Long-Distance Distribution of Genuine Energy-Time Entanglement

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Introduction

The experimental violation of Bell inequalities allows for communication with security guaranteed by the impossibility of signaling at superluminal speeds [1,2]. This type of secure communication requires distributing quantum entanglement over long distances. The most common method to do it in optical fibers is based on Franson's configuration [3] [See Fig. 1], which has an intrinsic geometrical loophole (post-selection of coincident detections between Alice and Bob), and therefore, cannot rule out all possible local explanations for the apparent violation of the Bell CHSH inequality [4, 5].

$$S \equiv |E(\Phi_A,\Phi_B) + E(\Phi'_A,\Phi_B) + E(\Phi_A,\Phi'_B) - E(\Phi'_A,\Phi'_B)| \leq 2$$

Where the probability coincidence distributions are

$$E(\Phi_A,\Phi_B) \equiv P_{11}(\Phi_A,\Phi_B) + P_{22}(\Phi_A,\Phi_B) - P_{12}(\Phi_A,\Phi_B) - P_{21}(\Phi_A,\Phi_B)$$

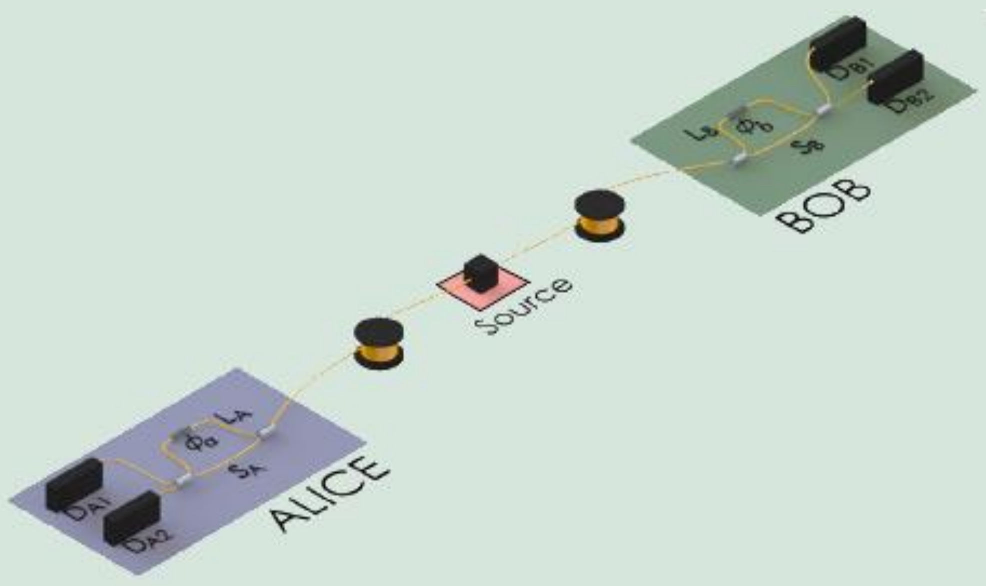

Fig.1: Franson Bell Test Configuration

On the practical side, this loophole can be exploited by eavesdroppers to break the security of the communication [6].

Here we report the first experimental violation of the Bell CHSH inequality with genuine energy-time entanglement (i.e., free of the post-selection loophole) distributed through more than 1 km of optical fibers.

Solution

In order to remove the post-selection loophole we replace the original scheme with two unbalanced interferometers in the “hug" configuration introduced in [5] [See Fig. 2], which has been demonstrated in table-top experiments [7, 8].

