

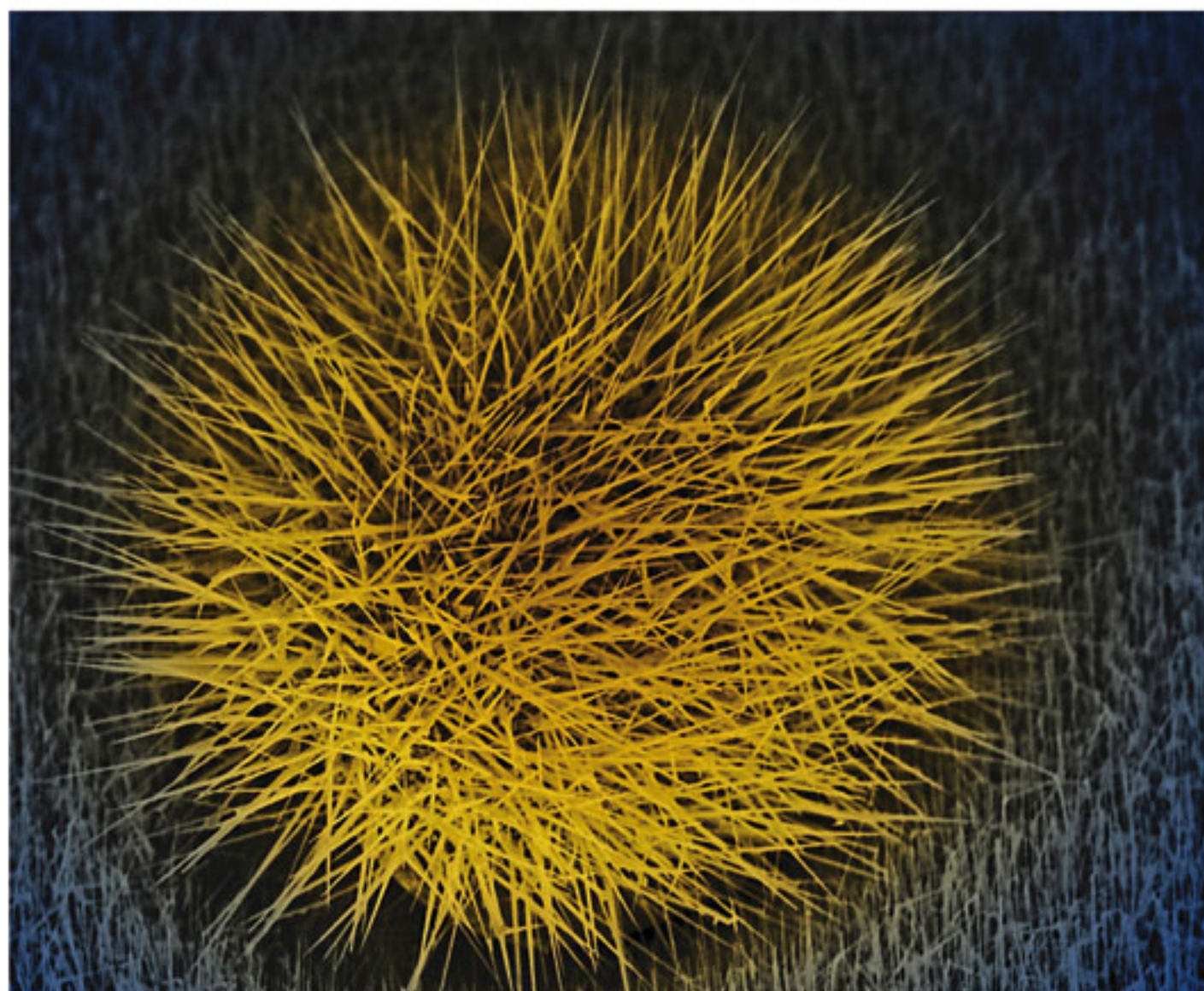
Victor E. Borisenko
Stefano Ossicini

 WILEY-VCH

What is What in the Nanoworld

A Handbook on Nanoscience and Nanotechnology

Third, Revised and Enlarged Edition



*Victor E. Borisenko and
Stefano Ossicini*

What is What in the Nanoworld

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Victor E. Borisenko and Stefano Ossicini

What is What in the Nanoworld

A Handbook on Nanoscience and Nanotechnology

3rd, revised and enlarged edition



WILEY-VCH Verlag GmbH & Co. KGaA

The Authors

Dr. Victor E. Borisenko

University of Informatics
and Radioelectronics
Minsk, Belarus
borisenko@bsuir.by

Prof. Stefano Ossicini

Uni. di Modena e Reggio Emilia
Sc. e Metodi dell'Ingegneria
Reggio Emilia, Italia
stefano.ossicini@unimore.it

Cover

Scanning Electron Microscope image
of Gallium Arsenide nanowires grown
using gold as catalyst.
Experiment: Faustino Martelli, Silvia Rubini,
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Library of Congress Card No.: applied for

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available
from the British Library.

Bibliographic information published by the Deutsche Nationalbibliothek

The Deutsche Nationalbibliothek
lists this publication in the Deutsche
Nationalbibliografie; detailed bibliographic
data are available in the Internet at
<<http://dnb.d-nb.de>>.

