AUTOPRESENTATION

1 NAME AND FAMILY NAME

Alexander Streltsov

born on 25 July 1983

2 DIPLOMAS AND SCIENTIFIC DEGREES

- **Doctor of Natural Science (Dr. rer. nat.)**
  Date: 14 June 2013
  Thesis title: *The role of quantum correlations beyond entanglement in quantum information theory*
  Supervisor: Prof. Dr. Dagmar Bruß
  Research unit: Faculty of Mathematics and Natural Sciences,
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  Grade: summa cum laude (best grade)
- **Diploma in Physics**
  Date: 30 September 2009
  Thesis title: *Entanglement of random states*
  Supervisor: Prof. Dr. Haye Hinrichsen
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3 INFORMATION ON PREVIOUS EMPLOYMENT IN SCIENTIFIC INSTITUTIONS

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- **Postdoctoral researcher, Polonez 2 fellow**
  Faculty of Applied Physics and Mathematics,
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- **Postdoctoral researcher, Humboldt fellow**
  Department of Physics, Freie Universität Berlin, Germany
  Dates: 2/2016 – 1/2017
- **Postdoctoral researcher, Humboldt fellow**
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  Dates: 11/2013 – 11/2015
- **Postdoctoral researcher**
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  Dates: 6/2013 – 9/2013

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- **Visiting student**
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  Visit upon invitation of Dr. Wojciech H. Żurek
  Dates: 7/2012-9/2012
- **PhD student**
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  Heinrich Heine University Düsseldorf, Germany
  Dates: 12/2009-6/2013

4 DESCRIPTION OF THE ACHIEVEMENT SET OUT IN ART. 219 PARA 1 POINT 2 OF THE ACT OF 20 JULY 2018 HIGHER EDUCATION AND SCIENCE LAW (JOURNAL OF LAWS OF 2018, ITEM 1668 WITH AMENDMENTS)

4.1 Title of the scientific achievement

A series of articles entitled:
Quantum resource theories and their applications for quantum communication

4.2 List of publications forming the scientific achievement (chronological order)

[H1] **A. Streltsov**, U. Singh, H. S. Dhar, M. N. Bera, and G. Adesso, *Measuring Quantum Coherence with Entanglement*, Phys. Rev. Lett. **115**, 020403 (2015).

[H2] **A. Streltsov**, S. Lee, and G. Adesso, *Concentrating Tripartite Quantum Information*, Phys. Rev. Lett. **115**, 030505 (2015).

[H3] **A. Streltsov**, E. Chitambar, S. Rana, M. N. Bera, A. Winter, and M. Lewenstein, *Entanglement and Coherence in Quantum State Merging*, Phys. Rev. Lett. **116**, 240405 (2016).

[H4] J. I. de Vicente and **A. Streltsov**, *Genuine quantum coherence*, J. Phys. A **50**, 045301 (2017).

[H5] **A. Streltsov**, S. Rana, M. N. Bera, and M. Lewenstein, *Towards Resource Theory of Coherence in Distributed Scenarios*, Phys. Rev. X **7**, 011024 (2017).

[H6] **A. Streltsov**, S. Rana, P. Boes, and J. Eisert, *Structure of the Resource Theory of Quantum Coherence*, Phys. Rev. Lett. **119**, 140402 (2017).

[H7] **A. Streltsov**, G. Adesso, and M. B. Plenio, *Colloquium: Quantum coherence as a resource*, Rev. Mod. Phys. **89**, 041003 (2017).

[H8] K.-D. Wu, T. Theurer, G.-Y. Xiang, C.-F. Li, G.-C. Guo, M. B. Plenio, and **A. Streltsov**, *Quantum coherence and state conversion: theory and experiment*, npj Quantum Information **6**, 22 (2020).

[H9] **A. Streltsov**, *Quantum state merging with bound entanglement*, New J. Phys. **22**, 023032 (2020).

[H10] **A. Streltsov**, C. Meignant, and J. Eisert, *Rates of Multipartite Entanglement Transformations*, Phys. Rev. Lett. **125**, 080502 (2020).

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4.3 Description of the scientific achievement

Quantum phenomena like entanglement and coherence are responsible for the departure between classical and quantum physics. They are also relevant for the rapidly developing quantum technologies, allowing for fundamentally new approaches for problems which are not solvable with the use of classical devices. The framework of quantum resource theories allows for a quantitative investigation of entanglement and coherence and their role in quantum technological applications.

All ten articles [H1-H10] which constitute the presented achievement explore quantum coherence and entanglement in quantum-mechanical systems, the interrelations between them, and applications of entanglement and coherence as resources for quantum communication tasks. In [H1] we presented the first theoretical approach for entanglement activation from quantum coherence, also giving a quantitative relation between entanglement and coherence in quantum systems. The results in [H1] can also be seen as a first step towards extending the resource theory of coherence to distributed scenarios, which has been developed further in [H5]. In [H6, H8] we explored the resource theory of coherence in the single-copy regime, characterizing transitions of quantum systems via incoherent processes, including experimental demonstration with quantum optics [H8]. In [H4] we introduced and studied an alternative approach for coherence theory, which respects possible energy constraints of the system. The role of coherence and entanglement for quantum communication has been investigated in [H2, H3, H9, H10]. The most recent review on the resource theory of quantum coherence and its role in quantum technology can be found in [H7].

This part of the autopresentation is organized as follows. Section 4.3.1 gives an introduction into quantum resource theories. Section 4.3.2 focuses on the resource theory of quantum coherence. Section 4.3.3 discusses the structure of coherence theory and incoherent state conversion. Section 4.3.4 considers the resource theory of coherence in distributed scenarios. Section 4.3.5 discusses the role of coherence and entanglement for quantum communication tasks. A brief summary and outlook are given in Section 4.3.6.

4.3.1 Introduction to quantum resource theories

Quantum resource theories [1] provide a strong mathematical framework, allowing for a systematic investigation of quantum features and their applications in quantum technologies. The basis of any quantum resource theory are free states and free operations. Free states are quantum states which are provided at no cost, and free operations are manipulations of the quantum system which can be performed without consumption of resources. The concrete choice of the free states and operations depends on the theory under study, and is typically justified by experimental and technological limitations. In the resource theory of entanglement [2, 3, 4, 5] the constraints are determined by the technological limitations of two spatially separated parties, who can perform quantum measurements in their local labs, but cannot exchange quantum particles between each other. Nevertheless, they can exchange classical information without additional cost, e.g. via a standard telephone. These are very natural assumptions which accurately capture the present state of the art in quantum technology: while we have very good control over quantum systems in a lab, sending entangled particles via large distances still remains a major challenge despite remarkable recent progress reporting entanglement distribution over 1200 kilometers [6]. The free operations in entanglement theory are usually denoted as local operations and classical communication (LOCC), and the free states are called separable states [5]:

$$\rho_{\mathrm{sep}} = \sum_i p_i \rho_i^A \otimes \rho_i^B. \tag{1}$$

An important state in entanglement theory is the singlet state:

$$|\Psi^-\rangle = \frac{1}{\sqrt{2}}(|01\rangle - |10\rangle). \tag{2}$$

This state can be regarded as a golden unit of the theory, as it can be converted into any other state via free operations [5]. Entanglement is one of the most important resources for quantum technology, as it can be used for such fundamental tasks as quantum teleportation [7] and quantum cryptography [8].

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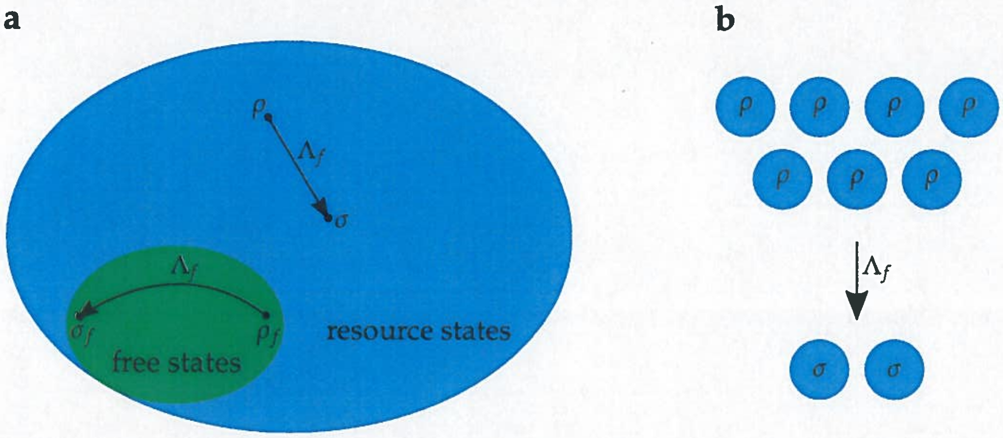

Figure 1: **a:** General structure of quantum resource theories. Any free operation Λ_f leaves a free state ρ_f within the set of free states (green area). States which are not free are also called *resource states* (blue area). Applying a free operation Λ_f onto a resource state ρ allows to convert it into another resource state σ. **b:** Asymptotic conversion between resource states $\rho \longrightarrow \sigma$ with rate 2/7.

