Complete Atomic Physics

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Contents

1 Early Atomic Physics

1.1 Core ideas

Atomic physics began when spectra and scattering showed that atoms have internal structure. Rutherford scattering revealed a small charged nucleus, while Balmer lines and the Bohr model showed that bound energies are discrete. Old quantum theory was incomplete, but it introduced angular momentum quantization, correspondence ideas, and the link between frequency and energy differences.

For review, be able to explain Rutherford scattering, use Bohr energies and radii, connect spectral lines to transitions, and state why full wave mechanics was needed. Keep the physical question visible: identify the degrees of freedom, the conserved quantities, the approximation being made, and the observable that would be measured.

1.2 Mathematical spine

$$E_n = -\frac{\mu e^4}{2(4\pi\epsilon_0)^2\hbar^2}\frac{1}{n^2} = -\frac{13.6\,\mathrm{eV}}{n^2} \qquad \text{(H)}$$

Section summary Spectroscopy and scattering forced the quantum view of atomic structure.

2 The Hydrogen Atom

2.1 Core ideas

Hydrogen is the central exactly soluble atom. Separating the Schrodinger equation in spherical coordinates gives quantum numbers n, ℓ, and m, radial wave functions, spherical harmonics, degeneracies, and selection rules. Reduced mass, spin-orbit coupling, relativistic corrections, and the Lamb shift refine the simple Coulomb spectrum.

For review, be able to write the Coulomb Hamiltonian, identify quantum numbers and degeneracy, use parity and angular momentum selection rules, and estimate fine-structure scales. Keep the physical question visible: identify the degrees of freedom, the conserved quantities, the approximation being made, and the observable that would be measured.

2.2 Mathematical spine

$$\hat{H} = -\frac{\hbar^2}{2\mu}\nabla^2 - \frac{e^2}{4\pi\epsilon_0 r}, \qquad E_n = -\frac{\mu e^4}{2(4\pi\epsilon_0)^2\hbar^2 n^2}$$

Section summary Hydrogen supplies the template for quantum numbers, orbitals, and atomic spectra.

3 Helium

3.1 Core ideas

Helium is the simplest atom where electron-electron repulsion matters. The independent-particle picture gives a starting point, but correlation and exchange split singlet and triplet states. Variational methods, perturbation theory, and Hartree–Fock ideas explain why identical-particle symmetry changes energies and spectra.

For review, be able to construct symmetric and antisymmetric two-electron states, distinguish singlet from triplet, estimate screening, and state why exact separation fails. Keep the physical question visible: identify the degrees of freedom, the conserved quantities, the approximation being made, and the observable that would be measured.

3.2 Mathematical spine

$$\hat{H} = \hat{h}(1) + \hat{h}(2) + \frac{e^2}{4\pi\epsilon_0 r_{12}}, \qquad \Psi_{\text{total}} \text{ antisymmetric}$$

Section summary Helium introduces correlation, exchange, and approximation methods.

4 The Alkalis

4.1 Core ideas

Alkali atoms have one valence electron outside closed shells. They are hydrogen-like at large radius, but core screening and penetration shift levels by quantum defects. Spin-orbit splitting and optical doublets make alkalis central in spectroscopy, laser cooling, clocks, and quantum control.

For review, be able to use effective one-electron energies, interpret quantum defects, identify fine-structure doublets, and connect spectra to valence-electron wave functions. Keep the physical question visible: identify the degrees of freedom, the conserved quantities, the approximation being made, and the observable that would be measured.

4.2 Mathematical spine

$$E_{n\ell} \approx -\frac{R_\infty hc}{(n-\delta_\ell)^2}, \qquad \Delta E_{\mathrm{so}} \propto \langle r^{-3} \rangle\, \boldsymbol{L} \cdot \boldsymbol{S}$$

Section summary Alkalis behave like corrected hydrogen atoms with experimentally useful optical lines.

