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Matvei Bronstein and quantum gravity: 70th anniversary of the unsolved problem

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Abstract. **Matvei Bronstein's 1935 work on quantum gravity, the first in-depth study of the problem, is analyzed in the context of the history of physics and the scientist's career. Bronstein's analysis of field measurability revealed "an essential difference between quantum electrodynamics and the quantum theory of the gravitational field" and showed that general relativity and quantum theory are fundamentally difficult to unify. Featured in the story are Planck, Einstein, Heisenberg, Pauli, Rosenfeld, Landau, and Bohr. The methodological uniqueness of the quantum gravity problem is discussed.**

1. Introduction

The subtitle of this article may perplex the reader. Indeed, what on earth happened in 1935? Had no one combined the words 'quantum' and 'gravity' before or written a formula containing all the three fundamental constants: c, G, and h (the speed of light, the gravitational constant, and the Planck constant)? Certainly, all this had been done, and the latter even preceded the former. However, it was in 1935 that the *problem of quantum gravity* was first comprehended in its depth. It was Matvei Bronstein who made this breakthrough in his doctoral dissertation defended at the Leningrad Physico-Technical Institute (LPTI) in November 1935; the results were published in two articles in 1936 [1, 2] and republished in part in [3].

Today, seventy years later, the real crux of the problem is especially evident since it is still unsolved and remains probably the most 'cursed' question of fundamental physics.

To better see the path that brought Bronstein to his work of 1935 and understand its meaning, we start with an overview of the historical background [1].

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2. Quantum gravity before 1935

The simplest and most tangible synonym of quantum gravity, the so-called *Planckian scales*, first emerged in Planck's article that dates back to 1900; it has no relation to quantum gravity, however. Nobody realized at that time that a new, quantum, era was about to begin in physics. Planck hoped that the newly proposed constant h (then denoted by the letter b) would be possible to integrate into the edifice of classical physics. He suggested new 'natural units of measure'

$$l_{\mathrm{Pl}} = \left(\frac{hG}{c^3}\right)^{1/2} \approx 10^{-33}\ \mathrm{cm}\,,$$

$$m_{\mathrm{Pl}} = \left(\frac{hc}{G}\right)^{1/2} \approx 10^{-5}\ \mathrm{g}\,, \quad t_{\mathrm{Pl}} = \left(\frac{hG}{c^5}\right)^{1/2} \approx 10^{-43}\ \mathrm{s}$$

with the sole 'practical' purpose that they 'retain their significance for all times and all cultures, even extraterrestrial and extrahuman ones" [5]. Such an exotic suggestion was based on a solid philosophy of the first pure theoretical physicist in which the ideal of classical physics is readily perceived. In Planck's view, a fundamental goal of physics was to liberate the physical world picture from the individuality of the creative mind, from any anthropomorphic element [5].

[1] More details can be found in [4].

Planck's strange quantities met with little sympathy. In 1922, they were 'disproved' by the famous experimental physicist P. Bridgman in his book *Dimensional Analysis* [6], whose philosophy of operationalism was distilled from the practice of physical measurements he mastered so well. He entered the history of physics by expanding the confines of the 'natural,' practically accessible pressure range that he extended from thousands to hundreds of thousands of atmospheres. These values were one hundred orders of magnitude below the Planck scales. It is easy to understand a 'convert to Bridgman's somewhat materialistic exposition' who would say there was no place for such values in physics; no wonder that Planck's 'natural units' looked ridiculous in the eyes of Bridgman. A length unit of 10^{-33} cm seemed so nonoperational that he did not care much about argumentation.

Such an impressive philosophical gap, which in addition has a quantitative scale, is a remarkable characteristic of the quantum gravity problem, even if neither Planck nor Bridgman talked about the theory of gravity as such.

Meanwhile, by the time Bridgman's book came out, the theory of gravity had undergone historic metamorphosis into the relativistic theory of gravity or general relativity (GR). Just a few months after GR had appeared, Einstein emphasized the necessity of unifying the new concept of gravity and the quantum theory. Having obtained the formula for the intensity of gravitational waves, he remarked: "Because of the intra-atomic movement of electrons, the atom must radiate not only electromagnetic but also gravitational energy, if only in minute amounts. Since, in reality, this cannot be the case in nature, then it appears that the quantum theory must modify not only Maxwell's electrodynamics but also the new theory of gravitation" [7] [2].

This short remark contains three important points. First, Einstein assigned a leading role to the quantum idea. Second, he implied parallelism between electrodynamics and gravity (in the 1920s, he turned this concept into the conviction that the two forces were closely related and set out on the path of the unified field theory, which led him nowhere). Finally, this remark shows that Einstein was a theorist of no less exalted thought than Planck; surely, his wording "in minute amounts" sounds too weak in this case.

Einstein made no quantitative estimates but evidently had in mind the famous problem of Rutherford's 'classical' atom collapse, where the electrons orbiting the nucleus should radiate and fall onto the nucleus. The loss of electromagnetic energy calculated by the formulas of Maxwell electrodynamics takes the extremely short time of $\sim 10^{-10}$ s to occur, whereas gravitational out-radiation calculated by Einstein's newly derived formulas would last $\sim 10^{30}$ years. Even the age of the universe, $\sim 10^{10}$ years, is insignificant compared with this time, although in 1916 such a phrase as 'age of the universe' made no sense in physics. Einstein's "this cannot be the case in nature" in fact related to the universe rather than to the atom. In the next year of 1917, Einstein demonstrated a way to treat the universe as a physical object. He attached little significance to the magnitude of the effect if it was to be rejected as contradicting his cosmological prerequisite, i.e., the static picture of the universe. In the eternal static universe, instability of atoms is unacceptable regardless of the magnitude of the effect.

After the discovery Hubble made in 1929, physicists for the first time obtained grounds on which to talk about the age of the universe as an experimentally measurable quantity. They could reject Einstein's static prerequisite for 'operational-measuring' reasons, but the thought of theorists flew higher than that. By historical coincidence, the article by Heisenberg and Pauli published in 1929, where the general scheme for quantization of the electromagnetic field was developed, optimistically stated that "quantization of the gravitational field, which appears to be necessary for some physical reasons, may be carried out without any new difficulties by means of a formalism wholly analogous to that applied here" [9, p. 3]. They referred to Einstein's aforementioned remark of 1916 and O Klein's statement of 1927 on the necessity of a unified description of gravitational and electromagnetic waves taking Planck's constant h into consideration. In other words, the analogy between gravity and electromagnetism was again implied.

Heisenberg and Pauli's optimistic confidence was apparently based on the idea that quantization should be applied to the equations of the weak gravitational field, or linearized equations of GR obtained by Einstein in 1916. Such an approach was employed in 1930 by Leon Rosenfeld (who worked under Pauli) to answer the question raised by Heisenberg [10]. The question was metaphysical rather than physical, that is, whether self-energy in quantum electrodynamics (QED) is infinite even in the absence of charges if the gravitational field of light is taken into account. Rosenfeld confirmed Heisenberg's supposition by showing the corresponding gravitational energy to be infinitely large, whence 'a new difficulty for the Heisenberg – Pauli quantum theory of wave fields emerged.' However, Rosenfeld did not explain why one should trust this new infinity inferred from the weak-field assumption.

Such was the rather poor state of quantum gravity by the time Bronstein interested in the problem. The general mood might be described as subdued optimism and summarized in the following way: *gravity should be quantized by using the same means as in electrodynamics, but these means must be properly developed to eliminate the infinities*. While the quantum theory of the electromagnetic field was indispensable to understand real phenomena in atomic and nuclear physics, the reasons for creating the quantum theory of gravity were merely some 'high-brow general considerations' not necessarily of interest to practical-minded physicists.

3. Semiconductors or quantum gravity?

Among the motives that led Bronstein to work on his dissertation on the quantum theory of gravity, one was quite practical and down-to-earth: there was no such thing as dissertations for a scientific degree in the USSR before 1934. The proletarian power abolished the old tsarist tables of ranks, including scientific ones. However, after the revolutionary fervor was pacified in the course of building Stalinism, the government decided to introduce the scientific degrees of Candidate and Doctor of Science (within two years starting from January 1934) "in order to stimulate research work and raise the skills of scientific and educational cadres." To make the new machinery workable, a certain number of degrees were conferred without defending the theses.

In this manner, Bronstein was given a candidate degree by the Scientific Council of LPTI (June 1935) for his work in astrophysics and invited to submit a doctoral dissertation on

[2] Einstein repeated this argument in [8].

'the theory of semiconductors.' Ya Frenkel, head of the Theoretical Department, wrote: "By now, he [Bronstein] has actually written his doctoral dissertation (on electronic semiconductors) and will defend it in the near future" [11]. The semiconductor studies carried out by Bronstein were equally highly valued by A Ioffe, director of LPTI [12, 13].