While the resource theory of entanglement was one of the first quantum resource theories, recent results show that not all quantum technological applications are based on the presence of entanglement, but require other types of nonclassicality, such as quantum discord [9] and coherence [H7]. This observation has led to the development of other quantum resource theories, such as quantum thermodynamics [10, 11] and coherence [12, 13]. In the resource theory of quantum thermodynamics the free operations preserve the total energy of a system and its environment, and the free state is the well-known Gibbs state. The resource theory of coherence captures the situation where one is lacking the ability to create superpositions in a reference basis. This theory will be discussed in more detail in the next section.

The sets of free states and operations define the basic structure of the resource theory, and in many cases allow to answer fundamental questions within the theory in question. One of the most important questions concerns the *state conversion problem*, asking whether two states can be converted into each other via a free operation, see Fig. 1 a. The solution to this problem defines an order on the state space, allowing to identify most useful states of the theory as those states from which all other states can be created. If a state ρ cannot be converted into another state σ with certainty, there might still be the possibility of stochastic conversion with probability $P(\rho \to \sigma)$. Another important problem within any quantum resource theory is concerned with asymptotic state conversion, where N copies of an initial state ρ are available. The aim of the process is to convert these N copies of ρ into M copies of another state σ, by using the free operations of the corresponding resource theory, see Fig. 1 b. The figure of merit in this context is the maximal conversion rate $R = M/N$, taken in the limit of infinitely many copies of the initial state. In the resource theory of entanglement one typically assumes that the target state σ is the singlet state $|\Psi^-\rangle$, in which case the rate R is called distillable entanglement [14, 4]. Alternatively, by setting the initial state to $|\Psi^-\rangle$, the inverse conversion rate $1/R$ is known as the entanglement cost [15] of the target state σ.

Resource measures allow to quantify the resource amount of a quantum state ρ. Any resource measure $R(\rho)$ is nonnegative, and $R(\sigma) = 0$ for any free state σ. Moreover, any resource measure does not increase under the action of free operations:

$$R(\Lambda_f[\rho]) \leq R(\rho) \tag{3}$$

for any free operation Λ_f. Distillable entanglement and entanglement cost discussed above are both resource measures within the resource theory of entanglement.

4.3.2 Resource theory of quantum coherence

Quantum coherence is a fundamental property of quantum systems which arises from the superposition principle of quantum mechanics. Given two orthogonal quantum states $|\uparrow\rangle$ and $|\downarrow\rangle$ (which could for example denote

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"spin up" and "spin down" for a spin-$\frac{1}{2}$ particle), any superposition of the form

$$|\psi\rangle = a\,|{\uparrow}\rangle + b\,|{\downarrow}\rangle \tag{4}$$

also denotes a valid quantum state if the normalization condition $|a|^2 + |b|^2 = 1$ is fulfilled. We say that for $a, b \neq 0$ the state $|\psi\rangle$ has coherence in the $\{|{\uparrow}\rangle, |{\downarrow}\rangle\}$ basis. Clearly, coherence is a basis-dependent concept, i.e., a state which has coherence in one particular basis does not necessarily have coherence in another. However, in many experimentally relevant scenarios one particular basis is indeed singled out by the unavoidable decoherence. This means that it is reasonable to treat different bases on a different footing.

Quantum coherence plays an important role in several tasks which are based on the laws on quantum mechanics [H7]. A prominent example is quantum metrology [16], where one aims to estimate a parameter φ, encoded in a unitary evolution $U_\varphi = e^{-i\varphi H}$. If the unitary U_φ acts on a quantum state $|\psi\rangle$, the final state $U_\varphi\,|\psi\rangle$ will contain information about φ if and only if the state $|\psi\rangle$ has coherence in the eigenbasis of H. In quantum thermodynamics, quantum coherence with respect to the energy eigenstates plays a crucial role for understanding possible transitions via energy-preserving processes [17, 18, 19, 20]. Recent results also show that quantum coherence is more relevant than entanglement for capturing the performance of certain quantum algorithms [21, 22]. In the light of these results, it is natural to ask about the general role of coherence in quantum information theory. One such general approach is the study of coherence as a resource for quantum state manipulation, i.e., the introduction of the *resource theory of coherence* [12, 13]. While other quantum resource theories – such as entanglement [2, 3, 4, 5] – have been investigated for a long time, it is surprising that the resource theory of coherence has been developed only quite recently. While the approach presented in [12] attracted considerable attention and most of today's literature on coherence is based on this work, first steps in this direction were made in [23], where a resource theory of superposition has been developed. Another related approach is known as the resource theory of asymmetry [24, 25].

In the resource theory of coherence the set of free states is called incoherent [12], these are all states which are diagonal in a fixed reference basis $\{|i\rangle\}$, i.e, they can be written as

$$\sigma = \sum_i p_i\,|i\rangle\langle i|\,. \tag{5}$$

The set of incoherent states will be denoted by $\mathcal{I}$. The definition of free operations is not unique, and several alternative concepts have been proposed over the last years, based on physical or mathematical considerations [H7]. The largest possible set of free operations is called maximally incoherent operations (MIO) [23]. These are quantum operations which preserve the set of incoherent states:

$$\Lambda_{\mathrm{MIO}}[\sigma] \in \mathcal{I} \tag{6}$$

for any $\sigma \in \mathcal{I}$. A subset of MIO are incoherent operations (IO) [12, 13]. These are operations which can be written as

$$\Lambda_{\mathrm{IO}}[\rho] = \sum_i K_i \rho K_i^\dagger \tag{7}$$

with incoherent Kraus operators K_i, i.e., $K_i \sigma K_i^\dagger / \mathrm{Tr}[K_i \sigma K_i^\dagger] \in \mathcal{I}$ for any incoherent state σ. This definition is motivated by the fact that the operation in Eq. (7) cannot create coherence even if interpreted as a generalized measurement with postselection on the possible outcomes. For an overview over the different classes of operations and their properties we refer to the review article [H7]. An important state in the resource theory of coherence is the maximally coherent state

$$|+\rangle_d = \frac{1}{\sqrt{d}} \sum_{i=0}^{d-1} |i\rangle\,, \tag{8}$$

where d is the dimension of the Hilbert space. By using incoherent operations, it is possible to convert $|+\rangle_d$ into any other state of the same dimension [12].

It is further interesting to observe that a general incoherent operation which is incoherent in one experimental

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realization can potentially create a large amount of coherence in a different experimental realization, i.e. in a different Kraus decomposition [H4]. As an example, consider a single-qubit operation with the Kraus operators

$$K_0 = |0\rangle\langle +|, \quad K_1 = |1\rangle\langle -| \tag{9}$$

with $|\pm\rangle = (|0\rangle \pm |1\rangle)/\sqrt{2}$. These Kraus operators are incoherent, since $K_i|\psi\rangle \sim |i\rangle$ for any pure state $|\psi\rangle$. However, the same operation can also be expressed with Kraus operators [H4]

$$L_\pm = \frac{1}{\sqrt{2}}(|0\rangle\langle +| \pm |1\rangle\langle -|). \tag{10}$$

These Kraus operators are not incoherent, since $L_\pm|0\rangle = |\pm\rangle$. This observation was the starting point of the investigation performed in [H4], where we introduced in particular the sets of operations listed in the following.

- Genuinely incoherent operations (GIO): operations which preserve all incoherent states, i.e., $\Lambda[\sigma] = \sigma$ for any incoherent state σ.
- Fully incoherent operations (FIO): operations which are incoherent in any Kraus decomposition.

GIO is a subset of FIO, which implies that both sets are incoherent regardless of their particular Kraus decomposition [H4]. The set GIO is also interesting from the point of view of quantum thermodynamics, since these operations do not allow for transitions between different incoherent states, and thus can be seen as incoherent operations with additional constraints (such as energy preservation) [H4].

A thorough investigation of GIO and FIO in [H4] reveals several interesting properties of these operations. In particular, GIO do not have a golden unit: there does not exist a single state which can be converted into all other states via GIO. While GIO allow only for transformations into states with the same diagonal elements, more general transformations can be obtained if probabilistic transitions are considered [H4]. While FIO is a superset of GIO, also this set of operations does not have a golden unit, and state transformations are in general only possible between restricted families of states [H4]. An important insight from these results is the finding that any resource theory of coherence which has a golden unit must contain free operations which create coherence in some Kraus decomposition [H4].

