Meditations on First Principles Underlying an Assumed Matter-Antimatter Gravitational Repulsion: a Dialectic Essay

Marcoen J.T.F. Cabbolet[a,b,*]

[a] *Center for Logic and Philosophy of Science, Vrije Universiteit Brussel*
Pleinlaan 2, 1050 Brussels (Belgium)
[b] *Institute of Theoretical Physics, Kharkov Institute of Physics and Technology*
Akademicheskaya str. 1, 61108 Kharkov (Ukraine)

Posted online: February 10, 2012 **This version**: February 16, 2014

Abstract

Although it is widely assumed that gravitation is attraction only, the existence of gravitational repulsion cannot be excluded. In a recent study, for the first time non-classical physical principles have been developed from the hypothesis that matter and antimatter repulse one another gravitationally. To explain why these principles – together called: the Elementary Process Theory (EPT) – are outside the framework of contemporary physical theories, this dialectic essay focusses on the all-determining first cycle of thesis, antithesis and synthesis of that study. A Cartesian analysis yields the unquestionable thesis that antimatter must have positive rest mass and negative gravitational mass, if the hypothesis is a fact of nature. The antithesis to this thesis is then that this combination of properties is impossible from the perspective of established theories. The synthesis is then that this combination of properties has to be underlied by a fundamentally new physical principle, which is that rest-mass-having particles alternate between a particlelike state and a wavelike state. The final section addresses the question of correctness and completeness of the EPT.

1 Introduction

Worldwide, it is virtually everywhere assumed in fundamental theoretical-physical research that gravitation is attraction only. This assumption has, however, not been tested in the realm of antimatter: the AEgIS project at CERN is aimed at establishing the gravitational acceleration of antihydrogen on earth. Amsler *et al.* have reported that results are expected in 2014-2015 [1]. If the results are inconclusive, then the AEgIS project may be succeeded by the GBAR project; this has the same experimental aim but uses ultracold trapped antihydrogen instead of a beam of antihydrogen [2]. But if results *are* conclusive, then a possible outcome is that rest-mass-having antimatter is repulsed by the gravitational field of ordinary matter: this is something we *know* in case the AEgIS experiment establishes that the gravitational acceleration of antihydrogen is the *precise opposite* of that of ordinary matter.

*E-mail: Marcoen.Cabbolet@vub.ac.be

In a recent study, published integrally in [3], the hypothesis was that gravitation can also be *repulsive*, in the sense that antimatter particles such as positrons, antiprotons, and antineutrons are repulsed by the gravitational field of 'ordinary' matter: the aim was to identify physical principles that would make such a repulsion possible. The main results of this study, i.e. the Elementary Process Theory (EPT) and some applications thereof to physics and cosmology, have also been published in [4], [5].

The purpose of this paper is to explain *why* the elementary principles underlying gravitational repulsion as laid down in the EPT find themselves outside the framework of contemporary physics. For that matter, the next three sections present the first dialectic cycle of thesis, antithesis and synthesis that in hindsight can be distinguished in the development of the EPT: Sect. 2 derives an unquestionable thesis from the hypothesis on gravitational repulsion; Sect. 3 formulates an antithesis to this unquestionable thesis from the perspective of the established theories; Sect. 4 solves the contradiction between unquestionable thesis and antithesis with the synthesis. Sect. 5 gives some concluding remarks.

2 From assumption to unquestionable thesis

The first step is a Cartesian analysis of the hypothesis on gravitational repulsion, that is, an analysis of that hypothesis in smallest possible terms, *in casu* the classical concepts 'inertial mass' and 'gravitational mass'.

To start with, let's recall that *inertial mass* is the resistance of a body against a change in motion, as laid down in Newton's second law:

$$\vec{F}_{net} = m_i \cdot \vec{a} \tag{1}$$

Here the vector $\vec{F}_{net}$ represents the net force on a body, the number m_i its inertial mass and the vector $\vec{a}$ its acceleration; *rest mass* m_0 is then the inertial mass of a body in rest, that is, that doesn't move relative to an observer. Now it has already been established that antimatter has *positive* rest mass: a negative rest mass would, for example, be impossible to reconcile with the recently observed stability of antihydrogen reported by Hangst *et al.* [6], because the Coulomb force would then cause the antiproton and the positron to accelerate away from each other. See figure 1 for an illustration.

