Eur. Phys. J. Special Topics **163**, 1–7 (2008)

DOI: 10.1140/epjst/e2008-00805-9

THE EUROPEAN PHYSICAL JOURNAL SPECIAL TOPICS

Astrophysics, atomic clocks and fundamental constants

S.G. Karshenboim[1,2,a] and E. Peik[3,b]

[1] Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany
[2] D.I. Mendeleev Institute for Metrology (VNIIM), St. Petersburg 190005, Russia
[3] Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, 38116 Braunschweig, Germany

Abstract. The paper gives a brief introduction to the special topic volume.

Since the end of the 19th century our understanding of natural laws has greatly advanced and has reached a quite deep fundamental level, involving quantum effects, special and general relativity, quantum electrodynamics and quantum field theories of other interactions. Approaching quantum gravity is a remaining experimental and theoretical challenge.

The already understood laws to be applied for a quantitative description of natural phenomena need certain 'input data'. While the presence of these parameters, considered as fundamental constants, is a common place of basic textbooks for the university and even for high school education, the origin of these parameters has not been really understood. Many of them appeared in textbooks more than a century ago and we still do not understand them appropriately. We have only learned that some natural parameters can be exactly or approximately expressed in terms of other natural parameters. But we still do not know why the fine structure constant

$$\alpha \simeq 1/137$$

has such a value as it has, whether it is calculable or not and whether it is really constant.

The scope of topics related to fundamental constants is very broad. It is ranging from methods and practice of precision measurements in various subfields of physics, which supply us with the most accurate values of fundamental constants [1] and offer the strongest constraints on their variations, to quantum gravity and super-string theories, which may provide us with explanations of the origin of fundamental constants. Considering the studied objects and phenomena in time and space, we find that we deal with laboratory data, obtained on Earth some months or years ago, with astrophysical data whose origin is separated from us by a time interval of 10^{10} years and by a distance of 10^{10} light years, and even with cosmological data and models related to the young universe. For the intermediate range we can look at data from various space projects like the Lunar Laser Ranging experiment or the tracking of the Pioneer space crafts.

Because of such a broad range there is no and there cannot be any single person who is an expert in the field. However, we hope that a collection of papers by world experts from various parts of physics may help to form a comprehensive review of the state of the art in the field. That is our second attempt to prepare such a collection following [2].

A large part of the most dynamic and most advanced contemporary physics is the development of new technologies, rather than new fundamental theories. New technologies allow to manipulate single particles, atoms and ions. They allow to create entangled states. In other

---

[a] e-mail: `savely.karshenboim@mpq.mpg.de`
[b] e-mail: `ekkehard.peik@ptb.de`

Table 1. Some constraints on variation of α and $\mu = m_p/m_e$ from the analysis of quasar absorption spectra. The constraints are related to a time separation of few gigayears.

Value	Constraint	Reference
$\Delta\alpha/\alpha$	$(-5.4 \pm 1.2) \times 10^{-6}$	[6,7]
$\Delta\alpha/\alpha$	$(-0.1 \pm 1.8) \times 10^{-6}$	[8]
$\Delta\mu/\mu$	$(2.6 \pm 0.6) \times 10^{-5}$	[9]
$\lvert\Delta\mu/\mu\rvert$	$\leq 4.9 \times 10^{-5}$ (CL = 95%)	[10]

words, they allow to perform what has been referred to as 'Gedankenexperiment' for a century, realizing fundamental kinematics in practice, with direct observation at the single-particle level. With fundamental kinematics, observing a well-controlled simple object, we can learn about various small effects and thus perform accurate tests of fundamental theories and search for new physics. This is a cross-over point where the new technologies meet new physics, enabling precision measurements at the quantum limit.

The search for a variation of constants may open a window to new physics. At present we have a lack of information on physics beyond the Standard model, and from the theoretical point of view this search offers a number of opportunities for new physics involving various extensions of the Standard model, quantum gravity etc.

