



**UvA-DARE (Digital Academic Repository)**

**A supersymmetric model for lattice fermions**

Huijse, L.

[Link to publication](#)

*Citation for published version (APA):*

Huijse, L. (2010). A supersymmetric model for lattice fermions

**General rights**

It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

**Disclaimer/Complaints regulations**

If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: <http://uba.uva.nl/en/contact>, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.

# Bibliography

- [1] L.D. Landau. The theory of a Fermi liquid. *Sov. Phys. JETP*, 3:920, 1956.
- [2] P.W. Anderson. *Basic notions in condensed matter physics*. Benjamin, 1984.
- [3] D. C. Tsui, H. L. Stormer, and A. C. Gossard. Two-dimensional magnetotransport in the extreme quantum limit. *Phys. Rev. Lett.*, 48(22):1559–1562, 1982.
- [4] R. de Picciotto, M. Reznikov, M. Heiblum, V. Umansky, G. Bunin, and D. Hahalu. Direct observation of a fractional charge. *Nature*, 389:162, 1997.
- [5] L. Saminadayar, D. C. Glattli, Y. Jin, and B. Etienne. Observation of the  $e/3$  fractionally charged Laughlin quasiparticle. *Phys. Rev. Lett.*, 79(13):2526–2529, 1997.
- [6] Z.-X. Shen, D. S. Dessau, B. O. Wells, D. M. King, W. E. Spicer, A. J. Arko, D. Marshall, L. W. Lombardo, A. Kapitulnik, P. Dickinson, S. Doniach, J. DiCarlo, T. Loeser, and C. H. Park. Anomalously large gap anisotropy in the a-b plane of  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ . *Phys. Rev. Lett.*, 70(10):1553–1556, 1993.
- [7] A. Damascelli, Z. Hussain, and Z.-X. Shen. Angle-resolved photoemission studies of the cuprate superconductors. *Rev. Mod. Phys.*, 75(2):473–541, 2003.
- [8] V. J. Emery and S. A. Kivelson. Superconductivity in bad metals. *Phys. Rev. Lett.*, 74(16):3253–3256, 1995.
- [9] C. Honerkamp and P. A. Lee. Staggered flux vortices and the superconducting transition in the layered cuprates. *Phys. Rev. Lett.*, 92(17):177002, 2004.
- [10] S. Chakravarty, R. B. Laughlin, D. K. Morr, and C. Nayak. Hidden order in the cuprates. *Phys. Rev. B*, 63(9):094503, 2001.
- [11] S. Martin, A. T. Fiory, R. M. Fleming, L. F. Schneemeyer, and J. V. Waszczak. Normal-state transport properties of  $\text{Bi}_{2+x}\text{Sr}_{2-y}\text{CuO}_{6+\delta}$  crystals. *Phys. Rev. B*, 41(1):846–849, 1990.
- [12] A. V. Puchkov, D. N. Basov, and T. Timusk. The pseudogap state in high- $T_c$  superconductors: an infrared study. *J. Phys.: Condens. Matter*, 8(48):10049–10082, 1996.
- [13] C. M. Varma, P. B. Littlewood, S. Schmitt-Rink, E. Abrahams, and A. E. Ruckenstein. Phenomenology of the normal state of Cu-O high-temperature superconductors. *Phys. Rev. Lett.*, 63(18):1996–1999, 1989.

