Self-presentation

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4. Indication of achievement under Art. 16.2 of the Act of 14 March 2003 on Academic Degrees and Title and Degrees and Title in Art (Journal of Laws No. 65, item 595, as amended.): series of 7 publications
   (a) title: *Quasiprobability, local realism and time symmetry breaking in quantum noninvasive measurements*
   (b) publications of the series:
   (c) Discussion of the scientific goal of the above mentioned works and achieved results together with discussion of their use.

   Introduction

   *Shut up and calculate!* – N. David Mermin [1] summarized the standard, Copenhagen interpretation of quantum mechanics, initiated by Born rule [2]. Accordingly, the quantum wavefunction, more generally density matrix, is not objectively real,
constitutes just a mathematical tool, while contact with reality occurs only during a measurement. Already Einstein opposed against such a state, asking if the Moon there is only if anybody looks [3]. Besides, the wavefunction (or density matrix) can be conventionally treated as a real object, but it must be nonlocal (accepted also by proponents of Bohm pilot wave [4]). Certainly, nonlocality is not always a problem, e.g. classical probability distributions can be nonlocal, but changes under external influences cannot spread infinitely fast (faster than light, according to theory of relativity). However, in Copenhagen interpretation, the measurement triggers collapse as a totally invasive and nonlocal effect [5], fixed in a form of a postulate by von Neumann [6]. Nonlocal effects of collapse are most dramatic for entangled states, noticed by Einstein, Podolsky and Rosen [7], while Einstein himself described such a situation as a spooky action at a distance [8]. Schrödinger noticed irrational consequences of collapse for a macroscopic (also irrational?) superposition of an alive/dead cat [9]. Bell [10] proposed an experimental test of nonlocality, however not yet performed in the way unequivocally excluding local realism, because of loopholes. Logical construction of real objects should be related to measurement results, not abstraction of a wavefunction (or density matrix). In the attempt by Wigner, a special function of a position and momentum has been proposed, which recovers correct probabilities of the measurement [11]. Wigner function would be a good real object, but unfortunately takes sometimes negative values, is a quasiprobability. Certainly, the quasiprobability cannot be measured directly, because Heisenberg uncertainty principle [12] forbids a simultaneous exact measurement of the position and momentum. Invasiveness of standard measurements makes an objectively real time resolved description impossible, because every measurement manifestly disturbs dynamics. In an extreme case, Zeno effect occurs — all dynamics gets frozen [13]. Problems of Copenhagen interpretation lead even to the irrational so-called many-worlds interpretation, where every measurement creates alternate realities [14].

The standard, projective quantum measurement [6] worked good in the early days of quantum physics, but experiments got more and more exact and the rigor of projection must have been relaxed. Theory of a generalized measurement has been invented [15], with auxiliary Kraus operators [16] instead of projections, known nowadays as positive operator-valued measure – POVM [17]. Importantly, the new approach is consistent with the old one by virtue of Naimark theorem, that every POVM is equivalent to some projective measurement, but in an extended space of states, taking a detector into account [18]. Such a measurement can be called also the indirect measurement, because it depends on an assumed detector model. It is natural, that the detector itself is a quantum system, so the measurement process should be described more precisely than a simple projection. For instance, in the Stern-Gerlach experiment [19], we apparently project on spin states, but in reality we separate electron beams by magnetic field. However, the measurement must be always somewhere finished, on a screen, in an eye (brain?) of an observer, which needs an appropriate mathematical postulate. Introduction of indirect measurements
freed physics from projective measurement constraints, but did not resolve alone the problem of interpretation. There are infinitely many indirect measurements, they depend on models, which are usually a result of real knowledge about the measurement process and arbitrary idealization. Indirect measurements are still invasive and nonlocal, but usually less than projections.