Quantum optics and specifically precision manipulations and precision measurements with ultra-cold atoms can be regarded as one of the most dynamic areas in modern physics. On the experimental side, there is for example the development of new frequency standards. We can anticipate in a decade a consideration of an optical definition of the second and a new turn of the International System of units. We can also expect progress in ground and space navigation directly related to the development of frequency metrology. The intensive development of optical frequency standards ('optical clocks') during the last decade was inspired by the discovery and successful realization of the so-called frequency comb technology. It is notable that the inventors of this technology, T.W. Hänsch [3] and J.L. Hall [4], were awarded the Nobel prize in 2005. It was the third Nobel prize for the quantum optics community received in short time (1997, 2001 and 2005) and all of them were awarded for recent results. While the first two prizes recognized efforts to cool atoms, the third prize was awarded for the revolutionary progress in accurate measurements of optical frequencies. Lack of this in the past had limited prospects for the construction of optical clocks. Only in the microwave domain, measurements of transition frequencies were practical with the highest accuracy. Now, this is not correct anymore. The possibility to compare two optical frequencies or an optical and a microwave frequency relatively easy caused fast progress in optical clocks.

In particular, if we compare the situation of 2003 reviewed in [2] with the present one, we note that there are more transitions measured with high accuracy (i.e. more candidate 'clocks'), more transitions measured and re-measured with a high accuracy (i.e. more data on possible variations of fundamental constants) and the accuracy is now higher than four years ago (see below).

Ancient atomic data are available from a study of interstellar absorption lines in the light from distant quasars. This allows to look at the universe that existed a few billion years ago. Since the publication by the group from the University of New South Wales on their observation of a non-zero signal of a α variation [5], the astrophysical studies were intensified. Here we present four contributions on the subject. Some of them state a non-zero signal for variation of α and m_p/m_e, while others insist that those constants in the remote past had values consistent with the present ones. The contradiction between the results exists and remains unresolved (see Table 1 for more detail).

In the meantime, progress in the development of atomic clocks and especially of optical atomic clocks allows laboratory comparisons with a high sensitivity and provides a strong constraint on a variation of α in the present epoch.

Table 2. The most stringent limits on variation of optical atomic transitions frequencies. Here: $\{f\}$ is the numerical value of a frequency in the SI hertz (i.e. in respect to the Cs hyperfine interval); $\Delta \ln\{f\}/\Delta t$ is the observed rate of its time variation in fractional units.

Atom, transition	$\Delta \ln\{f\}/\Delta t$	Reference	Sensitivity factor, A
^{1}H, $1S \to 2S$	$\bigl(-3.2 \pm 6.3\bigr) \times 10^{-15}\ \mathrm{yr}^{-1}$	[15]	0.00
^{171}Yb^{+}, $^{2}S_{1/2} \to {}^{2}D_{3/2}$	$\bigl(-0.78 \pm 1.40\bigr) \times 10^{-15}\ \mathrm{yr}^{-1}$	[16]	0.9
^{199}Hg^{+}, $^{2}S_{1/2} \to {}^{2}D_{5/2}$	$\bigl(0.37 \pm 0.39\bigr) \times 10^{-15}\ \mathrm{yr}^{-1}$	[12,17]	−3.2
^{87}Sr, $^{1}S_{0} \to {}^{3}P_{0}$	$\bigl(-0.7 \pm 1.8\bigr) \times 10^{-15}\ \mathrm{yr}^{-1}$	[18,19]	0.06

One type of new clocks makes use of ion trapping and of a double resonance spectroscopy scheme which allows accurate measurements with a single ion (see [11,12]). The scheme needs two transitions. One is an ultra narrow ‘clock’ transition, while the other transition, which is rather broad, serves for cooling and detection. Recent progress in the trapped-ion realization of quantum logic makes possible a two-ion clock with simultaneous trapping of two entangled ions of different kinds. Both transitions are realized, but one on one ion, the other on its entangled partner. The other promising type of optical clocks uses large number of ultra-cold neutral atoms. Ballistically expanding atomic clouds from magneto optical traps are now substituted by atoms trapped in an optical lattice [14]. This allows to suppress motional and density related frequency shifts, but still keeps the high stability obtainable with a high number of atoms. The approach is followed with Sr atoms in a number of groups and excellent agreement between three independent realizations have been observed [18].

Most precision measurements with optical clocks are done against the caesium standard. The most accurate recent results are presented in this volume. Comparing different measurements for the same transition frequency over a period of time we can find a value for its time derivative (see Table 2).