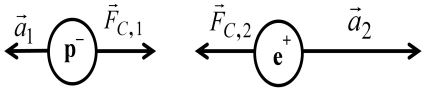

Figure 1: illustration of the mutual repulsion of a positron and an antiproton with negative inertial mass m_i due to the Coulomb force. The circle on the left is an antiproton p^-, the one on the right a positron e^+. The two arrows $\vec{F}_{C,1}$ and $\vec{F}_{C,2}$ represent the Coulomb forces on p^- and e^+, which are directed towards each other because of the opposite electric charge. The two arrows $\vec{a}_1$ and $\vec{a}_2$ represent the accelerations of p^- and e^+: these are then directed away from each other because $m_i < 0$. Clearly, antihydrogen can then not be stable.

Gravitational mass, on the other hand, is the 'charge' of a body for the gravitational force as laid down in Newton's law of gravitation, which in vector notation is the following:

$$\vec{F}_{12} = G \cdot \frac{m_{g(1)} \cdot m_{g(2)}}{r^2} \cdot \vec{e}_{12} \tag{2}$$

Here the vector $\vec{F}_{12}$ represents the gravitational force on the first body exerted by the second body, the number G is a constant, the numbers $m_{g(1)}$ and $m_{g(2)}$ the gravitational mass of

successively the first and the second body, the number r the distance between them, and the vector $\vec{e}_{12}$ is a unit vector from the position of the first body to that of the second.

Now consider a case in which the earth's gravitational force on a body of antimatter is the *only* force, so we have $\vec{F}_{12} = \vec{F}_{net}$. An observation of an upwards-directed acceleration—this is what will be observed in case of a repulsion—then means that the vector $\vec{a}$ in (1) is directed *away from* earth. And since antimatter has *positive* rest mass, on account of (1) the observer has to conclude that the net force $\vec{F}_{net}$ on the body of antimatter is also directed away from earth. And because in this case $\vec{F}_{net} = \vec{F}_{12}$, we have to conclude that the gravitational force $\vec{F}_{12}$ on the body of antimatter is also directed away from earth. But that is only possible if the gravitational mass of the body of antimatter is *negative*: all other factors on the right hand side of (2) are namely *positive*, and the unit vector $\vec{e}_{12}$ is directed *towards* earth. See figure 2 for an illustration.

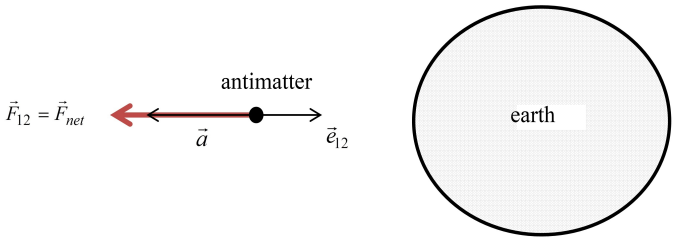

Figure 2: illustration of the Gedankenexperiment with a body of antimatter. The circle on the right is earth, the black dot on the left is the body of antimatter. The leftwards black arrow is then the observed acceleration $\vec{a}$, the rightwards black arrow the unit vector $\vec{e}_{12}$ from formula (2), and the red-brown arrow the gravitational force $\vec{F}_{12}$ that earth exerts on the body of antimatter: it has the same direction as the acceleration because $\vec{F}_{12} = \vec{F}_{net} = m_i \cdot \vec{a}$ and $m_i > 0$ for antimatter. When (2) is applied to this force, then it has thus to be the case that $m_g < 0$ for antimatter.

Thus speaking, if a matter-antimatter gravitational repulsion is a fact of nature, then the following conjunction *necessarily* holds for the observable properties gravitational mass $\overline{m}_g$ and rest mass $\overline{m}_0$ of antimatter particles such as positrons, antiprotons, etc.:

$$\overline{m}_0 > 0 \wedge \overline{m}_g < 0 \tag{3}$$

Note that this expression is model-free: it has been derived without any assumption on what antimatter *is*, and without taking a position on whether inertial mass and gravitational mass are *primary* or *secondary* properties as meant by Locke, that is, whether these are observable properties that are also present in the thing in itself, or properties that are observable but not present in the thing in itself. So however simple expression (3) is, it provides a criterion for theory evaluation: any theory inconsistent with the conjunction (3) is certain to be not universally true when a matter-antimatter gravitational repulsion is a fact of nature—consistency with (3) is necessary but not sufficient.

