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Quantum–Matter–Spacetime: Peter Mittelstaedt's Contributions to Physics and Its Foundations

Abstract In a period of over 50 years, Peter Mittelstaedt has made substantial and lasting contributions to several fields in theoretical physics as well as the foundations and philosophy of physics. Here we present an overview of his achievements in physics and its foundations which may serve as a guide to the bibliography (printed in this Festschrift) of his publications. An appraisal of Peter Mittelstaedt's work in the philosophy of physics is given in a separate contribution by B. Falkenburg.

Introduction

In a long and distinguished career, Peter Mittelstaedt has made numerous important contributions to fundamental physics, its foundations, and the philosophy of science. He has written more than 140 research papers and 10 books on topics in seemingly as diverse areas as nuclear and quantum many-body theory, relativity and cosmology, quantum logic, foundations of quantum mechanics, and philosophy of physics. It is Peter Mittelstaedt's deep concern about the unity of physics and the semantic consistency of physical theories that gives coherence to this impressive body of work.

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Peter Mittelstaedt the philosopher is portrayed in the article “Language and Reality” by Brigitte Falkenburg in this Festschrift. Here we summarize the highlights of the physicist’s work in the following areas: nuclear physics and quantum many-body theory (Sec. 2), relativity and cosmology (Sec. 3), quantum logic (Sec. 4), and foundations of quantum mechanics (Sec. 5). This sequence order reflects roughly the temporal succession in which Peter Mittelstaedt devoted his attention to problems in these fields, although the corresponding extensive time spans are largely overlapping. The section headings below match the headings of subsections of Section 2 in the bibliography of published papers which appears as a separate document in the Festschrift. Citations of papers in each section below refer to the corresponding subsection there and are prefixed with the appropriate subsection number; thus, for example, [1.1] refers to the first item under ‘Nuclear Physics...’. Similarly, citations of monographs and proceedings are numbered with a prefix M and P, respectively.

1 The Early Years (1953–1970): Nuclear Physics and Quantum Many-Body Theory

In the beginning of his scientific career Peter Mittelstaedt focussed his research work on problems in nuclear physics and, more generally, on the development of quantum many-body theories. Such theories evolved during this time period and reached rapidly a highly sophisticated level. They already showed at these early times their potentiality to serve as powerful tools for analyzing quantum liquids and fluids, qualitatively as well as quantitatively. Nuclear matter, neutron matter, and nuclei stood, during the second half of the 20th century, at the center of interest in physics. Many research institutes and scientific facilities dedicated their efforts to the exploration of experimental nuclear facts and their theoretical explanation by applying these new theoretical tools. During this period Peter Mittelstaedt had the fortune to work at such prominent places as the Max-Planck-Institute in Göttingen and later in Munich, where he could participate in important nuclear research activities and work in a very stimulating scientific atmosphere. It was therefore a natural choice for him to concentrate his work on these interesting research fields and to contribute his particular scientific share.

For about 17 years Peter Mittelstaedt devoted his research to various topics in nuclear and quantum many-body theory. He addressed problems in the theory of atomic nuclei [1.1; 1.2], worked on nuclear models, nuclear scattering theory, and investigated in depth the tool of optical nuclear potentials [1.3–1.5; 1.7–1.9]. His earliest contribution to nuclear science appeared in 1954 in a paper published in *Zeitschrift für Physik* where he reported on the construction of a nonlinear mesonic field approach to explain the saturation of nuclear forces in nuclei [1.1]. Next, he became involved in the development of appropriate microscopic theories and adequate techniques to elucidate properties of quantum liquids such as extended nuclear matter and superconducting states of fermion matter. The results of these investigations are published in internationally acknowledged journals. They cover topics in phenomenological approaches for describing the behavior of nuclear matter

[1.10–1.12] and topics where many-body methods based on first principles are developed and employed.

To deal with microscopic properties of nuclear matter, Peter Mittelstaedt worked on so-called rearrangement energies [1.13] , and on moments of inertia of large nuclei governed by pairing forces [1.16]. These explorations led him to study excitations of fermions or density fluctuations in superconducting states [1.14; 1.15; 1.17]. Returning to the single-particle approaches for describing nuclear matter he employed the reference spectrum method [1.18] (in terms of Brueckner diagrams). A further research step toward deeper insights in the physical properties of strongly correlated fermions under the presence of strongly repulsive interparticle forces was obtained in 1965 by emphasizing the role of effective interactions, if adequately constructed [1.19]. These studies then culminated in the development, application, and dissemination of the method of equivalent non-local potentials [1.20]. Peter Mittelstaedts early research period essentially concludes with a paper entitled "The equation of state of neutron matter" [1.21], with S. Kistler and W. Weyer as co-authors. This investigation arose from his great interest in the physics of the newly discovered neutron stars that induced him to focus his further interest more on problems related to cosmology.

