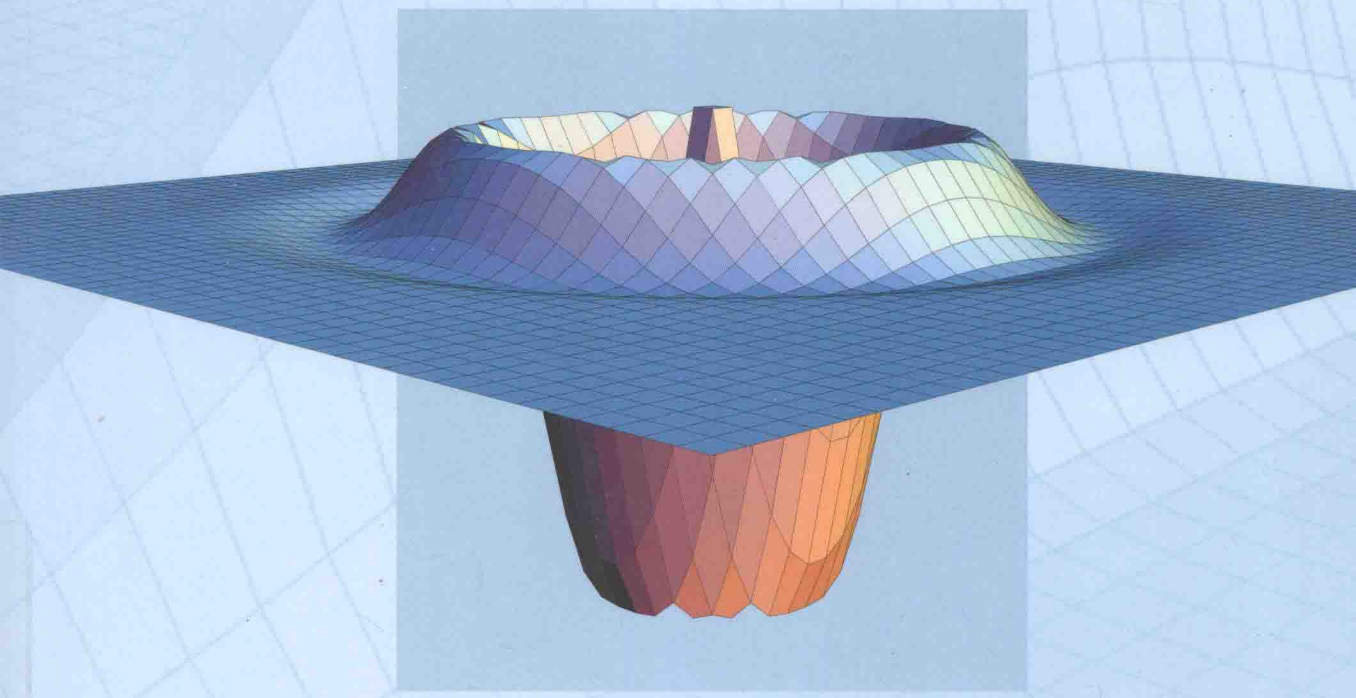
QUANTUM MECHANICS



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Quantum Mechanics

The important changes quantum mechanics has undergone in recent years are reflected in this new approach for students.

A strong narrative and over 300 worked problems lead the student from experiment, through general principles of the theory, to modern applications. Stepping through results allows students to gain a thorough understanding. Starting with basic quantum mechanics, the book moves on to more advanced theory, followed by applications, perturbation methods and special fields, and ending with new developments in the field. Historical, mathematical, and philosophical boxes guide the student through the theory. Unique to this textbook are chapters on measurement and quantum optics, both at the forefront of current research. Advanced undergraduate and graduate students will benefit from this new perspective on the fundamental physical paradigm and its applications.

Online resources including solutions to selected problems and 200 figures, with color versions of some figures, are available at www.cambridge.org/Auletta.

Gennaro Auletta is Scientific Director of Science and Philosophy at the Pontifical Gregorian University, Rome. His main areas of research are quantum mechanics, logic, cognitive sciences, information theory, and applications to biological systems.

