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Modular localization and the holistic structure of causal quantum theory, a historical perspective

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Dedicated to the memory of Jürgen Ehlers (1929–2008)

ABSTRACT

Recent insights into the conceptual structure of localization in QFT (modular localization) led to clarifications of old unsolved problems. The oldest one is the Einstein–Jordan conundrum which led Jordan in 1925 to the discovery of quantum field theory. This comparison of fluctuations in subsystems of heat bath systems (Einstein) with those resulting from the restriction of the QFT vacuum state to an open subvolume (Jordan) leads to a perfect analogy; the globally pure vacuum state becomes upon local restriction a strongly impure KMS state. This phenomenon of localization-caused thermal behavior as well as the vacuum-polarization clouds at the causal boundary of the localization region places localization in QFT into a sharp contrast with quantum mechanics and justifies the attribute “holstic”. In fact it positions the E–J Gedankenexperiment into the same conceptual category as the cosmological constant problem and the Unruh Gedankenexperiment. The holistic structure of QFT resulting from “modular localization” also leads to a revision of the conceptual origin of the crucial crossing property which entered particle theory at the time of the bootstrap S-matrix approach but suffered from incorrect use in the S-matrix settings of the dual model and string theory.

The new holistic point of view, which strengthens the autonomous aspect of QFT, also comes with new messages for gauge theory by exposing the clash between Hilbert space structure and localization and presenting alternative solutions based on the use of stringlocal fields in Hilbert space. Among other things this leads to a reformulation of the Englert–Higgs symmetry breaking mechanism.

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1. Preface

The subject of this paper grew out of many discussions about Jordan's discovery of quantum field theory (QFT) which I had with the late Jürgen Ehlers. They focussed in particular on events between the publication of Jordan's thesis on quantum aspects of statistical quantum mechanics in 1924 (Jordan, 1924a), and his discovery of QFT around 1925 which was published in one section of the famous 1926 “Dreimännerarbeit” (Born, Heisenberg, & Jordan, 1926) together with Born and Heisenberg. This paper was in fact the second paper after Heisenberg's discovery of quantum mechanics (QM). The resistance of Born and Heisenberg against Jordan's section has its natural explanation in that these two authors felt that Jordan was burdening the conceptual struggle to understand the new quantum mechanics with something which may distract from this project.

I met Jürgen Ehlers the first time around 1957 at the University of Hamburg when he was Jordan's assistant and played the leading role in Jordan's general relativity seminar. Our paths split, after I wrote my diploma thesis on a topic of particle theory at the time when particle physics moved away from the university physics institute to the newly constructed high energy laboratory at DESY. Contacts with Ehlers and the relativity group became less frequent and ended when both of us took up research associate positions at different universities in the US.

Only 40 years later, when Ehlers moved to Potsdam/Golm in the 1990s as the founding director of the new Albert Einstein Institute (AEI), we met a second time. After having done important research on problems of general relativity and astrophysics he became increasingly interested to understand some of Jordan's famous early work on quantum field theory about which we knew

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little at the time of Jordan's weekly relativity seminar.[2] Ehlers was in particular interested to understand some subtle points in a dispute between Jordan and Einstein concerning Einstein's use of statistical mechanics fluctuation arguments for black body radiation (Einstein, 1925). The ensuing dispute around this purely theoretical argument in favor of the existence of photons has been more recently referred to as the *Einstein–Jordan conundrum* (Duncan & Janssen, 2008).

As the terminology reveals, the E–J conundrum was a poorly understood relation between fluctuations caused by restricting the vacuum state to the observables in a subvolume in Jordan's newly discovered field quantization and Einstein's use of statistical mechanics within the old Bohr–Sommerfield quantum setting. This led him to identify a particle-like component in the fluctuation spectrum of a black body radiation ensemble (which he termed "Nadelstrahlung") with his 1905 interpretation of the photo-electric effect as a manifestation of the corpuscular nature of light.

The E–J conundrum has sometimes been seen as an illustration of the particle–wave dualism of quantum mechanics, but with the hindsight of modern QFT its real significance points into a much deeper level. This was certainly Ehler's view when he drew my attention to what he considered its real significance. Coming from general relativity and cosmology he thought that this problem is analogous (Ehlers, Hoffmann, & Renn, 2007) to the problems related to vacuum polarization used to explain the origin of the cosmological constant in terms of fluctuations of the quantum field theoretic vacuum. He hoped that with my experience of 40 years of QFT I could be of some help to obtain a better understanding.

I learned recently through John Stachel that conjectures about possible connections between thermal aspects of the subvolume fluctuations in QFT as they occur in the E–J conundrum and Hawking–Unruh problems already existed in the 1980s (Stachel, 1986). In fact it will become clear in the course of the present work that it indeed can and should be viewed this way.

