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Exploiting infinite dimensions for quantum information: discretization and hybrid systems

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Academic abstract

Wider research context: The fundamental understanding of quantum systems and their correlations, as well as their characterization and quantification are crucial for modern information processing and communication. Conventionally, the quantum information being processed is encoded either in discrete or continuous degrees of freedom. Qubits and harmonic oscillators are essential parts of quantum devices employed for the effective transmission and storage of quantum information, and also of optimal quantum engines. Accordingly, the dimension of system, finite or infinite, plays a key role in the information-processing capacity of such devices. These two types of systems have fundamentally different mathematical descriptions that marks a consistent division within the quantum information community. Objectives and approach: We aim to strengthen an alliance between the two parts, advancing in the informational-theoretic study of infinite-dimensional systems, identifying better resources for reliable tomography of continuous-variable systems, understanding the definite role of discretization strategies for their characterization, exploring unified descriptions for complex continuous-discrete hybrid systems, and progressing in the optimization of current resources for optimal measurements and data post-processing. There are multiple aspects of infinite-dimensional systems we would like to address. We would like to find an optimal discretization strategy and their effective dimension needed for reliable certification of their quantum properties, the corresponding sampling, measurement, and post-processing complexity, and to provide the scaling of error rates. In addition, we want to find an efficient and consistent way of characterizing and quantifying continuous-discrete correlations and to reveal the cost of the exchange of quantum information between the discrete and continuous degrees of freedom of hybrid systems. These quantumness measures will be formulated within an operational framework of experimentally friendly witnesses. Innovation: The overall goal of our proposal is to find optimal strategies to identify and exploit all the benefits of infinite-dimensional systems from an information-theoretical point of view. What we want is to compare, merge, and go beyond both independent, discrete and continuous variable, approaches and thus to explore new scenarios. We ambition to develop unified and accessible theoretical methods for characterizing, verifying, and benchmarking the quantum properties of such hybrid systems . Primary researchers involved: The present research project will be carried out by Dr. Elizabeth Agudelo, in collaboration with Dr. Marcus Huber at the Institute for Quantum Optics and Quantum Information (IQOQI) - Vienna. Vienna represents a solid ground for fruitful interactions due to the high amount of high quality theoretical and experimental groups working in quantum information and quantum optics.

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Project description

Scientific objectives and approach

Quantum mechanics was born out of the need for a physical description of systems at the microscopic level such as electrons, atoms, and light fields. Two mayor historical examples of our fundamental search for a better understanding of light-matter interaction are the black body radiation [1] and the photoelectric effect [2]. These last 120 years of quantum theory have turned into a success story regarding the understanding and development of new theories and technologies. Along this era, theoretical and experimental physicists, mathematicians, and philosophers have faced the challenge to construct models and design experiments in order to understand the mysterious microscopic world, and today, we are telling a new story. Quantum physics experiments are since long time out of our minds. We could forget the early *gedanken* experiments and focus on certifying the actual quantum nature of the physical world. Our modern capacity to manipulate and control single quantum systems [3, 4] opened the door to multiple applications. Nowadays, we are pursuing communication, simulation, computation, and sensing that overpower their classical counterparts due to the exploitation of quantum effects and quantum correlations [5–9]. By reason of the spectacular findings about light, matter, and their interactions, quantum theory has come to influence research in all the different fields of physics. It has tremendous intellectual and cultural implications. It represents a source of new and valuable knowledge about the physical world that led to a technological revolution improving many aspects of our life. The way we communicate, explore the universe, the current medical technology and others, represent fundamental areas that have been heavily influenced by the quantum theory. All these aspects motivate us to continue working on reaching an even deeper understanding of its conceptual foundations, the further development of its mathematical structures, and how to access its advantageous properties. The classification, characterization, and accessibility of quantum states and quantum correlations are old problems but the recent technological developments opened new doors, making these old issues hot topic again[10]. Our present possibilities drive us to expand and describe more accurately the quantum nature of the physical systems and in turn multiple possibilities are created for yet more technological advances.

Nowadays, there is a consistent division in the way we describe the quantum systems, some in terms of discrete variables (DV) and other in terms of continuous variables (CV). The differences that imply distinct mathematical characterizations of such systems led the community through two different paths and at a first glance it seems like they represent two incompatible descriptions of quantum systems. Their major distinction being the finite- versus infinite-dimensional Hilbert spaces. The best illustration of this discrepancy is the canonical commutation relation between the position and momentum operator, $[\mathrm{X},\mathrm{P}] = \mathbb{1}\mathrm{i}$, that is not possible to construct on a finite-dimensional Hilbert space. While one may consider this relation as a mathematical artefact only, a recent study has shown a sharp distinction in information-theoretic capacity between finite- and infinite-dimensional systems [11]. Historically, the notion of entanglement appeared explicitly in the literature first in 1935, long before the appearance of the relatively young field of quantum information, and without any reference to DV states. In fact, CV entangled states were treated in the seminal EPR paper [12] (EPR states are two-particle states quantum mechanically correlated with respect to their positions and momenta), that inspired the notion of entanglement as introduced then by Schrödinger [13]. Today, the study of quantum information in CV systems is limited. It relies on two main approaches: discretization techniques and unavoidable energy cut-offs [14, 15] or information-processing within particular classes of CV states, such as e.g. Gaussian states [16]. It is clear that the richness in dimensionality of CV systems offers enormous potential for information processing. For example, the implementation of high-capacity and ultra-secure quantum information networks rely on the possibility to generate and precisely manipulate multipartite, highly dimensional, and strongly correlated systems. These high-dimensional entangled states have been successfully generated experimentally [17–21], and they can, in principle, contain a large amount of entanglement, which represents a vital resource for applications in quantum information processing and quantum communications [22, 23]. To profit from the richness of infinite-dimensional systems we need to advance in the study of CV systems from an informational-theoretic approach. A scope that has not been yet studied enough.

Investigations of quantum correlations in high-dimensional systems and hybrid systems are especially interesting for the development of novel applications in quantum technologies. Therefore, the rich structure of quantum effects and correlations in such systems is of fundamental interest for quantum physicists and quantum information scientists. Many of the current quantum information and quantum thermodynamics applications are developed or proposed taking into account CV-DV hybrid systems. Qubits and (light) fields are essential parts of quantum devices necessary for the effective transmission and storage of quantum information, and are also part of optimal quantum engines [24–26]. One important aspect to be addressed within this project is the lack of an unified approach to encompass nonclassical properties of CV-DV systems. Hybrid systems are effectively infinite-dimensional. Its DV part is well understood from a quantum information perspective but its CV part not so well, hence, these hybrid systems constitute a level up of difficulty. In the context of fundamentally understanding and exploiting quantum features, it is essential to characterize, classify and quantify their correlations. This also includes the need for a joint description and unification of different notions of quantumness of different subsystems. We developed a first attempt of such a unification which will serve as starting point for our future research in this direction [27]. In this context, we recognize the need to address the following questions: **What are efficient and reliable ways of characterizing and quantifying CV-DV correlations? How can such a formalism incorporate the existing descriptions of CV-CV or DV-DV correlations in a consistent way? And how exactly and at which cost is it possible to exchange quantum information between DV and CV systems and vice versa?** We will develop an operational framework to encompass CV-DV correlations. These shall be further supplemented with a set of information-theoretic witnesses to guarantee their efficient experimental accessibility. We need to develop a flexible scheme, since noise and errors act differently on different degrees of freedom for different implementations. The necessity of properly classifying and describing nonclassical effects in hybrid systems and a universal way to access the nonclassicality of such systems, have to be understood for implementing quantum communication on a highly variable basis [28, 29]. The goal is to find an optimal strategy to identify and exploit all the benefits of hybrid systems. What we want is to compare, merge, and go beyond both independent approaches and thus to explore new scenarios.

There are two main aspects of infinite-dimensional systems we would like to address here. The first one is the problem of characterization. Modern quantum technologies depend on reliable characterization. To assure the correct functionality of a quantum device is of crucial importance for the new generation of Noisy Intermediate Scale Quantum Devices (NISQ) [30] which are not fully scalable nor protected by error correction. While the dimensionality scaling of composite quantum systems is an essential ingredient enabling quantum speed ups, this very advantage introduces an intrinsic barrier for their full characterization, as the required resources scale exponentially with the system size. The optimal scaling of error rates and measurement complexity are known for DV systems [31]. On the other hand, the situation with the CV systems is much less clear. In essence, the optimal scaling bounds for DV systems shall mirror all the characterization techniques for the CV systems based on discretization. Nevertheless, the statistical behavior of CV systems depends on a new relevant parameter: the energy of the system [32, 33] a quantity that has little relevance in the DV context. Therefore, the scaling of error rates heavily depends on the discretization basis. The second main problem, relevant for the CV analysis, is the quantification of errors. For DV systems the errors are estimated in relation to trace-distance norms and fidelities. However, the use of such error quantifiers for CV systems is questionable from the operational point of view [34]. These problems are in the focus of the present proposal. We would like to investigate into the following questions: **what is the sampling, measurement and post-processing complexity of characterization of CV systems? What are the energy bounds for efficient performance for particular tasks? Is there an intrinsic need for discretization? How do we quantify errors? And, how do we address the problem of infinite modes and infinite energy?** While one cannot expect to solve these problems in their full generality due the great complexity of the underlying Hilbert space, it is reasonable to believe that practically relevant situations may be found. We shall rely on techniques developed in both DV and CV communities to provide the rigorous statistical analysis (in terms of an information-theoretic convergence of estimation errors) and discover new reliable and efficient characterization methods for CV and CV-DV hybrid systems.

