Detecting gravitational waves using entangled photon states

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We propose a *thought technique* for detecting gravitational waves (GWs) using Einstein-Podolsky-Rosen photon entangled states. GWs decohere the entangled photon pairs, introduce a relative rotation, and desynchronize Alice's and Bob's reference frames, thus reducing the measured nonlocality of correlated quanta described by Bell's inequalities. Gravitational waves, distorting quantum encryption key statistics away from a pure white noise, act then as shadow eavesdroppers. The deviation from the intrinsic white-noise randomness of a quantum key distribution process can reveal the presence of a gravitational wave by analysis of the emerging color distortions in the key. Photon entangled states provide the key advantage of revealing the polarization rotation introduced by GWs without the need of previously fixed reference frames.

I. INTRODUCTION

Quantum cryptography provides a stunning application of Einstein-Podolsky-Rosen (EPR) correlations and Bell's inequalities [1–6,8]. Not only does it promise perfectly secure key distribution, but we argue that it may also allow the detection of the shadowy traces of gravitational waves (GWs) whose existence is one of the most important outstanding tests of Einstein's general relativity and the subject of a number of current and next-generation experiments [9–17,20]. Even though until now clear evidence of GWs has not been obtained with present-day detectors, an indirect proof of their existence was given in the 1970s by the radio-astronomical observations of Hulse-Taylor pulsars [21].

A general quantum key distribution (QKD) scheme consists of a random key generation by two parties *A* and *B* (Alice and Bob) interested in communicating securely. By performing a sequence of measurements on these entangled pairs of photons, decided by a previously chosen protocol [Bennett-Brassard 1984 (BB84), Bennett 1992 (B92)] [2,3,6], Alice and Bob determine the key they will use to encrypt their message. An attack may be made by an eavesdropper (Eve) who secretly attempts to determine the key as the pairs of entangled EPR quanta travel to Alice and Bob. The vital advantage that quantum mechanics provides lies in the *impossibility* that an eavesdropper (Eve) can intercept the secret key without giving away her presence to Alice and Bob, since such interception unavoidably alters the entanglement of EPR pairs.

Variants of the standard BB84 protocol based on the transmission of single pairs of EPR photons have been used recently in practical quantum key distribution over optic fiber networks more than 100 km in length [7]. Similar experiments have illustrated the feasibility of quantum encryption and single-photon exchange in practical situations outside of a research laboratory and in space-to-ground links [8,22–25].

Lorentz transformations, quantum metric fluctuations, gravitational waves, and, more generally, gravitational fields decohere and introduce nonunitarity in a single-qubit state and in entangled state [17,26–29] but a unitary, precise, theoretical description is still missing. Now the field is sufficiently mature to be a tool in fundamental research beyond the foundations of quantum mechanics.

In this paper we propose a simple gedanken experiment, a "thought technique," to detect the effects of gravitational waves through the distortions they cause in the statistics of the quantum keys determined by Alice and Bob. The interaction of the EPR pairs, shared between Alice and Bob, with the ripples of spacetime would produce similar effects to Eve's attacks.

II. PHOTON POLARIZATION STATES AND GWs

We start by considering the following thought experiment, in which Alice and Bob, in their reference frames $(x_A^0, x_A^1, x_A^2, x_A^3)$ and $(x_B^0, x_B^1, x_B^2, x_B^3)$, having null relative velocities in a Minkowsky spacetime, share entangled photons in the singlet state of Eq. (1):

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|H\rangle_A|V\rangle_B - |V\rangle_A|H\rangle_B). \qquad (1)$$

The subscripts $|\ \rangle_A$ and $|\ \rangle_B$ indicate that the physical quantities are measured in the reference frame of Alice or Bob, respectively. The two parties are separated by the distance l_{AB}, measured along the common direction of the x_A^1 and x_B^1 axes, which has the same length in both reference frames. The axes $x_{A,B}^2$ and $x_{A,B}^3$ coincide with the vertical and horizontal directions $|V\rangle_{A,B}$ and $|H\rangle_{A,B}$ of the photon polarization directions for both reference frames.