The combination of the results allows to constrain the time variation of the fine structure constant, α, and of the numerical value of the Rydberg constant in SI units, $\{\mathrm{Ry}\}$. We briefly recall that to arrive at the constraints we have to present any optical frequency in the form (see [11,20])

$$f = Ry\, c \times F(\alpha), \tag{1}$$

where $F(\alpha)$ is the relativistic correction which strongly depends on the transition under study. This is the dependence that allows to constrain the α-variation by comparing different transitions.

For the variation of the numerical value of the frequency in SI units, $\{f\}$, (i.e. a result from a comparison in respect to the caesium hyperfine interval) we obtain

$$\frac{\partial \ln\{f\}}{\partial t} = \frac{\partial \ln\{Ry\, c\}}{\partial t} + A \times \frac{\partial \ln \alpha}{\partial t}, \tag{2}$$

with the sensitivity coefficient

$$A = \frac{\partial F(\alpha)}{\partial \alpha}\ . \tag{3}$$

Applying (2) to the data, summarized in Table 2, we find

$$\frac{\partial \ln \alpha}{\partial t} = \bigl(-3.1 \pm 3.1\bigr) \times 10^{-16}\ \mathrm{yr}^{-1} \tag{4}$$

$$\frac{\partial \ln\{Ry\, c\}}{\partial t} = \bigl(-6.3 \pm 9.2\bigr) \times 10^{-16}\ \mathrm{yr}^{-1}. \tag{5}$$

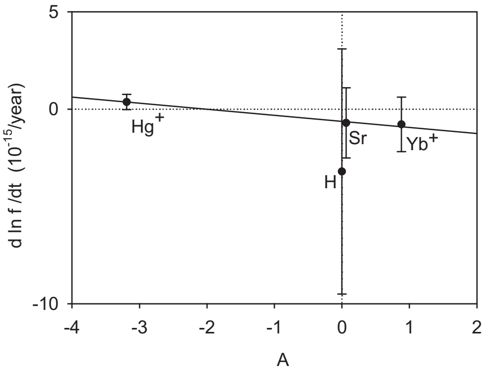

Fig. 1. Time variation of measured transition frequencies $\Delta \ln\{f\}/\Delta t$ as a function of their sensitivity coefficient A.

The data and the fit are presented graphically in Fig. 1. The sensitivity coefficients A can be found in [20,21].

More recently, a few experiments have been trying to set a constraint on an α-variation without involving the caesium microwave standard. In particular, a direct measurement of a highly sensitive transition in Dy [22,23] and a comparison of two optical transitions in Al^+ and Hg^+ performed at NIST [12,24] and delivering the strongest all-optical limitation, yield constraints

$$\frac{\partial \ln \alpha}{\partial t} = \big(-2.7 \pm 2.6\big) \times 10^{-15}\ \mathrm{yr}^{-1}, \quad \text{from Dy}, \tag{6}$$

$$\frac{\partial \ln \alpha}{\partial t} = \big(-1.6 \pm 2.3\big) \times 10^{-17}\ \mathrm{yr}^{-1}, \quad \text{from Al}^+/\text{Hg}^+. \tag{7}$$

The direct constraint on $\partial \ln \alpha/\partial t$ obtained from the optical frequency ratio measurement $\mathrm{Al}^+/\mathrm{Hg}^+$ is much stronger than the evaluation of the results of absolute measurements of optical frequencies. Using all the available data in a common least-squares adjustment, a more stringent constraint on the variation of the Rydberg constant can be obtained from a combination of (2) and (7)

$$\frac{\partial \ln\{Ry\, c\}}{\partial t} = \big(1.9 \pm 3.8\big) \times 10^{-16}\ \mathrm{yr}^{-1}. \tag{8}$$

The constraint on $\partial \ln\{Ry\, c\}/\partial t$ limits a possible common drift of all optical frequencies in respect to the caesium hyperfine structure, while a possible α-variation would induce relative drifts between the optical transitions. The combined constraint on the two constants in plotted in Fig. 2.

Quantum optics targeted new physics in many ways and one of them is a search for a violation of various fundamental symmetries and in particular of local time and position invariance and of Lorentz invariance [25,26]. Another attractive target is various general relativity tests. Such tests are related to the search for a time variation of atomic constants in many ways. The very variation of constants would be kind of a manifestation of violation of local time invariance, although not necessarily a violation at the fundamental level.

