# THEORY OF ELECTRIC POLARIZATION

C. J. F. BOTTCHER AND P. BORDEWIJK

VOLUME II

Dielectrics in time dependent fields

# THEORY OF ELECTRIC POLARIZATION

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# PREFACE

For the preparation of the second volume of the revised edition of this book, the same aims were set as for the first volume, namely, to maintain the character of the book as a comprehensive treatment of the theory of dielectrics, making any additions and alterations necessary to bring the book up-to-date. Applied to the theory of dielectrics in time-dependent fields, the main subject of this volume, this led to rather drastic changes.

As a starting point, some fundamental aspects of dielectric behaviour in time-dependent fields, relevant to both orientational polarization and induced polarization, are treated in Chapter VIII. This chapter is an extension of sections 42, 43, and 45 in Chapter VIII of the first edition. Next, the behaviour of the orientational polarization in time-dependent fields is discussed. This subject was originally treated in one chapter (Ch. X), but it has now been given three chapters. Chapter IX covers the phenomenological theory of dielectric relaxation, with an extensive survey of the various descriptions suggested in the literature and a discussion of their practical applicability. The relationship between macroscopic dielectric relaxation behaviour and the dipole correlation function is considered in Chapter X, and Chapter XI treats the molecular theory of the dipole correlation function under various conditions. In the latter chapter, data from dielectric measurements are also compared with other data concerning the molecular reorientation, *e.g.* derived from nuclear magnetic relaxation and obtained with spectroscopic techniques.

The material discussed in the remaining sections of Chapter VIII of the first edition is now presented in Chapter XII, with the exception of section 50, which has been expanded to make a new chapter (Ch. XIII) on the Kerr effect and related phenomena. Chapter XIV deals with the determination of permanent dipole moments (originally treated in Chapter IX), with an added section on the determination of permanent quadrupoles. As in the first edition, the last chapter deals with solids, but with the emphasis now placed on the dielectric properties of solids; spontaneous polarization is discussed only briefly, but a section on the dielectric properties of liquid crystals has been added. Two

Appendices are also included in this volume, one concerning complex numbers and the other Laplace and Fourier transforms.

As a selection for a course on dielectric theory, we suggest the whole of Chapter VIII, sections 54, 55, and 57 of Chapter IX, section 64 of Chapter X, and Chapter XI, where sections 73–77 can be omitted or included independently. The choice of material from the remaining part of the book will depend on the specific purpose of the course.

In concluding this preface, I wish to thank the many individuals who contributed in one way or other to the realization of this volume. Of the few who can be mentioned by name, I shall begin with Dr. O. C. van Belle and Mr. A. Rip, with whom I shared the responsibility for the first volume and who contributed valuable criticism on the present volume. Mr. Rip also drafted section 64 and the Appendices. I am grateful, too, for many discussions with Dr. J. C. Leyte on infrared bandshape analysis and nuclear magnetic relaxation, which greatly benefited the exposition in sections 68, 71, and 81. Section 97 could not have been written adequately without the discussions on the dielectric properties of liquid crystals that I had with Dr. W. H. de Jeu (Eindhoven). Dr. J. H. P. Colpa (Amsterdam) contributed the calculation of the Lorentz tensors in Table 54, as well as very useful criticism generally. Mr. M. Kunst assisted in reading the proofs. Finally, thanks are due to the Department of Physical Chemistry of the University of Leiden, which made it possible for me to spend so much time on the preparation of this revised edition.