In such circumstances, it was not at all trivial to choose quite a different subject for the dissertation. Still less trivial was the new subject. As Bronstein explained to his colleague I Kikoin, a doctoral dissertation should contain 'long unintelligible formulas' and, in this respect, gravity obviously has an advantage compared with semiconductor physics. This joke illustrates the sense of humour that physicists retained even under the tough Soviet regime of the 1930s.

Bronstein appears to have been writing his dissertation during the summer months of 1935; his first article on quantum gravity dates from August [1]. The session at which he defended his thesis was held on November 22, 1935, with I Tamm and V Fock as the official reviewers. The surviving shorthand records of the session and personal reminiscences show that Bronstein just reported his recent work and attacked rather than defended when he disagreed with the arguments of the reviewers [14].

There is no archival evidence on how much the colleagues of Bronstein were surprised by the drastic thematic change of his research, from semiconductors to quantum gravity. In those days, the gap between these subjects was no smaller than it is today. In the mid-1930s, the theory of gravity was concerned only with celestial mechanics and cosmology. All hopes to have a generalized theory of gravity or Unified Field Theory for earthly microphysics were in the past, even though a few enthusiasts still remained, including Einstein. The Soviet physics showed itself to be maturely independent in that no prominent theorist in the country shared Einstein's passion of that time despite the huge respect to the great physicist and the admiration of the work he had done in the first quarter of the century.

Certainly, the area of theoretical physics was much narrower then. In the mid-1930s, Lev Landau explained that "theoretical physics, unlike experimental physics, is a small science open to perception in its entirety by any theorist" [15]. Insofar as mastering theoretical physics meant active work rather than mere passive understanding, it was as small for Bronstein as for Landau.

Bronstein started on the path to science in the circle of physics lovers at Kiev University under the leadership of P Tartakovskii. In January 1925, the then 18 year-old Bronstein submitted an article 'On a Consequence of the Light Quanta Hypothesis' to the *Journal of the Russian Physical and Chemical Society* (the forerunner of the Journal of Experimental and Theoretical Physics). Assuming the photon structure of X-rays, he obtained the dependence of the boundary of a continuous X-ray spectrum on the radiation angle and came to the conclusion that the discovery of this effect added another argument in favor of the quantum theory of light; "otherwise, some light will be shed on the applicability limits of the quantum theory to the X-ray range." It is worthwhile to remind ourselves that the very idea of photons was at that time rejected by Bohr himself, who changed his view only after the 1925 Bothe – Geiger experiments. Thus, young Bronstein plunged into the troubled depths of physical discussions. In the same 1925, Bronstein published another article on the subject in the then most reputable German journal *Zeitschrift fur Physik* [16].

In 1926, Bronstein entered Leningrad University and soon joined the so-called 'jazz-band', a cheerful group of gifted young physicists. The core of the group were 'the three musketeers': George Gamow, Dmitry Ivanenko, and Lev Landau. Bronstein had to play D'Artagnan. Life separated the three musketeers much farther than Alexandre Dumas could have imagined, but it was only death that cut short the friendship of Landau and Bronstein [17].

In his student years, Bronstein made an important contribution to the theory of stellar atmospheres in the form of the so-called Hopf – Bronstein relation [18]. E Milne, one of the founders of the field, recommended Bronstein's paper for publication in the *Monthly Notices of the Royal Astronomical Society* [19].

In 1931, *Uspekhi Fizicheskikh Nauk* published a detailed survey by Bronstein entitled "The Modern State of Relativistic Cosmology" (that is, the state after the Hubble law, the first observational fact of physical cosmology was discovered in 1929) [19]. It was the first review of cosmology in the USSR.

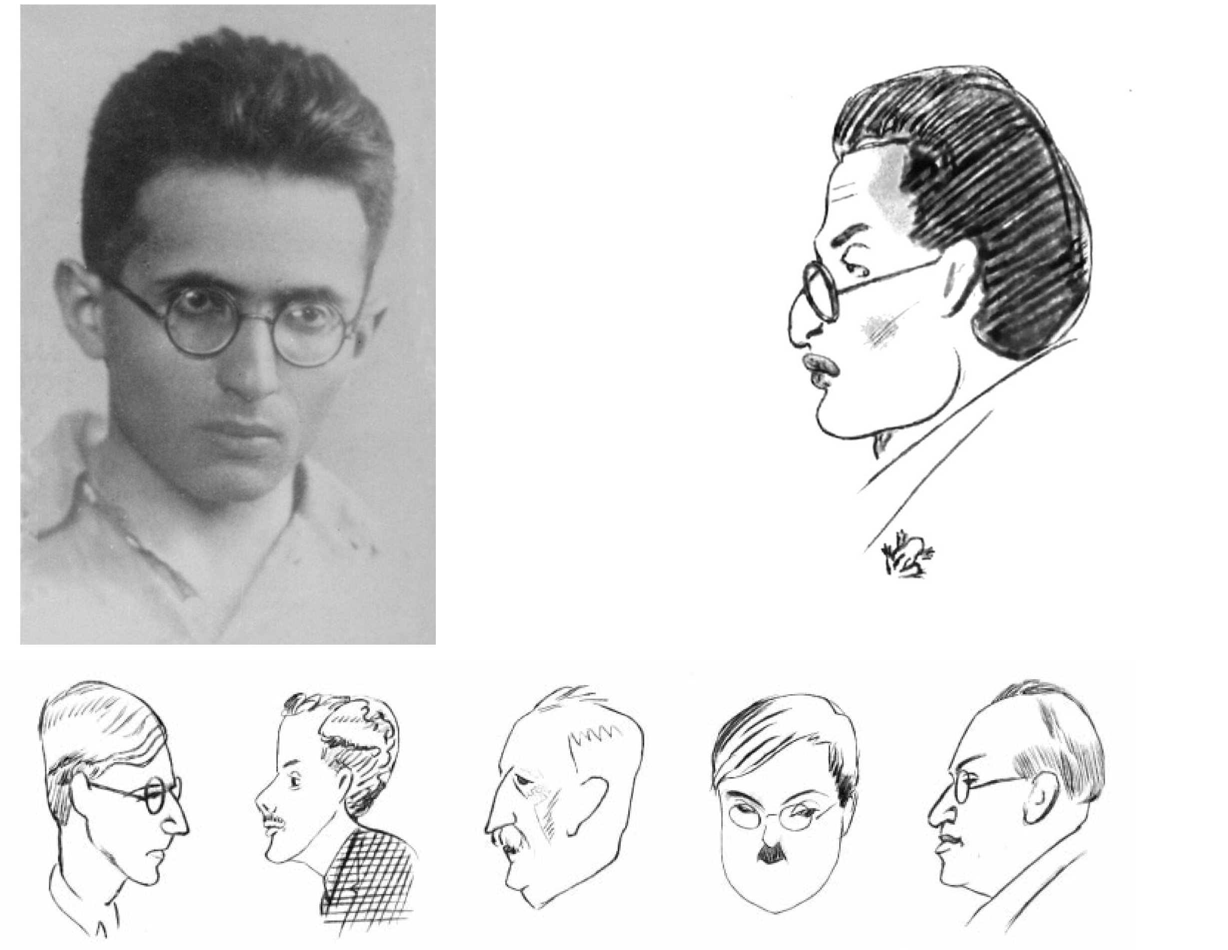
The young theorist felt at home on different floors of the physics building. This feeling emerges in Bronstein's reviews of conferences he wrote for scientific journals and popular science magazines [20].

Of special relevance was the conference on theoretical physics held in Kharkov in May 1934 that showed that Soviet theoretical physics as a whole and its Kharkov school in particular held an important place in world physics. The participants in the conference included, besides leading theorists from Moscow and Leningrad, Niels Bohr (for whom it was the first visit to the USSR) and his close associate Leon Rosenfeld. In Bronstein's words, "the conference was a kind of business meeting rather than a congress to demonstrate achievements"; he limited his account to ideas that could be of interest not only to theorists but also to physicists working in other fields [21, p. 516].

The participants discussed various 'business problems' of importance for physics at that time. The most dramatic reports were made by I Tamm. One of his works (in co-authorship with S Al'tshuler) predicted the neutron magnetic moment and was challenged by Bohr, who believed it was incompatible with the zero electric charge of the neutron. Here, the great Bohr was wrong.