Modern technological developments come with new challenges and accordingly the old methods need to be revisited and adapted. Apparently, DV and CV research communities are progressing independently without a significant alliance. Consider, e. g. the recent studies for DV systems on shadow tomography [35–37] , which show an enormous potential to surpass the dimensionality scaling for a large class of experimentally relevant situations. Remarkably, related techniques have been known in the CV community since the 1990's as the method based on measurement patterns [38]. This shows the lack of interdisciplinary research to study and merge both approaches to exploit the full benefits from its combined potential. **One of our the main goals is to revise, merge, and discover new reliable characterization techniques that can surpass dimensionality limitations for practically relevant situations.** We shall explore methods and techniques of both research communities in order to arrive at the feasible characterization framework for infinite-dimensional systems. **We seek for a more rigorous statistical analysis and operational error quantification keeping in mind energy costs of the characterization tasks.** In parallel, we will investigate the nonclassical properties of infinite-dimensional systems in an operational way. **We would like to develop an operational framework for nonclassicality measures in terms of experimentally directly accessible quantities and information-theoretic witnesses.** A good example in the context of DV systems is the direct fidelity estimation [39] or few-copy entanglement verification [40]. These techniques are formulated in information-theoretic language where the presence of a certain quantum resource is seen as the ability of a quantum systems to accomplish certain information-processing task. This is the idea behind an information-theoretic witness which plays the main role in quantum computing verification techniques [41]. We seek for similar direct methods for CV systems. The current project is placed at the multidisciplinary intersection of quantum information theory, quantum optics theory, and quantum technological applications. **The overall goal is to explore the potential of hybrid systems and to understand the scope of dimension appreciation for modern quantum technologies. Specifically, we adapt and further develop theoretical methods in order to maximally exploit characterization and quantification of quantum properties in complex systems.** Our research proposal has three main objectives. In consequence, it is divided in three work packages (WPs): the investigation of hybrid nonclassicality measures and information-theoretic witnesses (WP1), the certification of hybrid entanglement (WP2) and the development of methods for reliable characterization of infinite-dimensional systems (WP3).

Progress beyond the state of the art

We aim to advance in the informational-theoretic study of CV systems, identify the definite role of discretization strategies for the description of infinite-dimensional systems, explore an unified description for complex CV-DV hybrid systems, identify optimal resources for reliable CV tomography, and progress in the optimization of current resources for optimal measurement and data post-processing. Our project is extremely timely and our results are expected to go significantly beyond the present state of the art. We summarize our main goal as **to develop unifying and accessible theoretical methods for characterizing, verifying, and bench-marking quantum properties and states for hybrid systems with emphasis in its importance for applications, in this era of near term quantum devices.**

The originality and innovative aspects of this proposal rely on the fact that our proposal involves research in the borderline of an important set of areas: quantum optics, quantum information, and quantum technologies. In such scenario, a robust collaboration between experts is necessary for the successful accomplishment of the goals set here. Hence, the project will undoubtedly set new scientific trends, having potential to establish important "cross-border" breakthroughs. The accomplishment of our goals will traduce in **a general and experimentally accessible criteria to certify and verify quantum correlations present in hybrid finite and infinite systems** and also the understanding on these more general quantum systems. This will certainty motivate the exploration of systems and correlations traditionally studied in the frameworks of quantum optics and quantum information for applications on modern quantum technologies and vice versa. **We aim to unfold clever solutions that allow the further development of quantum devices.**

As a main goal, **we seek to advance in the knowledge and possibilities for characterizations of CV systems and CV-DV hybrid systems from an information-theoretical point of view.** Due to its infinite dimensionality, these kind of quantum systems are very promising for modern quantum technologies. Currently being optimal candidates for communication, simulation, computation, and sensing that overpower their classical counterparts. All these constitute a strong motivation for us to continue working on reaching an even deeper understanding of conceptual foundations, the further development of the mathematical structures, and how to access the advantageous properties of infinite-dimensional quantum systems. Quantum theory has led to a technology revolution improving many aspects of our life. We are convinced that the way we understand and explore the universe will continue being heavily influenced by new findings and advances regarding quantum devices and their performance.

Expected impact

The key results of our research will be published in appropriate scientific journals and will be made available online via arXiv. Participation to externally organized national/international conferences and workshops at various levels is planned. We acknowledge the importance of the proper dissemination of our results as they play a crucial role for creating a knowledge-based society which nowadays seems to be the key to preserve the high level of European economy and its competitiveness with other rapidly growing markets. We also recognize that public outreach and furthering scientific literacy in society constitutes one of the most important challenges of scientists today, mostly related to the highlighting of the fundamental role of theoretical physics and research on foundations of quantum mechanics for the future development of quantum technologies. Which has not just academic impact but also has tremendous intellectual and cultural implications. Furthermore, frequent meetings, are planned to create new collaboration opportunities and to enhance the impact of the project. During the meetings with other experts, Dr. Agudelo will present the outcomes and progress of the project via seminars. Research notices will be prepared for departmental websites and science portals, including press-releases for the general public.

The opportunity for the implementation of the project, translates to an excellent chance for Dr. Agudelo to continue learning and expanding her field of expertise. The multidisciplinary character of the project will strongly broaden her horizons. Learning new techniques and approaches, and interacting with experts in such a rich scientific environment, a research group, that works in close collaboration with multiple groups around the world, are big steps forward to a successful future academic career. To have the opportunity to continue her professional development as a physicist at IQOQI Vienna implies international recognition as a high quality researcher and therefore it opens the door to future opportunities.

Project management

Methodology and associated work plan

Our research project is divided in three work packages as described below.

WP1: Hybrid nonclassicality measures and information-theoretic witnesses

We project our investigation on nonclassicality measures and information-theoretic witnesses for complex infinite-dimensional systems onto two sub-topics.

Task 1.1: Unified approach to nonclassicality classifiers

For applications on hybrid scenarios, it is important to efficiently characterize the DV and CV subsystems and also the correlations between them. Based on different definitions of quantumness in individual subsystems, in our previous work, we have investigated how they extend to the joint description of correlations of a composite system [27]. Especially, we studied the bipartite case and the connection of two typically applied and distinctively different concepts of nonclassicality in quantum optics and quantum information. The detection of quantum correlations in CV-DV systems has been characterized [42] in terms of the so-called P-matrix which is the result of discretization on the DV mode. It was shown that our composition approach always includes entanglement as one form of quantum correlations. Based on the analysis of quantum superpositions, a general method for the construction of quasiprobability representations for arbitrary notions of quantum coherence was developed [43]. This technique yields a nonnegative probability distribution for the decomposition of any classical state. This is an example of an unifying method that combines well-established concepts, such as phase-space distributions in quantum optics, with resources of quantumness relevant for quantum technologies. Such a framework renders it possible to uncover complex quantum correlations between systems, for example, via quasiprobability representations of multipartite entanglement. With reference on these approaches, we would like to find, e.g., entanglement witnesses for hyper-entanglement between discrete and continuous degrees of freedom. In order to advance in the way of understanding hybrid schemes, we would like to characterize the family of states, $\sum_{n=1}^{d} \lambda_n |n\rangle \otimes |\alpha_n\rangle$ for qudit teleportation as a generalization of the qubit case ($d = 2$). Moreover, in order to map one system to another one can use the related transformation $T = \sum_{n=1}^{d} |n\rangle\langle\alpha_n|$. T maps a CV state (along with its properties) to a DV system. This is a useful tool to translate between quantumness of CV and DV degrees of freedom. There is another kind of hyper-entangled systems, with CV-CV and DV-DV subsystems in both parts. There is an actual interest in studying and experimentally generate systems that are partially correlated in continuous degrees of freedom and partially correlated in discrete degrees of freedom and then we want to use both of these correlations [44]. Hence, we need to address the following questions:

what is an efficient and consistent way of characterizing and quantifying CV-DV correlations? How can such a formalism incorporate the existing descriptions of CV-CV or DV-DV correlations in a consistent way? And how exactly and at which cost is it possible to exchange quantum information between DV and CV systems and vice versa?