Leiden, August 1977 P. Bordewijk

# IMPORTANT SYMBOLS

*(The numbers indicate the page where the symbol is introduced)*

| | |
|---|---|
| $a$ | radius of sphere or spherical cavity, half of principal axis of ellipsoid |
| $a$ | absorption coefficient, *II* 22 |
| $A$ | parameter characterizing anisotropy of moment of inertia for symmetric-top molecules, *II* 190 |
| $A_\lambda$ | ($\lambda = a, b, c$) shape factor for ellipsoid, *I* 79 |
| $\boldsymbol{A}$ | depolarizing tensor for ellipsoid *in vacuo*, *I* 316, *II* 428 |
| $\boldsymbol{A}^*$ | depolarizing tensor for ellipsoid in anisotropic dielectric, *II* 430 |
| $\mathcal{A}$ | first dielectric virial coefficient, *I* 232 |
| $A_R$ | first refractometric virial coefficient, *II* 291 |
| $A_k$ | first Kerr constant virial coefficient, *II* 333 |
| $\mathsf{A}$ | quadrupole polarizability, *II* 375 |
| $\mathsf{A}^{(3)}$ | octupole polarizability, *II* 436 |
| $\mathbf{A}$ | 3N-dimensional tensor connected with the polarizability of a system, *I* 209, *II* 404 |
| $b$ | half of principal axis of ellipsoid |
| $b$ | rate of temperature increase, *II* 127 |
| $b$ | distance between two nuclei, *II* 177 |
| $B$ | Kerr constant, *II* 315 |
| $\boldsymbol{B}$ | magnetic induction |
| $\mathcal{B}$ | second dielectric virial coefficient, *I* 232 |
| $B_R$ | second refractometric virial coefficient, *II* 291 |
| $B_k$ | second Kerr constant virial coefficient, *II* 333 |
| $\mathsf{B}$ | quadrupole polarizability, *II* 375 |
| $\mathsf{B}$ | sum of dipole–dipole interaction tensors over a sphere, *II* 432 |
| $c$ | half of principal axis of ellipsoid |
| $c$ | velocity of light |

| | |
|---|---|
| $C, C^*$ | Cotton–Mouton constants, *II* 370 |
| $[C]$ | molar Cotton–Mouton constant, *II* 370 |
| $C$ | dipole correlation function, *II* 151, 169 |
| $C_n$ | correlation function for Legendre polynomial $P_n$, *II* 175 |
| $C_{km}^{(n)}$ | correlation function for generalized spherical harmonic $D_{km}^{(n)}$, *II* 174 |
| $C_J$ | correlation function for angular momentum, *II* 196 |
| $C_{rv}$ | correlation function of rotational velocity, *II* 263 |
| $C_v$ | vibrational correlation function, *II* 310 |
| $\mathscr{C}$ | third dielectric virial coefficient, *I* 232 |
| $C_R$ | third refractometric virial coefficient, *II* 291 |
| $C_k$ | third Kerr constant virial coefficient, *II* 333 |
| $\boldsymbol{C}$ | quadrupole polarizability, *II* 375 |
| | |
| $d$ | density |
| $D$ | subsidiary order parameter, *II* 460 |
| $D_{km}^{(n)}$ | generalized spherical harmonic, element of Wigner rotation matrix $D^{(n)}$, *II* 174 |
| $\boldsymbol{D}$ | dielectric displacement, *I* 59 |
| $\hat{\boldsymbol{D}}$ | complex dielectric displacement, *II* 12 |
| $\mathscr{D}$ | generalized dielectric displacement, *II* 17 |
| $\mathbf{D}^{rot}$ | rotation-diffusion tensor, *II* 204 |
| $D^{rot}$ | rotation-diffusion constant |
| $D_V$ | diffusion constant for free volume, *II* 227 |
| $D_d$ | diffusion constant for defects, *II* 231 |
| | |
| $e_0$ | elementary charge |
| $\boldsymbol{e}, \boldsymbol{e}_{\parallel}$ | unit vector parallel to electric field, or to director |
| $\boldsymbol{e}_{\perp}$ | unit vector perpendicular to electric field, or to director |
| $\mathbf{e}$ | 3N-dimensional vector connected with unit vector $\boldsymbol{e}$, *I* 213 |
| $E_a$ | activation energy, *II* 118, 224 |
| $E_\beta(\omega)$ | average energy of oscillator with frequency $\omega$, *II* 147 |
| $\boldsymbol{E}$ | electric field, *I* 11, 59 |
| $\hat{\boldsymbol{E}}$ | complex electric field, *II* 12 |
| $\mathscr{E}$ | strength of electric field of optical frequency |
| $E'$ | intensity of electric field gradient, *II* 375 |
| $\boldsymbol{E}_0$ | external field |
| $\boldsymbol{E}_c$ | cavity field, *I* 78, 81 |