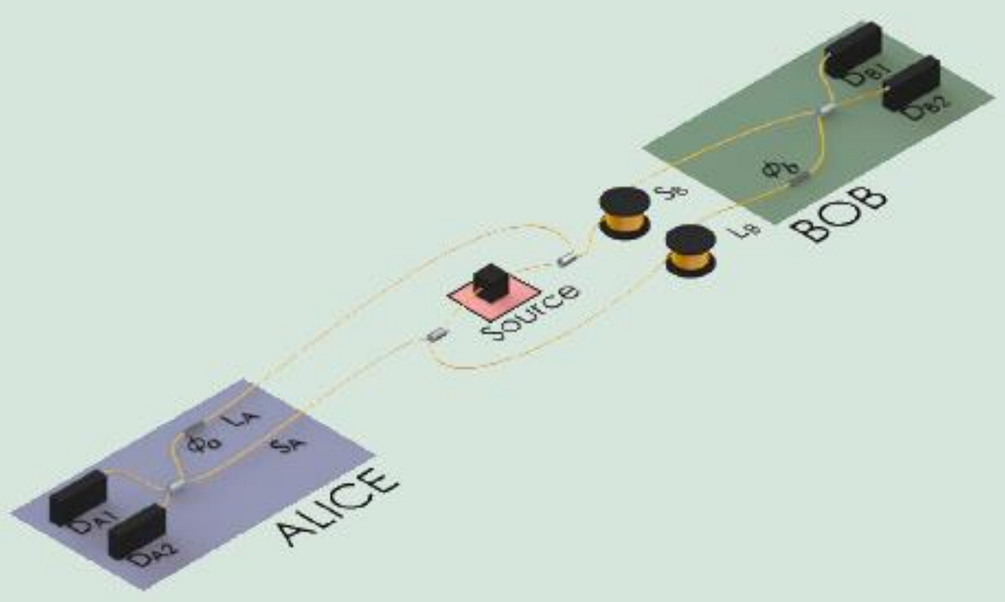

Fig.2: Genuine Energy-Time Hug Bell Test Configuration.

The degenerate 806 nm photon pairs are created in a PPKTP non-linear crystal through the process of spontaneous parametric down-conversion. The fundamental uncertainty in the emission time of the down-converted photons sets up as indistinguishable the possible paths they can take in both equally unbalanced interferometers [5]. When this condition is satisfied, the Bell state

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|SS\rangle + e^{i(\phi_A+\phi_B)}|LL\rangle\right)$$

is generated, where S and L indicate the short and long arms, respectively. The long-short paths length differences are $L_A - S_A = L_B - S_B = 2m$. The experimental setup used is depicted in Fig. 3.

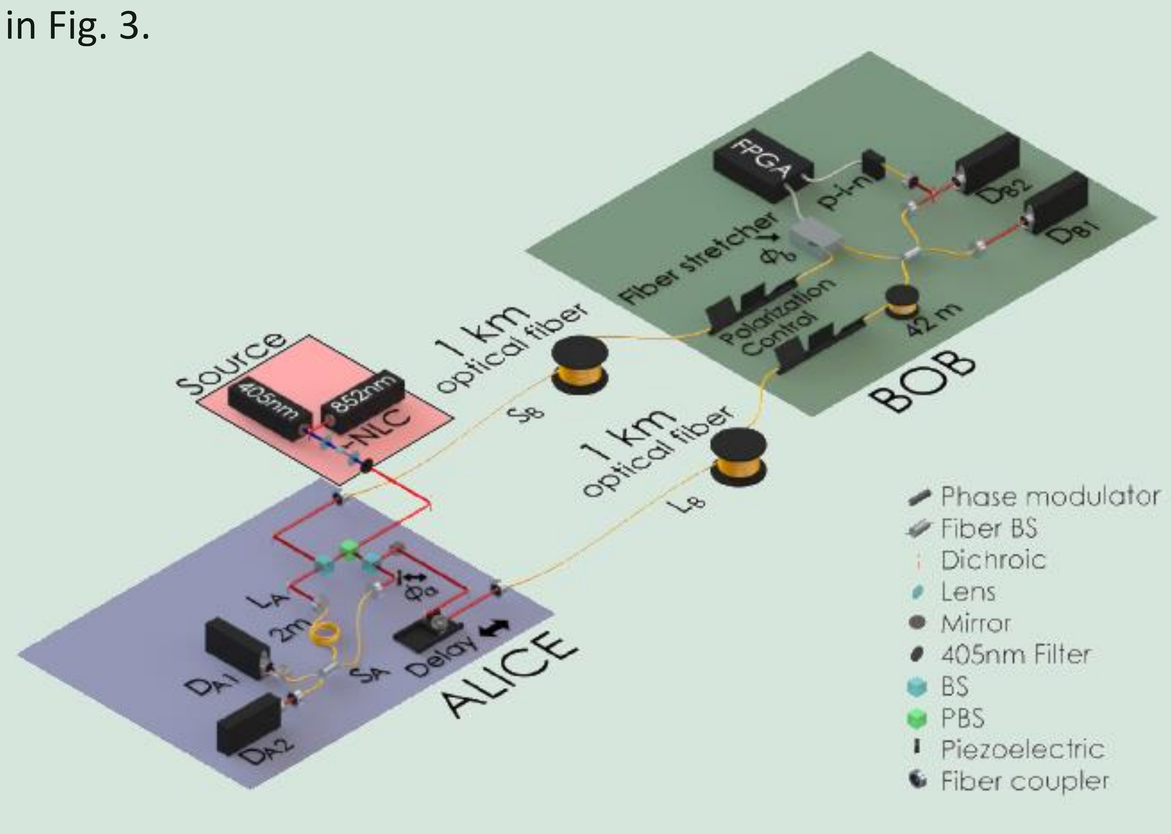

Fig.3: Experimental Setup.

