Autoreferat

25 marca 2014

1 First and last name.

Andrzej Dragan

2 Scientific degrees.

- PhD degree in physics (cum laude), *University of Warsaw*, Warsaw 2006. Thesis: *Single photon communication through noisy quantum channels*. Advisor: prof. dr hab. Krzysztof Wódkiewicz.
- MSc degree in physics (cum laude), *University of Warsaw*, Warsaw 2001. Thesis: *Homodyne Bell's inequalities for optical Schroedinger cat states*. Advisor: dr Konrad Banaszek.

3 Employment in academic institutions.

- 2010-2012: *Research Fellow* at *University of Nottingham.*
- 2008-2009: *Research Fellow* at *Imperial College London.*
- 2006-present: *Assistant professor* at *Institute of Theoretical Physics, University of Warsaw.*
- 2003-2004: *Scientific Secretary of the Head Committee of the Physics Olympiad.*

4 Scientific accomplishment

a) Title of the scientific accomplishment

Publication cycle: *Relativistic Quantum Information*.

b) (Authors, publication titles, publication year, journal name)

[1] A. Dragan, J. Doukas, E. Martin-Martinez, and D. E. Bruschi, *Localized projective measurement of a quantum field in non-inertial frames*, Class. Quantum Grav. **30**, 235006 (2013).

[2] D. E. Bruschi, A. Dragan, A. Lee, I. Fuentes, and J. Louko, *Relativistic Motion Generates Quantum Gates and Entanglement Resonances*, Phys. Rev. Lett. **111**, 090504 (2013).

[3] A. Dragan, J. Doukas, and E. Martin-Martinez, *Localized detection of quantum entanglement through the event horizon*, Phys. Rev. A **87** 052326 (2013).

[4] J. Doukas, E. G. Brown, A. Dragan, and R. B. Mann, *Entanglement and discord: Accelerated observations of local and global modes*, Phys. Rev. A **87**, 012306 (2013).

[5] D. E. Bruschi, A. Dragan, I. Fuentes, J. Louko, *Particle and antiparticle bosonic entanglement in noninertial frames*, Phys. Rev. D **86**, 025026 (2012).

[6] A. Dragan, I. Fuentes, and J. Louko, *Quantum accelerometer: Distinguishing inertial Bob from his accelerated twin Rob by a local measurement*, Phys. Rev. D **83**, 085020 (2011).

[7] D. E. Bruschi, J. Louko, E. Martin-Martinez, A. Dragan, and I. Fuentes, *Unruh effect in quantum information beyond the single-mode approximation*, Phys. Rev. A **82**, 042332 (2010).

c) Description of the scientific goal of the above mentioned works, obtained results and prospects of applications.

Research papers [1-7] listed above give rise to the present habilitation submission and references [8-23] refer to the remaining publications of the applicant not included in the cycle. Introduction to the topic of research is presented in Sec. 4.1, the phenomenon of dependence of entanglement on the observational reference frame is discussed in Sec. 4.2, Sec. 4.3 discusses the idea of quantum gates realized by motion, in Sec. 4.4 we review the work on quantum detection of the acceleration of the reference frame and finally Sec. 4.5 summarizes the discussion.

4.1 Introduction

The theory of quantum information originating from the 1980's has achieved an undoubted success. It is presently one of the most important branches of contemporary physics, both theoretical, and experimental. Questions concerning quantum non-locality, teleportation, cryptography, estimation, communication, or quantum computations are studied in most of the leading research centers in the world. Experimental results based on the theory of quantum information already found practical and commercial applications, fundamental experiments are carried out in scales reaching hundreds of kilometers, and the idea of bulding a quantum computer is currently one of the most important goals of contemporary science. The theory itself is a direct generalization of the classical theory of information developed by Shannon. The generalization involved taking into account quantum effects in the description of physical carriers of information and consequently replacing a clasical notion of a *bit* with a *qubit* - the basic unit of information encoded in the simplest possible state of the quantum system. This paradigm shift allowed one not only to generalize previously known results, but most of all discover new possibilities in the theory of information, not allowed in its classical version. A perfect example are the quantum cryptographic protocols allowing one to encode the transmitted classical information in a way that is impossible to decrypt by an unauthorized party due to fundamental limitations of the quantum theory. Although it could be expected at first that the quantum theory could only lead to further limitations stemming out, for example, from the Heisenberg principle of uncertainty, it turned out that the quantum theory used creatively leads to the new possibilities not allowed within the realm of classical physics.

Reality is, however, not only quantum, but also relativistic. Therefore a natural question arises: how relativity can influence phenomena described by the theory of quantum information? Does it lead only to new limitations, or perhaps it could also lead to improvements of the known results or even going beyond limitations imposed by the non-relativistic theory? Almost all important results of the quantum information theory are obtained within the non-relativistic approximation, or the assumption that the whole scheme is placed in a fixed, inertial frame of reference. In most of these examples it is not clear how the obtained results would change if non-inertial observers or gravitational effects were taken into account. Quite often already the correct formulation of a given scheme in the relativistic language operating with the notions of quantum field theory, can be a serious problem. The question worth asking at the beginning is, why should we make such an effort? One could argue that the relativistic effects can be completely neglected in most of the known experiments.

