

Contents

1	Introduction	1
2	The Tunable-Geometry Optical Lattice	7
2.1	Introduction	7
2.1.1	Overview	7
2.1.2	The lattice potential	9
2.2	Experimental implementation	12
2.2.1	Optical setup	12
2.2.2	Interference phase stabilization	14
2.2.3	Characterization of interference phase stability	19
2.2.4	Symmetry phase	21
2.2.5	Intensity tagging and stabilization	22
2.3	Band structure and tight-binding model	24
3	The Fermi-Hubbard model	33
3.1	Interacting ultracold gases	33
3.2	Constructing the Fermi-Hubbard model	37
3.3	High-temperature expansion in cubic lattices	39
3.3.1	Thermodynamic quantities	39
3.3.2	Observable evaluation technique	42
3.3.3	Results for the homogeneous cubic lattice	45
3.4	High-temperature expansion in dimerized lattices	47
3.4.1	Lowest order: atomic limit	48
3.4.2	Series expansion technique	49
3.4.3	Results for the homogeneous dimerized lattice	52
3.5	The harmonic trap and local density approximation	54
4	The experimental apparatus	57
4.1	Preparation cycle of the ultracold Fermi gases	57
4.2	Measurement techniques and accessible observables	61
4.2.1	Double occupancy	61
4.2.2	Quasi-momentum distribution	63
4.2.3	Trap frequencies	63
5	Probing nearest-neighbour correlations	67
5.1	Experimental preparation and detection	67

5.2	Theoretical modelling	69
5.2.1	Perturbation theory	69
5.2.2	Relation to nearest-neighbour correlator	71
5.3	Experimental results	72
5.4	Conclusion	74
6	Detecting spin correlations	77
6.1	Singlet-triplet oscillations on isolated double-wells	77
6.1.1	Two-state picture	77
6.1.2	The tilted double-well	78
6.1.3	Merging adjacent sites and singlet-triplet mapping	82
6.1.4	Singlet-triplet oscillations	86
6.1.5	Additional experimental contributions	90
6.2	Spin correlations in thermalized systems	92
6.2.1	Measuring spin correlations from singlet-triplet oscillations	92
6.2.2	Detection lattice ramp and projection	95
6.2.3	Cleaning of double occupancies	96
7	Quantum Magnetism	99
7.1	Introduction	99
7.2	Entropy redistribution and low temperatures	101
7.3	Spin correlations in dimerized lattices	104
7.3.1	Preparation and detection	104
7.3.2	Results	106
7.4	Antiferromagnetic spin correlations in anisotropic lattices	109
7.4.1	Preparation and detection	109
7.4.2	Results	112
7.5	Conclusion	112
8	Engineering Dirac points	115
8.1	Introduction	115
8.2	The honeycomb lattice	116
8.3	Preparation and detection	117
8.4	Moving and merging Dirac points	119
8.5	Conclusion	122
9	Outlook	123
A	Cubic lattice: high-temperature series	129
B	Dimerized lattice: high-temperature series	133
C	Physical constants and atomic properties	135
	Bibliography	136
	List of Publications	152

Acknowledgments

155

Curriculum Vitae

157