Let us consider for the sake of simplicity, and, without losing generality, the ideal case in which a monochromatic plane GW

$$h_{\mu\nu}^{(\mathrm{TT})} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ \cos\Theta & h_\times \cos\Theta & 0 \\ 0 & h_\times \cos\Theta & -h_+ \cos\Theta & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \qquad (2)$$

is propagating along the negative x_B^3 direction in Bob's reference frame. The wave equation is expressed in the

transverse-traceless (TT) gauge. $\lambda_{GW} \gg l_{AB}$ is the wavelength, $h_\times$ and h_+ are the amplitudes of the GW's polarization modes "$\times$" and "$+$," $\Theta = k_\mu x_B^\mu$ is the phase of the wave at the position x_B^μ, and $k^\mu = (2\pi/\lambda_g, 0, 0, -2\pi/\lambda_g)$ is the GW's wave vector. More generally, while Alice remains in a Minkowsky spacetime having Galilean metric tensor $g_{A,\mu\nu}^{(0)}$, Bob's region is described by a perturbed metric $g_{B,\mu\nu} = g_{\mu\nu}^{(0)} + h_{\mu\nu}$.

Alice and Bob then perform Bell state measurements with randomly swapped polarizers. If a polarizer happens to be correctly oriented, the incident photon is detected and a "1" is recorded; otherwise a "0." Repetition generates two equal-length binary strings K_A and K_B, corresponding to the measurements of Alice's and Bob's detectors.

Alice and Bob then publicly announce the orientations of their polarizers corresponding to each element in K_A and K_B. They then eliminate the elements of K_A and K_B corresponding to noncoincident orientations of the two polarizers. The string entries of the remaining subsets of K_A and K_B form the two quantum keys k_A and k_B. In the absence of gravitational waves and noise, the two keys coincide, $k_A = k_B$, since the photon pairs are perfectly entangled. After having built the key k_A, Alice proceeds with the transmission of an encrypted message to Bob, who decodes it with his key, k_B. However, this is not of interest to us now. Instead, cross correlation of the keys k_A and k_B allows, in principle, the detection of gravitational waves.

This detection proceeds thanks to a fundamental property of quantum cryptography: the key $K = k_A \otimes k_B$ of an ideal experiment is a Markovian process with zero-memory step, written in terms of a pure white-noise-generated discrete random sequence of 0's and 1's [30]. The presence of a gravitational wave colors the cross-correlation statistics so the keys are no longer white. So, for the strings k_A and k_B, the probability of having a 1 (a detection) is no longer equal to the probability of a 0 (a nondetection). In addition the two strings will no longer coincide element by element: $k_A \neq k_B$.

Seen from a classical point of view, a gravitational wave introduces a discoloration in the quantum key by changing the arrival time of the photons at Alice and Bob, by altering the detectors' local time and the path length l_{AB} traveled by the photons. Another relevant macroscopic effect is observed in Bob's x_B^2 and x_B^3 axes, which are misaligned with respect to the corresponding ones of Alice's reference frame because of a rotation $\Delta\theta \propto h$. At the quantum level, instead, the interaction of the GW with the photons of the entangled pairs can be described in terms of the interaction between a bath of coherent states of gravitons $|g\rangle$ [31] and photons, via elementary graviton-photon scattering processes (e.g., elastic gravitational Compton scattering, $g\gamma \rightarrow g\gamma$) that are shown to cause decoherence, but at the second order in the GW amplitude h [32–34].

Since $h^2 \ll h$ always, we focus on the effects that can cause a deviation of the quantum key distribution at first order h. The change of relative local times and the relative reference frame rotation of Alice and Bob will introduce a perturbation at the first order in h. To reveal the change of local times, the quantum cryptographic setup would require a sensitivity better than the time coherence of the entangled photons and an extremely precise synchronization of the two reference frames.
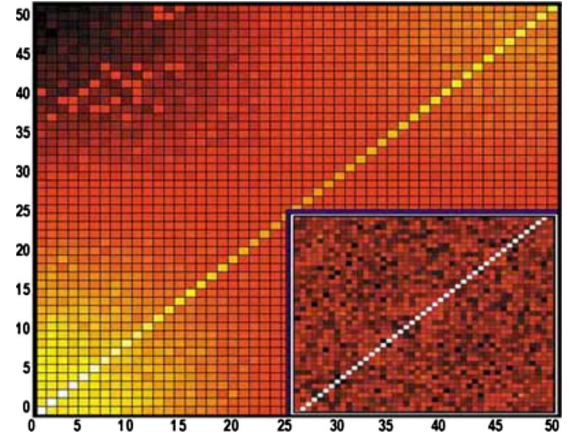

