Nº PROYECTO : 11110115  
DURACIÓN : 3 años  
AÑO ETAPA : 2013

TÍTULO PROYECTO : EXPERIMENTAL QUANTUM CRYPTOGRAPHY AND VIOLATION OF BELL’S INEQUALITIES 
EMPLOYING GENUINE ENERGY-TIME ENTANGLEMENT IN LONG OPTICAL FIBERS

DISCIPLINA PRINCIPAL : OPTICA QUÁNTICA 
GRUPO DE ESTUDIO : FISICA TEORICA Y EXP 
INVESTIGADOR(A) RESPONSABLE : GUILHERME BARRETO XAVIER 
DIRECCIÓN : 
COMUNA : 
CIUDAD : Concepcion 
REGIÓN : VIII REGION

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OBJETIVOS

Cumplimiento de los Objetivos planteados en la etapa final, o pendientes de cumplir. Recuerde que en esta sección debe referirse a objetivos desarrollados, NO listar actividades desarrolladas.

<table>
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<tr>
<th>Nº</th>
<th>OBJETIVOS</th>
<th>CUMPLIMIENTO</th>
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<tr>
<td>1</td>
<td>Violation of Bell's inequalities with genuine energy-time entanglement while simultaneously closing the locality and post-selection loopholes</td>
<td>PARCIAL</td>
<td>The post-selection loophole was closed, and important results have been demonstrated that this experimental configuration can be used to close the locality loophole. Unforeseen problems in the installed fiber link (optical fiber type, geographical configuration, etc...) have rendered impossible that the locality loophole be closed in the final year of the project (some changes to the optical components are needed). More details are provided in the report. Nevertheless the important result that was obtained will be sent for publication soon.</td>
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<tr>
<td>2</td>
<td>Quantum key distribution using genuine energy-time entanglement</td>
<td>PARCIAL</td>
<td>The experiment of QKD using genuine energy-time entanglement is currently being performed in the lab and we expect results within the next two months. Due to the long-time required to obtain the two-photon interference curves from objective 1 (in the 3.7 km installed fiber link), the attempt to perform QKD only began recently. Nevertheless another paper was published with an analysis of the noise impact on QKD systems from multiple telecom channels on optical fibers. Two other papers were published that employed the electronic systems developed for this objective. Finally a full QKD session was performed in free space with high-dimensional quantum systems, which also required the use of the automated electronic systems.</td>
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Otro(s) aspecto(s) que Ud. considere importante(s) en la evaluación del cumplimiento de objetivos planteados en la propuesta original o en las modificaciones autorizadas por los Consejos.

Although the final original objectives were not accomplished as they were originally stated, the main hypothesis of this project was positively answered: That it is possible to perform QKD free of the post-selection and locality loopholes in optical fibers using genuine energy-time entanglement. Our obtained results when put together indicate this. This project has produced important results in this direction, with the main one being published in Nature Communications. The electronics developed to be used in the project...
have been used in other experiments that have been published and are in preparation, with one of them in Physical Review Letters.
RESULTS OBTAINED:
For each specific goal, describe or summarize the results obtained. Relate each one to work already published and/or manuscripts submitted. In the Annex section include additional information deemed pertinent and relevant to the evaluation process.
The maximum length for this section is 5 pages. (Arial or Verdana, font size 10).

For the final year of the project the specific goals were: 1) to install and perform the violation of Bell’s inequalities with genuine energy-time entanglement while simultaneously closing the postselection and locality loopholes; 2) Implement a quantum key distribution link using genuine energy-time entanglement. Here we report the progress and results obtained in both goals, as well as other advances performed.

1) One important result obtained is the publication of the results from the second year on Nature Communications, A. Cuevas et al, Nat. Commun. 4, 2871 (2013). The paper was under review when the last yearly report for this project was submitted, and was finally published in November 2013.

Regarding the first goal, the biggest difficulty is to implement the active phase stabilization as well as the violation of the CHSH Bell inequality under field conditions. We obtained access to a 3.7 km link inside the university campus. The setup was then assembled over the course of several months as displayed in figure 1. The source is placed within Alice, as well as the additional lasers for phase control and synchronization. New electronics were developed to perform the synchronization across the campus, as well as employing a very narrow coincidence window (1 ns), in order to further remove background noise (accidental coincidences). A paper is being prepared with the results of this new development in electronics.

