Quantum key distribution (QKD) \cite{1,2}, based on intrinsic properties of quantum systems, can extract a secret key from correlations against an all powerful adversary \cite{3,5}. The QKD scheme has been successfully implemented over long distances \cite{4,14}. Nevertheless, the implementation of these QKD protocols depends on perfect characteristics of the underlying source or detection devices, which cannot always be satisfied in practice. This dependence leads to various quantum hacking strategies \cite{1,13}. By exploiting the violation of a Bell inequality, device-independent QKD (DIQKD) \cite{14–18} can achieve secure key distribution without detailed device characterization. This will close the gap between theoretical analyses and practical realizations of QKD, enabling the systems more reliable against such attacks. The unprecedented level of security of DIQKD makes it the ultimate goal of researchers in the field of quantum communications despite current experimental challenges \cite{19}.

Protocols for DIQKD rely on a Bell test, typically the Clauser-Horne-Shimony-Holt (CHSH) test \cite{20}, which requires a pair of entangled states shared between two distant systems. In traditional setups \cite{14}, distant entanglement is usually generated by photons distributed via an optical fiber. Unfortunately, photon losses impair the entangled state detection efficiency. Even by using novel techniques such as heralded qubit amplifier \cite{21} or local Bell test \cite{22}, the secure key rate of DIQKD is still extremely limited at practical distances. One solution to the above limitation is heralded entangling scheme \cite{23,24}, in which photon losses do not influence the entangled state detection efficiency or fidelity. However, previous heralded schemes suffer from low entanglement rate, leading to a low key rate for long distance. Besides, for the point-to-point lossy quantum channel without quantum repeaters, the secret-key capacity \cite{25,26} is restrained by the Pirandola-Laurenza-Ottaviani-Bianchi (PLOB) bound \cite{24}. To increase the key rate and transmission distance of DIQKD, in this paper we propose a different heralded scheme utilizing single-photon-type interference \cite{27,28,29,30}, which was first proposed in the twin-field QKD \cite{42}.

In previous heralded entanglement schemes \cite{23,25}, the two distant parties, Alice and Bob, each generate a pair of qubits in the spin–photon entanglement $|\phi^+\rangle = (|+z\rangle |+z\rangle + |−z\rangle |−z\rangle)/\sqrt{2}$, where $|±z\rangle$ represent the eigenstates of Pauli operator $\sigma_z$. They send one photon respectively to the central station ‘Charlie’, who could even be untrusted. Subsequently, Charlie performs a Bell-state measurement (BSM) on the two received photons, causing a two-photon interference followed by a coincidence count in Charlie’s detectors. Detection of the photons heralds the projection of the spin qubits onto an entangled state. By applying these schemes to DIQKD, the key rate is linearly dependent on channel transmittance $\eta$.

In our heralded scheme, the generation of entanglement between distant systems is based on entangled coherent states (ECSs) \cite{34}. First, Alice and Bob each prepare an entangled atom-light Schrödinger cat state, where cat state refers to a superposition of two coherent states with opposite phases and arbitrary amplitudes. Then they send their optical states to the beam splitter (BS) of Charlie to generate a ECS by a single-photon interference, leading to successful entanglement between Alice’s and Bob’s atoms \cite{37}. In this way, the key rate of DIQKD will scale with $\sqrt{\eta}$, making it feasible to overcome the PLOB bound. Although there still exist difficulties generating entangled atom–light cat states with high rate, recent works have shown great experimental progress. An entangled artificial atom-cat state in a cavity has been created with high-fidelity state measurement \cite{35}. Furthermore, deterministic realization of entanglement state with atom–light Schrödinger cat states has been successfully demonstrated \cite{36}. With this backdrop, we could expect ECS to become a promising alternative to Bell state for intercity-distance entanglement swapping in the near future.