4.3.3 Structure of coherence theory and incoherent state conversion

A general quantum operation acting on a Hilbert space of dimension d can always be written as $\Lambda[\rho] = \sum_i K_i \rho K_i^\dagger$ with (at most) d^2 Kraus operators. Recalling that an incoherent operation can always be decomposed into incoherent Kraus operators K_i, it is interesting to ask how many incoherent Kraus operators are required in this decomposition. Note that the minimal number of incoherent Kraus operators might (in general) be larger than d^2. This problem was addressed in [H6], where we have shown that any incoherent operation admits a decomposition with at most $d^4 + 1$ incoherent Kraus operators. For $d = 2$ and $d = 3$ we improved these numbers to 5 and 39 incoherent Kraus operators, respectively. We note that these bounds are not optimal in general. In particular, it has been proven later that for $d = 2$ any incoherent operation can be represented with (at most) 4 incoherent Kraus operators [26].

The results in [H6] served as a basis for investigating quantum state conversion via incoherent operations, both in deterministic and stochastic setups. A state ρ can be converted into another state σ via deterministic incoherent operations if

$$\sigma = \Lambda[\rho] \tag{11}$$

for some incoherent operation Λ. If deterministic conversion between two states ρ and σ is not possible, they might still allow for stochastic incoherent conversion

$$\sigma = \frac{1}{q}\sum_i K_i \rho K_i^\dagger \tag{12}$$

with an incomplete set of incoherent Kraus operators K_i such that $\sum_i K_i^\dagger K_i \leq \mathbb{1}$ and probability $q = \mathrm{Tr}[\sum_i K_i \rho K_i^\dagger]$.

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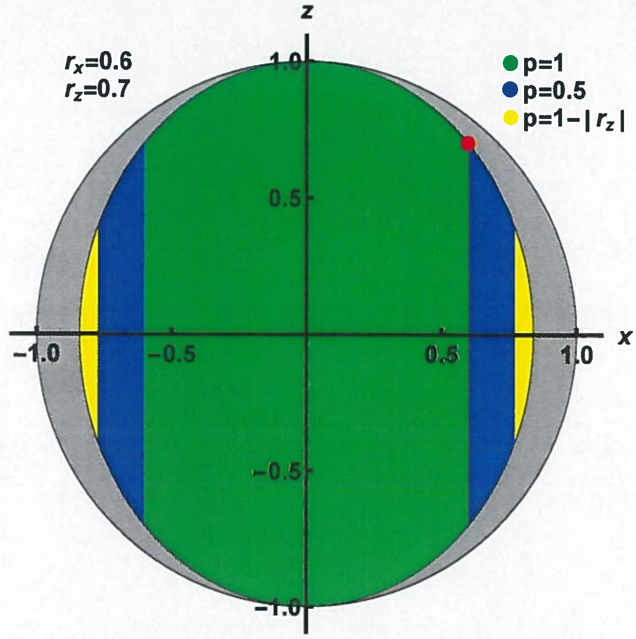

Figure 2: Stochastic incoherent state conversion for the initial state with Bloch vector $\boldsymbol{r} = (0.6, 0, 0.7)$. Green area shows the region of states achievable with probability 1. All states in the blue area are achievable with probability $p \geq 0.5$, see also Eq. (15). All states in the yellow area are achievable with probability $p \geq 1 - |r_z| = 0.3$. Gray area is not accessible with any nonzero probability. The figure shows the x-z plane of the Bloch sphere, the entire achievable region is obtained by rotation around the z-axis. The figure is taken from [27].

The figure of merit in this task is the optimal conversion probability, defined as

$$P(\rho \to \sigma) = \sup\left\{\mathrm{Tr}\left[\sum_i K_i \rho K_i^\dagger\right] : \sigma = \frac{\sum_i K_i \rho K_i^\dagger}{\mathrm{Tr}\left[\sum_i K_i \rho K_i^\dagger\right]}\right\}. \tag{13}$$

In [H8] we gave a closed expression for $P(\rho \to \sigma)$ for any pair of single-qubit states. Denoting the Bloch vectors of the initial and the final state with $\boldsymbol{r}$ and $\boldsymbol{s}$, respectively, and defining $r = \sqrt{r_x^2 + r_y^2}$, it holds that $P(\rho \to \sigma) = 0$ if

$$r^2 s_z^2 + (1 - r_z^2) s^2 > r^2, \tag{14}$$

and otherwise

$$P(\rho \to \sigma) = \min\left\{\frac{r^2}{(1 + |r_z|)\, s^2}\left[1 + \sqrt{1 - \frac{s^2\left(1 - r_z^2\right)}{r^2}}\right], 1\right\}. \tag{15}$$

The deterministic conversion $P(\rho \to \sigma) = 1$ is contained in Eq. (15) as a special case. The deterministic case has been considered previously in [H6] and [28, 29, 30]. In Fig. 2 we show the set of states achievable via deterministic and stochastic incoherent operations for an initial state with the Bloch vector $\boldsymbol{r} = (0.6, 0, 0.7)$. Interestingly, for mixed initial states there exists a region of states which is not accessible with any non-zero probability (gray area in Fig. 2).

Experimental incoherent state conversion has been performed in [H8]. For this, an optical setup has been devised, allowing to perform optimal incoherent operations which lead to the maximal conversion probability given in Eq. (15). This setup has also been used for assisted incoherent state conversion which will be discussed in more detail in the next section.

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4.3.4 Resource theory of coherence in distributed scenarios

In [H1, H5, H8] we developed the resource theory of coherence in distributed scenarios, allowing to investigate quantum coherence as a resource in multipartite quantum systems. The basis for this framework is the definition of fully incoherent states [H1]

$$\sigma^{AB} = \sum_{i,j} p_{ij} |i\rangle\langle i|^A \otimes |j\rangle\langle j|^B, \tag{16}$$

where $|i\rangle^A$ and $|j\rangle^B$ are incoherent states of the subsystem A and B respectively. A bipartite incoherent operation is then defined via $\Lambda[\rho^{AB}] = \sum_i K_i \rho^{AB} K_i^\dagger$, where the Kraus operators K_i do not create coherence in the product basis $\{|i\rangle^A |j\rangle^B\}$. As was shown in [H1], via bipartite incoherent operations any nonzero amount of coherence can always be converted into entanglement. In particular, given a state ρ and an ancilla in some incoherent state σ_i, via bipartite incoherent operations it is possible to create entanglement from the total state $\rho \otimes \sigma_i$ if and only if the state ρ has coherence. A quantitative relation between coherence and entanglement was also presented in [H1], making use of general distance-based entanglement and coherence measures:

$$E(\rho) = \min_{\mu \in \mathcal{S}} D(\rho, \mu), \qquad C(\rho) = \min_{\sigma \in \mathcal{I}} D(\rho, \sigma). \tag{17}$$

Here, $\mathcal{S}$ is the set of separable states, and D is a contractive distance on the set of quantum states, having the property $D(\Lambda[\rho], \Lambda[\sigma]) \leq D(\rho, \sigma)$ for any quantum operation Λ. In this way, the quantities in Eq. (17) are monotonic under the corresponding class of free operations. As was shown in [H1], for any entanglement and coherence measure of the form (17) the amount of entanglement generated from a state ρ via a bipartite incoherent operation Λ acting on $\rho \otimes \sigma_i$ is bounded above by the coherence of ρ:

$$E(\Lambda[\rho \otimes \sigma_i]) \leq C(\rho). \tag{18}$$

Moreover, given an arbitrary entanglement measure, the maximal amount of entanglement that can be created from the state $\rho \otimes \sigma_i$ via bipartite incoherent operations always gives rise to a coherence measure on ρ [H1].

Another important element of coherence theory in distributed scenarios are *local incoherent operations and classical communication (LICC)*. The LICC operations were introduced and studied in [H5] and independently in [31]: they capture the situation of two spatially separated parties Alice and Bob who can perform incoherent operations in their local labs. Moreover, Alice and Bob have access to a classical communication channel. Thus, LICC operations play a similar role as LOCC in entanglement theory. LICC operations transform a fully incoherent state into another fully incoherent state, see Eq. (16).

