Experimental Free-Space Distribution of Entangled Photon Pairs Over 13 km: Towards Satellite-Based Global Quantum Communication

Cheng-Zhi Peng,[1,2] Tao Yang,[1] Xiao-Hui Bao,[1] Jun Zhang,[1] Xian-Min Jin,[1] Fa-Yong Feng,[1] Bin Yang,[1] Jian Yang,[1] Juan Yin,[1] Qiang Zhang,[1] Nan Li,[1] Bao-Li Tian,[1] and Jian-Wei Pan[1,2]

[1]*Department of Modern Physics and Hefei National Laboratory for Physical Sciences at Microscale, University of Science and Technology of China, Hefei, Anhui 230026, China*

[2]*Physikalisches Institut der Universitaet Heidelberg, Philosophenweg 12, Heidelberg 69120, Germany*

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We report free-space distribution of entangled photon pairs over a noisy ground atmosphere of 13 km. It is shown that the desired entanglement can still survive after both entangled photons have passed through the noisy ground atmosphere with a distance beyond the effective thickness of the aerosphere. This is confirmed by observing a spacelike separated violation of Bell inequality of 2.45 ± 0.09. On this basis, we exploit the distributed entangled photon source to demonstrate the Bennett-Brassard 1984 quantum cryptography scheme. The distribution distance of entangled photon pairs achieved in the experiment is for the first time well beyond the effective thickness of the aerosphere, hence presenting a significant step towards satellite-based global quantum communication.

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In a future large scale realization of quantum communication schemes [1–3], we have to solve the problems caused by photon loss and decoherence in the transmission channel. For example, because of the photon loss and the unavoidable dark count of the current available single-photon detectors, the maximum distance in the fiber-based quantum cryptography is limited to the order of 100 km [4]. The quantum repeater scheme that combines entanglement swapping, entanglement purification, and quantum memory [5–7] proposed an efficient way to generate highly entangled states between distant locations, hence providing an elegant solution to the photon loss and decoherence problem. In recent years, significant experimental progress has been achieved in the demonstration of entanglement swapping, entanglement purification, and quantum memory [8–11], and even in the demonstration of a prototype of quantum relay [12,13]. However, one still has a long way to go before the above techniques can be finally integrated into a single unit in order to be useful for realistic quantum communication over large distances.

Another promising way to realize long-distance quantum communication is to exploit satellite-based free-space distribution of single photons or entangled photon pairs [14]. In the scheme, the photonic quantum states are first sent through the aerosphere, then reflected from one satellite to another, and finally sent back to the earth. Since the effective thickness of the aerosphere is on the order of 5–10 km (i.e., the whole aerosphere is equivalent to 5–10 km ground atmosphere) and in the outer space the photon loss and decoherence is negligible, with the help of satellites one can achieve global free-space quantum communication as long as the quantum states can still survive after penetrating the aerosphere [14].

Along this line, important experimental progress has been made very recently in the free-space distribution of attenuated laser pulses (over 23.4 km) and entangled photon pairs (over 600 m) [15,16]. However, on the one hand, in the quantum cryptography experiment with attenuated laser pulses [15] the huge photon loss in the transmission channel leaves an eavesdropping loophole. This is because the eavesdropper could, in principle, exploit a transmission channel with less photon loss and allow only those attenuated laser pulses containing two or more photons to reach the receiver. In this way, the eavesdropper can use a beam splitter to steal at least one photon from these specific attenuated laser pulses without being detected. On the other hand, while the achieved distance in the previous entanglement distribution experiment [16] is only on the order of 600 m which is far below the effective thickness of the aerosphere, the achieved low transmission efficiency ($\sim 10^{-3}$) would not enable a sufficient link efficiency over large distances, which is, however, required for satellite-based free-space quantum communication [14].

In this Letter, with the help of a laser-pulse-assisted synchronization method and our own designed telescope systems we drive the free-space technology further by reporting free-space distribution of entangled photon pairs over a noisy ground atmosphere of 13 km. We confirm that the desired entanglement can still survive after both entangled photons have passed through the noisy ground atmosphere with a distance beyond the effective thickness of the aerosphere. In addition, we also exploit the distributed entangled photon source to experimentally demonstrate the Bennett-Brassard 1984 (BB84) quantum cryptography scheme [1] without the eavesdropping loophole. The distribution distance of entangled photon pairs achieved in our experiment is for the first time well beyond the effective thickness of the aerosphere, hence presenting a significant step towards satellite-based global quantum communication.

In the experiment, as shown in Fig. 1, a sender is located on the top of Dashu Mountain in Hefei of China, with an elevation of 281 m, and two receivers (Alice and Bob) are located on the west campus of USTC and at Feixi of Hefei, respectively. The direct distance between the two receivers is about 10.5 km. The distances from the sender to Alice and from the sender to Bob are 7.7 and 5.3 km, respectively [17]. One of the two entangled photons passes through nearly half of Hefei city, experiencing an extremely challenging environment above the city. The two receivers are not in sight with each other due to the existence of many buildings between them.