There are experiments which deal with the ‘observational’ violation of the Lorentz invariance. One can recall that an alternative of special relativity was ether, i.e. a certain medium. At present we consider a number of substances occupying space. Those substances choose their preferred rest frames. Any experiment targeting an interaction with such a substance looks for a kind of violation of relativity. It is indeed driven by the presence of a ‘medium’, but from the observational side there is no difference between a fundamental violation and a matter-driven one. One such experiment is DAMA [27]. It is directed at a search for an interaction of dark matter particles with a laboratory target. Because of our motion in respect to the frame where dark matter is locally at rest, the signal is modulated with an annual period.

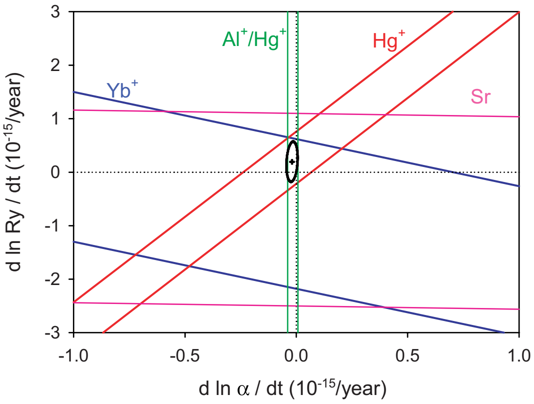

Fig. 2. Constraints on $\partial \ln\{Ry\}/\partial t$ and $\partial \ln \alpha/\partial t$ from different experiments (cf. Table 2) and standard uncertainty ellipse of the combined data.

Dark matter is an example of a classical kind of substance (but of unknown nature) occupying the Universe. There may also be substance of a quantum kind, which means a vacuum field. Such fields are introduced in many theories (but not necessary in a Lorentz-symmetry-violating way) and, perhaps, the very existence of dark energy is a confirmation that such fields are present. Some theories which consider quantum fields, e.g., the quintessence (see e.g. [28–30]), suggest that the variation of constants is related to a violation of the equivalence principle, tests of which are part of general relativity tests. As well as searches for the variations of constants, the tests of the equivalence principle (see, e.g. [25, 26]) rather see no convincing non-zero signal.

It is important to consider searches for variations of the constants and violations of the symmetries together, since it is expected that they come from the same source which may be unification theory, quantum gravity, superstrings etc. In the meantime, the tests of general relativity supply us with a constraint on a possible time variation of the Newtonian gravitation constant (see [25] for detail)

$$\frac{\partial \ln G}{\partial t} = \big(5 \pm 6\big) \times 10^{-13}\ \mathrm{yr}^{-1}. \tag{9}$$

The recent evidence of existence of dark matter and dark energy has demonstrated that observational astrophysics and cosmology is now not only an experimental support of theoretical cosmology but also a new source of the most fundamental physics. A study of dark matter, the density of which dominates over the density of common (baryonic) matter, is very important for understanding not only cosmology but also particle physics, because the contents of the dark matter does not fit any known particles. It seems that cosmology is now also one of the most dynamic parts of contemporary physics. Awarding the Nobel prize for a study of the cosmic microwave background radiation in 2006 is a signal of that.

While cosmology deals with fundamental physics and is rather far from practical applications, the quantum optics technologies are used not only for precision clocks but also for other measurements. In particular, atom interferometers provide an important source for the determination of the value of the fine structure constant α (see Fig. 3).

For a while, the value of α has been determined based on a measurement from a single group [31] and on the calculation from a single group: QED calculation of many few-loop diagrams are used to extract the value of α from the Penning-trap measurement of the anomalous magnetic moment of the electron. The gap in accuracy between this value and those obtained with other techniques was very large. Recently, an independent and more accurate measurement [32] delivered an independent value of the anomalous magnetic moment, while the theory is still developed only by Kinoshita and coauthors [34–37]. The CODATA recommended values of α in [41–43] were determined by the contemporary results from the anomalous magnetic moment of the electron (they are presented in Fig. 3 with closed circles). The most