One has to notice a few relevant facts in this context. It is known that general-relativistic effects play a crucial role in achieving high precision of the *GPS* devices. Without taking into account relativistic corrections, positioning of these devices would lead to a significant increase of the errors. This indicates that one has to carefully analyze influence of these and similar effects onto the quantum experiments carried out in increasingly large scales. The moment, when *GPS* becomes replaced by its upgraded, quantum version, this knowledge will be absolutely crucial.

There is also a number of other reasons pointing out at the need for generalizing the quantum information theory to the relativistic case. The famous Hawking's work [24] on the evaporation of black holes seems to suggest that the physical information does not have to be necessarily preserved in all physical processes. There are arguments suggesting that in some extreme cases quantum information can be irreversibly erased, therefore leading to a non-unitary evolution of quantum states. Within the present-day formulation of the quantum information theory, such a possibility is absolutely excluded. If the Hawking's hypothesis about the erasure of the quantum information was true, all of the present-day quantum information theory would only be an approximation of an unknown, relativistic theory of quantum information. Can there be an observation that is more important from the point of view of this theory?

We also know that the quantum state itself, being in the very heart of the quantum theory of information, undergoes non-trivial changes due to the change of a reference system. One of the most well known examples of this phenomenon is the Unruh effect [25], according to which a quantum vacuum of a relativistic quantum field for one inertial observer is actually a thermal state filled with particles for another, uniformly accelerated observer. This fact has s great impact onto the construction and description of quantum information protocols carried out between arbitrary, and not only inertial, observers. It seems that taking into account the motion of the parties of the quantum communication protocols, as well, as the effect of gravity onto these protocols in some circumstances can crucially affect most of the presently known results.

One can also ask constructive questions: can the theory of relativity provide new ways to improve efficiency of the known protocols of the quantum information? An interesting example is so called entanglement of the vacuum [26]. It is known that the vacuum state of the quantum field observed by a pair of non-inertial observers reveals a rich structure of entanglement. In various models of interaction between matter and quantum fields one can show that this entanglement can be extracted and possibly used in communication protocols, such as teleportation. This indicates that relativity provides a way to explore new quantum resources, completely unavailable in the non-relativistic vervions of the theory. It is therefore worth asking about the feasibility of this type of resource in a realistic physical situation.

In this submission we present a number of new results concerning relativistic extension of the quantum theory of information as a step towards the full understanding of the concept of information and its relation with the basic laws of physics. In the presented works we pose and solve problems being on the front of contemporary studies of relativistic quantum information. We attempt to put a stress on giving the obtained results an operational sense, and in some cases we point out possible experimental realizations within the present-day or near-future experimental setups allowing one to empirically test these ideas.

4.2 Dependence of entanglement on the observer

One of the most fundamental phenomena of the quantum information theory is the dependence of the quantum state on the observer. Let us assume that some observer prepares a given entangled state and another observer measures it. In general, the outcomes will depend on the relative motion or absolute acceleration between these two frames, which is of a crucial importance in communication protocols. If a given quantum state of two subsystems is used for teleportation of information between two observers being in two different frames of reference, the efficiency of teleportation may directly depend on the relative motion of the two [27]. This phenomenon is particularly interesting, when one of the observers is at rest and the other undergoes a relativistically accelerated motion. According to Einstein's principle of equivalence, this physical situation is equivalent to the case, when one of the observers is influenced by a static gravitational field. Therefore this scheme allows one to test the effect of gravity onto the quantum entanglement. First works on this topic [28] were, as it was found later, assuming impossible conditions and the first mathematically correct description of the dependence of the amount of entanglement on the acceleration of the observer was given in [7]. In this paper we have considered a maximally entangled state of modes A and B of the scalar, real Klein-Gordon field assuming that the mode A is measured by the same inertial observer, who prepared the overall state, and the mode B undergoes measurements carried out by another, uniformly accelerated observer. The Bogolyubov transformation from the inertial (Minkowski) frame to the uniformly accelerated (Rindler) frame can be decomposed into two stages by introducing an intermediate basis of (Unruh) modes sharing the same vacuum state with the Minkowski modes. Unruh modes are constructed in such a way that the Bogolyubov transformation $M \to U$ represents a change of basis not mixing the positive and negative frequencies, and the transformation $U \to R$ is diagonal, i.e. it does not mix-up different positive frequencies, but changes the state of the vacuum. Also, the mathematical form of the transformation $U \to R$ is particularly simple and convenient in calculations, therefore it is useful to study the quantum state expressed in terms of the Unruh modes basis in order to easily transform it to the accelerated frame of reference. The proposed method turned out not only to be very successful and simple to apply, but also proved to be easy to be generalized to many other types of fields and states [29]. We have studied spinor fields, Grassman scalars, and in [5] we have extended the analysis to complex scalar fields allowing electric charge discriminating between particles and antiparticles.