At the sender, we utilize type-II parametric down-conversion to generate entangled photon pairs [18]. The argon ion laser used to pump the beta-barium-borate crystal has a wavelength of 351 nm. When the pump power is about 300 mW, with narrow bandwidth filters of 2.8 nm in front of single-photon detectors, we locally collect about 10 000 pairs of entangled photons per second.

In order to optimize the transmission efficiency and its stability, we have designed two sets of transmission system ourselves, which contain four large telescopes of refraction type. Each telescope weighs about 800 kg, with a focus length about 2 m. The main weight of the telescope is contributed from its base, which is necessary to achieve the stability of the telescope on the ground. However, such a heavy base is not necessary if we install the telescope on the satellite. Lenses used in the telescope are coated to maximize the peak transmission rate at the wavelength of entangled photons (702 nm). Each transmission system composed of two telescopes can achieve a transmission rate of above 70%. The wild environment on the top of Dashu Mountain causes many difficulties, and we have taken several measures to overcome them. The two telescopes at the sender are specially designed to be robust against the strong wind.

The entangled photons at the sender are collected into two single-mode fibers, which are connected to the two sending telescopes, respectively. Because of the disturbance of the atmosphere, the size and position of the received beam vary randomly, causing a reduction of the collecting efficiency. To solve this problem, we have used the two sending telescopes to expand the beam diameter to about 12 cm for long-distance propagation. Moreover, at each receiver a similar telescope is used to receive the entangled photons. After being focused, entangled photons are coupled into 62.5 μm multimode fibers and finally sent to single-photon detectors. With these efforts, we manage to keep the transmission system working stably for a couple of hours. For example, in the right photograph of Fig. 1 we can see at the Alice side a bright and stable adjusting laser beam from the sender.

Since the distances from the sender to Alice and to Bob are not equal, the two entangled photons will arrive at each receiver at different times. The air disturbance will cause this time difference to vary randomly, resulting in a time difference shake (ΔT). To coincide the detected events at the two receivers, we have to make sure that the coincident time window is wider than (ΔT). However, when we widen the coincident time window to get the adequate true coincident events, the accidental coincident count rate also increases and thus results in a reduction of the visibility. In our experiment, we utilized the method of laser pulse synchronization to achieve time coincidence between the two receivers (see Fig. 2). At the sender, Q-switched laser pulses with a wavelength of 532 nm are separated into two parts, and then sent to the receivers, experiencing the same optical path as the entangled photons. At each receiver, we measure the time difference between the signal of the single-photon event and the signal of the corresponding synchronous laser pulse for the subsequent coincidence via the classical communication link. Considering other ingredients causing time shake, we set the time window to 20 ns in our experiment.

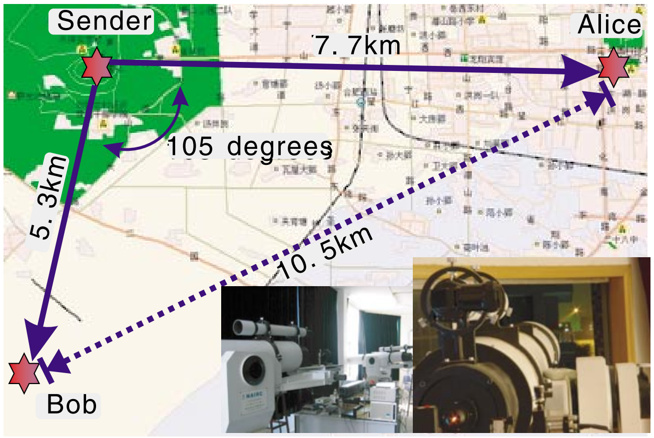

FIG. 1 (color). Schematic diagram of locations in our experiment. The source of entangled photons is located at the foot of a high television tower, on the top of Dashu Mountain. Alice is located on the west campus of USTC, and Bob is located at Feixi, a county of Hefei city. Photons from the sender to the receivers experience a noisy city environment. Therefore, strongly influenced by the air pollution and noisy background lights, even after rain with less air pollution, the background count rate can reach about 30 000 per second at night without using interference filters.

Finally, to minimize the background count rate, the experiment is performed during night, and 2.8 nm interference filters are utilized at each receiver to block the noisy background light. With the filters added, the average background count rate is about 400 per second. When the weather condition is perfect with a considerably high visibility (>15 km), the total single-photon count rate is about 40 000 per second at Bob and about 18 000 per second at Alice; the coincident count rate is about 300 per second. At the normal visibility (10 km), the coincident count rate is about 150 per second.