FIG. 1. (Color online) Averaged cross-correlation matrix of sample 50-element keys K_A and K_B. Inset: The idealized white-noise case (without gravitational waves) of the 50x50 cross correlation matrix. The diagonal dominates in the large key length limit where the cross-correlation is simply proportional to δ_{ij}. The main figure schematically shows the off-diagonal power induced by a deterministic gravitational wave that colors the white noise of the ideal uncorrelated and unperturbed string.

Generally, the detection coincidences dramatically depend on the synchronization of Alice's and Bob's reference frames and it is still not clear whether entanglement could always be an intrinsic invariant relativistic property of the pair [35,36]. Crucial effects such as geodesic deviations of entangled quanta in a curved spacetime, the problem's arising from synchronization of the two observers and from the coupling terms, and the potentials existing between the entangled quanta (e.g., the effect of a Coulomb potential between two entangled ions) have not been yet completely faced in a fully relativistic approach. For this reason, the detection of gravitational waves with entangled atom interferometers realized with massive quanta must take into account all of these important effects because the ions (or atoms) experience the presence of a non-negligible interparticle potential that still do not have a clear relativistic description [37]. Entangled photons may provide a simpler approach to this problem: quantum field effects such as photon-photon interaction and the interaction potential between two entangled photons traveling along opposite directions can be neglected in our approach, since they give terms proportional to h^2 or at even higher order.

Neglecting at this first stage also the effects due to the lack of time synchronization between Alice and Bob (see, e.g., [17]), we focus now on the disentanglement due to the rotation $\Delta\theta$ of the two reference frames. The parallel transport of the polarization vector direction between A and B will then reveal the presence of a gravitational wave. In order to analyze this effect one may construct the cross-correlation matrix between the two keys k_A and k_B and search for off-diagonal power (see Fig. 1).

By using the quantum key, we then define the *accumulated fluctuation* $\xi(t)$ as the absolute value of the difference, for a given temporal length t, of the number of nondetections, $N_{[0]}$, and detections, $N_{[1]}$, in K, viz., $\xi(t) \equiv |aN_{[1]} - bN_{[0]}| = 0$, where a and b are real numbers that depend on

the angles used in the protocol. This procedure is equivalent to the accumulation in time of the effects of GWs, making their detection possible in principle.

Let us consider the general effect of the gravitational field in more detail. Each polarizer is described by the states $|H\rangle\cos\varphi_{A,B}+|V\rangle\sin\varphi_{A,B}$, where the angles φ_A and φ_B swap between chosen values. The probability that the Bell state overlaps with the vector describing the polarizer is $P^{\Psi_1} = \frac{1}{2}\sin^2(\varphi_A+\varphi_B)$. If $\varphi_A=-\varphi_B$ and the two photons are detected the corresponding bit in the string is set to 1; when $\varphi_A \neq \varphi_B$ or the two photons are not detected a 0 is recorded. The probability of having a 1 in the string is $P_1=\frac{1}{2}\sin^2(\psi)$, where $\psi=2\varphi_A$ while the probability of having a 0 in the string is $P_0=1-\frac{1}{2}\sin^2(\psi)$. The standard angles used in the most common protocols like BB84 and/or B92 (i.e., $0, \pm\pi/4, \pi$) show a dependence on the GW effect only at the second order in h. This would make GWs far from detectable with this method. By using instead the angles $\varphi_{A,B}=(-\pi/6,\pi/6)$ as proposed in [18,19] to obtain a secure QKD with Wigner inequalities, the detection and nondetection probabilities are $P_1=\frac{3}{8}$ and $P_0=\frac{5}{8}$, respectively, with a linear dependence on the GW amplitude h.

