Victor E. Borisenko
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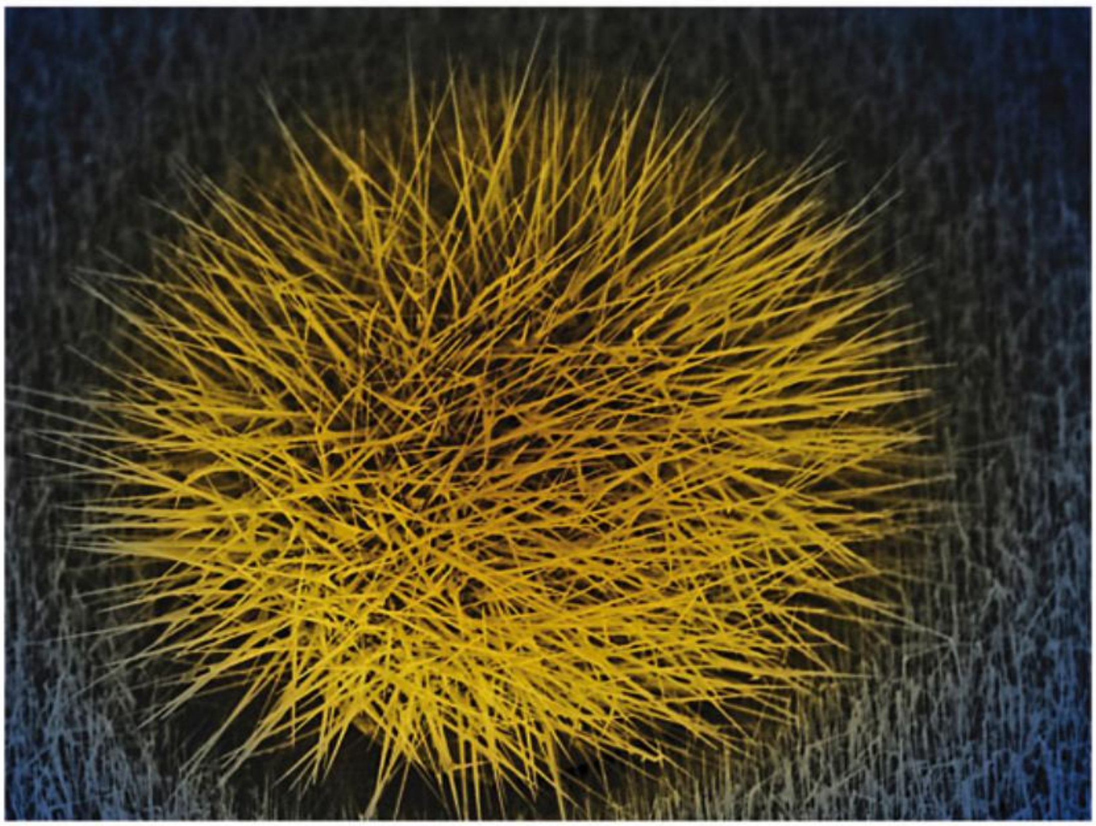
What is What in the Nanoworld

A Handbook on Nanoscience and Nanotechnology

Third, Revised and Enlarged Edition



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Cover

Scanning Electron Microscope image of Gallium Arsenide nanowires grown using gold as catalyst.

Experiment: Faustino Martelli, Silvia Rubini, TASC, Trieste.

Artwork: Lucia Covi, from “Blow-up. Images from the Nanoworld” Copyright S3, 2007.

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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 Carriere, 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

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January 2012

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	Dictionaries
http://web.mit.edu/redingtn/www/netadv/	The Net Advance of Physics.
	Review Articles and Tutorials
	in an Encyclopedic Format