Fully incoherent states in Eq. (16) capture a symmetric scenario, where Alice and Bob are both subject to the same local constraints. It is also interesting to consider an asymmetric setting, where Alice can perform arbitrary quantum operations locally, while Bob can only perform incoherent operations in his lab. In this setting, an important family are quantum-incoherent states (see [H5], [O14], and [32, 22]):

$$\sigma^{AB} = \sum_i p_i \sigma_i^A \otimes |i\rangle\langle i|^B, \tag{19}$$

where $\{|i\rangle^B\}$ is the fixed incoherent basis of Bob and σ_i^A are arbitrary states of Alice. The importance of this class lies in the fact that this class is invariant under *local quantum-incoherent operations and classical communication (LQICC)* (see [H5] and [O14]). The LQICC operations are defined in the same way as LICC, up to the fact that Alice can perform all quantum operations locally.

Both, the LICC and LQICC operations are notoriously difficult to characterize mathematically, a problem which they share with LOCC [5, 33]. However, in entanglement theory this problem can be partially resolved by introducing separable operations. These are operations acting on bipartite states ρ^{AB} as

$$\Lambda_s[\rho^{AB}] = \sum_i A_i \otimes B_i \rho^{AB} A_i^\dagger \otimes B_i^\dagger \tag{20}$$

with the Kraus operators $A_i \otimes B_i$ fulfilling the completeness condition $\sum_i A_i^\dagger A_i \otimes B_i^\dagger B_i = \mathbb{1}_{AB}$. While the set

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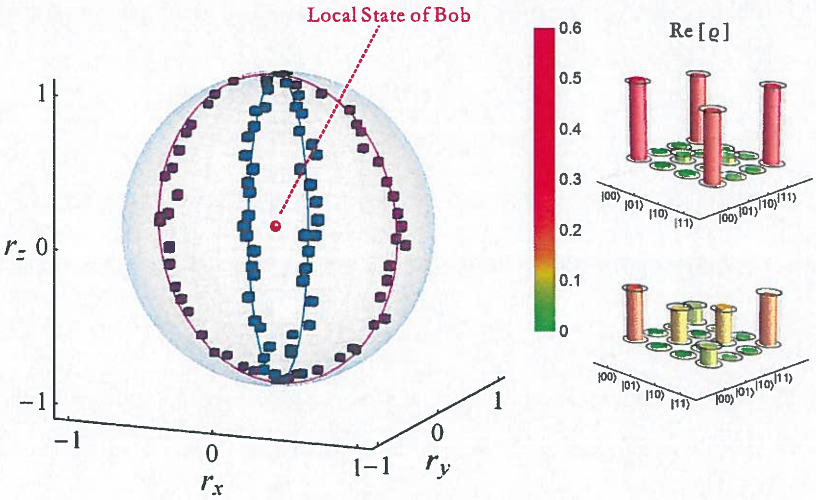

Figure 3: Assisted incoherent state conversion for Werner states with $q = 0.8245$ and $q = 0.2075$. The right figure shows the real parts of the tomographically reconstructed quantum states ρ_{W}^{AB}. The corresponding fidelities are 0.986 and 0.997. The left part shows the boundary of the achievable region for the conversion in the x-z plane. Solid lines show the theoretically predicted boundaries characterized by Eq. (24). Cubes show the experimentally achieved values. Figure is taken from [H8].

of separable operations is strictly larger than LOCC [34], it still preserves the main features of LOCC [5, 33]. Inspired by these results, in [H5] we introduced the class of *separable incoherent (SI) operations*. These are separable operations with the property that the operators A_i and B_i do not create local coherence:

$$A_i \ket{k}^A \sim \ket{l}^A, \quad B_i \ket{m}^B \sim \ket{n}^B. \tag{21}$$

Note that LICC and SI have many common features, most importantly both preserve the set of fully incoherent states, see Eq. (16). In [H5] we further investigated other sets of operations, such as *separable quantum-incoherent (SQI)* operations. These are quantum operations which can be written as in Eq. (20) with incoherent operators B_i.

In [H5] we studied inclusion relations between these sets, proving in particular that SI operations are a strict superset of LICC, and that SQI is a strict superset of LQICC. We further analyzed the performance of these operations for assisted coherence distillation, a task where Bob aims to asymptotically extract local coherence by getting assistance from Alice. In [H5] we proved that for pure states all the aforementioned operations lead to the same performance in this task. We further showed that SQI has an advantage compared to the other classes in quantum state merging, we refer to Section 4.3.5 for more details.

In [H8] we introduced and studied the task called *assisted incoherent state conversion*. In this task, two remote parties, Alice and Bob, share a quantum state ρ^{AB}, and aim to convert it into a local state σ^B on Bob's side via LQICC operations. In [H8] we determined the optimal probability for this process if Alice and Bob share a pure two-qubit state $\ket{\psi}^{AB}$:

$$P_{\mathrm{a}}\left(\ket{\psi}^{AB} \to \sigma^B\right) = \min\left\{1, (1-|r_z|)\,\frac{1+\sqrt{1-s_x^2-s_y^2}}{s_x^2+s_y^2}\right\}. \tag{22}$$

Here, $\boldsymbol{r} = (r_x, r_y, r_z)$ denotes the Bloch vector of Bob's initial state $\rho^B = \mathrm{Tr}_A[\ket{\psi}\bra{\psi}]^{AB}$, and $\boldsymbol{s} = (s_x, s_y, s_z)$ denotes the Bloch vector of the target state σ^B. We also determined the optimal conversion probability if Alice

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and Bob share a two-qubit Werner state

$$\rho_{\rm w}^{AB} = q\,|\phi^+\rangle\langle\phi^+| + (1-q)\frac{\mathbb{1}}{4}. \tag{23}$$

In this case the optimal probability is given by

$$P_{\rm a}\left(\rho_{\rm w}^{AB} \to \sigma^B\right) = \begin{cases} 1 & \text{if } q \geq \frac{s_x^2+s_y^2}{\sqrt{1-s_z^2}}, \\ 0 & \text{otherwise.} \end{cases} \tag{24}$$

The experimental setup for incoherent state conversion (see previous section) has also been used to perform assisted incoherent state conversion with linear optics, by making use of entangled photon pairs [H8]. In this way, the probabilities given in Eqs. (22) and (24) have been confirmed experimentally. For Werner states the experimental results are shown in Fig. 3.

4.3.5 Entanglement and coherence in quantum communication tasks

In [H3] we presented one of the first applications of the aforementioned framework of coherence in distributed scenarios. In particular, we studied the role of entanglement and coherence in quantum state merging, which is a fundamental task in quantum information theory [35, 36]. In this task, two parties (Alice and Bob) aim to merge their parts of a tripartite pure state $|\psi\rangle^{RAB}$ on Bob's side in such a way that the whole state remains intact. In particular, the final state $|\psi\rangle^{RBB'}$ should be the same as $|\psi\rangle^{RAB}$, but both particles B and B' are now in Bob's hands, see Fig. 4. To achieve this goal, Alice and Bob are allowed to use additional singlets, and the natural question is about the minimal singlet rate needed for the procedure in the limit of many copies of the state $|\psi\rangle^{RAB}$. The answer to this question was found in [35, 36]: the minimal singlet rate for this procedure is given by the conditional entropy

$$S(A|B) = S(\rho^{AB}) - S(\rho^B), \tag{25}$$

where $S(\rho) = -\mathrm{Tr}[\rho \log_2 \rho]$ is the von Neumann entropy.

Interestingly, while the classical conditional entropy is never negative, the quantum conditional entropy can be positive or negative. Crucially, the result in [35, 36] admits an operational interpretation in both cases. If the conditional entropy is positive, merging is possible with singlets at rate $S(A|B)$. If the conditional entropy is negative, merging is possible without any entanglement. Apart from merging the state for free, Alice and Bob can additionally gain singlets at rate $-S(A|B)$.

In [H3] we introduced and studied the task of *incoherent quantum state merging*. In contrast to standard quantum state merging, in our case Bob is restricted to local incoherent operations, and needs an additional source of coherence if he wants to implement a more general operation locally. Alice is allowed to perform arbitrary quantum operations locally, and the two parties also have access to a classical channel. In other words, the set of free operations in this task is the set of LQICC operations between Alice and Bob, see previous section for their definition. The resources are quantified by entanglement-coherence pairs (E, C). We are interested in achievable entanglement-coherence pairs (E, C), i.e., rates of entanglement E and Bob's local coherence C for which merging is possible.