- 
- [14] J. Zaanen and O. Gunnarsson. Charged magnetic domain lines and the magnetism of high- $T_c$  oxides. *Phys. Rev. B*, 40(10):7391–7394, 1989.
- [15] M. Troyer and U.-J. Wiese. Computational complexity and fundamental limitations to fermionic Quantum Monte Carlo simulations. *Phys. Rev. Lett.*, 94(17):170201, 2005.
- [16] J. Zaanen, F. Krüger, J.-H. She, D. Sadri, and S. I. Mukhin. Pacifying the Fermi-liquid: battling the devious fermion signs. *Ir. J. Phys. Res.*, 8(2):39, 2008.
- [17] S. Sachdev and M. Müller. Quantum criticality and black holes. *J. Phys.: Condens. Matter*, 21(16):164216, 2009.
- [18] C. L. Henley and N.-G. Zhang. Spinless fermions and charged stripes at the strong-coupling limit. *Phys. Rev. B*, 63(23):233107, 2001.
- [19] N. G. Zhang and C. L. Henley. Stripes and holes in a two-dimensional model of spinless fermions or hardcore bosons. *Phys. Rev. B*, 68(1):014506, 2003.
- [20] U. Hizi and C. L. Henley. Hole on a stripe in a spinless fermion model. *Europhys. Lett.*, 65(2):228–234, 2004.
- [21] P. Fendley and K. Schoutens. Exact results for strongly-correlated fermions in 2+1 dimensions. *Phys. Rev. Lett.*, 95:046403, 2005.
- [22] P. Fendley, K. Schoutens, and J. de Boer. Lattice models with  $\mathcal{N} = 2$  supersymmetry. *Phys. Rev. Lett.*, 90:120402, 2003.
- [23] P. Fendley, B. Nienhuis, and K. Schoutens. Lattice fermion models with supersymmetry. *J. Phys. A*, 36:12399, 2003.
- [24] L. Huijse and K. Schoutens. Superfrustration of charge degrees of freedom. *EPJ B*, 64:543–550, 2008.
- [25] S. Sachdev. *Quantum phase transitions*. Cambridge University Press, 1999.
- [26] For a review see M. R. Norman and C. Pepin. The electronic nature of high temperature cuprate superconductors. *Rep. Prog. Phys.*, 66(10):1547–1610, 2003.
- [27] For a review see G. R. Stewart. Heavy-fermion systems. *Rev. Mod. Phys.*, 56(4):755–787, 1984.
- [28] Th. Giamarchi. *Quantum physics in one dimension*. Oxford university press, 2004.
- [29] H. Mutka. Proceedings of the Highly Frustrated Magnetism 2003 Conference. *J. Phys: Condens. Matter*, 16(11), 2004.
- [30] E. Runge and P. Fulde. Charge degrees of freedom in frustrated lattice structures. *Phys. Rev. B*, 70(24):245113, 2004.
- [31] J. Bagger, S. Duplij, and W. Siegel, editors. *Concise Encyclopedia of SUPERSYMMETRY and noncommutative structures in mathematics and physics*. Kluwer Academic Publishers, Dordrecht, 2003.

- 
- [32] E. Witten. Constraints on supersymmetry breaking. *Nucl. Phys. B*, 202(2):253–316, 1982.
- [33] R. Bott and L.W. Tu. *Differential Forms in Algebraic Topology*. Springer Verlag, New York, 1982.
- [34] L. Huijse, J. Halverson, P. Fendley, and K. Schoutens. Charge frustration and quantum criticality for strongly correlated fermions. *Phys. Rev. Lett.*, 101:146406, 2008.
- [35] L. Huijse and K. Schoutens. Supersymmetry, lattice fermions, independence complexes and cohomology theory. *Adv. Theor. Math. Phys.*, 14.2, 2010. Preprint [ArXiv:0903.0784].
- [36] P. Fendley, K. Schoutens, and H. van Eerten. Hard squares at negative activity. *J. Phys. A*, 38:315, 2005.
- [37] J. Jonsson. Hard squares with negative activity and rhombus tilings of the plane. *Electr. J. Comb.*, 13(1):#R67, 2006.
- [38] J. Jonsson. Hard squares on grids with diagonal boundary conditions. Preprint, 2006.
- [39] J. Jonsson. Certain homology cycles of the independence complex of grid graphs. *Discrete Comput. Geom.*, 2010.
- [40] R.J. Baxter. Hard hexagons: exact solution. *J. Phys. A: Math. Gen.*, 13:L61–L70, 1980.
- [41] N. P. Warner.  $\mathcal{N} = 2$  supersymmetric integrable models and topological field theories. In *High Energy Physics and Cosmology*, E. Gava, K. Narain, S. Randjbar-Daemi, E. Sezgin, and Q. Shafi (Eds.), page 143, 1993.
- [42] Ph. Di Francesco, P. Mathieu, and D. Sénéchal. *Conformal field theory*. Springer Verlag, 1997.
- [43] W. Boucher, D. Friedan, and A. Kent. Determinant formulae and unitarity for the  $\mathcal{N} = 2$  superconformal algebras in two dimensions or exact results on string compactification. *Phys. Lett. B*, 172(3-4):316–322, 1986.
- [44] P. Di Vecchia, J. L. Petersen, and H. B. Zheng.  $\mathcal{N} = 2$  extended superconformal theories in two dimensions. *Phys. Lett. B*, 162(4-6):327–332, 1985.
- [45] B. L. Feigin and D. B. Fuchs. Skew-symmetric differential operators on the line and Verma modules over the Virasoro algebra. *Functs. Anal. Prilozhen*, 16:47, 1982.
- [46] B. L. Feigin and D. B. Fuchs. Verma modules over the Virasoro algebra. In *Topology, Proceedings of Leningrad conference, 1982, Lecture Notes in Mathematics*, L. D. Faddeev and A. A. Malcev (Eds.), volume 1060. Springer, New York, 1985.
- [47] D. Friedan, Z. Qiu, and S. Shenker. Conformal invariance, unitarity, and critical exponents in two dimensions. *Phys. Rev. Lett.*, 52(18):1575–1578, 1984.
- [48] Z.-A. Qiu. Nonlocal current algebra and  $\mathcal{N} = 2$  superconformal field theory in two dimensions. *Phys. Lett. B*, 188:207, 1987.