As regards his other work on the hypothesis of pair forces in the nucleus, Tamm knew himself that he was 'wrong' but nevertheless reported the negative result of his calculations. Today, we understand that this work was an important step to the Yukawa meson and that Tamm regarded his 'wrong' idea as his strongest one. Here is how Bronstein described this dramatic episode: "Tamm told how, based on the Fermi theory of beta-decay, one can calculate the interaction between a proton and a neutron. It is called an exchange interaction during which a proton and a neutron switch roles as they exchange electron and neutrino or positron and neutrino. In his calculations, Tamm assumes that both the proton and the neutron are stable. As a result, he comes to the conclusion that the interaction is too weak to explain the binding of proton and neutron in the nucleus. Tamm's paper provoked an animated discussion. His methods of calculation were criticized by Landau; opinions on the issue differed" [21, p. 518]. [3]

[3] Thus, it is clear that the term "Tamm – Ivanenko forces" does not reflect historical reality, contrary to the opinion of S Gershtein [22] and in accordance with the testimony of E Feinberg [23] (see [24] for details).



G Gamow, P Dirac, A Ioffe, V Fock , Ya Frenkel

Figure 1. The early 1930s. Bronstein and some participants in the 1933 All-Union Conference on Nuclear Physics (drawings by N Mamontov from Bronstein's account of the conference). Bronstein is said to have had the picture of a frog on his arm-band that he wore as a secretary for the conference. The picture was apparently prompted by a German phrase then popular with theorists: "Jetzt kommt der Moment, wo der Frosch ins Wasser springt" (Here comes the moment when the frog jumps into the water). Physicists of that time anticipated some radically new idea jumping out of the troubled water to help in comprehending the microworld.

Bronstein combined interest in topical problems and a broad view on the general architecture of the edifice of physics then under construction. It was he who introduced the currently well-known *cGh*-plan of this edifice or "Relations of Physical Theories to Each Other and to the Cosmological Theory" as he titled a section in his 1933 article [25], where he schematically ranked the existing and anticipated theories according to their applicability taking the fundamental constants *c*, *G*, and *h* into account. At that time, physics was waiting for a 'relativistic quantum theory' or *ch*-theory. But Bronstein looked farther than that: "After the relativistic quantum theory is created, the task will be to develop the next part of our scheme, that is to unify quantum theory (with its constant *h*), special relativity (with constant *c*), and the theory of gravitation (with its *G*) into a single theory."

It those days, astrophysics already had a focus of its own for the *ch*-theory: white dwarfs. There was also a vague hope first expressed by Bohr in the late 1920s that the relativistic quantum theory would be able to account for the source of stellar energy. For all that, gravity remained an external factor, like the walls of a container. Bronstein realized the need for the *cGh*-theory in astrophysics and explained it in a very simple way: if the sun were compressed to nuclear density, its radius would be comparable with the gravitational radius [26].

In Bronstein's view, however, cosmology should be the main task for the *cGh*-theory: "...a solution to the cosmological problem requires first to create a unified theory of electromagnetism, gravity, and quanta." [25, p. 28]. The addition of fundamental forces unknown in 1933 to electromagnetism would make quite a modern, even if pretty banal, statement. But in 1933, such an understanding of the cosmological problem was new.

Because Bronstein made calculations in both astrophysics and cosmology, these were not merely 'general considerations' for him but were too general for a man with imagination and enthusiasm to be absorbed in writing 'long unintelligible formulas' of quantum gravity, be it for the sake of his own dissertation or for world science.

Indeed, Bronstein as a theorist had a more specific reason for investigating not only in the breadth but also in the depth of the problem. History preserves some evidence, e.g., a photo in the newspaper *Khar'kovskii rabochii* [*Kharkov worker*] of May 20, 1934, published to illustrate information about the

Figure 2. The photo published in the newspaper *Khar'kovskii rabochii* (*Kharkov worker*) on May 20, 1934 among materials on the conference on theoretical physics. Left to right: Landau, Bohr, Rosenfeld, and Bronstein.

aforementioned conference on theoretical physics; the photo features Landau, Bohr, Rosenfeld, and Bronstein sitting at a round table and conversing.

They did have a common topic for the conversation, it being the subject of their articles. Nothing is said about this subject in Bronstein's review of the conference published in *Uspekhi Fizicheskikh Nauk* in 1934 because his aim was to dwell on matters interesting 'not only for theorists.' Meanwhile, the 'common topic' of the four researchers, the coming relativistic quantum theory, was so theoretical that it could be of interest only to a very few. In modern vocabulary, the term should be substituted by 'quantum electrodynamics,' but such a substitution would not give the feeling of the dramatic changes in the mentality of microphysics theorists experienced in the early 1930s.

The quantum theory of the electromagnetic field was regarded as an important component of the relativistic quantum theory, but not the sole one. In the late 1920s, nobody thought about forces of the microworld other than electromagnetism, and what was known about electromagnetism could not explain how the nucleus confined its positive charge. In that pre-neutron epoch, nuclei were believed to be composed of protons and 'intranuclear' electrons. The uncertainty relation and the small size of the nucleus suggested a high relativistic speed of 'intranuclear' electrons. At the same time, before the positron was discovered, Dirac's *ch*-equation was considered to be burdened with a most serious 'plus – minus' problem. Therefore, theorists hoped that the coming relativistic quantum theory would solve a cluster of puzzling problems, such as infinities, nuclear spins, and continuous spectra of beta-decay.

They awaited the revolutionary reconstruction of physics comparable with relativistic and quantum physics. Niels Bohr, the chief inspirer of the revolutionary mood, was even prepared to sacrifice the energy conservation law for the sake of successful reconstruction. This attitude was shared by Landau, who had met Bohr in 1930 and at once adopted him as his sole teacher.

Landau soon made a step from general hope to specific calculations. In January 1931, he and R Peierls arrived at a revolutionary conclusion, which is that the most natural problem of the 'relativistic quantum theory' — the quantum theory of the electromagnetic field — is unsolvable because of the defectiveness of the basic 'field at a point' notion. It was the beginning of the story, the development of which was to be discussed by the four theorists gathered at the round table in Kharkov in May 1934.

4. The problem of *ch*-measurability. Is the uncertainty principle too certain?

Quantum mechanics and its uncertainty principle (1927) brought some limitations on the applicability of concepts inherited from classical physics. These '*h*-limitations' concerned joint measurability of certain pairs of variables, such as coordinate and momentum: $\Delta x \Delta p > h$, but at the same time left open the possibility of obtaining an arbitrarily accurate value of either variable. This gave reason to apply these variables in the *h*-theory.

Soon after the meaning of *h*-limitations was understood, the question arose as to the character of quantum constraints imposed when relativity was taken into account, or *ch*-limitations. Thought experiments (such as the 'Heisenberg microscope') provided arbitrarily accurate results only if the *c*-theory was ignored. However, a most important physical object, the electromagnetic field, was relativistic even before the theory of relativity was created, because the Maxwell equations contained the constant *c*.

An article published by Landau and Peierls in 1931 was entitled "Extension of the uncertainty principle to the relativistic quantum theory." After having considered thought experiments in the *ch*-domain, the authors arrived at the conclusion that not only were combined pair uncertainties inevitable but so were individual ones. The physics of the new limitation was related to the fact that measurement of 'the field at a point' required maximally accurate measurement of the position of the test charge possible only at a sufficiently large momentum (therefore, small wave length) of the measuring particle. In this case, however, the recoil momentum of the test charge produced an additional electromagnetic field that distorted the field being measured. Hence, the conclusion that the notion of 'field at a point' is undefinable. Based on this inference, the authors questioned the then accepted approach to quantization of the electromagnetic field and predicted that "the correct relativistic quantum theory to come will contain neither physical quantities nor measurements in the sense of wave mechanics." [27].

This paper written in Zurich (in January 1931) manifested the great influence of Bohr by referring to his articles and oral discussions in Copenhagen. Evidently, the authors were sure they were developing Bohr's ideas, in particular by theoretically substantiating his hypothesis about energy non-conservation in *ch*-physics. However, when Landau and Peierls came to Copenhagen to see Bohr in February 1931, he rejected their conclusion. The situation is depicted in a drawing by G Gamow and in recollections by Leon Rosenfeld, then Bohr's assistant:

"When I arrived at the institute on the last day of February 1931, for my annual stay, the first person I saw was Gamow. As I asked him about the news, he replied in his own picturesque way by showing me a neat pen drawing he had just made. It represented Landau, tightly bound to a chair and gagged, while Bohr, standing before him with upraised forefinger, was saying 'Bitte, bitte. Landau, muss ich nur ein Wort sagen!' ('Please, please, Landau, may I just say a word?') I learned that Landau and Peierls had just come a few days before with some new paper of theirs which they wanted to

Figure 3. Landau and Bohr discussing measurability of field, 1931.

show Bohr, 'but' (Gamow added airily) 'he does not seem to agree — and this is the kind of discussion which has been going on all the time.' Peierls had left the day before, 'in a state of complete exhaustion,' Gamow said. Landau stayed for a few weeks longer, and I had the opportunity of ascertaining that Gamow's representation of the situation was only exaggerated to the extent usually conceded to artistic fantasy." [28].

Nevertheless, Landau held to his opinion and the paper was published.