Historically, the combination of positive inertial mass and negative gravitational mass has occurred in the literature since the late 1950's [7, 8, 9]; in their 1957 essay, Morrison and Gold were the first to conclude that antimatter must have this combination of properties in case of a matter-antimatter gravitational repulsion. In more recent times, it has also in the works of Hajdukovic [10] and of Benoit-Lévy and Chardin [11] been assumed that antimatter has the combination of properties (3) in the context of a matter-antimatter gravitational repulsion.

3 Antithesis and rejection of established theories

Diametrically opposed to this thesis that the hypothesis implies that antimatter particles with positive rest mass have negative gravitational mass, is the **antithesis** that it is *absolutely impossible* that antimatter particles can have this property according to contemporary physical theories.

General Relativity (GR) contains the weak equivalence principle (WEP): this equates inertial mass and gravitational mass, so in particular we have

$$\overline{m}_g = \overline{m}_i > 0 \tag{4}$$

for the gravitational mass $\overline{m}_g$ and the inertial mass $\overline{m}_i$ of antimatter particles. On account of this WEP, it is thus absolutely impossible from the perspective of GR that rest mass and gravitational mass of antimatter have opposite signs. That is, GR is inconsistent with the criterion (3) derived in the previous section. A similar argument against GR can also be found in [8, 9, 12].

Besides that, the Standard Model of particles and interactions (SM) contains the so-called CPT-invariance. Kellerbauer *et al.* stated that "the problem of the gravitational interaction of antimatter is completely independent from the question of matter-antimatter symmetry (CPT), as CPT-invariance merely dictates the equality of the inertial masses of particle and antiparticle pairs, but places no restriction on the gravitational masses" [13]. But that is not true: CPT-invariance, *if correct*, means namely that the difference between the properties of a matter particle and those of its antimatter counterpart is *completely* described by C-inversion, which doesn't affect gravitational mass. So contrary to the statement of Kellerbauer *et al.*, C-inversion as currently defined *does* place a restriction on gravitational mass: we get

$$\overline{m}_g = C(m_g) = m_g > 0 \tag{5}$$

for the relation between the gravitational masses m_g and $\overline{m}_g$ of a particle and its antimatter counterpart. A neutron and an antineutron, for example, differ thus only with respect to some quantum numbers that have no relation to gravitation whatsoever. The SM thus also excludes that antimatter with positive rest mass can have negative gravitational mass: like GR, the SM is inconsistent with the criterion (3). That is, the C-inversion as incorporated in the SM is *incorrect* if a matter-antimatter gravitational repulsion is a fact of nature. Now one might be inclined to believe that this incorrectness is a mere incompleteness which can easily be resolved, but from that belief it does **absolutely not** follow that a future formulation of the SM consistent with the criterion (3) will ever exist: one cannot bluntly start adding minus signs to such basic concepts like mass and energy, and expect that the whole remains consistent—cf.[14]!

Interestingly, Villata recently claimed in [15] that an equation describing gravitational repulsion of matter and antimatter *does* appear as a prediction of GR when it is extended with the CPT theorem. In [16], however, it was argued on ontological and methodological grounds that this extended GR cannot be a fundamental theory; subsequently, cf. [17], it became clear that Villata's equation was meant as a starting point in astronomy for studies of the consequences of gravitational repulsion: Villata's theory has thus not to be seen as *fundamental*, but as *emergent* at macroscopic scale. While this may provide an interesting new approach for studies of the large-scale structure of the universe, in the present study we are interested in the *fundamental* physical principles that underlie gravitational repulsion: for that matter, we have to look beyond Villata's theory.

So this is certain: if these established theories correspond with physical reality, then our hypothesis is absolutely impossible. And vice versa: if the hypothesis on gravitational repulsion would be a fact of nature, then gravitation is not what is laid down in GR and antimatter is not what is currently laid down in the SM. Given this incompatibility of the hypothesis with both GR and the SM, the radical decision was made to reject both GR and the SM *in their entirety*

as not universally valid. So these established theories are not rejected because we have found a proof that they cannot be correct, but because from the perspective of our research hypothesis we have found a reason to doubt them: this is the Cartesian criterium for the rejection of theories[1] [18].

