Quantum correlations from wave-particle unity and locality: Resolution of the EPR puzzle

C. S. Unnikrishnan

Gravitation Group, Tata Institute of Fundamental Research,
Homi Bhabha Road, Mumbai - 400 005, INDIA,
and
NAPP Group, Indian Institute of Astrophysics,
Koramangala, Bangalore - 560 034, INDIA
email address: unni@tifr.res.in

ABSTRACT. The complex wave nature exhibited by quantum systems is at the heart of the nonclassical features of quantum phenomena. The widely discussed Einstein-Podolsky-Rosen nonlocality puzzle has remained unresolved because of not taking into account the phase coherence between local quantities that describe individual particles of a correlated quantum system. We show that the EPR puzzle is resolved if the quantum correlations are calculated directly from local probability amplitudes. Correct quantum correlations are reproduced assuming strict locality. The realism is at the level of phases instead of at the level of eigenvalues. This implies that a measurement on one particle does not collapse the companion particle to a definite state. Apart from resolving the EPR puzzle this approach shows that the physical interpretation of apparently 'nonlocal' effects like quantum teleportation and entanglement swapping are different from what is usually assumed. Bell type measurements do not cause distant collapses. Yet the correlations are correctly reproduced, when measured, due to quantum coherence at source. Our approach shows the limited validity of the Bell's theorem, being valid only when the wave nature of individual quantum particles and possible phase coherences at source are not correctly accounted for. Hence it is the concept of wave-particle unity, advanced by de Broglie, which formed the core of quantum phenomena, that resolves the EPR puzzle sixty five years after it was first discussed.

1 Introduction

1.1 The nonlocality puzzle

Wave nature exhibited by microscopic single particle systems is at the heart of all puzzling aspects of quantum phenomena. The quantum theoretical predictions are for the expectation values and use a wave function or equivalent descriptions represented by suitable complex functions. But the quantum measurements could be on single systems, with their result as one of the possible values of a spectrum of results, manifesting a randomness that makes the theory nondeterministic. It is natural to ask the question whether there is sense in ascribing a definite but unknown value to an observable before the act of measurement. In classical mechanical situations that show statistical randomness, this makes sense and the indeterminism is only apparent. Attempts to formulate quantum mechanics including objective reality – existence of definite, yet unknown and random values – to unmeasured observables, AND locality in the sense of Einstein did not succeed. The well known Bell's inequalities quantifies this failure.

In 1935, Einstein, Podolsky and Rosen (EPR) [1] considered the question whether the wave-function represented a complete description of reality in quantum mechanics, and argued that it didn't. The crucial and essential assumption in their argument was strict locality, in the spirit of special relativity. Also, they had *defined* and included the concept of objective reality in the analysis. If the value of an observable was predictable with certainty without a measurement, the observable had a physical reality according to EPR. They considered a quantum mechanical system consisting of two particles with well defined simultaneous values for their *total* momentum and their *relative* positions, $p_1 + p_2$ and $q_1 - q_2$, represented by commuting observables. The system is represented in standard quantum mechanics by an entangled wavefunction, and the state of each particle is not characterized by a definite value for either position or momentum. But measuring any one of these variables on one particle enables a prediction with certainty of the value of the same variable on the other particle without a measurement. Then according to the EPR definition of reality, the second particle possesses a definite value for this variable before the measurement. Since the decision of which variable is to measured on the first particle can be done after the two particles are separated into space-like separated regions and due to assumption of strict locality, by which the first measurement cannot influence the state of the second particle in any way superluminally, it is clear that the particles should possess objective reality (definite values prior to the measurement) for both variables. But the momentum and position for each particle are noncommuting observables and the wavefunction description does not contain such a simultaneous reality.

In other words, under the assumption of locality and a reasonable definition of reality, quantum systems that are entangled seem to imply simultaneous objective reality for noncommuting observables. Therefore the wavefunction description of quantum mechanics should be considered incomplete. Their assertions lead to attempts at constructing a hidden variable theory that was more complete.

