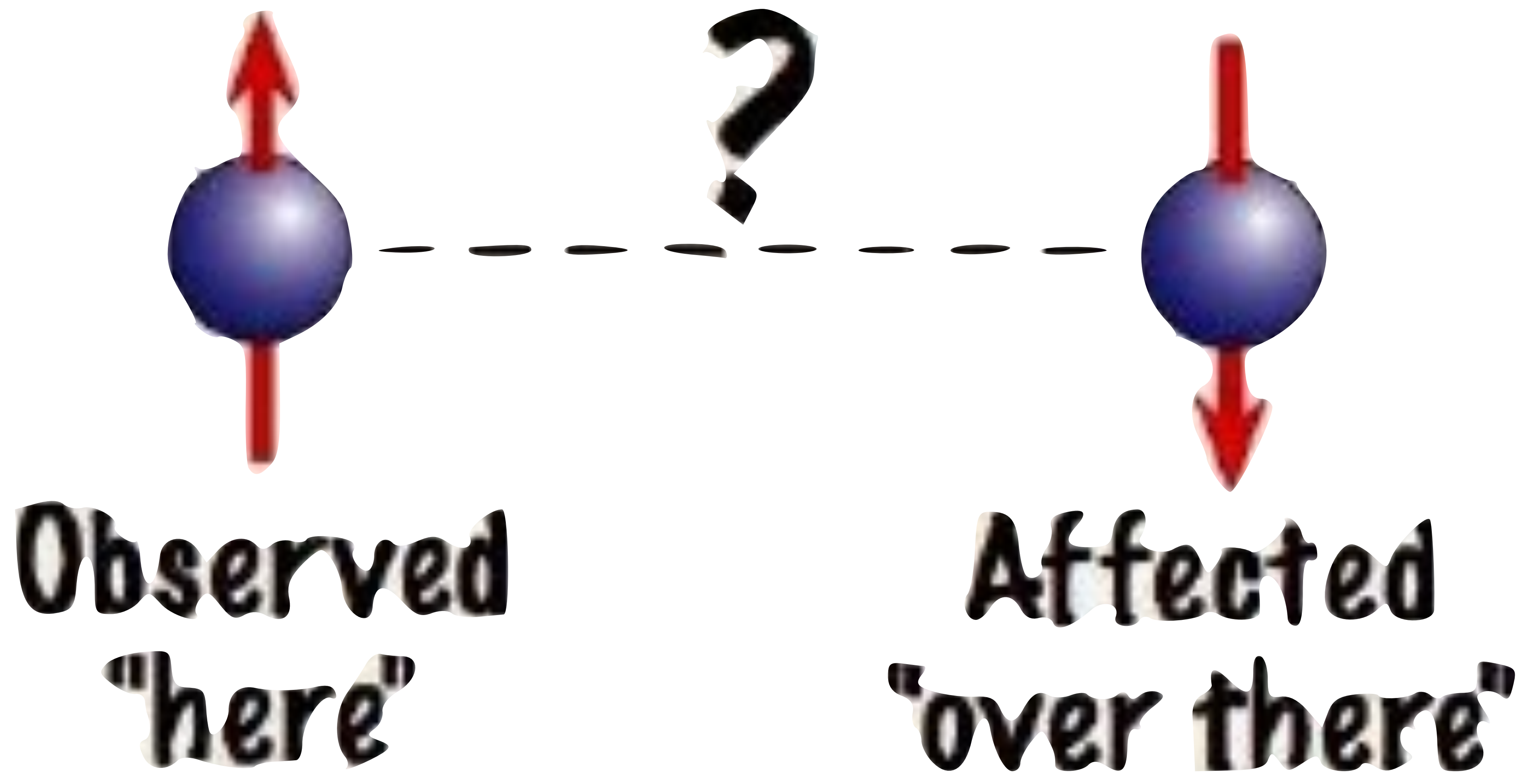
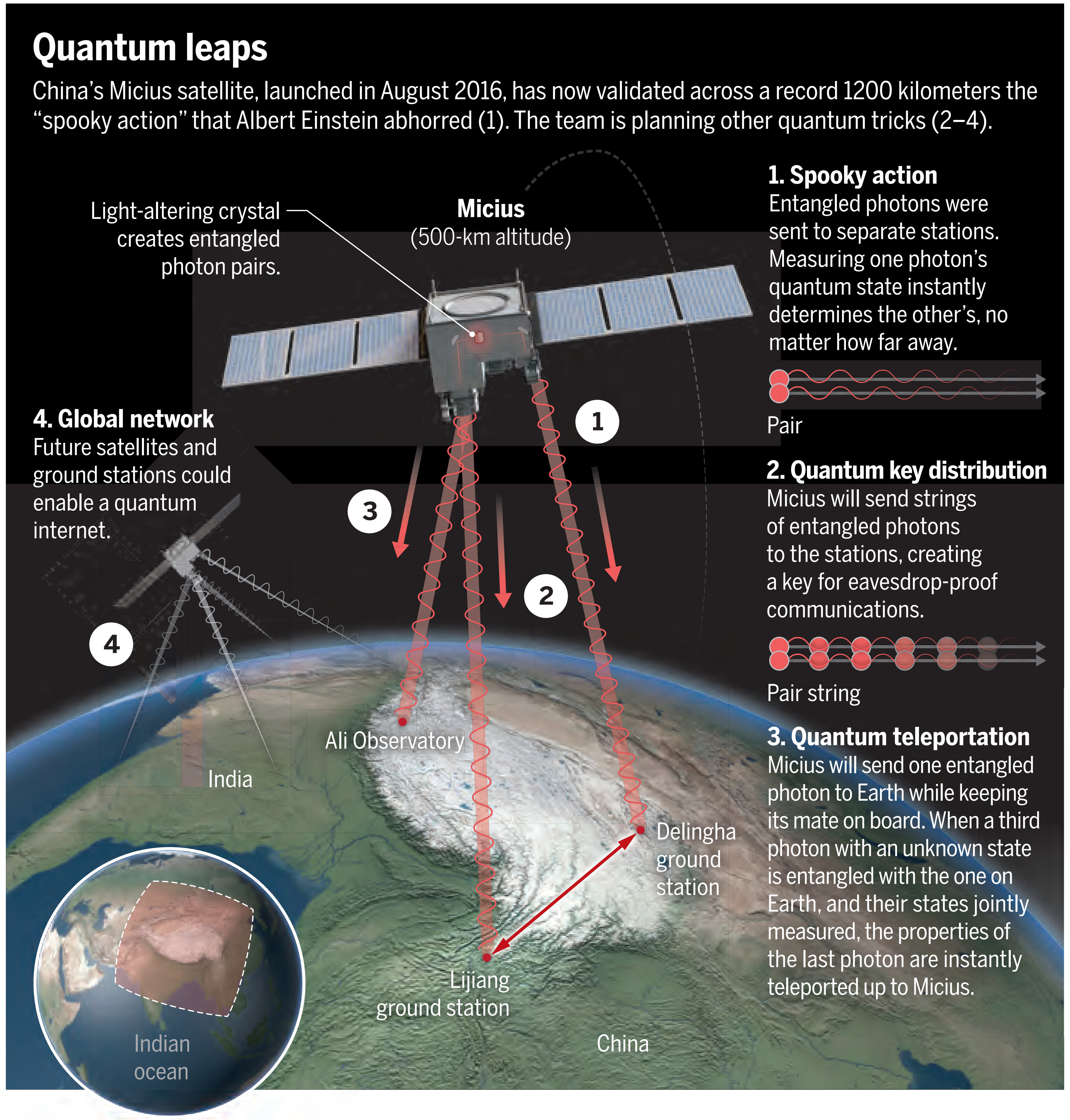
Applied Physics Seminar: Entanglement

Notes on digital computers and quantum computers



Entanglement Outline

What is entanglement?