Indirect measurement motivated another quantum interpretation, by means of objective collapse: measurements, indirect and low invasive, occur objectively, independently of our will, while their results are classically available [20]. It seems a good direction, looking for a correct quantum interpretation, but such a collapse has to modify (slightly) manifestly dynamics and cause heating (also slight) of the Universe, because of entropy production. Since effects of collapse could be softened, why not to eliminate them completely? It requires a concept of the noninvasive measurement. Leggett and Garg [21] were first to consider such measurements, proposing also a test, to be satisfied by such measurements, resembling Bell test [10]. Unfortunately, they did not construct quantum noninvasive measurements, only restricted themselves to the conclusion that standard measurements do not pass their test, so they are invasive. Later, Aharonov, Albert and Vaidman [22] defined the weak measurement as the indirect measurement in a (specially defined) limit of zero measurement strength. Authors focused on the surprising property of such measurements that they can give results far beyond the projective measurements spectrum, which is possible because of large uncertainty of the weak measurement. From today’s perspective, the weak measurement is just the wanted noninvasive measurement.

The goal of the hereby series of works is to describe construction and properties of the noninvasive measurement, partly nonclassical: quasiprobability – "negative probability", weak positivity – second order correlations alone are still classical, local realism – depends on interpretation, and completely surprising time symmetry breaking. It is worth to add that, from an experimental point of view, the noninvasive measurement is more natural than the projective one and most of modern measurements are just noninvasive. One can even say that the "noninvasive measurement" is for physicists like "prose" for Mr. Jourdain (The Bourgeois Gentleman, Moliere), used, but not defined.

Discussion of the results

The first paper [H1] was not yet motivated by [21,22], but by a way to calculate electric current noise in semiconductor junctions at nonzero frequencies. The problem reduces to the question of ordering operators in the expression \( \langle I(t)I(s) \rangle \), where \( I \) is the current at time \( t \) or \( s \). Earlier, it had been used a simple symmetrization trick \( 2I(t)I(s) \rightarrow I(t)I(s) + I(s)I(t) \), taken from Landau Lifshitz book [23], given there without reason. In [H1], it has been derived using the concept of generalized measurements, described by a Gaussian Kraus operator, in a noninvasive limit. Measured correlations are a convolution of detection noise (divergent in the noninvasive limit, but independent of the measured system) and internal stati-
stics of the measured system. The latter statistics is not described by a probability but a quasiprobability, which can take negative values and this has been shown in the paper. The paper contains also discussion and calculation of contributions and corrections to noise from finite invasiveness of the measurement.

The next paper [H2] still concentrates on the current in semiconductor junction. Following Naimark theorem [18], Kraus operators have been replaced by a concrete detection model, in particular the so-called quantum tape — one-dimensional field which moves at constant velocity (figure). At one point, the field interacts with the measured system and then goes uniformly away, so that the position corresponds to the moment of interaction. Far from the interaction point, a projective measurement is performed. The interaction is scaled by a parameter (strength of the measurement), which gives the noninvasive measurement in the zero limit. The model indeed recovers results of [H1], but only for a special range of parameters. Nevertheless, the general class of noninvasive measurement models from [H2], based on the concept of the quantum tape, is the most natural. Apart from the symmetrization case, a new interesting case gives nonsymmetrized noise, i.e. where current as a function of frequency $\omega$ is not symmetrized but stays in the form $\langle I(-\omega)I(\omega)\rangle$, considered also in the new paper [24], as a special measurement with memory. The work [H2] contains also technical details of calculation of correlations and explanation of the negative quasiprobability in tunnel junctions.

