Large scale EPR correlations and cosmic gravitational waves

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Abstract. - We study how quantum correlations survive at large scales in spite of their exposition to stochastic backgrounds of gravitational waves. We consider Einstein-Podolski-Rosen (EPR) correlations built up on the polarizations of photon pairs and evaluate how they are affected by the cosmic gravitational wave background (CGWB). We evaluate the quantum decoherence of the EPR correlations in terms of a reduction of the violation of the Bell inequality as written by Clauser, Horne, Shimony and Holt (CHSH). We show that this decoherence remains small and that EPR correlations can in principle survive up to the largest cosmic scales.

It has long ago been suggested by Feynman that gravitation could be at the origin of a universal decoherence mechanism preventing macroscopic systems to exhibit quantum coherence properties \cite{1}. This idea has been considered since that time through the study of different mechanisms \cite{2,3,4,5,6,7}, some of them involving Planck-scale physics \cite{8,9,10}.

These important theoretical questions can also be addressed as experimental challenges. In particular the following questions have been discussed in this context \cite{11} : (i) are quantum interferences limited to microscopic objects having masses or energies smaller than some intrinsic limit ? (ii) are quantum correlations limited to experiments performed on length scales smaller than some intrinsic limit ? These two questions have led to efforts for producing evidence for quantum interferences with larger and larger molecules \cite{12} as well as quantum correlations on larger and larger distances \cite{13}. Up to now, the reported limits are associated with practical rather than fundamental issues. Efforts are going on for mastering these technical limitations and approaching closer and closer the underlying fundamental questions in future experiments \cite{11,14}.

Here, we will study the effect of the unavoidable interaction with the gravitational waves backgrounds which pervade our spacetime environment. It has already been shown that such an interaction was responsible for an intrinsic decoherence mechanism in atomic interferometry. The mechanism is more and more efficient for larger and larger masses, but it depends also on other parameters. With this model of spacetime fluctuations, it is possible to associate quantitative estimations to the qualitative Feynman argument, using only known gravitational physics, astrophysics and cosmology \cite{15}.

In the present paper, we give quantitative estimations for the case of Einstein-Podolski-
Rosen (EPR) quantum correlations between polarization entangled pairs of photons \[16\]. Precisely, we study how the violation of the Bell inequality \[17\], under the form written by Clauser, Horne, Shimony and Holt (CHSH) \[18\], is affected after the propagation of photons over some large distance. We evaluate the effect of the binary confusion background (BCB) and of the cosmic gravitational wave background (CGWB) \[19\]. The former is a classical background resulting from the confusion of gravitational waves emitted in the Galaxy and its vicinity. The latter, predicted to have been created from quantum fluctuations of the metric in primordial cosmology \[20\], is essentially characterized by the dimensionless parameter $\Omega_{gw}$ which measures the energy density of gravitational waves with respect to the critical density energy.

The main result of the paper will be that the reduction of the violation of CHSH inequality is bound by the value of $\Omega_{gw}$ and therefore remains small even after propagation at the largest cosmic distances. This means that EPR polarization entanglement is predicted to survive at these extreme scales without being washed out by the interaction with gravitational waves backgrounds.

**Polarization entangled photon pairs.** – The Bell test experiment considered in this paper is schematized on the spacetime diagram of fig. 1. A source S (placed for example on Earth) sends pairs of polarization entangled photons towards two detectors A and B. The geodesic motion of S, A and B is represented by the worldlines which are nearly vertical of fig. 1 (their velocities are much smaller than $c$). The lines inclined at $\pm 45^\circ$ with respect to the space and time axis correspond to the propagation of the photons over a time of flight $\tau$.