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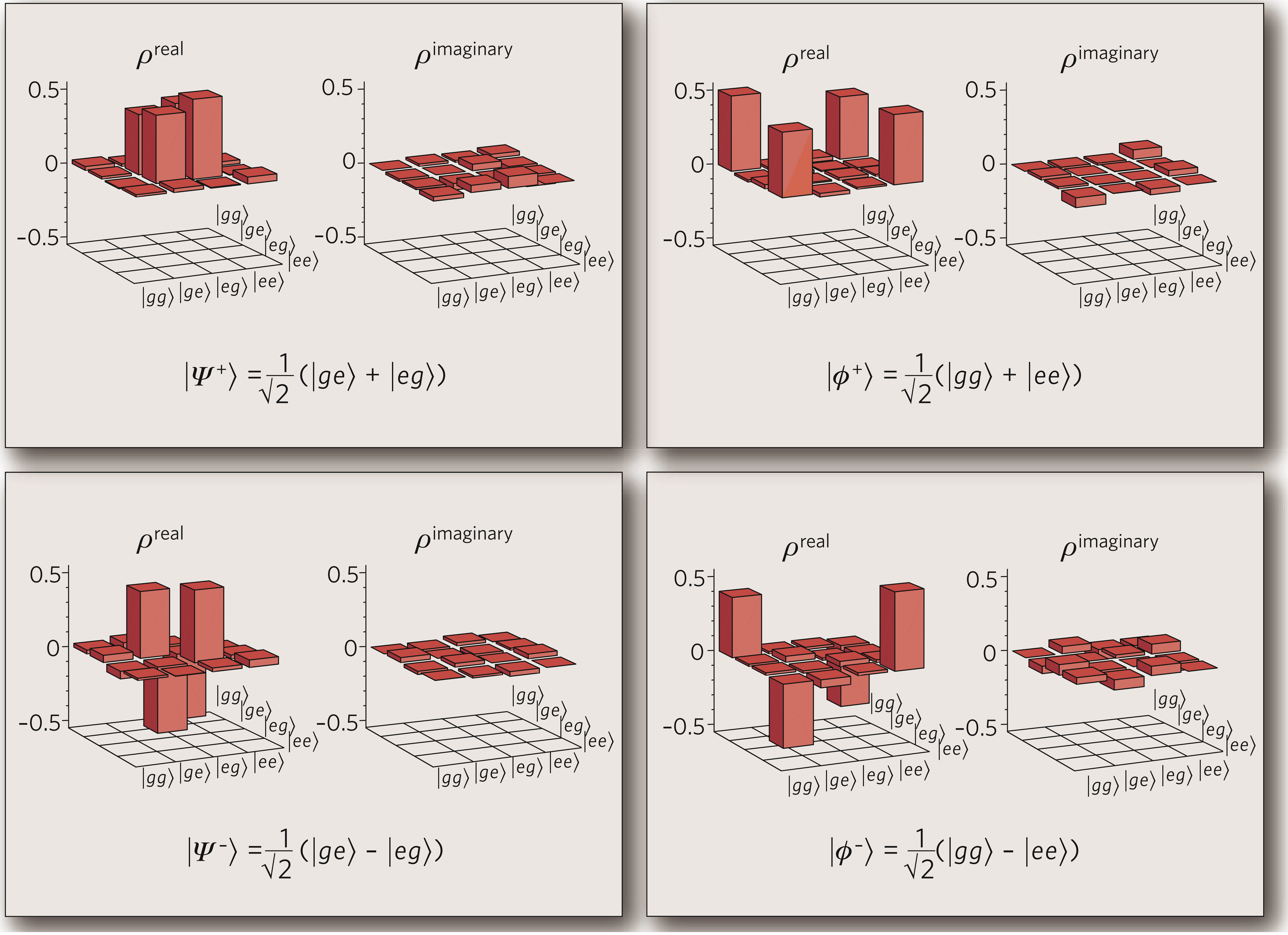
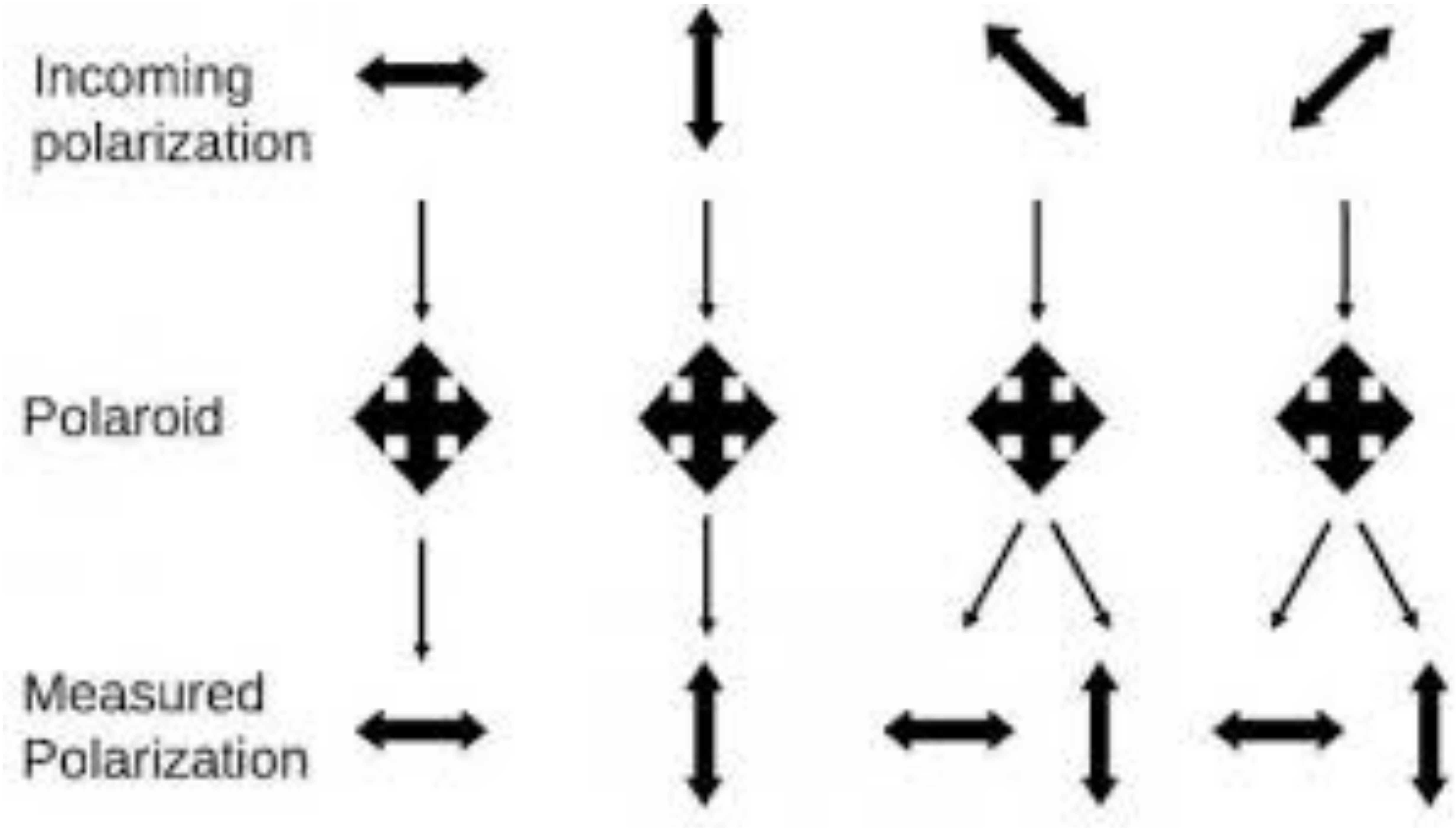
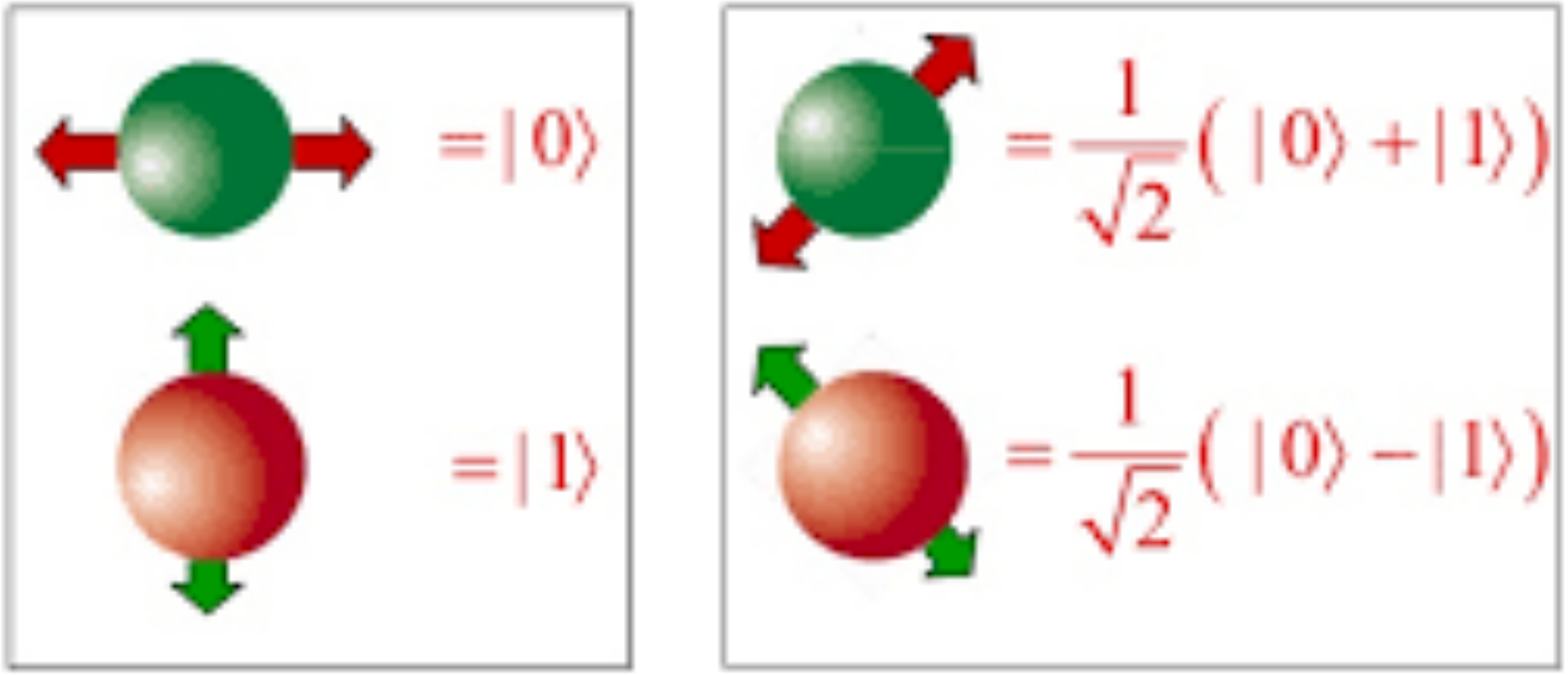
How to use "standard" state-space algebra?