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Symbols

Latin letters

a	proposition, number
$\hat{a} = \sqrt{\frac{m}{2\hbar\omega}}\left(\omega\hat{x} + \imath\hat{\dot{x}}\right)$	annihilation operator
$\hat{a}_{\mathbf{k}}$	annihilation operator of the **k**-th mode of the electromagnetic field
$\hat{a}^{\dagger} = \sqrt{\frac{m}{2\hbar\omega}}\left(\omega\hat{x} - \imath\hat{\dot{x}}\right)$	creation operator
$\hat{a}^{\dagger}_{\mathbf{k}}$	creation operator of the **k**-th mode of the electromagnetic field
$\vert a\rangle$	(polarization) state vector (along the direction **a**)
$\vert a_j\rangle$	element of a discrete vector basis $\{\vert a_j\rangle\}$
A	number
$\mathrm{A}(\zeta)$	Airy function
$\mathbf{A}$	vector potential
$\hat{\mathbf{A}}(\mathbf{r}, t) = \sum_{\mathbf{k}} c_{\mathbf{k}} \times \left[\hat{a}_{\mathbf{k}}\mathbf{u}_{\mathbf{k}}(\mathbf{r})e^{-\imath\omega_{\mathbf{k}}t} + \hat{a}^{\dagger}_{\mathbf{k}}\mathbf{u}^{*}_{\mathbf{k}}(\mathbf{r})e^{\imath\omega_{\mathbf{k}}t}\right]$	vector potential operator
$\mathcal{A}$	apparatus
$\vert\mathcal{A}\rangle$	ket describing a generic state of the apparatus
b	proposition, number
$\vert b\rangle$	(polarization) state vector (along the direction **b**)
$\vert b_j\rangle$	element vector of a discrete basis $\{\vert b_j\rangle\}$
B	number, intensity of the magnetic field
$\mathrm{B} = h/8\pi^2\mathrm{I}$	rotational constant of the rigid rotator
$\mathbf{B} = \nabla \times \mathbf{A}$	classical magnetic field
$\hat{\mathbf{B}}(\mathbf{r}, t) = \imath\sum_{\mathbf{k}}\left(\frac{\hbar k}{2cL^3\epsilon_0}\right)^{\frac{1}{2}} \times \left[\hat{a}_{\mathbf{k}}e^{\imath(\mathbf{k}\cdot\mathbf{r}-\omega_{\mathbf{k}}t)} - \hat{a}^{\dagger}_{\mathbf{k}}e^{-\imath(\mathbf{k}\cdot\mathbf{r}-\omega_{\mathbf{k}}t)}\right]\mathbf{b}_{\lambda}$	magnetic field operator
c	speed of light, proposition
c_j, c'_j	generic coefficients of the j-th element of a given discrete expansion
c_{a_j}	coefficient of the basis element $\vert a_j\rangle$
c_{b_j}	coefficient of the basis element $\vert b_j\rangle$
$c_n^{(0)}$	coefficients of the expansion of a state vector in stationary state at an initial moment $t_0 = 0$

$c(\eta), c(\xi)$	coefficient of the eigenkets of continuous observables $\hat{\eta}$ and $\hat{\xi}$, respectively
$\vert c\rangle$	polarization state vector (along the direction **c**)
C, C'	constants
C	coulomb charge unit, correlation function
$\mathcal{C}$	cost function
C_{jk}	cost incurred by choosing the j-th hypothesis when the k-th hypothesis is true
$\mathbb{C}$	field of complex numbers
d	electric dipole
d	distance
$\mathcal{D}$	decoherence functional
$\hat{D}(\alpha) = e^{\alpha\hat{a}^\dagger - \alpha^*\hat{a}}$	displacement operator
e	exponential function
e	electric charge
$\mathbf{e} = (e_x, e_y, e_z)$	vector orthogonal to the propagation direction of the electromagnetic field
$\vert e\rangle$	excited state
$\vert e_k\rangle$	k-th ket of the environment's eigenbasis $\{\vert e_j\rangle\}$
E	energy
E_n	n-th energy level, energy eigenvalue
E_0	energy value of the ground state
E	one-dimensional electric field
$\mathbf{E} = -\nabla V_e - \frac{\partial}{\partial t}\mathbf{A}$	classical electric field
$\hat{\mathbf{E}}(\mathbf{r}, t) = \imath \sum_{\mathbf{k}} \left(\frac{\hbar\omega_{\mathbf{k}}}{2\epsilon_0}\right)^{\frac{1}{2}} \times \left[\hat{a}_{\mathbf{k}}\mathbf{u}_{\mathbf{k}}(\mathbf{r})e^{-\imath\omega_{\mathbf{k}}t} - \hat{a}^\dagger_{\mathbf{k}}\mathbf{u}^*_{\mathbf{k}}(\mathbf{r})e^{\imath\omega_{\mathbf{k}}t}\right]$	electric field operator
$\mathcal{E}$	environment
$\hat{E}$	effect
$\vert\mathcal{E}\rangle$	ket describing a generic state of the environment
f	arbitrary function
$\mathbf{f}, \mathbf{f}'$	arbitrary vectors
$\vert f\rangle$	final state vector
F	force, arbitrary classical physical quantity
$\mathbf{F}_e$	classically electrical force
$\mathbf{F}_m$	classically magnetic force
$\mathrm{F}_m(\phi)$	eigenfunctions of $\hat{l}_z$
$\mathcal{F}(x) = \wp(\xi < x)$	distribution function of a random variable that can take values $< x$
g	arbitrary function, gravitational acceleration
$\vert g\rangle$	ground state
$G^{(n)}$	coherence of the n-th order

