

RICE UNIVERSITY

**Some Research Project That Nobody Else Cares About
But You Have to Finish to Graduate**

by

Graduate Student

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE

Doctor of Philosophy

APPROVED, THESIS COMMITTEE:

Your Boss
Professor of Some Principle

Someone Else
J.S. Bach Professor of Some Principle

Another Person
Associate Professor of Some Principle

Fourth Member
Assistant Professor of Some Other Principle

HOUSTON, TEXAS

August, 2021

ABSTRACT

Some Research Project That Nobody Else Cares About But You Have to Finish to Graduate

by

Graduate Student

Main text of abstract.

Acknowledgments

We all deserve this.

Contents

Abstract	ii
Acknowledgments	iii
1 Introduction	1
1.1 Section 1	1
1.2 Section 2	1
2 The Experiment	2
3 Signal Reconstruction of the Experiment	3
4 Something else of the Experiment	4
5 Search for something in data from the Experiment	5
6 Future of the Experiment	6

Chapter 1

Introduction

Some shit.

1.1 Section 1

Some bullshit to see how the formatting and layout works. Some more bullshit so that it span through several lines hopefully. Even more bullshit and meaningless texts for the same purpose.

Another line of placeholder text to see how changing line works.

1.2 Section 2

Chapter 2

The Experiment

Chapter 3

Signal Reconstruction of the Experiment

Chapter 4

Something else of the Experiment

Chapter 5

Search for something in data from the Experiment

Chapter 6

Future of the Experiment

Bibliography

1. Delaquis, S. *et al.* Deep Neural Networks for Energy and Position Reconstruction in EXO-200. *JINST* **13**, P08023. arXiv: 1804.09641 [physics.ins-det] (2018).
2. Anton, G. *et al.* Search for Neutrinoless Double- β Decay with the Complete EXO-200 Dataset. *Phys. Rev. Lett.* **123**, 161802. arXiv: 1906.02723 [hep-ex] (2019).
3. Billard, J. *et al.* Direct Detection of Dark Matter – APPEC Committee Report. arXiv: 2104.07634 [hep-ex] (Apr. 2021).
4. Aprile, E. *et al.* Observation of two-neutrino double electron capture in ^{124}Xe with XENON1T. *Nature* **568**, 532–535. arXiv: 1904.11002 [nucl-ex] (2019).
5. Aprile, E. *et al.* Projected WIMP sensitivity of the XENONnT dark matter experiment. *JCAP* **11**, 031. arXiv: 2007.08796 [physics.ins-det] (2020).
6. Schechter, J. & Valle, J. W. F. Neutrinoless Double beta Decay in $\text{SU}(2) \times \text{U}(1)$ Theories. *Phys. Rev. D* **25**, 2951 (1982).
7. Dolinski, M. J., Poon, A. W. P. & Rodejohann, W. Neutrinoless Double-Beta Decay: Status and Prospects. *Ann. Rev. Nucl. Part. Sci.* **69**, 219–251. arXiv: 1902.04097 [nucl-ex] (2019).
8. Umehara, S. *et al.* Neutrino-less double-beta decay of Ca-48 studied by Ca F(2)(Eu) scintillators. *Phys. Rev. C* **78**, 058501. arXiv: 0810.4746 [nucl-ex] (2008).
9. Agostini, M. *et al.* Improved Limit on Neutrinoless Double- β Decay of ^{76}Ge from GERDA Phase II. *Phys. Rev. Lett.* **120**, 132503. arXiv: 1803.11100 [nucl-ex] (2018).
10. Aalseth, C. E. *et al.* Search for Neutrinoless Double- β Decay in ^{76}Ge with the Majorana Demonstrator. *Phys. Rev. Lett.* **120**, 132502. arXiv: 1710.11608 [nucl-ex] (2018).
11. Alduino, C. *et al.* First Results from CUORE: A Search for Lepton Number Violation via $0\nu\beta\beta$ Decay of ^{130}Te . *Phys. Rev. Lett.* **120**, 132501. arXiv: 1710.07988 [nucl-ex] (2018).
12. Gando, A. *et al.* Search for Majorana Neutrinos near the Inverted Mass Hierarchy Region with KamLAND-Zen. *Phys. Rev. Lett.* **117**. [Addendum: Phys.Rev.Lett. 117, 109903 (2016)], 082503. arXiv: 1605.02889 [hep-ex] (2016).
13. Albert, J. B. *et al.* Search for Neutrinoless Double-Beta Decay with the Upgraded EXO-200 Detector. *Phys. Rev. Lett.* **120**, 072701. arXiv: 1707.08707 [hep-ex] (2018).
14. Moe, M. The First Direct Observation of Double-Beta Decay. *Ann. Rev. Nucl. Part. Sci.* **64**, 247–267 (2014).
15. Zyla, P. A. *et al.* Review of Particle Physics. *PTEP* **2020**, 083C01 (2020).