For two years, high-brow theorists regarded this paper as very important, although it closed the old direction of thought rather than opening a new one — various paradoxical problems in 'paranuclear' physics turned out to have a common deep root. This opinion was shared by Bronstein, who in his very first article had mentioned the possibility that experiment would demonstrate "applicability limits of the theory"; here, the applicability limits came from 'theoretical experiments.'

Considerations of observability and measurability played an important role in the analysis of the simultaneity notion in the theory of relativity. In quantum mechanics, such consideration had become an ordinary tool and even commonplace. In his 1931 review of Dirac's book, [4] Bronstein reproached the author for the underestimation of quantum – relativistic problems and quoted witty Pauli's definition: "Die Observable ist eine Groesse, die man nicht messen kann" (The observable is a variable that is unmeasurable) and suggested that "The uncertainty principle of ordinary quantum mechanics is too certain for the relativistic quantum theory" [30].

Meanwhile, Bohr worked together with Rosenfeld to transform his oral objections to Landau into a well-grounded text to defend quantum uncertainty from the 'relativistic threat'. The work took two years to complete and resulted in a lengthy article, "famously obscure and difficult" in the words of the well-known physicist and historian of science S Schweber [31]. Indeed, this super-theoretical article is frightening both in its volume (more than 60 pages) and the abundance of laboratory terminology used to describe thought experiments, such as test bodies of arbitrary mass and charge able to penetrate each other, countless small mirrors at every part of the test body, rigid bindings to a hard frame, flexible magnetic threads, etc. [32, 33, pp. 139 – 142].

However, the main idea of the defense is clearly formulated at the very first pages of the article, indicating the weak point of Landau – Peierls's reasoning: to measure the field, they used point-like charges as test bodies, the idealization taken from the quantum mechanics of atomic phenomena. But the notion of the point-like charge is illegitimate in classical field theory. On the other hand, classical physics allows measuring an average field in a finite space region with any desired accuracy. If such measurement is impossible for some *ch*-reason, a certain characteristic length should exist that limits the size of the space region where measurement is still possible. However, the quantum theory of the electromagnetic field is based only on two universal constants, c and h, that could produce no characteristic length. Values of charges and masses of elementary particles are merely external characteristics not integrated into the edifice of the theory [33, p. 121].

For all the power of dimensionality considerations, they are no more than 'theoretical physics for the poor (experimenters)' because they can yield a result but cannot account for it. Meanwhile, Bohr sought to obtain a comprehensive explanation, and the essence of his paper was to the effect that a measuring instrument must be macroscopic (i.e., classical) in principle. The physical idea underlying his laboratory technique can be described as follows: if a field is to be measured with a desired accuracy, the test body must be chosen such as to have a relatively large mass in order that the recoil momentum does not produce too large a field. Thus: "...as regards the measurability problem, the quantum field theory is a controversy-free idealization insofar as it permits abstraction from all constraints imposed by the atomistic structure of field sources and measuring devices" [33, p. 162].

If Bohr's intention was to make Landau change his mind, he did not succeed because Landau never recognized that his work with Peierls was erroneous. But Bronstein not only understood and accepted Bohr and Rosenfeld's result but also seemed to comprehend it even better than the authors. This follows from Bronstein's short note submitted to the *Doklady Akademii Nauk* in January 1934 [34]. In this three-page presentation, instead of the sixty pages written by Bohr and Rosenfeld, Bronsteinimproved the logic of their thought experiments. The line of reasoning followed by Bronstein was more consistent with the tentative character of thought experiments and more explicitly brought out the physical essence of Bohr's conclusion of the 'nonfatal' nature of *ch*-limitations for electrodynamics: a thought experimenter needed unlimited freedom to choose the charge and the mass of the test body. The general conclusion remained the same but Bronstein emphasized that potentialities of any theory must correspond to those of nature. "The impossibility, in principle, to measure, with an arbitrary accuracy, a field in the coming relativistic quantum theory will be essentially a consequence of the atomism of matter, i.e., the impossibility, in principle, to infinitely increase [charge density]" [34, p. 389].

[4] The book was published in Russian in 1932 [29].

Bronstein's note had already been published when a newsman took photo of the four physicists at the round table in Kharkov in May 1934. It is very likely that the common *ch*-topic was not central to their discussion. The situation radically changed after 1931 when Landau put the *ch*-problem point-blank. There was no longer a need to cut the Gordian knot of quantum – relativistic problems. Most of them had been solved by that time by experimenters. The neutron, positron, and neutrino were within a few months integrated into the physical world picture; as a result, a number of former problems turned out to be a triumphant confirmation of theoretical propositions. In light of present knowledge, the solution to a number of puzzling problems achieved at those times may seem rather prosaic, but physicists of that period thought differently. For them, the picture of the microworld changed drastically; suffice it to say that they had to do with four times the number of elementary particles and antiparticles than they had before (eight instead of two). In that situation, gravity appeared to have little relevance to microphysics. But, strange as it may seem, it eventually proved to be part and parcel to the *history* of microphysics.

5. Gravity and microphysics in the 1930s

The neutrino had the most ambiguous status of all the newly obtained particles, with its direct experimental observation being a matter of the remote future. Bohr's hypothesis of nonconservation of energy in the 'relativistic quantum theory' successfully competed against the neutrino hypothesis suggested by Pauli to explain the continuous spectrum of beta-electrons. The work by Landau on the mass limit of a star composed of a Fermi gas (1932), which is now considered in the context of the theory of white dwarfs and black holes, was viewed differently at those times. Landau himself believed that he substantiated the existence of 'pathological' regions in stars that required the *ch*-theory to be described and, in accordance with Bohr's idea, generated stellar radiation energy from 'nothing.' "Following the beautiful idea of professor N Bohr, one may think that stellar radiation is due to a mere violation of the law of energy conservation that does not hold, as was first noticed by Bohr, in the relativistic quantum theory where the laws of ordinary quantum mechanics fail (as confirmed by experiments on the continuous spectrum of electrons in beta-decay and ensues from theoretical considerations [27]). We expect all this to be manifest when matter density comes to be so large that atomic nuclei get in close contact to give rise to a single giant nucleus" [35].

In the same frame of mind, in his paper "On the Expanding Universe" (1933), Bronstein suggested a cosmological model with which to realize Bohr's hypothesis; the nonconservation of energy was effectively taken into consideration in the equations of GR in the form of a time-dependent cosmological lambda-term. Einstein's theory of gravity was thus brought in touch with microphysics and actually invalidated the Bohr's hypothesis. The supplementary note to Bronstein's paper dated 13 January 1933 read as follows: "Landau drew my attention to the fact that the validity of the gravitational equations of Einstein's theory for empty space surrounding a material body is incompatible with the nonconservation of its mass. This inference is strictly verified for the solution of Schwarzschild (spherical symmetry); physically, it is related to the fact that Einstein's equations of gravitation allow only transverse but not longitudinal gravitational waves..." [36].

In other words, no matter how exotic the physics of the nucleus (or the 'pathological region' of a star) might be, the laws of GR (far from any exoticism) forbid the mass – energy variability.

As soon as Bohr came to know this simple consideration (from Gamov's letter), he replied to the effect that 'so much the worse for gravity,' namely, "I fully agree that a renunciation of energy conservation will bring with it equally sweeping consequences for Einstein's theory of gravitation as a possible renunciation of conservation of charge would have for Maxwell's theory." And he blurted out right away his own quantum-relativistic news: "In the course of the autumn, Rosenfeld and I have succeeded ... in verifying the complete correspondence between the basis of the formalism of quantum electrodynamics and the measurability of the electromagnetic field quantities. I hope it will be a comfort for Landau and Peierls that the stupidities they have committed in this respect are no worse than those which we all, including Heisenberg and Pauli, have been guilty of in this controversial subject" [37].

In 1934, in connection with the same remark from Landau, Bohr still desperately asked: "Shall we necessarily demand that all these gravitational effects be as closely associated with atomic particles as electrical charges are with electrons?" [38]. But by this time, the idea of the neutrino was widely accepted in physics, supported by both experimental findings and Fermi's theory of beta-decay. An evidence is I Tamm's work on pair nuclear forces. One week before the conference in Kharkov opened, Tamm wrote to Dirac: "What do you think of this Fermi theory? I have some distaste for the idea of the neutrino, but at present I see no other way to overcome the difficulties. Enclosed please find a short note on some corollaries from Fermi's theory. Would you kindly submit it to *Nature* if you find it interesting enough" [39].

A modern physicist may feel awkward that the great Bohr so insistently tried to discredit the energy conservation law or be disappointed at the 'childish' argument of the great Landau (because of ridiculously small gravity effects in microphysics). But the embarrassment turns to sympathy when one comes to know that the great Pauli (who never believed in the nonconservation of energy and instead invented a new neutral particle *ad hoc*) described Landau's gravitational argument as an important achievement in a lecture delivered during his stay in the USSR at the end of 1937 (in the published lecture, this achievement was attributed to Einstein, not Landau, probably because Landau had been arrested by that time) [38].