| | |
|---|---|
| $\boldsymbol{E}_l$ | local field, *I* 208 |
| $\boldsymbol{E}_l^*$ | part of local field proportional with the external field, *II* 408 |
| $\mathbf{E}_0$ | 3N-dimensional vector connected with the external field, *I* 209 |
| $\mathbf{E}_l$ | 3N-dimensional vector connected with the local field, *I* 209 |
| | |
| $f$ | reaction field factor, *I* 129, 134 |
| $f$ | distribution function in phase space, *II* 142 |
| $f$ | distribution function of molecular orientations, *II* 217 |
| $f_{A,B}$ | pulse-response function of $A$ as a response to $B$ |
| $f_D$ | pulse-response function of dielectric displacement, *II* 8 |
| $f_{\mathscr{D}}$ | pulse-response function of generalized dielectric displacement, *II* 18 |
| $f_I$ | pulse-response function of current density, *II* 16 |
| $f_P$ | pulse-response function of polarization, *II* 8 |
| $f_P^{or}$ | pulse-response function of orientational polarization, *II* 9 |
| $f_{sph}$ | pulse-response function of electric moment of a sphere, *II* 26 |
| $F_D$ | step-response function of dielectric displacement, *II* 8 |
| $F_I$ | step-response function of current density, *II* 16 |
| $F_P$ | step-response function of polarization, *II* 6 |
| $F_P^{or}$ | step-response function of orientational polarization, *II* 9 |
| ${}_1F_1$ | Kummer's hypergeometric series, *II* 192 |
| $\boldsymbol{F}$ | reaction field tensor, *I* 130 |
| $\mathscr{F}$ | Fourier transform, *II* 520 |
| | |
| $g$ | Kirkwood correlation factor, *I* 249 |
| $g_2$ | correlation factor for second Legendre polynomial, *II* 346 |
| $g_k$ | weight factor of relaxation time $\tau_k$, *II* 39 |
| $g$ | distribution function of relaxation times, *II* 39, of activation energies, *II* 120 |
| $\boldsymbol{g}$ | magnetogyric-ratio tensor, *II* 418 |
| $G$ | logarithmic distribution function of relaxation times, *II* 45 |
| $G$ | microscopic correlation factor connected with Kerr effect, *II* 354 |
| $G$ | intensity of velocity gradient, *II* 379 |
| $G_a$ | free enthalpy of activation, *II* 224 |
| | |
| $h$ | Planck's constant |
| $h$ | intensity function, *II* 55 |
| $h$ | correction factor for molar polarization, *I* 193 |

| | |
|---|---|
| $h^e$ | correction factor for molar refraction, *II* 292 |
| $H_a$ | activation enthalpy, *II* 225 |
| $\boldsymbol{H}$ | magnetic field |
| $\mathcal{H}$ | Hamiltonian, *II* 140 |
| | |
| $i$ | $(-1)^{\frac{1}{2}}$, *II* 493 |
| $I$ | Intensity of electromagnetic radiation, *II* 317 |
| $I$ | nuclear spin quantum number, *II* 177 |
| $\boldsymbol{I}$ | current density |
| $I$ | moment of inertia, *II* 183 |
| $\boldsymbol{I}$ | unit tensor |
| $\mathbf{I}$ | 3N-dimensional unit tensor |
| | |
| $J$ | quantum number of angular momentum, *II* 392 |
| $\underset{\sim}{J}$ | angular momentum, *II* 184 |
| | |
| $k$ | Boltzmann's constant |
| $k$ | absorption index, *II* 21 |
| $k$ | reaction constant, *II* 259 |
| $\mathscr{k}$ | rate of reorientation, *II* 220 |
| $K$ | second quantum number for free rotation, *II* 392 |
| $K$ | probability function for molecular reorientation, *II* 172 |
| $K$ | Kerr constant, *II* 116 |
| $[K]$ | molar Kerr constant, *II* 316 |
| $[K^{opt}]$ | molar Kerr constant for optical inducing field, *II* 317 |
| $[K_1]$ | contribution to molar Kerr constant by permanent dipoles, *II* 321, 337 |
| $[K_2]$ | contribution to molar Kerr constant by anisotropy of the polarizabilities, *II* 321, 337 |
| $[K_3]$ | contribution to molar Kerr constant by first hyperpolarizabilities, *II* 321, 337 |
| $[K_4]$ | contribution to molar Kerr constant by second hyperpolarizabilities, *II* 321, 337 |
| $K_0$ | equilibrium constant, *II* 259 |
| $K_0$ | memory function of dipole correlation function, *II* 264 |
| $K_J$ | memory function of angular momentum, *II* 201 |
| $\boldsymbol{K}$ | local field tensor, *II* 336, 405 |
| $\boldsymbol{K}^e$ | local field tensor for electronic polarization, *II* 335 |