Task 1.2: Information-theoretic witnesses

We aim to determine experimentally friendly quantumness witnesses. In general, verification protocols need to be not only based on experimental accessibility but also on resource-efficiency. One standard tool for verifying quantum properties is via mean values of witness operators (such as entanglement witness [45]). While being a very powerful mechanism for small-scale quantum systems, its applicability is limited for systems of large dimensions due to increasing measurement and sampling complexity. When these methods are translated to the information-theoretic paradigm, the existence or absence of a certain quantum property translates directly as the ability of the given quantum system to accomplish certain information-processing task [40]. Such procedure enables a dramatic reduction of necessary resources for the certification of quantum properties with a very high probability. Interestingly, in the case of entanglement, as the dimension of a system grows even a single copy (one measurement click) is sufficient for reliable verification [46, 47]. Our idea is to extend this information-theoretic approach to the infinite-dimensional systems and their nonclassicality witnesses and other classifiers (c.f. task 1.1). In contrast to tomographic tasks, this method (based on information-theoretic witnesses for DV systems) shows a favourable scaling with the system size, thus we expect to derive a plethora of practically relevant results for CV and CV-DV scenarios.

WP2: Hybrid CV-DV entanglement certification

Currently, methods in entanglement detection and utilisation are mostly split in either DV or CV implementations. While some notable results have bridged the gap, characterising the entanglement of continuous degrees of freedom through discretisation [48, 49]. In this work package we want to make notable progress in this direction along two lines.

Task 2.1: Hybrid systems in Bloch representation

The Bloch representation serves as a uniquely useful tool in the characterisation of qubits and finite dimensional quantum systems [50–53]. Extending the representation to multipartite quantum systems allowed to build an operational and observable based approach to characterising entanglement and was instrumental in many basic proofs of entanglement monogamy and entropy inequalities [54, 55]. A recent proposal by the co-applicant also describes a possible extension of the Bloch representation to continuous variable systems [56], outlining also the potential for using it for entanglement detection. We want to extend this representation in a comprehensive manner, extending it's range of utility to a multitude of possible CV states that are relevant in quantum optics and most importantly introduce a hybrid Bloch representation for CV-DV systems. Such a representation will help characterise such systems and build operational entanglement criteria therein.

Task 2.2: Hyper-hybrid entanglement

The workhorse of quantum optics experiments are photons created in downcoversion. Focusing on the single photon part of weak light enables high-dimensional entanglement creation in polarisation (DV), position-momentum (CV) and sprectral (CV) degrees of freedom that are usually discretised to yield a high-information capacity and noise resistance [57, 58]. Traditional quantum optics often focuses on the second quantization, i.e. characterising the quantum nature of light fields modes containing multiple photons. Using the methods developed in Task 2.1, we want to go one step further in unifying the approaches and developing experimental proposals that truly combine the techniques from the different fields. We will study the prospects of multi-photon generation in spontaneous down-conversion processes, and see if their entanglement in Fock space and the individual Hilbert spaces can be harnessed simultaneously. A starting point is to take seriously the two-photon contribution of strongly pumped photon pair generation using a Sagnac source for creating time energy entanglement conventionally addressed through time-bins [21, 58]. Such time-bin entanglement is usually divided into frames, which are subdivided into bins. Ideally, pumping needs to be sufficiently weak for the predominant contribution per frame are single-photon pairs, as multiphoton contributions in a single frame are discarded as noise. We will explore which technology would be able to also utilise such multiphoton contributions, such as number-resolving detectors or pre-detection multiplexing. We will use these insights to propose concrete experiments that could be implemented by the many collaborators of the Huber group.

WP3: Reliable characterization of infinite-dimensional systems

Our goal is to investigate methods and techniques developed in DV systems and implement its assets accordingly to the description of CV systems. Here we identify three main tasks.

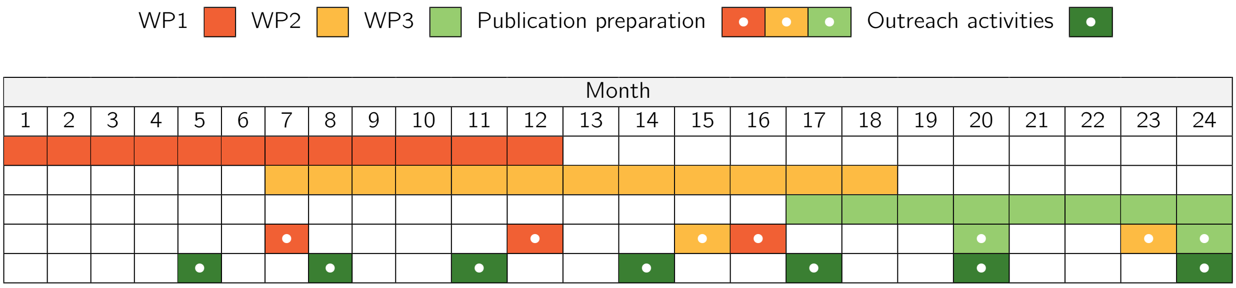
Task 3.1: Discretized systems— One approach to study CV systems is their approximation as the limit to high-dimensional DV systems and then the strategy is to exploit descriptions traditionally used for the characterization of qudits. In DV regime (qudits), the explicit optimal sampling, measurement, and post-processing complexity are known [31]. We shall translate these results to the CV regime and find the corresponding complexities. While the mathematical prescription is clear, the questions to be addressed are related to the applicability of optimal DV tasks for discretized CV system, i.e. **what are the measurements needed to execute the task efficiently? Can they be implemented in practice? What is the energy cost for the implementation?** We would like to significantly advance our knowledge about the best way of discretization and the effective dimension on complex systems in order to certify its quantum properties.

Task 3.2: Shadow tomography for CV systems— Pattern functions are a well-known strategy for tomographic methods [59] and quasiprobability reconstructions [60, 61] in the CV regime. An alternative form of these measurement patterns have been recently exploited for the characterization of DV systems, in this case they are called "classical shadows" [35, 37]. In this information-theoretic framework, it is possible to predict an exponential number of properties from very few measurement samples, thus completely surpassing the dimension limitations. As a consequence, one can extract the mean value of M number of observables by using only $\log(M)$ copies of a quantum state. We wonder, does the same cost of $\log(M)$ translates to the CV regime? Are the same conditions over the bounds of the norm of the observables sufficient to ensure logarithmic scaling? What are the observables that can be reliably measured? What is the analogy of optimal measurements (Clifford circuits) in the context of CVs? Can we implement them efficiently? In addition, the concept of selective quantum state tomography, a tomographic scheme that enables a user to estimate arbitrary elements of an unknown quantum state using a fixed measurement record (no dimension scaling) was recently proposed [36]. On the other hand, the measurement pattern method for CV systems suffers from intrinsic energy limitations [33]. **We shall answer why is this discrepancy? We would like to investigate if there is an efficient scheme to reproduce the selective tomography result for CV systems.**

Task 3.3: Quantification of errors, effective description and energy costs— The common way of quantifying the errors for DV systems is via trace-distance norms and fidelities. Nevertheless, for CV systems, it is know that quantum states may be very close in Hilbert space while being very far in terms of physical properties [34]. Thus, the proper quantification of errors is crucial for shadow-tomographic tasks, as they need extraction of mean values of observables rather than tomography of quantum states. Therefore, **the use of the standard error quantifiers has to be examined with great care in conjunction with a tomographic set of additional constraints, e.g. energy limitations.** This is our main goal here. This will go in parallel with **the investigations of an optimal discretization basis, description of an effective Hilbert space, and optimization of the energy costs.**

Timeline

The following Gantt chart describes the project schedule for the period of 24 months. It includes the timing of the preparation of publications and teaching/outreach activities.



The plan and development of our research project is as follows: during the first year it is expected to achieve the planned tasks without mayor difficulties since they are related directly with Dr. Agudelo and Dr. Huber experience. As expected, later the research field will be widened and the project will lean also on the development of new methods. In our proposal, there is a continuous transition between the different WPs. Some tasks can be addressed in parallel such that one can switch from one to the other when difficulties arise and thus ensure a continuous activity. All meetings and dissemination activities will provide constant feedback, collaboration and help in designing strategies to overcome risks and difficulties.

Research strategy and risk management

An ambitious and multidisciplinary research project as this one is subject to a certain degree of risk. Due to the theoretical character of the fellowship, the project potential risks consist of unexpected results encountered during research that contradict the predictions specified in the project proposal. In such scenario, we will focus on solving the problem for the most interesting tasks and applications attempting a joint description, evaluating the relevance of the results case by case. Still, the planned project is based on topics well known to Dr. Agudelo, Dr. Huber and their international collaborators. In addition, the extra tools, skills and knowledge acquired during the development of the project, and the collaborations set up, will help to focus on concrete results achievable analytically. In any case, our goals are planned such that numerical results can be obtained with well known techniques, even if the mathematical problems encountered appear to have no closed analytical solutions.