To sum up, the score in the match between Bohr and Landau was 1 to 1 to the benefit of science after Bohr had neutralized the radicalism of Landau's inference with respect to the *ch*-theory and Landau 'rendered harmless' Bohr's radical theory of nonconservation of energy with the aid of the *cG*-theory or nonquantum theory of gravity. [5]

Bronstein appears to have been motivated to address the quantum gravity problem by the outcome of the first period of this match. Also important was the fact that gravity was in Bronstein's field of vision, as it was in Landau's, who displayed his interest in the second round.

[5] Landau most likely believed that the score was actually 1.5 to 0.5 in his favor; he did not disprove Bohr's reasoning but considered his thought measurements too abstract and unrealizable in practice. Peierls was of the same opinion (see [41]).

6. "...An essential difference between quantum electrodynamics and the quantum theory of the gravitational field"

It seems reasonable to associate the origin of the problem with a short note by Bronstein published in 1934 where he showed that to measure electromagnetic field, Bohrs thought experimenter must be able to set the arbitrary charge and mass densities of the test body. Bronstein could notice that gravity gives no such freedom for two reasons. First, the gravitational charge and mass are the same. Second, when arbitrarily increasing the density of such a body, the observer would inevitably encounter the gravitational radius and would therefore lose the sight of the test body. Hence, the logic of the Bohr – Rosenfeld defense fails.

The limitation of the Bohr – Rosenfeld argumentation is even more apparent if their idea that the universal constants of quantum electrodynamics, c and h, produce no characteristic length is extended to gravity. The theory of gravity involves three constants, c, G, and h, whose combination $l_{\rm Pl} = (hG/c^3)^{1/2} = 10^{-33}$ cm gives the Planck length. However, there is no evidence in Bronstein's writings that he was aware of this simple argument, nor did any of the theorists appear to have mentioned Planckian values until the mid-1950s. (By strange coincidence, the book by Bridgman [42] translated into Russian and published in 1934 where the Planckian values were mentioned — and renounced — was edited by S I Vavilov, director of the Physical Institute where Bronstein worked as a researcher.)

True, the dimensional argument does not provide as strong a motivation to pose the *cGh*-problem as the difference between the charge freedom in electrodynamics and gravity, the source of the real problem.

Before addressing this problem, Bronstein constructed a quantum theory of the weak gravitational field by solving two problems natural in this approximation and required by the correspondence principle: emission of gravitational waves and Newton's law of gravity. Representing gravitational interaction of material bodies via "an intermediate agent — gravitational quanta," Bronstein obtained, from the *cGh*-theory of the weak field, Einstein's *cG*-formula of gravitational radiation in the nonquantum limit and Newton's *G*-law of universal gravitation in the classical limit.

The solution of these problems occupied the major part of Bronstein's theses, and the results, even if expected, were absolutely necessary to seriously consider the very possibility of quantizing gravity. In connection with this part of the dissertation, V A Fock, who spoke at the meeting where it was presented, said: "This work of Matvei Petrovich is the first one devoted to quantization of gravitational waves in which final physical results have been obtained. Rosenfeld, who worked out the same problem, reported only general mathematical results... The approximation considered by Matvei Petrovich (weak-field approximation — *G E G*) raises no doubt. The result would be the same even if Einstein's theory turned out to be wrong" [43, p. 317].

However, Bronstein was perfectly aware that the main physical problems requiring quantum gravity in order to be solved (the final states of stars and the initial state of the Universe) equally required a strong-field treatment. The only way to somehow try to explore the strong-field case was the analysis of measurability. Landau and Peierls suggested this method to deal with the formal problem of infinity in the *ch*-theory in a physically meaningful way. Bohr and Rosenfeld further developed and modified it along the same physical, but not formal, line. Bronstein applied this approach to the *cGh*-theory.

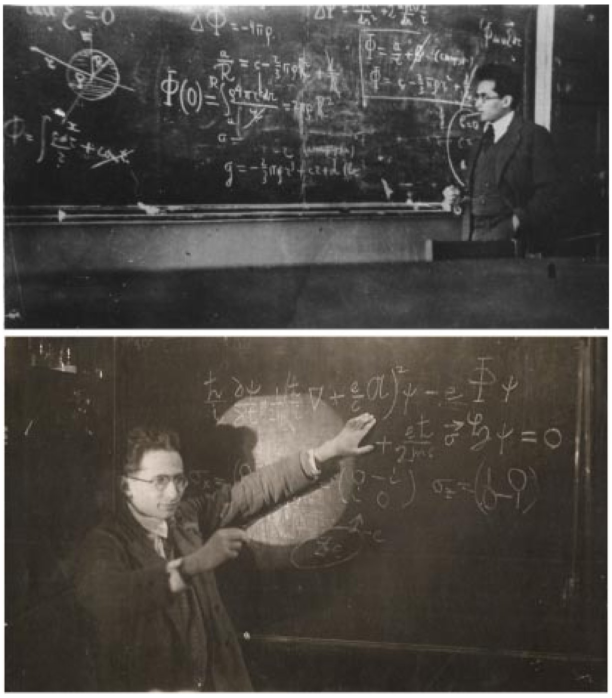


Figure 4. M P Bronstein reading a lecture on the theory of gravity and quantum theory.

Bronstein treated the measurability problem in a separate paragraph ("Let us make some thought experimentation!") in the first of the two papers on quantum gravity (August 1935 [1]); in the second one (December 1935), he went on with the analysis and carried it through to achieve a definitive conclusion.

'A device' for measuring a gravitational field (with the role of the field strength played by the Christoffel symbol [00,1], or Γ^1_{00} in modern notation) is governed by equations of GR in the weak-field approximation ($g_{mn} = \varepsilon_{mn} + h_{mn}$, $h_{mn} \ll 1$). The equation of motion for the test body (the equation for a geodesic) has the form

$$\frac{\partial^2}{\partial t^2}\, x = \Gamma^1_{00} = \frac{\partial}{\partial t}\, h_{01} - \frac{1}{2}\,\frac{\partial}{\partial x}\, h_{00}\,.$$

According to Bohr and Rosenfeld, to measure the value of Γ averaged over the volume V and time T, one uses a test body of volume V (and mass ρV) whose momentum is measured in the beginning and in the end of the time interval T. If the duration of measurement is Δt ($\ll T$) and Δx is the coordinate uncertainty, then the uncertainty Δp is the sum of the usual quantum-mechanical uncertainty $h/\Delta x$ and the gravitational field uncertainty created by the recoil of the test body during the measurement (the recoil field being given by Einstein's equation of gravity $\Box h_{01} = G\rho v_x$).

By adding constraints on the parameters of the measuring procedure, $\Delta x \ll V^{1/3}$ (implied by the meaning of measuring the average over V) and $\Delta x < c\Delta t$ (relativistic constraint), Bronstein obtained two boundaries from below for the uncertainty $\Delta\Gamma$ of the field being measured:

$$\frac{h}{\rho\, T V^{4/3}} \quad \text{and} \quad \frac{h^{2/3} G^{1/3}}{c^{1/3} \rho^{1/3} V^{2/3} T}\,.$$

He concluded: "Of these two boundaries for the case of light test bodies ($\rho V < (hc/G)^{1/2}$, i.e., smaller than 0.01 mg), the former is the only essential one. The latter boundary is essential for heavier test bodies. Evidently, a heavy test body should be recommended for the most accurate possible measurement [00,1]; this means that theoretically only the second boundary is of importance. Finally, we have

$$\Delta[00,\,1] > \frac{h^{2/3}G^{1/3}}{c^{1/3}\rho^{1/3}V^{2/3}T}\,.$$

Thus, it is clear that in a region where all h_{mn} are small compared with 1 (this is what is meant by 'weak' in the title of this work), the accuracy of gravitational measurements can be made arbitrarily high: because approximate linearized equations are applicable in this region and the superposition principle is valid, there is always a possibility to have a test body of arbitrarily large density ρ. We therefore conclude that it is possible to construct a consistent quantum theory of gravity in the framework of the special theory of relativity (i.e., when the space–time continuum is 'Euclidean'); such an attempt is made in this work. Matters are different, however, in the realm of the theory of general relativity, where deviations from 'Euclidean conditions' may be arbitrarily large. The thing is, the gravitational radius of the test body ($G\rho V/c^2$) used in the measurements should by no means be larger than its linear dimensions ($V^{1/3}$); hence, the upper boundary for its density ($\rho < c^2/GV^{2/3}$). Thus, the possibilities for measurements in this region are even more restricted than follows from the quantum-mechanical commutation relations. It appears hardly possible to extend the quantum theory of gravity to this region without profound modification of classical notions" [1, pp. 149, 150].