The obtained results enabled a much better understanding of the mathematical structure of the Unruh effect and a related effect - degradation of entanglement due to acceleration and gravity. However, on the path to the full understanding of all the aspects of this phenomenon there were still a few crucial steps missing . Most of all, Unruh modes are, just as plain waves, a family of global modes. Moreover, their spatial structure is heavily complicated, practically impossible to implement experimentally. It would be much more desirable for the considered entangled states to involve spatially localized modes, even if the wave-packets were only to vanish sufficiently fast in the infinity. The mode localization would allow for a much clearer physical interpretation of the results, because the proper acceleration in the Rindler frame depends crucially on the position. Moreover, the mathematical scheme used in the works [7, 5] allowed only to analyze the entanglement in the Rindler frame characterized by a uniquely chosen acceleration parameter. Consequently, for each individual acceleration it was necessary to consider another entangled state. It would be worth to find another scheme, where a fixed considered entangled state could be analyzed by a family of different, uniformly accelerated observers. Such a model has been introduced and studied in [1]. We have considered a decomposition of the field operator into the family of localized (up to sufficiently decaying tails) wavepackets, prepared in a state measured by a pair of observers: one resting, and the other uniformly accelerated. Since the Bogolyubov transformation is linear, the proposed model was particularly useful for applications to the family of Gaussian states that does not change under linear transformations. The simplest Gaussian state is the vacuum, whose properties have been studied and compared with the known from the literature results obtained with other methods [30]. Using localized modes we have studied the Unruh effect, as well as the vacuum entanglement effect and the dependence of the observable entanglement on the proper acceleration of the detectors. Apart from the full agreement within the range of applicability of all the models, we have also determined a previously unknown correction to the Unruh effect stemming from the finite size of the measurement apparatus.

A model of the field state measurement in the uniformly accelerated frame has been used to study the dependence of the entanglement on the proper acceleration of the measuring device. In [3] we have considered a two-mode squeezed state of two localized modes as an input. The state was prepared in a resting, inertial frame. One of the modes was measured in the same frame, while the other one by a similar detector, but moving with a relativistic acceleration. The analysis has shown, how the measured entanglement decays with the increasing proper acceleration of one of the detectors. It has turned out that in the limit of large accelerations, the entanglement vanishes completely. We have also asked a question, whether this entanglement degradation due to acceleration can be compensated in order to maximize the extracted non-local correlations from the considered state. In order to solve this problem we have considered an accelerated detector, whose characteristics can be modified depending on the acceleration. We have managed to find an optimum setting leading to the best possible efficiency of entanglement extraction. It turned out that the degradation of entanglement can be almost perfectly compensated in a large regime of accelerations. Only for the accelerations, for which the considered mode inevitably submerges under the event horizon (approaching the detector with increasing proper acceleration), the amount of the detected entanglement must be reduced. What is more interesting, in the limit of infinitely large accelerations a fraction of the initial entanglement is still measurable, because for geometrical reasons only a half of the considered mode can be submerged under the event horizon. Therefore some part of the mode will always stay within the reach of the accelerated detector and even in the limit of infinitely high acceleration some part of the entanglement will always be available. This result, which is different from the result of the analysis using non-localized Unruh modes, shows how carefully one has to study the problem of mode localization of a given quantum state. Emerging differences stemming from the localization of the field modes have been analyzed in detail and explained in [4]. In this work we have also studied the dependence of all the non-local correlations on the acceleration of the observer, including the discord. The analysis was carried out both for localized and non-localized modes.

The series of works [1, 3, 4, 5, 7] described in this section is the first complete description of the phenomenon of degradation of entanglement in accelerated reference frames. It is worth underlining that for Gaussian states, the introduced formalism allows one to carry out strict and analytical calculations on the level of the covariance matrix, which fully characterizes considered states and their measurements outcomes. Therefore the full physical picture of the situation described in [1, 3, 4] is characterized by giving a symplectic covariance matrix of the dimension 4, representing two modes of the quantum field measured by two different observers.

4.3 Quantum gates generated by motion

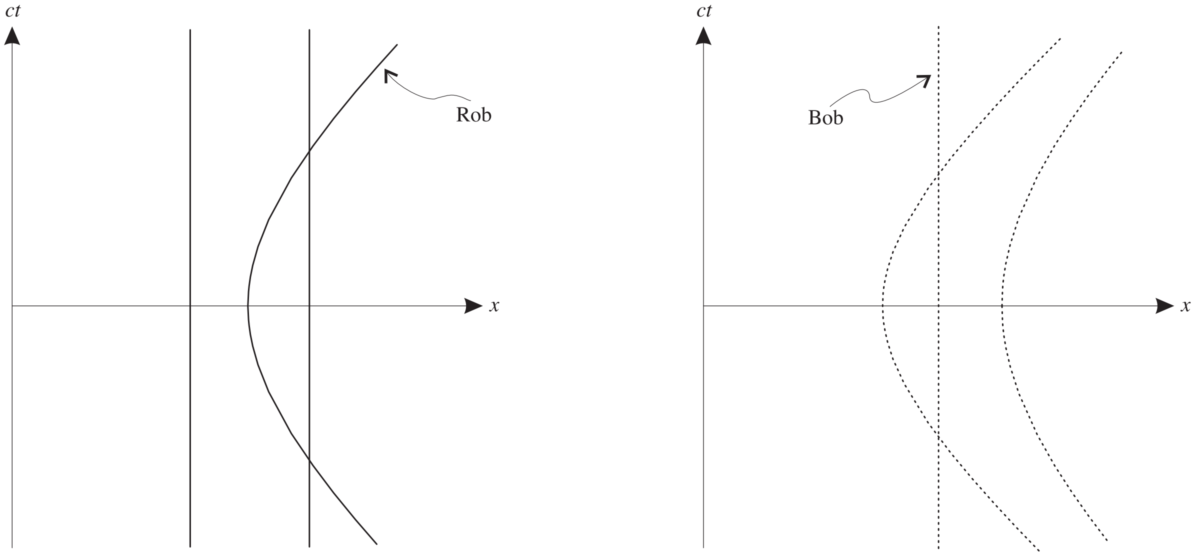
One of the concepts that strongly contributed to the flourishing of the quantum theory of information is the idea of a quantum computer - a device basing its design on the laws of quantum physics, not classical binary logic. The notion of a *bit* is replaced by a notion of a *qubit* allowing for the quantum computer to achieve computational power unreachable for the current technology computers, at least in theory. For example a quantum algorithm to decompose large numbers into primes would allow one to breach present-day security cryptographic schemes. Similarly to classical computing, quantum computation is based on a set of gates transforming input qubit states and using only a finite number of types of gates one can generate an arbitrary quantum algorithm. Two-qubit gates are built in practice using non-linear interactions between two quantum systems giving rise to a given type of evolution. The interactions must be strong enough for the involved qubit to get entangled, however it is then difficult to get rid of the interactions with the surrounding environment that leads to decoherence. The main challenge at the moment in the struggle to build the first quantum computer is to limit the influence of the environment onto the computation and design efficient error correction codes.