One of our main results in [H3] was a lower-bound on the entanglement-coherence sum for any achievable pair:

$$E + C \geq S(\Delta^{AB}[\rho^{RAB}]) - S(\Delta^B[\rho^{RAB}]). \tag{26}$$

Here, $\Delta^X[\rho] = \sum_i |i\rangle\langle i|^X \rho\, |i\rangle\langle i|^X$ denotes full dephasing of ρ with respect to a (possibly multipartite) subsystem X. It is interesting to note that the result in Eq. (26) holds for arbitrary mixed states ρ^{RAB}, i.e., it goes beyond the pure-state scenario studied in standard quantum state merging. This result leads to a fundamental insight on the state merging procedure: since the right-hand side of Eq. (26) is nonnegative, the entanglement-coherence sum $E + C$ is also nonnegative. Thus, no state merging procedure can lead to a gain of entanglement and coherence simultaneously, i.e., entanglement can only be gained if coherence is provided and vice versa. This nonintuitive result shows a fundamental interrelation between entanglement and coherence in distributed scenarios.

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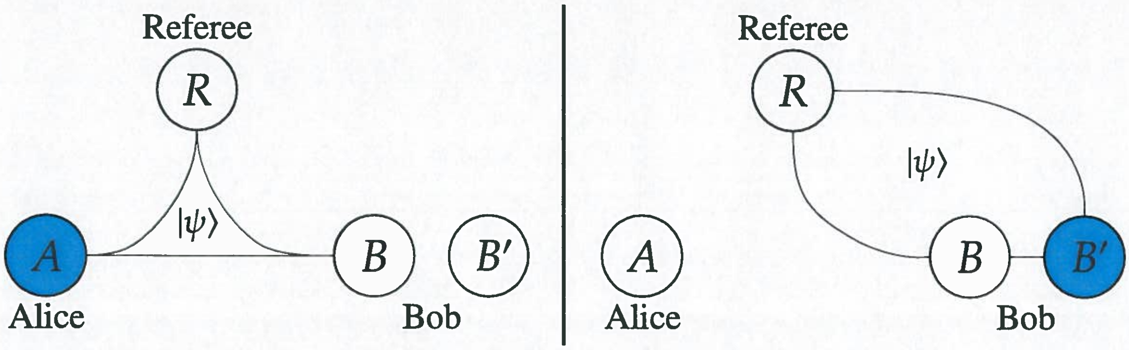

Figure 4: Quantum state merging. Alice, Bob, and a referee share a pure state $|\psi\rangle = |\psi\rangle^{RAB}$. Additionally, Bob is in possession of a register B' (left part). The aim of the task is to obtain the final state $|\psi\rangle^{RBB'}$, which is the same as $|\psi\rangle^{RAB}$, apart from the fact that A and B' are relabeled (right part). To achieve this, Alice and Bob have access to additional singlets and classical communication.

It was also shown in [H3] that the bound in Eq. (26) is tight for all pure states. In particular, any pure state $|\psi\rangle^{RAB}$ can be merged without local coherence on Bob's side by using singlets at rate

$$E_0 = S(\Delta^{AB}[\rho^{AB}]) - S(\Delta^{B}[\rho^{B}]). \tag{27}$$

This result shows the important role of the dephased state $\Delta^{AB}[\rho^{AB}]$ for incoherent quantum state merging. While in standard quantum state merging the amount of required entanglement is given by the conditional entropy of ρ^{AB}, the amount of entanglement required for quantum state merging without using local coherence is given by the conditional entropy of $\Delta^{AB}[\rho^{AB}]$.

Quantum state merging has also proven to be a useful tool for multipartite entanglement transformation [H10]. In particular, given two multipartite states ρ and σ, the optimal rate for the conversion $\rho \to \sigma$ via multipartite LOCC operations in the asymptotic limit is defined as

$$R(\rho \to \sigma) = \sup\left\{r : \lim_{k\to\infty}\left(\inf_{\Lambda_{\mathrm{LOCC}}}\left\|\Lambda_{\mathrm{LOCC}}\left(\rho^{\otimes k}\right) - \sigma^{\otimes\lfloor rk\rfloor}\right\|_1\right) = 0\right\}. \tag{28}$$

Here, Λ_{LOCC} reflects a multipartite LOCC operation and $||M||_1 = \mathrm{Tr}\sqrt{M^\dagger M}$ denotes the trace norm. If ρ and σ are bipartite pure states, the corresponding conversion rate can be written as [37]

$$R(\psi^{AB} \to \phi^{AB}) = \frac{S(\psi^A)}{S(\phi^A)}, \tag{29}$$

where $\psi^{AB} = |\psi\rangle\langle\psi|^{AB}$ denotes the projector onto a pure state $|\psi\rangle^{AB}$ and $\psi^A = \mathrm{Tr}_B[\psi^{AB}]$ is the reduced state of Alice. In [H10] we extended these results to more than two parties, giving upper and lower bounds for conversion rates. For conversion between tripartite pure states $\psi^{ABC} \to \phi^{ABC}$ we found the upper bound [H10]

$$R(\psi^{ABC} \to \phi^{ABC}) \leq \min\left\{\frac{S(\psi^A)}{S(\phi^A)}, \frac{S(\psi^B)}{S(\phi^B)}, \frac{S(\psi^C)}{S(\phi^C)}\right\} \tag{30}$$

and the lower bound [H10]

$$R(\psi^{ABC} \to \phi^{ABC}) \geq \min\left\{\frac{S(\psi^A)}{S(\phi^B) + S(\phi^C)}, \frac{S(\psi^B)}{S(\phi^B)}, \frac{S(\psi^C)}{S(\phi^C)}\right\}. \tag{31}$$

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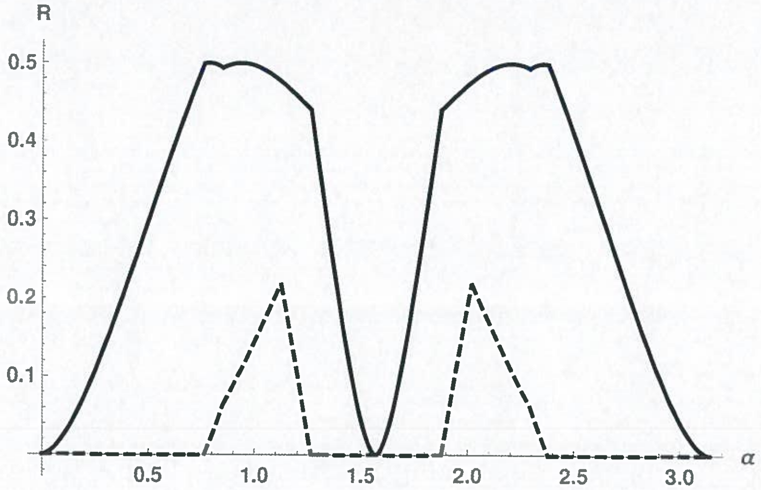

Figure 5: Lower bound for the conversion rate from the state $|\psi\rangle^{ABC}$ in Eq. (34) into a GHZ state [solid line] and the difference between the upper and lower bound [dashed line] for $\beta = 1/2$. The figure is taken from [H10].

This bound can be further improved by permuting the parties, i.e.,

$$R(\psi^{ABC} \to \phi^{ABC}) \geq \min\left\{\frac{S(\psi^B)}{S(\phi^A) + S(\phi^C)}, \frac{S(\psi^A)}{S(\phi^A)}, \frac{S(\psi^C)}{S(\phi^C)}\right\}, \tag{32}$$

$$R(\psi^{ABC} \to \phi^{ABC}) \geq \min\left\{\frac{S(\psi^C)}{S(\phi^A) + S(\phi^B)}, \frac{S(\psi^A)}{S(\phi^A)}, \frac{S(\psi^B)}{S(\phi^B)}\right\}. \tag{33}$$

The best bound is obtained by taking the maximum of Eqs. (31), (32) and (33). Notably, the upper and lower bounds coincide in many relevant setups, which can be demonstrated by considering pure states of the form

$$|\psi\rangle^{ABC} = \cos\alpha\,|000\rangle + \sin\alpha\sin\beta\,|011\rangle + \sin\alpha\cos\beta\,|101\rangle \tag{34}$$

with real α, β which we aim to convert into the GHZ state

$$|\phi\rangle^{ABC} = \frac{1}{\sqrt{2}}(|000\rangle + |111\rangle). \tag{35}$$

In Fig. 5 we show our lower bound maximized over Eqs. (31), (32) and (33) [solid line]. We also show the difference between the upper bound (30) and the lower bound [dashed line] as a function of α for $\beta = 1/2$. The bounds coincide for a large parameter range of α, which means that our bound gives the exact conversion rate in these cases. For more than 3 parties we denote the initial and the target state by $\psi^{AB_1 \ldots B_N}$ and $\phi^{AB_1 \ldots B_N}$, respectively. Upper and lower bounds for the conversion rate are then given by [H10]

$$\min_X\left\{\frac{S(\psi^{AX})}{\sum_{B_i \notin X} S(\phi^{B_i})}\right\} \leq R(\psi^{AB_1 \ldots B_N} \to \phi^{AB_1 \ldots B_N}) \leq \min_i \frac{S(\psi^{B_i})}{S(\phi^{B_i})}, \tag{36}$$

where X denotes a subsystem of all Bobs, including the empty set.

