

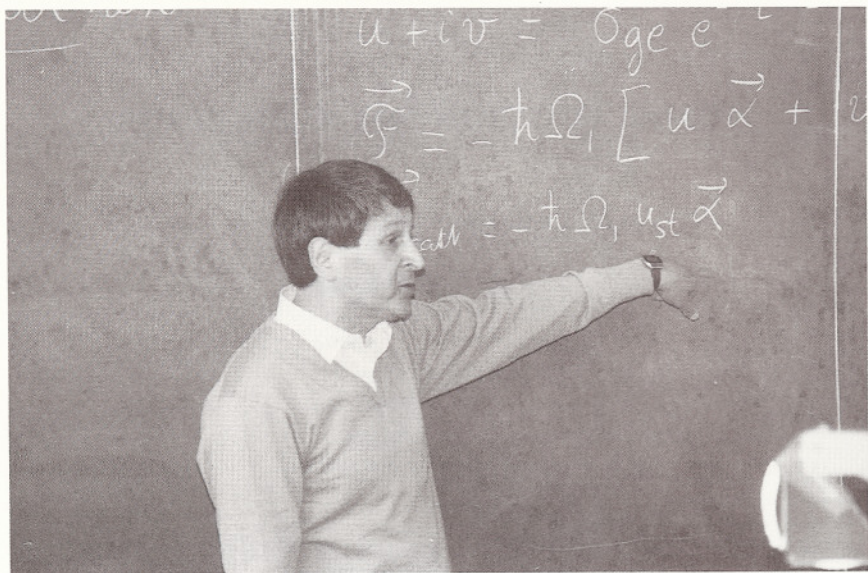
COURSE 1

ATOMIC MOTION IN LASER LIGHT

C. COHEN-TANNOUJJI

*Collège de France
and
Département de Physique de
l'Ecole Normale Supérieure
Paris, France*

*J. Dalibard, J.M. Raimond and J. Zinn-Justin, eds.
Les Houches, Session LIII, 1990
Systèmes Fondamentaux en Optique Quantique
/Fundamental Systems in Quantum Optics
© Elsevier Science Publishers B.V., 1992*



1. General introduction	7
1.1. Purpose of this course	7
1.2. The interacting systems	7
1.3. Characteristic times	8
1.4. Outline of the course	10
<i>Two-level atoms</i>	12
2. Radiative force in the semi-classical limit	12
2.1. Hamiltonian	12
2.2. Heisenberg equations	13
2.3. Semiclassical limit	15
2.3.1. Localization conditions	15
2.3.2. Is localization maintained at later times?	17
2.4. Mean force and Langevin force	19
2.5. Optical Bloch equations (OBE)	21
3. Mean radiative force for a two-level atom initially at rest	23
3.1. Steady-state solution of optical Bloch equations	24
3.2. Reactive response and dissipative response	24
3.3. Dissipative force - Radiation pressure	26
3.4. Reactive force - Dipole force	28
4. Moving atom. Friction force	30
4.1. Simple case of a laser plane wave	31
4.2. Laser standing wave	33
4.2.1. Limit of small velocities ($k_L v_0 \ll \Gamma$)	34
4.2.2. Arbitrary velocity. Method of continued fractions	36
4.3. The $\sigma^+ - \sigma^-$ configuration for a $J_g = 0 \leftrightarrow J_e = 1$ transition	38
5. Fluctuations of radiative forces	39
5.1. Classical Brownian motion	40
5.1.1. Langevin equation	40
5.1.2. Momentum diffusion coefficient	41
5.1.3. Classical regression theorem	42

Contents

1. General introduction	7
1.1. Purpose of this course	7
1.2. The interacting systems	7
1.3. Characteristic times	8
1.4. Outline of the course	10
<i>I Two-level atoms</i>	12
2. Radiative force in the semi-classical limit	12
2.1. Hamiltonian	12
2.2. Heisenberg equations	13
2.3. Semiclassical limit	15
2.3.1. Localization conditions	15
2.3.2. Is localization maintained at later times?	17
2.4. Mean force and Langevin force	19
2.5. Optical Bloch equations (OBE)	21
3. Mean radiative force for a two-level atom initially at rest	23
3.1. Steady-state solution of optical Bloch equations	24
3.2. Reactive response and dissipative response	24
3.3. Dissipative force - Radiation pressure	26
3.4. Reactive force - Dipole force	28
4. Moving atom. Friction force	30
4.1. Simple case of a laser plane wave	31
4.2. Laser standing wave	33
4.2.1. Limit of small velocities ($k_L v_0 \ll \Gamma$)	34
4.2.2. Arbitrary velocity. Method of continued fractions	36
4.3. The $\sigma^+ - \sigma^-$ configuration for a $J_g = 0 \leftrightarrow J_e = 1$ transition	38
5. Fluctuations of radiative forces	39
5.1. Classical Brownian motion	40
5.1.1. Langevin equation	40
5.1.2. Momentum diffusion coefficient	41
5.1.3. Classical regression theorem	42
5.1.4. Kramers-Fokker-Planck equation	44
5.2. Analysis of momentum diffusion in the Heisenberg picture	46
5.2.1. Momentum diffusion coefficient and Langevin force operator	46
5.2.2. Correlation function of the Langevin force operator	47
5.2.3. Physical discussion	48
5.2.4. The Doppler limit in laser cooling	52
5.3. Quantum kinetic equation for the atomic Wigner function	53
5.3.1. Atomic Wigner function	53