© 2012 Wiley-VCH Verlag & Co. KGaA,
Boschstr. 12, 69469 Weinheim, Germany

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Print ISBN: 978-3-527-41141-2

ePDF ISBN: 978-3-527-64839-9

ePub ISBN: 978-3-527-64838-2

mobi ISBN: 978-3-527-64837-5

oBook ISBN: 978-3-527-64836-8

Cover Design Grafik-Design Schulz,
Fußgönheim

Typesetting Laserwords Private Limited,
Chennai, India

Printing and Binding Markono Print Media
Pte Ltd, Singapore

Printed on acid-free paper

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Preface to the Third Edition

This is the third, enlarged, and updated edition of our book. From about 1400 entries in the first edition we have now reached to more than 2300 terms and definitions. Moreover, a large number of the previous entries have been improved or extended. The gallery of illustrations has been enriched by new figures, and new tables are added throughout the book. The presented terms, phenomena, regulations, and experimental and theoretical tools are very easy to consult since they are arranged in alphabetical order, with a chapter for each letter. The great majority of the terms have additional information in the form of notes such as “*First described in: ...*”, “*More details in ...*”, and “*Recognition: ...*”, thus giving a historical retrospective of the subject with references to further sources of extended information, which can be pioneering papers, books, review papers, or web sites.

In particular, in this third edition, following the advices of friends and readers, we have tried, for the overwhelming majority of the entries, to find out the most authoritative and/or most recent work to be inserted in the voice “*More details in ...*”, we consider all these additional notes to be quite useful. Moreover, a particular attention has been paid to augmenting the number of entries dedicated to experimental techniques recently developed within nanoscience. Only eight years separate this third edition from the first one. Nevertheless, we have seen not only a true explosion of research in nanoscience and developments of nanotechnologies but also an avalanche increase in the number of new journals that contain the stem “nano” in their title. A list of more than 100 “nano” journals is presented at the end of this book. A large majority appeared in the last few years.

The last decade has witnessed also the digital revolution. We have seen an incredible diffusion of the use of Internet, especially of web sites such as Wikipedia or similar, yet is legitimate to question whether it still makes sense to rely on books and manuals/handbooks in particular. Our answer is clearly yes.

The reason is twofold. First of all, as suggested by two bibliophiles, the Italian critic and writer Umberto Eco and the French screenwriter and playwright Jean-Claude Carrière, in their “playdoyer” *This is Not the End of the Book*, appeared in 2011, “... A book is like spoons, hammers, wheels, and scissors. Once you’ve invented them, there’s nothing left to improve them”. Second, in the short story *On Rigor in Science* (the original Spanish-language novel *Del rigor en la ciencia*

appeared in 1946), the Argentine writers Jorge Luis Borges and Adolf Bioy Casares described the inability to construct a map as big as the territory it represents, the mythical map 1:1, which, overlapping and corresponding well to the physical space it represents, results useless and unnecessary. With it, the two writers have given us a reflection not only on the difficult and problematic nature of any summary but also on the true necessity to take responsibility and to perform a synthesis, a selection. We hope that our map regarding the Nanoworld will be useful to the readers, independently of their experience in “nano,” if they are motivated with a goal to know more and more about the Nanoworld.

Minsk
Modena-Reggio Emilia
January 2012

Victor E. Borisenko
Stefano Ossicini

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Encyclopedia
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Eric Weisstein's World of Physics
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MATHEMATICS ARCHIVE
Named Things in Chemistry and Physics
HYPERDICTIONARY
WordReference.com. French, German, Italian and Spanish Dictionary with Collins Dictionaries
The Net Advance of Physics. Review Articles and Tutorials in an Encyclopedic Format

Fundamental Constants Used in Formulas

$a_B = 5.29177 \times 10^{-11} \text{ m}$
 $c = 2.99792458 \times 10^8 \text{ m/s}$
 $e = 1.602177 \times 10^{-19} \text{ C}$
 $h = 6.626076 \times 10^{-34} \text{ J}\cdot\text{s}$
 $\hbar = h/2\pi = 1.054573 \times 10^{-34} \text{ J}\cdot\text{s}$
 $i = \sqrt{-1}$
 $k_B = 1.380658 \times 10^{-23} \text{ J/K}$ ($8.617385 \times 10^{-5} \text{ eV/K}$)
 $m_0 = 9.10939 \times 10^{-31} \text{ kg}$
 $n_A = 6.0221367 \times 10^{23} \text{ mol}^{-1}$
 $R_0 = 8.314510 \text{ J/(K}\cdot\text{mol)}$
 $r_e = 2.817938 \times 10^{-15} \text{ m}$
 $\alpha = \mu_0 c e^2 / 2h = 7.297353 \times 10^{-3}$
 $\epsilon_0 = 8.854187817 \times 10^{-12} \text{ F/m}$
 $\mu_0 = 4\pi \times 10^{-7} \text{ H/m}$
 $\mu_B = 9.27402 \times 10^{-24} \text{ A}\cdot\text{m}^2$
 $\pi = 3.14159$
 $\sigma = 5.6697 \times 10^{-5} \text{ erg/(cm}^2\cdot\text{s}\cdot\text{K)}$

Bohr radius
light speed in vacuum
charge of an electron
Planck constant
reduced Planck constant
imaginary unit
Boltzmann constant
electron rest mass
Avogadro constant
universal gas constant
radius of an electron
fine structure constant
permittivity of vacuum
permeability of vacuum
Bohr magneton

Stefan–Boltzmann constant

A

From Abbe's principle to Azbel'–Kaner cyclotron resonance

Abbe's principle states that the smallest distance that can be resolved between two lines by optical instruments is proportional to the wavelength and inversely proportional to the angular distribution of the light observed ($d_{min} = \lambda/n \sin \alpha$). It establishes a prominent physical problem, known as the “diffraction limit”. That is why it is also called **Abbe's resolution limit**. No matter how perfect an optical instrument is, its resolving capability will always have this diffraction limit. The limits of light microscopy are thus determined by the wavelength of visible light, which is 400–700 nm; the maximum resolving power of the light microscope is limited to about half the wavelength, typically about 300 nm. This value is close to the diameter of a small **bacterium**, and **viruses**, which cannot therefore be visualized. To attain sublight microscopic resolution, a new type of instrument would be needed; as we know today, accelerated electrons, which have a much smaller wavelength, are used in suitable instruments to scrutinize structures down to the 1 nm range.