The entangled state prepared at the sender can be expressed as follows:

$$|\psi^-\rangle = \frac{1}{\sqrt{2}}(|H\rangle_A|V\rangle_B - |V\rangle_A|H\rangle_B), \tag{1}$$

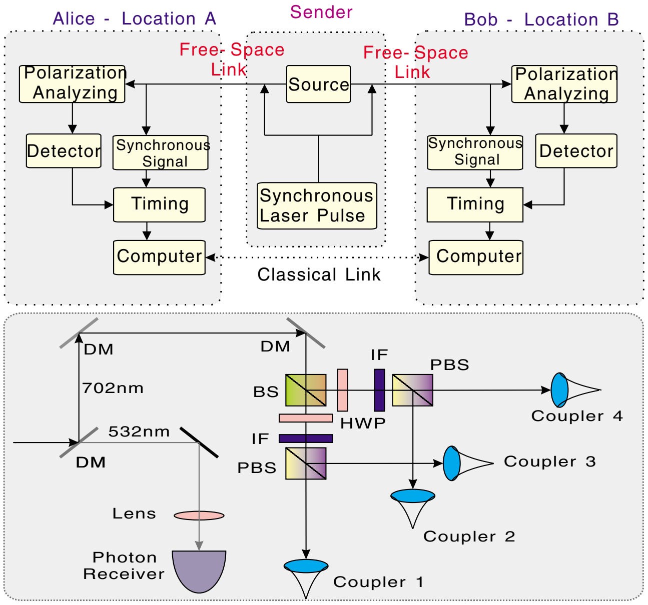

FIG. 2 (color). Block diagram of the experiment and optical setup at the receivers. As shown in the left part, we combine the entangled photons with the synchronous pulsed laser beam utilizing a dichroic mirror (DM) at the sender and separate them at each receiver with a DM. Then it follows with single-photon polarization analysis and time synchronization. In the lower part, a beam splitter (BS) is used to achieve random basis selection, and a half-wave plate (HWP) together with a polarization beam splitter (PBS) makes up an apparatus for polarization measurement. Interference filters (IF) are used to get rid of noisy background light.

where photon A is sent to Alice, photon B is sent to Bob, and H and V represent horizontal and vertical polarization. The local visibility at the sender is about 98% in the H/V basis, and 94% in the $+45/-45$ basis. The observed visibilities between two separated receivers are 94% and 89% in the H/V and $+45/-45$ bases, respectively (see Fig. 3). Hence the average visibility reaches 91%, which is well beyond 71% required for a violation of Bell inequality. In order to further test the quality of the entangled state, we measured the Clauser-Horne-Shimony-Holt (CHSH) inequality which is one type of the Bell inequalities [19]. The polarization correlation coefficient is defined as follows:

$$E(\phi_A, \phi_B) = \frac{N_{++} + N_{--} - N_{+-} - N_{-+}}{N_{++} + N_{--} + N_{+-} + N_{-+}}, \tag{2}$$

where $N_{ij}(\phi_A, \phi_B)$ are the coincidences between the i channel of the polarizer of Alice set at angle ϕ_A and the j channel of the polarizer of Bob set at angle ϕ_B. In the CHSH inequality, parameter S is defined as

$$S = |E(\phi_A, \phi_B) - E(\phi_A, \phi'_B) + E(\phi'_A, \phi_B) + E(\phi'_A, \phi'_B)|. \tag{3}$$

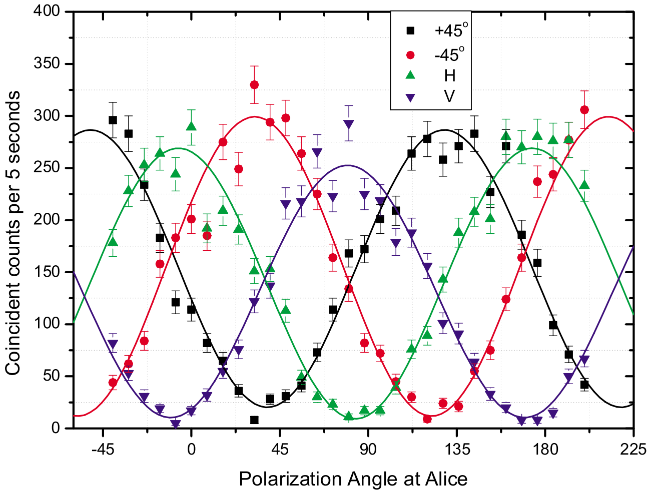

FIG. 3 (color). Verification of the distributed quantum entanglement. In order to test the quality of the entangled state between the two receivers, we measured the coincident count as a function of Alice's polarization angle. Four curves correspond to four polarization angles ($H, V, +45, -45$) set at Bob. The data are best fitted with sin functions, showing that the visibility is 94% in the H/V basis, and it is 89% in the $+45/-45$ basis. The average visibility has reached 91%, which is far beyond the threshold required for a violation of the Bell inequality.