G	Green function
$G_0(\mathbf{r}', t'; \mathbf{r}, t) = -\imath \left[\frac{m}{2\pi\imath\hbar(t'-t)}\right]^{\frac{3}{2}} e^{\frac{\imath m\|\mathbf{r}'-\mathbf{r}\|^2}{2\hbar(t'-t)}}$	free Green function
$\mathcal{G}$	group
$\hat{G}$	generator of a a continuos transformation or of a group
$h = 6.626069 \times 10^{-34}\mathrm{J} \cdot \mathrm{s}$	Planck constant
$\hbar = h/2\pi$	
$\|h\rangle$	state of horizontal polarization
$\mathcal{H}$	Hilbert space
$\mathcal{H}_{\mathcal{A}}$	Hilbert space of the apparatus
$\mathcal{H}_{\mathcal{S}}$	Hilbert space of the system
$\hat{H}$	Hamiltonian operator
$\hat{H}_0$	unperturbed Hamiltonian
$\hat{H}_A$	Hamiltonian of a free atom
$\hat{H}_F$	field Hamiltonian
$\hat{H}_{\mathrm{I}}$	interaction Hamiltonian
$\hat{H}_{\mathrm{I}}^{\mathrm{I}}$	interaction Hamiltonian in Dirac picture
$\hat{H}_{JC}$	Jaynes–Cummings Hamiltonian
$\hat{H}_r$	planar part of the Hamiltonian
$\mathrm{H}_n(\zeta) = (-1)^n e^{\zeta^2} \frac{d^n}{d\zeta^n} e^{-\zeta^2}$ n-th	Hermite polynomial, for all $n \neq 0$
$\imath$	imaginary unity
$\boldsymbol{\imath}$ x	Cartesian versor
$\|i\rangle$	initial state vector
I	intensity (of radiation)
I	moment of inertia
$\hat{I}$	identity operator
$\Im(z) = \frac{z-z^*}{2\imath}$	imaginary part of a complex number z
$\boldsymbol{\jmath}$ y	Cartesian versor
$\hat{\boldsymbol{\jmath}} = \hat{\boldsymbol{J}}/\hbar = (\hat{\jmath}_x, \hat{\jmath}_y, \hat{\jmath}_z)$	
$\|j\rangle$	arbitrary ket, element of a continuous or discrete basis
$\|j, m\rangle$	eigenket of $\hat{J}_z$
$\mathbf{J}$	density of the probability current
J_{I}	incidental current density
J_R	reflected current density
J_{T}	transmitted current density
$\hat{\mathbf{J}} = \hat{\mathbf{L}} + \hat{\mathbf{S}} = (\hat{J}_x, \hat{J}_y, \hat{J}_z)$	total angular momentum
$\hat{\hat{\mathcal{J}}}$	jump superoperator
$k, \mathbf{k}$	wave vector
$\boldsymbol{k}$ z	Cartesian versor
k_{B}	Boltzmann constant
$\|k\rangle$	generic ket, element of a continuous or discrete basis