![Figure 1 – Genuine energy-time setup with Alice inside the Optoelectronics laboratory in the Engineering Faculty, and Bob being placed in the TIGO station (Transportable Integrated Geodesic Observatory), both inside the University of Concepción.](image)

We recently obtained successful two-photon interference across the campus with the genuine energy-time configuration seen in Figure 1. These curves (normalized) are shown in Figure 2. These results are very important as they show for the first time that the “hug” configuration (i.e. genuine energy-time) is capable of being deployed under realistic field conditions. Furthermore it opens up the path to close the locality loophole with the same configuration. The results from figure 2 took several months to be obtained, due to many unforeseen problems that came up in the final year of the experiment. They were mostly related to working at 800 nm wavelength for the single-photons, while the fibers are optimized for 1550 nm.
These preliminary results were presented in two conferences: Bell’s [Un]Speakables II in Vienna in June, and QCrypt 2014 in the beginning of September in Paris. The main problem we are currently facing is that due to the configuration we have access to (i.e. source inside Alice, and 3.7 km connecting Alice to Bob), we need an extra 2 km interferometric delay inside Alice. This is to guarantee that Alice and Bob’s random settings have independent light cones, a requirement to close the locality loophole. This extra 2 km interferometer will place an extra loss we cannot cope with our current configuration, as the interferometric visibility of the curves in Fig. 2 is already close to the limit to violate the CHSH Bell inequality. The two possible solutions would be employing a shorter link (which is not possible in a short period in the university), or working with telecom wavelengths (1550 nm), which have approximately 10 times lower losses. This will also have the additional advantage of removing some of the problems we are currently facing due to the multimode propagation in telecom fibers. This is a major change, and requires many components to be replaced, therefore it cannot be implemented straightaway. However a continuation of this line of investigation is on track, to be implemented under a new Regular Fondecyt project postulated by the same PI of this current project.

Nevertheless the obtained results will be sent for publication soon, together with the QKD part of the experiment (Please see point 2). We expect the results to be sent to an important journal like Physical Review Letters.

2) The paper reporting the experimental demonstration of measurement device-independent quantum key distribution (MDI-QKD), which was under review when the last yearly report was sent, has been published – T. Ferreira da Silva et al, Phys. Rev. A, 88 052303 (2013). This paper was, together with three other independent research groups, the first experimental demonstration of MDI-QKD, and was important in this project to develop new electronic capabilities for long-distance communication with photon pairs.

After the results from figure 2 were obtained, the focus was on performing QKD inside the lab, in order to develop the new electronics and optical techniques needed without the difficulties of working in the field. Furthermore, since two extra modulators are needed, it is not yet clear if with the newly added losses the QKD experiment will work in our 3.7 km field link as the visibilities shown in Figure 2 are on the limit to perform QKD. The current plan is to finish the QKD experiment in the lab in the next two months, and then do a final attempt on the field. With all the results obtained a new paper will be written and submitted. In retrospect to the original plan, the unforeseen problems faced in the last year to obtain the two-photon interference across the campus of the university, modified the attainable goals of the project. Nevertheless this experimental line is very promising, and after a considerable investment of time and money, it will continue with the required modifications.
Other results obtained:

- The impact on the key generation rate in a QKD system from the scattered noise generated from multiple classical channels inside the same optical fiber was published as T. Ferreira da Silva et al, IEEE/OSA Journal of Lightwave Technology, 32 2332-2339 (2014). This is relevant to quantify the feasibility of implementing QKD systems (based on entanglement or not) on fibers populated with classical signals, which is highly attractive from a commercial point of view.