In [2] we have introduced an idea of building multi-qubit quantum gates without the need of interactions between individual qubits, which could help limiting the effect of the environment onto the quantum system. In the proposed scheme two input states undergo a unitary entangling transformation only due to motion of the physical systems. This purely relativistic effect, completely unknown in non-relativistic theory, has been proposed based on the scheme of a resonance cavity, whose mirrors move along controllable classical trajectories. The motion of the cavity causes the quantum state of the field in the cavity to undergo a transformation depending on the choice of the trajectory. We have shown [2], how to use natural resonances due to motion in order to generate and enhance entanglement created between individual modes of the cavity. In order to create measurable amounts of entanglement, the proper acceleration a of the mirrors must be of the order of $a \propto \frac{c^2}{L}$, where L is the length of the cavity and c the speed of light. This value is practically impossible to reach for realistic cavities, however using natural resonances allows one to enhance the effect even for small accelerations. This is possible by cyclic repetitions of appropriately chosen trajectory. In [2] we have shown how to choose the trajectory in order for the amount of generated entanglement grew linearly with the number of cycles.

The scheme proposed in [2] is based on the observation that a Bogolyubov transformation responsible for the change of the quantum state preserves the family of Gaussian states. Thanks to that the calculations can be made using covariance matrix formalism, provided that the initial state of the system was Gaussian. The calculations have been carried out for the cavity prepared initially in the vacuum state of all the modes and we have characterized the amount of entanglement of the final state using known Gaussian measures of entanglement. We have found that to a good approximation the two first eigenmodes of the cavity are transformed into a pure, entangled state due to the change in acceleration of the cavity. The generated entangled state, up to local operations turned out to be just a two-mode squeezed state and our formalism allowed us to completely characterize that state for an arbitrary choice of the trajectory. Assuming the full control over the choice of the trajectory, we could show how to enhance the generated two-mode squeezing using the natural resonances of the relativistic motion.

4.4 Testing the absolute acceleration of the reference frame using local interactions with a quantum field

The dependence of the quantum state of the motion of the observer leads to various interesting consequences. As was shown in [2], the quantum state of the field can also undergo transformation if the cavity itself is accelerated. This phenomenon can be used to determine the absolute acceleration of the observer. In [6] we have investigated the possibility of using this effect to determine an absolute acceleration of an Unruh-DeWitt particle deterctor - a device completely characterized by a quantum degree of freedom described by a single annihilation operator $\hat{d}$ [30]. The detector is approximately described by a point-like



Rysunek 1: Left: uniformly accelerated observer, Rob, measures a state of a resting cavity; right: a resting observer Bob measures the state of the accelerated cavity.

position and consequently a classical trajectory chosen at will. The description of the detector is therefore quasi-classical, but it does interact with a fully quantum and relativistic scalar field via minimum coupling introduced through the Hamiltonian:

$$\hat{H}_I(\tau) \propto \epsilon(\tau)\hat{\phi}\left[x(\tau)\right]\left(\hat{d}e^{-i\omega\tau} + \hat{d}^{\dagger}e^{i\omega\tau}\right), \tag{1}$$

where τ is the proper time along the selected tranectory $x(\tau)$ of the detector, $\epsilon(\tau)$ is a time-dependent coupling, $\hat{\phi}$ is the field operator and ω is the gap frequency characterizing the detector. In [13] we have studied two scenarios concerning the motion of the considered system, as shown in Fig. 1.

In the first scenario a uniformly accelerated detector moves along the inside of a resting cavity, as depicted on the left part of Fig. 1. The initial state of the cavity according to the resting detector is the vacuum state of al the modes. From the perspective of the accelerated observer the cavity, however, is not empty, but contains particle in all its modes. One can verify that by studying the final state of the detector after it left the cavity. We have assumed that the initial state of the detector is the ground state and the interaction with the field was turned on when the detector entered the cavity. We have calculated [6] the probability of excitation of the detector the moment it leaves the cavity, depending on the introduced proper acceleration. The calculations were carried out in the first order perturbation expansion.