4 Synthesis: *thinking outside-the-box*

Having rejected both GR and the SM, it thus required a *thinking outside-the-box* to identify new universal elementary principles underlying a gravitational repulsion of matter and antimatter. That is, the present study included a search for first principles *outside* the framework of contemporary physics. To solve the question how antimatter with positive rest mass can have negative gravitational mass, the proposition – the **synthesis** – was put forward that all rest-mass-having constituents (like electrons, positrons, protons, etc.) alternate between a particlelike state of rest and a wavelike state of motion: gravitation then takes place in a wavelike state, and rest mass and gravitational mass are then observable properties of respectively the particlelike state of rest and the wavelike state of motion. Because rest mass and gravitational mass are then properties of *different* physical states, they do not necessarily have to be the same in sign or in absolute value. Not going into the formalism of the EPT, the process of alternation can be summarized by these two expressions:

$$\text{particle} \rightarrow \text{matter wave} \tag{6}$$

$$\text{matter wave} \rightsquigarrow \text{new particle} \; + \; \text{excess energy} \tag{7}$$

So first a discrete transition (6) occurs, by which a rest-mass-having particle transforms from a motionless particlelike state into a matter wave[2]. In this step, energy can be absorbed from the surroundings: the matter wave may contain more energy than the particlelike state. Then, by a *series* of discrete transitions—as indicated by the symbol '$\rightsquigarrow$' in (7)—the rest-mass-having particle transforms from a matter wave back into a new particlelike state, whereby any excess energy is emitted to the surroundings[3]. The particlelike states are devoid of motion: this alternating between two kinds of states corresponds with a concept of stepwise motion as illustrated in figure 3—all rest-mass-having constituents have, thus, a definite position every time they are in a state of rest, also in absence of observation.

Such a definite position in absence of observation is, however, absolutely impossible in the framework of Quantum Mechanics (QM): in the latter framework, a particle has a definite position if and only if the position is measured. That is thus the antithesis in a new cycle of thesis, antithesis and synthesis. This led to the rejection of QM: it turned out to be impossible to describe the alternation between a particlelike state and a wavelike state in the framework of QM. Therefore, the identification of physical principles of gravitational repulsion required not only the introduction of some new primitive concepts, but in addition it required a new mathematical formalism for the formulation of elementary principles governing this process of alternation. As a result, the matter waves meant in (6) and (7), which have gravitational mass as an observable property, do not occur in the framework of any established theory. However,

[1] Thus speaking, on the one hand experimental confirmation of predictions compels us to accept that GR and the SM are very successful *in their respective areas of application*, but on the other hand an observation of a matter-antimatter gravitational repulsion would compel us to doubt that these theories are *universally* applicable.

[2] In the language of the EPT, the particlelike states are *extended particle phase quanta* denoted by symbols ${}^{EP}\Phi_k^x$, and the matter waves are *nonlocal wavelike phase quanta* denoted by symbols ${}^{NW}\Phi_k^x$. Here the Greek letter Φ stands for 'phase quantum' (a primitive notion), the left superscript indicates the type of phase quantum (e.g. *EP*: **e**xtended **p**articlelike), the right superscript x is an integer indicating the discrete degree of evolution at which it is created, and the right subscript k is the number of the individual process—of which there are finitely many at every degree of evolution—in which the phase quantum participates.

[3] In the universe of the EPT, this excess energy is emitted in the form of a local wavelike phase quantum, denoted by a symbol ${}^{LW}\Phi_k^{x+1}$. So eq. (7) becomes: ${}^{NW}\Phi_k^x \rightsquigarrow {}^{EP}\Phi_k^{x+1} + {}^{LW}\Phi_k^{x+1}$.

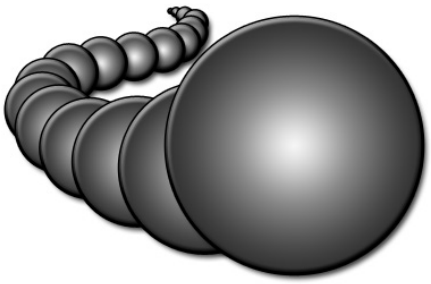

Figure 3: illustration of the stepwise motion of an electron. The balls are abstract representations of successive particlelike states of rest of the electron: in such a state of rest the electron has a definite spatiotemporal position and is devoid of motion. The wavelike states of motion (not depicted) exist in between the states of rest: the electron is then a matter wave spread out over space. Source of the figure: [5].

similar matter waves have been proposed in the 1920's by Erwin Schrödinger in his original formulation of his wave mechanics:

> *The point of view taken here, which was first published in a series of German papers, is that material points consist of, or are nothing but, wave-systems. (... ...) The charge of the electron is not concentrated in a point, but is spread out through the whole space, proportional to* $\psi\bar{\psi}$ [19].