| | |
|---|---|
| $l$ | optical path, *II* 316 |
| L | Liouville operator, *II* 140 |
| $L$ | angular momentum of electrons, *II* 417 |
| $\boldsymbol{L}$ | Lorentz tensor, *II* 433 |
| $\mathbf{L}$ | 3*n*-dimensional tensor connected with the Lorentz tensors for a crystal with *n* molecules in the unit cell, *II* 434 |
| $\mathscr{L}$ | Laplace transform, *II* 509 |
| $m$ | mass |
| $m_e$ | mass of electron |
| $m_p$ | mass of proton |
| $m^*$ | generalized mass corresponding with reaction coordinate, *II* 223 |
| $\boldsymbol{m}$ | electric moment of molecule, *I* 109, of a macroscopic body, *II* 26 |
| $\boldsymbol{m}^{m}$ | magnetic moment of molecule, *II* 416 |
| $\mathbf{m}$ | 3N-dimensional vector connected with the molecular dipole moments, *I* 209 |
| $M$ | molecular weight, average molecular weight, *II* 316 |
| $M$ | third quantum number for free rotation, *II* 393 |
| $\boldsymbol{M}$ | electric moment of a system, *I* 207 |
| $\boldsymbol{M}_1$ | sum of permanent dipole moments in a small sphere in a dielectric, *II* 152 |
| $n, n'$ | refractive index, *II* 21 |
| $\hat{n}$ | complex refractive index, *II* 21 |
| $n_\infty^*$ | refractive index extrapolated to infinite wavelength, *II* 289 |
| $\boldsymbol{n}$ | unit vector normal to surface |
| $N$ | number density |
| $N'$ | reciprocal volume of unit cell, *II* 434 |
| $N_A$ | Avogadro's number |
| N | number of molecules in the system, *I* 207 |
| $\mathscr{N}$ | number of molecules in a small sphere in the system *I* 207 |
| $p$ | pressure |
| $p$ | imaginary component of complex frequency, *II* 31 |
| $p$ | distribution parameter for Matsumoto–Higasi distribution, *II* 87 |
| $p_i$ | momentum conjugated with generalized coordinate $q_i$, *II* 140 |
| $\boldsymbol{p}$ | induced moment of a molecule, *I* 109 |

| | |
|---|---|
| $\mathbf{p}$ | 3N-dimensional vector connected with induced moments, *II* 334 |
| $P$ | probability, *II* 227 |
| $P_n$ | Legendre polynomial, *I* 357 |
| $\boldsymbol{P}$ | electric polarization, *I* 22, 69 |
| $[P]$ | molar polarization, *I* 170 |
| $[\tilde{P}]_k$ | apparent molar polarization of component $k$ in a mixture, *II* 397 |
| $q$ | partition function, *II* 224 |
| $q$ | height of nematic potential, *II* 408 |
| $q_i$ | generalized coordinate, *II* 140 |
| $Q$ | numerical constant characterizing cubic lattice, *II* 407 |
| $\boldsymbol{Q}$ | quadrupole moment, *I* 44 |
| $r$ | polar coordinate, *I* 333, *II* 495 |
| $r$ | polarization index, *II* 180 |
| $\boldsymbol{r}$ | radius vector |
| $R$ | gas constant |
| $R_K$ | macroscopic correlation factor connected with Kerr effect, *II* 352 |
| $[R]$ | molar refraction, *II* 290 |
| $[R^*_\infty]$ | molar refraction extrapolated to infinite wavelength, *II* 291 |
| $S_-$ | unit-step function, *II* 6, 509 |
| $S$ | order parameter, *II* 458 |
| $S_a$ | activation entropy, *II* 224 |
| $t$ | time |
| $t$ | temperature in centigrades |
| $T$ | absolute temperature |
| $T_c$ | clearing point, *II* 459 |
| $T_1$ | nuclear magnetic relaxation time, *II* 176 |
| $\boldsymbol{T}$ | torque |
| $\mathrm{T}$ | magnitude of torque |
| $\boldsymbol{T}$ | dipole–dipole interaction tensor, *I* 18, 116 |
| $\mathbf{T}$ | 3N-dimensional tensor connected with the dipole–dipole interactions, *II* 209 |
| $\boldsymbol{u}$ | unit vector |