When applying our heralded scheme to DIQKD, based on time-reversed idea \cite{40}, Alice and Bob can alternatively measure the atom spins they have kept before Charlie performs the ECS measurement \cite{38}. In this
opposite phases. Then Alice chooses to measure spin

Alice and Bob each prepare a pair of qubits in the spin-photon entangled state $|\phi^+\rangle = (|+z\rangle|\alpha\rangle + |-z\rangle|-\alpha\rangle)/\sqrt{2}$ and send one photon respectively to the central station Charlie. Entanglement between distant spins is realized through an ECS measurement performed by Charlie. Entanglement between distant spins is achieved through a BSM performed by Charlie. (b) Alice and Bob each prepare an entangled atom–light Schrödinger cat state $|\Phi^+\rangle = (|+z\rangle|\alpha\rangle + |-z\rangle|-\alpha\rangle)/\sqrt{2}$ and send optical pulse respectively to the central station Charlie.

The key idea of heralded schemes is to record an additional signal announced by Charlie, which indicates whether the entangled state was successfully shared between Alice and Bob. When Charlie announces a successful detection signal, the corresponding trial operated by Alice and Bob will be valid. That is, failed entanglement distribution events can be excluded upfront from being used in the trial. It needs to be pointed out that our secret key rate analysis is under the assumption of collective attacks in the asymptotic regime. By using the entropy accumulation theorem \[17\], our protocol can be proven secure against the general attacks in the framework of universal composability. We let the probability of both Alice and Bob choosing $Z$ basis $p_{zz} \approx 1$ in the asymptotic limit. Therefore, the key rate of our protocol is \[14\]

$$R = Q_{zz} \left[ 1 - H_2(e_{zz}) - H_2 \left( 1 + \sqrt{(2S/2)^2 - 1} \right) \right],$$

where $Q_{zz}$ denotes the total gain of the $Z$ basis and $H_2(x) = -x \log_2(x) - (1 - x) \log_2(1 - x)$ is the binary Shannon entropy function.

We use the compressed subscript notation $x_{a,a'}$ ($x_{b,b'}$) to indicate $x_a$, $x_{a'}$ ($x_b$, $x_{b'}$), where the first label refers to Alice’s (Bob’s) atom and the second to pulse sent by Alice (Bob). By combining the initial states $|\Phi^+\rangle_{aa'}$ and $|\Phi^+\rangle_{bb'}$, we obtain

$$|\Phi^+\rangle_{aa'} |\Phi^+\rangle_{bb'} = \frac{1}{2\sqrt{2}} \left( \sqrt{N_x^+} |\phi^+\rangle_{ab} |\phi(\alpha)^+\rangle_{a'b'} + \sqrt{N_-^+} |\phi^-\rangle_{ab} |\phi(\alpha)^-\rangle_{a'b'} \right) + \sqrt{N_+^-} |\psi^+\rangle_{ab} |\psi(\alpha)^+\rangle_{a'b'} + \sqrt{N_-^-} |\psi^-\rangle_{ab} |\psi(\alpha)^-\rangle_{a'b'},

where the forms of four ECSs \[11\] are $|\phi(\alpha)^\pm\rangle = 1/\sqrt{N_x^\pm} |\alpha\rangle |\alpha\rangle \pm |\alpha\rangle \pm |\alpha\rangle \rangle$ and $|\psi(\alpha)^\pm\rangle = 1/\sqrt{N_+^-} |\alpha\rangle |\alpha\rangle \pm |\alpha\rangle \rangle$. $N_{\pm} = 2(1 \pm e^{-4\mu})$ are the normalization factors, with intensity of coherent state $\mu = |\alpha|^2$. The four Bell states are $|\phi^\pm\rangle = 1/\sqrt{2} (|+z\rangle |+z\rangle \pm |\alpha\rangle \rangle |\alpha\rangle \rangle \rangle$ and $|\psi^\pm\rangle = 1/\sqrt{2} (|+z\rangle |\alpha\rangle \rangle |\alpha\rangle \rangle \rangle)$. Let two inputs of BS as $a$ and $b$ modes while the two outputs modes are $c = (a + b)/\sqrt{2}$ and $d = (a - b)/\sqrt{2}$, detected by D1 and D2 detectors, respectively. After passing through the lossless symmetric BS, the above four ECSs are evolved into \[37\]

$$|\phi(\alpha)^+\rangle_{a'b'} \xrightarrow{\text{BS}} |\text{even}\rangle_c |0\rangle_d,$$