![Spacetime diagram associated with a Bell test experiment with polarization entangled photon pairs; the nearly vertical lines represent the motions of the source S and detectors A and B while the inclined lines correspond to photons from source to detectors; $\tau$ is the time of flight from S to A or B and $T$ is the integration time needed to estimate correlations.](image)

Fig. 1: Spacetime diagram associated with a Bell test experiment with polarization entangled photon pairs; the nearly vertical lines represent the motions of the source S and detectors A and B while the inclined lines correspond to photons from source to detectors; $\tau$ is the time of flight from S to A or B and $T$ is the integration time needed to estimate correlations.

The source S emits pairs of polarization entangled photons. We consider that the corresponding two-photon state has a null momentum and a null spin (singlet state). From conservation and parity arguments \[21\], it is thus deduced that the photon pairs are described by a Bell state

$$|\psi_S\rangle = \frac{1}{\sqrt{2}}(|R_{\leftarrow}, R_{\rightarrow} \rangle - |L_{\leftarrow}, L_{\rightarrow} \rangle),$$

(1)

where $R$ and $L$ denote right-handed and left-handed circular polarizations while $\leftarrow$ and $\rightarrow$ refer to the photons propagating from S towards respectively A and B. One of the latter observers, say A, measures the polarization of photons with polarization beam splitters and photodetectors. He attributes $+$ and $-$ values to detections in the two polarization channels, when the polarization measurement setup has a local orientation defined by the angle $\Theta_A$. 
The origin of this orientation is defined by a local reference. The observers A and B count the coincidences over a measurement time $T$ for the 4 possibilities $++$, $+-$, $-+$ and $--$, and they measure probabilities (average numbers for each possibility divided by the number of all coincidences)

$$P_{++} = P_{--} = \left| \frac{e^{i\Theta} - e^{-i\Theta}}{2} \right|^2 = \frac{\sin^2 \Theta}{2},$$

$$P_{+-} = P_{-+} = \left| \frac{e^{i\Theta} + e^{-i\Theta}}{2} \right|^2 = \frac{\cos^2 \Theta}{2},$$

$$\Theta = \Theta_B - \Theta_A.$$  \hspace{1cm} (2)

The two observers A and B then evaluate correlation functions $E$ and $S$ defined respectively for 2 and 4 orientations of the polarization measurement setups \cite{18}

$$E_{AB} = P_{++} + P_{--} - P_{+-} - P_{-+} = -\cos(2\Theta),$$

$$S = E_{AB} - E_{AB}' + E_{A'B} + E_{A'B}'.$$  \hspace{1cm} (3)

Should the conditions of Bell theorem be obeyed \cite{17}, the following CHSH inequality would be deduced \cite{13}

$$|S| \leq 2$$  \hspace{1cm} (4)

As is well known, this inequality is violated by the polarization entangled photon pairs described by the preceding equations (1-3). The maximum violation is predicted for example with the angles $\Theta_A = 0$, $\Theta_B = \pi/8$, $\Theta_A' = \pi/4$ and $\Theta_B' = 3\pi/8$, which lead to $|S_{\text{max}}| = 2\sqrt{2}$.

We want to stress at this point that the effects of gravitation have been ignored in the discussion up to now. In particular, the orientation of the polarization measurements setups at A and B raises no fundamental question in the absence of spacetime curvature but it has to be carefully defined in the context of general relativity. We note that the orientation can be controlled by using the expression (3), allowing the two remote observers to exploit the available quantum correlations to get a relation between the angles $\Theta_A$ and $\Theta_B$.

**Effect of gravitational fields.** – We now consider the same problem in general relativity, taking into account the effect of gravitational fields, and in particular gravitational waves, on polarization entangled photon pairs. To this aim, we have to study the propagation of polarized electromagnetic fields in general relativity. The dominant effect is a rotation of the polarization of light along the ray \cite{22}. The use of this effect for the purpose of detecting gravitational waves has been studied \cite{23, 24} as well as its possible contribution to decoherence \cite{25}. Here, we consider the decoherence of the photon pairs due to the interaction with the gravitational waves background.