The diffraction limit of light was first surpassed by the use of **scanning near-field optical microscopes**; by positioning a sharp optical probe only a few nanometers away from the object, the regime of far-field wave physics is circumvented, and the resolution is determined by the probe–sample distance and by the size of the probe which is scanned over the sample.

Also, fluorescence light microscopy based techniques have been developed in order to break the diffraction barrier, as in the case of **fluorescence nanoscopy**.

First described in: E. Abbe, *Beiträge zur Theorie des Mikroskops und der mikroskopischen Wahrnehmung*, *Schultzes Archiv für mikroskopische Anatomie* **9**, 413–668 (1873).

Abbe's resolution limit → **Abbe's principle**.

More details in: R. Leach, *Fundamental Principles of Engineering Nanometrology* (Elsevier, London, 2010).

aberration – any image defect revealed as distortion or blurring in optics. This deviation from perfect image formation can be produced by optical lenses, mirrors and electron lens systems. Examples are astigmatism, chromatic or lateral aberration, coma, curvature of field, distortion, and spherical aberration.

ab initio (approach, theory, calculations)

In astronomy, it is an apparent angular displacement in the direction of motion of the observer of any celestial object due to the combination of the velocity of light and of the velocity of the observer.

ab initio (approach, theory, calculations) – Latin meaning “from the beginning”. It supposes that primary postulates, also called first principles, form the background of the referred theory, approach or calculations. The primary postulates are not so directly obvious from experiment, but owe their acceptance to the fact that conclusions drawn from them, often by long chains of reasoning, agree with experiment in all of the tests which have been made. For example, calculations based on the **Schrödinger wave equation**, as well as on the basis of **Newton equations** of motion or any other fundamental equations, are considered to be *ab initio* calculations.

Abney's law states that the shift in apparent hue of spectral color that is desaturated by addition of white light is toward the red end of the spectrum if the wavelength is below 570 nm and toward the blue if it is above.

First described in: W. Abney, E. R. Festing, *Colour photometry*, Phil. Trans. Roy. Soc. London **177**, 423–456 (1886).

More details in: W. Abney, *Researches in colour vision* (Longmans & Green, London, 1913).

Abrikosov vortex – a specific arrangement of lines of a magnetic field in a **type II superconductor**.

First described in: A. A. Abrikosov, *An influence of the size on the critical field for type II superconductors*, Doklady Akademii Nauk SSSR **86**(3), 489–492 (1952) – in Russian.

Recognition: in 2003 A. A. Abrikosov, V. L. Ginzburg, A. J. Leggett received the Nobel Prize in Physics for pioneering contributions to the theory of superconductors and superfluids.

See also www.nobel.se/physics/laureates/2003/index.html.

More details in: A. A. Abrikosov, Nobel Lecture: *Type-II superconductors and the vortex lattice*, Rev. Mod. Phys. **76**(3), 975–979 (2004).

absorption – a phenomenon arising when electromagnetic radiation or atomic particles enter matter. In general, two kinds of attenuation accompany the passage of radiation and particles through matter, which are absorption and scattering. Both obey the law $I = I_0 \exp(-\alpha x)$, where I_0 is the intensity (flux density) of radiation entering the matter, and I is the intensity depth x . In the absence of scatter, α is the **absorption coefficient**, and in the absence of absorption, α is the scattering coefficient. If both forms of attenuation are present, α is termed the total absorption coefficient → **dielectric function**.

acceptor (atom) – an impurity atom, typically in semiconductors, which accepts electron(s). Acceptor atoms usually form electron energy levels slightly higher than the uppermost field energy band, which is the valence band in semiconductors and dielectrics. An electron from this band is readily excited into the acceptor level. The consequent deficiency in the previously filled band contributes to the hole conduction.

achiral → **chirality**.

acoustic phonon – a quantum of excitation related to an acoustic mode of atomic vibrations in solids → **phonon**.

actinic – pertaining to electromagnetic radiation capable of initiating photochemical reactions, as in photography or the fading of pigments.

actinodielectric – a dielectric exhibiting an increase in electrical conductivity when electromagnetic radiation is incident upon it.

activation energy – an energy in excess over a ground state, which must be added to a system to allow a particular process to take place.

adatom – an atom adsorbed on a solid surface.

adduct – a chemical compound that forms from the addition of two or more substances. The term comes from Latin meaning “drawn toward”. An adduct is a product of the direct addition of two or more distinct molecules, resulting in a single reaction product containing all atoms of all components, with formation of two chemical bonds and a net reduction in bond multiplicity in at least one of the reactants. The resultant is considered a distinct molecular species. In general, the term is often used specifically for products of addition reactions.

adiabatic approximation is used to solve the **Schrödinger equation** for electrons in solids. It assumes that a change in the coordinates of a nucleus passes no energy to electrons, that is the electrons respond adiabatically, which then allows the decoupling of the motion of the nuclei and electrons → **Born-Oppenheimer approximation**.

adhesion – the property of a solid to cling to another solid controlled by intermolecular forces at their interface.

adiabatic principle – perturbations produced in a system by altering slowly external conditions resulting, in general, in a change in the energy distribution in it, but leaving the phase integrals unchanged.