Simple Example: photon polarization





Simple Example: two photons

$$|\psi_1\rangle = a_h |H_1\rangle + a_v |V_1\rangle$$
$$|\psi_2\rangle = b_h |H_2\rangle + b_v |V_2\rangle$$

$$|\psi_1 \psi_2\rangle = a_{hh} |H_1 H_2\rangle + a_{hv} |H_1 V_2\rangle + a_{vh} |V_1 H_2\rangle + a_{vv} |V_1 V_2\rangle$$

Example: two ***not*** tangled photons

$$|\psi_1\rangle = \frac{1}{\sqrt{2}}|H_1\rangle + \frac{1}{\sqrt{2}}|V_1\rangle$$

$$|\psi_2\rangle = \frac{1}{\sqrt{2}}|H_2\rangle - \frac{1}{\sqrt{2}}|V_2\rangle$$

$$|\psi_1\psi_2\rangle = \frac{1}{2}|H_1H_2\rangle - \frac{1}{2}|H_1V_2\rangle + \frac{1}{2}|V_1H_2\rangle - \frac{1}{2}|V_1V_2\rangle$$

$$|\psi_1\psi_2\rangle = \left(\frac{1}{\sqrt{2}}|H_1\rangle + \frac{1}{\sqrt{2}}|V_1\rangle\right) \otimes \left(\frac{1}{\sqrt{2}}|H_2\rangle - \frac{1}{\sqrt{2}}|V_2\rangle\right)$$

Example: two ***not*** tangled photons

$$|\psi_1\rangle = |H_1\rangle + 0\,|V_1\rangle$$

$$|\psi_2\rangle = 0\,|H_2\rangle - |V_2\rangle$$

$$|\psi_1\psi_2\rangle = -\,|H_1 V_2\rangle$$

$$|\psi_1\psi_2\rangle = (|H_1\rangle + 0\,|V_1\rangle) \otimes (0\,|H_2\rangle - |V_2\rangle)$$

Example: two ***not*** tangled photons

$$|\psi_1\rangle = \frac{1}{\sqrt{2}}|H_1\rangle + \frac{i}{\sqrt{2}}|V_1\rangle$$

$$|\psi_2\rangle = \frac{1}{\sqrt{2}}|H_2\rangle - \frac{i}{\sqrt{2}}|V_2\rangle$$

$$|\psi_1\psi_2\rangle = \frac{1}{2}|H_1H_2\rangle - \frac{i}{2}|H_1V_2\rangle + \frac{i}{2}|V_1H_2\rangle + \frac{1}{2}|V_1V_2\rangle$$

$$|\psi_1\psi_2\rangle = \left(\frac{1}{\sqrt{2}}|H_1\rangle + \frac{i}{\sqrt{2}}|V_1\rangle\right) \otimes \left(\frac{1}{\sqrt{2}}|H_2\rangle - \frac{i}{\sqrt{2}}|V_2\rangle\right)$$

Example: two ***entangled*** photons

$$|\psi_1\psi_2\rangle = \frac{1}{\sqrt{2}}|H_1H_2\rangle + \frac{1}{\sqrt{2}}|V_1V_2\rangle$$

Example: two ***entangled*** photons

$$|\psi_1\psi_2\rangle = \frac{1}{\sqrt{2}}|H_1H_2\rangle + \frac{1}{\sqrt{2}}|V_1V_2\rangle$$

$$|\psi_1\psi_2\rangle = \frac{1}{\sqrt{2}}|H_1H_2\rangle - \frac{1}{\sqrt{2}}|V_1V_2\rangle$$

$$|\psi_1\psi_2\rangle = \frac{1}{\sqrt{2}}|H_1V_2\rangle + \frac{1}{\sqrt{2}}|V_1H_2\rangle$$

$$|\psi_1\psi_2\rangle = \frac{1}{\sqrt{2}}|H_1V_2\rangle - \frac{1}{\sqrt{2}}|V_1H_2\rangle$$

Maximally entangled "Bell States"

Yin *et al.*, *Science* **356**, 1140–1144 (2017)   16 June 2017

Satellite-based entanglement distribution over 1200 kilometers

Juan Yin,[1,2] Yuan Cao,[1,2] Yu-Huai Li,[1,2] Sheng-Kai Liao,[1,2] Liang Zhang,[2,3] Ji-Gang Ren,[1,2] Wen-Qi Cai,[1,2] Wei-Yue Liu,[1,2] Bo Li,[1,2] Hui Dai,[1,2] Guang-Bing Li,[1,2] Qi-Ming Lu,[1,2] Yun-Hong Gong,[1,2] Yu Xu,[1,2] Shuang-Lin Li,[1,2] Feng-Zhi Li,[1,2] Ya-Yun Yin,[1,2] Zi-Qing Jiang,[3] Ming Li,[3] Jian-Jun Jia,[3] Ge Ren,[4] Dong He,[4] Yi-Lin Zhou,[5] Xiao-Xiang Zhang,[6] Na Wang,[7] Xiang Chang,[8] Zhen-Cai Zhu,[5] Nai-Le Liu,[1,2] Yu-Ao Chen,[1,2] Chao-Yang Lu,[1,2] Rong Shu,[2,3] Cheng-Zhi Peng,[1,2]* Jian-Yu Wang,[2,3]* Jian-Wei Pan[1,2]*

Space calling Earth, on the quantum line

A successful quantum communication network will rely on the ability to distribute entangled photons over large distances between receiver stations. So far, free-space demonstrations have been limited to line-of-sight links across cities or between mountaintops. Scattering and coherence decay have limited the link separations to around 100 km. Yin *et al.* used the Micius satellite, which was launched last year and is equipped with a specialized quantum optical payload. They successfully demonstrated the satellite-based entanglement distribution to receiver stations separated by more than 1200 km. The results illustrate the possibility of a future global quantum communication network.