Figure 5. Friendly jest showing how Bronstein saw the socialist planning of science (all-union conferences were held to discuss the topic): "Any plan is a forecast." However, he predicted the theory of quantum gravity without making use of tarot cards, by sheer force of scientific logic.

The denominator in the formula for $\Delta\Gamma$ contains the volume V and the averaging time τ, but they can be used to reduce the minimum uncertainty only by increasing V and T, that is, by expanding the region of averaging, i.e., by disregarding localization of the measurement, which should be point-like in the limit.

We note the 'accidental' appearance of the Planckian mass scale, "$(hc/G)^{1/2}$, i.e., smaller than 0.01 mg" and the cautious general conclusion: "hardly possible."

Three months after the paper was submitted for publication, Bronstein defended his thesis. The unanimous verdict of Fock and Tamm, the official reviewers, was "deserves" (the scientific degree). More interesting, however, was a disagreement between them and the dissertator, briefly (and probably incompletely) recorded in the minutes of the meeting [43, p. 317).

Fock: "Of interest here is the analogy between gravitational and electromagnetic waves. This analogy, interesting in itself from the physical standpoint, made it possible to use the apparatus of electrodynamics. Einstein's equations are nonlinear ones... There is yet no nonlinear theory in electrodynamics, and the generalization concerning it is still in the bud. The work of Matvei Petrovich [Bronstein] is of value in that it may shed light on the relationship between linear and nonlinear theories. As regards measurability of the gravitational field, there is again an analogy with the situation in electrodynamics. Therefore, the introduction of the gravitational radius raises the same objections as in electrodynamics. The results obtained by Matvei Petrovich are beyond any doubt, and I have nothing to do but wind up."

However, Bronstein challenged this view: "For me, the analogy between the nonlinear theory of gravity and nonlinear electrodynamics, such as the Born–Infeld theory, is debatable. Nonlinear electrodynamics is actually unitary, while the general theory of relativity is not. I don't think any important corollaries can be deduced from the comparison of the present theory and the general theory of relativity."

In the vocabulary of those times, the term 'unitary' was applied to a field theory in which a 'particle' was a specific field configuration and its mass stood for the energy of this field. The standard electrodynamics was regarded as dualistic because its notions of field and particle were independent (see, e.g., [44]). It was hoped that nonlinear electrodynamics would be instrumental in the solution to the problem of the electron's infinite self-energy, and its concrete variant, the Born–Infeld theory, was based on the Lagrangian that was not derived from any profound physical considerations but was 'hand-made' such that the infinities be avoided even at the classical level: $L_{\rm BI} = \varepsilon^{-1}(1 + \varepsilon L_{\rm M})^{1/2}$, where $L_{\rm M}$ is the usual Maxwell Lagrangian and ε is a small constant (needed to obtain classical electrodynamics in the linear approximation).

It is therefore difficult to agree with Fock's analogy between the electron radius in the Born–Infeld theory (as a characteristic distance at which the field behavior begins to deviate from the Coulomb one) and the gravitational radius associated with the fundamental physical fact of equality between gravitational and inert masses or with the theoretical expression of this fact, the equivalence principle.

Although the very notion of gravitational radius was introduced to physics only in conjunction with the Schwarzschild solution and Riemannian geometry of GR, the phenomenon of the black hole was known even to Laplace as early as 1798; therefore, it was even then possible to speak about a gravitational radius to which a body should be compressed to prevent its light from escaping, i.e., to have the escape velocity equal the speed of light (see, e.g., [45]). The physics of this phenomenon is determined by Newton's law of gravitation (it would be impossible to 'run away' to infinity if the force of gravity decreased, e.g., according to the law $1/r$). The forerunner of this universal phenomenon, the fact that the escape velocity is independent of the mass of a 'spacecraft,' was discovered by Galileo, who found that the motion of a body under gravity is independent of the mass of the (test) body. This fact is certainly very far from the notion of the 'event horizon' and other geometric subtleties, but the physical essence of Einstein's geometrization of gravity is rooted in Galileo's discovery.

Bronstein displayed the common sense of a theorist in the concluding comments on the criticism of his theses. Frenkel, speaking about "the brilliant work" of the dissertator, remarked that "when constructing a quantum theory of gravity, one should describe and establish the relationship between this theory and electrodynamics. Matvei Petrovich did not take this into account, although it would be desirable to do so in a work like this." Bronstein's opinion was that "this advice is dangerously misleading. As is known, Einstein wallowed in failure trying to establish the relationship between these theories." The last question was asked by V K Frederiks: "What influence can the physical effect of gravitational wave emission have?" The theoretical experimenter answered that this effect would change the rotation of a binary star.

It follows from the above that Bronstein's colleagues who opposed his thesis all agreed on the analogy between gravity and electromagnetism and did not appreciate the fundamental difference between the two indicated by the dissertator. This probably made him reemphasize his view in the second (more comprehensive) paper published in *Zhurnal Eksperimental'noy i Teoreticheskoy Fiziki* (*Journal of Experimental and Theoretical Physics*), dated December 14, 1935.

"Until now, all considerations have on the whole paralleled those in quantum electrodynamics; but here we must take into account a fact that exposes an essential difference between quantum electrodynamics and the quantum theory of the gravitational field. The difference is due to the absence of any consideration limiting the increase of density ρ in formal quantum electrodynamics that disregards the structure of an elementary charge. Components of the electric field can be measured with an arbitrarily high accuracy provided the charge density is sufficiently large. In nature, there are probably some fundamental limits on the electric charge density (no more than one elementary charge per volume of linear dimensions comparable with the length of the classical electron radius), but formal quantum electrodynamics does not takes these limitations into account. Due to this, we may consider measurements of electrodynamic quantities 'predictable' without falling into contradiction. Matters are different in the quantum theory of the gravitational field. It has to take into consideration the limitation arising because the gravitational radius of the test-body... cannot be larger than its real linear dimension... whence

$$\Delta[00,1] > h^{2/3} G^{2/3} / cTV^{4/9} \, .$$

(This minimal uncertainty of the gravitational field can be written as $(1/T)(l_{\mathrm{Pl}}/L)^{4/3}$, where T and L are the time interval and the linear dimensions of the field measurement region, respectively — *G E G*.)

Thus, the quantity in the right-hand side of this inequality represents the absolute uncertainty minimum in the measurement of the components of the strength of the gravitational force that cannot be exceeded by introducing an adequately chosen measuring device. This absolute limit is a result of very rough calculations, because deviations from the superposition principle are likely to interfere when the measuring device has a sufficiently large mass (here, we consider the case of gravitational waves, that is, approximately assume the equations of gravity to be linear; this approximation ceases to be valid near the surface of a heavy body whose gravitational radius tends to equal its real dimensions). It may be thought, however, that a similar result will be preserved in a more precise theory because it does not in itself follow from the principle of superposition and only corresponds to the fact that the general theory of relativity does not allow bodies of a given volume to have an arbitrarily large mass. There is no analogy to this fact in electrodynamics (just because it obeys the superposition principle); that is why quantum electrodynamics can be free from internal controversy. In contrast, it is impossible to overcome the internal controversy in the theory of gravitational waves; measurements of the gravitational field values may be regarded as 'predictable' only if the consideration is restricted to sufficiently large volumes and time intervals. The elimination of the logical inconsistencies connected with this requires a radical reconstruction of the theory, and in particular, the rejection of a Riemannian geometry dealing, as we see here, with values unobservable in principle, and perhaps also the rejection of our ordinary concepts of space and time, modifying them by some much deeper and nonevident concepts. Wer's nicht glaubt, bezahlt einen Thaler." [2, pp. 217, 218] (see also [3, pp. 441, 442]).

The conclusion is formulated resolutely and shows that the author was fully aware of its radicalism. It is further emphasized by the German phrase standing for an exclamation mark: "He who does not believe it owes one thaler." [6] In 1936, this radical forecast brought to memory Landau and Pieirls's argument stated five years earlier and thereafter refuted by Bohr and Rosenfeld; therefore, Bronstein's enthusiasm for the prediction had to be moderated and at the same time accentuated.

7. Expansion of the universe in 1937

Bronstein defended his thesis a few days before his 29th birthday. He had only one and a half years to live until August 1937. But he managed to do much within his very short lifespan. He combined his work for the Leningrad Physico-Technical Institute and lecturing at Leningrad University (A B Migdal was his postgraduate student in 1937 and Ya A Smorodinskii one of his undergraduates). He translated *Electron Theory* by R Becker and *The Principles of Quantum Mechanics* by P Dirac (and also edited its second

[6] This phrase concludes the story of the incredible adventures of the heroes in the Brothers Grimm fairy tale "The Valiant Little Tailor".