The work [H3] refers already to the weak measurement [22]. It contains general formulation of the weak, noninvasive measurement for an arbitrary sequence of measured quantities, in terms of Gaussian POVM. Again, it is characterized by a convolution of internal detection noise and a quasiprobability. For the first time, there has been written down a simple formula for correlations of arbitrary order, for the quasiprobability: $\langle a_1a_2\cdots a_n\rangle = \langle A_1\{A_2,\{\cdots A_n\}\}\rangle/2^{n-1}$, where $a_k$ is the result of the measurement of a quantity $A_k$ while $\{A,B\} = AB + BA$ (anticommutator) and the order of measurements is preserved. The defined quasiprobability is consistent with Wigner function [11], local, but cannot be alone a real object, because it is sometimes negative. It is this negativity that explains unusual results of the weak measurement [22]. In [H3] it has been proposed a concrete test of the negativity for fourth order current correlations in the tunneling limit. The test is based on classical Cauchy-Bunyakowski-Schwarz inequality $\langle XY\rangle^2 \leq \langle X^2\rangle\langle Y^2\rangle$, where $X, Y = I(-\omega_{x,y})I(\omega_{x,y})$ are noises at some frequencies. For the quasiprobability, the
above inequality is predicted to be violated so it must be negative. Remember that a negative probability cannot be measured directly—it is always accompanied by large detection noise, which can be interpreted partially as belonging to the measured system itself. Such an approach is a new quantum interpretation.

The following paper [H4] describes the problem of local realism in terms of noninvasive measurements. The important result is weak positivity. It states that correlations of the second order alone, both in noninvasive measurements and usual compatible measurements (commuting), can be recovered by a normal probability, \( \propto \exp(-\sum_{XY} C_{XY}^{-1}XY/2) \), where \( C \) is a positive definite correlation matrix with elements \( 2C_{XY} = \langle XY + YX \rangle \) and \( C^{-1} \) is its inverse (first order averages are included, e.g. by centering). So no test of nonlocality or negativity of the quasiprobability can involve solely second order correlations, denying earlier proposals, e.g. [25]. Such a test must include correlations of at least fourth order, as in the example from [H3].

Since the main goal of [H4] is discussion of local realism, let us recall the Bell test [10]. The test requires two separated observers, Alice and Bob (A and B), who are free (independently) to choose a measurement (influence on the measured system) and perform the measurement in a sufficiently short time. We assume only two choices, 1 and 2. If there are more, they are binned. We assume also (for a moment) only two measurement outcomes \( \pm 1 \) (if there are more, they can be binned again). Alice and Bob make the choice and measure faster than the maximal time of possible communication between them (bounded by speed of light). Results for a given observer and choice are denoted \( A_1, B_1 \), respectively. Pairs choice-measurement are numbered and written into protocols, which are compared at the end, averaging correlations for the same choices and numbers. Local realism is possible only if

\[
-2 \leq \langle AB \rangle + \langle A_B \rangle + \langle A_2B_1 \rangle - \langle A_2B_2 \rangle \leq 2,
\]

up to statistical error. Violation of this inequality means excluding local realism. We should stress that the violation alone is not sufficient, all above conditions for an experiment are necessary. Relaxing any condition introduces a loophole, allowing local realism.

Quantum example violating Bell inequality is as follows. We take two orthonormal states \( |\pm\rangle \) for each observer and construct product states \( |ab\rangle \), where \( a,b = \pm \) for Alice and Bob, respectively. Every observer can choose the following quantity to measure, \( O = X \cos \phi + Z \sin \phi \), where \( X = |+\rangle\langle-|+\rangle\langle+| \) and \( Z = |+\rangle\langle+| - |\rangle\langle-| \). Possible outcomes of \( O \) are \( \pm 1 \) because \( O^2 = 1 \). Let us now take the Bell singlet state \( |\psi\rangle \) defined by \( \sqrt{2}|\psi\rangle = |++\rangle - |--\rangle \). For \( O = A, B \) and \( \phi = \alpha, \beta \), respectively, we get \( \langle AB \rangle = - \cos(\alpha - \beta) \). Taking \( \alpha_1 = 0, \alpha_2 = \pi/2, \beta_1 = 5\pi/4, \beta_2 = 3\pi/4 \) (figure), we obtain finally \( \langle A_1B_1 \rangle = \langle A_1B_2 \rangle = \langle A_2B_1 \rangle = - \langle A_2B_2 \rangle = 1/\sqrt{2} \), so

\[
\langle A_1B_1 \rangle + \langle A_1B_2 \rangle + \langle A_2B_1 \rangle - \langle A_2B_2 \rangle = 2\sqrt{2} > 2,
\]