5 The LS-Coupling Scheme

5.1 Core ideas

Many-electron atoms are organized by adding orbital and spin angular momenta. In light atoms, electrostatic interactions usually establish total L and S first, then spin-orbit coupling forms J. Term symbols encode S, L, J, parity, and selection rules; Hund's rules give useful energy ordering.

For review, be able to read and build term symbols, apply angular momentum addition, use Hund's rules qualitatively, and know when jj coupling replaces LS coupling. Keep the physical question visible: identify the degrees of freedom, the conserved quantities, the approximation being made, and the observable that would be measured.

5.2 Mathematical spine

$$^{2S+1}L_J, \qquad \boldsymbol{L} = \sum_i \boldsymbol{\ell}_i, \quad \boldsymbol{S} = \sum_i \boldsymbol{s}_i, \quad \boldsymbol{J} = \boldsymbol{L} + \boldsymbol{S}$$

Section summary Coupling schemes turn complicated spectra into angular-momentum bookkeeping.

6 Hyperfine Structure and Isotope Shift

6.1 Core ideas

Hyperfine structure comes from nuclear spin interacting with electronic magnetic fields and electric field gradients. Isotope shifts come from nuclear mass and charge-radius differences. These small splittings are essential in clocks, precision tests, and laser spectroscopy.

For review, be able to combine I and J into F, compute allowed F values, identify magnetic dipole hyperfine splitting, and separate normal mass, specific mass, and field shifts. Keep the physical question visible: identify the degrees of freedom, the conserved quantities, the approximation being made, and the observable that would be measured.

6.2 Mathematical spine

$$\boldsymbol{F} = \boldsymbol{I} + \boldsymbol{J}, \qquad E_F = \frac{A}{2}\left[F(F+1) - I(I+1) - J(J+1)\right]$$

Section summary Nuclear properties leave precise fingerprints in atomic spectra.

7 Interaction of Atoms with Radiation

7.1 Core ideas

Light drives transitions through the electric dipole interaction, with rates controlled by matrix elements, density of states, detuning, and polarization. Einstein coefficients, Rabi oscillations, optical Bloch equations, selection rules, and spontaneous emission connect quantum amplitudes to observed absorption and fluorescence.

For review, be able to derive dipole selection rules, define Rabi frequency and detuning, distinguish absorption, stimulated emission, and spontaneous emission, and interpret saturation. Keep the physical question visible: identify the degrees of freedom, the conserved quantities, the approximation being made, and the observable that would be measured.

7.2 Mathematical spine

$$H_{\text{int}} = -\boldsymbol{d} \cdot \boldsymbol{E}, \qquad \Omega = \frac{\boldsymbol{d}_{eg} \cdot \boldsymbol{E}_0}{\hbar}, \qquad \Delta = \omega - \omega_0$$

Section summary Atom-light interaction is controlled by dipole matrix elements and resonance.

8 Laser Cooling, Trapping, and Modern Experiments

8.1 Core ideas

Laser cooling uses momentum exchange between photons and atoms. Doppler cooling, optical molasses, magneto-optical traps, dipole traps, evaporative cooling, and ion traps exploit scattering forces, light shifts, and magnetic gradients. The key idea is to engineer dissipation without losing quantum control.

For review, be able to estimate recoil momentum and Doppler limit, explain MOT restoring forces, distinguish scattering and dipole forces, and name common routes to ultracold gases. Keep the physical question visible: identify the degrees of freedom, the conserved quantities, the approximation being made, and the observable that would be measured.

8.2 Mathematical spine

$$k_B T_D = \frac{\hbar\Gamma}{2}, \qquad \boldsymbol{F}_{\text{sc}} \approx \hbar\boldsymbol{k}\,\Gamma\,\frac{s/2}{1 + s + (2\Delta/\Gamma)^2}$$

Section summary Modern atomic physics uses light and fields to cool, trap, and control single quantum systems.