In the framework of the EPT, the idea is then that in such an indivisible matter wave Φ an amount of energy E is spread out over space, with $\|\Phi\|^2 = E^2 = m_g^2$ for all rest-mass-having constituents like electrons, positrons, (anti)protons, etc. Another difference with Schrödinger's idea is then that it is not the case that these rest-mass-having constituents are *nothing but* wave-systems: due to this alternating between two states, all these rest-mass-having constituents are subdividable into *two* parts, one of which has thus a definite position regardless whether someone is watching or not. This also gives rise to a new approach to the dark energy problem. The principle idea is that the rest mass of protons gradually decreases, so that every time an alternation takes place the loss of rest mass is emitted as excess energy as in (7): this excess energy then creates the substance 'space'—the distance between objects then increases not because the objects move, but because more space is created in between them. So although the EPT has been developed from the assumption that there is a matter-antimatter gravitational repulsion, the approach to the dark energy problem has nothing to do with gravitational repulsion—the substantival constituents of space that are created from the individual processes *are* the dark energy.

5 Concluding remarks: correctness and completeness

Proceeding in the above way, the EPT has been developed in a finite Hegelian dialectic process; naturally, questions about correctness and completeness then arise. About that, Einstein, Podolsky and Rosen wrote the following in their famous EPR paper [20]:

> *In attempting to judge the success of a physical theory, we may ask ourselves two questions: (1) "Is the theory correct?" and (2) "Is the description given by the theory complete?" It is only in the case in which positive answers may be given to both of these questions, that the concepts of the theory may be said to be satisfactory.*

Currently, the EPT is *assumed* to be correct and complete: [3] and [4] contain an exposition on *how* the EPT is understood to be correct and complete. To give a proof/substantiation of this correctness and completeness is what further research in this direction is all about. The EPR paper gives guidance on how to proceed: the correctness of a theory, its 1:1 correspondence with physical reality, can be judged by the agreement of the predictions of the theory with observation; and a necessary and sufficient condition for completeness is that (i) *every* element of the physical reality must have a counterpart in the physical theory, and that (ii) *every* element of physical reality, predicted with certainty by the theory, must indeed exist.

Of course, the correctness of the EPT can be disproved by the results of the AEGIS project at CERN: if gravitation is found to be attraction only, then the EPT has been developed from a *falsum* and has to be discarded as incorrect. If, on the other hand, the existence of a matter-antimatter repulsion is experimentally confirmed, then no other theory can give a deeper explanation of this phenomenon than the EPT does: that would be a very strong motivation for further research on the correctness of the EPT. Anticipating this situation, the upcoming years work will be done to prove that the EPT satisfies the correspondence principle: that is an essential step in substantiating its correctness. The current state of affairs is that it is not understood how established theories, known to be correct in some area of application, emerge from the EPT; as remarked in [3] and [4], the main difficulty is that the EPT is formalized in an entirely different mathematical setting than GR and the SM – the difference is comparable to the difference between set theory and real calculus. The general approach to this problem of the correspondence principle has been set forth in [3] and, less elaborate, in [4]; it involves developing a concrete mathematical model of the EPT, and from there showing that GR and the SM emerge from an aggregation of individual processes described by the EPT. Concerning this correspondence principle, we can agree with Villata that his main equation for the motion of antimatter in the gravitational field of matter

$$\frac{\mathrm{d}^2\mathrm{x}^\lambda}{\mathrm{d}\tau^2} = +\frac{\mathrm{dx}^\mu}{\mathrm{d}\tau}\Gamma^\lambda_{\mu\nu}\frac{\mathrm{dx}^\nu}{\mathrm{d}\tau} \tag{8}$$

describes what would be observed at macroscopic scale in case of a repulsive gravity (2011, personal communication). So this is an *emergent* law of fundamental significance: a concrete mathematical model of the EPT must yield this equation at macroscopic scale.

Concerning completeness, some work has already been done: in [3] and [4], a variety of observed particles and processes has been formalized in the framework of the EPT:

- rest-mass-having particles like electrons, positrons, (anti)protons, (anti)neutrons, and particles without rest mass like photons and neutrinos;
- processes like a neutron gravitating towards earth, an electron moving in an electron shell, the formation of deuterium, the annihilation of a proton/antiproton pair, and the decay of a neutron.