16. Kotila, J. & Iachello, F. Phase space factors for double- β decay. *Phys. Rev. C* **85**, 034316. arXiv: 1209.5722 [nucl-th] (2012).
17. Aalbers, J., Pelssers, B., Antochi, V. C., Tan, P. L. & Conrad, J. Finding dark matter faster with explicit profile likelihoods. *Phys. Rev. D* **102**, 072010. arXiv: 2003.12483 [physics.ins-det] (2020).
18. Canetti, L., Drewes, M. & Shaposhnikov, M. Matter and Antimatter in the Universe. *New J. Phys.* **14**, 095012. arXiv: 1204.4186 [hep-ph] (2012).
19. Vergados, J. D., Ejiri, H. & Simkovic, F. Theory of Neutrinoless Double Beta Decay. *Rept. Prog. Phys.* **75**, 106301. arXiv: 1205.0649 [hep-ph] (2012).
20. Baudis, L. *et al.* Neutrino physics with multi-ton scale liquid xenon detectors. *JCAP* **01**, 044. arXiv: 1309.7024 [physics.ins-det] (2014).
21. Wittweg, C., Lenardo, B., Fieguth, A. & Weinheimer, C. Detection prospects for the second-order weak decays of ^{124}Xe in multi-tonne xenon time projection chambers. *Eur. Phys. J. C* **80**, 1161. arXiv: 2002.04239 [nucl-ex] (2020).
22. Akerib, D. S. *et al.* Projected sensitivity of the LUX-ZEPLIN experiment to the $0\nu\beta\beta$ decay of ^{136}Xe . *Phys. Rev. C* **102**, 014602. arXiv: 1912.04248 [nucl-ex] (2020).
23. Lambers, M. Mappings between Sphere, Disc, and Square. *Journal of Computer Graphics Techniques (JCGT)* **5**, 1–21. ISSN: 2331-7418. <http://jcgt.org/published/0005/02/01/> (Apr. 2016).
24. Fong, C. Analytical methods for squaring the disc. *arXiv preprint arXiv:1509.06344* (2015).
25. Fernandez Gausti, M. Classroom notes. *International Journal of Mathematical Education in Science and Technology* **23**, 895–913. eprint: <https://doi.org/10.1080/0020739920230607>. <https://doi.org/10.1080/0020739920230607> (1992).
26. Xu, K., Hu, W., Leskovec, J. & Jegelka, S. How powerful are graph neural networks? *arXiv preprint arXiv:1810.00826* (2018).
27. Aprile, E. *et al.* Observation and applications of single-electron charge signals in the XENON100 experiment. *J. Phys. G* **41**, 035201. arXiv: 1311.1088 [physics.ins-det] (2014).
28. Angevaere, J. R. & Wenz, D. *Strax and Straxen: Streaming analysis for xenon experiments* Nov. 2020. <https://doi.org/10.5281/zenodo.4275862>.
29. Martin Abadi *et al.* *TensorFlow: Large-Scale Machine Learning on Heterogeneous Systems* Software available from tensorflow.org. 2015. <https://www.tensorflow.org/>.
30. Kingma, D. P. & Ba, J. Adam: A method for stochastic optimization. *arXiv preprint arXiv:1412.6980* (2014).
31. Szydagis, M. *et al.* *Noble Element Simulation Technique v2.0* version v2.0.0. July 2018. <https://doi.org/10.5281/zenodo.1314669>.