Bell's analysis of the EPR problem in the early sixties established the Bell's inequalities obeyed in any local hidden variable theory for the correlations of entangled particles [2]. Quantum mechanical correlations calculated using the entangled wave-function and spin operators violate these inequalities. This means that any local realistic theory that assumes Einstein locality and the EPR kind of objective reality necessarily predicts results for correlation that does not agree with the quantum mechanical predictions. Subsequently, various experiments have established beyond doubt that there cannot be a viable local realistic hidden variable description of quantum mechanics [3]. These results have been interpreted as evidence for nonlocal influences in quantum measurements involving entangled particles. In the realist view, measurement of an observable on one of the particles in an entangled pair seems to convey the result of this measurement instantaneously to the other particle resulting in the correct nonclassical correlations. In the quantum mechanical terminology, the measurement of an observable on one of the particles collapses the entire wave-function instantaneously and nonlocally. In both views, the second particle *nonlocally acquires* a definite value for the observable. The no signalling theorems in this context prohibit any faster than light signalling using this feature, and therefore signal locality is not violated. But the stronger requirement of Einstein locality is violated.

Quantum nonlocality as manifested in the EPR correlations has been, without doubt, the most important unresolved problem in the foundational aspects of physics. Yet, we understand neither the nature of this nonlocality nor the physical mechanism that establishes the nonlocal correlations. The conflict with the spirit of relativity is serious. If one measurement precedes the other in one frame, one can always find a moving frame in which the converse is true; the second measurement preceding the first [4]. Therefore, one cannot attribute cause and effect relationships for measurements that cause nonlocal collapse.

1.2 Resolution of the EPR puzzle

Given the fact that there was no satisfactory resolution of the nonlocality puzzle for over half a century, it might come as a 'bolt in the blue' that the EPR puzzle is resolved in a straightforward and simple way [5, 6, 7] when the wave nature of single particle systems is taken into account correctly – a physical input that was not considered by the local realists. The point is that though the experimenter measures properties that are attributed to particles, like position, spin direction etc., the quantum behaviour itself is governed by the inherent wave nature. Therefore calculations of quantum correlations should use probability amplitudes, instead of average over product of eigenvalues. These amplitudes are purely local quantities describing the behaviour of each particle locally and separately. This possibility of strict local description is not available when entangled multiparticle wavefunction is used. The squares of the amplitudes give the probabilities for local measurements. Correlations at source of several particles separated into space-like regions are encoded in the mutual coherence or relative phase of these probability amplitudes. Clearly, the correlation then is calculated by taking a suitable product of the probability amplitudes first and then squaring this amplitude correlation, instead of simply multiplying the eigenvalues and averaging as in the local realistic theories. This physical insight that is so familiar in the context of interference phenomena in quantum mechanics is the key to the calculation of quantum correlations.

The EPR definition of objective reality is strongly motivated by classical particle mechanics. This is reflected in the correlation function used by local realists and in Bell's analysis; the correlation function is the average of the product of the results of measurements on the two particles. But this has the serious flaw of not preserving the crucial phase information. For any physical system with wave properties, the wave amplitude and phase are the basic quantities. We will see that if the probability amplitudes for each particle are used for the calculation, quantum correlations are reproduced within the assumption of strict locality. This means that the EPR definition of objective reality was too restrictive. There is objective reality, but that is at the level of quantum phases and not at the level of eigenvalues.

In the analysis that follows we will use the same assumptions used by Bell [2], but the correlation function is calculated from local probability amplitudes instead of merely multiplying the eigenvalues and averaging.

This is the major difference between the present formalism and Bell's analysis. The deviation from the standard quantum mechanical path is that we use local probability amplitudes instead of the multiparticle wave function that is inherently spread out and nonlocal. In fact, physically it is clear that we should be able to use a local description for local measurements, preserving the quantum properties, since the experimenter performing measurements on a local quantum system need not know what are the previous entanglements of the local system. This information is required only for explaining any correlations, and not for explaining the results of local measurements. But habitual use of the multiparticle wavefunction, instead of local amplitudes or single particle wavefunctions, have brought spurious nonlocality into the standard quantum description. Though we use local probability amplitudes in this paper, one can also use single particle wavefunctions and local operators provided the phase coherence between the single particle wavefunctions pertaining to the correlated particles are incorporated. The wave function description also requires that the constraint of conservation laws (like the conservation of the total angular momentum for entangled singlet system) be incorporated consistently on the total wavefunction [8].