l	arbitrary length
$\hat{\mathbf{l}} = (\hat{l}_x, \hat{l}_y, \hat{l}_z) = \hat{\mathbf{L}}/\hbar$	
$\hat{l}_\pm = \hat{l}_x \pm \imath \hat{l}_y$	raising and lowering operators for the levels of the angular momentum
$\|l\rangle$	generic ket
$\|l, m_l\rangle$	eigenket of $\hat{l}_z$
$\mathrm{L}(q_1, \ldots, q_n; \dot{q}_1, \ldots, \dot{q}_n)$	classical Lagrangian function
$\hat{\mathrm{L}}$	Lagrangian multiplier operator
$\hat{\mathbf{L}} = (L_x, L_y, L_z)$	orbital angular momentum
$\hat{\hat{\mathcal{L}}}$	Lindblad superoperator
m	mass of a particle
m_e	mass of the electron
m_n	mass of the nucleus
m_p	mass of the proton
m_l	magnetic quantum number
m_j	eigenvalue of $\hat{j}_z$
m_s	spin magnetic quantum number or secondary spin quantum number
$\|m\rangle$	generic ket, eigenket of the energy
M	measure of purity
$\mathcal{M}$	meter
$\hat{M}$	arbitrary matrix
$\mathbf{n}, \mathbf{n}'$	direction vectors
$\|n\rangle$	eigenvector of the harmonic oscillator Hamiltonian or of the number operator
N	number of elements of a given set
$\mathcal{N}$	normalization constant
$\hat{N} = \hat{a}^\dagger \hat{a}$	number operator
$\hat{N}_\mathbf{k} = \hat{a}_\mathbf{k}^\dagger \hat{a}_\mathbf{k}$	
o_j	j-th eigenvalue of the observable $\hat{O}$
$\|o\rangle$	eigenket of the observable $\hat{O}$
$\|o_j\rangle$	j-th eigenket of the observable $\hat{O}$
$\hat{O}, \hat{O}', \hat{O}''$	generic operators, generic observables
$\hat{O}^\mathrm{H}$	observable in the Heisenberg picture
$\hat{O}^\mathrm{I}$	observable in the Dirac picture
$\hat{O}^\mathrm{S}$	observable in the Schrödinger picture
$\hat{O}_\mathcal{A}$	apparatus' pointer
$\hat{O}_\mathcal{S}$	observable of the object system
$\hat{O}_\mathrm{ND}$	non-demolition observable
$\|\hat{O}\}$	super-ket (or S-ket)
p_k	classical generalized momentum component
$\hat{\mathbf{p}} = (\hat{p}_x, \hat{p}_y, \hat{p}_z)$	three-dimensional momentum operator
$\hat{p}_x$	one-dimensional momentum operator

$\dot{\hat{p}}_x$	time derivative of $\hat{p}_x$
$\hat{p}_r = -\imath\hbar\frac{1}{r}\frac{\partial}{\partial r}r$	radial part of the momentum operator
$\mathrm{P}(\alpha, \alpha^*)$	P-function
$\hat{P}_j$	projection onto the state $\| j\rangle$ or $\|b_j\rangle$
$\mathcal{P}$	path predictability
$\hat{\mathcal{P}}$	path predicability operator
$\wp_j$ or $\wp(j)$	probability of the event j
$\wp_k(\mathbf{D}) = \wp(\mathbf{D}\|\mathrm{H}_k)$	probability density function that the particular set $\mathbf{D}$ of data is observed when the system is actually in state k
$\wp(\mathrm{H}_j\|\mathrm{H}_k) = \mathrm{Tr}\left(\hat{\rho}_k\hat{E}_{\mathrm{H}_j}\right)$	conditional probability that one chooses the hypothesis H_j when H_k is true
q_k	classical generalized position component
Q	charge density
$\mathrm{Q}(\alpha, \alpha^*) = \frac{1}{\pi}\langle\alpha\|\hat{\rho}\|\alpha\rangle$	Q-function
$\mathcal{Q}$	quantum algebra
$\mathbb{Q}$	field of rational numbers
r	spherical coordinate
$\mathbf{r}\cdot\mathbf{r}'$	scalar product between vectors $\mathbf{r}$ and $\mathbf{r}'$
r_k	k-th eigenvalue of a density matrix
$r_0 = \frac{\hbar^2}{me^2}$	Bohr's radius
$\hat{\mathbf{r}} = (\hat{x}, \hat{y}, \hat{z})$	three-dimensional position operator
R	reflection coefficient
$\mathrm{R}(r)$	radial part of the eigenfunctions of $\hat{l}_z$ in speherical coordinates
$\mathcal{R}, \mathcal{R}'$	reference frames
$\mathcal{R}$	reservoir
$\mathbb{R}$	field of real numbers
$\Re(z) = \frac{z+z^*}{2}$	real part of a complex quantity z
$\hat{R}, \hat{\mathbf{R}}(\beta, \phi, \theta)$	rotation operator, generator of rotations
$\hat{\mathrm{R}}_{\hat{O}}$	resolvent of the operator $\hat{O}$
$\hat{\mathcal{R}}_j = \sum_{k=1}^{N}\wp_k^{\mathrm{A}}C_{jk}\hat{\rho}_k$	risk operator for the j-th hypothesis
$\| R\rangle$	initial state of the reservoir
s	spin quantum number
$\hat{\mathbf{s}} = (\hat{s}_x, \hat{s}_y, \hat{s}_z) = \hat{\mathbf{S}}/\hbar$	spin vector operator
$\hat{s}_\pm = \hat{s}_x \pm \imath\hat{s}_y$	raising and lowering spin operators
S	action
$\mathcal{S}$	generic quantum system
S	entropy
$\hat{\mathbf{S}} = (\hat{S}_x, \hat{S}_y, \hat{S}_z)$	spin observable
t	time
$\hat{t}$	time operator
$\| t\rangle$	eigenket of the time operator