$$|\phi(\alpha)^-\rangle_{a'b'} \xrightarrow{\text{BS}} |\text{odd}\rangle_c |0\rangle_d,$$

$$|\psi(\alpha)^+\rangle_{a'b'} \xrightarrow{\text{BS}} |0\rangle_c |\text{even}\rangle_d,$$

$$|\psi(\alpha)^-\rangle_{a'b'} \xrightarrow{\text{BS}} |0\rangle_c |\text{odd}\rangle_d.$$
where \(| even \rangle_k \) \((| odd \rangle_k \) means that the output mode \(k \) contains even \((odd\) number of photons. For the case of lossless channel and ideal photon-number-resolving detector, we can unambiguously discriminate the four ECSs using photon-number parity measurement. However, since practical detectors are threshold detectors, only the case with or without detector clicks can be discriminable. For the states \(| \phi(\alpha) \rangle^+ \) and \(| \psi(\alpha) \rangle^+ \), the zero-photon component is close to unit when we choose small intensity \(\mu\), leading to the low click probabilities. Therefore, we make only D1 \((D2) \) click represent that the result of the ECS measurement is the state \(| \phi(\alpha)^- \rangle \) \((| \psi(\alpha)^- \rangle \) ), which indicates the bell state \(| \phi^- \rangle \) \((| \psi^- \rangle \) ) has been successfully shared between Alice and Bob. As a result, the states \(| \phi(\alpha) \rangle^+ \) and \(| \psi(\alpha) \rangle^+ \) will always be mismeasured as quantum states \(| \phi(\alpha)^- \rangle \) and \(| \psi(\alpha)^- \rangle \), respectively. This introduces an intrinsic error, making the CHSH value less than \(2\sqrt{2} \) even in the case of ideal threshold detectors and lossless channel.

It is convenient to define \(\chi_\theta := \cos \theta \sigma_z + \sin \theta \sigma_x \). Thus we can rewrite \(A_0 = B_1 = \chi_0, A_1 = \chi_\frac{\pi}{2}, A_2 = \chi_{-\frac{\pi}{2}} \), and \(B_2 = \chi_\frac{\pi}{2} \). The entangled atom–light cat states along the direction \(\chi_\theta \) can be expressed as

\[
\begin{align*}
| \Phi^+ \rangle &= \frac{1}{\sqrt{2}} \left( | +z \rangle | \alpha \rangle + | -z \rangle | -\alpha \rangle \right) \\
&= \frac{1}{\sqrt{2}} \left( M^+ \ | +\xi \rangle^\theta \langle \xi^+(\alpha) |^\theta + M^- \ | -\xi \rangle^\theta \langle \xi^-(\alpha) |^\theta \right),
\end{align*}
\]

where \(| +\xi \rangle^\theta = \cos \frac{\theta}{2} | +z \rangle + \sin \frac{\theta}{2} | -z \rangle \) and \(| -\xi \rangle^\theta = \sin \frac{\theta}{2} | +z \rangle - \cos \frac{\theta}{2} | -z \rangle \) represent the atom spin eigenstates in \(\chi_\theta \) basis, corresponding to outcomes \(+1 \) and \(-1 \), respectively. \(| \xi^+(\alpha) \rangle^\theta = \frac{1}{\sqrt{2}} (\cos \frac{\theta}{2} | +\alpha \rangle + \sin \frac{\theta}{2} | -\alpha \rangle) \) and \(| \xi^-(\alpha) \rangle^\theta = \frac{1}{\sqrt{2}} (\sin \frac{\theta}{2} | +\alpha \rangle - \cos \frac{\theta}{2} | -\alpha \rangle) \) are corresponding optical modes sent to Charlie, where \(M^\pm = \sqrt{1 \pm \sin \theta} e^{-\mu} \) are the respective normalization factors.