In the absence of gravitational waves, we build with our protocol a discrete zero-mean Markovian process $\xi_{A,B}(t) \equiv 5N_{[1]}(t)-3N_{[0]}(t)$. By approximating the data record of length T with a continuous process, in the large-number limit we obtain

$$\xi_{A,B}(T) \simeq \frac{\Gamma_{\text{ph}}}{2}\int_0^T dt(5P_1 - 3P_0), \qquad (3)$$

where Γ_{ph} is the detection rate of coincidences between entangled photon pairs. The presence of GWs induces a discoloration in $\xi_{A,B}(t)$ and in the quantum key affecting the statistical properties of the accumulated fluctuations.

The detection and nondetection probabilities (P_1, P_0) in the presence of a gravitational wave become of linear order in the GW amplitude, $P_1 \simeq \frac{3}{8}+\frac{\sqrt{3}}{4}\Delta\theta$ and $P_0 \simeq \frac{5}{8}-\frac{\sqrt{3}}{4}\Delta\theta$, since $\Delta\theta \propto h$. The accumulated fluctuation at time T in the long-wavelength limit will become $\xi(T)=2\sqrt{3}\Gamma_{\text{ph}}\int_0^T h(t)dt$. By assuming, for example, $\Gamma_{\text{ph}}\sim 10^5$, $h=10^{-18}$, and polarization sensitivity 10^{-10} [38,39], we would obtain a signal of 0.0035 qubits/s emerging from a pure white noise data record (i.e., ~ 12 qubits after 1 h of integration). It is easy to infer that, even if the probability of detecting a GW is not null, to obtain a realistic estimate of GWs' effects we would need an extremely low-noise setup.

In the idealized case where complex and experiment-specific noise sources (such as thermal and seismic fluctuations influencing also the polarizing axis of the polarizer) are neglected, the intrinsic fluctuations in the time series due to the fluctuations of the polarization directions are described by a frequency-independent random process characterized by the noise spectral density—the noise-induced mean square fluctuations per unit frequency that can be modeled for a precise setup and then measured after the construction. In the following, we estimate the noise level due to the uncertainty in the measurement of the polarization angle of the entangled photons. For the sake of simplicity we will assume that each

element of the qubit series sent to both Alice and Bob is affected by white noise, represented by a Gaussian process with zero mean and variance equal to the error $\Delta\theta$ in the polarization measure: $\langle n_I\rangle=0$ and $\langle n_I n_J\rangle=\delta_{IJ}(\Delta\theta)^2$ ($I,J = 1,\ldots,N$), where $N=N_c/2$ and N_c is the number of pairs of entangled photons so far detected.

In order to compare the noise floor to a typical value for current earth-based detectors, we now compute the noise spectral density (i.e., the noise power per unit frequency). Taking the discrete Fourier transform of the noise

$$\tilde{n}_J = \delta t\sum_{I=0}^{N-1} e^{-2\pi IJ/(N-1)}n_I \qquad (4)$$

where δt is the sampling time of the qubit series, it is straightforward to show that

$$\langle\tilde{n}_I\tilde{n}_J^*\rangle = [\delta t(N-1)\delta_{IJ}]\delta t(\Delta\theta)^2. \qquad (5)$$

The quantity between square brackets is the discretization of the Dirac δ function in Fourier space so the noise spectral density for each element of the qubit series is $\tilde{S}_n=\delta t(\Delta\theta)^2$. We now divide the qubit series into M segments each containing L qubits such that $(ML=N=N_c/2)$. For each segment the noise spectral density is reduced by a factor L with respect to the value corresponding to a single qubit, so

$$\tilde{S}_n^{(J)} = \frac{1}{L}\delta t(\Delta\theta)^2 \quad (J=1,\ldots,M). \qquad (6)$$