The project is organized such that in the first year the phases with minor risk are present. The study will be within the field of expertise of the fellow who knows very well analytical and numerical tools to deal with possible problems encountered. Apart from monitoring the status, strategies to avoid delays will be put in place whenever difficulties arise. In order to have some flexibility of action, we propose to work with a variety of systems and we seek to characterize them from different perspectives, which allows us to move to the next goal when we encounter some problematic issue as contingency plan. We recognise the importance of the scientific community, therefore, we understand that help will also come from the ongoing collaborations with our partners in Vienna and internationally. IQOQI Vienna makes part of the Vienna Center for Quantum Science and Technology (VCQ)—that unites quantum physicists of Vienna's research institutions in one collaborative center—constitutes an in-site highly qualified international community which can be consulted regularly to minimize the risks. Note that due to the theoretical nature of the present proposal, all the planned discussions and necessary meetings can be held online, therefore, a situation like the one placed nowadays due to the current pandemic does not mean a significant risk increase for the successful completion of our project. All together, this guarantees the planned achievement of the initial goals.

Role and profile of applicant and co-applicant

Applicant's background and expertise

Dr. Agudelo is a theoretical physicist with interest and experience in the fields of quantum optics and quantum information. Her studies have been focused on open quantum systems and the characterization of quantum correlations, covering both, discrete and continuous variable regimes. The applicant's research interests could be broadly defined as studies of the fundamentals of quantum physics. This includes the quantum description of open and interacting quantum systems, for example, in her Bachelor and Master projects, and the classification of multipartite quantum correlations, e.g., in her PhD project. In particular, she became an expert in the classification of the nonclassical character of multimode quantum light fields. She received her Bachelor degree from the Universidad de Antioquia, Medellín, Colombia. Her bachelor thesis–a product of a long-distance collaboration, pursued under the supervision of Prof. K. M. Fonseca-Romero (Universidad Nacional de Colombia, Bogotá)– was awarded First Place in the Natural Sciences area of the 12th Otto de Greiff, National Prize for best undergraduate thesis, Colombia. Since early years, the applicant shows initiative and independence. Afterwards, she applied for an opportunity to do the Master in the Universidade Federal de Minas Gerais, Brazil. She was awarded with a full master's scholarship from the Brazilian National Council for Research (CNPq). In Brazil, she had the opportunity to work under the supervision of Prof. Dr. M. C. Nemes (Physics) and Prof. C. Moreira (Mathematics). Developing a project on stochastic processes in open quantum systems. The applicant's enthusiasm for physics is not limited to research, she also deeply enjoys teaching, an activity to which she dedicated two years after obtaining the master degree. As a physics teacher at the Universidad de Antioquia in Colombia, she was responsible for some basic and advanced physics courses for students of physics, mathematics and engineering. Also during her time in Germany (PhD), she gave seminars on theoretical physics and lab courses. Dr. Agudelo did her PhD under supervision of Prof. Werner Vogel and Dr. Jan Sperling. Prof. Vogel is a world expert on quantum optics and widely recognized for his work on fundamental quantum mechanics. Her PhD thesis is entitled "Multimode nonclassicality in the phase space". During her PhD she had published 5 papers in high impact journals, one in Physical Review Letters [42], three in Physical Review A [61–63], and one in Journal of Physics B: Atomic, Molecular and Optical Physics [27]. She had the opportunity to work with recognized scientists in the fields of theoretical and experimental quantum optics as: J. Sperling and I. Walmsley (Oxford), M. Bellini and A. Zavatta (Florence) and B. Hage (Rostock). Dr. Agudelo recognizes the importance of discussing her work with broader audiences and creating scientific network so she has extensively disseminated her results in international scientific meetings. Since 2017, she has held postdoc positions in Germany, Italy, and Austria. Actively working in widening her knowledge and strengthening her collaboration network. In this last year she has concluded 5 more papers two of them published in high impact journals as PRL [64] and Quantum [65] and the rest [66–68] are now under review.

It is important to emphasize that half of her papers include collaborations with different experimentalists and that her international net of collaborators will translate in new collaboration opportunities for the host organisation. Especially, she analyzed measured data (including rigorous error estimations) on many occasions and is therefore highly educated in understanding not only the theory, but also the experimental implementation of physical concepts. This extra knowledge is an asset of great value for any theoretical physicist. Her professional experience in research and teaching, her successful work with different research groups, her interdisciplinary collaborations, and her commitment to work on various problems in physics, show her high degree of independence and research maturity.

Dr. Agudelo's near-future research interests include to address fundamental questions regarding high-dimensional systems and in particular questions related to quantum information theory, where the co-applicant of this proposed project, Dr. Huber is a world leading recognized expert. The development of the present proposal will reinforce her line of expertise and open the possibility to expand her knowledge to new research fields. She will for sure gain some mathematical and other methodological competences that will broaden her view between foundations, quantum information and quantum technologies. The Huber group is an interconnected and a dynamical team, where discussions and cooperative work are part of the daily research process, resulting in an inspiring working environment, ideal for acquiring the new knowledge and skills Dr. Agudelo aims to. The possibility of working with Dr. Huber represents also an opportunity to enhance the creative and the independent thinking required for being a successful scientist.

Co-applicant's background and expertise

The proposed project will be carried out in collaboration with and under the supervision of Dr. Marcus Huber at the Institute of Quantum Optics and Quantum Information (IQOQI) in Vienna. His publication track record features numerous papers on the theory of multipartite entanglement [69–71], and ranges from the mathematical foundation of the field [72–75] to the active participation in designing experiments and subsequent entanglement certification [17, 19, 44, 76]. Furthermore, he was a pioneer of applying quantum information concepts to the field of thermodynamics [77, 78]. In addition, he was invited to write a review article [79], which is the most cited paper from the journal in 2016. He also developed the concept of fully autonomous engines [80, 81] and experimental proposals [82, 83], and continues to publish high-impact results [84–86]. His frequent collaborators and academic network includes many of the world-leading researchers of the field, among them the ERC awardees Gerardo Adesso, Antonio Acín, Nicolas Brunner, Nicolas Gisin, Otfried Gühne, Martin Plenio, Sandu Popescu, Andreas Winter, Anton Zeilinger and many more researchers around the globe. In addition he has established himself as a group leader with numerous successful grant applications as principal investigator (PI) or co-author (FWF-P21947N1 stand-alone project, 300.000€; Juan de la Cierva fellow, 90.000€; FIS 2013-40627-P grant MINECO, 175.000€; AMBIZIONE-grant from the SNF, 590.000€; FWF international collaboration I-3053 N-27 MultiQUEST 236.000€). Notably, he was awarded the Award of Excellence from the Austrian ministry of science after his PhD and in 2015 he won the START-Prize from the FWF (1.200.000€) which enabled him to establish the group in IQOQI. He also supervises the Lise Meitner research project of Dr. G. Vitagliano. His current research efforts extend beyond entanglement theory, as he was among the pioneering researchers in the recently revived interest in quantum thermodynamics within the quantum information community [77, 79, 81, 87]. This also provides him with the relevant background for the methods required for the success of the project.

As part of the Huber group at the IQOQI Vienna, Dr. Agudelo has the opportunity to join the regular meetings that are held between different groups in IQOQI and the Vienna Center for Quantum Science and Technology (VCQ), which unites quantum physicists of Vienna's research institutions in one collaborative center. The group is well integrated into the wider scope of the institute with regular collaborations with the experiments of the Ursin's and Zeilinger's groups on entanglement certification, which will provide Dr. Agudelo with the opportunity to widen her collaborations and to develop her methods guided by the direct needs and expertise of experimentalists who would immediately apply the cutting edge methods in entanglement detection she is expected to develop.

Applicant and co-applicant - two-way transfer of knowledge

During her stay in Vienna, the fellow will have the opportunity to develop her own project in an environment very well suited for her research plan, being surrounded and guided by expert scientists in a friendly and collaborative atmosphere. The supervisor, Dr. Marcus Huber, is one of the world's top experts in entanglement theory and quantum thermodynamics. In addition, many of the groups at IQOQI have interests and expertise connected to foundational questions and quantum information, perfectly suited for the proposed research. The fellow will have here a valuable opportunity to broaden her scientific basis. The training will thus enhance a lot the mathematical skills of Dr. Agudelo on topics connected with quantum information e.g. Shannon theory, information theory, quantum coding, convex geometry, optimization theory, probability theory etc. on the quantum information side. On top of that it will give Dr. Agudelo the unique opportunity to learn about statistical physics and quantum thermodynamics while offering valuable contributions to open problems in the field. Finally, it will also lead to direct contact with the experimentalists here, at IQOQI. This allows theoretical research to be guided by actual experimental and practical challenges and will impact directly the design of next generation experimental setups.