In order to treat consistently this problem in general relativity, one has to deal not only with the polarization of electromagnetic field but also with the orientation of the local reference axis at the two observers. In the eikonal approximation which is sufficient for the purpose of this letter, both problems are treated by solving the geodesic equation for the motion and parallel transport for the polarization of light and orientation of the polarizers. It is only by taking both effects into account that one obtains a properly defined observable, associated with a gauge invariant expression. In the following, we use the results of detailed calculations presented in \cite{26}.

A proper observable is defined by comparing the rotation of the photon polarization along the ray $\to$ from the source S to the detector B and the rotation of local reference orientations at the source and detector. At first order in the gravitational perturbation, this observable has the following expression

$$\alpha_{\to}(t) = \frac{1}{2} \int_{ct}^{ct + ct'} (\partial_1 h_{23} - \partial_2 h_{13}) d\sigma.$$  \hspace{1cm} (5)
The integral is taken along the unperturbed path of the photons from the time $t$ to the time $t + \tau$, with $\tau$ the time of flight and $\sigma$ the time parameter along this path. The notations for the metric are the same as in [27] and the expression (5) is written for a propagation along the direction $x_3$. The angle $\alpha_{\rightarrow}$ and the similarly defined $\alpha_{\leftarrow}$ are gauge invariant observables.

Considering first the case of stationary gravitational fields, we see that eqs.(2,3) are changed as follows:

\begin{align*}
P^{++} &= P^{--} = \frac{|e^{i\Theta}e^{-i\alpha} - e^{-i\Theta}e^{i\alpha}|^2}{2}, \\
P^{+-} &= P^{-+} = \frac{|e^{i\Theta}e^{-i\alpha} + e^{-i\Theta}e^{i\alpha}|^2}{2}, \\
E_{AB}^g &= -\cos(2(\Theta - \alpha)), \quad \alpha = \alpha_{\rightarrow} - \alpha_{\leftarrow}.
\end{align*}

A comparison of (6) with (3) shows that stationary gravitational fields lead to a relative rotation of the orientations at A and B, taking into account the parallel transport of photon polarization as well as that of orientation of the polarizers. The structure of the formula can also be understood in analogy with an interferometric signal: the rotation of linear polarizations is indeed equivalent to different dephasings $e^{\pm i\alpha}$ for the two circular polarization states. Using this analogy, we will be able in the next sections to use results already known for interferometers and apply them to the case of Bell test experiment.

Up to now we have supposed that the angle $\alpha$ is time independent or at least that it varies slowly enough so that it does not affect the measurements during the integration time $T$. In this case, the already discussed trick can still be used: the two observers at A and B can in fact compensate for the slow effect of gravitational fields by adjusting their local orientation references. It follows that the maximum violation of Bell’s inequality is not affected, though the orientation of the polarizers may have to be changed in order to attain it. Of course, this can no longer be the case when rapid fluctuations cause a blurring of the correlation and lead to a decrease of the maximum violation of CHSH inequality. We focus the discussion on this effect in the sequel of this letter.

**Effect of stochastic gravitational waves.** – We now discuss the effect of stochastic backgrounds of gravitational waves, which produce not only drifts but also fluctuations.

We first remind that two stochastic backgrounds are usually studied. The so-called binary confusion background (BCB) is the sum of signals of all unknown binaries in our Galaxy and its vicinity. Its stochastic nature is only due to the confusion of a large number of poorly known sources. In particular, each binary system produces a classical gravitational wave, so that the superposition of all contributions remains a classical stochastic background. In contrast, the cosmological gravitational wave background (CGWB) stems from quantum fluctuations created during the primordial cosmic era and then amplified by a huge factor through their coupling to the evolution of Universe [20].