The Eq.\((\ref{eq:chsh}) \) means that when Alice (Bob) measures atom along \(\chi_{\theta_a} \) \((\chi_{\theta_b} \) ) and gets outcome \(a_i \) \((b_j \) ), the joint quantum states sent to Charlie are projected into \(| \xi_{a_i}(\alpha) \rangle^\theta_{b_j} \) \((| \xi_{b_j}(\alpha) \rangle^\theta_{a_i} \) ) correspondingly. Considering the case of ideal threshold detectors and lossless channel, we can get the total gain of the Z basis \(Q_{zz} = 1 - e^{-2\mu} \) and CHSH value \(S = \sqrt{2(1 + e^{-2\mu})} \), in violation of the CHSH-Bell inequality \(S \leq 2 \) when \(\mu \leq 0.4407 \).

For the practical case with threshold detectors and a lossy channel which is assumed symmetrical for Alice and Bob, we have \(Q_{zz} = \frac{1}{2} (1 - p_d) [1 - (1 - 2p_d) e^{-2\mu}] \), the CHSH value \(S = 2\sqrt{2} \left\{ \sinh(2\mu) - \cosh[2\mu (1 - \eta)] + (1 - p_d)e^{-2\mu(1 - \eta)} \right\} \left( e^{2\mu} - (1 - 2p_d)e^{2\mu(1 - \eta)} \right), \) and the QBER of the Z basis \(e_{zz} = p_d e^{2\mu(1 - \eta)} / \left\{ e^{2\mu} - (1 - 2p_d)e^{2\mu(1 - \eta)} \right\} \), where \(p_d \) is the dark count rate, \(\eta = \eta_d x 10^{-\frac{P_{ch}}{16}} \), \(\eta_d \) is the total efficiency of detector, \(\beta \) denotes the intrinsic loss coefficient of fiber channel and \(L \) represents the distance between Alice and Bob. Note that the factor \(L/2 \) in \(\eta \) is due to Charlie being placed midway between Alice and Bob.

We simulate the performance of the heralded DIQKD protocol utilizing different light sources under practical experimental environments. Specifically, we numerically optimize the secret key rate of ECS protocol over the free parameter \(\mu \). The simulation results are shown in Fig. \ref{fig:chsh}. We can see that the ECS protocol can exceed the Bell-state protocol when 100 km \(< L < 450 \) km, and its key rate achieves 4 orders of magnitude higher than the one using a Bell state at 400 km. However, the maximum transmission distance of ECS protocol is less than Bell-state protocol. This zero key rate at long distance of ECS protocol when 100 km due to Charlie being placed midway between Alice and Bob.

In the following, we investigate the performances of our heralded DIQKD protocol with ECSs considering misalignment errors. Define \(\delta_0 \) as the fixed phase drift difference between the two phases from Alice and Bob owing to propagation in fibers, causing the intrinsic misalignment error \(\epsilon_d = 1 - \cos \delta_0 \). As a consequence, after going through the channel and BS, the four joint coher-
In summary, we introduce a novel heralded DIQKD scheme that uses ECSs to establish entanglement between distant users. Compared with former heralded protocols, the key rate of our protocol is increased by approximately 2–4 orders of magnitude at intercity distances. Additionally, our protocol is able to exceed the PLOB bound when $L > 150$ km with practical settings such as dark counts, detector efficiency and misalignment errors. These improvements make a proof-of-principle experimental demonstration of DIQKD more feasible. Future work can focus on developing new techniques with the ECS source to reduce the intrinsic error rate, so that the secure transmission distance can be further increased. Because the ECS measurement devices are identical to the BSM devices, our process is compatible with the previous infrastructure. We could therefore envision an unconditional secure global quantum network combined with ECS scheme at short and medium distances and traditional Bell-state scheme at long distance.

ACKNOWLEDGMENTS

We gratefully acknowledge support from the National Natural Science Foundation of China (61801420), the Key Research and Development Program of Guangdong Province (2020B0303040001) and the Fundamental Research Funds for the Central Universities.