Frequent visits and two-way interactions with groups outside of the IQOQI are customarily planned, which will have a positive impact for the successful completion of the project, that will improve also her skills in collaborating and disseminating the results. She will also have the chance to participate in multiple scientific meetings and is expected that her future results are published in high impact scientific journals as have been usual for her and for the members of Huber group. Being in an institute of international prestige like IQOQI, with large and important research groups, the applicant will have the opportunity to travel, to interact with major world experts in a broad range of fields of her potential interest and to teach and supervise students. In parallel, this will provide the applicant with a wide range of sophisticated advice from researchers and group leaders at different stages in their career and significantly widen her prospective future professional network. Finally, she will enhance her communication skills by reporting the output of the project in conferences and will be trained in organizing dissemination and outreach activities (e.g. workshops, schools etc.).

Dr. Agudelo herself has also a very broad and interdisciplinary background. Her studies has been focused on foundations and characterization of quantum correlations, covering both, discrete and continuous variable regimes. The host group will benefit for her experience in theoretical quantum optics and her knowledge on methods and techniques related with the certification of quantum correlations of continuous-variables systems. Furthermore, during her young career, the applicant has already shown capacity of research maturity and independence, successfully developing her own ideas and projects and being the main author of almost all of her publications and participating in close collaborations with experimentalists. She gained very much experience in travelling to create new collaboration opportunities and disseminating her work participating in international scientific meetings. Thus, the already open and interdisciplinary environments at IQOQI can benefit a lot from the broad knowledge of the fellow and from her collaborative aptitude and her capacity of independently addressing new questions and set up new collaborations, even at the border between various disciplines.

Dissemination and communication strategies

This research project is planned so to include several strategies to properly disseminate the results. First of all, the key results will be published in appropriate scientific journals. Before submission to reputable journals our articles will be made available online (via the open access arXiv). Participation to externally organized national/international conferences and workshops at various levels is planned at least three times per year and the organization of events connected with the topic of the proposed research are planned. Furthermore, frequent meetings, are planned to create new collaboration opportunities and to enhance the impact of the project. During such meetings, Dr. Agudelo will present the outcomes and progress of the project via seminars. Research notices will be prepared for departmental websites and science portals, including press-releases for the general public.

The applicant and the co-applicant acknowledge the importance of outreach activities, which successfully popularize the importance, potential, pervasiveness, and ubiquity of science among the general public. Outreach activities play also a crucial role for creating a knowledge-based society which nowadays seems to be the key to preserve the high level of European economy and its competitiveness with other rapidly growing markets. We also recognize that public outreach and furthering scientific literacy in society constitutes one of the most important challenges of scientists today, mostly related to the highlighting of the fundamental role of theoretical physics and research on foundations of quantum mechanics for the future development of quantum technologies. Which has not just academic impact but also has tremendous intellectual and cultural implications. Therefore, the Fellow will have the opportunity to participate in various outreach activities, engage the general public with her own research, pass her inspiration and passion to local-school teachers and their pupils, and, as such, develop the related skills. In particular, Dr. Agudelo will work on a daily basis with students at all levels, she will take an active part in seminars held in different institutes in Vienna presenting her up-to-date results, she will participate in the above events, and give public lectures either popularizing science, in particular related with quantum technologies. She is also interested in contributing with promoting the role of women in physics. Accordingly, she plan to be part of programs and activities that advance education and diversity in the physics community. She is one of the main organisers of Q-Turn 2020 (www.q-turn.org). Q-turn is a unique international quantum information workshop series. Its core mission is to foster an inclusive community and highlight outstanding research that may be under-appreciated in other high-impact venues due to systemic biases. The applicant will prepare detailed press-releases regarding her new results intended for departmental websites, local newspapers, and scientific magazines and will engage in activities such as lab-visits, public talks, workshops, school visits, and special activities for high school students. All these activities are capable of inspiring and creating awareness of the FWF and the importance of research in fundamental physics among a wider audience. It should be stressed that the Fellow's mother tongue is Spanish, but she is also fluent in Portuguese and English. She has additional knowledge of basic German and Italian. Therefore, her integration with the scientific community and the general public will be very efficient and very profitable not just for Austria but also in a broader territory.

Ethics and safety-related aspects

The proposed project does not raise any ethical issues. Due to the nature of this theoretical physics research project, no relevant ethical or safety aspects are envisaged to arise that would need to be considered.

The proposed project does not raise any sex-specific and gender-related issues. This project is in the area of theoretical physics and concerns questions regarding the physical aspects of quantum technologies, we do not envision it to produce sex-specific and gender-related findings.

Annex 1: List of References

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Annex 2: Academic curricula vitae and description of previous research achievements

Dr. Elizabeth Agudelo

Current position

2019 - Postdoc, Marie Skłodowska-Curie Fellow - InDiQE Individual Fellowship
M. Huber Group - Institute for Quantum Optics and Quantum Information (IQOQI) Vienna of the Austrian Academy of Sciences (ÖAW), Boltzmanngasse 3, 1090 Vienna, Austria.
Contact: elizabeth.agudelo@oeaw.ac.at - ORCID: 0000-0002-5604-9407

Scientific achievements

Main areas of research: Theoretical quantum optics and quantum information
Published Papers: 9
Papers under Review: 4
Citation Indices (Google Scholar): • h-factor: 6 • i10-factor: 5 • Citations: 145
Participation in Scientific Meetings: • 4 Invited Seminars • 9 Contributed Talks • 6 Posters
Referee for: • Phys. Rev. Lett. • Phys. Rev. A • Phys. Rev. Applied
Organizing committee: Main organiser, Q-Turn 2020 (November 23rd-27th, 2020)

Education

2017 **PhD Physics** (Dr. rer. Nat.), October 2011 - June 2017. Thesis: *Multimode nonclassicality in the phase space*. Advisor: Prof. Werner Vogel. Universität Rostock, Rostock, Germany.

2009 **MSc Physics**, August 2007 - August 2009. Thesis: *Stochastic Processes in the Light-Matter Interaction* Advisor: Prof. Maria Carolina Nemes and Prof. Carlos H. C. Moreira. Universidade Federal de Minas Gerais, Belo Horizonte, Brazil.

2007 **BSc Physics**, March 2001 - October 2007. Thesis: *Decoherence and Entanglement in a tripartite system: Interaction between a two level atom and two dissipative QED cavities*. Advisors: Prof. Karen M. Fonseca Romero and Prof. Boris A. Rodríguez. Universidad de Antioquia, Medellín, Colombia.

*** From September 2009 to July 2011 the applicant worked as Lecturer at Universidad de Antioquia, Medellín, Colombia (see the teaching activities section).

Previous positions

10.2018 - 05.2019	Postdoc, QSTAR, Istituto Nazionale di Ottica - CNR, Florence, Italy
07.2018 - 10.2018	Visiting Researcher, Grupo de Física Atómica y Molecular Universidad de Antioquia, Medellín, Colombia
07.2017 - 06.2018	Honorary Research Associate, W. Vogel Research Group Universität Rostock, Rostock, Germany
10.2011 - 06.2017	Research Assistant, W. Vogel Research Group Universität Rostock, Rostock, Germany
09.2009 - 07.2011	Lecturer, Universidad de Antioquia, Medellín, Colombia
08.2006 - 06.2007	Teaching Assistant, Universidad de Antioquia, Medellín, Colombia

Grants and awards

06.2019 - 05.2021	Marie Skłodowska-Curie - Individual Fellowship InDiQE (174 k€)
10.2011 - 06.2017	PhD Fellowship. Collaborative research center 652 (DFG 2017.), Project B12. Germany. (Following the decision to go to Germany to do my PhD two grants were declined. One from the Universidade Federal de Minas Gerais, Belo Horizonte, Brazil and the other one from the Universidad de los Andes, Bogotá, Colombia)
08.2007 - 08.2009	Scholarship. Brazilian National Council for Research (CNPq). Brazil.
2008	*Otto de Greiff.* National Prize to the best undergraduate thesis. First Place in the Natural Sciences area. Colombia.
2007	*Mención Especial* to the undergraduate thesis. Universidad de Antioquia, Colombia.

Supervision of Graduate Students

SS2018 Karsten Weiher (Master Student at Universität Rostock) - Erasmus project supervisor (INO-CNR, Florence, Italy). Publication: Phys. Rev. A 100, 043812 (2019)

Teaching Activities

Universität Rostock, Rostock, Germany

WS2016/17	**Teaching Assistant.** Foundations of Life, Light and Matter Research. Course for Physics master students.
SS2015 - SS2016	**Project Advisor.** Forschungspraktikum. Project: Nonclassicality test with simulated and experimental data. Course for Physics master students.