The results discussed so far concern asymptotic setting, where many copies of the state ρ^{RAB} are available. However, such asymptotic setups are out of reach with current experimental techniques, which makes it important to consider single-copy settings. In [H2] we investigated the situation where Alice and Bob aim to merge a single copy of the state ρ^{RAB} by using LOCC operations. In [H9] we analyzed this procedure if Alice and Bob additionally have access to quantum states with positive partial transpose (PPT). The corresponding task was termed LOCC quantum state merging (LQSM) [H2] and PPT quantum state merging (PQSM) [H9]. For both

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setups, the figure of merit is defined as

$$\mathcal{F}_{\mathrm{LOCC}}(\rho) = \sup_{\Lambda_{\mathrm{LOCC}}} F(\sigma_f, \sigma_t), \qquad \mathcal{F}_{\mathrm{PPT}}(\rho) = \sup_{\Lambda_{\mathrm{PPT}}} F(\sigma_f, \sigma_t). \tag{37}$$

Here, $\rho = \rho^{RAB}$ denotes the initial state and $F(\rho, \sigma) = \mathrm{Tr}(\sqrt{\rho}\sigma\sqrt{\rho})^{1/2}$ is the fidelity. The target state $\sigma_t = \sigma_t^{RBB'}$ is the same as the initial state $\rho = \rho^{RAB}$, up to relabeling the subsystems A and B'. For $\mathcal{F}_{\mathrm{LOCC}}$ the final state σ_f is defined as

$$\sigma_f = \mathrm{Tr}_A\left[\Lambda_{\mathrm{LOCC}}\left(\rho^{RAB} \otimes \rho^{B'}\right)\right], \tag{38}$$

where Λ_{LOCC} is an LOCC operation between Alice's system A and Bob's system BB', and $\rho^{B'}$ is an arbitrary initial state of Bob's register B'. Similarly, for $\mathcal{F}_{\mathrm{PPT}}$ the final state is defined as

$$\sigma_f = \mathrm{Tr}_{A\tilde{A}\tilde{B}}\left[\Lambda_{\mathrm{LOCC}}\left(\rho^{RAB} \otimes \rho^{B'} \otimes \mu_{\mathrm{PPT}}^{\tilde{A}\tilde{B}}\right)\right], \tag{39}$$

where $\mu_{\mathrm{PPT}}^{\tilde{A}\tilde{B}}$ is an arbitrary PPT state shared by Alice and Bob.

As was proven in [H2, H9], the fidelities (37) admit the following bounds:

$$\mathcal{F}_{\mathrm{PPT}}(\rho) \geq \mathcal{F}_{\mathrm{LOCC}}(\rho) \geq 2^{\frac{1}{2}[\mathcal{J}(\rho) - I^{R:AB}(\rho)]}. \tag{40}$$

Here, $I^{X:Y}(\mu)$ is the mutual information between the subsystems X and Y of a state $\mu = \mu^{XY}$:

$$I^{X:Y}(\mu) = S(\mu^X) + S(\mu^Y) - S(\mu). \tag{41}$$

Moreover, $\mathcal{J}$ is the concentrated information, defined as the maximal mutual information between Bob and the referee, achievable via LOCC performed by Alice and Bob [H2]:

$$\mathcal{J}(\rho) = \sup_{\Lambda_{\mathrm{LOCC}}} I^{R:BB'}(\sigma_f), \tag{42}$$

where σ_f is defined as in Eq. (38). The proof of the second inequality in Eq. (40) was provided in [H2], and makes use of seminal results of Fawzi and Renner [38].

The results in [H2, H9] allow to analyze the possibility to merge a quantum state via LOCC (with and without additional PPT states) on a single-copy level. A state ρ admits perfect single-shot LQSM if and only if $\mathcal{F}_{\mathrm{LOCC}}(\rho) = 1$. Correspondingly, a state admits perfect single-shot PQSM if and only if $\mathcal{F}_{\mathrm{PPT}}(\rho) = 1$. Moreover, the fidelities (37) can be extended to the asymptotic setting, by defining [H2, H9]

$$\mathcal{F}_{\mathrm{LOCC}}^{\infty}(\rho) = \lim_{n\to\infty} \mathcal{F}_{\mathrm{LOCC}}(\rho^{\otimes n}), \qquad \mathcal{F}_{\mathrm{PPT}}^{\infty}(\rho) = \lim_{n\to\infty} \mathcal{F}_{\mathrm{PPT}}(\rho^{\otimes n}). \tag{43}$$

A quantum state admits perfect asymptotic LQSM if and only if $\mathcal{F}_{\mathrm{LOCC}}^{\infty}(\rho) = 1$. Similarly, it admits perfect asymptotic PQSM if and only if $\mathcal{F}_{\mathrm{PPT}}^{\infty}(\rho) = 1$.

One of the main results of [H9] is the inequality

$$\mathcal{F}_{\mathrm{PPT}}(\rho) \geq \mathcal{F}_{\mathrm{PPT}}(\rho^{\otimes n}), \tag{44}$$

which holds true for any state ρ which is PPT with respect to the bipartition $RA : B$ and any number of copies $n \geq 1$. This result implies that for all such states perfect single-shot PQSM is equivalent to perfect asymptotic PQSM [H9]:

$$\mathcal{F}_{\mathrm{PPT}}(\rho) = 1 \Longleftrightarrow \mathcal{F}_{\mathrm{PPT}}^{\infty}(\rho) = 1. \tag{45}$$

In other words, states with this property can be merged asymptotically if and only if they can be merged on the single-copy level. As an application of this result, in [H9] we presented a family of fully separable mixed states which do not admit perfect asymptotic PQSM. It was further shown in [H9] that PPT entangled states do not provide any advantage for merging of pure states. In particular, if Alice and Bob aim to merge the state $|\psi\rangle^{RAB}$, the singlet rate required for merging is given by the conditional entropy in Eq. (25), even if Alice and Bob have unlimited access to PPT entangled states.

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The role of quantum coherence in single-shot quantum state merging without entanglement has been investigated in [H5]. In particular, we used the quantum state merging task to prove a separation between SQI operations and other classes discussed in Section 4.3.4 (in particular LICC, LQICC, and SI). As was shown in [H5], there exist mixed states which can be perfectly merged via SQI, but cannot be merged via any other set of operations in the single-copy setting, if no additional entanglement is provided.

4.3.6 Summary and outlook

In summary, the articles forming the scientific achievement have significantly improved our understanding of fundamental quantum features, such as entanglement and quantum coherence, the relation between them, and their role in quantum communication tasks. Our research shows how local constraints can be taken into account in quantum communication protocols, and the developed tools will be useful for solving other related problems. One potential future direction is to investigate quantum communication with local energy constraints, arising from the resource theory of thermodynamics. Another promising direction is the investigation of quantum phenomena relevant for quantum computation. While an ideal quantum computer – operating on noiseless pure states – requires entanglement to show exponential speedup over classical computation [39], the situation is much less clear if the quantum computer uses noisy mixed states [40]. This opens the possibility for quantum algorithms operating on unentangled noisy states at a high temperature, while still solving certain classes of problems exponentially faster than any known classical algorithm. We hope that the methods developed in [H1-H10] will be useful for solving these and related problems in the near future.

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5 PRESENTATION OF SIGNIFICANT SCIENTIFIC ACTIVITY CARRIED OUT AT MORE THAN ONE SCIENTIFIC INSTITUTION

5.1 List of publications with more than one affiliation not included in the achievement indicated in section 4

[O1] **A. Streltsov** and W. H. Zurek, *Quantum Discord Cannot Be Shared*, Phys. Rev. Lett. **111**, 040401 (2013), highlighted as Editor's Suggestion.

[O2] **A. Streltsov**, H. Kampermann, and D. Bruß, *Limits for entanglement distribution with separable states*, Phys. Rev. A **90**, 032323 (2014).

[O3] **A. Streltsov**, H. Kampermann, S. Wölk, M. Gessner, and D. Bruß, *Maximal coherence and the resource theory of purity*, New J. Phys. **20**, 053058 (2018).