Gravitational waves may be described in linearized general relativity and the fluctuations of the metric field described by correlation functions (all notations are as in [27]). The backgrounds appear stationary for not too long observations. We also use simple assumptions of unpolarized and isotropic backgrounds, which are valid for the CGWB and first approximations for the BCB. All information about the backgrounds is thus contained in the one-sided spectral density $S_{gw}$ [19]

\begin{equation}
S_{gw}[\omega] = \int_{-\infty}^{\infty} dt \exp (-i\omega t) \langle h(t)h(0) \rangle,
\end{equation}

where $h$ is any one of the amplitudes $h_{12}$ or $(h_{11} - h_{22})/2$ (or other ones obtained after spatial rotations). The spectrum $S_{gw}$ can equivalently be described as a spectral density
of energy, or a number of graviton per mode \( n_{gw} \) (much larger than unity for all modes of interest),

\[
\hbar \omega n_{gw}[\omega] = \frac{5c^5}{16G} S_{gw}[\omega].
\] (8)

For the CGWB, the spectrum \( S_{gw} \) is often written as

\[
S_{gw} = \frac{12\pi H_0^2}{5\omega^3} \Omega_{gw},
\] (9)

where \( H_0 \) is the present day Hubble rate (\( H_0 = \dot{a}/a \) where \( a \) is the cosmic size parameter) while the dimensionless quantity \( \Omega_{gw} \) represents the energy density of the background compared to the present value of the critical energy density for closing the Universe.

![Figure 2: Spectra \( S_{gw} \) considered in the discussions: the full (blue) line corresponds to the CGWB with \( \Omega_{gw} = 10^{-14} \) and the dashed (red) line to the BCB (model given in [29]).](image)

The parameter \( \Omega_{gw} \) might depend on frequency but it is often considered as constant over broad frequency intervals. Though the CGWB has not been detected up to now, constraints on the value of \( \Omega_{gw} \) may be drawn from a variety of observations [19]. In particular, \( \Omega_{gw} \) has to be smaller than a few \( 10^{-14} \) at \( \omega \sim 10^{-16} \) Hz (cosmic limit), a few \( 10^{-8} \) at \( \omega \sim 10^{-8} \) Hz (pulsar limit), and a few \( 10^{-6} \) at \( \omega \sim 10^2 \) Hz (laser interferometry limit) [28]. We have drawn as the full (blue) line on Fig.2 the spectrum \( S_{gw} \) corresponding to the CGWB with \( \Omega_{gw} = 10^{-14} \). For the sake of comparison, we have shown as the dashed (red) line on the same plot the spectrum corresponding to the BCB, with the model given in [29]. These two spectra will be used for some computations in the sequel of this letter.

Using equations (5-7), it is now possible to deduce the correlation function \( E_{gw} \) now obtained after a double averaging over the gravitational environment and over the measurement time

\[
E_{gw}^{AB} = -\langle \cos (2(\Theta - \alpha)) \rangle,
\] (10)

where the symbols \( \langle \rangle \) and \( \sim \) represent respectively a trace over the stochastic gravitational waves background and an averaging over the measurement time \( T \). In a linearized treatment, the variable \( \alpha \) has a gaussian distribution so that the correlation function \( E_{gw}^{AB} \) can be rewritten

\[
E_{gw}^{AB} = C \cos \left( 2\Theta - 2\langle \alpha \rangle \right), \quad (11)
\]

\[
C = \langle \cos (2\delta\alpha) \rangle = \exp \left( -2\Delta\alpha^2 \right),
\]

\[
\delta\alpha = \alpha - \langle \alpha \rangle, \quad \Delta\alpha^2 = \langle (\delta\alpha)^2 \rangle.
\]

The interaction with gravitational waves leads to two different effects: the first one is a mean rotation angle \( \langle \alpha \rangle \) which, as already discussed, can be compensated by rotating
the polarizers. In contrast, the second effect is a net reduction of the correlation function due to the fluctuations $\delta \alpha$ which is an exponential function of the variance $\Delta \alpha^2$ of these fluctuations.