and Bell inequality is violated. Violation of Bell inequality has been confirmed experimentally, but no experiment satisfied simultaneously all conditions of Bell test
(e.g. some events are ignored or the distance Alice-Bob is too short), so loopholes still allow local realism. It should be stressed that freedom of choice and a finite measurement time will be always assessed subjectively, although they are necessary in science (free choice is a foundation of the law and all interfaces, e.g. keyboards, while measurements must become useful in a finite time). There is neither objective criterion of freedom of choice (superdeterminism is possible) nor an end of measurement (on a screen, paper, in an eye (brain?) of a reader). In this way, local realism can be defended practically endless, even if the presently identified loopholes are one day closed.

Can one propose a Bell-type test without dichotomy ±1, allowing arbitrary real outcomes? Certainly one can always assign two values to arbitrary sets, but we look for a moment-based test involving correlations \( \langle A^k B^l \rangle \), with \( k + l \) as low as possible. The question had been already formulated [26], but local realism could be excluded there only at \( k + l = 20 \). In [H4], there is shown a test containing only fourth order correlations, \( k + l = 4 \), the only known at present. Note: Bell inequality is of the second order, \( k + l = 2 \), because we assume dichotomy, equivalent to the assumption about fourth moments \( \langle (A^2 - 1)^2 \rangle = \langle A^4 \rangle - 2\langle A^2 \rangle + 1 = 0 \). The test reduces to the inequality

\[
2\left| \langle A_1 B_2 (A_1^2 + B_1^2) \rangle + \langle A_2 B_1 (A_2^2 + B_1^2) \rangle + \langle A_1 B_2 (A_1^2 + B_2^2) \rangle - \langle A_2 B_2 (A_2^2 + B_2^2) \rangle \right| \leq 2 \left( \langle A_1^4 \rangle + \langle A_2^4 \rangle + \langle B_1^4 \rangle + \langle B_2^4 \rangle \right) + \sum_{C,D,E=(A_1,A_2,B_1,B_2)} D \neq C; E \neq C,D,D' \sqrt{\langle C^4 \rangle} \sqrt{\langle D^4 \rangle} \langle (D^2 - E^2) \rangle^2,
\]

where \( D' = A, B_{3-k} \) if \( D = A, B_k \). If \( A, B = \pm 1 \), then the test reduces to the standard Bell test. Violation of the inequality means that the statistics must be described by negative quasiprobability, or the local realism is excluded.

The proposed inequality can be tested in tunnel junctions, measuring noninvasively impulses of the current. It corresponds to a simple picture of creation of entangled electron-hole pairs in the junctions, in presence of voltage difference [25] (figure). The inequality can be indeed violated, but (i) subtracting (arbitrary) detection noise and (ii) for measurements close to the junctions (allowed communication). Therefore the test contains still loopholes, although less than earlier proposals [25]. Anyway, loopholes appear in every realistic proposal of Bell test, which suggests that apparently practical problems, e.g. decoherence, uncertainty of measurements, etc., can be responsible for the fundamental conservation of local realism.
Since various tests of negative quasiprobability could be based on fourth order correlations, why not to test negativity of Wigner function in this way? From [H3], it is known that Wigner functions appears for the noninvasive measurement of the position \( x \) and the momentum \( p \) (arbitrary order), while on the other hand it is known that it takes negative values [11]. However, there had been no earlier proposal to verify the negativity using moments (they had been used to test negativity of the relative, "more negative" Glauber-Sudarshan function \( P \) [27]). This exactly has been presented in [H5]. Second moments are certainly not sufficient but already the correlation \( \langle (2xp)^2 \rangle \) can be negative, and even approach \(-1\) for the wavefunction \( \psi \sim |x|^{-1/2} \) (regularized, used earlier in a completely different problem [28]). For rotationally symmetric states in phase plane \((x,p)\), one needs 8 moments to show negativity. In the last part of the work, it has been proposed to determine noninvasively moments of Wigner function. The paper [H5] got fast experimental response [29], where the moments of Wigner function have been measured to confirm the negativity.