Science, this issue p. 1140

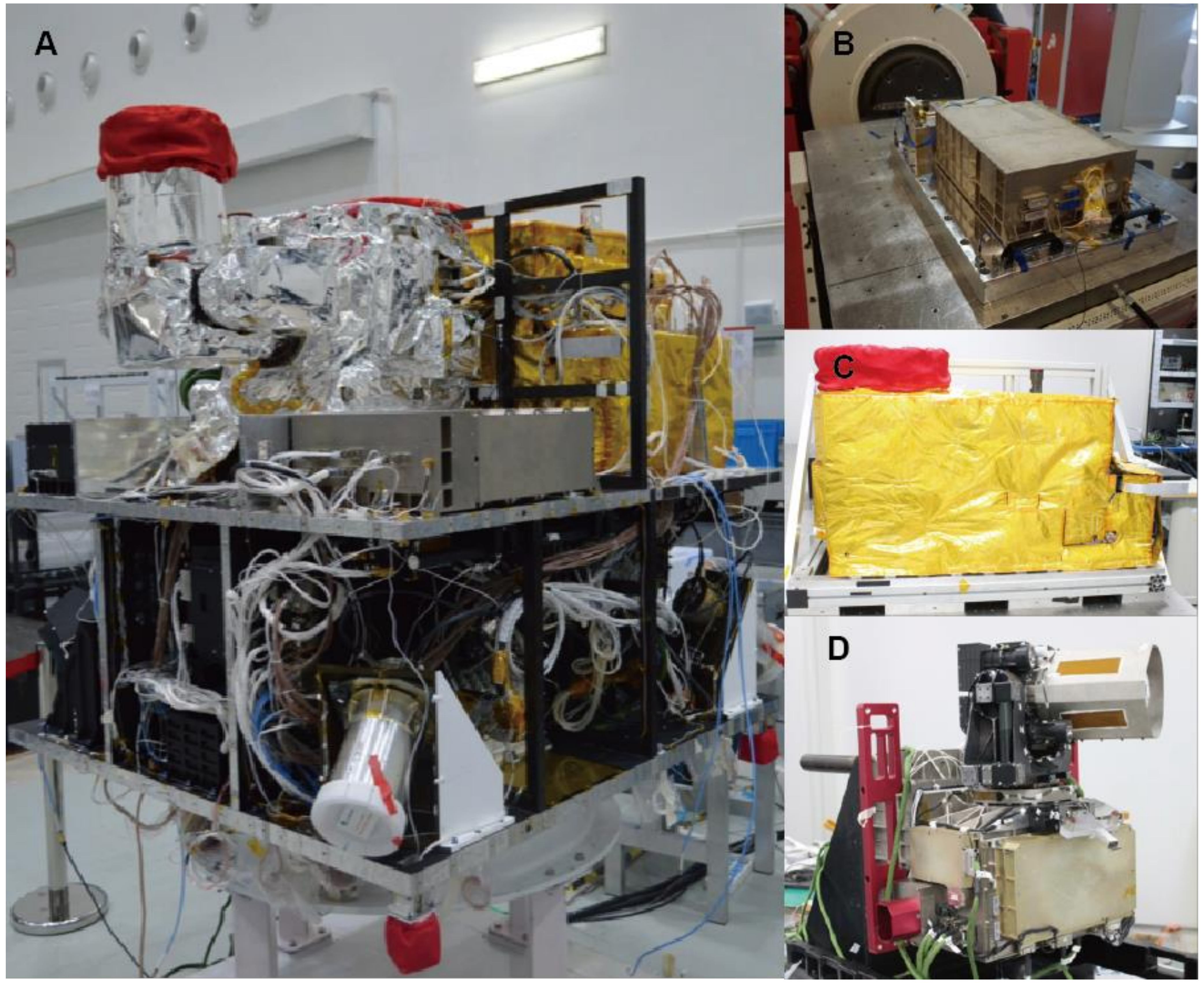


Fig. S1

The pictures of payloads in the satellite. (A) The payload layout. (B) The SPES in mechanics test. (C) The transmitter 1 with a diameter of 300 mm. (D) The transmitter 2 with a diameter of 180 mm.