adiabatic process

adiabatic process – a thermodynamic procedure which take place in a system without an exchange of heat with surroundings.

adjacent charge rule states that it is possible to write formal electronic structures for some molecules where adjacent atoms have formal charges of the same sign. In the Pauling formulation (1939), it states that such structures will not be important owing to instability resulting from the charge distribution.

adjoint operator – an operator **B** such that the inner products (Ax,y) and (x,By) are equal for a given operator **A** and for all elements x and y of the **Hilbert space**. It is also known as **associate operator** and **Hermitian conjugate operator**.

adjoint wave functions – functions in the Dirac electron theory which are formed by applying the **Dirac matrix** to the **adjoint operators** of the original wave functions.

admittance – a measure of how readily alternating current will flow in an electric circuit. It is the reciprocal of **impedance**. The term was introduced by Heaviside (1878).

adsorption – a type of **absorption**, in which only the surface of a matter acts as the absorbing medium. **Physisorption** and **chemisorption** are distinguished as adsorption mechanisms.

Term coined by: H. Kayser Über die Verdichtung von Gasen an Oberflächen in ihrer Abhängigkeit von Druck und Temperatur, Ann. Phys. 12, 526–547 (1880).

AES – an acronym for **Auger electron spectroscopy**.

affinity → **electron affinity**.

AFM – an acronym for **atomic force microscopy**.

Aharonov–Bohm effect – the total amplitude of electron waves at a certain point oscillates periodically with respect to the magnetic flux enclosed by the two paths due to the interference effect. The design of the interferometer appropriate for experimental observation of this effect is shown in Figure A.1. Electron waves come from the waveguide to left terminal, split into two equal amplitudes going around the two halves of the ring, meet each other and interfere in the right part of the ring, and leave it through the right terminal. A small solenoid carrying magnetic flux Φ is positioned entirely inside the ring so that its magnetic field passes through the annulus of the ring. It is preferable to have the waveguide sufficiently small in order to restrict a number of possible coming electron modes to one or a few.

The overall current through the structure from the left port to the right one depends on the relation between the length of the ring arms and the inelastic mean

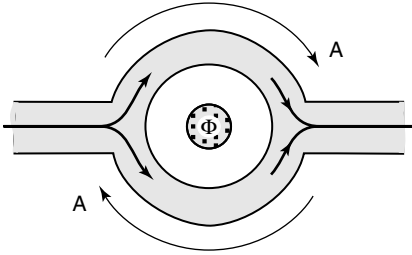


Figure A.1 Schematic layout of the interferometer for observation of the Aharonov–Bohm effect. Small solenoid inside the ring produces the magnetic field of the flux Φ enclosed between the two arms and characterized by the vector potential \mathbf{A} .

free path of electrons in the ring material. If this relation meets the requirements for quasi-ballistic transport, the current is determined by the phase interference of the electron waves at the exit (right) terminal. The vector potential \mathbf{A} of the magnetic field passing through the ring annulus is azimuthal. Hence electrons travelling in either arms of the ring move either parallel or antiparallel to the vector potential. As a result, there is a difference in the phases of the electron waves coming to the exit port from different arms. It is defined to be $\Delta\Phi = 2\pi(\Phi/\Phi_0)$, where $\Phi_0 = h/e$ is the quantum of flux. The interference of the electron waves appears to be periodic in the number of flux quanta passing through the ring. It is constructive when Φ is a multiple of Φ_0 and destructive halfway between. It produces a periodic modulation in the transverse conductance (resistance) of the ring by the magnetic field, which is known as the magnetic Aharonov–Bohm effect. It is worthwhile to note here that real devices hardly meet the requirements for observation of “pure” Aharonov–Bohm effect. The point is that the magnetic field penetrates the arms of the interferometer, not just the area enclosed by them. This leads to additional current variations at high magnetic fields, while the enclosed flux dominates at low magnetic fields.

First described in: Y. Aharonov, D. Bohm, *Significance of electromagnetic potentials in the quantum theory*, Phys. Rev. **115**(3), 485–491 (1959).

More details in: A. Batelaan, A. Tonomura, *The Aharonov–Bohm effects: Variations on a subtle theme*. Phys. Today **62**(9), 38–43 (2009).

Aharonov–Casher effect supposes that a beam of neutral particles with magnetic dipole moments passing around opposite sides of a line charge will undergo a relative quantum phase shift. The effect has a “duality” with the **Aharonov–Bohm effect**, where charged particles passing around a magnetic solenoid experience a phase shift despite, it is claimed, experiencing no classical force. It is pointed out that a magnetic dipole particle passing a line charge does indeed experience a classical electromagnetic force in the usual electric-current model for a magnetic dipole. This force will produce a relative lag between dipoles passing on opposite

Airy equation

sides of the line charge, and the classical lag then leads to a quantum phase shift. Thus, the effect has a transparent explanation as a classical lag effect.

First described in: Y. Aharonov, A. Casher, *Topological quantum effects for neutral particles*, Phys. Rev. Lett. **53**(4), 319–321 (1984).

More details in: D. Rohrlich, *The Aharonov-Casher effect*, in: *Compendium of Quantum Physics: Concepts, Experiments, History and Philosophy*, edited by F. Weinert, K. Hentschel, D. Greenberger, B. Falkenburg (Springer, Berlin, 2009).

Airy equation – the second order differential equation $d^2y/dx^2 = xy$, also known as the **Stokes equation**. Here x represents the independent variable and y is the value of the function.