In the following section we derive the correct quantum correlations assuming strict locality, without using negative probabilities. This was considered impossible in the light of Bell's theorem. But Bell's theorem has limited validity due to the classical correlation function used that is not suitable for systems that have both particle and wave properties.

2 Quantum correlations from local amplitudes

2.1 The basic formalism

Consider the breaking up of a singlet state as in the standard Bohm version of the EPR problem [9]. The two-particle state is described by the wave function

$$\Psi_S = \frac{1}{\sqrt{2}}\{|1,-1\rangle - |-1,1\rangle\} \tag{1}$$

where the state $|1,-1\rangle$ is short form for $|1\rangle_1 |-1\rangle_2$, and represents an eigenvalue of $+1$ for the first particle and -1 for the second particle *if measured* in any particular direction. Ψ_S is inherently nonlocal, describing both particles together, even when they are far apart in space-like separated regions.

Two observers make measurements on these particles individually at space like separated regions with time stamps such that these results can be correlated later through a classical channel. We assume that strict locality is valid at the level of probability amplitudes [5]. A measurement changes probability amplitudes only locally. *Measurements performed in one region do not change the magnitude or phase of the complex amplitude for the companion particle in a space-like separated region.* (Note that this is probably the strictest form of locality that can be assumed for quantum systems. Some physicists use separability of probability as a criterion for locality. But this mixes up objective reality of particle like properties and the concept of locality, and the criterion is most obviously not valid for particles that exhibit wave properties. Measurements on systems with wave properties need not obey separability of probability even under strict locality). The local setting of the polarizers, Stern-Gerlach analyzers, detectors etc. (collectively denoted as analyzer) is represented by **a** and **b** for the two distant apparatus. These could be the directions of the analyzers, for example. Since we need to deal with correlated particles which may have a definite phase relationship at source (when the particles are produced together, for example) we introduce internal variables associated with each particle. We denote these variable as ϕ_1 and ϕ_2. Their values are unaltered once the particles are separated. Measurement on one particle does not change the value of this internal variable for the other particle. The assumption of locality is that the amplitudes are functions of only these local variables.

We now state the primary assumptions:

1. Locality: The local amplitude for the first particle C_1 that decide the passage of the particle through an analyzer depends only on the local variables **a** and ϕ_1. Similarly C_2 depends only on **b** and ϕ_2. If we denote the passage as $+$ and the alternate outcome as $-$, then the statement of locality is for the relevant amplitudes is

$$C_{1\pm} = C_{1\pm}(\mathbf{a}, \phi_1), \quad C_{2\pm} = C_{2\pm}(\mathbf{b}, \phi_2) \tag{2}$$

2. Coherence at source: The correlations of the particles are encoded in the difference of the internal variables ϕ_1 and ϕ_2. If the particles have perfect correlations at source then all the pairs in the ensemble have the same value for the difference $|\phi_1 - \phi_2| = \phi_0$.

We do not make any assumption on determinism. Given the initial values of the internal variables ϕ_1 and ϕ_2, we do not attempt to make any prediction of the eigenvalues that would be measured in each run of the experiment. We do not assume any hidden variable that determines the results of the measurements. The variables ϕ_1 and ϕ_2 could be considered as hidden variables in a formal sense, but such initial undetermined phases are already part of the quantum formalism, though unused.

We will also state the locality at the level of the eigenvalues, though we do not use this in the calculation. For observables A and B,

$$A(\mathbf{a},\phi_1) = \pm 1, \quad B(\mathbf{b},\phi_2) = \pm 1 \tag{3}$$

This is the same locality assumption as in the local realistic theories [2]. But, this has a meaning different from its meaning in standard local realistic theories. Here, this means that the outcomes, *when measured*, depend only on the local setting and the local internal variable. There is no objective reality to A and B before a measurement. There is objective reality to ϕ_1 and ϕ_2, but there is no way to observe these absolute phases.