5.3.2. Generalized optical Bloch equations	54
5.3.3. Approximations leading to a Kramers–Fokker–Planck equation	55
5.3.4. Physical discussion	56
6. Basic physical processes in the perturbative limit	59
6.1. Introduction	59
6.2. Simple case of an atom in a laser plane wave	60
6.3. Atom in a node of a standing wave	64
6.3.1. Initial state of the atom + field system	64
6.3.2. Amplitude to remain in one of the initially populated states	65
6.3.3. Physical discussion	69
6.4. Atom at rest in any point of a standing wave	72
6.4.1. Initial atomic state	72
6.4.2. New expression for the state vector of A+F at time T	72
6.4.3. Absorption of the incident photon	74
6.4.4. Uncorrelated redistribution and dipole forces	75
6.4.5. Total momentum diffusion coefficient	75
6.5. Atom moving in a standing wave	76
7. Physical mechanisms in the high intensity limit	78
7.1. Introduction	78
7.2. The dressed-atom approach	79
7.3. Dressed-atom interpretation of dipole forces	82
7.4. Atomic motion in an intense laser standing wave – Sisyphus cooling	85
 <i>II Multi-level atoms</i>	 88
8. Optical pumping, light shifts and mean radiative forces	88
8.1. Introduction	88
8.2. Basic equations for multilevel atoms	89
8.2.1. Approximations	89
8.2.2. Operator form of optical Bloch equations	91
8.2.3. Expression of the mean force	92
8.3. Limit of low saturation and low velocity	92
8.3.1. New possible approximations	92
8.3.2. Adiabatic elimination of the excited state	93
8.3.3. Equation of motion of the ground-state density matrix	94
8.4. Light shifts of the ground-state sublevels	96
8.4.1. Hamiltonian part of the equations of motion	96
8.4.2. Properties of light shifts	96
8.5. Relaxation associated with optical pumping	97
8.5.1. Departure rates	97
8.5.2. Feeding of the ground state by spontaneous emission	98
8.5.3. Zeeman coherence effects	99
8.5.4. Case of a moving atom	99
8.6. General properties of the mean force	100
8.6.1. Reactive component and dissipative component	100
8.6.2. Interpretation of the reactive component	101
8.6.3. Interpretation of the dissipative component	104

8.6.4. Particular case of one-dimensional molasses	105
9. Low intensity Sisyphus cooling	105
9.1. Introduction	105
9.2. Presentation of the model	107
9.2.1. Laser configuration	107
9.2.2. Atomic transition. Simplifications for the mean force	108
9.3. Dynamics of the internal degrees of freedom	109
9.3.1. Light shifts of the ground-state sublevels	109
9.3.2. Optical pumping rates	111
9.3.3. Steady-state populations for an atom at rest	112
9.4. Cooling mechanism for a moving atom	113
9.4.1. Sisyphus effect	113
9.4.2. Threshold intensity – Cooling limit	114
9.4.3. Comparison of internal and external times	115
9.5. The jumping regime ($\Omega_{osc}\tau_P \ll 1$)	116
9.5.1. Internal state for an atom with velocity v	117
9.5.2. Velocity dependent mean force. Friction coefficient	118
9.5.3. Equilibrium temperature	119
9.6. The limits of low intensity Sisyphus cooling	120
9.6.1. Results of a full quantum treatment	121
9.6.2. The oscillating regime ($\Omega_{osc}\tau_P \gg 1$)	122
10. The $\sigma^+ - \sigma^-$ laser configuration – Semiclassical theory	123
10.1. Introduction	123
10.2. General expression of the mean force	126
10.2.1. Effective Hamiltonian associated with light shifts	126
10.2.2. Reactive force	127
10.2.3. Dissipative force	128
10.3. Internal state of an atom at rest	128
10.3.1. Light shifts	128
10.3.2. Optical pumping and steady-state populations	130
10.4. Internal state for a moving atom	132
10.4.1. Transformation to the moving rotating frame	132
10.4.2. New Hamiltonian – new equations of motion	133
10.4.3. New expression of the mean force	134
10.5. Friction force for a $J_g = 1 \leftrightarrow J_e = 2$ transition	136
10.5.1. Friction coefficient	136
10.5.2. Velocity capture range	138
10.5.3. Order of magnitude of the equilibrium temperature	139
10.5.4. Anomalous momentum diffusion	140
10.6. Coherent population trapping for a $J_g = 1 \leftrightarrow J_e = 1$ transition	141
10.6.1. Qualitative discussion	141
10.6.2. Velocity dependence of the total fluorescence rate	143
10.6.3. Consequences for atomic motion	144
11. Laser cooling below the single photon recoil limit	144
11.1. Introduction	144
11.1.1. The single photon recoil limit	144
11.1.2. Velocity selective coherent population trapping	145
11.1.3. Optical pumping in velocity space	146
11.1.4. Failure of semi-classical treatments	146

Contents

11.2. One-dimensional quantum treatment	147
11.2.1. Quantum atomic states uncoupled to the laser light	147
11.2.2. Couplings induced by atomic motion	148
11.2.3. Decay rates due to spontaneous emission	149
11.2.4. Spontaneous transfers between different families	154
11.2.5. Expected final momentum distribution	156
11.3. Generalization to higher dimensions	157
11.3.1. Equivalent expression for the absorption amplitude	157
11.3.2. Conditions for having a trapping state	158
11.3.3. Finding a trapping state	159
References	161