Results

A great challenge in this implementation is the compensation of random phase fluctuations caused by the environment in long interferometers. We solved this by injecting a second laser into the system to provide real-time feedback for the field programmable gate array (FPGA) based control electronics [9].

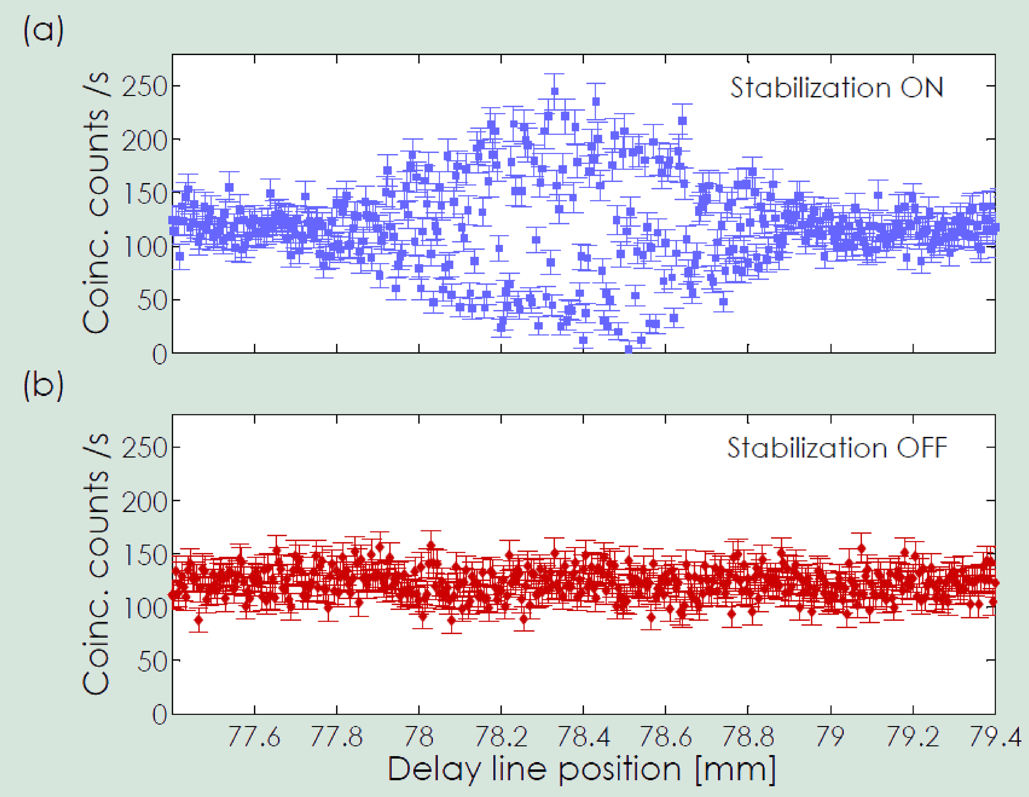

Fig 4: Net Coincident Counts vs Delay-line Position

The violation of the Bell CHSH inequality was performed with the delay line set at the center of the two-photon interference pattern, the active phase control is kept active and a piezo-mounted mirror slowly modulated. The phase control system is used to switch between Bob's two phase settings 0 and $\pi/2$. And the measured curves across all output combinations are displayed in Fig. 5(a)-(d).