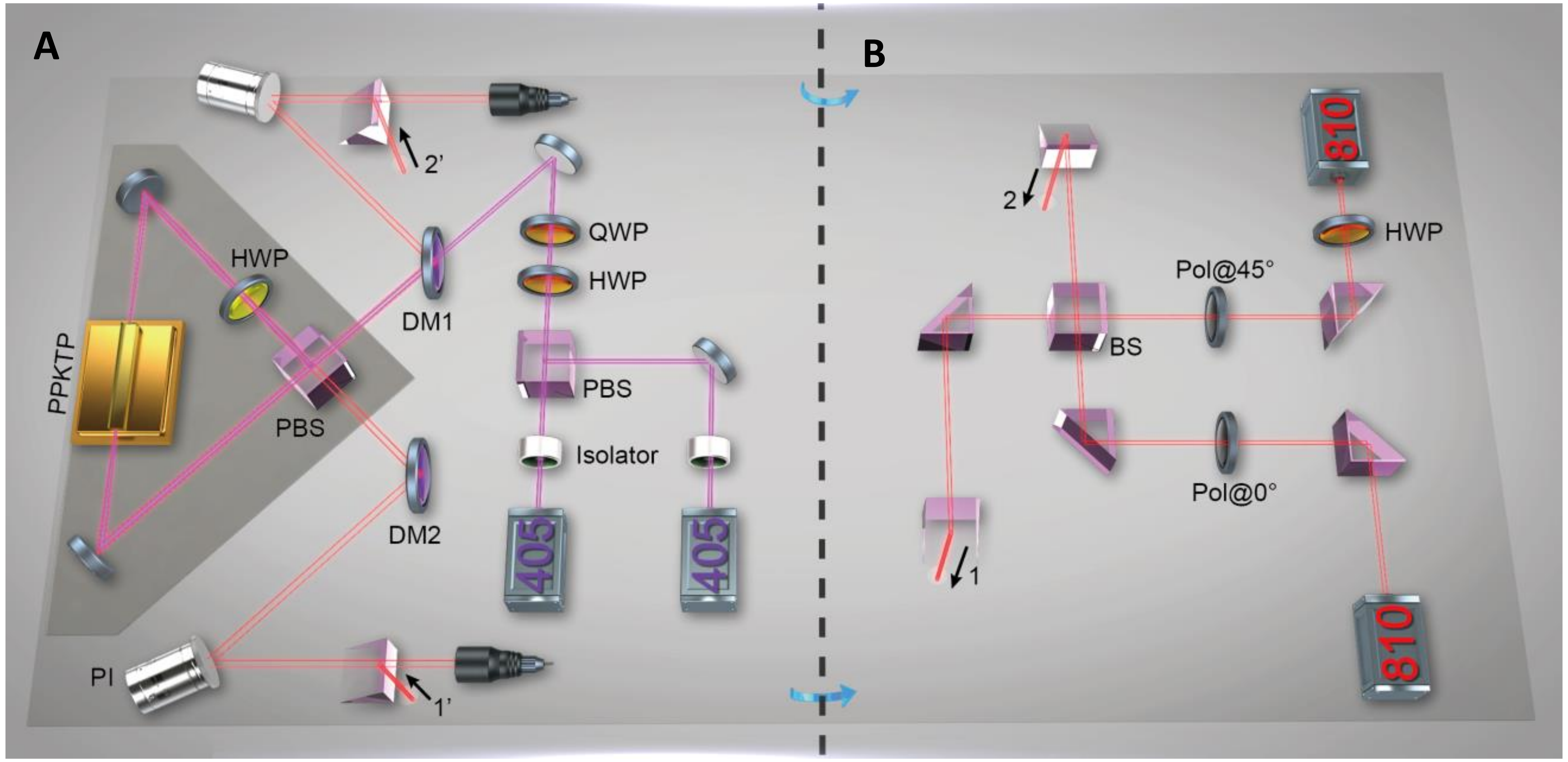


Fig. S2

Schematic diagram of the SEPS. The optical elements are mounted and glued on the both side of a titanium alloy base board. (A) The upper side generates entangled photon pairs. (B) The bottom side offers reference lasers for polarization control process and freespace channel testing. Two lasers with wavelength around 810 nm are polarized at 0 and 45-degree, respectively. Both laser beams are split on a beam splitter (BS) and combined with the entangled-photon beams by two pairs of prism. HWP, half-wave plate; QWP, quarter-wave plate; BS, beam splitter; PBS, polarizing beam splitter; DM, dichroic mirror; PI, piezo steering mirror; PPKTP, periodically poled KTiOPO4.

Spaceborne entangled photons