First described in: G. B. Airy, Trans. Camb. Phil. Soc. **6**, 379 (1838); G. B. Airy, *An Elementary Treatise on Partial Differential Equations* (1866).

Airy functions – solutions of the **Airy equation**. The equation has two linearly independent solutions, conventionally taken as the Airy integral functions $Ai(x)$ and $Bi(x)$. They are plotted in Figure A.2. There are no simple expressions for them in terms of elementary functions, while for large absolute values of x : $Ai(x) \sim \pi^{-1/2}x^{-1/4}\exp[-(2/3)x^{3/2}]$, $Ai(-x) \sim (1/2)\pi^{-1/2}x^{-1/4}\cos[-(2/3)x^{3/2} - \pi/4]$. Airy functions arise in solutions of the **Schrödinger equation** for some particular cases.

First described in: G. B. Airy, *An Elementary Treatise on Partial Differential Equations* (1866).

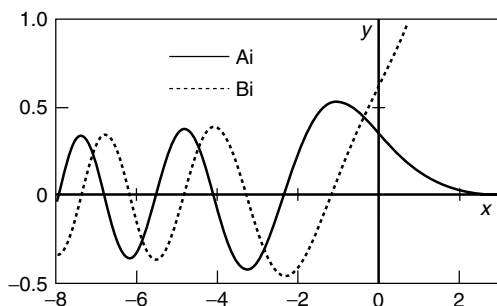


Figure A.2 Airy functions.

Airy spirals – spiral interference patterns formed by quartz cut perpendicularly to the axis in convergent circularly polarized light.

Recognition: in 1831 G. B. Airy received the Copley Medal of the Royal Society for their studies on optical subjects.

ALD – an acronym for **atomic layer deposition**.

aldehydes – organic compounds that have at least one hydrogen atom bonded to the **carbonyl group** ($>C=O$). These may be $RCHO$ or $ArCHO$ compounds with R representing an **alkyl group** ($-C_nH_{2n+1}$) and Ar representing an **aromatic ring**.

algorithm – a set of well-defined rules for the solution of a problem in a finite number of steps.

aliphatic compound – an organic compound in which carbon atoms are joined together in straight or branched chains. The simplest aliphatic compound is methane (CH_4). Most aliphatic compounds provide exothermic combustion reactions, thus allowing their use as a fuel.

alkanes → hydrocarbons.

alkenes → hydrocarbons.

alkyl groups → hydrocarbons.

allotropy – the property of a chemical element to exist in two or more different structural modifications in the solid state. The term **polymorphism** is used for compounds.

alternating current Josephson effect → Josephson effects.

Al'tshuler–Aronov–Spivak effect – occurs when the resistance of the conductor in the shape of a hollow cylinder oscillates as a function of the magnetic flux threading through the hollow with a period of $hc/2e$. This effect was predicted for the diffusive regime of the charge transport where the mean free path of the electrons is much smaller than the sample size. The conductance amplitude of the oscillations is of the order of e^2/h and depends on the phase coherence length over which an electron maintains its phase coherence. Coherent backscattering of an electron when there is interference in a pair of backscattered spatial waves with time-reversal symmetry causes the oscillations.

First described in: B. L. Al'tshuler, A. G. Aronov, B. Z. Spivak, *Aharonov–Bohm effect in non-ordered conductors*, Pis'ma Zh. Eksp. Teor. Fiz. **33**(2), 101–103 (1981) – in Russian.

More details in: K. Nakamura, T. Harayama, *Quantum Chaos and Quantum Dots* (Oxford University Press, Oxford, 2004).

amides – organic compounds that are nitrogen derivatives of **carboxylic acids**. The carbon atom of a carbonyl group ($>\text{C}=\text{O}$) is bonded directly to a nitrogen atom of an $-\text{NH}_2$, $-\text{NHR}$ or $-\text{NR}_2$ group, where R represents an **alkyl group** ($-\text{C}_n\text{H}_{2n+1}$). The general formula of amides is RCONH_2 .

amines – organic compounds that are ammonia molecules with hydrogen substituted by **alkyl groups** ($-\text{C}_n\text{H}_{2n+1}$) or **aromatic rings**. These can be RNH_2 , R_2NH , or R_3N , where R is an alkyl or aromatic group.

amino acid

amino acid – an organic compound containing an amino group (NH₂), a carboxylic acid group (COOH), and any of various side groups that are linked together by **peptide bonds**. The basic formula is NH₂CHRCOOH. Amino acids are building blocks of **proteins**.

There are twenty standard amino acids used in protein biosynthesis. These are presented in Figure A.3.