The next paper [H6] contains discussion of noninvasive measurement as a limit of a continuous measurement. The continuous measurement cannot be simply reduced to the projective measurement, as in Naimark theorem [18]. It is necessary to make a special limit, discrete \( \rightarrow \) continuous. Seminal papers are quite old [30], and the topic is partially in textbooks, e.g. [17]. In [H6], it has been presented continuous Gaussian measurement, its separation into (white) detection noise and a quasiprobability functional for an arbitrary strength of the measurement. Again, weak positivity holds, for an arbitrary strength of the measurement, while time correlations are expressed in a compact form. Properties of such correlations have been discussed for two examples: a two-level atom and harmonic oscillator. In the two-level case, it is interesting to ask if oscillations between levels can be registered as an oscillating trajectory. The answer is negative, at least in a single experiment (unless it is repeated and averaged). It is connected with Zeno effect [13]: a too strong measurement destroys oscillations, while a too weak one is noisy. However, subtracting the noise, one can show again the negative quasiprobability, in the spirit of Leggett and Garg [21], taking fourth order correlations. The test is based on the inequality \( \langle A^2 \rangle \geq 0 \), where

\[
A = Z(0)Z(2t) + Z(-t)Z(t) + 2.
\]

Taking the chaotic state (infinite temperature) and dynamics given by the Hamiltonian \( H = \hbar \omega X/2 \) (notation as above for Bell test) and \( t = \pi/2\omega \), one gets \( \langle A^2 \rangle = -2 \).
for the noninvasive measurement. The negativity shows up for a sufficiently weak measurement and disappears for a strong one (Zeno effect occurs, $A = 4$). In the harmonic oscillator case the dynamics is almost classical, it suffices to replace the classical probability by Wigner function (similarly as in [H5]). The measurement contributes only to variance (time-dependent), while only noise grows fast instead of Zeno effect.

The last paper [H7], concerns the new (without a trace in previous literature), completely surprising paradox of the noninvasive measurement – violation of time symmetry. To understand the paradox, let us recall classical time symmetry. We do not mean symmetry of dynamics, but only existence of a possibility to reverse dynamics, so that the new dynamics is still allowed. Therefore, it is irrelevant if equations of motion (Hamiltonian) are time-symmetric, or satisfy charge-parity-time CPT symmetry, known in high energy physics [31]. The system does not need even to be in an equilibrium state, although in equilibrium the second law of thermodynamics can be ignored (macroscopic irreversibility). If only a time reversal for every quantity, dynamics and initial state is possible, then for an arbitrary sequence of classical noninvasive measurements of $A_1,..., A_n$ at times $t_1 \leq \cdots \leq t_n$ with results $a_1,...,a_n$, the symmetry holds

$$Q^T(a_1^T(-t_1),...,a_n^T(-t_n)) = Q(a_n(t_n),...,a_1(t_1)),$$

where $Q$ is probability while $T$ denotes time reversal, here applied to all considered quantities, states and dynamics of the system. On the other hand, the above symmetry is broken quantum mechanically. To understand the breaking mechanism, let us write the formula for statistics of noninvasive measurements, using superoperators:

$$Q(a_n,...a_1) = \langle \delta(a_n - \tilde{A}_n) \cdots \delta(a_1 - \tilde{A}_1) \rangle,$$

where $\tilde{A}B = (AB + BA)/2$. The above formula is classically a normal probability, time-symmetric. In the quantum case, it is a quasiprobability where $\tilde{A}$ are not commuting in general, so their order cannot be reversed (density matrix is always on the right).