In the second scenario we have assumed the opposite setting: a resting detector enters inside an accelerated cavity, which was initially empty according to the co-moving observer (the proper number of particles inside the cavity vanishes). From the perspective of the resting detector the cavity is not empty, which again can be verified by calculating the probability of exciting the detector from its initial ground state.

For small proper accelerations, when the event horizon is far outside the region of interactions, both scenarios are kinematically equivalent. From the perspective of an observer co-moving the the detector, in both scenarios the cavity accelerates relative to the detector. The question that we have studied in [6] is: in what circumstances the probability of exciting the detector in both scenarios differs. We have found that when the resonance cavity was initially empty and the scalar field considered was massless - both scenarios give identical results in the limit of small accelerations. Similarly, when the cavity initially contains some massless particles (in both scenarios). The situation changes only when the cavity field becomes massive. For initially empty cavities the two scenarios are still almost indistinguishable. But when the cavity initially has particles in one of the modes, the two scenarios lead to different results. The first and the second scenario lead to different excitation rates of the detectors in the limit of small accelerations only when the considered quantum field is massive and the cavity contains particles (in the co-moving frame of reference). For concreteness we have studied an example of a fixed number of particles (a Fock state) of one of the modes. Our conclusion gives rise to an interesting contribution to the discussion of the role of mass in relativity. It turns out that in order to detect absolute acceleration of the point-like detector one needs a massive field containing particles. Only in this case such a detector can be used to determine whether it has an asbsolute, or only relative acceleration. In the considered scheme the way the mass introduced the asymmetry between considered scenarios was due to violating conformal invariance of the field equation: only for massless fields (in a 1+1 dimensional space-time that has been studied for simplicity in [6]) the Klein-Gordon field equation is conformally invatiant. It can be explicitly shown that the predictions of the Unruh-DeWitt detection model are identical in both scenarios always, when the quantum field is indeed conformally invariant. The mass parameter of the Klein-Gordon equation is responsible for the violation of that symmetry.

4.5 Summary

The publication cycle [1, 2, 3, 4, 5, 6, 7] concerning the problems of relativistic quantum information theory is an attempt to go beyond the standard framework of quantum information. It happens often that already the relativistic formulation of a given problem can be challenging, therefore the fact that the problems presented here could be posed and solved, often without the need of using approximations, is undoubtedly a great success. The paradigm that has been employed here, that says that gravitational effects can be studied by writing down field equations of a curved background is naturally only a conceptual simplification. It is expected that the still unknown quantum gravity theory should be much more complicated. However, the approach used here allows one to obtain intermediate results between the quantum field theory and still unknown quantum gravity. Moreover, it is also expected that the results obtained with this method should, in some limit, be present also in the quantum gravity. Consequently, relativistic quantum information theory can be one of possible methods of studying the asymptotic of the quantum gravity theory. The questions about the status of the notion of quantum information and its properties in the relativistic context remind of the questions that were asked in early stages of the quantum theory. The Bohr's model of an atom being an attempt to marry the classical theory with an arbitrary postulate of quantizing the angular momentum was also fundamentally wrong, however it lead to new insights into the structure of still unknown, at that time, quantum theory of the atom and eventually - the discovery of the Schroedinger equation. The presented cycle of publications is a step towards deeper understanding of the properties of quantum information and quantum entanglement, as well as their relativistic structure.

5 Other research accomplishments

a) bibliometric data (as for 25 marca 2014)

21 research papers published in world-leading journals (mainly Phys. Rev. Lett., Phys. Rev. A, Phys. Rev. D, Class. Quantum Grav.) and 5 preprints with a total number of

394 citations and Hirsch index 9 according to *Google Scholar* and 246 citations and Hirsch index 8 according to *Web of Science*. Total Impact Factor: 67.5.

b) research not contributing to the habilitation

Below we present the remaining part of the research studies carried out by the applicant. It concerns the phenomenon of quantum non-locality (5.1), application of entangled states in quantum communication (5.2), a single collective measurement of a large number of particles (5.3), as well as a number of other topics not related directly to the main theme of the present submission (5.4).

5.1 Quantum non-locality

One of the most interesting aspects of the quantum theory is its non-locality, i.e. the fundamental inability to describe the experimental outcomes by a set of local hidden variables. As a consequence, the nature, as described by the quantum theory, cannot be both deterministic and local. This phenomenon has been studied in [20, 21]. In [21] we consider an entangled state of a qubit and a coherent state of harmonic oscillator. We have studied an optimal scheme for revealing non-locality using balanced homodyne detection scheme with imperfect particle detectors. We have analyzed the violation of Bell's inequalities depending on the quantum efficiency of the detectors and the amount of entanglement between the considered degrees of freedom. We have determined the minimum detection efficiencies allowing one for the observation of non-locality.

In [20] we have considered a different scheme for violation of the Bell's inequalities using a state of a single photon split at a symmetric beam splitter, as well as a two-mode squeezed state of the vacuum. The detection scheme involved an unbalanced homodyne detector that measured the parity operator giving a direct insight into the phase-space structure of the state. It has been shown that by an appropriate choice of the probe-points in phase-space one can study the non-locality of the input state. We have found an optimum scheme of detection even for imperfect particle detectors involved, in order to allow for a direct comparison with the available, realistic experimental setups.