Russian edition). He wrote a few articles for the encyclopaedic *Physical Dictionary* and worked on a textbook on statistical physics. Most surprisingly, Bronstein wrote three popular science books: *Solar Matter*, *X-Rays*, and *Inventors of Radiotelegraph*, which were edited by his wife, Lidiya Korneevna Chukovskaya. The fourth book in the same line was to be about Galileo. He was attracted to children's literature by S Ya Marshak

Bronstein's last two papers were published in *Zhurnal Eksperimental'noy i Teoreticheskoy Fiziki* in March 1937. One of them, presenting nuclear-physics calculations requested by I V Kurchatov, testifies to the author's interest in 'earthly' scientific problems [46]. The other, a larger and 'extraterrestrial' article, was "On the Possibility of the Spontaneous Splitting of Photons" [47] (an excerpt is published in [3, pp. 283–290]); in fact, it became the first paper dealing with 'cosmomicrophysics' (using modern terminology), the first real result of 'cooperation' between the physics of elementary particles and cosmology. The result was so elegant that Ya B Zeldovich and I D Novikov included it in their famous monograph on cosmology, even though it was "no more" than the substantiation of the expansion of the universe [48].

In 1937, the situation looked much more dramatic. Hubble's red shift in the spectra of remote galaxies interpreted as the Doppler effect in the expanding universe gave evidence that its age had to be some 2 billion years in the then accepted astronomical time scale, in tremendous contrast to the results of isotopic dating in accordance with which the geological history of the Earth spanned several billion years. Bronstein pointed out this discrepancy in his review published in *Uspekhi Fizicheskikh Nauk* in 1931 [49].

As early as 1929, the well-known astrophysicist F Zwicky proposed a simpler explanation for the Hubble law describing the grandiose picture of receding galaxies. According to Zwicky, the galaxies did not recede; rather, photons emanating from them had enough time "to become reddish" during their long journey: the longer they traveled, the greater the red shift. This astronomical hypothesis was quite unexpectedly supported by a new physical concept, the theory of electron–positron vacuum, when Halpern hypothesized in 1933 that the red shift was due to the interaction of photons with this vacuum and Heitler expounded this hypothesis in 1936 in the well-known monograph on quantum electrodynamics [50].

Figure 6. The last photograph of Bronstein

Bronstein refuted this hypothesis by showing that regardless of the mechanism of "spontaneous splitting of a photon," the relativity principle definitely implied the frequency dependence of the probability of photon decay per unit time. In other words, had the corresponding red shift effect actually existed it should have been different in different regions of the spectrum, rather than homogeneous as in the Hubble law and Doppler effect. Thus, the only observable fact of cosmological character known then was given a microphysical substantiation.

In addition, Bronstein directly calculated a hypothetical process in the framework of QED of that time (a small effect could be superimposed on the Doppler shift) and obtained zero probability of spontaneous photon decay (the calculation occupied the main part of the paper). This agreement was essential for the physics of those days because, as Bronstein put it, "At present, there is no complete theory of vacuum polarization."

However, he was not fated to participate in the further development of such a theory. It is not known whether he managed to submit more papers for publication. If he did, their fate could be illustrated by a miraculously preserved trace of his destroyed article entitled "Quantum Statistics" in the second volume of the Physical Dictionary published in 1937. One of the 14,000 copies of the volume retains the concluding part of this article with the name of Bronstein under it, along with another version having the same page number but signed by a different author; in other words, the entry begins as one and ends as two, evidently due to the carelessness of a printer who forgot to remove one page.

Matvei Petrovich Bronstein was arrested on the night of August 6, 1937. He was then thirty. They demanded that he turn over his arms and poisons — he gave a low laugh as his response. Bronstein was executed in a Leningrad prison in February 1938.

8. Decades later

In the 1930s, the problem of quantum gravity was not regarded as topical or having any practical significance; most researchers were concentrated on a variety of vital tasks posed by the physics of the nucleus, molecules, and the condensed state. Only one, the French physicist Jacques Solomon (1908–1942), undertook to develop Bronstein's idea and appreciated his result regarding the unmeasurability of a strong gravitational field. However, he was not destined to continue the work either — in 1942, he was arrested as an activist of the French Resistance and executed by the German Gestapo [51].

For all that, Bronstein's studies were not forgotten in his own country ten years after his death. Fock wrote in the official review of a work nominated for the Stalin prize in 1948: "The work of Ivanenko and Sokolov is entitled 'Quantum Theory of Gravity.' This title is at variance with the contents and should be replaced by a less ambitious one, e.g., 'Simplified Exposition of the Quantum Theory of

Gravity.' The thing is, the true quantum theory of gravity was created by M P Bronstein, a physicist who worked in Leningrad and expounded it in his paper "Quantization of Gravitational Waves" (*Zhurnal Eksperimental'noy I Teoreticheskoy Fiziki*, Vol. 6, pp. 195–236) published in 1936. Ivanenko and Sokolov use Bronstein's results but make no reference to his work in their text... Regardless of the reasons that may have led the authors to abstain from mentioning the contribution made by Bronstein, their work can by no means be regarded as the creation of the quantum theory of gravity because such a theory was constructed by Bronstein 11 years before" (cited from [52]).

The work nominated for the Stalin prize contained the concept of the weak-field approximation but no new physics whatsoever, even though Ivanenko spoke about the conversion of gravitons to other particles as an indication of the conversion of space–time to matter. The coefficient $\sim 10^{-40}$ characterizing the ratio between the forces of gravity and electromagnetism in the microworld efficiently protected any calculation from experimental verification. (It should be noted that Bronstein did not use the term 'graviton' even though the word had already been applied as early as 1934 [53]).

Twenty years later, several physicists almost simultaneously, using different approaches, reopened the theme of quantum gravity discovered by Bronstein.

Landau pointed out the gravitational boundary of QED at which two fundamental interactions are equalized and beyond which QED cannot be regarded as a closed theory due to the necessity of taking gravity [54]. O Klein discovered the gravitational boundary of the relativistic quantum theory [55]. Finally, J Wheeler discovered the quantum boundary of GR [56]. As a result, the triple physical sense of Planckian scales was exposed even though none of the researchers mentioned Planck's name. The now universally accepted notion of 'Planck values' was introduced by Wheeler two years later [57]. [7]

Meanwhile, nobody reproduced Bronstein's 'renunciation of Riemannian geometry.' On the contrary, attempts to quantize gravity continued by means of crossing Riemannian geometry of GR and quantum theory. This unrestrained optimism was probably encouraged by the success of QED, the construction of which was so advanced by the late 1940s as to transform it into the most exact physical theory, in compliance with the optimistic prediction Bohr and Rosenfeld made in 1933.

Thirty years later, a notable event was Rosenfeld's hypothesis that quantization of gravity might make no sense because such a field has a purely classical macroscopic nature [58]. It should be recalled that Rosenfeld was the author of the first work concerning quantum gravity, published in 1930, implying that "quantization of the gravitational field may be carried out without any new difficulties by means of a formalism wholly analogous to" electrodynamics.

Bronstein thought otherwise after he found an essential difference between quantum electrodynamics and quantum gravity and spoke about "the rejection of the ordinary notions of space and time and their substitution by some much deeper and nonevident concepts."

The very first physical model of this kind ('gravity as an elasticity of a quantum vacuum') was suggested by A D Sakharov in 1967 [59]. This model was enthusiastically welcomed by Wheeler, a pioneer of quantum gravity [60].

By another coincidence, the name of Bronstein was almost officially mentioned in the gala volume of *Oktyabr' i nauchny progress* (October [Revolution] and Scientific Progress), where Tamm summarized the achievements of Soviet theoretical physics. He wrote: "Some exceptionally bright and promising physicists of this generation passed away prematurely: M P Bronstein, S P Shubin, A A Vitt" [61] (these physicists of the first generation educated in the Soviet Union were arrested in 1937 and all died in 1938, even though one was sentenced to be shot and the two others were given eight and five-year labor camp sentences respectively).

Forty years later, after the discovery of Hawking's effect (evaporation of black holes), quantum gravity became a respectable area of research [62]. Since then, around 60 books having the word combination 'quantum gravity' in their titles have been published and dozens of conferences held (a bit too many for a still nonexistent theory).

The centenary of Einstein's birth in 1979 was commemorated by the publication of collected original works "that have made an important contribution to the development of the theory of gravitation." This volume included a section entitled "The general theory of relativity and the physics of the microworld," which contained papers by Bronstein, Ivanenko–Sokolov, and Fock (we recall that the last author compared the works of the first two in his review of 1948) [3].