For the CGWB, which corresponds to quantum fluctuations, the variance may then be written as the following integral over frequencies

$$\Delta \alpha_{\text{CGWB}}^2 = \int_0^\infty \frac{d\omega}{2\pi} S_{\text{gw}}[\omega] A[\omega].$$

(12)

The dimensionless apparatus function $A$ characterizes the response of the experiment to gravitational waves at frequency $\omega$. It depends on the geometry of the experiment, and in particular on the time of flight $\tau$. Its calculation is done in a similar way to that of similar functions appearing in the study of decoherence in interferometers [15] or of sensitivity to gravitational waves of clock synchronization [30]. At the end of this calculation, it may be written

$$A[\omega] = \frac{5}{8} \int_{-1}^1 \frac{d\mu}{2} |\beta_{\rightarrow} - \beta_{\leftarrow}|^2,$$

(13)

$$\beta_{\rightarrow}[\omega, \mu] = (1 - \mu) \left( e^{-i\omega\tau(1+\mu)} - 1 \right),$$

$$\beta_{\leftarrow}[\omega, \mu] = (1 + \mu) \left( e^{-i\omega\tau(1-\mu)} - 1 \right).$$

The amplitudes $\beta_{\leftrightarrow}$ measure the sensitivity to the gravitational mode at frequency $\omega$ and wavevector with $\mu = ck^3/\omega$ the direction of $k^3$ ($\mu$ is defined for the photon $\rightarrow$, and replaced by $-\mu$ for the photon $\leftarrow$).

After straightforward integrations, the function $A$ is finally written as

$$A[\omega] = \frac{5}{16} \left( 8 - \frac{24 + 6 \cos(2\omega\tau)}{(\omega\tau)^2} + \frac{15 \sin(2\omega\tau)}{(\omega\tau)^3} \right).$$

(14)

The result is drawn on Fig. 3 as a function of $\omega\tau$. It tends to the constant $5/2$ at the limit of high frequencies and behaves as $(\omega\tau)^4/21$ at the limit of low frequencies. For the purpose of comparing the two effects, we give also the variance for the BCB, which corresponds to classical fluctuations and leads to a slightly different expression

$$\Delta \alpha_{\text{BCB}}^2 = \int_0^\infty \frac{d\omega}{2\pi} S_{\text{gw}}[\omega] A[\omega] \mathcal{F}[\omega]$$

(15)

$$\mathcal{F}[\omega] = 1 - \left( \frac{\sin(\omega\tau)}{\omega\tau} \right)^2, \quad \text{sinc}(x) = \frac{\sin x}{x}.$$
The two variances (12) and (15) are integrals of the gravitational waves background over frequencies $\omega$ larger than the inverse of one of the typical time involved in the correlation measurement. For the CGWB, this time is just the time of flight $\tau$ of the photons from the source to the detectors. For the BCB, this time is the longer one of the time of flight $\tau$ and the measurement time $T$. The effect associated with $\tau$ may be considered as intrinsic, as it cannot be reduced for a given geometry. In contrast, the effect associated with $T$ can in principle be limited by having this measurement time shorter than $\tau$.

**Discussion and conclusions.** – We now come to the discussion of the decrease of EPR quantum correlations, i.e. the reduction of the maximal violation of the CSHS inequality (4), due to the effect of the CGWB. For completeness, we also present results for the BCB.

From eq.(11), we deduce the maximal value $S_{\text{max}}$ of the parameter $S$, after optimal angles have been chosen,

$$S_{\text{max}} = C 2\sqrt{2} = 2\sqrt{2} \exp(-2\Delta\alpha^2) .$$

(16)

Following the analogy between the EPR correlation function and interferences, it turns out that the reduction of the maximal violation of Bell-CSHS inequality is analogous to the decoherence effect already studied for interferometers [15]. The main difference is that the reduction is determined by the variance of an angle $\alpha$ whereas it was determined by the variance of a phase for interferometers.