Universidad de Antioquia, Medellín, Colombia

2009-2011	**Lecturer.** Oscillations and waves, General Physics, Mechanics, Physics I (Newtonian mechanics) and Experimental Physics II (Electromagnetism). Courses for bachelor students of Natural and Exact Sciences Faculty, Engineering and Pharmaceutical Chemical program.
2006	**Teaching Assistant.** Experimental Physics I (Newtonian mechanics) and Experimental Physics III (Oscillations and waves). Experimental courses in basic physics for bachelor students of the Engineering Faculty.

Language Skills

- Spanish (native speaker)
- English (proficient)
- Portuguese (proficient)
- German (intermediate)
- Italian (basic)

Publications

Non-peer-reviewed

P13. S. Köhnke, E. Agudelo, M. Schünemann, O. Schlettwein, W. Vogel, J. Sperling, B. Hage *Quantum Correlations beyond Entanglement and Discord* arXiv ID: 2010.03490

P12. Nicola Biagi, Martin Bohmann, Elizabeth Agudelo, Marco Bellini, and Alessandro Zavatta, *Experimental certification of nonclassicality via phase-space inequalities*, arXiv ID: 2010.00259

P11. Simon Morelli, Ayaka Usui, Elizabeth Agudelo, and Nicolai Friis, *Bayesian parameter estimation using Gaussian states and measurements*, arXiv ID: 2009.03709

P10. Rodolfo Restrepo-Villegas, Elizabeth Agudelo, Jhonny Castrillón, and Boris A. Rodríguez, *Local Classical Strategies vs Geometrical Quantum Constraints*, arXiv ID: 1809.03662

Peer-reviewed

P9. Martin Bohmann, Elizabeth Agudelo, and Jan Sperling, *Probing nonclassicality with matrices of phase-space distributions*, Quantum 4, 343 (2020)
DOI: 10.22331/q-2020-10-15-343 - arXiv ID: 2003.11031

P8. Martin Bohmann and Elizabeth Agudelo, *Phase-space inequalities beyond negativities*, Phys. Rev. Lett. 124, 133601 (2020)
DOI: 10.1103/PhysRevLett.124.133601 - arXiv ID: 1909.10534

P7. Karsten Weiher, Elizabeth Agudelo, and Martin Bohmann, *Conditional nonclassical field generation in cavity QED*, Phys. Rev. A 100, 043812 (2019)
DOI: 10.1103/PhysRevA.100.043812 - arXiv ID: 1907.10076

P6. Elizabeth Agudelo, Jan Sperling, Luca S. Constanzo, Marco Bellini, Alessandro Zavatta, and Werner Vogel, *Conditional hybrid nonclassicality*, Phys. Rev. Lett. 119, 120403 (2017)
DOI: 10.1103/PhysRevLett.119.120403 - arXiv ID: 1702.04257

P5. Jan Sperling, Elizabeth Agudelo, Ian A. Walmsley, and Werner Vogel, *Quantum correlations in composite systems*, J. Phys. B: At. Mol. Opt. Phys. 50, 134003 (2017)
DOI: 10.1088/1361-6455/aa7438 - arXiv ID: 1703.05063

P4. Elizabeth Agudelo, Jan Sperling, Werner Vogel, Semjon Köhnke, Melanie Mraz, and Boris Hage, *Continuous sampling of the squeezed state nonclassicality*, Phys. Rev. A 92, 033837 (2015)
DOI: 10.1103/PhysRevA.92.033837 - arXiv ID: 1411.6869

P3. Sergej Ryl, Jan Sperling, Elizabeth Agudelo, Melanie Mraz, Semjon Köhnke, Boris Hage, and Werner Vogel, *Unified nonclassicality criteria*, Phys. Rev. A 92, 011801(R) (2015)
DOI: 10.1103/PhysRevA.92.011801 - arXiv ID: 1505.06089

P2. Elizabeth Agudelo, Jan Sperling and Werner Vogel, *Quasiprobabilities for multipartite quantum correlations of light*, Phys. Rev. A 87, 033811 (2013)
DOI: 10.1103/PhysRevA.87.033811 - arXiv ID: 1211.1585

P1. Elizabeth Agudelo, K. M. Fonseca and B. A. Rodríguez, *Decoherencia y entrelazamiento en un sistema tri-partito: interacción de un átomo con dos cavidades QED disipativas*, Rev. Col. Física 40, 2 (2008) English version: arXiv ID: 1002.4242

Dr. Marcus Huber

Current position

2016 - **IQOQI - Vienna**, Group Leader
Institute for Quantum Optics and Quantum Information (IQOQI) Vienna of the Austrian Academy of Sciences (ÖAW), Boltzmanngasse 3, 1090 Vienna, Austria.
Homepage: https://www.iqoqi-vienna.at/research/huber-group/
Contact: marcus.huber@oeaw.ac.at - ORCID: 0000-0003-1985-4623

Scientific Achievements

Main areas of research: Quantum information, quantum thermodynamics
Published Papers: 95 • Under Review: 8 • Invited opinion articles: 2 • Books chapters: 2
Citation Indices (Google Scholar): • h-factor: 43 • i10-factor: 85 • Citations: >5500
Participation in Scientific Meetings: • >25 Invited Talks • 10 Contributed Talks • 3 Posters
Editor for Physical Review X
Founder and executive board member of the journal QUANTUM

Education

2018 **Habilitation** Quantum entanglement beyond qubits
Faculty of Physics, University of Vienna, Austria

2010 **PhD** Entanglement and Geometry in Multipartite Quantum Systems
Graduation: with distinction, Faculty of Physics, Particle Physics Group, University of Vienna, Austria

2008 **Master** Entanglement and Quantum Information
Graduation: with distinction, Faculty of Physics, Particle Physics Group, University of Vienna, Austria

Previous positions

2015 - 2016 **University of Geneva**, AMBIZIONE Grantee
2014 - 2015 **Universitat Autònoma de Barcelona**, Juan de la Cierva Research Fellow
2013 - 2016 **ICFO**, Visiting Scientist in the group of Prof. A. Acín
2013 - 2014 **Universitat Autònoma de Barcelona**, Marie Curie Research Fellow, FP7, IEF
2012 - 2013 **University of Bristol**, Marie Curie Research Fellow, FP7, IEF
2012 - 2012 **University of Bristol**, Research Associate in the Department of Applied Mathematics
2010 - 2012 **University of Vienna**, Post-doctoral Researcher in the Austrian science fund project: FWF-P21947N16
2009 - 2012 **University of Applied Sciences, Technikum Wien**, Lecturer in physics
2008 - 2010 **University of Vienna**, Teacher of various physics courses
2008 - 2008 **University of Vienna**, Research Assistant in the department of Particle Physics

Fellowships and awards

2.717 Mio € as PI:

2019 FQXi large grant (293 k€)
2019 ESQ discovery grant (50 k€)
2017 ESQ discovery grant (ca. 96 k€)
2016 FWF-International Project (ca. 236 k€)
2015 FWF-START-Prize (1.2 Mio€)
2015 SNF-Ambizione (ca. 600 k€)
2013 MINECO-Juan de la Cierva (ca. 90 k€),

2011 EC-Marie-Curie (ca 150 k€)
2010 Award of Excellence from the Austrian Ministry of Science (2500 €)

1.317 Mio € as co-applicant/co-PI:
2019 ESQ Postdoc supervisor (Fellow: Simon Milz, 170 k€)
2019 ESQ Postdoc supervisor (Fellow: Mateus Araujo, 170 k€)
2019 Marie Curie Supervisor (Fellow: Elizabeth Agudelo, 170 k€)
2018 ESQ Postdoc supervisor (Fellow: Felix Binder, 170 k€)
2018 Lise Meitner supervisor (Fellow: Giuseppe Vitagliano, 170 k€)
2017 ESQ Discovery (PI Jessica Bavaresco, ca 17 k€)
2014 MINECO-FIS project (PI Ramon Muñoz Tapia, ca. 150 k€)
2009 FWF-stand-alone project (PI Beatrix Hiesmayr, ca. 300 k€)

Graduate and postdoctoral alumni

2018-2020 Faraj Bakhshinezhad (PhD and PostDoc, Huber group), now PostDoc at Lund University
2015-2020 Fabien Clivaz (PhD student, University of Geneva), now PostDoc at IQOQI Vienna
2018-2019 Robert Fickler (Senior PostDoc Huber group), now assistant professor at Tampere University
2016-2018 Matej Pivoluska (PostDoc Huber group), now senior researcher at Masaryk University
2016-2019 Yelena Guryanova (PostDoc Huber group), now young group leader at IQOQI Vienna
2016-2018 Mehul Malik (Senior PostDoc Huber group), now associate professor at HWU Edinburgh
2014-2018 Paul Erker (joint PhD student, UAB & USI), now PostDoc at IQOQI Vienna
2013-2018 Claude Klöckl (joint PhD student UAB, then PostDoc Huber group), now PostDoc at Boku Vienna

Current supervision of graduate students and postdoctoral fellows

14 PostDocs: Nicolai Friis (FWF project leader), Flavien Hisch (SNF early PostDoc fellow), Maximilian P. E. Lock, Giuseppe Vitagliano (Lise Meitner fellow), Felix Binder (ESQ fellow), Elizabeth Agudelo (MSCA fellow), Simon Milz (ESQ fellow, co-hosted by the YIRG group at IQOQI), Cornelia Spee (Schrödinger fellow), Mateus Araujo (ESQ fellow), Fabien Clivaz, Hayata Yamasaki (JSPS fellow), Armin Tavakoli (SNF early PostDoc fellow), Michael Scheucher, Paul Erker

5 PhD students: Paul Appel, Jessica Bavaresco, Simon Morelli (co-supervised with Nicolai Friis in my group), Emanuel Schwarzhans, Phil Taranto

Teaching activities

Altogether: **>100 ECTS** of which >80 ECTS as lecturer (Lehrveranstaltungsleiter) and **106** hours of ungraded lecturing, as well as 5 summer/winter school lectures.