2 Relativity and Cosmology

While Peter Mittelstaedt focused his scientific interests and research on problems in nuclear physics he also became interested in problems of relativity theory and cosmology. This can be understood against the background of the—at this time—recently discovered neutron stars and pulsars, which made a focus on relativistic and cosmological investigations necessary. Peter Mittelstaedt started in 1964 with a contribution to the so called 'clock paradox' in special and general relativity [2.1] . More detailed investigations of this topic can be found in the monograph "Philosophische Probleme der modernen Physik [M1], [M4]. In 1967 and 1968 respectively, studies on the geometrical interpretation of the theory of gravitation in flat space and cosmological solutions of Lorentz-invariant theories of gravitation followed [2.2; 2.3; 2.5]. The dualism between field and matter in general relativity [2.7] belongs to this field of research, too. In addition, a consideration of the formulation of laws of physics in accelerated frames of reference must not be omitted in the domain of general relativity [2.4]. Peter Mittelstaedt published this paper together with H. Heintzmann in 1968.

In his 1977 paper [2.6] Peter Mittelstaedt took part in the debate on conventionalism in special relativity, opposing A. Grünbaum, B. Ellis and P. Bowman. There exists a strong link between the conventionality-problem on the one hand and an operational approach to physical theories as proposed by P. Lorenzen and his group on the other hand. In "Protophysik und spezielle Relativitätstheorie" [2.8] Peter Mittelstaedt refutes the thesis that a theory of relativity being based upon a conventional or operational foundation necessarily leads into a methodological circle. Similar considerations can already be found in [5.9]. Although not directly related to protophysics the article “Hätte Newton die Relativitätstheorie finden können” [5.33] belongs to this context, too.

As a fine case study of a positive operational reconstruction of physical theories, Peter Mittelstaedt gave a derivation of the Lorentz transformations between inertial frames of reference from postulates describing properties of the trajectories of a finite ensemble of free test particles. The postulates involved are specifications of the invariance statements of the Relativity Principle, stipulated to hold for the motion of free particles rather than *all* physical processes. They lead to a generalized form of Lorentz transformation, with a finite or infinite limit velocity constant if in addition the invariance of the temporal order of causally connected event pairs is postulated. Finally, the constancy of the vacuum speed of light then leads to the Lorentz transformation proper whereas the Galilei transformation would result if instantaneous signalling was assumed. This *minimalist* derivation of the Lorentz transformation has been incorporated as a new chapter in the 2nd edition of 1995 of the classic text monograph “Klassische Mechanik” [M2].

As a result of collaborations with colleagues from the Experimental Physics Institutes at the University of Cologne, Peter Mittelstaedt published (together with W. Klein) ‘A Simple Experimental Demonstration of the Principle of Equivalence’ [2.10] and a discussion of the impact of the possibility of superluminal signals on the special theory of relativity [2.11], also the subject of a conference he organized together with G. Nimtz [P9].

The concept of time has been a central issue in Peter Mittelstaedt’s work in relativity theory and beyond. This is evident from the fact that one of his monographs [M5] is devoted to the concept of time in physics and that furthermore he returned to this subject in a recent investigation entitled “Concepts of Time in Physics and Cosmology” [5.44].

Peter Mittelstaedt can be regarded as both physicist and philosopher; accordingly many of the works surveyed here under ‘Relativity and Cosmology’ could equally well be included under the heading ‘Philosophy of Science’. It is a strikingly effective combination of methods and perspectives of the two disciplines that characterizes Peter Mittelstaedt’s unique style.

3 Quantum Logic

Peter Mittelstaedts research in the field of quantum logic departed from his philosophical investigations of the concepts of substance in classical physics and in quantum mechanics [3.1; 3.3; M1, Chapters 4–6; M4] . He observed specifically that Kant’s concept of substance, although valid for classical physics since for all measurable properties of a classical system values can be associated to the system, loses its unrestricted applicability in quantum mechanics. For quantum mechanical objects, Kant’s category of substance can only be applied to compatible observables which can be considered to be “objective” (inherent to the system) if the quantum mechanical state of the object associates values to these observables. Consequently, if proofs of propositions about properties of a quantum mechanical object (observables having particular values) are established by measurements, classical logic which would allow truth-values for all propositions cannot be valid for quantum mechanical propositions.