Note that ϕ is not a dynamical phase evolving as the particle propagates. It is an internal variable whose difference (possibly zero) remains constant for the particles of the correlated pair. The value of ϕ can vary from particle to particle, but the relative phase ϕ_0 between the two particles in all correlated pairs is constant. Consider ϕ as a reference for the particles to determine the angle of a polarizer or analyzer encountered on their way, *locally.*

The first particle encounters analyzer1 kept at an angle θ_1 with respect to some global direction. We denote this angle of the analyzer with reference to ϕ as θ. Similarly, the second particle which has the internal phase angle $\phi + \phi_0$, where ϕ_0 is a constant, encounters the second analyzer oriented at angle θ_2 at another space-like separated point. Let the orientation of this analyzer with respect to the internal phase angle of the second particle is θ'. We have $\theta - \theta' = \theta_1 - \theta_2 + \phi_0$.

An experiment in which each particle is analyzed by orienting the analyzers at various angles θ_1 and θ_2 is considered next. At each location the result is two-valued denoted by $(+1)$ for transmission and (-1) for absorption of each particle, for any angle of orientation. The classical correlation function, which is also the experimenter's correlation function, $P(\mathbf{a}, \mathbf{b}) = \frac{1}{N}\sum(A_i B_i)$ satisfies $-1 \leq P(\mathbf{a}, \mathbf{b}) \leq 1$. Here $(\mathbf{a}, \mathbf{b})$ denotes the two directions along which the analyzers are oriented and A_i and B_i are the two valued results. We note that $P(\mathbf{a}, \mathbf{b})$ denotes the average of the quantity (*number of detections in coincidence − number of* *detections in anticoincidence*), where 'coincidence' denotes both particles showing same value for the measurement and 'anticoincidence' denotes those with opposite values. The defect in the local realistic theories is that the correlation is calculated essentially by averaging over the products of eigenvalues. Obviously the phase information is thrown away in this procedure and there is no way, conceptually, such an attempt would have reproduced quantum mechanical results. We calculate the experimenter's correlations starting from local amplitudes [5, 6, 7].

Now we state the expressions for the amplitudes and the amplitude correlation function. These are similar to the Feynman amplitudes, for example the amplitude for the particle to go from a point x_1 to x_2.

1. The local amplitudes for transmission associated with the first particle is $C_{1+} = \frac{1}{\sqrt{2}} \exp(i\theta s)$ for measurements at analyzer1, and for the second particle it is $C_{2+} = \frac{1}{\sqrt{2}} \exp(i\theta' s)$ at analyzer2. The amplitudes for the orthogonal outcome are C_{1-} and C_{2-} and these are rotated by $\pi/2$ in the complex plane from the amplitudes for transmission. The square of the amplitudes give the corresponding probabilities ($C_{1+}C_{1+}^*$ gives the probability for transmission, for example). s is the spin of the particle (1 for photons and $\frac{1}{2}$ for the spin-$\frac{1}{2}$ singlet state- see below)

2. The amplitude correlation function is a normalized inner product of the amplitudes. This is of the form

$$U(\mathbf{a}, \mathbf{b}) = \ Real(NC_iC_j^*) \tag{4}$$

   where N is the normalization constant related to the total joint probability. The square of the amplitude correlation function gives the joint probabilities for events of the form $(++)$, $(--)$, $(+-)$, and $(-+)$. All probabilities are guaranteed to be positive definite in our formalism since the amplitude correlation function is real.

Let us consider the maximally entangled singlet system which is the most widely discussed example in the context of nonlocality. The local amplitudes are $C_{1+} = \frac{1}{\sqrt{2}} \exp\{is(\theta_1 - \phi_1)\}$ for the first particle at the first polarizer and $C_{2+} = \frac{1}{\sqrt{2}} \exp\{is(\theta_2 - \phi_2)\}$ for the second particle at the second polarizer. The amplitudes C_{1-} and C_{2-} for the events denoted by '$-$' differ only in the phase for the maximally entangled state.