Examples of organisation and recognition

2019 Consulting Editor for Physical Review X
2019 Invited Review in Nature Reviews: "Entanglement certification from theory to experiment"
2018 Multiple program committee and advisory committee for conferences and workshops, member of AQIS 2018, CEQIP 2018, QTURN, and advisory board of YQIS 2018.
2017 Q&A article in Physics (APS) about my work "Questioning the limit of quantum machines"
2017 - Scientific board member of the Open Quantum Problems Initiative
2016 - Founder and executive board member of the journal QUANTUM
2016 Outstanding Reviewer Award from New Journal of Physics 2016 and 2017 (IOP publishing)
2016 Invited topical review on Quantum Information in Thermodynamics for Journal of Physics A, "The role of quantum information in thermodynamics"

2014 Guest editor for the special issue "50 years of Bell's theorem" in Journal of Physics A, IOP.

2013 Invited Fellow at Newton Institute for Mathematical Sciences in Cambridge/UK for the program: Mathematical Challenges in Quantum Information (MQI)

10 most cited publications

1. The role of quantum information in thermodynamics — a topical review
   J. Phys. A: Math. Theor. 49 143001(2016) DOI: 10.1088/1751-8113/49/14/143001 - arXiv ID: 1505.07835
2. Generation and Confirmation of a (100×100)-dimensional entangled Quantum System
   PNAS 111(17), 6243-6247 (2014) DOI: 10.1073/pnas.1402365111 - arXiv ID: 1306.0096
3. Detection of high-dimensional genuine multi-partite entanglement of mixed states
   Phys. Rev. Lett. 104, 210501 (2010) DOI: 10.1103/PhysRevLett.104.210501 - arXiv ID: 0912.1870
4. Multi-photon entanglement in high dimensions
   Nature Photonics 10, 248-252 (2016) DOI: 10.1038/nphoton.2016.12 - arXiv ID: 1509.02561
5. Observation of Entangled States of a Fully Controlled 20-Qubit System
   Phys. Rev. X 8, 021012 (2018) DOI: 10.1103/PhysRevX.8.021012 - arXiv ID: 1711.11092
6. Extractable work from correlations
   Phys. Rev. X 5, 041011 (2015) DOI: 10.1103/PhysRevX.5.041011 - arXiv ID: 1407.7765
7. Measure of genuine multipartite entanglement with computable lower bounds
   Phys. Rev. A 83, 062325 (2011) DOI: 10.1103/PhysRevA.83.062325 - arXiv ID: 1101.2001
8. Entanglement enhances cooling in microscopic quantum refrigerators
   Phys. Rev. E 89, 032115 (2014) DOI: 10.1103/PhysRevE.89.032115 - arXiv ID: 1305.6009
9. Entanglement Generation is Not Necessary for Optimal Work Extraction
   Phys. Rev. Lett. 111, 240401 (2013) DOI: 10.1103/PhysRevLett.111.240401 - arXiv ID: 1303.4686
10. Interface between path and orbital angular momentum entanglement for high-dimensional photonic quantum information Nat Commun 5, 4502 (2014) DOI: 10.1038/ncomms5502 - arXiv ID: 1402.2423

In total, 95 peer reviewed papers with over 100 co-authors across different fields of science, including leading figures in theoretical and experimental physics, such as Antonio Acín, Rainer Blatt, Andrew Briggs, Jeremy O'Brien, Nicolas Brunner, Dagmar Bruß, Joseph Eberly, Jens Eisert, Guan-Can Guo, Noah Linden, Nicolas Gisin, Otfried Gühne, Miles Padgett, Martin Plenio, Sandu Popescu, John Rarity, Jörg Schmiedmayer, Rupert Ursin, Andreas Winter and Anton Zeilinger.

On-going grants

Project Title	Funding source	Amount (Euros)	Period	Role
The role of quantum information in thermodynamics	FWF	1.2 Mio €	2016-2022	PI
Infinite-dimensional quantum effects (InDiQE)	MSCA/EC	170 k€	2019-2021	Supervisor
Macroscopic Quantum Coherence: detection and Quantification (maquacoh)	Lise Meitner/FWF	170 k€	2018-2020	Supervisor
Fueling quantum field machines with information	FQXi	293 k€	2019-2022	PI
Emergence of physical laws: From mathematical foundations to applications in many body physics	ESQ	50 k€	2019-2020	PI

Grant applications

Project Title	Funding source	Amount (Euros)	Period	Role
High-Dimensional Quantum Information Processing (HD-QIP)	FWF-IP	342 k€ for my group	2020-2022	PI

Annex 3: Career plan

Career development plan

Current academic status

- ✓ Research Interests: Interplay between quantum optics and quantum information.
- ✓ Scientific Achievements:

  Published Papers: 9
  Papers under Review: 4
  Citation Indices (Google Scholar): • h-factor: 6 • i10-factor: 5 • Citations: 145
  Participation in Scientific Meetings: • 4 Invited Seminars • 9 Contributed Talks • 6 Posters
  Referee for: • Phys. Rev. Lett. • Phys. Rev. A • Phys. Rev. Applied
  Organizing committee: Main organiser, Q-Turn 2020 (November 23rd-27th, 2020)

- ✓ Scientific network: Marcus Huber, Nicola Friis, and Martin Bohmann (IQOQI - Vienna, Austria), Jan Sperling (Uni Paderborn, Germany), Werner Vogel (Uni Rostock, Germany), Boris Rodríguez (Universidad de Antioquia, Colombia), Marco Bellini and Alessandro Zavatta (INO Florence, Italy).

My Goals

Short Term (1-2 years)

I expect to broaden my knowledge and boost my record of high quality scientific publications, awards, prizes, invited presentations in well-established international conferences, and teaching experience. Two more years time as a postdoc will be also fundamental for me to continue fortifying my collaborators network.

- ✓ Career advancement: Independent postdoc fellowship
- ✓ Research profile enhancement: development of independent projects (Lise Meitner Programme), Further high-impact publications, review papers, widened research network

Mid Term (3-5 years)

The next natural step for me is to plan my long-term research and to apply for extensive financial security to build up my own research group.

- ✓ Career advancement: Tenure track position
- ✓ Research profile enhancement: To secure funding for independent projects as a leader of research team (FWF START Programme or ERC Starting Grant)

Long Term (> 5 years)

- ✓ Career advancement: Permanent research position

Motivation statement

Quantum information and foundations of quantum mechanics are two fields that represent two of the most active and prolific areas of physics. As a scientist, to continue learning and expanding the field of expertise is fundamental. Learning new techniques and approaches, and interacting with numerous experts in a rich scientific environment, a research group, that works in close collaboration with multiple groups around the world, are big steps forward to a successful future academic career. The multidisciplinary character of the project will strongly broaden my horizons. Other aspects that will improve my competences are the opportunities to teach and supervise students, organize scientific events, and in the future apply for further independent funding. Dr. Huber recognizes these aspects as crucial for all the members of his team.

Regarding my international experience, I have extensively contributed to the processes of: knowledge-transfer across borders, scientific level convergence, and integration of the European society. In particular as a Latin-American scientist the relationships and networks established at the University of Vienna and with the international collaborators let me to have the opportunity to create a solid network within the circle of scientists conducting research of highest standards which allows me to have a role of connection between the Latin-American community and my collaborators in Europe. I have demonstrated research independence and evidence of maturity through significant publications (as main author) in leading international peer-reviewed journals of my respective field. I was awarded with and individual fellowship under Marie Skłodowska-Curie Actions, therefore, I have shown that I am able to write a successful project proposal with interesting and creative ideas that meets the high standards of the EU Programmes and to pursue the proposed research in an innovative and mature way. The two years of funding that the Lise Meitner Programm offers represent for me the perfect opportunity for consolidating my promising track record of early achievements appropriate to my research field and career stage. After this experience, I would be a competitive applicant for either the prestigious (FWF) START Programme or an ERC Starting Grant. Towards the end of this opportunity, I will be prepared for planning my long-term research and to establish my own research group. This experience will certainly boost my efforts to build a name and set me on the right track to attain a leading independent position in the future.