- [49] A. Schwimmer and N. Seiberg. Comments on the  $\mathcal{N} = 2, 3, 4$  superconformal algebras in two dimensions. *Phys. Lett. B*, 184(2-3):191–196, 1987.
- [50] W. Lerche, C. Vafa, and N. P. Warner. Chiral rings in  $\mathcal{N} = 2$  superconformal theories. *Nucl. Phys. B*, 324(2):427–474, 1989.
- [51] M. Beccaria and G. F. De Angelis. Exact ground state and finite size scaling in a supersymmetric lattice model. *Phys. Rev. Lett.*, 94:100401, 2005.
- [52] H. B. Thacker. Exact integrability in quantum field theory and statistical systems. *Rev. Mod. Phys.*, 53(2):253–285, 1981.
- [53] D. Friedan and A. Kent. Supersymmetric critical phenomena and the two dimensional gaussian model. In *Conformal Invariance and Applications to Statistical Mechanics*, eds. C. Itzykson, H. Saleur, and J.B. Zuber (World Scientific, Singapore, 1988), pp. 578–579, 1988.
- [54] G. Waterson. Bosonic construction of an  $\mathcal{N} = 2$  extended superconformal theory in two dimensions. *Phys. Lett. B*, 171:77–80, 1986.
- [55] I. Affleck. Field theory methods and quantum critical phenomena. In *Fields, strings, critical phenomena: proceedings of Les Houches Summer School in Theoretical Physics 1988.*, E. Brezin and J. Zinn-Justin (Eds.), volume Session 49. North-Holland, 1990.
- [56] G. Veneziano and J. Wosiek. Planar quantum mechanics: an intriguing supersymmetric example. *JHEP*, 2006(01):156, 2006.
- [57] G. Veneziano and J. Wosiek. A supersymmetric matrix model: III. hidden susy in statistical systems. *JHEP*, 2006(11):030, 2006.
- [58] X. Yang and P. Fendley. Non-local spacetime supersymmetry on the lattice. *J. Phys. A: Math. Gen.*, 37(38):8937, 2004.
- [59] G. Veneziano and J. Wosiek. A supersymmetric matrix model: II. exploring higher-fermion-number sectors. *JHEP*, 2006(10):033, 2006.
- [60] A. Armoni, M. Shifman, and G. Veneziano. Exact results in non-supersymmetric large  $n$  orientifold field theories. *Nucl. Phys. B*, 667(1-2):170–182, 2003.
- [61] P. Korcyl. Detailed study of a transition point in the Veneziano-Wosiek model of planar quantum mechanics. *Acta Phys. Pol.*, B38:3169–3180, 2007.
- [62] M. Beccaria. On the supersymmetric vacua of the Veneziano-Wosiek model. *JHEP*, 2007(03):117, 2007.
- [63] H. W. J. Blöte, J. L. Cardy, and M. P. Nightingale. Conformal invariance, the central charge, and universal finite-size amplitudes at criticality. *Phys. Rev. Lett.*, 56(7):742–745, 1986.
- [64] I. Affleck. Universal term in the free energy at a critical point and the conformal anomaly. *Phys. Rev. Lett.*, 56(7):746–748, 1986.