T	transmission coefficient
T	temperature, classical kinetic energy
$\hat{T}$	kinetic energy operator
$\hat{\mathcal{T}}$	time reversal operator
$\hat{\hat{\mathcal{T}}}, \mathcal{T}$	generic transformation
$u(\nu, T)$	energy density
$\mathbf{u_k(r)} = \frac{\mathbf{e}}{L^{\frac{3}{2}}} e^{\imath \mathbf{k}\cdot\mathbf{r}}$	**k**-th mode function of the electromagnetic field
U	scalar potential
$\hat{U}$	unitary operator
$\hat{U}_{\mathrm{BS}}$	beam splitting unitary operator
$\hat{U}_{\mathrm{PBS}}$	polarization beam-splitting unitary operator
$\hat{U}_{\mathrm{CNOT}}$	unitary controlled-not operator
$\hat{U}_f$	Boolean unitary transformation
$\hat{U}_F$	Fourier unitary transformation
$\hat{U}_H$	unitary Hadamard operator
$\hat{U}_{\mathbf{p}}(\mathbf{v})$	unitary momentum translation
$\hat{U}_P$	permutation operator
$\hat{U}_{\mathbf{R}}(\phi)$	rotation operator
$\hat{U}_{\mathcal{R}}$	space-reflection operator
$\hat{U}_t$	time translation unitary operator
$\hat{U}_x(a)$	one-dimensional space translation unitary operator
$\hat{U}_{\mathbf{r}}(\mathbf{a})$	three-dimensional space translation unitary operator
$\hat{U}_\theta$	unitary rotation operator
$\hat{U}_\phi$	unitary phase operator
$\hat{U}_\tau^{\mathcal{SA}} = e^{-\frac{\imath}{\hbar}\int_0^\tau dt \hat{H}_{\mathcal{SA}}(t)}$	unitary operator coupling system and apparatus for time interval τ
$\hat{U}_t^{\mathcal{SA,E}} = e^{-\frac{\imath}{\hbar} t \hat{H}_{\mathcal{SA,E}}}$	unitary operator which couples the environment $\mathcal{E}$ to the system and apparatus $\mathcal{S}+\mathcal{A}$ at time t
$\hat{\tilde{U}}$	antiunitary operator
$\hat{\tilde{U}}_{\mathcal{T}}$	time reversal
$\hat{\mathcal{U}}$	generic transformation that can be either unitary or antiunitary
$\vert v\rangle$	state of vertical polarization
$\vert v_n\rangle$	element of a discrete basis
V	potential energy
V_e	scalar potential of the electromagnetic field
$V_c(r) = \frac{\hbar^2 l(l+1)}{2mr^2}$	centrifugal-barrier potential energy
V_{c}	classical potential energy
$\hat{V}$	potential energy operator