5.2 Optimum communication using entangled states of light

A cycle of research papers [13, 14, 15, 16, 17] concerning the problem of communication using entangled states of light was a basis of the PhD dissertation awarded *cum laude* in 2006 in the *Physics Department* of the *University of Warsaw*.

In [17] we have studied the imperfect classical communication through a quantum channel with ideally correlated noise, i.e. disturbances that affect every transmitted particle of a given bit in exactly the same way. We have studied and determined the optimal scheme for encoding the classical information using alphabet of pairs of particles in separable (classical scenario) and entangled (quantum scenario) states. We have shown that using the entanglement increases the quantum efficiency of communication by the factor of 2.5 confirming practical usefulness of non-local states of light in communication.

In [13] we have used stochastical approach in the description of quantum channels to study other types of noise present in communication and their effect on the communication efficiency.

One of the simplest realizations of a quantum channel with correlated noise is a single mode fiber capable of transmitting photon pairs in given polarization input states. Thermal and mechanical fluctuations disturb the polarization of the transmitted pairs of photons in such a way that the output polarization state is nearly random. However due to typically long time-scales of the fluctuations, as compared to the temporal distance between the transmitted photons, the introduced disturbance is almost identical for both particles. As a consequence, due to the imperfections of the channel each individual photon of a pair undergoes the same unitary transformation. This observation allowed one to carry out an experiment verifying the theoretical results discussed earlier. Works [16, 14] introduce the experimental scheme that has been built, in which we have generated pairs of photons in well-controlled entangled states that were coupled to a 20m long single-mode fiber undergoing mechanical distortions. The photons were measured after leaving the fiber . We have managed to confirm the possibility of communication despite of the effect of the extremely noisy environment. We have reached a full agreement with the theoretical results by proving that indeed, entangled states of light give rise to substantial improvement of the communication efficiency using the polarization degree of freedom.

The source of entangled pairs used in the experiment [16, 14] was a non-linear BBO crystal generating a parametric down-conversion process. In [15] we have studied quantum-optical properties of this source of pairs of photons to determine and optimize efficiencies of photon pair generation and their coupling into single-mode fibers. The analysis was carried out particularly for the sake of experimental use and aimed at optimizing the generation and detection rates.

5.3 Single collective measurement of a large number of particles

One of the less known aspects of the quantum theory was the problem of a single collective measurement of a large number of particles. This gap has been filled partially in by the research paper [12], where we have studied the probability distribution of obtaining given histograms in the position measurements of a large number of interfering particles. Although the result of a single measurement in the quantum theory is in general indefinite in advance, in the case of collective measurement one can predict general features characterizing the obtained histograms. In [12] we have analytically proven the results that were previously only studied experimentally and numerically. We have investigated the effect of interference of two independent Bose-Einstein condensates and showed that even when the relative phase between the two condensates is indetermined, it will spontaneously induce itself during the measurement process.

Another problem devoted to the dynamics of the Bose-Einstein condensate, namely concerning the interaction between the condensate and surrounding thermal cloud, has been studied in [19]. The calculations were made for the condensate of Helium-4 atoms in the concrete experimental realization carried out in the experimental group of *Vrije Universiteit* in Amsterdam (Holland).

5.4 Other studies

Other research topics of the applicant involve a wide spectrum of problems. The works [8, 18] are related to special relativity: in [18] we have derived a detailed expression describing observable shapes of objects moving with relativistic speeds taking into account the delay of light reaching the observer, and in [8] we have presented a new, very simple and general derivation of the Thomas precession, i.e. the effect of change of spacial orientation of an object moving along a time-dependent trajectory.

In [11] we have introduced and studied a model of interaction between a network of qubits that leads to generation of cluster states, i.e. the basic resource for quantum computing in the measurement based formulation. We have investigated the conditions for which the cluster states can be generated simply by cooling down an interacting quantum system with appropriately chosen Hamiltonian.

The problem of interaction between a qubit and continuous variable system has been studied in [10] using James-Cummings model. We have analytically shown how entanglement can be swapped between a qubit and a harmonic oscillator system and discussed the role of collapses and revivals known from the systems having equally spaced spectrum of energies.

In our work [9] we have proposed a new way of precise measurements of the low temperatures using Berry phase induced in the Unruh-DeWitt model of interaction for the case, when the interaction effectively takes place with only a single mode of the quantum field. We have shown how highly precise measurements can be achieved, although the measurement device does not reach thermal equilibrium with the surrounding environment, as for the most examples of thermometers.

c) awards

- Scholarship *Socrates-Erazmus*, *Vrije Universiteit*, Amsterdam, Holland (2000).
- Scholarship from *European Science Foundation*, *University of Oxford*, UK (2001).
- *First Award of the Polish Physical Society* for the best MSc thesis in physics in Poland in 2001.
- Scholarship from *Clarendon Laboratory*, *University of Oxford*, UK (2002).
- Scholarship from *European Science Foundation*, *University of Oxford*, UK (2002).
- Yearly *National Award for Young Scholars, Foundation for Polish Science* (2003).