- [65] N. Yu and M. Fowler. Twisted boundary conditions and the adiabatic ground state for the attractive XXZ Luttinger liquid. *Phys. Rev. B*, 46(22):14583–14593, 1992.
- [66] M. Campostrini. Private communication.
- [67] C. Holzhey, F. Larsen, and F. Wilczek. Geometric and renormalized entropy in conformal field theory. *Nucl. Phys. B*, 424(3):443–467, 1994.
- [68] G. Vidal, J. I. Latorre, E. Rico, and A. Kitaev. Entanglement in quantum critical phenomena. *Phys. Rev. Lett.*, 90(22):227902, 2003.
- [69] P. Calabrese and J. Cardy. Entanglement entropy and quantum field theory. *J. Stat. Mech.*, 2004(06):P06002, 2004.
- [70] V. E. Korepin. Universality of entropy scaling in one dimensional gapless models. *Phys. Rev. Lett.*, 92(9):096402, 2004.
- [71] S. R. White. Density matrix formulation for quantum renormalization groups. *Phys. Rev. Lett.*, 69(19):2863–2866, 1992.
- [72] S. R. White. Density-matrix algorithms for quantum renormalization groups. *Phys. Rev. B*, 48(14):10345–10356, 1993.
- [73] U. Schollwöck. The density-matrix renormalization group. *Rev. Mod. Phys.*, 77(1):259–315, 2005.
- [74] R.J. Baxter. Hard squares for  $z = -1$ . Preprint, 2007.
- [75] M. Bousquet-Melou, S. Linusson, and E. Nevo. On the independence complex of square grids. *J. Alg. Comb.*, 27:423–450, 2008.
- [76] A. Engström. Upper bounds on the Witten index for supersymmetric lattice models by discrete Morse theory. *Eur. J. Comb.*, 30(2):429–438, 2009.
- [77] P. Csorba. Subdivision yields Alexander duality on independence complexes. *Electr. J. Comb.*, 16(2):#R11, 2009.
- [78] H. van Eerten. Extensive ground state entropy in supersymmetric lattice models. *J. Math. Phys.*, 46:123302, 2005.
- [79] A. W. Rost, R. S. Perry, J.-F. Mercure, A. P. Mackenzie, and S. A. Grigera. Entropy landscape of phase formation associated with quantum criticality in  $\text{Sr}_3\text{Ru}_2\text{O}_7$ . *Science*, 325(5946):1360–1363, 2009.
- [80] Z. Fisk. The thermodynamics of quantum critical points. *Science*, 325:1348–1349, 2009.
- [81] A. Sütö. Models of superfrustration. *Zeit. Phys. B Cond. Matt.*, 44(1):121–127, 1981.
- [82] P. W. Kasteleyn. Dimer statistics and phase transitions. *J. Math. Phys.*, 4:287–293, 1963.

- [83] F. Y. Wu. Remarks on the modified Potassium Dihydrogen Phosphate model of a ferroelectric. *Phys. Rev.*, 168(2):539–543, 1968.
- [84] J. Jonsson. Hard squares with negative activity on cylinders with odd circumference. *Electr. J. Comb.*, 16(2):#R5, 2009.
- [85] L. Huijse and K. Schoutens. Quantum phases of supersymmetric lattice models. In *XVITH International congress on mathematical physics*, P. Exner (Ed.), pages 635–639. World Scientific, 2010.
- [86] D. L. Bergman, C. Wu, and L. Balents. Band touching from real-space topology in frustrated hopping models. *Phys. Rev. B*, 78(12):125104, 2008.
- [87] M. E. Zhitomirsky and H. Tsunetsugu. Exact low-temperature behavior of a kagomé antiferromagnet at high fields. *Phys. Rev. B*, 70(10):100403, 2004.
- [88] C. K. Majumdar and D. K. Ghosh. On next-nearest-neighbor interaction in linear chain. *J. Math. Phys.*, 10(8):1388–1398, 1969.
- [89] L. Dixon, P. Ginsparg, and J. Harvey. superconformal field theory. *Nucl. Phys. B*, 306(3):470–496, 1988.
- [90] L. van der Noort. Supersymmetric lattice models and quantum criticality. master thesis, 2007.
- [91] R. Santachiara and K. Schoutens. Supersymmetric model of spin-1/2 fermions on a chain. *J. Phys. A: Math. Gen.*, 38(24):5425, 2005.
- [92] P. Fendley and K. Schoutens. Cooper pairs and exclusion statistics from coupled free-fermion chains. *J. Stat. Mech.*, 2007(02):P02017, 2007.
- [93] F. D. M. Haldane. Exact Jastrow-Gutzwiller resonating-valence-bond ground state of the spin-1/2 antiferromagnetic Heisenberg chain with  $1/r^2$  exchange. *Phys. Rev. Lett.*, 60(7):635–638, 1988.
- [94] J. Zaanen. A theoretical physicist journeys to a hairy black hole’s horizon. Nature’s journal club, 2009.
- [95] S. A. Hartnoll, C. P. Herzog, and G. T. Horowitz. Holographic superconductors. *JHEP*, 2008(12):015, 2008.
- [96] O. Aharony, S.S. Gubser, J. Maldacena, H. Ooguri, and Y. Oz. Large n field theories, string theory and gravity - the rac. *Phys. Rep.*, 323:183–386(204), 2000.
- [97] M. Cubrovic, J. Zaanen, and K. Schalm. String theory, quantum phase transitions, and the emergent fermi liquid. *Science*, 325(5939):439–444, 2009.
- [98] T. Faulkner, H. Liu, J. McGreevy, and D. Vegh. Emergent quantum criticality, fermi surfaces, and AdS2. Preprint [ArXiv:0907.2694v1 (hep-th)], 2009.