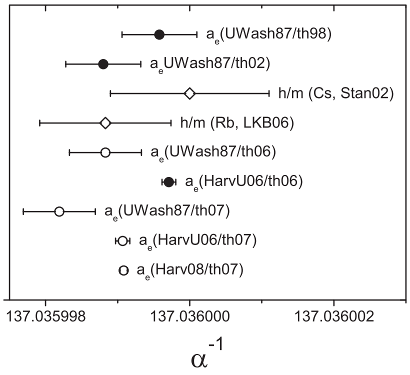

Fig. 3. Determination of the fine structure constant α. References: measurements of the electron anomalous magnetic moment: *UWash87* [31] and *HarvU06* [32], *HarvU08* [33]; theory: *th98* [34], *th02* [35], *th06* [36], *th07* [37]; atomic recoil data from h/m in Cs [38] and Rb [39,40].

accurate value at present [33,44] is also determined by an a_e datum and it differs from the CODATA's value [43] because the theoretical correction [37] was discovered after the CODATA's analysis was already completed. The experiment was also improved recently [33].

Indeed, it is desirable to have a completely independent approach to reach a value of α. The measurements of recoil frequencies in atomic interferometry now provide us with such accurate values of the fine structure constant [38–40], which make the α value more reliable.

Progress in the determination of fundamental constants drives a suggestion that in some time we will be able to maintain and reproduce all units only with the help of quantum phenomena and thus to arrive at the quantum SI. The first step was already done many years ago when the definitions of the SI second and metre were related to certain atomic lines which are natural constants.

Adopting an exact value of the speed of light c was an important step in involving fundamental constants and quantum phenomena. Quantum physics is not presented at the surface in this definition, however in practice the master relation for realization of the metre was related to wavelengths and frequencies of atomic lines

$$\lambda \times \nu = c.$$

The fundamental constants appeared in the SI much earlier when the definition of the ampere was accepted. However, the most fruitful use of fundamental constants for metrology occurs when the constants are involved in quantum phenomena, because classical phenomena used to be relatively uncertain in precision applications.

A recent proposal [45] on a possible redefinition of the kilogram initiated numerous discussions. The situation is reviewed in [46]. An important part of this problem is related to an accurate determination of the Planck constant h and the Avogadro constant N_A, considered in detail in [47].

In conclusion, we expect soon various important contributions from studies of fundamental constants. Supplying practitioners with new standards or delivering fundamental data to theoreticians – we just do not know in which way they will come first.

Support from the Wilhelm und Else Heraeus-Stiftung and from the Foundational Questions Institute (fqxi.org) is gratefully acknowledged.

References

1. P.J. Mohr, B.N. Taylor, D.B. Newell, Phys. Today **60**, 52 (2007)
2. *Astrophysics, Clocks and Fundamental Constants*, edited by S.G. Karshenboim, E. Peik, Lect. Not. Phys. **648** (Springer, Berlin, Heidelberg, 2004)