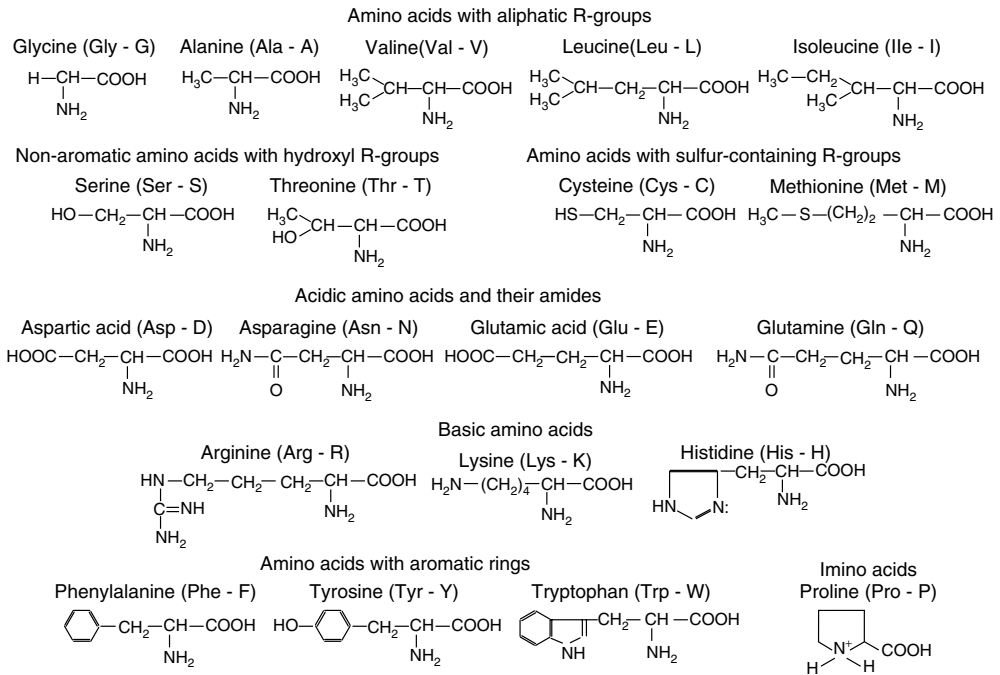


Figure A.3 Amino acids found in proteins. Their symbols are shown in parentheses.

Just as the letters of the alphabet can be combined to form an almost endless variety of words, amino acids can be linked in varying sequences to form a huge variety of proteins.

More details in: [//en.wikipedia.org/wiki/Amino_acid](https://en.wikipedia.org/wiki/Amino_acid).

Amontons' law currently supposes the statement that the friction force between two bodies is directly proportional to the applied load (normal), with a constant of proportionality that is the friction coefficient. This force is constant and independent of the contact area, the surface roughness and the sliding velocity.

In fact, this statement is a combination of a few laws: the law of Euler and Amontons stating that friction is proportional to the loading force, the law of Coulomb → **Coulomb law (mechanics)** stating that friction is independent of the velocity, and the law of Leonardo da Vinci stating that friction is independent of the area of contact. In particular, Leonardo da Vinci arrived (1500) at the result that

on an inclined plane a slider would move if the ratio between the tangential and normal components of the gravitational force exceeded one-fourth.

First described in: G. Amontons, *De la résistance causée dans les machines*, Mem. Acad. Roy. Sci. A, 206–222 (1699).

More details in: R. Schnurmann, *Amontons' law, "traces" of frictional contact, and experiments on adhesion*, J. Appl. Phys. **13**(4), 235 (1942).

amorphous solid – a solid with no long-range atomic order.

Ampère currents – molecular-ring currents postulated to explain the phenomenon of magnetism as well as the apparent nonexistence of isolated magnetic poles.

Ampère's law, as amended by Maxwell, states that magnetomotive force round any closed curve equals the electric current flowing through any closed surface bounded by the curve. The force appears clockwise to an observer looking in the direction of the current. It means that $\int \mathbf{H}d\mathbf{l} = I$, where \mathbf{H} is the magnetic field strength, I is the current enclosed. The linear integral is taken round any closed path. If the current is flowing in a conducting medium, $I = \int \mathbf{J}d\mathbf{s}$, where \mathbf{J} is the current density. Finally, it may be shown that $\nabla \times \mathbf{H} = \mathbf{J}$, which is a statement of Ampère's law at a point in a conducting medium.

First described in: A. M. Ampère, *Mémoire sur les effets du courant électrique*, Annales de chimie et de physique **15**, 59–118 (1820).

More details in: André-Marie Ampère, *Exposé méthodique des phénomènes électrodynamiques et des lois de ces phénomènes* (Plasson, Paris, 1822).

Ampère's rule states that the direction of the magnetic field surrounding a conductor will be clockwise when viewed from the conductor if the direction of current flow is away from the observer.

First described in: A. M. Ampère, *Mémoire sur les effets du courant électrique*, Annales de chimie et de physique **15**, 59–118 (1820).

More details in: André-Marie Ampère, *Exposé méthodique des phénomènes électrodynamiques et des lois de ces phénomènes* (Plasson, Paris, 1822).

Ampère's theorem states that an electric current flowing in a circuit produces a magnetic field at external points equivalent to that due to a magnetic shell whose bounding edge is the the conductor and whose strength is equal to the strength of the current.

First described in: A. M. Ampère, *Mémoire sur les effets du courant électrique*, Annales de chimie et de physique **15**, 59–118 (1820).

More details in: André-Marie Ampère, *Exposé méthodique des phénomènes électrodynamiques et des lois de ces phénomènes* (Plasson, Paris, 1822).

amphichiral → **chirality**.

AND operator

AND operator → **logic operator**.

Anderson insulator – a solid state material with insulating properties defined by the interaction of electrons with impurities and other lattice imperfections. The material is characterized by a robust energy gap, which is a gap for charge excitations between the **Fermi energy** and spatially extended states. Any related metal-to-insulator transition is a type of quantum phase transitions in which the energy gap is formed.

More details in: F. Gebhard, *The Mott Metal-Insulator Transition: Models and Methods* (Springer, Heidelberg, 2010).

Andersen-Nose algorithm – a method used in **molecular dynamics simulation** for numerical integration of ordinary differential equation systems based on a quadratic presentation of time-dependent atom displacement.

First described in: S. Nose, F. Yonezawa, *Isothermal–isobaric computer simulations of melting and crystallization of a Lennard–Jones system*, J. Chem. Phys. **84**(3), 1803–1812 (1986).