For some time this problem remained out of my range of interest; I did not want to loose time on something which would draw me into opaque historical problems away from my research on new foundational insights into to QFT via "modular localization"[3] (Schroer, 1999). During a 2 year stay (2002/2003) in Brazil, a CNPq supported research project "The Modular Structure of Causal Quantum Physics" provided the chance to extend this research. Around 2007 I suddenly realized that the complete understanding of the E–J conundrum can be obtained with the help of precisely those newly gained insights. One just had to apply the *principle of modular localization*, which assigns a certain number of unexpected properties to localized subalgebras. Whereas the global vacuum state is pure, the restriction to a causally localized subalgebra renders it impure; in fact its impurity can be described as a thermodynamic KMS state (Haag, 1996) with respect to a "modular Hamiltonian". This is a general result of the application of the so-called Tomita–Takesaki modular theory of local operator algebras to the subalgebra which observables localized in a spacetime region (whose causal completion remains smaller than Minkowski spacetime) generate.

This reduced vacuum state is entangled in a more radical sense than the entanglement of particle states in Schrödinger's QM of particle states under a binary split of the system into spatial inside/outside subsystems. Entanglement in quantum mechanics resulting from binary inside/outside splits of degrees of freedom resulting from the reduction to the inside and the ensuing loss of the outside information is a well-known phenomenon; it has been observed in quantum optical experiments and the results led to a Nobel prize. But the quantum mechanical "vacuum" (the mathematical reference state which one needs for the "second quantization" multiparticle description of QM) remains completely inert against entanglement. In fact *the singular vacuum entanglement caused by localization in QFT is characteristic for the enormous conceptual distance between the two quantum theories*. The terminology E–J "conundrum" refers to the fact that for a long time this aspect of the vacuum remained outside theoretical comprehension.

In fact most theoretical physicists became for the first time aware of the KMS nature of the QFT restricted vacuum state in connection with the Unruh's "Gedankenexperiment" in which the localization region is a spacetime wedge. This aspect of vacuum entanglement also points at the "fleeting" nature of this effect; it remains many orders of magnitude below the measured quantum optical entanglement of quantum mechanical particle states. But even if it will always remain a "Gedanken" concept,[4] it is at the heart of QFT and follows directly from the *quantum adaptation of the* Faraday–Maxwell "action at the neighborhood" which Einstein converted into the Minkowski spacetime *causality principle*. Its quantum counterpart is of a radically different nature whose physical manifestations are somewhat unexpected. It will be referred to as *modular localization*; a terminology which relates its mathematical formulation with its physical implications. In the present work it will be shown that its conceptual range is not limited to shed light into dark corners of QFT's history as the before mentioned E–J conundrum, but it also plays an important role in an ongoing conceptual reformulation of QFT (which includes gauge theories and the recently much discussed "Higgs mechanism").

The two components in Einstein's statistical mechanics fluctuation properties are indeed, as Jordan claimed, also present in the physical vacuum state after restricting it to the ensemble of observables which are localized in a subvolume. It is important to not impose boundary restrictions (box quantization) but remain within the realm of "open systems". Here it is irrelevant whether Jordan's calculation treated this aspect correctly (Duncan & Janssen, 2008); many important observations in the history of quantum physics have been made within doubtful calculations.

When I was about to explain my findings (Schroer, 2011c, 2013, 2012) in 2008 to Ehlers, I learned that he passed away shortly before my return to Berlin.

The main aim of this paper, which I dedicate to the memory of Jürgen Ehlers, is to explain my findings and their relation to the ongoing research in QFT in more details and a larger context than previously in Schroer (2013).

I remember that Ehlers, in his capacity as the founding director of the AEI in Potsdam, took an interest in string theory (ST). He was however annoyed by the fact that he was unable to bridge the gaps between his understanding of spacetime properties of gravity and the (sometimes bizarre) claims of members of the ST group at the AEI; notwithstanding the fact of the enormous amount of mathematical sophistication and the professional reputation of some of the protagonists of ST.

The work on modular localization also led me to string-localized fields and their improved short distance property which promised a radical extension of renormalization theory to interaction between fields with higher spins. The reason why I mention

[2] After WWII Jordan's interest was mainly focussed on general relativity and philosophical implications of quantum theory. Since he never mentioned his early work on QFT, we remained quite ignorant about it.

[3] Here modular localization stands for an intrinsic formulation of causal localization which is independent on what quantum field "coordinatization" one uses in order to describe the particular model of QFT.

[4] The situation becomes less "fleeting" if the horizon of the localization region is an (Unruh observer-independent) black hole "event horizon".