The explicit dependence of the amplitude on the spin of the particle is motivated by the fact that we are dealing with systems with phases and the phase associated with the spin rotations (a geometric phase) is a necessary input in this description [10]. The correlation at source is encoded in ϕ_0. The locality assumption is strictly enforced since the two amplitudes depend only on local variables and on an internal variable generated at the source and then individually carried by the particles without any subsequent interaction of any sort. The individual measurements at each end separately will now give the correct result for transmission for any angle of orientation. These probabilities are

$$C_1 C_1^* = C_2 C_2^* = \frac{1}{2} \tag{5}$$

Events of both types $(++)$ and $(--)$ contribute to a "coincidence". The correlation function for an outcome of either $(++)$ or $(--)$ of two maximally entangled particles is

$$U(\theta_1, \theta_2, \phi_o) = 2\ Re(C_1 C_2^*) = \cos\{s(\theta_1 - \theta_2) + s\phi_o\}. \tag{6}$$

It is normalized such that its square will give the conditional joint probabilities of the type 'outcome + for the second particle, given that the outcome for the first particle is +, etc. All references to the individual values of the internal variable ϕ has dropped out.

We now derive the relation between this correlation function and the experimenter's correlation function $P(\mathbf{a}, \mathbf{b}) = \frac{1}{N}\sum(A_i B_i)$. Since $U^2_{++} = U^2_{--}$ for the maximally entangled state, $U^2(\theta_1, \theta_2, \phi_o)$ is the probability for a coincidence detection ($++$ or $--$), and $(1 - U^2(\theta_1, \theta_2, \phi_o))$ is the probability for an anticoincidence (events of the type $+-$ and $-+$). Since the average of the quantity (number of coincidences − number of anticoincidences) =

$$U^2(\theta_1, \theta_2, \phi_o) - (1 - U^2(\theta_1, \theta_2, \phi_o)) = 2U^2(\theta_1, \theta_2, \phi_o) - 1, \tag{7}$$

the correspondence between $P(\mathbf{a}, \mathbf{b})$ and $U(\theta_1, \theta_2, \phi_o)$ is given by the expression,

$$\begin{aligned} P(\mathbf{a}, \mathbf{b}) &= 2U^2(\theta_1, \theta_2, \phi_o) - 1 \\ &= 2\cos^2\{s(\theta_1 - \theta_2) + s\phi_o\} - 1 \end{aligned} \tag{8}$$

There is a remarkable difference between the correlation function used in Bell's analysis and the one given above. Our correlation function contains the wave properties inherent in quantum particles, whereas

Bell's correlation function does not have this feature. Both analysis use the *same* assumptions on locality. Now we discuss some specific examples.

2.2 Spin-$\frac{1}{2}$ particles and Photons

Consider the singlet state breaking up into two spin-$\frac{1}{2}$ particles propagating in opposite directions to spatially separated regions. Since orthogonality of the two particles in any basis implies a relative angle of π for spinors, we set $\phi_o = \pi$. Then the correlation function and $P(\mathbf{a}, \mathbf{b})$ calculated from this function are

$$\begin{aligned} U(\theta_1, \theta_2, \phi_o) &= \cos\{s(\theta_1 - \theta_2) + s\phi_o\} \\ &= \cos\{\frac{1}{2}(\theta_1 - \theta_2) + \pi/2\} \\ &= -\sin\frac{1}{2}(\theta_1 - \theta_2) \end{aligned} \tag{9}$$

$$\begin{aligned} P(\mathbf{a}, \mathbf{b}) &= 2\sin^2(\frac{1}{2}(\theta_1 - \theta_2)) - 1 \\ &= -\cos(\theta_1 - \theta_2) = -\mathbf{a} \cdot \mathbf{b} \end{aligned} \tag{10}$$

This is identical to the quantum mechanical predictions obtained from the singlet entangled state and Pauli spin operators. We have reproduced the correct correlation function using local amplitudes.