We show on Fig.4 the results of the evaluation of the quantity $2\Delta\alpha^2$ which appears in the exponential factor in eq.(16). The full (blue) line corresponds to the effect (12) of the CGWB ($\Omega_{gw} = 10^{-14}$), and the dashed (red) line to the effect (15) of the BCB ((model given in [29])). All curves are drawn as functions of the time of flight $\tau$ varying from $10^{-3}$s - typical time of flight from a station on Earth to the ISS - to $10^{6}$s - time of flight corresponding to the scale of the solar system ($\approx 2000$ astronomical units). For the case of the BCB, the various curves correspond to different values of the measurement time $T$ varying also from $10^{-3}$s to $10^{9}$s. As expected all variances are increased when the time of exposition ($\tau$ or $T$) to the gravitational wave backgrounds are increased. The effect of the BCB is larger than that of the CGWB for not too large times of exposition, which just reflects the shapes of the corresponding spectra which were plotted on Fig.2.

![Fig. 4: Variances $2\Delta\alpha^2$ appearing in the exponential factor in eq.(16) plotted as functions of the time of flight $\tau$: the full (blue) line corresponds to the effect (12) of the CGWB ($\Omega_{gw} = 10^{-14}$), and the dashed (red) line to the effect (15) of the BCB ((model given in [29])); in the latter case, the various curves correspond to different values of the measurement time $T = 10^{-3}$, 1, 10$^{3}$ and 10$^{6}$s.](image-url)
polarization entangled pairs of photons should survive the exposition to gravitational wave backgrounds in any presently foreseeable experiment. In fact, this conclusion can be made even more general through an argument which sheds light on an unexpected deep connection between the discussion of large scale EPR correlations and cosmology.

In order to write down this argument, we may rewrite the reduction factor $C$ appearing in eqs. (11,16) as follows, under the assumption of a constant value for $\Omega_{gw}$:

$$C = e^{-\Gamma \Omega_{gw}}, \quad \Gamma = \frac{24H_0^2}{5} \int_0^{\infty} \frac{d\omega}{\omega^5} A(\omega).$$

(17)

When the form (14) of $A$ is used, the integration leads to the closed expression

$$\Gamma = \frac{3}{5}(H_0\tau)^2.$$

(18)

The resulting $\Gamma(\tau)$ is the straight line appearing on the log-log plot of Fig.5 which we have drawn for $\tau$ varying up to the Hubble time $\tau \approx 10^{18}$s.

Fig. 5: Dimensionless factor $\Gamma$ as a function of the time of flight $\tau$ on log-log scales; the full (blue) line corresponds to the CGWB, while the dotted and dashed (red) lines corresponds to the BCB with $T \ll \tau$ and $T = 1000$ s respectively.

Fig.5 shows that the number $\Gamma$ is extremely small at all scales small with respect to the Hubble scale. In fact, $\Gamma$ increases as the square of the time scale of the experiment and it would approach unity only at the largest cosmological scales. When evaluating the reduction factor $C$ in (17), the small number $\Gamma$ has first to be multiplied by a second small number $\Omega_{gw}$ and then exponentiated. As a consequence, the reduction has to remain negligible in any experiment. A different conclusion could only be obtained at the largest cosmological scales, if the energy of gravitational waves would be a dominant constituent of the content of the Universe.

As a conclusion, we have shown that the quantum correlations coded in polarization should survive the exposition to gravitational wave backgrounds. In particular, initial quantum correlation arising from primordial cosmic processes are still present in current day Universe even if their detection is a challenge. Note that these conclusions have been obtained for gravitational wave backgrounds as they are predicted by standard calculations, and they would of course be affected if larger fluctuations were produced by physical processes beyond the standard model. Note also that this conclusion relies on a fascinating and unexpected connection between the reduction of EPR quantum correlations at large scales and the fundamental cosmic parameter $\Omega_{gw}$.
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