V	volume
$\mathbf{V}$	generic vector
$\mathcal{V}$	visibility of interference, generic vectorial space
$\hat{\mathcal{V}}$	visibility of interference operator
w_k	k-th probability weight
$\vert w_n\rangle$	element of a discrete basis vector
$W(\alpha,\alpha^*) = \frac{1}{\pi^2}\int d^2\alpha e^{-\eta\alpha^*+\eta^*\alpha}\chi_W(\eta,\eta^*)$	Wigner function
x	first Cartesian axis, coordinate
$\vert x\rangle$	eigenket of $\hat{x}$
$\hat{x}$	one-dimensional position operator
$\dot{\hat{x}}$	time derivative of $\hat{x}$
$\hat{X}_1 = \frac{1}{\sqrt{2}}(\hat{a}^\dagger + \hat{a})$	quadrature
$\hat{X}_2 = \frac{\imath}{\sqrt{2}}(\hat{a}^\dagger - \hat{a})$	quadrature
$\mathcal{X}$	set
y	second Cartesian axis, coordinate
$Y_{lm}(\theta,\phi)$	spherical harmonics
z	third Cartesian axis, coordinate
Z	atomic number
$Z(\beta) = \mathrm{Tr}\left(e^{-\beta\hat{H}}\right)$	partition function
$\mathcal{Z}$	parameter space
$\mathbb{Z}$	field of integer numbers

Greek letters

α	angle, (complex) number
$\vert\alpha\rangle = e^{-\frac{\vert\alpha\vert^2}{2}}\sum_{n=0}^{\infty}\frac{\alpha^n}{\sqrt{n!}}\vert n\rangle$	coherent state
β	angle, (complex) number, thermodynamic variable = $(k_\mathrm{B}T)^{-1}$
$\vert\beta\rangle$	coherent state
γ	damping constant
Γ	Euler gamma function
Γ	phase space
$\hat{\Gamma}_k$	reservoir operator
δ_{jk}	Kronecker symbol
$\delta(x)$	Dirac delta function
$\Delta = \nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$	Laplacian
Δ_ψ	uncertainty in the state $\vert\psi\rangle$
ϵ	small quantity
ϵ_{jkn}	Levi–Civita tensor
ε	coupling constant
$\varepsilon_0 = \left(\frac{\omega}{2\epsilon_0\hbar l^3}\right)^{\frac{1}{2}}\vert\mathbf{d}\cdot\mathbf{e}\vert$	vacuum Rabi frequency

$\varepsilon_n = \varepsilon_0\sqrt{n+1}$	Rabi frequency
$\varepsilon_{\mathcal{SA}}$	coupling between object system and apparatus
$\varepsilon_{\mathcal{SM}}$	coupling between object system and meter
ζ	arbitrary variable, arbitrary (wave) function
ζ_S, ζ_A	number of possible configurations of bosons and fermions, respectively
η	arbitrary variable, arbitrary (wave) function
$\hat{\eta}$	arbitrary (continuous) observable
$\|\eta\rangle$	eigenkets of $\hat{\eta}$
θ	angle, spherical coordinate
ϑ	generic amplitude
$\hat{\vartheta}_k(m) = \left\langle m \left\| \hat{U}_t \right\| k \right\rangle$	amplitude operator connecting a premeasurement ($\|k\rangle$), a unitary evolution ($\hat{U}_t$), and a measurement ($\|m\rangle$)
$\Theta_{lm}(\theta)$	theta component of the spherical harmonics
$\Theta(\theta)$	part of the spherical harmonics depending on the polar coordinate θ
$\hat{\Theta}, \hat{\hat{\Theta}}$	arbitrary transformation (superoperator)
ι	constant, parameter
$\|\iota\rangle$	internal state of a system
κ	parameter
λ	wavelength
$\lambda_c = h/mc$	Compton wavelength of the electron
$\lambda_T = \frac{\hbar}{\sqrt{2mk_{\rm B}T}}$	thermal wavelength
$\Lambda = \mu_B B_{\rm ext}$	constant used in the Paschen–Bach effect
$\hat{\Lambda}_j$	Lindblad operator
$\boldsymbol{\mu}$	classically magnetic dipole momentum
$\hat{\boldsymbol{\mu}}_l = \frac{e\hbar}{2m}\hat{\mathbf{l}}$	orbital magnetic momentum of a massive particle
$\hat{\boldsymbol{\mu}}_s = Q\frac{e\hbar}{2m}\hat{\mathbf{s}}$	spin magnetic momentum
$\mu_B = \frac{e\hbar}{2m}$	Bohr magneton
μ_0	magnetic permeability
ν	frequency
ξ	random variable, variable
$\xi(r) = R(r)r$	change of variable for the radial part of the wave function
$\hat{\xi}$	arbitrary (continuous) observable
$\|\xi\rangle$	eigenkets of $\hat{\xi}$
$\Xi(x)$	Heaviside step function
$\hat{\Pi}$	parity operator
ρ	(classical) probability density
$\hat{\rho}$	density matrix (pure state)
$\hat{\hat{\hat{\rho}}}$	time-evolved density matrix