- The electronics that were developed to randomly choose the measurements settings by Alice and Bob, as well as record the data, were used in two other experiments. Both experiments employed spatial light modulators (SLMs) working with higher-dimensional quantum states encoded on the transverse linear momentum of single-photons. The first experiment used an 8-dimensional system to test a Kochen-Specker set that is formally equivalent to performing Mermin's inequality on a Greenberger-Horne-Zeilinger state. This is a known connection between quantum contextuality and quantum non-locality. The results were published in G. Cañas et al, Phys. Rev. A 90, 012119 (2014). Using another setup based on this one, it an important practical application was demonstrated for Kochen-Specker sets: the certification that the number of dimensions accessed by the measurement hardware is the correct one. These results were published as G. Cañas et al, Phys. Rev. Lett. 113, 090404 (2014).
OTHER ACHIEVEMENTS OF THE PROJECT:
- Research visit(s) to other institution(s).
- Outreach activities related to the project’s main topic.
- Any other contribution, not addressed elsewhere, that you consider important.

The maximum length for this section is 1 page. (Arial or Verdana, font size 10).

- Prof. Adán Cabello from the University of Seville visited the university in January to discuss many points related to this project, including the current experiment and new ideas. He was joined by Professors Paolo Mataloni (University of Rome, “La Sapienza”), Jan-Åke Larsson (University of Linköping) and Marcelo Terra Cunha (Federal University of Minas Gerais), who all took rounds of discussion on the project and future experiments directly related to the project.

- Two poster presentations were made at two conferences. The first one named “Towards genuine energy-time entanglement-based quantum key distribution over installed telecom optical fibers”, was presented in Vienna, at the conference Quantum [Un]Speakables II, to celebrate the 50th anniversary of Bell’s inequalities. The second was named “Towards genuine energy-time entanglement quantum cryptography in installed telecom fibers”, and was presented in Paris at the QCrypt 2014.

- With the knowledge gained from the development of the electronics, a simple QKD prototype is being built for demonstration purposes. We expect this will be important to divulgate to the Chilean society the practical impacts that QKD will have on the future of telecommunications.

- The PI will give a talk as an invited speaker at the Latin American conference on Optics and Photonics (LAOP) 2014 in Cancún, Mexico in November 2014. The talk will focus on how optical and electronic instrumentation can help advance the engineering aspects of long-distance secure quantum communications in optical fibers. This will include the phase stabilization systems used and further developed in this project, as well as the distribution of genuine energy-time entanglement across the campus of the University of Concepción.
Prof. Cabello was the original proposer of the experimental configuration we are using (so-called genuine energy-time entanglement). He has given strong theoretical support in this project. His visit in January was essential to discuss the progress of the experiment, as well as discuss new ideas. He has taken part in three publications that were generated from this project:


The three publications have been officially included in the project's report. Publication 1 was the demonstration that genuine energy-time entanglement can be distributed through long optical fibers. Papers 2 and 3 were direct applications of the electronics that were developed for implementing quantum cryptography with genuine energy-time entanglement.

PRODUCTOS

ARTÍCULOS
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<td>Scientific Reports</td>
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Nombre Completo de la Revista : Physical Review A
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Towards genuine energy-time entanglement quantum cryptography in installed telecom fibers

Carvacho, G.; Saavedra, G.; Cuevas, A.; Carine, J.; Meunier M.; Figueroa, M.; Larsson J-A.; Cabello, A.; Mataloni, P.; Lima, G.; Xavier GB.

Qcrypt 2014

FRANCIA

Paris

01/09/2014

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Distribución de entrelazamiento energía-tiempo genuino en grandes distancias

Alvaro Cuevas

Guilherme Barreto Xavier

Magister

Universidad de Concepcion

CHILE

Concepcion

Terminada

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Criptografía cuántica ocupando fotones entrelazados con energía-tiempo genuino

Gonzalo Carvacho

Guilherme Barreto Xavier

Magister

Universidad de Concepcion
País : CHILE
Ciudad : Concepción
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Fecha Inicio : 01/03/2012
Fecha Término : 01/03/2014
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Título de Tesis : Propagación de fotones con entrelazamiento energía-tiempo genuino a través de fibras ópticas para grandes distancias
Nombre y Apellidos del(de la) Alumno(a) : Gabriel Saavedra
Nombre y Apellidos del(de la) Tutor(a) : Guilherme Barreto Xavier
Título Grado : Magister
Institución : Universidad de Concepcion
País : CHILE
Ciudad : Concepción
Estado de Tesis : Terminada
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