For the case of photons entangled in orthogonal polarization states we get, by setting $s = 1$ and $\phi_o = \pi/2$ to represent orthogonal polarization,

$$\begin{aligned} U(\theta_1, \theta_2, \phi_o) &= \cos\{(\theta_1 - \theta_2) + \pi/2\} \\ &= -\sin(\theta_1 - \theta_2) \end{aligned} \tag{11}$$

$$P(\mathbf{a}, \mathbf{b}) = 2\sin^2(\theta_1 - \theta_2) - 1 = -\cos(2((\theta_1 - \theta_2)) \tag{12}$$

which is the correct quantum mechanical correlation.

2.3 Three-particle GHZ correlations

One of the most remarkable results of the formalism presented here is that it reproduces the quantum correlations of multiparticle systems with more than two entangled particles in a physically transparent and insightful way. We consider the three particle GHZ state [11] defined as

$$|\Psi_{GHZ}\rangle = \frac{1}{\sqrt{2}}(|1,1,1\rangle - |-1,-1,-1\rangle) \tag{13}$$

where the eigenlabels in the kets are with respect to the z-axis basis.

The prediction from quantum mechanics for the measurement represented by the operator $\sigma_x^1 \otimes \sigma_x^2 \otimes \sigma_x^3$ is given by

$$\sigma_x^1 \otimes \sigma_x^2 \otimes \sigma_x^3 \,|\Psi_{GHZ}\rangle = -\,|\Psi_{GHZ}\rangle \tag{14}$$

Equivalently the joint probabilities for various outcomes in the x direction are

$$P(+,+,+) = P(-,-,+) = P(+,-,-) = P(-,+,-) = 0 \tag{15}$$
$$P(-,-,-) = P(+,+,-) = P(+,-,+) = P(-,+,+) = 1 \tag{16}$$

Local realistic theories predict that the product of the outcomes in the x direction for the three particles should be $+1$, i.e.,

$$P(+,+,+) = P(-,-,+) = P(+,-,-) = P(-,+,-) = 1 \tag{17}$$

The other four joint probabilities are zero. This contradicts Eqs. 14-16 and highlights the conflict between a local realistic theory and quantum mechanics.

We define the local amplitudes for the outcomes $+$ and $-$ at the analyzer (with respect to the x basis) for the first particle as $C_{1+} = \frac{1}{\sqrt{2}}\exp(i\theta_1)$, and $C_{1-} = \frac{1}{\sqrt{2}}\exp(i(\theta_1 + \pi/2))$. The amplitude C_{1-} contains the added angle $\pi/2$ because this amplitude is orthogonal to C_{1+}. Similarly, we have $C_{2+} = \frac{1}{\sqrt{2}}\exp(i\theta_2)$, and $C_{2-} = \frac{1}{\sqrt{2}}\exp(i(\theta_2 + \pi/2))$ for the second particle and $C_{3+} = \frac{1}{\sqrt{2}}\exp(i\theta_3)$, and $C_{3-} = \frac{1}{\sqrt{2}}\exp(i(\theta_3 + \pi/2))$ for the third particle [12].

Correlation function is obtained from $N\mathrm{Real}(C_1 C_2^* C_3^*)$, where N is a normalization constant, and its square is the relevant joint probability. (There is no unique definition of the amplitude correlation function. The final results are independent of the particular definition we use). Since we want $N\mathrm{Re}(C_{1-}C^*_{2-}C^*_{3-}) = \pm 1$, we choose $C_{1-}C^*_{2-}C^*_{3-}$ to be pure real. This gives

$$\frac{N}{2\sqrt{2}} Real(\exp i(\theta_1 - \theta_2 - \theta_3 - \pi/2)) = \pm 1$$

$$\theta_1 - \theta_2 - \theta_3 - \pi/2 = 0 \text{ or} \pm \pi$$

We can choose the relevant relative phases to satisfy this condition. Then we get

$$P(-,-,-) = 1$$

Rest of the joint probabilities given in Eqs. 15 and 16 automatically follow, since flipping sign once rotates the complex number $C_{1-}C^*_{2-}C^*_{3-}$ through $\pi/2$. The square of $N\mathrm{Real}(C_1C^*_2C^*_3)$ is then 1 for an odd number of $(-)$ outcomes and 0 for even number of $(-)$ outcomes.