| | |
|---|---|
| $U$ | energy of a system |
| $\mathbf{U}$ | octupole moment, *I* 44 |
| | |
| $v$ | volume |
| $v$ | phase velocity of a travelling wave, *II* 21 |
| $V$ | molecular volume, *II* 206 |
| $V_a$ | activation volume, *II* 244 |
| | |
| $W$ | work, energy of a molecule |
| | |
| $x$ | molar fraction, molar fraction of solute |
| $x(t)$ | fraction of molecules not reorienting during time interval $t$, *II* 220 |
| $x^*$ | reaction coordinate, *II* 223 |
| | |
| $\alpha$ | distribution parameter in Cole–Cole equation, *II* 62, Havriliak–Negami equation, *II* 72, Fuoss–Kirkwood description, *II* 76 |
| $\alpha$ | degree of complexation, *II* 250 |
| $\alpha_p$ | thermal expansion coefficient, *II* 293 |
| $\alpha$ | polarizability |
| $\hat{\alpha}$ | complex polarizability, *II* 26, 304 |
| $\hat{\alpha}^*$ | effective complex polarizability, *II* 306 |
| $\alpha^e$ | polarizability connected with electronic polarization, *I* 173 |
| $\alpha^a$ | polarizability connected with atomic polarization, *I* 191 |
| $\boldsymbol{\alpha}$ | polarizability tensor, *I* 87 |
| $\boldsymbol{\alpha}^*$ | effective polarizability tensor, *II* 343, 433 |
| $\boldsymbol{\alpha}$ | 3N-dimensional tensor connected with the polarizabilities of the molecules, *II* 404 |
| $\Delta\alpha$ | anisotropy of the polarizability |
| | |
| $\beta$ | distribution parameter in Cole–Davidson equation, *II* 67, Havriliak–Negami equation, *II* 72, Williams–Watts equation, *II* 80 |
| $\beta$ | collision frequency, *II* 197 |
| $\beta$, $\beta_T$ | isothermal compressibility, *I* 319 |
| $\beta$ | average first hyperpolarizability, *II* 324 |
| $\beta^*$ | average effective first hyperpolarizability, *II* 350 |
| $\boldsymbol{\beta}$ | first hyperpolarizability, *I* 310, *II* 317 |
| $\boldsymbol{\beta}^*$ | effective first hyperpolarizability, *II* 350 |

| | |
|---|---|
| $\Delta\beta$ | first hyperpolarizability anisotropy, *II* 324 |
| $\gamma$ | microscopic correlation function, *II* 152 |
| $\gamma$ | gyromagnetic ratio of a nucleus, *II* 177 |
| $\gamma_n$ | limiting value of $C_n$ for free rotation, *II* 197 |
| $\gamma$ | average second hyperpolarizability, *II* 325 |
| $\gamma^*$ | average effective second hyperpolarizability, *II* 340 |
| $\boldsymbol{\gamma}$ | second hyperpolarizability, *I* 310, *II* 317 |
| $\Gamma$ | gamma function, *II* 514 |
| $\delta$ | delta function, *I* 352, *II* 510 |
| $\delta$ | Kronecker delta, *I* 341 |
| $\delta$ | phase difference between dielectric displacement and electric field, loss angle, *II* 2, 15 |
| $\Delta_u$ | depolarization of the Rayleigh scattering for unpolarized incident light, *II* 323 |
| $\Delta_v$ | depolarization of the Rayleigh scattering for vertically polarized incident light, *II* 323 |
| $\varepsilon$ | static dielectric constant, permittivity, *I* 1, 71, 159, *II* 1 |
| $\varepsilon'$ | frequency-dependent dielectric constant, *II* 3, 11 |
| $\varepsilon''$ | loss factor, *II* 3, 11 |
| $\hat{\varepsilon}$ | complex dielectric constant, *II* 12 |
| $\varepsilon^*$ | apparent dielectric constant of a heterogeneous system, *II* 476 |
| $\varepsilon_\infty$ | dielectric constant of induced polarization, *I* 172, *II* 9 |
| $\boldsymbol{\varepsilon}$ | dielectric tensor, *I* 71, *II* 426 |
| $\Delta\varepsilon$ | dielectric anisotropy, *II* 462 |
| $\zeta$ | parameter for the angle of intersection at the low-frequency side of the Cole–Cole plot, *II* 51 |
| $\eta$ | viscosity |
| $\eta$ | parameter for the angle of intersection at the high-frequency side of the Cole–Cole plot, *II* 51 |
| $\hat{\eta}$ | generalized complex dielectric constant, *II* 18 |
| $\boldsymbol{\eta}$ | tensor accounting for the dependence of the polarizability on the magnetic field strength, *II* 371 |