In the local realistic view, no matter what angles ϕ_A and ϕ_B are set to, parameter S should be below 2. But in view of the quantum mechanics, S will get to the maximal value $2\sqrt{2}$ when the polarization angles are set to $(\phi_A, \phi'_A, \phi_B, \phi'_B) = (0°, 45°, 22.5°, 67.5°)$.

As the detection loophole existed in all previous photonic tests of local realism [20–22], here we are going to show only a violation of Bell inequality with spacelike separated observers. To do so, at each observer a beam splitter (see Fig. 2) is used to achieve the true random basis selection and use four single-photon detectors to perform the $(0°, 45°, 22.5°, 67.5°)$ polarization measurement. With emphasis, we note that our passive beam splitter is sufficient to provide a bona fide test of the locality loophole. This is because in experiments using low efficient detectors the locality problem can be dealt with by using active or passive switches [23]. In our experiment, the whole measurement process was completed in 20 s. Note that, all the 16 coincident counts are measured simultaneously with two receivers spacelike separated. Moreover, since different detectors have different detection efficiency, twofold coincidence normalization has been performed based on the single count rate. The measured result of parameter S is 2.45 ± 0.09, with a violation of the CHSH inequality by 5 standard deviations (see Table I for details). This result firmly ascertains that entanglement has been built between the two distant receivers.

In the cryptography experiment, we take a variant scheme of BB84 with entangled photons [1]. In this scheme, with the help of the beam splitter Alice and Bob randomly measure her/his received photons in the H/V or

TABLE I. Measured correlation coefficients required for the CHSH inequality.

$E(\phi_A, \phi_B)$	$(0°, 22.5°)$	$(0°, 67.5°)$	$(45°, 22.5°)$	$(45°, 67.5°)$
Value	-0.681	0.764	-0.421	-0.581
Deviation	0.040	0.036	0.052	0.046

$+45/-45$ basis. Because of the perpendicular property in polarization of $|\psi^-\rangle$, when they have chosen the same basis, their private keys are anticorrelated. Then identical keys can be easily obtained, if one of them converts all her/his keys. In 4 min, we obtained 29 433 coincidence events. Because of the difference of the collecting efficiency of the four couplers at each receiver, we have randomly discarded some events related to the high-efficiency couplers in order to make the efficiency of the couplers at each receiver equal, and, after this process, we got 15 308 coincidence events. Discarding the events where Alice and Bob had chosen different bases, we got 7956 bits of sifted key, and the quantum bits error rate (QBER) is 5.83%. Then we did error correction, and decreased the key size to 4869 bits with an error rate of 1.46%. After the privacy amplification procedure depending on the QBER, finally we got 2435 bits of final secure key. This corresponds to an average key distribution rate of 10 bits/s. Note that, using a high-intensity entangled photon source [24], one can easily increase the average key distribution rate to a few hundreds per second.

Although compared to the previous experiments our experimental results might seem to be only a modest step forward, the implication is profound. First, our experiment demonstrated for the first time that entanglement can still survive after penetrating the effective thickness of the aerosphere by showing a violation of the Bell inequality with spacelike separated observers. Obviously, the strong violation of the Bell inequality is sufficient to guarantee the absolute security of the quantum cryptography scheme, hence closing the eavesdropping loophole. Second, the link efficiency of entangled photon pairs achieved in our experiment is about a few percent, which is well beyond the threshold required for satellite-based free-space quantum communication [14]. Moreover, the methods developed in the present experiment to establish a high stable transmission channel and achieve synchronization between two distant receivers provide the necessary technology for future experimental investigations of global quantum cryptography and quantum teleportation in free space. Finally, it is worth noting that by exploiting a pulsed and gateable entangled photon source and using high precision spatial and spectra filtering the technology developed here would also allow free-space quantum communication even in the daytime [25].

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[17] Since in realistic free-space quantum communication the two users, Alice and Bob, will usually be located on the Earth, we have to demonstrate that the entanglement can still survive after both entangled photons have passed through a noisy ground atmosphere with a distance beyond the equivalent of the aerosphere. In our experiment, 702 nm light is used for entanglement distribution. The transmission of 702 nm light from the whole vertical atmosphere is about 70% under good weather conditions. The horizontal attenuation coefficient measured in Hefei was approximately $\alpha = 0.19/\text{km}$. The horizontal distance with the same attenuation as the whole atmosphere vertically is $L = -\ln(0.7)/\alpha = 1.9$ km. Further calculation shows that even under bad weather conditions, say, with a low visibility of 5 km, the distances that we have achieved are still well beyond the atmospheric equivalent.

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