* hlyin@nju.edu.cn
* zbchen@nju.edu.cn

[1] C. H. Bennett and G. Brassard, in Proceedings of the Conference on Computers, Systems and Signal Processing (IEEE Press, New York, 1984), pp. 175–179.
[2] A. K. Ekert, Physical Review Letters 67, 661 (1991).
[3] H.-K. Lo and H. F. Chau, Science 283, 2050 (1999).
[4] P. W. Shor and J. Preskill, Physical Review Letters 85, 441 (2000).
[5] D. Mayers, Journal of the ACM 48, 351 (2001).
[6] H.-L. Yin, T.-Y. Chen, Z.-W. Yu, H. Liu, L.-X. You, Y.-H. Zhou, S.-J. Chen, Y. Mao, M.-Q. Huang, W.-J. Zhang, et al., Physical Review Letters 117, 190501 (2016).
[7] A. Boaron, G. Bosco, D. Rusca, C. Valléez, C. Autebert, M. Caloz, M. Perrenoud, G. Gras, F. Bussières, M.-J. Li, et al., Phys. Rev. Lett. 121, 190502 (2018).
[8] X.-T. Fang, P. Zeng, H. Liu, M. Zou, W. Wu, Y.-L. Tang, Y.-J. Sheng, Y. Xiang, W. Zhang, H. Li, et al., Nature Photonics 14, 422 (2020).
[9] J.-P. Chen, C. Zhang, Y. Liu, C. Jiang, W. Zhang, X.-L. Hu, J.-Y. Guan, Z.-W. Yu, H. Xu, J. Lin, et al., Phys. Rev. Lett. 124, 070501 (2020).
[10] J. Yin, Y.-H. Li, S.-K. Liao, M. Yang, Y. Cao, L. Zhang, J.-G. Ren, W.-Q. Cai, W.-Y. Liu, S.-L. Li, et al., Nature 582, 501 (2020).
[11] Y. Zhao, C.-H. F. Fung, B. Qi, C. Chen, and H.-K. Lo, Physical Review A 78, 042333 (2008).
[12] L. Lydersen, C. Wiechers, C. Wittmann, D. Elser, J. Skaar, and V. Makarov, Nature Photonics 4, 686 (2010).
[13] I. Gerhardt, Q. Liu, A. Lamas-Linares, J. Skaar, C. Kurt-siefer, and V. Makarov, Nature Communications 2, 349 (2011).
[14] A. Acín, N. Brunner, N. Gisin, S. Massar, S. Pironio, and V. Scarani, Physical Review Letters 98, 230501 (2007).
[15] L. Masanes, S. Pironio, and A. Acín, Nature Communications 2, 238 (2011).
[16] U. Vazirani and T. Vidick, Phys. Rev. Lett. 113, 140501 (2014).
[17] R. Arnon-Friedman, F. Dupuis, O. Fawzi, R. Renner, and T. Vidick, Nature Communications 3, 238 (2011).
[18] C. C. W. Lim, C. Portmann, M. Tomamichel, R. Renner, and N. Gisin, Physical Review Letters 123, 100505 (2019).
[19] N. Gisin, S. Pironio, and N. Sangouard, Physical Review Letters 105, 070501 (2010).
[20] J. F. Clauser, M. A. Horne, A. Shimony, and R. A. Holt, Physical Review Letters 23, 880 (1969), URL https://doi.org/10.1103/PhysRevLett.23.880.
[21] R. Arnon-Friedman, F. Dupuis, O. Fawzi, R. Renner, and T. Vidick, Nature Communications 9, 459 (2018).
[22] E. Y.-Z. Tan, C. C.-W. Lim, and R. Renner, Phys. Rev. Lett. 124, 020502 (2020).
[23] J. S. Bell, Comments At. Mol. Phys. 9, 121 (1980).
[24] M. Žukowski, A. Zeilinger, M. A. Horne, and A. K. Ekert, Physical Review Letters 71, 4287 (1993).
[25] M. Takeoka, S. Guha, and M. M. Wilde, Nature Communications 5, 5235 (2014).
[26] S. Pirandola, R. Laurenza, C. Ottaviani, and L. Banchi, Nature Communications 8, 15043 (2017).
[27] X.-B. Wang, Z.-W. Yu, and X.-L. Hu, Phys. Rev. A 98, 062323 (2018), URL https://link.aps.org/doi/10.1103/PhysRevA.98.062323.
[28] X. Ma, P. Zeng, and H. Zhou, Phys. Rev. X 8, 031043 (2018), URL https://link.aps.org/doi/10.1103/PhysRevX.8.031043.