| | |
|---|---|
| $\theta$ | polar angle, *I* 333, Eulerian angle, *II* 171 |
| $\Theta$ | permanent quadrupole strength of a molecule |
| $\boldsymbol{\Theta}$ | permanent electric quadrupole moment of a molecule, *I* 109 |
| $\boldsymbol{\Theta}_{norm}$ | permanent electric quadrupole moment of a molecule according to Buckingham, *II* 419 |
| | |
| $\kappa$ | extinction coefficient, *II* 22 |
| $\kappa$ | ratio between dielectric constant and dielectric constant of induced polarization, *II* 163 |
| $\kappa$ | anisotropy parameter of the polarizability, *II* 321 |
| $\kappa^e$ | anisotropy parameter of the electronic polarizability, *II* 321 |
| | |
| $\lambda$ | complex frequency, *II* 31 |
| $\lambda$ | wavelength |
| $\lambda_0$ | wavelength *in vacuo* |
| | |
| $\hat{\mu}$ | complex magnetic permeability, *II* 20 |
| $\mu_n$ | nuclear magnetic moment, *II* 177 |
| $\boldsymbol{\mu}$ | permanent dipole moment of a molecule, *I* 109 |
| $\boldsymbol{\mu}^*$ | effective dipole moment, dipole moment in solution, *II* 348, 395 |
| $\boldsymbol{\mu}_d$ | dipole moment enlarged due to induced polarization, *I* 251, *II* 465 |
| $\mathbf{\mu}$ | 3N-dimensional vector connected with the permanent dipole moments of the molecules, *I* 209 |
| | |
| $\pi$ | ratio between circumference and diameter of circle |
| $\boldsymbol{\pi}$ | differential polarizability, *II* 336 |
| $\boldsymbol{\pi}^e$ | differential polarizability for field of optical frequency, *II* 317, 371, 376 |
| $\boldsymbol{\pi}$ | 3N-dimensional tensor connected with the differential polarizabilities of the molecules, *II* 334 |
| $\mathbf{\Pi}$ | 3N-dimensional tensor connected with the differential polarizability of the system, *II* 334 |
| | |
| $\rho$ | volume charge density |
| | |
| $\sigma$ | electric conductivity |
| $\sigma$ | standard deviation, *II* 83 |

| | |
|---|---|
| $\tau$ | dielectric relaxation time, *II* 38 |
| $\tau_0$ | characteristic dielectric relaxation time for distribution of relaxation times |
| $\tau^*_{av}$ | average microscopic relaxation time, *II* 163 |
| $\tau^*$ | characteristic time of free rotation, *II* 392 |
| $\tau_n$ | correlation time for Legendre polynomial of degree *n*, *II* 175 |
| $\tau_J$ | correlation time of angular momentum, *II* 196 |
| $\varphi$ | polar angle, *I* 333, *II* 495, Eulerian angle, *II* 171 |
| $\varphi$ | molar volume |
| $\varphi$ | volume fraction occupied by the molecules, *II* 293 |
| $\varphi_k$ | volume fraction of component *k* |
| $\phi$ | potential of electric field, *I* 13 |
| $\hat{\phi}$ | potential of complex electric field, *II* 23 |
| $\Phi_{sph}$ | autocorrelation function of electric moment of a sphere, *II* 147 |
| $\Phi^{or}_{sph}$ | autocorrelation function of orientational polarization of a sphere, *II* 150 |
| $\chi$ | dielectric susceptibility, *I* 70 |
| $\chi$ | magnetic susceptibility of a molecule, *II* 418 |
| $\boldsymbol{\chi}$ | magnetic susceptibility tensor of a molecule, *II* 370 |
| $\chi^V$ | macroscopic magnetic susceptibility, *II* 461 |
| $\Delta\chi^V$ | anisotropy of macroscopic magnetic susceptibility, *II* 461 |
| $\psi$ | Eulerian angle, *II* 171 |
| $\omega$ | angular frequency, *II* 2 |
| $\boldsymbol{\omega}$ | angular velocity, *II* 182 |
| $d\Omega$ | infinitesimal space angle |

## CONTENTS