- Yearly *National Award for Young Scholars, Foundation for Polish Science* (2004).
- *Stay with us* scholarship from the major weekly Polish magazine *Polityka* (2004).
- Three-year *Scholarship for Outstanding Young Scientists from Polish Minister of Education.* (2010-2013).

d) directing research projects

- *Sonata BIS - Relativistic Quantum Information*, research grant from *National Science Center* founded to create a research group, Poland (2013-2017).

e) participation in research projects

- Grant *Laboratorium Krajowe FAMO*, Poland (2002).
- Grant *Coherent States in Quantum Information*, *Imperial College London*, UK (2008-2009).
- Grant *Relativistic Quantum Information*, *University of Nottingham* (2010-2012).

f) invited conference talks

- *International Conference of Quantum Optics*, Mińsk, Belarus (2004).
- *Relativistic Quantum Information*, Brisbane, Australia (2010).
- *Relativistic Quantum Information*, Durban, South Africa (2010).
- *Relativistic Quantum Information*, Brisbane, Australia (2011).
- *Relativistic Quantum Information Workshop*, Nottingham, UK (organizer, 2013).
- *Entanglement in Curved Spacetimes*, BANFF, Canada (2013).
- *Conference of the National Center for Quantum Information*, Gdańsk, Poland (2013).
- *Zjazd Fizyków Polskich*, Poznań, Poland (2013).

- *International Program on Quantum Information*, Bhubaneswar, Indie (2014; participation cancelled).
- *Relativistic Quantum Metrology*, Nottingham, UK (2014).
- *SPIE Quantum Communications and Quantum Imaging XII Conference*, San Diego, USA (2014).
- *International Workshop on Relativistic Quantum Information*, Seoul, South Korea (2014).

g) national and international collaboration

- *Vrije Universiteit* (Amsterdam, Holland) - collaboration with prof. Wim Vassen on the dynamics of the Bose-Einstein condensate (1999-2000).
- *University of Oxford* (UK) - collaboration with prof. Konrad Banaszek on the quantum nonlocality and optimal strategy in quantum communication (2001-2002).
- *National Institute for Informatics* (Tokio, Japan) - collaboration with dr. Jason Doukas on the localised detection scheme of relativistic fields in non-inertial frames (2011-2013).
- *IQC, University of Wateloo, Perimeter Institute* (Canada) - collaboration with prof. Robert Mann on the use of quantum interactions in precise thermometry (2012-2014).
- *University of Queensland* (Australia) - collaboration with prof. Tim Ralph on the quantum communcation in curved spacetime (2012).
- Participation in the Council of the *International Society of Relativistic Quantum Information* (2013).
- Co-establishing the *Relatvistic Quantum Information Group of University of Nottingham and University of Warsaw* (UK), (2013).

- *Adama Mickiewicz University* (Poznań, Poland) - collaboration with prof. Andrzej Grudka on the interactions of point-like quantum systems with the vacuum (2013-2014).

- *Centre for Quantum Technologies* (Singapore) - collaboration with dr. Agata Chęcińska on the Bogolyubov transformation invariants and their connection with the black hole dynamics (2013-2014).

- *Hebrew University of Jerusalem* (Israel) - collaboration with dr. David Bruschi on the cavity resonances and their role in entanglement generation due to motion (2013-2014).

Literatura

[1] A. Dragan, J. Doukas, E. Martin-Martinez, and DE Bruschi, *Localized projective measurement of a quantum field in non-inertial frames*, Class. Quantum Grav. **30**, 235006 (2013).

[2] D. E. Bruschi, A. Dragan, A. Lee, I. Fuentes, and J. Louko, *Relativistic Motion Generates Quantum Gates and Entanglement Resonances*, Phys. Rev. Lett. **111**, 090504 (2013).

[3] A. Dragan, J. Doukas, and E. Martin-Martinez, *Localized detection of quantum entanglement through the event horizon*, Phys. Rev. A **87** 052326 (2013).

[4] J. Doukas, E. G. Brown, A. Dragan, and R. B. Mann, *Entanglement and discord: Accelerated observations of local and global modes*, Phys. Rev. A **87**, 012306 (2013).

[5] D. E. Bruschi, A. Dragan, I. Fuentes, J. Louko, *Particle and antiparticle bosonic entanglement in noninertial frames*, Phys. Rev. D **86**, 025026 (2012).

[6] A. Dragan, I. Fuentes, and J. Louko, *Quantum accelerometer: Distinguishing inertial Bob from his accelerated twin Rob by a local measurement*, Phys. Rev. D **83**, 085020 (2011).

[7] D. E. Bruschi, J. Louko, E. Martin-Martinez, A. Dragan, and I. Fuentes, *Unruh effect in quantum information beyond the single-mode approximation*, Phys. Rev. A **82**, 042332 (2010).

[8] A. Dragan and T. Odrzygozdz, *Half-page derivation of the Thomas precession*, Am. J. Phys. **81**, 631 (2013).

[9] E. Martin-Martinez, A. Dragan, R. B. Mann, and I. Fuentes, *Berry phase quantum thermometer*, New. J. Phys **15**, 053036 (2013).

[10] R. Kennedy, L. Horstmeyer, A. Dragan, and T. Rudolph, *Qubit initialization and readout with finite coherent amplitudes in cavity QED*, Phys. Rev. A **82**, 054302 (2010).