In the 1980s, the author of the present communication published a few articles on the history of science that would not in fact be mentioned here for reasons of modesty had they not introduced the works of Bronstein to western science in the 1990s [4, 63]. [8]

The seventy years of developments were summarized in two monographs published in 2004 under the same title, 'Quantum Gravity,' by the largest scientific publishing houses [65]. The two authors recognize that the problem remains unsolved but present the work of Bronstein quite differently. One quotes the measurability considerations of Landau and Bohr and alludes to Bronstein's paper only to renounce both his inference and basic logic of his analysis. The other sympathetically cites the 'negative' conclusion of Bronstein but does not explain his argumentation of measurability.

This discrepancy perhaps most adequately reflects the current state of the 70 year-long problem.

9. How to attain inner perfection without external confirmation

In his 'Autobiographical Notes,' Einstein pointed out the two main criteria for the assessment of a theory: its 'external confirmation' as an agreement with empirical facts, and its 'inner perfection' as a naturalness and logical simplicity [66].

These criteria seem sound and even trivial for the entire realm of physics ... barring the problem of quantum gravity. Its 'external confirmation' is counteracted by the astronomical number 10^{40}. This limitation manifested itself in the very first argument of Einstein in favor of gravity quantization

[7] In a letter to the author of the present publication, Wheeler wrote that he did not know of Planck's 'natural units' in 1955.

[8] J Stachel was the first western author to expound on the works of Bronstein [64]. He is a prominent science historian and Einstein expert, the founding editor of the serial publication *Einstein Studies* and of the academic edition of Einstein's works *The collected papers of Albert Einstein* (Princeton University Press).

(gravitational collapse of the atom). Theoretically, it would be possible to deal with numbers of such astronomical scale by means of transition from physical experiments to astronomical observations, but no practical way to address real *cGh*-objects of observation is thus far available. The difficulty of such transition provoked Landau to say about astrophysicists that they are often in error but never in doubt (true, this aphorism was coined before the new astrophysical era that began in the 1960s).

It is a bit awkward to talk about 'inner perfection' in relation to the attempts to quantize gravity when one looks through a wide variety of unworkable theoretical constructions and sees the authors' vain zeal that was never realized into anything of immortal value. The graveyard of theoretical constructions reminds one of the abandoned graveyards of perpetual motion projects or hydrodynamic theories of the ether. Flushes of pioneer optimism are easier to explain by the 'semicriterion' of external attractiveness of the next candidate theory. Added to this is a popular belief among physics students that 'mathematics is cleverer than man' and that careful calculations are the only thing actually needed because sooner or later they produce a physical result. True, Einstein did not mention the first semicriterion, perhaps for the obvious reason that there is nothing to say about it: "a mutiny was never a success, otherwise it would be called differently." As regards the second semicriterion, Einstein said that mathematics is the best way to fool oneself.

The analysis of field measurability that interested physicists of the 1930s may be called, in addition to Einstein's criteria, 'inner justification' of the theory. In fact, it was the analysis of its applicability limits carried out from the inside, until a more general theory was created. Certainly, such an analysis cannot be absolutely rigorous and does not lead to physical corollaries amenable to direct verification in experiment. Corollaries remain in the history of physics; they manifest themselves after many years and cannot be as convincing as direct experimental findings. Nonetheless, the analysis of field measurability is a physical but not formal mathematical analysis.

The disagreement of Landau, the initiator of the analysis, with the results of its extended and in-depth version, looks strange but had its reasons. The freedom of thought experiment that Bohr accepted because it was not forbidden by the known laws of nature was out of the question for Landau, who saw no means to realize this freedom in experiment. Indeed, how was it possible to consider test bodies of an arbitrary mass and charge in the framework of microphysics when only a few elementary particles were really known? Even later, when more particles were discovered, there was no evidence of the arbitrariness of their mass and charge.

Nevertheless, the guarantee given by Bohr and Rosenfeld to the constructors of QED in 1933 proved valid 15 years later, when the most accurate physical theory was created.

Bronstein's 1935 prediction with respect to quantum gravity was of a prohibitive character: it forbade the solution of the problem 'at a small price' while preserving the Riemannian geometry of GR. In itself, this by no means compromises the prediction. Great physical laws are of such character, as exemplified by the prohibition on the existence of perpetual motion machines of the first and second kinds. Underlying the special theory of relativity is the impossibility of finding the speed of a light source from measurements of the speed of light.

The problem is how to deduce physically meaningful results from Bronstein's prohibition. By way of a modest example, I try to defend quantum gravity from one of the founders of QED.

F Dyson has recently suggested that "quantum gravity is physically meaningless." Therefore, the 70 year-old history of research endeavors has come to an end and they should be stopped for the lack of a subject to study. He argues as follows:

"The essence of any theory of quantum gravity is that there exists a particle called the graviton which is a quantum of gravity, just like the photon which is a quantum of light.... It is easy to detect individual photons, as Einstein showed, by observing the behaviour of electrons kicked out of metal surfaces by light incident on the metal. The difference between photons and gravitons is that gravitational interactions are enormously weaker than electromagnetic interactions. If you try to detect individual gravitons by observing electrons kicked out of a metal surface by incident gravitational waves, you find that you have to wait longer than the age of the universe before you are likely to see a graviton.... If individual gravitons cannot be observed in any conceivable experiment, then they have no physical reality and we might as well consider them non-existent. They are like the ether, the elastic solid medium which nineteenth-century physicists imagined filling space.... Einstein built his theory of relativity without the ether, and showed that the ether would be unobservable if it existed. He was happy to get rid of the ether, and I feel the same way about gravitons. According to my hypothesis, the gravitational field described by Einstein's theory of general relativity is a purely classical field without any quantum behaviour" [67].

This reasoning has a weak point in the very beginning. No matter how commonplace the analogy between the photon and the graviton is and for all the similarity of the Coulomb law and the Newton law of gravitation, the two interactions are 'different in principle,' as was emphasized by Bronstein. The difference undermines the consistent notion of the 'graviton' as a one standing on an equal footing with the notion of the 'photon.' Bronstein actually discovered that the usual notion of 'field quantum,' as applied to gravitation, is essentially approximate like many other important 'working' physical notions, such as absolute space, simultaneity, ray of light, temperature, etc., that are also approximate or rather have limited applicability. It can be said that Bohr and Rosenfeld justified the notion of the photon in the framework of electrodynamics and Bronstein showed defectiveness (approximate nature) of the graviton notion in the gravity theory. This essential difference arises from the equality of inert and gravitational masses, an experimental fact that is sometimes referred to as the first great discovery of modern science and provides the basis for one of the greatest theories, GR.

In other words, the graviton is not intrinsic in the anticipated theory of quantum gravity as the photon is in QED. Only a formal approach can associate any wave with a certain quantum. There is hardly anyone who would associate a wave on the sea surface (even one called gravitational) with a 'surfon' particle in order to study the behavior of such a wave.

Moreover, Dyson did not propose what to do with two physical phenomena of primary importance, the earliest stage of cosmological expansion and the final stage of stellar collapse. What theory except quantum gravity could explain them? In either case, the need of a new theory is determined by the Planckian scale. Bronstein was the first to show that this quantitative characteristic reflects physical nature rather than mere dimensional considerations.

It is not necessary to use an advanced apparatus to obtain this quantitative borderline. Suffice it to resort to the simplest gravity and quantum physics, i.e., Newton's law of gravity and quantum postulate suggested by Bohr in 1913 (and the reminder that the black hole phenomenon was predicted in classical physics). Following the example of Bohr and Bronstein to take advantage of full quantitative freedom, we consider a simple physical system of a 'double star' (or a 'gravitium' molecule in the language of the microworld), that is, two identical point-like masses m bound by gravitational interaction and moving in a circular orbit with radius r. Submitting this system to classical mechanics and the Bohr quantum postulate makes it possible to determine the values of system parameters at which its description must essentially take both quantum and 'black hole' effects into account; this procedure yields Planckian values of m and r. Before the era of quantum mechanics, such a derivation would not have been less 'legal' than Bronstein's reasoning in 1935 or Klein and Wheeler's in the 1950s.

Bronstein's papers contain no exact directions on whether it is necessary "to reject the ordinary notions of space and time and substitute them by some much deeper and less evident concepts" and, if 'yes', what these new concepts must be. By way of example, it can be imagined that such a substitution would entail the replacement of the formula for the Planck length, $l_{\mathrm{Pl}} = (hG/c^3)^{1/2}$, by the formula for the classical gravitational constant, like $G = l^2 c^3/h$, where l is a certain constant of the theory of quantum gravity to come.

The history of quantum gravity makes one think that the majority of publications would have never appeared had their authors known and seriously apprehended the analysis of the problem undertaken by Bronstein. At the very least, this would have saved a large amount of paper and working time.

Could Matvei Bronstein have promoted the development of the theory of quantum gravity if Russian history had not killed him at the age of 30? Unfortunately, a historian of science cannot answer questions like this. He can only offer his historic thaler to the one who can.

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