In our design of a spaceborne entangled-photon source (Fig. 1A), a continuous-wave laser diode with a central wavelength of 405 nm and a linewidth of ~160 MHz is used to pump a periodically poled $KTiOPO_4$ crystal inside a Sagnac interferometer. The pump laser, split by a polarizing beam splitter, passes through the nonlinear crystal in the clockwise and anticlockwise directions simultaneously, which produces down-converted photon pairs at a wavelength of ~810 nm in polarization-entangled states close to the form $|\psi\rangle_{1,2} = (|H\rangle_1|V\rangle_2 + |V\rangle_1|H\rangle_2)/\sqrt{2}$, where $|H\rangle$ and $|V\rangle$ denote the horizontal and vertical polarization states, respectively, and the subscripts 1 and 2 denote the two output spatial modes. This source is robust against various vibration, temperature, and

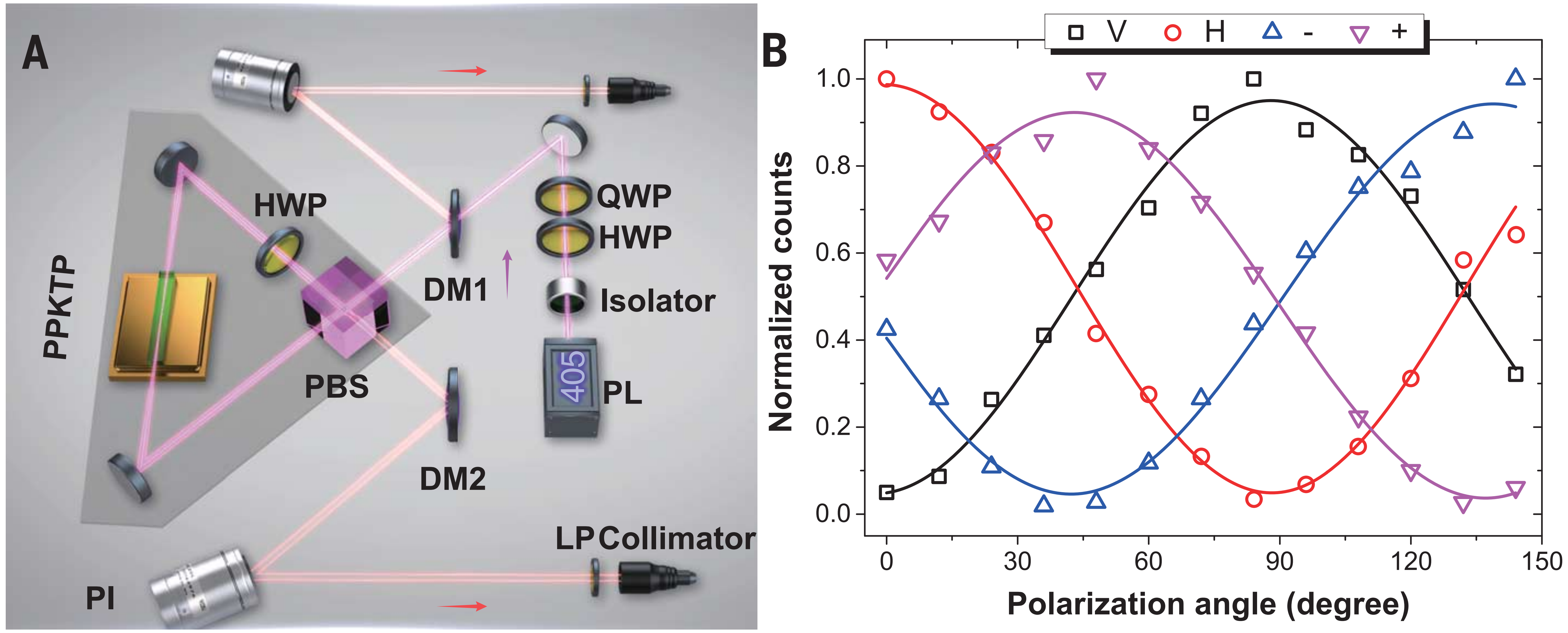
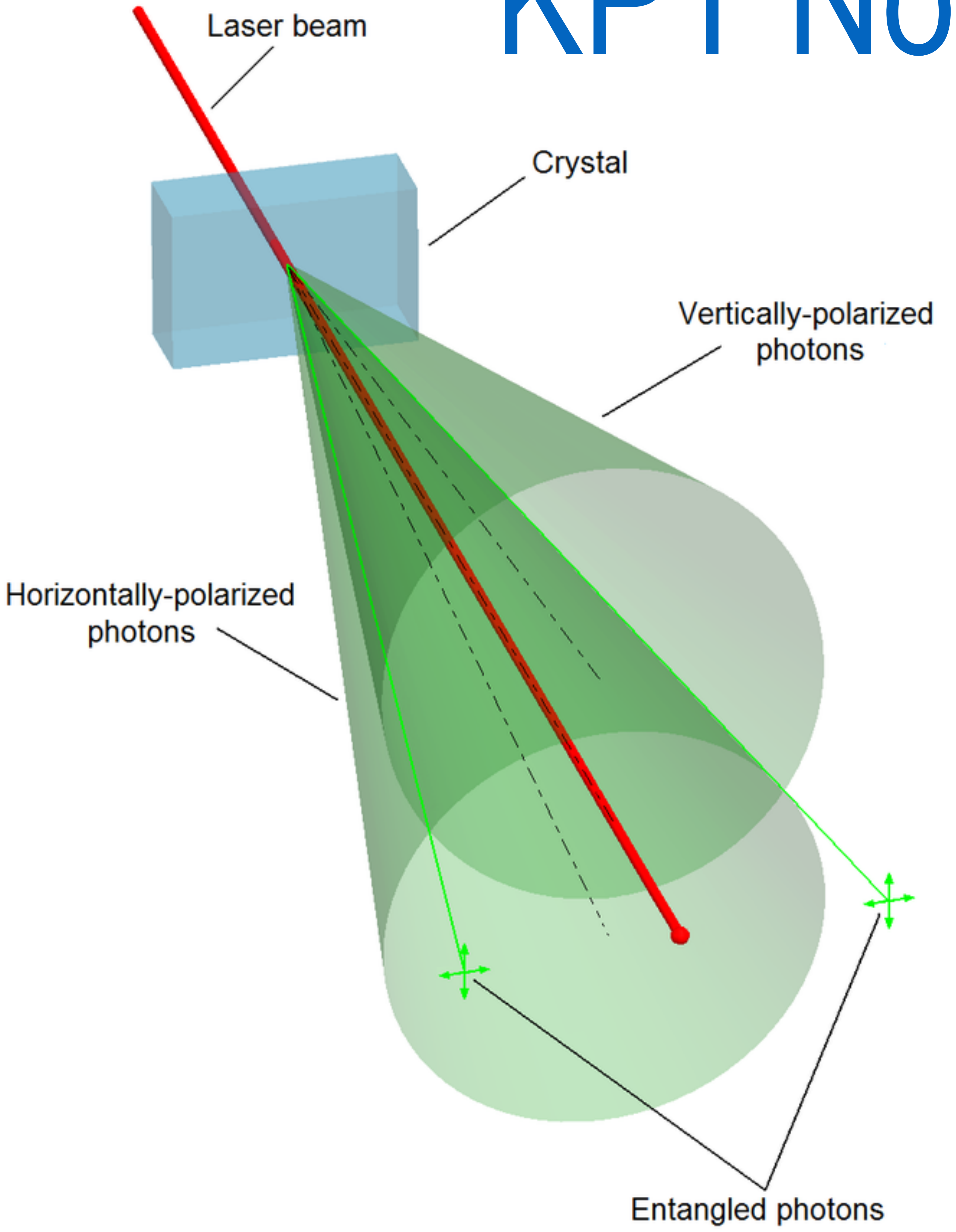
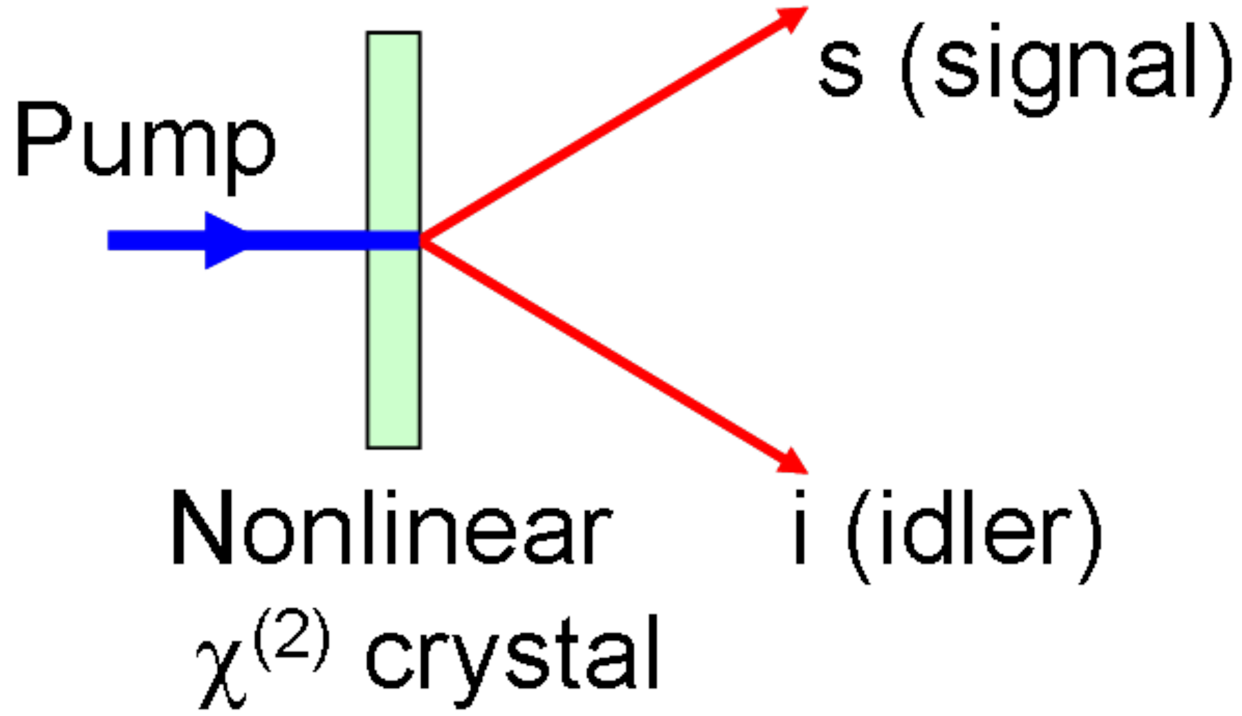