[11] D. Jennings, A. Dragan, S. D. Barrett, S. D. Bartlett, and T. Rudolph, *Quantum computation via measurements on the low-temperature state*, Phys. Rev. A **80**, 032328 (2009).

[12] A. Dragan and P. Zin, *Interference of Fock states in a single measurement*, Phys. Rev. A **76**, 42124 (2007).

[13] A. Dragan and K. Wodkiewicz, *Depolarization channels with zero-bandwidth noises*, Phys. Rev. A **71**, 012322 (2005).

[14] A. Dragan, W. Wasilewski, K. Banaszek, and C. Radzewicz, *Demonstrating Entanglement-Enhanced Communication over Noisy Comm. Channels*, AIP Conf. Proc. **734**, 55 (2004).

[15] A. Dragan, *Efficient fiber coupling of down-conversion photon pairs*, Phys. Rev. A **70**, 053814 (2004).

[16] K. Banaszek, A. Dragan, W. Wasilewski, and C Radzewicz, *Experimental demonstration of entanglement-enhanced classical communication*, Phys. Rev. Lett. **92**, 257901 (2004).

[17] J. Ball, A. Dragan, and K. Banaszek, *Exploiting entanglement in communication channels with correlated noise*, Phys. Rev. A **69**, 042324 (2004).

[18] A. Nowojewski, J. Kallas, and A. Dragan, *On the Appearance of Moving Bodies*, Amer. math. month. **111**, 817 (2004).

[19] P. Ziń, A. Dragan, S. Charzyński, N. Herschbach, P. Tol, W. Hogervorst, and W. Vassen, *The effect of atomic transfer on the decay of a BEC*, J. Phys. B 36, L149 (2003).

[20] K Banaszek, A Dragan, K Wódkiewicz, and C Radzewicz, *Direct measurement of optical quasidistribution functions: Multimode theory*, Phys. Rev. A **66**, 043803 (2002).

[21] A. Dragan, and K. Banaszek, *Homodyne Bell's inequalities for entangled mesoscopic superpositions*, Phys. Rev. A 63, 062102 (2001).

[22] J. Lindkvist, C. Sabín, I. Fuentes, A. Dragan, I. Svensson, P. Delsing, and G. Johansson, *Twin paradox with superconducting circuits*, arXiv/quant-ph:1401.0129 (2014).

[23] J. Doukas, G. Adesso, S. Pirandola, and A. Dragan, *Discriminating quantum field theories in curved spacetime*, arXiv/quant-ph:1306.4474 (2013).

[24] S. W. Hawking, *Black hole explosions?*, Nature **248**, 5443 (1974):

[25] W. G. Unruh, *Notes on black-hole evaporation*, Phys. Rev. D **14**, 870 (1976).

[26] B. Reznik, A. Retzker, and J. Silman, *Violating Bell's inequalities in vacuum*, Phys. Rev. A **71**, 042104 (2005).

[27] N. Friis, A. R. Lee, K. Truong, C. Sabín, E. Solano, G. Johansson, and I. Fuentes, *Relativistic Quantum Teleportation with Superconducting Circuits*, Phys. Rev. Lett. **110**, 113602 (2013).

[28] P. M. Alsing and G. J. Milburn, Phys. Rev. Lett. **91**, 180404 (2003); I. Fuentes-Schuller, and R. B. Mann, Phys. Rev. Lett. **95**, 120404 (2005).

[29] M. Montero and E. Martín-Martínez, Phys. Rev. A **85**, 024301 (2012); J. Chang and Y. Kwon Phys. Rev. A **85**, 032302 (2012); D. Hosler, C. van de Bruck, and P. Kok Phys. Rev. A **85**, 042312 (2012); M. Ramzan, Quantum Information Processing, January

2013, Volume 12, Issue 1, pp 83-95; M. Ramzan Chinese Physics Letters **29**, 020302 (2012); J. Wang and J. Jing Phys. Rev. A **83**, 022314 (2011); E. Martín-Martínez and I. Fuentes Phys. Rev. A **83**, 052306 (2011); M. Montero and E. Martín- Martínez Phys. Rev. A **83**, 062323 (2011); M. Montero and E. Martín-Martínez Phys. Rev. A **84**, 012337 (2011); B. Nasr Esfahani, M. Shamirzaie, and M. Soltani Phys. Rev. D **84**, 025024 (2011); M. Montero, J. Leon, and E. Martín-Martínez Phys. Rev. A **84**, 042320 (2011); N. Friis, P. Kohler, E. Martín-Martínez, and R. A. Bertlmann Phys. Rev. A **84**, 062111 (2011); A. Smith and R.B. Mann, Phys. Rev. A **86**, 012306 (2012); M. Ramzan, M. K. Khan Quant. Inf. Process. **11**, 443 (2012); J. Wang, J. Jing Ann. Phys. (NY) **327**, 283 (2012); Min-Zhe Piao, X. Ji, J. Mod. Opt. **59** 21 (2011); S. Khan J. Mod. Opt. **59** 250 (2012); Y. Wang, X. Ji, J. Mod. Opt. **59** 571 (2012);J. Deng, J. Wang, J. Jing, Phys. Lett. B **695**, 495 (2011).

[30] N. D. Birrell, P. C. W. Davies, *Quantum Fields in Curved Space*, Cambridge Monographs on Mathematical Physics (Cambridge, 1984).