3. T.W. Hänsch, Rev. Mod. Phys. **78**, 1297 (2006)
4. J.L. Hall, Rev. Mod. Phys. **78**, 1279 (2006)
5. J.K. Webb, V.V. Flambaum, C.W. Churchill, M.J. Drinkwater, J.D. Barrow, Phys. Rev. Lett. **82**, 884 (1999); J.K. Webb, M.T. Murphy, V.V. Flambaum, V.A. Dzuba, J.D. Barrow, C.W. Churchill, J.X. Prochaska, A.M. Wolfe, Phys. Rev. Lett. **87**, 091301 (2001)
6. M.T. Murphy, V.V. Flambaum, J.K. Webb, V.V. Dzuba, J.X. Prochaska, A.M. Wolfe, *Constraining Variations in the Fine-Structure Constant, Quark Masses and the Strong Interaction* in [2], p. 131
7. V.V. Flambaum, Eur. Phys. J. Special Topics **163**, 159 (2008)
8. P. Molaro, et al., Eur. Phys. J. Special Topics **163**, 173 (2008)
9. A. Ivanchik, et al., Eur. Phys. J. Special Topics **163**, 191 (2008)
10. M. Wendt, D. Reimers, Eur. Phys. J. Special Topics **163**, 197 (2008)
11. S.N. Lea, Eur. Phys. J. Special Topics **163**, 37 (2008)
12. L. Lorini, et al., Eur. Phys. J. Special Topics **163**, 19 (2008)
13. P.O. Schmidt, et al., Science **309**, 749 (2005)
14. M. Takamoto, et al., Nature **435**, 321 (2005)
15. M. Fischer, et al., Phys. Rev. Lett. **92**, 230802 (2004); M. Fischer, et al., *Precision Spectroscopy of Atomic Hydrogen and Variations of Fundamental Constants* in [2], p. 209
16. E. Peik, et al. (2006) [`arXiv:physics/0611088`]
17. T. Fortier, et al., Phys. Rev. Lett. **98**, 070801 (2007)
18. S. Blatt, et al. (2008) [`arXiv/0801.1874`]
19. A.D. Ludlow, et al., Eur. Phys. J. Special Topics **163**, 9 (2008); A.D. Ludlow, et al., Science **319**, 1805 (2008)
20. S.G. Karshenboim, V. Flambaum, E. Peik, *Atomic Clocks and Constraint on Variations of Fundamental Constants*, edited by G.W.F. Drake, *Springer Handbook on Atomic, Molecular and Optical Physics* (Springer, New York, 2005)
21. E.J. Angstmann, Phys. Rev. A **70**, 014102 (2004)
22. A. Cingöz, et al., Phys. Rev. Lett. **98**, 040801 (2007)
23. A. Cingöz, et al., Eur. Phys. J. Special Topics **163**, 71 (2008)
24. T. Rosenband, et al., Science **319**, 1808 (2008)
25. S.G. Turyshev, Eur. Phys. J. Special Topics **163**, 227 (2008)
26. C. Lämmerzahl, Eur. Phys. J. Special Topics **163**, 255 (2008)
27. R. Bernabei, Eur. Phys. J. Special Topics **163**, 207 (2008)
28. J.-Ph. Uzan, Rev. Mod. Phys. **75**, 403 (2003)
29. Th. Damour, F. Piazza, G. Veneziano, Phys. Rev. Lett. **89**, 081601 (2002)
30. T. Dent, Eur. Phys. J. Special Topics **163**, 297 (2008)
31. R.S. Van Dyck, Jr., P.B. Schwinberg, H.G. Dehmelt, Phys. Rev. Lett. **59**, 26 (1987)
32. B. Odom, D. Hanneke, B. D'Urso, G. Gabrielse, Phys. Rev. Lett. **97**, 030801 (2006)
33. D. Hanneke, S. Forgwell, G. Gabrielse, Phys. Rev. Lett. **100**, 120801 (2008)
34. V.W. Hughes, T. Kinoshita, Rev. Mod. Phys. **71**, S133 (1999)
35. T. Kinoshita, M. Nio, Phys. Rev. Lett. **90**, 021803 (2003)
36. T. Kinoshita, M. Nio, Phys. Rev. D **73**, 013003 (2006)
37. T. Aoyama, M. Hayakawa, T. Kinoshita, M. Nio, Phys. Rev. Lett. **99**, 110406 (2007); T. Aoyama, M. Hayakawa, T. Kinoshita, M. Nio, Phys. Rev. D **77**, 053012 (2008)
38. A. Wicht, J.M. Hensley, E. Sarajlic, S. Chu, Phys. Scr. T **102**, 82 (2002)
39. P. Cladé, E. de Mirandes, M. Cadoret, S. Guellati-Khélifa, C. Schwob, F. Nez, L. Julien, F. Biraben, Phys. Rev. Lett. **96**, 033001 (2006)
40. M. Cadoret, et al., Eur. Phys. J. Special Topics **163**, 101 (2008)
41. P.J. Mohr, B.N. Taylor, Rev. Mod. Phys. **72**, 351 (2000)
42. P.J. Mohr, B.N. Taylor, Rev. Mod. Phys. **77**, 1 (2005)
43. P.J. Mohr, B.N. Taylor, D.B. Newell, Rev. Mod. Phys. **80**, 633 (2008) [`arXiv:0801.0028`]
44. G. Gabrielse, D. Hanneke, T. Kinoshita, M. Nio, B. Odom, Phys. Rev. Lett. **99**, 039902 (2007)
45. I.M. Mills, P.J. Mohr, T.J. Quinn, B.N. Taylor, E.R. Williams, Metrologia **42**, 71 (2005)
46. S.G. Karshenboim, Eur. Phys. J. Special Topics **163**, 141 (2008)
47. P. Becker, Eur. Phys. J. Special Topics **163**, 127 (2008)