5.2 Description of research performed at more than one scientific institution

I obtained my PhD in June 2013 from the Heinrich Heine University Düsseldorf (Germany) working on the thesis "The role of quantum correlations beyond entanglement in quantum information theory" under the supervision of Prof. Dr. Dagmar Bruß. The main goal of the research was the investigation of general quantum correlations beyond entanglement (also known as quantum discord), and its applications in quantum information theory. In the period July - September 2012 I was visiting researcher at Los Alamos National Laboratory (Los Alamos, USA), where I collaborated with Dr. Wojciech H. Zurek. This research visit has led to the publication [O1], investigating shareability properties of quantum discord and its meaning for the quantum measurement process. The publication [O1] was highlighted as Editors' Suggestion by Physical Review Letters.

After the PhD I was principal investigator of my own project at ICFO (Barcelona, Spain) supported by the Alexander von Humboldt Foundation. In this period I worked on entanglement distribution [O2], making use of the tools developed during my PhD studies. Also at ICFO I started to work on the resource theory of quantum coherence which is discussed in more detail in section 4 of this autopresentation. In February 2016 I moved to Freie Universität Berlin (Germany), again as a principal investigator of my own project supported by the Alexander von Humboldt Foundation. The research carried out at ICFO and Freie Universität Berlin has led to the publication [H3], discussing the role of local coherence for quantum communication, and to the publication [H4], where we introduced and studied the concept of genuine quantum coherence. As these publications are part of the scientific achievement, we refer to section 4 for more details.

In February 2017 I moved to Gdańsk University of Technology, as a principal investigator of my own project supported by the Polonez 2 Fellowship Programme, co-financed by the EU and the Polish National Science Centre. In this period I published the article [H5], investigating the resource theory of coherence in distributed scenarios. The expertise that I gained at ICFO, Freie Universität Berlin, and Gdańsk University of Technology also made it possible to write the main review article on quantum coherence and its applications in quantum technology [H7]. The research performed at Freie Universität Berlin and Gdańsk University of Technology has further led to the publication [H6] discussing the structure of the resource theory of quantum coherence. Also at Freie Universität Berlin and Gdańsk University of Technology I established a quantitative connection between the resource theories of coherence and purity, showing that purity corresponds to the maximal coherence achievable via unitary operations [O3]. It was further shown in [O3] that there exist universal maximally coherent mixed states, which are optimal resources in coherence theory among all states with a fixed spectrum. For multipartite settings quantitative bounds between purity, coherence, entanglement, and quantum discord were also provided [O3].

In December 2018 I moved to the Centre for Quantum Optical Technologies (QOT), Centre of New Technologies, University of Warsaw, where I am leading a group working on quantum resource theories and their applications for quantum technology. In this period I published the article [H10], providing powerful bounds for transformation rates in multipartite entanglement theory. This article is based on research performed at Freie Universität Berlin, Gdańsk University of Technology, and Centre for Quantum Optical Technologies.

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6 TEACHING AND ORGANIZATIONAL ACHIEVEMENTS

6.1 Teaching achievements

Since December 2018 I am holding a Group Leader position at the Centre for Quantum Optical Technologies (QOT), Centre of New Technologies, University of Warsaw. This position does not require teaching. However, I have volunteered for teaching at the Faculty of Physics, University of Warsaw, in the Summer semester 2019/20, and gave the lecture "*Advanced quantum information: entanglement and nonlocality*". The total number of hours of the lecture was 30. The lecture was shared between me and Dr. Jędrzej Kaniewski, each of us delivered 15 hours of lecture. Due to the COVID-19 pandemic most of the lecture was done remotely. To ensure a high quality of teaching despite this extreme situation we delivered weekly online classes to the students, which took place in time slots originally reserved for the lecture. Apart from presenting the lecture materials to the students, the online classes were also useful to answer potential questions from the students. Additionally, we provided the students with very detailed lecture notes. We further issued five homework sheets (three by myself and two by Dr. Kaniewski), which the students should solve at home, with the help of the detailed lecture notes. At the end of the lecture we prepared an exam sheet which the students should solve individually, and be able to discuss it in the final oral exam, which again took place online. Most of the students have successfully passed the final exam, and we also received a positive feedback about the lecture from several students.

In the period of my PhD (December 2009 - June 2013) I was teaching assistant at the Faculty of Mathematics and Natural Sciences, Heinrich Heine University Düsseldorf. In this period I conducted lecture materials, exercises, and student seminars for the following lectures: Theoretical Mechanics, Mathematical Methods I, Theoretical Quantum Optics and Quantum Information, Advanced Quantum Information Theory. A complete list summarizing my teaching experience is provided below:

2010	Lecture: Theoretical Mechanics Contribution: Preparing exercises and performing student seminars
2010–2011	Lecture: Mathematical Methods I Contribution: Preparing exercises and performing student seminars
2011	Lecture: Theoretical Quantum Optics and Quantum Information Contribution: Preparation of lecture materials
2011–2012	Lecture: Mathematical Methods I Contribution: Preparing exercises and performing student seminars
2012	Lecture: Theoretical Quantum Optics and Quantum Information Contribution: Preparing exercises and performing student seminars
2012–2013	Lecture: Advanced Quantum Information Theory Contribution: Preparing exercises and lecture materials, presenting two hours of lecture
2013	Lecture: Theoretical Quantum Optics and Quantum Information Contribution: Preparing exercises and performing student seminars
2019–2020	Lecture: Advanced quantum information: entanglement and nonlocality Contribution: Preparing lecture materials and exercises, preparing and conducting the final exam, presenting 15 hours of lecture

Since the start of the Group Leader position at the Centre for Quantum Optical Technologies (QOT), Centre of New Technologies, University of Warsaw, I have supervised 1 Master student and 2 PhD students. The PhD student Tulja Varun Kondra has joined my team in October 2019, and is working on quantum resource theories and quantum thermodynamics. Under my supervision Mr Kondra has contributed to a recent article on the resource theory of imaginarity, which has been submitted for review very recently [Wu *et al.*, *Operational resource theory of imaginarity*, arXiv:2007.14847]. The PhD student Manfredi Scalici has joined my team in April 2020, and is performing research on entanglement and quantum coherence in open quantum systems, supported by myself and the postdoc Marek Miller. The Master student Ewelina Bednarz has performed a Master's

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project with me in the period April 2019 - June 2020, analyzing the behavior of trace distance under completely positive trace-preserving maps. In the period October 2019 - February 2020 I further hosted Kang-Da Wu from the University of Science and Technology, Hefei, China. Kang-Da Wu is doing a PhD in experimental quantum optics and is the first author of the aforementioned publication on the resource theory of imaginarity. Moreover, since December 2018 I have supervised 3 postdoctoral researchers.

6.2 Organizational achievements

Together with Prof. Dr. Dagmar Bruß I organized the 586. WE-Heraeus-Seminar: *Quantum Correlations beyond Entanglement*, which took place in Bad Honnef (Germany) in April 2015, and had 16 invited speakers and 65 participants. Together with Prof. Dr. Gerardo Adesso I organized the Symposium *Quantum Coherence in Quantum Technology*, which was part of the yearly meeting of the German Physical Society in Erlangen (Germany) in March 2018. The symposium had four invited speakers, and was accessible to all participants of the yearly meeting.

I am guest editor for the *Special Issue on Quantum Coherence* (together with Prof. Eric Chitambar and Prof. Xiongfeng Ma), published in Journal of Physics A in October 2018, containing 18 articles discussing different aspects of coherence theory.

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7 OTHER RESEARCH ACCOMPLISHMENTS

7.1 List of publications not included in sections 4 and 5

[O4] **A. Streltsov**, H. Kampermann, and D. Bruß, *Linking a distance measure of entanglement to its convex roof*, New J. Phys. **12**, 123004 (2010).

[O5] **A. Streltsov**, H. Kampermann, and D. Bruß, *Simple algorithm for computing the geometric measure of entanglement*, Phys. Rev. A **84**, 022323 (2011).

[O6] **A. Streltsov**, H. Kampermann, and D. Bruß, *Linking Quantum Discord to Entanglement in a Measurement*, Phys. Rev. Lett. **106**, 160401 (2011).

[O7] **A. Streltsov**, H. Kampermann, and D. Bruß, *Behavior of Quantum Correlations under Local Noise*, Phys. Rev. Lett. **107**, 170502 (2011).

[O8] **A. Streltsov**, H. Kampermann, and D. Bruß, *Quantum Cost for Sending Entanglement*, Phys. Rev. Lett. **108**, 250501 (2012).

[O9] **A. Streltsov**, G. Adesso, M. Piani, and D. Bruß, *Are General Quantum Correlations Monogamous?*, Phys. Rev. Lett. **109**, 050503 (2012).