Dr. Elizabeth Agudelo Ospina
Applicant

Dr. Marcus Huber
Co-applicant

Annex 4: Co-applicant's letter of recommendation

ÖAW AUSTRIAN ACADEMY OF SCIENCES

IQOQI VIENNA – INSTITUTE FOR QUANTUM OPTICS AND QUANTUM INFORMATION

To: whom it may concern

November 30, 2020
Dr. Marcus Huber | marcus.huber@univie.ac.at | +29562

Letter of recommendation for Elizabeth Agudelo

With this letter I want to express my enthusiastic recommendation of Dr Elizabeth Agudelo for the Lise Meitner program of the Austrian Science Fund. She is currently working as a senior PostDoc in my group, using the prestigious and competitive Marie-Sklodowska Curie Action (MSCA) fellowship, which she won in 2018. The current proposal builds on the solid foundation of her research here and makes courageous steps towards unifying the two paradigmatic approaches to quantum photonics. I believe that this postdoctoral phase is a natural and effective progression of her academic career and believe it would greatly benefit both my group and the academic environment of Vienna if we managed to keep that talent here.

Dr Agudelo completed her PhD in 2017 at the University of Rostock. When she first contacted me regarding a postdoctoral position, she had outstanding recommendations and in her visit proved to be scientifically experienced well beyond the level expected from a recent PhD graduate. Indeed, I immediately decided to support her MSCA application, which after some Postdoctoral time of her in Germany and Italy turned out to be a resounding success (with more than 93% score average). She finally joined the group in May 2019 and seamlessly continued her excellent scientific work on infinite dimensional quantum systems. In her 18 months she finished 6 new papers, that are partially pre-prints under review and otherwise published in Physical Review A, Quantum and Physical Review Letters. In those recent works, she has charted the notion of phase space inequalities and their use in quantum information theory, ventured into new territory to apply her knowledge of infinite dimensional quantum systems to Bayesian metrology and helped develop and analyse quantum optics experiments. While all the aforementioned publications are completed within her independent collaboration network or in the context of my group, we are also working on joint projects that will soon come to fruition. We expect to finish at least two more preprints before her MSCA fellowship finishes. But this is only the beginning of a larger story, whose narrative is detailed in her most excellent proposal. By moving beyond the divide between infinite dimensional quantum systems and discrete degrees of freedom, she intends to develop overarching methods that will allow for a smooth treatment of all regimes, and more importantly hybrid systems that display both characteristics. In addition to her theory work, we are again setting up our own lab within the group and are well connected to the local experimental groups in quantum photonics. So a direct benefit of continuing with my group as a host is not just the uninterrupted continuation of scientific theory development, but the direct application of the results to

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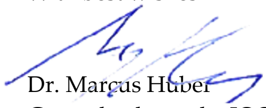
IQOQI Vienna

cutting edge quantum optics experiments. With her academic track record, combined with her motivation and drive, I have no doubt that the project will be an outstanding success

In addition to an excellent scholar, Dr Agudelo has a great ability to collaborate and form new connections as witnessed by her independent collaborations and newly formed collaborations within the group. That social talent is also manifest in her strive to make academia a better place for all to work within. From her engagement to provide opportunities to underprivileged students, especially in her hometown of Medellín, to recently organizing one of the fields biggest conferences in the field of quantum information: Q-turn. The 2020 edition she organised has not only drawn record number of participants, but also sheds light on many critical issues that academics across the globe face and that detrimentally impact scientific progress as well as producing unnecessary hardship for many individuals. A vocal advocate for academic integrity and equal opportunity, I believe academia needs scholars of her conviction to improve and thrive in the coming decades.

To summarise, I believe that Eliza is an outstanding scientist that will greatly benefit from the fellowship and who will bring many benefits to the host group. Her career plan is a testament to her dedication to science and academia as a whole and I would throughout provide the support necessary for her to progress in her academic career. I can only repeat my enthusiasm for this application and hope this will enable our continued collaboration for the coming years.

With best wishes



Dr. Marcus Huber
Group leader at the IQOQI Vienna

Annex 6: One additional letter of recommendation

UNIVERSITÄT PADERBORN
Die Universität der Informationsgesellschaft

FAKULTÄT FÜR NATURWISSENSCHAFTEN

UNIVERSITÄT PADERBORN | 33095 PADERBORN

Dr. rer. nat. habil.
Dipl.-Phys. Dipl.-Math.
Jan Sperling

Warburger Str. 100
33098 Paderborn
Germany

room P5.2.08
phone +49 5251 60-5962
email jan.sperling@upb.de

October 30, 2020

Letter of Recommendation for Dr Elizabeth Agudelo Ospina

To whom it may concern,

It is my great pleasure to offer this recommendation letter on behalf of the applicant Dr Elizabeth Agudelo.
I met Elizabeth when she started her PhD project at the Universität Rostock, where she received her PhD in 2017 through the dissertation "Multimode quantum correlations in phase space," under the supervision of Prof Werner Vogel and my co-supervision. Prior to that, Elizabeth received her Master degree from the Universidade Federal de Minas Gerais, Brazil, and her Bachelor degree from the Universidad de Antioquia, Colombia. Elizabeth was a postdoc at the Istituto Nazionale di Ottica (INO-CNR). Currently, she holds a position as a Marie Skłodowska-Curie postdoc at the Austrian Academy of Science, Marcus Huber Group at IQOQI (Institute for Quantum Optics and Quantum Information, Vienna), after she was awarded with this prestigious fellowship. I closely followed Elizabeth's academic career and enjoy to observe her commitment to work on fundamental problems in theoretical and applied physics.
Dr Agudelo is a highly qualified and independent researcher who significantly contributes to the scientific development in quantum physics. This makes her an ideal candidate for the esteemed Lise Meitner programme (FWF). Elizabeth's research interests can be broadly defined through the fields of fundamental quantum physics, quantum optics, and quantum information theory. This includes the quantum description of open and interacting quantum systems and the characterization of general multipartite quantum correlations. In particular, Elizabeth is an expert in the characterization of the nonclassical properties of multimode quantized radiation fields.

Elizabeth has a number of well-recognized publications in internationally renown peer-review journals, such as Physical Review Letters, certifying her ability to work along and with top-ranked scientists. Beyond her experience in putting forward new theoretical concepts for exploring quantum phenomena in complex systems, it is equally important to emphasize that Elizabeth's work includes several collaborations, not only with theory groups but also with different experimental groups. For example, two of her most recent works, available as preprints, concerned the experimental identification of novel quantum features, using methods she herself developed, and which have been implemented by the groups of Prof Boris Hage in Rostock, Germany, and Prof Marco Bellini in Florence, Italy. To me, this undoubtedly demonstrates that, beyond her excellent research at the forefront of theoretical quantum physics, she is highly interested in probing her theoretical findings in practical scenarios with importance for future quantum technologies.

Beyond her interest in science itself, Elizabeth is also a proponent of diversity and equal opportunity in science in general. In fact, as a woman in a male-dominated field and with a Latin-American background, she has already overcome many hurdles herself and, moreover, supports others with advise. Elizabeth speaks Spanish, Portuguese, English, German, and Italian. She is experienced in teaching and supervising students. In addition to working as a teacher earlier, she gave seminars on theoretical physics and lab courses in Germany. Elizabeth is respected and popular in the community and among fellow group members. Currently, she organizes the quantum information workshop Q-Turn in 2020, with the essential missions to foster science in an inclusive community. To me, it is a great pleasure to take part in inspiring discussions with Elizabeth and to collaborate with her.

In conclusion, Dr Elizabeth Agudelo is a highly talented young scientist, successfully working on resolving fundamental questions concerning various vital aspects of quantum physics. She communicates the results of her cutting-edge research to other scientists in a rigorous, yet easily accessible manner, opening up new connections between theoretical and experimental physics. Her scientific excellence is further acknowledged by the European Union through awarding her with a Marie Skłodowska-Curie fellowship. Elizabeth is a kind, honest, and supportive personality who treats everyone on an equal basis.

For the above reasons, I strongly support Dr Agudelo's application to further foster her scientific career, being well on track to becoming a leading scientist in the broad and lively field of quantum physics.

If you have any further questions, please do not hesitate to contact me.

Sincerely yours,

Jan Sperling