rev. A*, 48:4411–4420, Dec 1993.

[51] X. Qian, K. Allada, C. Dutta, J. Huang, J. Katich, Y. Wang, Y. Zhang, K. Aniol, J. R. M. Annand, T. Averett, F. Benmokhtar, W. Bertozzi, P. C. Bradshaw, P. Bosted, A. Camsonne, M. Canan, G. D. Cates, C. Chen, J.-P. Chen, W. Chen, K. Chirapatpimol, E. Chudakov, E. Cisbani, J. C. Cornejo, F. Cusanno, M. M. Dalton, W. Deconinck, C. W. de Jager, R. De Leo, X. Deng, A. Deur, H. Ding, P. A. M. Dolph, D. Dutta, L. El Fassi, S. Frullani, H. Gao, F. Garibaldi, D. Gaskell, S. Gilad, R. Gilman, O. Glamazdin, S. Golge, L. Guo, D. Hamilton, O. Hansen, D. W. Higinbotham, T. Holmstrom, M. Huang, H. F. Ibrahim, M. Iodice, X. Jiang, G. Jin, M. K. Jones, A. Kelleher, W. Kim, A. Kolarkar, W. Korsch, J. J. LeRose, X. Li, Y. Li, R. Lindgren, N. Liyanage, E. Long, H.-J. Lu, D. J. Margaziotis, P. Markowitz, S. Marrone, D. McNulty, Z.-E. Meziani, R. Michaels, B. Moffit, C. Muñoz Camacho, S. Nanda, A. Narayan, V. Nelyubin, B. Norum, Y. Oh, M. Osipenko, D. Parno, J. C. Peng, S. K. Phillips, M. Posik, A. J. R. Puckett, Y. Qiang, A. Rakhman, R. D. Ransome, S. Riordan, A. Saha, B. Sawatzky, E. Schulte, A. Shahinyan, M. H. Shabestari, S. Širca, S. Stepanyan, R. Subedi, V. Sulkosky, L.-G. Tang, A. Tobias, G. M. Urciuoli, I. Vilardi, K. Wang, B. Wojtsekhowski, X. Yan, H. Yao, Y. Ye, Z. Ye, L. Yuan, X. Zhan, Y.-W. Zhang, B. Zhao, X. Zheng, L. Zhu, X. Zhu, and X. Zong. Single spin asymmetries in charged pion production from semi-inclusive deep inelastic scattering on a transversely polarized ^{3}He target at $Q^2 = 1.4\breve{~}2.7$ gev^2. *Phys. Rev. Lett.*, 107:072003, Aug 2011.

[52] I. I. Rabi, N. F. Ramsey, and J. Schwinger. Use of rotating coordinates in magnetic resonance problems. *Rev. Mod. Phys.*, 26:167–171, Apr 1954.

[53] M. L. R.Barbe and F. Laloe. Experimental verifications - measurement of the he3 self-diffusion coefficient. 35:935–951, 1974.

[54] S. Riordan, S. Abrahamyan, B. Craver, A. Kelleher, A. Kolarkar, J. Miller, G. D. Cates, N. Liyanage, B. Wojtsekhowski, A. Acha, K. Allada, B. Anderson, K. A. Aniol, J. R. M. Annand, J. Arrington, T. Averett, A. Beck, M. Bellis, W. Boeglin, H. Breuer, J. R. Calarco, A. Camsonne, J. P. Chen, E. Chudakov, L. Coman, B. Crowe, F. Cusanno, D. Day, P. Degtyarenko, P. A. M. Dolph, C. Dutta, C. Ferdi, C. Fernández-Ramírez, R. Feuerbach, L. M. Fraile, G. Franklin, S. Frullani, S. Fuchs, F. Garibaldi, N. Gevorgyan, R. Gilman, A. Glamazdin, J. Gomez, K. Grimm, J.-O. Hansen, J. L. Herraiz, D. W. Higinbotham, R. Holmes, T. Holmstrom, D. Howell, C. W. de Jager, X. Jiang, M. K. Jones, J. Katich, L. J. Kaufman, M. Khandaker, J. J. Kelly, D. Kiselev, W. Korsch, J. LeRose, R. Lindgren, P. Markowitz, D. J. Margaziotis, S. M.-T. Beck, S. Mayilyan, K. McCormick, Z.-E. Meziani, R. Michaels, B. Moffit, S. Nanda, V. Nelyubin, T. Ngo, D. M. Nikolenko, B. Norum, L. Pentchev, C. F. Perdrisat, E. Piasetzky, R. Pomatsalyuk, D. Protopopescu, A. J. R. Puckett, V. A. Punjabi, X. Qian, Y. Qiang, B. Quinn, I. Rachek, R. D. Ransome, P. E. Reimer, B. Reitz, J. Roche, G. Ron, O. Rondon, G. Rosner, A. Saha, M. M. Sargsian, B. Sawatzky, J. Segal, M. Shabestari, A. Shahinyan, Y. Shestakov, J. Singh, S. Širca, P. Souder, S. Stepanyan, V. Stibunov, V. Sulkosky, S. Tajima, W. A. Tobias, J. M. Udias, G. M. Urciuoli, B. Vlahovic, H. Voskanyan, K. Wang, F. R. Wesselmann, J. R. Vignote, S. A. Wood, J. Wright, H. Yao, and X. Zhu. Measurements of the electric form factor of the neutron up to $Q^2 = 3.4$ gev^2 using