[O10] S. M. Giampaolo, **A. Streltsov**, W. Roga, D. Bruß, and F. Illuminati, *Quantifying nonclassicality: Global impact of local unitary evolutions*, Phys. Rev. A **87**, 012313 (2013).

[O11] **A. Streltsov**, *Quantum Correlations Beyond Entanglement: and Their Role in Quantum Information Theory*, SpringerBriefs in Physics 2015.

[O12] **A. Streltsov**, R. Augusiak, M. Demianowicz, and M. Lewenstein, *Progress towards a unified approach to entanglement distribution*, Phys. Rev. A **92**, 012335 (2015).

[O13] R. Augusiak, J. Kołodyński, **A. Streltsov**, M. N. Bera, A. Acin, and M. Lewenstein, *Asymptotic role of entanglement in quantum metrology*, Phys. Rev. A **94**, 012339 (2016).

[O14] E. Chitambar, **A. Streltsov**, S. Rana, M. N. Bera, G. Adesso, and M. Lewenstein, *Assisted Distillation of Quantum Coherence*, Phys. Rev. Lett. **116**, 070402 (2016).

[O15] **A. Streltsov**, H. Kampermann, and D. Bruß, *Entanglement Distribution and Quantum Discord.* In: Fanchini F., Soares Pinto D., Adesso G. (eds) Lectures on General Quantum Correlations and their Applications. Quantum Science and Technology. Springer, Cham (2017).

[O16] B. Regula, L. Lami, and **A. Streltsov**, *Nonasymptotic assisted distillation of quantum coherence*, Phys. Rev. A **98**, 052329 (2018).

[O17] L.-F. Qiao, **A. Streltsov**, J. Gao, S. Rana, R.-J. Ren, Z.-Q. Jiao, C.-Q. Hu, X.-Y. Xu, C.-Y. Wang, H. Tang, A.-L. Yang, Z.-H. Ma, M. Lewenstein, and X.-M. Jin, *Entanglement activation from quantum coherence and superposition,* Phys. Rev. A **98**, 052351 (2018).

[O18] B. Regula, M. Piani, M. Cianciaruso, T. R. Bromley, **A. Streltsov**, and G. Adesso, *Converting multilevel nonclassicality into genuine multipartite entanglement*, New J. Phys. **20**, 033012 (2018).

[O19] J. Kołodyński, S. Rana, and **A. Streltsov**, *Entanglement negativity as a universal non-Markovianity witness*, Phys. Rev. A **101**, 020303(R) (2020).

[O20] Y. Yuan, Z. Hou, J.-F. Tang, **A. Streltsov**, G.-Y. Xiang, C.-F. Li, and G.-C. Guo, *Direct estimation of quantum coherence by collective measurements*, npj Quantum Information **6**, 46 (2020).

7.2 Description of research not included in sections 4 and 5

In the following, we will describe research accomplishments which were not mentioned in sections 4 and 5 of this autopresentation[1]. During the PhD studies at Heinrich Heine University Düsseldorf (Germany) we established a fundamental link between quantum discord and entanglement in the quantum measurement process [O6]. As was further shown in [O8, O12], quantum discord plays an important role in the task of entanglement distribution, and a review on this topic can be found in [O15]. The behavior of quantum discord under local noise [O7] and its monogamy properties [O9] have also been investigated. We further proposed a new approach for quantifying general quantum correlations, based on the global change induced by local unitary evolutions [O10]. Further results obtained during the PhD studies concern methods for entanglement quantification [O4], including a new algorithm for entanglement computation [O5]. My PhD thesis served as a basis for a review article [O11], discussing the role of quantum discord in quantum information theory.

After the PhD I mainly worked on the topics contributing to my scientific achievement, which are discussed in more detail in section 4. Moreover, I contributed to the development of assisted coherence distillation, a new task in quantum information theory which has been introduced and studied in [O14]. In this task, one party assists a second remote party in extracting local coherence. In the asymptotic setting, the optimal rate of maximally coherent qubit states obtainable locally is known as distillable coherence of collaboration, and a closed formula for it has been given for all bipartite pure states [O14]. In [O16] we studied this task in the single-copy scenario, where the interesting quantity is the optimal fidelity, attainable via LQICC operations between a local state and the maximally coherent state $|+\rangle_d = 1/\sqrt{d}\sum_{i=0}^{d-1}|i\rangle$, where d is the corresponding local dimension. For systems of local dimension 2 and 3 a complete solution to this problem has been presented in [O16], for the case that the overall shared state is pure. Experimental assisted coherence distillation with linear optics has been performed in [41].

In [O17] we investigated possibilities and limitations of entanglement activation from superpositions, based on the resource theory of quantum superposition proposed in [42]. Also in [O17] we used methods from the resource theory of coherence for solving an open problem in entanglement theory, proving that the trace norm entanglement

$$E(\rho) = \min_{\sigma\in S} ||\rho - \sigma||_1 \tag{46}$$

with the trace norm $||M||_1 = \mathrm{Tr}\sqrt{M^\dagger M}$ violates strong monotonicity, i.e., it can increase on average under local operations and classical communication. Experimental entanglement activation from quantum coherence has also been performed in [O17]. Theoretical results concerning conversion of coherence into multipartite entanglement have been presented in [O18].

An efficient measurement scheme for estimating the amount of coherence in a quantum state via collective measurements has been presented in [O20]. In particular, we show by theoretical analysis that for estimating the amount of coherence in a qubit state it is advantageous to perform collective Bell measurements on two copies of the state. The performance of this scheme is compared to other estimation techniques, such as quantum state tomography, and adaptive procedure for estimating x and y-components of the Bloch vector. We discuss potential applications for larger dimensions, and demonstrate that the method is readily applicable for coherence estimation in optical systems [O20].

The role of entanglement for the theory of open quantum systems has been investigated in [O19]. An important problem in the theory of open quantum systems is to decide whether a given evolution Λ_t is Markovian or not, i.e., whether it admits a decomposition

$$\Lambda_t = V_{t,s} \circ \Lambda_s \tag{47}$$

with a completely positive trace preserving map $V_{t,s}$ for all times $0 \leq s \leq t$. Quantifiers of correlations in bipartite quantum systems – such as entanglement, quantum discord, and mutual information – turn out to be useful tools to study this problem [43]. In fact, any entanglement measure decreases under local Markovian evolutions [44]. This implies that a sufficient criterion for non-Markovianity of a given evolution Λ_t^A acting on a particle A is that some entanglement measure increases for some two-particle state ρ^{AB} and some time $t > 0$. Nevertheless, despite significant amount of research over the last years, until very recently it remained unclear

[1] Section 5 only contains publications with at least two affiliations, and at least one affiliation from outside Poland.

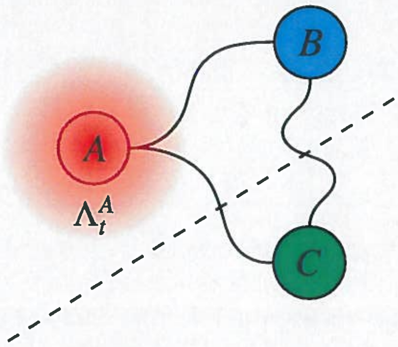

Figure 6: Non-Markovianity of a qubit evolution Λ_t^A can be universally detected by considering entanglement negativity in the cut $AB|C$ of a tripartite state ρ^{ABC}.

whether entanglement measures can be used as universal non-Markovianity witnesses, i.e., whether every non-Markovian evolution also leads to an entanglement increase. This question has been resolved only very recently in [O19], where it has been shown that in a tripartite configuration it is indeed possible to faithfully witness non-Markovianity of (almost) all evolutions by entanglement measures. For this, we assume that the dynamics Λ_t^A is acting on the particle A of a tripartite state ρ^{ABC}. We now choose E to be entanglement negativity [45, 46], and consider it in the cut $AB|C$, see Fig. 6. Then, for any non-Markovian qubit dynamics Λ_t^A there exists a tripartite state ρ^{ABC} such that

$$\frac{\mathrm{d}}{\mathrm{d}t}E^{AB|C}(\Lambda_t^A \otimes \mathbb{1}^{BC}[\rho^{ABC}]) > 0 \tag{48}$$

for some $t > 0$ [O19]. This result extends to systems of arbitrary dimension if the dynamics Λ_t^A is invertible. These results for the first time demonstrate that well established entanglement quantifiers can faithfully detect non-Markovianity in all single-qubit evolutions and almost all dynamics of arbitrary dimension.

The role of entanglement in quantum metrology has been investigated in [O13], whereby we showed that it is possible to achieve precision scaling arbitrary close to the Heisenberg limit, even if the system exhibits arbitrarily small amount of entanglement with increasing number of particles.

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