
Contents

Contents	v
1 Introduction	1
1.1 Quantum Computation	2
1.2 Quantum Simulation	3
1.3 Quantum State Engineering	4
1.4 Our Work	5
1.5 Thesis Layout	6
2 The $^9\text{Be}^+$ Qubit	9
2.1 Atomic Structure	9
2.2 Hyperfine Structure and Field-Independent Qubits	11
2.3 Qubit Initialization	16
2.4 Qubit Readout	20
2.4.1 Readout Error - Dark to Bright State Leakage	20
2.4.2 Readout Error - Bright to Dark State Pumping	24
2.4.3 Simulation Results and Discussion	25
2.5 Stimulated Raman Transitions	26
2.5.1 Multiple Excited States	29
2.5.2 Ion's Motion	30
2.6 Quantum Gates	33
2.6.1 Single-Qubit Quantum Gates	33
2.6.2 Two-Qubit Quantum Gates	33
2.7 Off-Resonant Spontaneous Photon Scattering	41
3 The $^{40}\text{Ca}^+$ Qubit	49
3.1 Photoionization of Neutral Calcium Atoms	49
3.2 Atomic Structure	52
3.3 Optical Bloch Equations for an Eight-Level Atomic System	54

4	Ion Trap and Imaging System	63
4.1	Ion Trap	63
4.1.1	Trapping Principles	63
4.1.2	Micromotion	66
4.1.3	Three-Dimensional Segmented Linear Paul Trap	66
4.1.4	DC Voltage Source	68
4.2	Imaging System	69
4.3	Experimental Control	83
5	Beryllium Laser Systems	85
5.1	Overview	86
5.2	Laser Source at 235 nm	87
5.2.1	First SHG Stage: 940 to 470 nm	89
5.2.2	Second SHG Stage: 470 to 235 nm	90
5.3	Laser Source at 313 nm	93
5.3.1	SFG Stage: Infrared to 626 nm	93
5.3.2	SHG stage: 626 to 313 nm	97
5.4	Iodine Spectroscopy	99
5.5	Beryllium Doppler Cooling/Detection Beam Lines	103
5.6	Beryllium Repumping Beam Lines	105
5.7	Beryllium Raman Beam Lines	107
6	$^9\text{Be}^+$ Qubit Control and Measurement	111
6.1	Ion Loading	111
6.2	Qubit Readout/Fluorescence Detection	112
6.2.1	Readout Error Analysis	114
6.2.2	Improving Readout Fidelity Through Shelving	116
6.2.3	Optimal Detection Time for Readout Fidelity	117
6.3	Optical Pumping	120
6.4	Resolved Sideband Cooling	123
6.5	Spin Coherence - Robust Quantum Memory	125
6.6	Micromotion Compensation	127
6.6.1	Intrinsic Micromotion	128
6.6.2	Excess Micromotion	129
6.7	Conclusions	138
7	Squeezed Schrödinger's Cat States	141
7.1	Dissipative Quantum State Preparation	142
7.1.1	Reservoir Engineering	142
7.1.2	Squeezed Vacuum State Preparation	144
7.2	Creation of Squeezed Schrödinger's Cat States	145
7.2.1	Theoretical Description	145
7.2.2	Experimental Details	146
7.2.3	Experimental Results and Discussions	147

7.2.4	Validity of Lamb-Dicke Approximation	152
7.2.5	Simulations for the Coherence of Squeezed Cats	154
7.2.6	Number State Probability Distributions for the Displaced- Squeezed State	154
7.2.7	Possible Applications	157
8	Summary and Outlook	159
8.1	Summary	159
8.2	Outlook	161
A	Matrix Elements for the Electric-Quadrupole Interaction	165
B	Lens Data	167
C	Second-Harmonic-Generation Efficiency	169
	Bibliography	173