Well aware of the danger of circularity arising from the fact that the formulation of quantum theory itself is based on the use of logic, and of the objection that the laws of logic do not depend on the empirical content of the propositions and hence are not restricted to a special type of propositions but should derive their validity exclusively by their inherent evidence and irrespectively of all empirical knowledge (again Kant's approach), Peter Mittelstaedt investigated the role and validity of logic in nature [3.2; 3.4]. In particular, he resorted to Paul Lorenzen's operational foundation of logic according to which the laws of logic are completely determined by the possibilities of proving elementary propositions and compound propositions in a dialogue game independently of the factual content of the elementary propositions. Peter Mittelstaedt made clear that in the framework of this dialogical foundation of logic it is tacitly assumed that proofs of elementary propositions performed in a certain stage of the dialogue game are "unrestrictedly available" in an arbitrary context of subsequent proofs of other elementary propositions implying that they may be "quoted" in an arbitrary stage of the dialogue game [M1; 3.5]. His own investigation resulted in a more general dialogue game semantics which includes testing procedures for commensurability propositions (stating the mutual commensurability of propositions put forward in the dialogue game) from which a more general propositional calculus (calculus of effective quantum logic) could be derived [M6, Chapters 3–4]; cf. also [3.8–3.11; M7, Chapters 4–5].

Furthermore, by making use of a weak assumption concerning the measurability of elementary and commensurability propositions, Peter Mittelstaedt could extend this calculus to the calculus of full quantum logic incorporating the principle of excluded middle as a general law [3.12]. He could then show that this calculus of full quantum logic is a model of an orthocomplemented and quasimodular (orthomodular) lattice [M6, Chapter 6] which has been obtained previously from the algebraic structure of quantum mechanical observables based on the work of Birkhoff and von Neumann. As Peter Mittelstaedt pointed out, this "quantum logic" is universal in the sense that the validity of its laws is not dependent on empirical knowledge and, hence, not restricted to a special type of propositions. Instead, the laws of quantum logic are equally valid for all propositions of classical physics and quantum physics. On the other hand, the metalogic of quantum logic which is generated by the formalism of quantum logic itself agrees with ordinary logic since meta-propositions are mutually commensurable [3.14; 3.17].

Peter Mittelstaedt's contributions to the logical interpretation of the orthomodular lattice furthermore include the definition and investigation of the properties of the commensurability relation and the material implication [3.5; 3.7; M6, Chapter 2].

As a next step for constituting a comprehensive formal language for physics, Peter Mittelstaedt introduced the modalities "necessary" and "possible" as well as the concept of probability as metalinguistic concepts [3.6; 3.13; 3.15; 3.16; 3.18; 3.20; M7, Chapter 6] and showed in detail how their interpretation depends on the object language (classical or quantum language) to which they refer. In the quantum language the concepts of possibility and probability turn out to be indispensable elements of the language which, unlike the language of classical physics, cannot be replaced by other semantical concepts. Hence, as Peter Mittelstaedt pointed out, an adequate Kripke-like possible-worlds semantics could only be formulated if appropriate notions of "temporal identity" and "trans-world identity" were guaranteed. This led him to investigate the possibilities of naming and identifying quantum physical objects. He established that in general names can only approximately be given to classes of indistinguishable objects, but that this method of naming is sufficient for establishing the "temporal identity" and "trans-world identity" of the classes in question. On the basis of this concept of "trans-world identity", he was then able to formulate an adequate possible-worlds semantics of modalities in the quantum language [3.24; 3.26; 3.28; M7, Chapter 8; 3.30].

As a further decisive extension of the formal quantum language, Peter Mittelstaedt investigated the general conditions imposed on the validity of propositions in relativistic space-time. Starting from the local concepts of the language constituted so far and taking into account Minkowskian space-time of special relativity, he developed a relativistic generalization of the formal language called Relativistic Quantum Logic [3.21; 3.23; M7, Chapter 7]. Although this language was obtained without recourse to Hilbert space quantum mechanics, it turned out to be in accordance with well-known facts of relativistic quantum physics in Hilbert space. In particular, Peter Mittelstaedt applied this language to an analysis of the well-known EPR-experiment. He could show that the contradiction between quantum physics and the usual locality assumption underlying the so-called EPR paradox can be resolved by a relaxation of the locality principle and that this relaxation is consistent with relativistic Einstein causality [3.22; 3.25; 3.27].

4 Foundations of Quantum Mechanics

The constructive phase of the Cologne Quantum Logic Programme ended in the late 1980s with applications to the EPR paradox and the problem of the constitution and identification of quantum physical objects. Since the mid-1980s, Peter Mittelstaedt has been concentrating his research activities on problems in the foundations of quantum mechanics. His choice of topics reflects the philosophical issues that are close to his heart: the question of the unity of physics, the semantical consistency of physical theories, and the nature of physical reality are in fact brought into focus by the foundational problems of quantum mechanics. It is therefore not surprising that the impressive list of Peter Mittelstaedt's quantum physical investigations of the last fifteen years is matched by an equally rich number of studies of the same set of problems from a philosophical perspective, and written up with a philosophical audience in mind (see Section 2.5 of the Bibliography).