In [H7], there is presented a natural quantum-classical model of the noninvasive measurement (figure). It is important, that even the classical noninvasive measurement is an idealization, while usually noninvasiveness is obtained in the limit of zero
measurement strength. A detector prepared in a Gaussian state interacts instantly with the system by the Hamiltonian \( \sim gpA \), where \( g \) is a measurement strength, \( p \) – detector’s momentum and \( A \) – measured quantity. Then the position \( q \) of the detector gets shifted by \( gA \) and the final distribution of positions is the convolution \( P(q) = \int da D(q - ga)Q(a) \), where \( D \) is internal detection noise, and the limit \( g \rightarrow 0 \) is made. Then \( Q \) is given as above. In the work, there are examples of time symmetry breaking in thermal equilibrium state: third order correlations of the position in a double-well and charge in a quantum dot. The latter example opens a possibility for an experimental test. Summarizing properties of measurements in zero strength limit:

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<tr>
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<th>CLASSICAL</th>
<th>QUANTUM</th>
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<tr>
<td>NONINVASIVENESS</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>POSITIVITY</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>TIME SYMMETRY</td>
<td>YES</td>
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Criticism

Before publishing the works of the series went through hard reviews, with arguments against the results. Here are the most interesting objections, which must have been refuted in final publications

- **Weak positivity is false, because there exist tests of nonclassicality based on 2. order correlations**
  In all such tests, there are additional assumptions constraining values of results, in fact equivalent to use of higher moments (e.g. \( A = \pm 1 \) is equivalent to \( \langle (A^2 - 1)^2 \rangle = 0 \))

- **Weak positivity is a simple consequence of Robertson-Schrödinger uncertainty principle**
  Schrödinger [32] generalized Heisenberg uncertainty principle for a pair of observables, while Robertson [33] generalized it further to more observables. In Robertson’s papers, one can find a statement about a positive definite correlation matrix, but weak positivity requires also giving an example of a suitable positive probability (it is a Gaussian distribution in [H4] and [H6]).

- **Correlations in the quantum continuous measurement have been already described in [34] and the book [17]**
  In [34], there is given a construction of the continuous measurement, but not derived time correlations (only single-time), in [17] there are only second order correlations, while [H6,H7] describe time correlations of the arbitrary order.

- **The smaller the strength of the measurement, the less both disturbance and signal, so time symmetry breaking can be a result of disturbance**
  Indeed both signal and disturbance get smaller with the decreasing strength of the measurement. Disturbance indeed affects the result of the measurement but two orders (in the measurement strength) weaker than the leading noninvasive
contribution. The same happens in classical measurements, where the symmetry is restored in the limit.

- **Even the weakest measurement changes density matrix, so it is invasive**
  Density matrix indeed changes during measurement, but it is read-off, not disturbance. Only change of the matrix integrated over all results is real disturbance.

- **Time symmetry holds anyway only for equilibrium states**
  It we consider microscopic dynamics, it is reversible even out of equilibrium and classical symmetry holds. Reversal of dynamics is then certainly more difficult experimentally. On the other hand dynamics of equilibrium states is reversible both micro- and macroscopically, so symmetry breaking in these states is more surprising and easier verifiable experimentally.

- **But quantum time symmetries hold, e.g. pre-postselection symmetry [35] and CPT [31]**
  Pre-postselection symmetry, under exchange of the selection of initial and final states indeed holds, but for arbitrary measurements, even invasive, and has nothing to do with the symmetry from [H7]. CPT symmetry concerns only dynamics, not measurements. For measurements, CPT holds if they are spacelike separated, because they are commuting. If not, CPT is broken.

- **For two-level systems correlations of noninvasive measurements are the same as of projections, so the asymmetry is not surprising**
  Indeed, for very simple systems, correlations accidentally are independent of the measurements strength. But this is surprising! Classically, the smaller strength, the lower invasiveness, so the symmetry should be gradually restored.

- **Weak measurements for two-level systems, including time correlations, had been already investigated**
  Only single-time or second order correlations could have been considered, while in [H6,H7] arbitrary correlations are considered.

- **Classical measurements also break time symmetry**
  Yes, but only invasive. In the noninvasive limit the symmetry is restored.

- **Violation of time symmetry in [H7] is not fundamental because quantum and classical mechanics differ**
  Classical and quantum mechanics differ in description and some simple analogies do not work, but usually the only difference is that the same phenomenon is described simpler quantum than classically. Violation of time symmetry in [H7] is about the fundamental analogy between classical and quantum measurements, which cannot be replaced or simplified.