Fig. 1. Schematic of the spaceborne entangled-photon source and its in-orbit performance. (**A**) The thickness of the $KTiOPO_4$ (PPKTP) crystal is 15 mm. A pair of off-axis concave mirrors focus the pump laser (PL) in the center of the PPKTP crystal. At the output of the Sagnac interferometer, two dichromatic mirrors (DMs) and long-pass filters are used to separate the signal photons from the pump laser. Two additional electrically driven piezo steering mirrors (PIs), remotely controllable on the ground, are used for fine adjustment of the beam-pointing for an optimal collection efficiency into the single-mode fibers. QWP, quarter-wave plate; HWP, half-wave plate; PBS, polarizing beam splitter. (**B**) The two-photon correlation curves measured on-satellite by sampling 1% of each path of the entangled photons. The count rate measured from the overall 0.01% sampling is about 590 Hz, from which we can estimate the source brightness of 5.9 MHz.

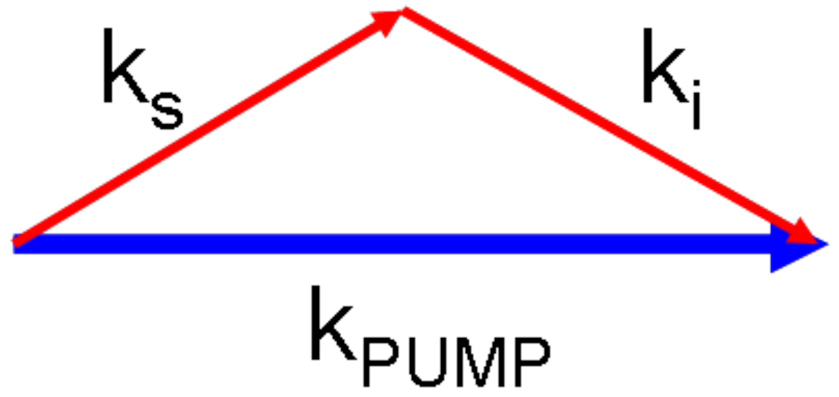
KPT Nonlinear Optical Crystal



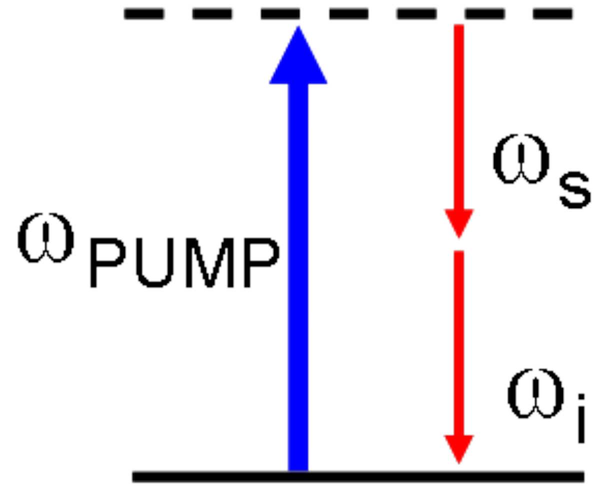
Spontaneous Parametric Downconversion



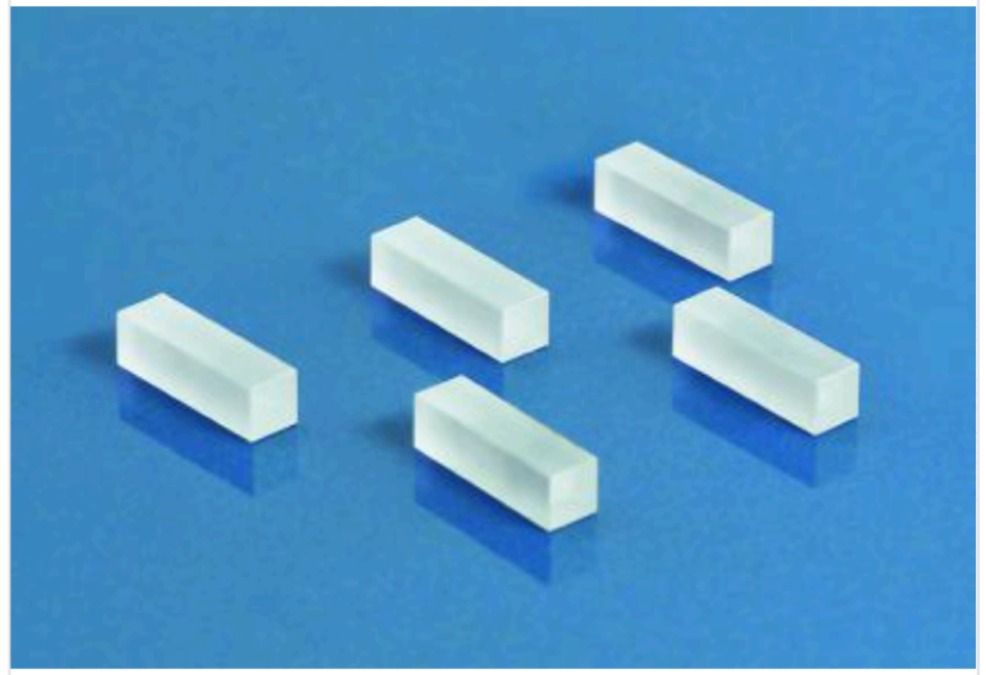
Momentum Conservation



Energy conservation



$$\varphi_{PUMP} = \varphi_s + \varphi_i$$



POTASSIUM TITANYL PHOSPHATE – KTP CRYSTALS

KTP (KTiOPO4) is a nonlinear optical crystal, which possesses excellent nonlinear, electrooptical and acoustooptical properties.

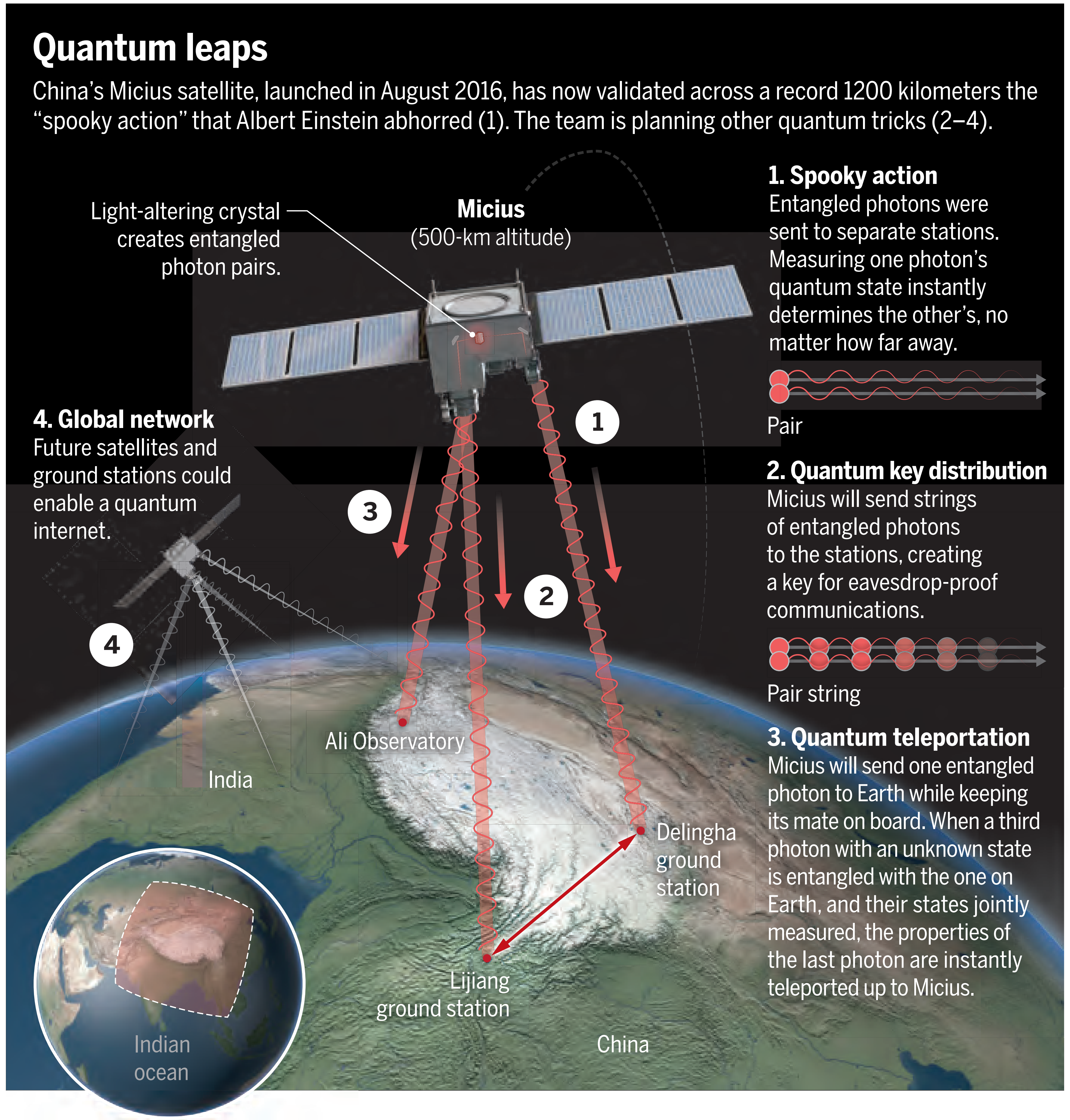
Request

EKSMA OPTICS

ESTIMATED DELIVERY TIME: 4 - 5 DAYS

CHOOSE PRODUCT

SEND REQUEST FOR CUSTOM PRODUCT



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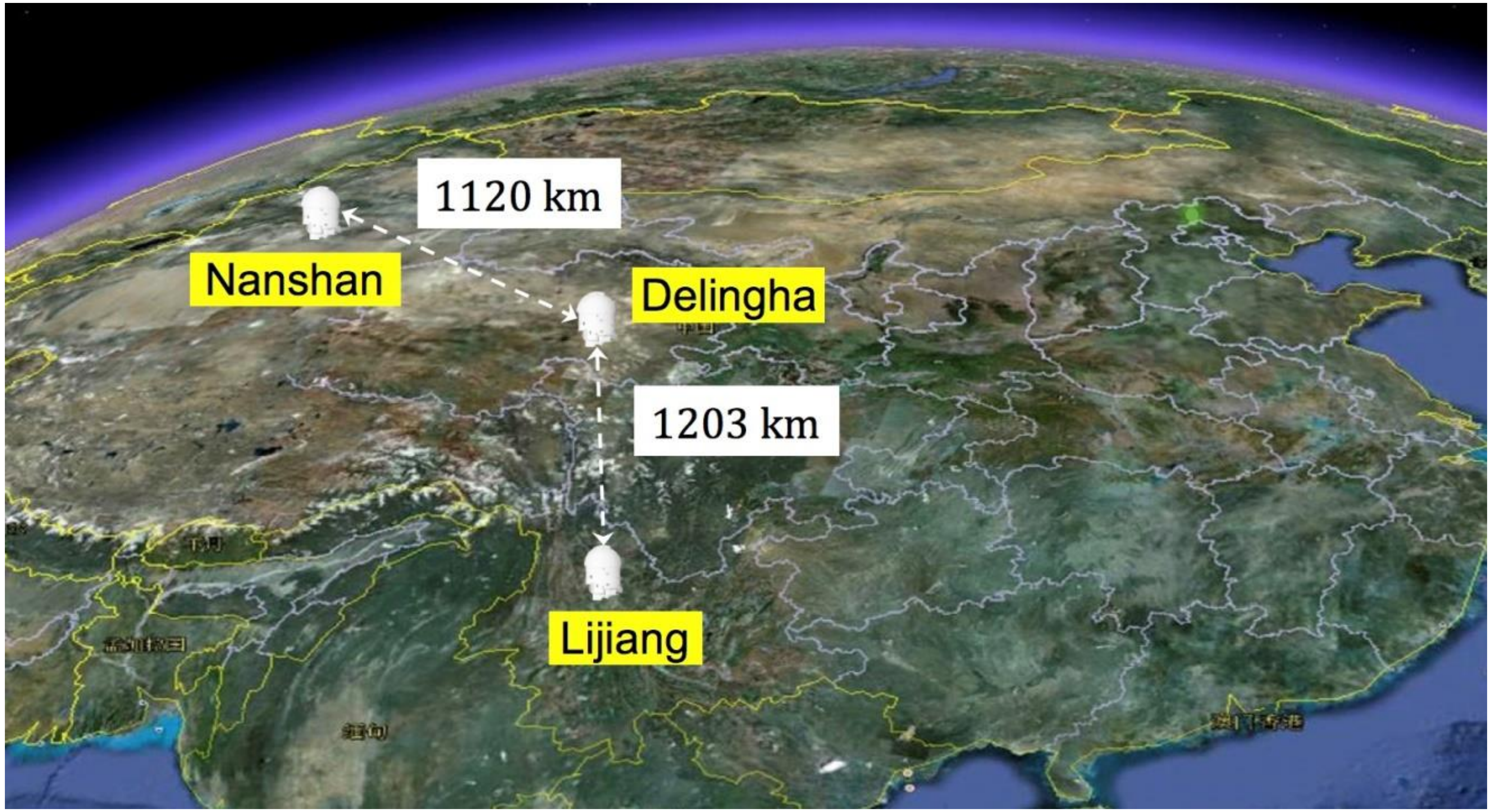