These elements of physical reality have, thus, a counterpart in the theory. However, although this may add to the *substantiation* of a claim of completeness, it is insufficient as a *proof* thereof. To further substantiate that claim, the upcoming years the prediction of the EPT will be investigated that in individual processes *space* is formed as a substance – that is, the EPT predicts the existence of 'elements of physical reality' that constitute space itself. The idea is then to model this mechanism quantitatively, and to investigate whether this yields a solution to the dark energy problem in physical cosmology. However, additional results are needed before the claim that the EPT is complete can be considered *sufficiently* substantiated.

Acknowledgement This research has been facilitated by the Foundation Liberalitas (the Netherlands).

References

[1] Amsler, C. *et al.* (AEgIS collaboration): A new application of emulsions to measure the gravitational force on antihydrogen, *J. Instrum.* **8**(02), P02015 (2013)

[2] Debu, P. *et al.* (GBAR collaboration): GBAR. Gravitational behavior of antimatter in rest, *Hyperfine Interact.* **212**(1-3), 51-59 (2012)

[3] Cabbolet, M.J.T.F.: *Elementary Process Theory: axiomatic introduction and applications*, PhD thesis, Vrije Universiteit Brussel (2011)

[4] Cabbolet, M.J.T.F.: Elementary Process Theory: a Formal Axiomatic System With a Potential Application as a Foundational Framework for Physics Supporting Gravitational Repulsion of Matter and Antimatter, *Ann. Phys. (Berlin)*, **522**(10), 699-738 (2010)

[5] Cabbolet, M.J.T.F.: Addendum to the Elementary Process Theory, *Ann. Phys. (Berlin)*, **523**(12), 990-994 (2011)

[6] Hangst, J.S. *et al.* (ALPHA collaboration): Confinement of antihydrogen for 1,000 seconds, *Nature Physics* **7**, 558-564 (2011)

[7] Bondi H., *Rev. Mod. Phys.* **29**(3), 423-428 (1957)

[8] Morrison P., Gold T., On the gravitational interaction of matter and antimatter, Essay written for the Gravity Research Foundation 1957 Awards for Essays on Gravitation, in: Essays on Gravity: Nine winning essays of the annual award (1949-1958) of the Gravity Research Foundation (New Boston, N.H.: Gravity Research Foundation, 1958), pp. 45-50

[9] Morrison P., *Am. J. Phys.* **26**, 358-368 (1958)

[10] Hajdukovic D.S., *Astrophys. Space Sci.* **334**(2), 215-218 (2011)

[11] Benoit-Lévy A, Chardin G., *Astron. Astrophys.* **537**, A78 (2012)

[12] Drobychev, G. Yu. *et al.* (AEgIS collaboration): Proposal for the AEgIS experiment at the CERN antiproton decelerator. *CERN Technical Report SPSC-P-334* (2007)

[13] Kellerbauer, A. *et al.* (AEgIS collaboration): Proposed antimatter gravity measurement with an antihydrogen beam, *Nucl. Instr. and Meth. in Phys. Res.* B **266**, 351-356 (2008)

[14] Cabbolet, M.J.T.F.: Incompatibility of QED/QCD and repulsive gravity, and implications for some recent approaches to dark energy, *Astrophys. Space Sci.*, in press (2014)

[15] Villata, M.: CPT symmetry and antimatter gravity in general relativity, *EPL* **94**, 20001 (2011)

[16] Cabbolet, M.J.T.F.: Comment to a paper of M. Villata on antigravity, *Astrophys. Space Sci.* **337**, 5-7 (2012)

[17] Villata, M.: Reply to "Comment to a paper of M. Villata on antigravity", *Astrophys. Space Sci.* **337**, 15-17 (2012)

[18] Descartes, R.: *Discourse de la méthode*, I. Maire, Leiden (1637)

[19] Schrödinger, E.: An Undulatory Theory of the Mechanics of Atoms and Molecules, *Phys. Rev.* **28**(6), 1049-1070 (1926)

[20] Einstein A., Podolsky B., Rosen N.,: Can Quantum-Mechanical Description of Physical Reality Be Considered Complete? *Phys. Rev.* **47**(10), 777-780 (1935)