Fundamental Constants Used in Formulas

$a_B = 5.29177 \times 10^{-11}$ m	Bohr radius
$c = 2.99792458 \times 10^{8}$ m/s	light speed in vacuum
$e = 1.602177 \times 10^{-19}$ C	charge of an electron
$h = 6.626076 \times 10^{-34}$ J·s	Planck constant
$\hbar = h/2\pi = 1.054573 \times 10^{-34}$ J·s	reduced Planck constant
$\mathrm{i} = \sqrt{-1}$	imaginary unit
$k_B = 1.380658 \times 10^{-23}$ J/K (8.617385×10^{-5} eV/K)	Boltzmann constant
$m_0 = 9.10939 \times 10^{-31}$ kg	electron rest mass
$n_A = 6.0221367 \times 10^{23}$ mol^{-1}	Avogadro constant
$R_0 = 8.314510$ J/(K·mol)	universal gas constant

$r_e = 2.817938 \times 10^{-15}$ m	radius of an electron
$\alpha = \mu_0 ce^2/2h = 7.297353 \times 10^{-3}$	fine structure constant
$\varepsilon_0 = 8.854187817 \times 10^{-12}$ F/m	permittivity of vacuum
$\mu_0 = 4\pi \times 10^{-7}$ H/m	permeability of vacuum
$\mu_B = 9.27402 \times 10^{-24}$ A·m^2	Bohr magneton
$\pi = 3.14159$	
$\sigma = 5.6697 \times 10^{-5}$ erg/(cm^2 · s · K)	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 **virus**es, 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.

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 — 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 (**A***x,y*) and (*x*,**B***y*) 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).

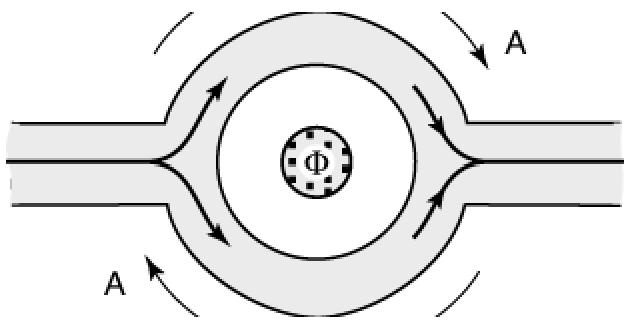
AES — an acronym for **Auger electron spectroscopy**.

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.

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 **A**.



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 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 **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 $\mathbf{\Delta}\Phi = \mathbf{2}\pi(\Phi/\Phi_0)$, 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 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).

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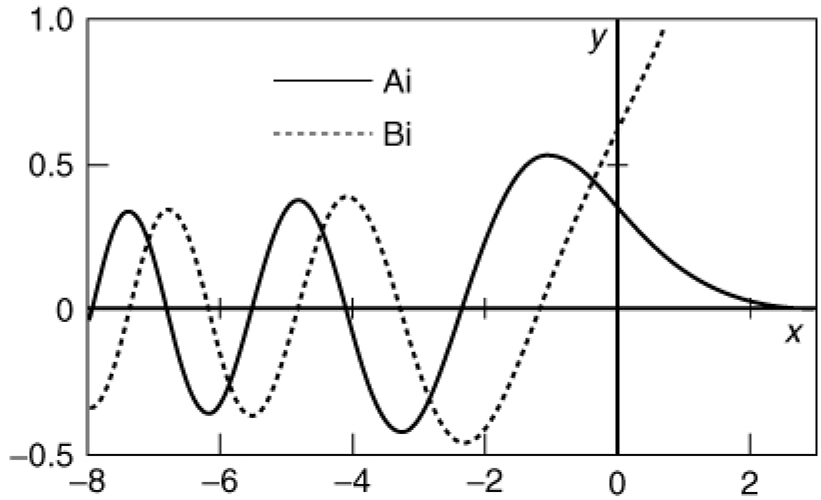
Airy equation — the second order differential equation $d^2y/dx^2 = xy$, also known as the **Stokes equation**. Here x represents the independent variable and y is the value of the function.

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: $\mathrm{Ai}(x) \sim \pi^{-1/2}x^{-1/4}\exp[-(2/3)x^{3/2}]$, $\mathrm{Ai}(-x) \sim (1/2)\pi^{-1/2}x^{-1/4}\cos[-(2/3)x^{3/2} - \pi/4]$. Airy functions arise in solutions of the **Schrödinger equation** for some particular cases.

Figure A.2 Airy functions.



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

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**.