$\hat{\hat{\rho}}$	mixed density matrix
$\hat{\rho}_f$	density matrix for the final state of a system
$\hat{\rho}_i$	density matrix for the initial state of a system
$\hat{\varrho}_j$	reduced density matrix of the j-th subsystem
$\hat{\rho}_{\mathcal{SA}}$	density matrix of the system plus apparatus
$\hat{\rho}_{\mathcal{SAE}}$	density matrix of the system plus apparatus plus environment
$\sigma_x^2 = \langle \hat{x}^2 \rangle - \langle \hat{x} \rangle^2$	variance of $\hat{x}$
σ_x	standard deviation (square root of the variance) of $\hat{x}$
$\sigma_p^2 = \langle \hat{p}_x^2 \rangle - \langle \hat{p}_x \rangle^2$	variance of $\hat{p}_x$
σ_p	standard deviation (square root of the variance) of $\hat{p}_x$
$\hat{\sigma}_+ = \| e \rangle \langle g \|$	raising operator
$\hat{\sigma}_- = \| g \rangle \langle e \|$	lowering operator
$\hat{\boldsymbol{\sigma}} = (\hat{\sigma}_x, \hat{\sigma}_y, \hat{\sigma}_z)$	Pauli (two-dimensional) spin matrices
$\varsigma(s)$	wave component of the spin
$\| \varsigma \rangle$	ket of the object system
τ	time interval, interaction time between two or more systems
$\tau_d \simeq \gamma^{-1} \left(\frac{\lambda_T}{\Delta x} \right)^2$	decoherence time
ϕ	angle, spherical coordinate
$\hat{\phi}$	angle operator
$\| \phi \rangle$	eigenket of the angle operator
$\| \varphi \rangle, \| \varphi' \rangle$	state vectors
$\varphi(\xi)$	eigenfunctions of the observable with eigenvector $\| \xi \rangle$
$\varphi_k(x)$	plane waves
$\varphi_{\mathbf{k}}(\mathbf{r})$	spherical waves
$\varphi_p(x)$	momentum eigenfunctions in the position representation
$\varphi_{x_0}(x)$	position eigenfunctions in the position representation
$\tilde{\varphi}_{p_0}(p_x)$	momentum eigenfunctions in the momentum representation
$\tilde{\varphi}_x(p_x)$	position eigenfunctions in the momentum representation
$\varphi_\xi(x)$	scalar product $\langle x \| \xi \rangle$
$\varphi_\eta(\xi)$	scalar product $\langle \xi \| \eta \rangle$
Φ	flux of electric current
Φ_M	magnetic flux
$\| \Phi \rangle$	generic ket for compound systems
$\chi_\xi(\eta) = \int d\mathcal{F}(x) e^{\imath \eta x}$	classical characteristic function of a random variable ξ

$\chi(\eta, \eta^*) = e^{\lvert\eta\rvert^2} \int d^2\alpha e^{\eta\alpha^* - \alpha\eta^*} Q(\alpha, \alpha^*)$	characteristic function
$\chi_W(\eta, \eta^*) = e^{-\frac{1}{2}\lvert\eta\rvert^2} \chi(\eta, \eta^*)$	Wigner characteristic function
$\lvert\psi\rangle, \lvert\psi'\rangle$	state vectors
$\lvert\psi(t)\rangle$	time-evolved or time-dependent state vector
$\lvert\psi_E\rangle$	Eigenket of energy corresponding to eigenvalue E (in the continuous case)
$\lvert\Psi_F\rangle$	quantum state of the electromagnetic field
$\lvert\psi_n\rangle$	n-th stationary state
$\lvert\psi\rangle_H$	state vector in the Heisenberg picture
$\lvert\psi\rangle_I$	state vector in the Dirac picture
$\lvert\psi\rangle_S$	state vector in the Schrödinger picture
$\psi(x), \psi(\mathbf{r})$	wave functions in the position representation
$\psi(\eta), \psi(\xi)$	wave functions of two arbitrary continuous observables, η and ξ, respectively
$\tilde{\psi}(p_x), \tilde{\psi}(\mathbf{p})$	Fourier transform of the wave functions
$\psi(\mathbf{r}, s)$	wave function with a spinor component
$\psi(r, \theta, \phi)$	eigenfunctions of $\hat{l}_z$ in spherical coordinates
$\psi_p(x), \psi_\mathbf{p}(\mathbf{r}), \psi_k(x), \psi_\mathbf{k}(\mathbf{r})$	momentum eigenfunctions in the position representation
$\psi_E(x)$	energy eigenfucntion in the position representation
ψ_S, ψ_A	symmetric and antisymmetric wavefucntions, respectively
$\lvert\Psi\rangle$	ket of a compund system
$\lvert\Psi\rangle_{\mathcal{SA}}$	ket describing an objects system plus apparatus compound system
$\lvert\Psi\rangle_{\mathcal{SM}}$	ket describing an objects system plus meter compound system
$\lvert\Psi\rangle_{\mathcal{SAE}}$	ket describing an objects system plus apparatus plus environment compound system
$\Psi(x), \Psi(\mathbf{r})$	wave function of a compound system
$\omega = 2\pi\nu$	angular frequency
$\omega_B = \frac{eB}{m}$	electron cyclotron frequency
ω_{jk}	ratio between energy levels $E_k - E_j$ and $\hbar$
Ω	space