Assuming that the production rate Γ_{ph} of entangled pairs of photons is equal to the detection rate $(\Gamma_{\text{ph}}=2\delta t^{-1})$, we obtain

$$\tilde{S}_n^{(J)} = \frac{4}{\tau}\left(\frac{\Delta\theta}{\Gamma_{\text{ph}}}\right)^2 \quad (J=1,\ldots,M), \qquad (7)$$

where τ is the time duration of the segment. So the spectral amplitude of the noise $\tilde{h}_n=\sqrt{\tilde{S}_n}$ for each segment is

$$\tilde{h}_n^{(J)} = 2\times 10^{-23}\left(\frac{\Delta\theta}{10^{-10}\text{rad}}\right)\left(\frac{10^6\text{ s}}{\tau}\right)^{1/2}\left(\frac{10^{10}\text{ s}^{-1}}{\Gamma_{\text{ph}}}\right)\text{ (Hz)}^{-1/2}, \qquad (8)$$

to be compared with the best Laser Interferometer Gravitational-Wave Observatory (LIGO) design sensitivity (around 100 Hz) [40], $\tilde{h}_n \sim 3\times 10^{-23}$ Hz$^{-1/2}$.

Since those quantum entangled state based detectors use the properties of photon-photon correlations of each single entangled pair, the accumulated fluctuation is a random process with zero mean and linearly increasing variance. However this detection method can be better improved by applying the technique of the randomness of the choices of measurement basis by Alice and Bob [41], which gives significant advantages in cases where the qubit error rate is crucial. What we have shown is that gravitational waves will act as *shadow eavesdroppers*, reducing the degree of entanglement between quantum states controlled by Bell's inequalities.

III. DISCUSSION AND CONCLUSIONS

We have outlined how quantum technology may be exploited to yield a potentially sensitive detector of gravitational waves. The setup can measure angular deviations that are first order in the GW amplitude h and, we point out that, counting the coincidences between detections of the EPR pairs, the setup will not be affected by the laser's shot noise. This makes our setup a good candidate to detect high-frequency GWs, typical of string-cosmology scenarios [42].

The advantages of this setup with respect to a classical GW detector based on polarization change of an electromagnetic wave [12] is provided by the properties of twin- and entangled-photon ellipsometry that are part of a QKD scheme. This permits estimation with high precision of the deviation $\Delta\theta$ of the polarization vectors in each pair accumulated during the travels from the source to the observers Alice and Bob. This procedure may improve the detection of GWs, especially in situations when the orientation between Alice and Bob's reference frames becomes crucial, as in space-based experiments. With quantum ellipsometry techniques, in fact, the experimenter does not need to fix the direction of its reference frame (e.g., with respect to the stars) and ideally does not even need to characterize for each measurement its optical setup, reaching in principle the quantum limit [31,43,44]. The crucial additional advantage of using entangled states instead of twin (or correlated) photons is that the building of the cryptographic keys permits the use of stochastic techniques to accumulate the effects of GWs and, also, to detect the presence of a stochastic gravitational wave background. This setup could benefit or give advantages to atom interferometry techniques recently proposed [45,46].

The setup we propose is probably the simplest approach to detect the presence of gravitational waves using the new emerging quantum technology. For example, the use of n Greenberger-Horne-Zeilinger (GHZ) states may help in principle to beat the shot noise limitation, having a $1/n$ dependence, but it presents the disadvantage of having a fainter and fainter source the more complex is the GHZ state [47,48], making this proposal not realistically applicable. Also, quantum teleportation of spatial directions and even of whole reference frames between different points of space-time could be proposed to detect GWs [47,49–54], but all these pioneering techniques still require a too critical and difficult local control of the quantum states, a fine tuning of the coupling between the quanta, and the communication of different quantum states over large distances which would unavoidably strongly affect their performances.

In principle, our gedanken experiment could represent an alternative approach to the already existing interferometric detectors in the high-frequency domain. Our estimations show that the noise level of this ideal setup is of the same order of magnitude as in the best LIGO design sensitivity. In any case, a real, detailed, understanding of all relevant noise sources is still lacking and depends on exact details of the detector setup and on the future development of detector and source technology. But this goes beyond the purpose of this paper.

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