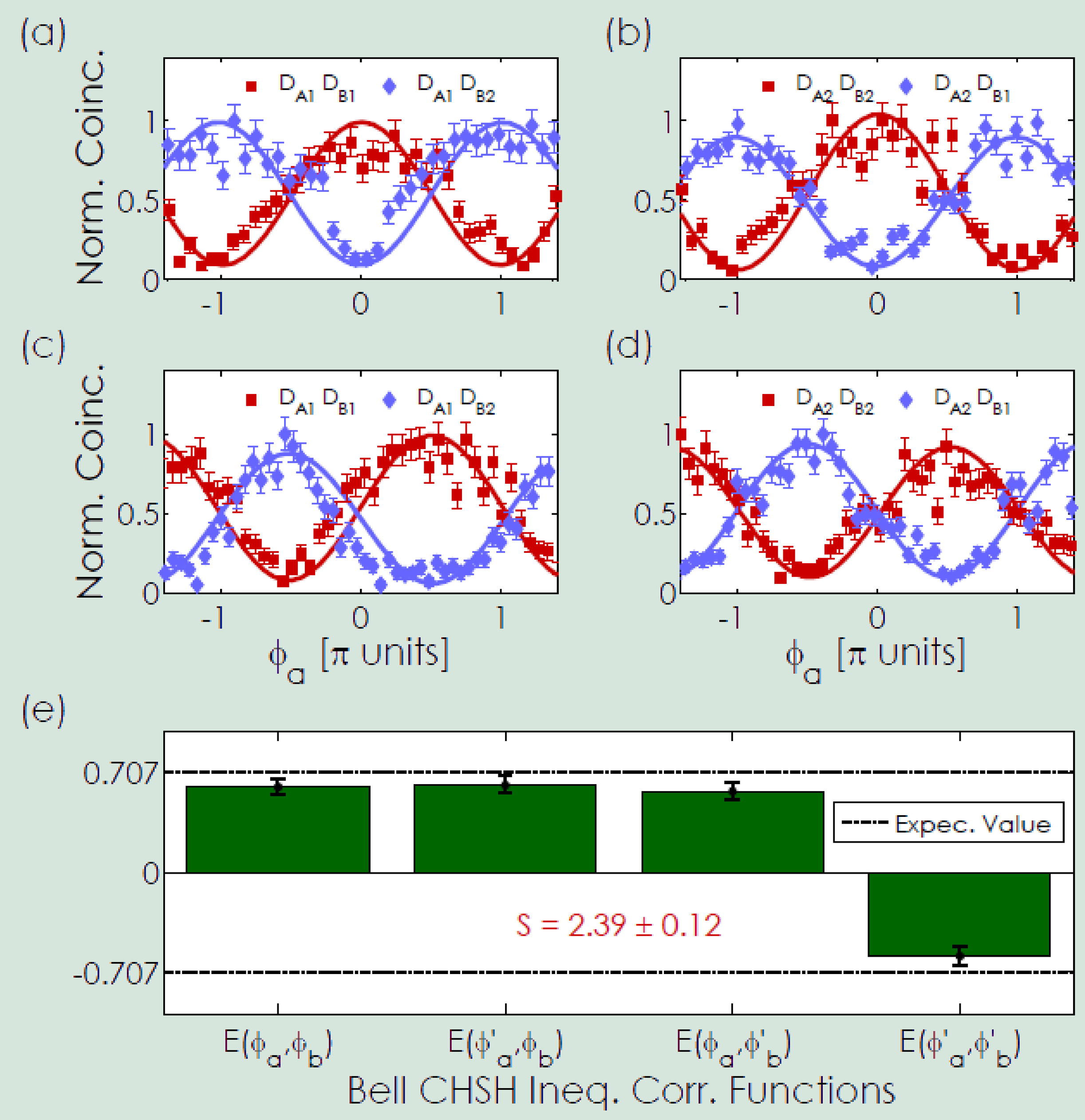

Fig.5: Coincidence interference curves and Bell CHSH inequality violation. (a) and (b) correspond to the cases where Φ_B = 0 and (c) and (d) to the cases where Φ_B= 2.

For the maximum violation of the Bell CHSH inequality the phase settings are $\phi_A = \pi/4$, $\phi_B = 0$, $\phi_A = -\pi/4$ y $\phi_B = \pi/2$ [7], which gives us the theoretical value $S = 2\sqrt{2}$.

The measured average raw visibility was $(84.36 \pm 0.47)\%$, and the corresponding violation of the Bell CHSH inequality in this case yields $S = 2.39 \pm 0.12$, surpassing the classical limit by 3.25 standard deviations.

We have successfully demonstrated the long-distance distribution of genuine energy-time entanglement over 1 km long optical fibers. These results represent an important step towards secure quantum communications in optical fibers

References

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