Anderson localization means that electron wave function becomes spatially localized and the conductivity vanishes at zero temperature when the mean free path of electrons is short comparable to the Fermi wavelength ($\lambda_F = 2\pi/k_F$); multiple scattering becomes important. Metal-insulator transition takes place due to disorders. In the localized states, the wave function decays exponentially away from the localization center, that is $\psi(r) \sim \exp(-r/\xi)$, where ξ is called the localization length. Anderson localization depends strongly on dimensionality.

First described in: P. W. Anderson, *Absence of diffusion in certain random lattices*, Phys. Rev. **109**(5), 1492–1505 (1958).

Recognition: in 1977 P. W. Anderson, N. F. Mott and J. H. van Vleck received the Nobel Prize in Physics for their fundamental theoretical investigations of the electronic structure of magnetic and disordered systems.

See also www.nobel.se/physics/laureates/1977/index.html.

Anderson rule, which is also called the **electron affinity rule**, states that vacuum levels of two materials forming a **heterojunction** should be lined up. It is used for construction of energy band diagrams of **heterojunctions** and **quantum wells**.

The **electron affinity** χ of the materials is used for the lining up procedure. This material parameter is nearly independent of the position of the Fermi level, unlike the **work function**, which is measured from the Fermi level and therefore depends strongly on doping.

Figure A.4 shows the band alignment at the interface between small band gap material A with the electron affinity χ_A and large band gap material B with the electron affinity χ_B supposing $\chi_A > \chi_B$. According to the rule the offset of the conduction band $\Delta E_c = \Delta E_{cB} - \Delta E_{cA} = \chi_A - \chi_B$. Correspondingly, the offset of the valence band ΔE_v can be predicted from the above diagram accounting for both electron affinities and band gaps of the materials. At a temperature above absolute zero the

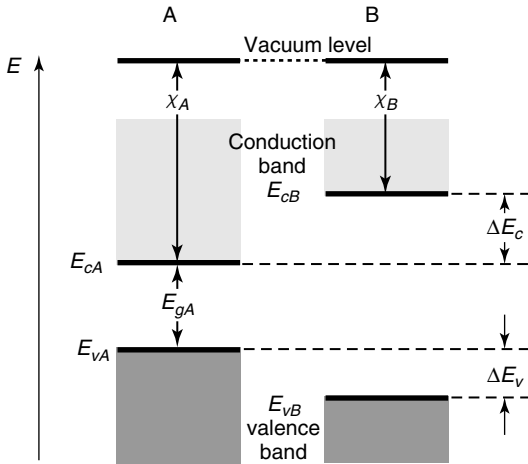


Figure A.4 Alignment of the bands at a heterojunction according to Anderson's rule.

misalignment of the Fermi levels, if there is any, is eliminated by redistribution of free charge carriers at the interface between the barrier and well regions.

The validity of the rule was discussed by H. Kroemer in his paper *Problems in the theory heterojunction discontinuities* CRC Crit. Rev. Solid State Sci. 5(4), 555–564 (1975). The hidden assumption about the relation between the properties of the interface between two semiconductors and those of the much more drastic vacuum-to-semiconductor interface is a weak point of the rule.

First described in: R. L. Anderson, *Germanium-gallium arsenide heterojunction*, IBM J. Res. Dev. 4(3), 283–287 (1960).

Andreev process – reflection of a **quasiparticle** from the potential barrier formed by normal **conductor** and **superconductor** when the barrier height is less than the particle energy. It results in the temperature leap at the barrier if a heat flow takes place there. The conductor part of the structure can be made of a metal, **semimetal** or degenerate **semiconductor**.

The basic concept of the process is schematically illustrated in Figure A.5 for an electron crossing the interface between a conductor and superconductor.

There is a superconducting energy gap opened up for a single electron on the superconductor side. Thus, an electron approaching the barrier from the metal side with the energy above the **Fermi level**, but still within the gap, cannot be accommodated in the superconductor as a single particle. It can only form a **Cooper pair** there that needs an additional electron from the metal side with the energy below the Fermi level to come. This removed electron leaves behind a hole in the Fermi sea. If the incident electron had a momentum $\hbar k$, the generated hole has the momentum $-\hbar k$. It traces the same path as the electron, but in the opposite direction. Describing the phenomenon one says that the incident electron is reflected as a hole.

Ångstrom

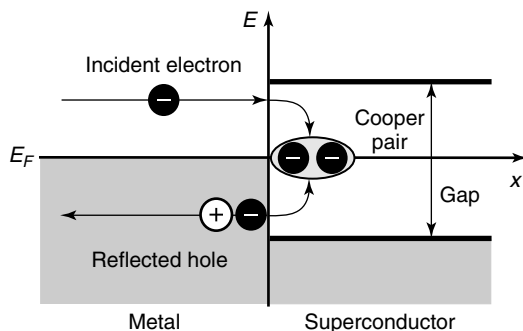


Figure A.5 Andreev reflection process.

First described in: A. F. Andreev, *Thermal conductivity of the intermediate state of superconductors*, Zh. Exp. Teor. Fiz. **46**(5), 1823–1928 (1964) – in Russian.

More details in: C. W. J. Beenakker, *Colloquium: Andreev reflection and Klein tunneling in graphene*, Rev. Mod. Phys. **80**(4), 1337–1354 (2008).