As noted at the end of the section on quantum logic, Peter Mittelstaedt used the general quantum language to resolve the Einstein-Podolsky-Rosen paradox [3.22]. This was also extended to an analysis of Wheeler's delayed choice variant of a two-path interference experiment [3.29]. These investigations marked the beginning of one strand of activity: the conceptual analysis of fundamental quantum experiments. The EPR experiment, which had been discussed already in 1974 in the context of the question of hidden variables in quantum mechanics [4.1], was revisited again later to elucidate its connections with the quantum measurement problem (specifically the problem of decoherence) [4.27] and with Einstein causality [4.23; 4.35].

In 1987 Peter Mittelstaedt with his student Annette Prieur and experimental physics colleague Rudolf Schieder carried out a Mach-Zehnder interference experiments with (practically) single photons, presenting an in-principle demonstration of a joint unsharp determination of path properties and an interference observable [4.2; 4.4; 4.11]. By varying the transmissivity of the mirrors, a trade-off between path knowledge and interference contrast could be established, confirming information-theoretic uncertainty relations predicted in the first theoretical proposal of an experiment of this type by Wootters and Zurek in 1979 [1]. These experiments can also be interpreted in terms of simultaneous elements of unsharp reality, where the path can be approximately real to 99% while the photons are still capable of producing a significant interference pattern.

In the 1990s, Peter Mittelstaedt's interest focused on the quantum theory of measurement, specifically the problem of objectification, and on the problem of interpreting quantum mechanics. Together with Paul Busch and Pekka Lahti he presented a detailed technical exposition of the measurement problem in the 1991 book, "The Quantum Theory of Measurement" [M8], which also contains a survey of the various interpretations of quantum mechanics and the ways in which they address this problem. This was followed by numerous papers that provided further detail on the interpretational options and philosophical elucidations of various aspects of the objectification problem [4.6; 4.8-4.10; 4.14-4.18]. This culminated in the question, at the end of the 20^{th} century, whether one had to accept that quantum mechanics was "universal and inconsistent"; that is, that this theory failed to be semantically consistent, its attempted application to the measuring processes that define its concepts and means of testing leads to the *aporia* of the objectification problem [4.25]. A crystal-clear philosophical exposition of this problematic can be found in the 1998 landmark monograph, "The Interpretation of Quantum Mechanics and the Measurement Process" [M9].

Peter Mittelstaedt's conclusion, discussed in detail in the contribution by Brigitte Falkenburg [2], is that the objectification problem results from the attempt to import classical ontological prejudices into the language of quantum theory. According to this point of view, it is the appearance of a classical world at the macroscopic level that requires explanation. As a case study illustrating this take on the quantum-to-classical transition problem was given in a paper with Bernd Fischer providing a quantum mechanical explanation of "chirality as a quasi-classical property of molecular systems" [4.7].

The task then remains of developing a new understanding of quantum physical reality—and thus an interpretation of quantum mechanics—that does not rely on unjustifiable assumptions of the classical physical ontology. Peter Mittelstaedt approached this problem from many angles. Here one finds extensive analyses of the connections between language, objectivity and reality in quantum physics [4.3; 4.5], the notion of objectivity of quantum observables [4.12; 4.13], the role and status of probability in quantum mechanics [4.20; 4.21; 4.24; 4.28], and the constitution of objects in quantum physics, including the question of the indistinguishability and identification of individuals in a compound system of identical constituents [4.19; 4.22; 4.26; 4.36; 4.37].

A new strand of studies started some ten years ago yielding a rich harvest of insights gained by revisiting foundational problems of quantum mechanics in the light of quantum logic. Topics studied in this phase include the problem of decoherence and the tensions between quantum mechanics and classical mechanics [4.29; 4.31; 4.32; 4.34], a lucid presentation of the status of Planck's constant in the formulation of quantum mechanics [4.34], and incisive criticisms of the various interpretations of quantum mechanics, specifically a recent relapse into an extreme instrumentalism [4.30; 4.33].

In summary, the result of Peter Mittelstaedt's studies in foundations of quantum mechanics is *not* the pretence of a novel and coherent *Cologne Interpretation of Quantum Mechanics*, nor a claim to have solved all the difficult conceptual problems of quantum mechanics. However, there is the specific Cologne approach to Quantum Logic and Quantum Language that has provided deep insights into the operational and ontological underpinnings of Hilbert space quantum mechanics. Finally, Peter Mittelstaedt has provided lucid and precise formulations of the most important foundational problems and puzzles of quantum physics, developed solutions where feasible, and with great clarity and cogency laid out venues for further investigations where a full solution appeared to be beyond reach.

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