Other Symbols

∇	Nabla operator
$\langle\cdot \mid \cdot\cdot\rangle$	scalar product
$\langle j_1, j_2, m_1, m_2 \mid j, m\rangle$	Clebsch–Gordan coefficient
$\lvert\cdot\rangle\langle\cdot\rvert$	external product
$\langle\cdot\rangle$	mean value

$\mathrm{Tr}(\hat{O})$	trace of the operator $\hat{O}$
$\otimes$	direct product
$\oplus$	direct sum
$\forall$	for all ...
$\exists$	there is at least one ... such that
$a \in X$	the element a pertains to the set X
$X \subset Y$	X is a proper subset of Y
$a \Longrightarrow b$	a is sufficient condition of b
$\vee$	inclusive disjunction (OR)
$\wedge$	conjunction (AND)
$a \mapsto b$	a maps to b
$\rightarrow$	tends to ...
$\vert 0\rangle, \vert 1\rangle$	arbitrary basis for a two-level system, qubits
$\vert 1\rangle, \vert 2\rangle, \vert 3\rangle, \vert 4\rangle$	set of eigenstates of a path observable
$\vert \mathbf{0}\rangle = \vert 0, 0, 0\rangle$	vacuum state
$\vert \uparrow\rangle, \vert \downarrow\rangle$	arbitrary basis for a two-level system, eigenstates of the spin observable (in the z-direction)
$\vert \leftrightarrow\rangle$	state of horizontal polarization
$\vert \updownarrow\rangle$	state of vertical polarization
$\vert \nearrow\rangle$	state of 45° polarization
$\vert \nwarrow\rangle$	state of 135° polarization
$\vert \smile\rangle_c, \vert \frown\rangle_c$	living- and dead-cat states, respectively
$[\cdot, \cdot\cdot]_- = [\cdot, \cdot\cdot]$	commutator
$[\cdot, \cdot\cdot]_+$	anticommutator
$\{\cdot, \cdot\cdot\}$	Poisson brackets
$\partial_t = \frac{\partial}{\partial t}$	partial derivatives
$\partial_j = \frac{\partial}{\partial j}$, with $j = x, y, z$	

Abbreviations

AB	Aharonov–Bohm
BS	beam splitter
Ch.	chapter
CH	Clauser and Horne
CHSH	Clauser, Horne, Shimony, and Holt
Cor.	corollary
cw	continuous wave
Def.	definition
EPR	Einstein, Podoloski, and Rosen
EPRB	Einstein, Podoloski, Rosen, and Bohm
Fig.	figure
GHSZ	Greenberger, Horne, Shimony, and Zeilinger
GHZ	Greenberger, Horne, and Zeilinger
iff	if and only if
HV	hidden variable
LASER	light amplification by stimulated emission of radiation
LCAO	linear combination of atomic orbitals
lhs	left-hand side
MWI	many world interpretation
p.	page
PBS	polarization beam splitter
POSet	partially ordered set
Post.	postulate
POVM	positive operator valued measure
Pr.	principle
Prob.	problem
PVM	projector valued measure
rhs	right-hand side
Sec.	section
SGM	Stern–Gerlach magnet
SPDC	spontaneous parametric down conversion
SQUID	superconducting quantum interference device
Subsec.	subsection
Tab.	table
Th.	theorem
VBM	valence bond method

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