**References**

5. Discussion of the other scientific achievements

Before PhD I showed a simple proof of the partition function counting for the two-dimensional Ising model (A. Bednorz, J. Phys. A 33, 5457 (2000)). In MSc thesis, under supervision of Prof. M. Napiórkowski, I described the problem of interface fluctuations for wedge geometry (A. Bednorz, M. Napiórkowski, Phys. Rev. E 63, 031602 (2001)) and non-uniqueness of description of such fluctuations using path integrals (A. Bednorz, M. Napiórkowski, J. Phys. A 33, L353 (2000)). In PhD thesis, under supervision of Prof. B. Cichocki, defended in 2003, I proved irreversibility of dynamics of classical hard-sphere fluid by growth of entropy (generalization of Boltzmann $H$ theorem for ideal gas, where $H$ corresponded to entropy), by systematic truncation of correlations from a fixed order (A. Bednorz, B. Cichocki, J. Stat. Phys. 114, 327 (2004)). The only reversible state (constant entropy) is the Gibbs state, for a fixed average total momentum, angular momentum, energy and number of particles. I should stress that the irreversibility in such a description is derived modifying equations of motion. Breaking of time symmetry is here of a completely different origin than in [H7], where dynamics is not modified and breaking occurs only quantum mechanically. To describe nonequilibrium states and their entropy, I invented diagrammatic rules for nonequilibrium classical correlation functions (A. Bednorz, Physica A 298, 400 (2001)). For states close to equilibrium, I invented linear description with a symmetry similar to quantum Hermitian symmetry (A. Bednorz, Phys. Rev. E 67, 021201 (2003)). After PhD, I demonstrated usefulness of this description to calculate corrections to transport coefficients of hard-sphere fluid (A. Bednorz, Phys. Rev. E 73, 011203 (2006). Besides, after PhD, I got involved in curiosities from various fields of physics. I showed necessity of random choices in the genuine Bell test (A. Bednorz, J. Zieliński, Phys. Lett. A 314, 362 (2003)). I showed that fermions (anticommuting) on three-dimensional lattice (+ time) can be bosonized – expressed by bosons (commuting), with help of certain limit (A. Bednorz, J. Phys. A 37, 8901 (2004)). Earlier, bosonizations had been derived only in one and, under certain conditions, two dimensions. I showed that, for special electromagnetic configurations, massless charges, moving at the speed of light, do not self-interact (A. Bednorz, J. Phys. A 38, L667 (2005)). Apart from the series [H], I am the first co-author of the paper about maximal possible positive correlations in a semiconductor-superconductor junction (A. Bednorz, J. Tworzydło, J. Wróbel, T. Dietl, Phys. Rev. B 79, 245408 (2009)), which opens a possibility for an analogous Bell test as in [H4].
At present, two works are under review: the first (A. Bednorz, arXiv:1209.0209) contains a proof of relativistic invariance of vacuum, earlier proved only for free fields and postulated otherwise (Wightman); the second (A. Bednorz, C. Bruder, B. Reulet, W. Belzig, arXiv:1211.6056) describes generalized approach to noninvasive measurements, allowing memory of the measurement. The measurement with memory can be parameterized by detector’s temperature, which determines properties of statistics. In equilibrium with the measured system, all correlations vanish, which is consistent with absence of information flow in a state of maximal entropy. In contrast to the memoryless measurement, the generalized version can violate weak positivity, which is confirmed by examples – one of them is now realized experimentally by the group of B. Reulet. For the measurement with memory, ordering of operators depends on temperature: "normal" i.e. negative frequencies before positive for the low, opposite for the high. In the case of harmonic oscillator, one gets classical equations of motion and "relatives" of Wigner function, Glauber-Sudarshan $P$ function and Husimi-Kato $Q$ function. There is an analogy between optical squeezed states (decreasing position uncertainty, increasing momentum uncertainty, according to Heisenberg) with violation of weak positivity, e.g. in tunnel junctions.