32. Aprile, E. *et al.* Energy resolution and linearity of XENON1T in the MeV energy range. *Eur. Phys. J. C* **80**, 785. arXiv: 2003.03825 [physics.ins-det] (2020).
33. Gonzalez-Garcia, M. C. & Maltoni, M. Phenomenology with Massive Neutrinos. *Phys. Rept.* **460**, 1–129. arXiv: 0704.1800 [hep-ph] (2008).
34. Aker, M. *et al.* Improved Upper Limit on the Neutrino Mass from a Direct Kinematic Method by KATRIN. *Phys. Rev. Lett.* **123**, 221802. arXiv: 1909.06048 [hep-ex] (2019).
35. Pelssers, B. E. J. *Enhancing Direct Searches for Dark Matter: Spatial-Temporal Modeling and Explicit Likelihoods* PhD thesis (Department of Physics, Stockholm University, 2020).
36. Solovov, V. N. *et al.* Position Reconstruction in a Dual Phase Xenon Scintillation Detector. *IEEE Trans. Nucl. Sci.* **59** (ed Label, K.) 3286–3293. arXiv: 1112.1481 [physics.ins-det] (2012).
37. Aprile, E. *et al.* XENON1T Dark Matter Data Analysis: Signal Reconstruction, Calibration and Event Selection. *Phys. Rev. D* **100**, 052014. arXiv: 1906.04717 [physics.ins-det] (2019).
38. Shlomi, J., Battaglia, P. & Vlimant, J.-R. Graph Neural Networks in Particle Physics. arXiv: 2007.13681 [hep-ex] (July 2020).
39. Goodfellow, I., Bengio, Y. & Courville, A. *Deep Learning* <http://www.deeplearningbook.org> (MIT Press, 2016).
40. *WFSim, The XENON waveform simulator* <https://github.com/XENONnT/WFSim>.
41. Avignone, F. T., King, G. S. & Zdesenko, Y. G. Next generation double-beta decay experiments: Metrics for their evaluation. *New J. Phys.* **7**, 6 (2005).
42. Redshaw, M., Wingfield, E., McDaniel, J. & Myers, E. G. Mass and double-beta-decay Q value of Xe-136. *Phys. Rev. Lett.* **98**, 053003 (2007).
43. Feldman, G. J. & Cousins, R. D. A Unified approach to the classical statistical analysis of small signals. *Phys. Rev. D* **57**, 3873–3889. arXiv: physics/9711021 (1998).
44. James, F. *Statistical methods in experimental physics* ISBN: 978-981-256-795-6, 978-981-270-527-3 (2006).
45. Bilenky, S. Neutrinos: Majorana or Dirac? arXiv: 2008.02110 [hep-ph] (Aug. 2020).
46. Paschos, E. A. Leptogenesis with Majorana neutrinos. *Nucl. Phys. B Proc. Suppl.* **112** (eds Morfin, J. G., Sakuda, M. & Suzuki, Y.) 36–41. arXiv: hep-ph/0204137 (2002).
47. Andreev, V. *et al.* Improved limit on the electric dipole moment of the electron. *Nature* **562**, 355–360 (2018).
48. Kolb, E. W. & Turner, M. S. Grand Unified Theories and the Origin of the Baryon Asymmetry. *Ann. Rev. Nucl. Part. Sci.* **33**, 645–696 (1983).
49. Fukugita, M. & Yanagida, T. Baryogenesis Without Grand Unification. *Phys. Lett. B* **174**, 45–47 (1986).