the reaction $^3\overrightarrow{\text{he}}(\vec{e}, e'n)pp$. *Phys. Rev. Lett.*, 105:262302, Dec 2010.

[55] M. V. Romalis and G. D. Cates. Accurate ^{3}He polarimetry using the rb zeeman frequency shift due to the Rb$-^3$He spin-exchange collisions. *Phys. Rev. A*, 58:3004–3011, Oct 1998.

[56] M. V. Romalis, E. Miron, and G. D. Cates. Pressure broadening of rb d_1 and d_2 lines by ^{3}he, ^{4}he, n_2, and xe: line cores and near wings. *Phys. Rev. A*, 56(6), 1997.

[57] L. D. Schearer, F. D. Colegrove, and G. K. Walters. Large he^3 nuclear polarization. *Phys. Rev. Lett.*, 10:108–110, Feb 1963.

[58] L. D. Schearer and G. K. Walters. Nuclear spin-lattice relaxation in the presence of magnetic-field gradients. *Phys. Rev.*, 139:A1398–A1402, Aug 1965.

[59] J. Schmiedeskamp, W. Heil, W. E. Otten, K. R. Kremer, A. Simon, and J. Zimmer. Paramagnetic relaxation of spin polarized 3he at bare glass surfaces. *The European Physical Journal D - Atomic, Molecular, Optical and Plasma Physics*, 38(3):427–438, 2006.

[60] J. T. Singh, P. A. M. Dolph, W. A. Tobias, T. D. Averett, A. Kelleher, K. E. Mooney, V. V. Nelyubin, Y. Wang, Y. Zheng, and G. D. Cates. Development of high-performance alkali-hybrid polarized ^{3}He targets for electron scattering. *Phys. Rev. C*, 91:055205, May 2015.

[61] C. P. Slichter. *Principles of Magnetic Resonance.*

[62] W. Smythe. *Static and Dynamic Electricity.*

[63] A. E. A. M. I. Technologies. *http://www.ableelectropolishing.com.*

[64] T. V. Tscherbul, P. Zhang, H. R. Sadeghpour, and A. Dalgarno. Anisotropic hyperfine interactions limit the efficiency of spin-exchange optical pumping of ^{3}He nuclei. *Phys. Rev. Lett.*, 107:023204, Jul 2011.

[65] M. Wagshul and T. Chupp. Optical pumping of high-density rb with a broadband dye laser and gaalas diode laser arrays: Application to ^{3}he polarization. *Phys. Rev. A.*, 40, 1989.

[66] M. Wagshul and T. Chupp. Laser optical pumping of high-density rb in polarized ^{3}he targets. *Phys. Rev. A*, 49:3854–3869, 1994.

[67] T. G. Walker and W. Happer. Spin-exchange optical pumping of noble-gas nuclei. *Rev. Mod. Phys.*, 69:629–642, Apr 1997.

[68] T. G. Walker, I. A. Nelson, and S. Kadlecek. Method for deducing anisotropic spin-exchange rates. *Phys. Rev. A*, 81:032709, Mar 2010.

[69] T. G. Walker, J. H. Thywissen, and W. Happer. Spin-rotation interaction of alkali-metal˘he-atom pairs. *Phys. Rev. A*, 56:2090–2094, Sep 1997.

[70] D. K. Walter, W. Happer, and T. G. Walker. Estimates of the relative magnitudes of the isotropic and anisotropic magnetic-dipole hyperfine interactions in alkali-metal˘noble-gas systems. *Phys. Rev. A*, 58:3642–3653, Nov 1998.

[71] Y. Zheng. Low field mri and the development of polarized nuclear imaging (pni)-a new imaging modality, 2015.