Fig. S5

Geographic map of the ground stations.

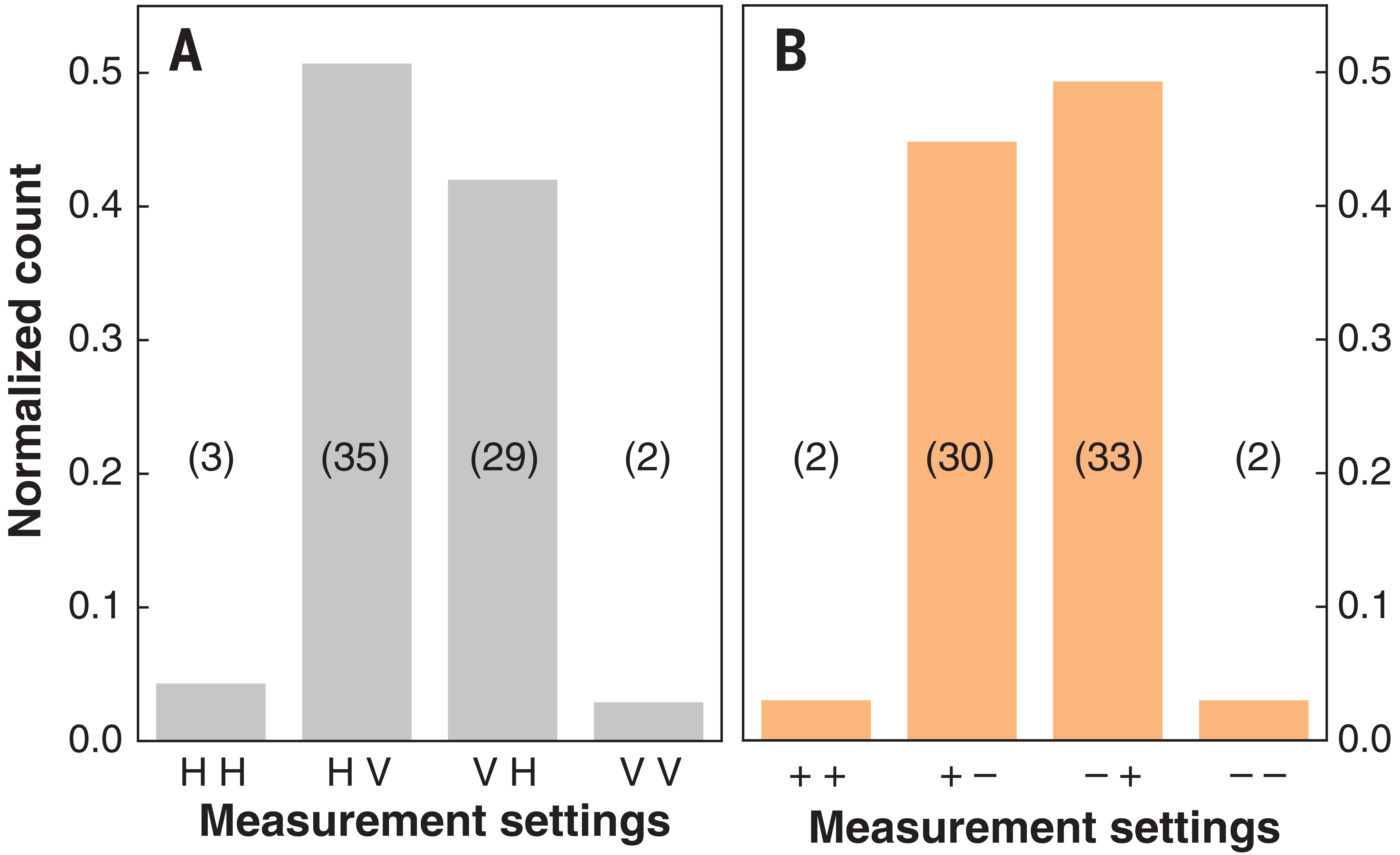

Fig. 4. Measurement of the received entangled photons after transmission by the two-downlink channel. (**A**) Normalized two-photon coincidence counts in the measurement setting of the $|H\rangle/|V\rangle$ basis. (**B**) Normalized counts in the diagonal $|\pm\rangle$ basis. Numbers in parentheses represent the raw coincidence counts of different measurement settings.

Concluding Remarks

Concluding remarks

We have demonstrated the distribution of two entangled photons from a satellite to two ground stations that are physically separated by 1203 km and have observed the survival of entanglement and violation of Bell inequality. The distributed entangled photons are readily useful for entanglement-based quantum key distribution (*7*), which, so far, is the only way that has been demonstrated to establish secure keys between two distant locations with a separation of thousands of kilometers on Earth without relying on trustful relay. Another immediate application is to exploit the distributed entanglement to perform a variant of the quantum teleportation protocol (*32*) for remote preparation and control of quantum states, which can be a useful ingredient in distributed quantum networks. The satellite-based technology that we developed opens up a new avenue to both practical quantum communications and fundamental quantum optics experiments at distances previously inaccessible on the ground (*33*, *34*).

Quantum Cryptography Based on Bell's Theorem

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(Received 18 April 1991)

Practical application of the generalized Bell's theorem in the so-called key distribution process in cryptography is reported. The proposed scheme is based on the Bohm's version of the Einstein-Podolsky-Rosen *gedanken experiment* and Bell's theorem is used to test for eavesdropping.

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rithm. The encrypting and decrypting algorithms are publicly announced; the security of the cryptogram depends entirely on the secrecy of the key, and this key, which is very important, may consist of any *randomly chosen,* sufficiently long string of bits. Once the key is established, subsequent communication involves sending cryptograms over a public channel which is vulnerable to total passive interception (e.g., public announcement in mass media). However, in order to establish the key, two users, who share no secret information initially, must at a certain stage of communication use a reliable and a very secure channel. Since the interception is a set of measurements performed by the eavesdropper on this channel, however difficult this might be from a technological point of view, *in principle* any classical channel can always be passively monitored, without the legitimate users being aware that any eavesdropping has taken place. This is not so for quantum channels [3]. In the following