Ångstrom – a metric unit of length measurements that corresponds to 10^{-10} m. The atomic diameters are in the range of 1–2 Å. It is named in honor of the nineteenth-century physicist Anders Jonas Ångstrom, one of the founders of modern spectroscopy.

angular momentum – the energy of a rotating particle. It is quantized for quantum particles as $L^2 = l(l + 1)\hbar^2$, where $l = 0, 1, 2, n - 1$, where n is the principal quantum number. In an atom electrons with $l = 0$ are termed s states, $l = 1$ (p states), $l = 2$ (d states), $l = 3$ (f states), $l = 4$ (g states). The letters s, p, d were first used to describe characteristic features of spectroscopic lines and stand for “sharp”, “principal”, and “diffuse”. After d the letters run alphabetically.

anisodesmic structure – a structure of an ionic crystal in which bound groups of ions tend to be formed → **mesodesmic** and **isodesmic structures**.

anisotropy (of matter) – different physical properties of a medium in different directions. The alternative is **isotropy**.

anisotropic magnetic resistance – the difference in **magnetoresistance** when the resistance of a **conductor** is measured by the current passing either parallel or perpendicular to the material → **giant magnetoresistance effect**.

First described in: W. Thomson (Lord Kelvin), *On the electro-dynamic qualities of metals: effects of magnetization on the electric conductivity of nickel and of iron*, Proc. R. Soc. London **8**, 546–550 (1856).

anodizing = anodic oxidation, is the formation of an adherent oxide film on the surface of a metal or semiconductor when it is anodically polarized in a suitable electrolyte or plasma of an electric discharge in a gas.

anomalous Hall effect – an additional voltage proportional to the magnetization arising in **Hall effect** measurements in **ferromagnetic** materials. Unlike the ordinary **Hall effect**, this contribution is strongly temperature dependent.

The related transverse resistivity ρ_{xy} in ferromagnetics contains the contribution due to the magnetization M in addition to the usual **Hall effect**: $\rho_{xy} = R_0 B + 4\pi R_a M$, where B is the magnetic field induction, R_0 is the usual Hall coefficient, and R_a is the anomalous Hall coefficient. This expression can be used as an experimental tool to measure the magnetization as a function of temperature.

In general, the anomalous Hall effect occurs in solids with broken time-reversal symmetry, typically in a ferromagnetic phase, as a consequence of **spin-orbit coupling**.

First described in: E. H. Hall, *On the new action of magnetism on a permanent electric current*, Philos. Mag. **10**, 301–329 (1880); E. H. Hall, *On the possibility of transverse currents in ferromagnets*, Philos. Mag. **12**, 157–160 (1881).

More details in: N. Nagaosa, J. Sinova, S. Onoda, A. H. MacDonald, N. P. Ong, *Anomalous Hall effect*, Rev. Mod. Phys. **82**(2), 1539–1592 (2010).

See also www.lakeshore.com/pdf-files/systems/Hall-Data-Sheets/Anomalous-Hall1.pdf.

anomalous Zeeman effect → **Zeeman effect**.

antibody – an inducible immunoglobulin **protein** produced by B lymphocytes of the immune system, in humans and other higher animals, which recognizes and binds to a specific **antigen** molecule of a foreign substance introduced into the organism. When antibodies bind to corresponding antigens they set in motion a process to eliminate the antigens.

antibonding orbital – the orbital which, if occupied, raises the energy of a molecule relative to the separated atoms. The corresponding wave function is orthogonal to that of the bonding state → **bonding orbital**.

antiferroelectric – a dielectric of high permittivity, which undergoes a change in crystal structure at a certain transition temperature, usually called the antiferroelectric **Curie temperature**. The antiferroelectric state in contrast to a **ferroelectric** state possesses no net spontaneous polarization below the Curie temperature. No hysteresis effects are therefore exhibited by this type of materials. Examples: BaTiO_3 , PbZrO_3 , NaNbO_3 .

antiferromagnetic → **magnetism**.

antigen

antigen – any foreign substance, such as virus, bacterium, or **protein**, which, after introduction into an organism (humans and higher animals), elicits an immune response by stimulating the production of specific **antibodies**. It also can be any large molecule, which binds specifically to an antibody.

anti-Stokes line → Raman effect.

anti-dot – a **quantum dot** made of wider band gap semiconductor in/on a smaller band gap semiconductor, for example Si dot in/on Ge substrate. It repels charge carriers rather than attracting them.

anti-wires – the **quantum wires** made of wider band gap semiconductor in/on a smaller band gap semiconductor. They repel charge carriers rather than attracting them.

APCVD – an acronym for **atmospheric pressure chemical vapor deposition**.

APFIM – an acronym for **atom probe field ion microscopy**.

a priori – Latin meaning “before the day”. It usually indicates some postulates or facts known logically prior to the referred proposition. It pertains to deductive reasoning from assumed axioms or self-evident principles.

approximate self-consistent molecular orbital method – the **Hartree-Fock theory** as it stands is too time consuming for use in large systems. However, it can be used in a parametrized form, and this is the basis of many of the semi-empirical codes used like **Complete Neglect of Differential Overlap (CNDO)** and **Intermediate Neglect of Differential Overlap (INDO)**.

In the **CNDO** method all integrals involving different atomic orbitals are ignored. Thus, the overlap matrix becomes the unit matrix. Moreover, all the two-center electron integrals between a pair of atoms are set equal and the resonance integrals are set proportional to the overlap matrix. A minimum basis set of valence orbital is chosen using **Slater type orbitals**. These approximations strongly simplify the Fock equation.

In the **INDO** method the constraint present in CNDO that the monocentric two-electron integrals are set equal is removed. Since INDO and CNDO execute on a computer at about the same speed and INDO contains some important integrals neglected in CNDO, INDO performs much better than CNDO especially in prediction of molecular spectral properties.

It is interesting to note that the first papers dealing with the CNDO method appear in a supplementary issue of the Journal of Chemical Physics that contains the proceedings of the International Symposium on Atomic and Molecular Quantum