Similar construction also applies to four-particle maximally entangled state [13] and general multiparticle maximally entangled states.

We have also constructed local amplitudes for the Hardy experiment [14] in which quantum mechanics predicts three particular zero joint probabilities and one nonzero joint probability (the other possible joint probabilities in the problem can be nonzero and are not relevant for the demonstration of nonlocality). Local complex amplitudes that reproduce the four relevant joint probabilities can be constructed easily. It is impossible to achieve this if local realism at the level of eigenvalues is assumed.

2.4 Multiparticle interference

Similar considerations apply well for particles entangled in other sets of variables like momentum and coordinate, and energy and time. These cases of two-particle entanglement can be mapped on to the spin-$\frac{1}{2}$ singlet problem with two-valued outcomes [6]. Starting from the local amplitudes $C_1 = \frac{1}{\sqrt{2}}\exp(i\alpha k(x_1 - x_o)/2)$, and $C_2 = \frac{1}{\sqrt{2}}\exp(i\alpha k(x_2 - x_o)/2)$ we can derive the probability for coincidence detection as

$$P(x_1, x_2) = \cos^2(\alpha k(x_1, x_2)/2) = \frac{1}{2}(1 + \cos k\alpha(x_1 - x_2)) \qquad (18)$$

This is the two photon correlation pattern with 100% visibility, *obtained without nonlocality.* x_1 and x_2 are the coordinates of the two detectors separated by a space-like interval. k is the wave vector and α is a scaling factor for the angle subtended by the two slits at the detectors, source etc. Clearly, none of the experiments using entangled down-converted photons in interferometers imply any nonlocality.

The example of multiparticle interference is also revealing in another way. It is only one quantum step away from the familiar Brown-Twiss intensity interferometry in which the correlation of intensity fluctuations in space-like separated detectors is manifested as an interference pattern that depends on the separation of the detectors [15]. The intensity correlation, for wave amplitudes distributed as Gaussian, is given by [16]

$$< I_1(t+\tau)I_2(\tau) >=< I_1 >< I_2 > (1+|\gamma_{12}(\tau)|^2) \qquad (19)$$

There is no nonlocality. $\gamma_{12}(\tau)$ is the measure of the coherence of the source. Our assertion that the separability of probability is not a suitable criterion of locality when wave nature is to be taken into account is evident already in the case of Brown-Twiss interferometry [17]. The average of intensity correlations is not the product of averages of intensities .

3 Concluding remarks

3.1 The virgin quantum state

There is a subtle but real difference between an unmeasured quantum particle that has never gone through a classical apparatus and another particle that has been prepared in a definite but random and unknown (to the experimenter) state. In the latter case there is reality to the eigenvalue, though unknown, whereas in the former case no objective reality can be ascribed at the level of eigenvalues. The state of each particle in an entangled multiparticle system is such a *virgin state.* This is described by the complex probability amplitudes employed in our analysis. A real measurement involves the interaction of such a quantum state and a classical apparatus. The result can be used to predict the result of a similar measurement on the companion particle, but our analysis shows that there is no nonlocal influence. Though the result, if measured, for the second particle can be predicted with certainty, its state is still a virgin state and not one with a definite eigenvalue as EPR thought. This means that quantum systems have their objective reality at a level deeper than that described by the EPR definition of reality. *So, predictability with certainty does not amount to a state reduction or* *measurement.* In fact, the real measurement and state reduction are always accompanied by a dispersion in the conjugate variable [18]. But, in the case of the EPR pair, measurement on one particle does not lead to a dispersion in the conjugate variable for the companion particle. This fact is obvious from an analysis of the Popper's gedanken experiment, as well as from its recent experimental realization [19, 20, 21]. The uncertainty principle is the basic pillar of quantum theory, and it requires that state reduction is accompanied by inevitable dispersion in the conjugate variable. Therefore, measurement on one of the particles of an EPR pair does not lead to the widely but wrongly believed nonlocal state reduction. Our analysis using local amplitudes is the theoretical basis for this assertion, since it correctly reproduces the quantum joint probabilities within strict locality. Popper's experiment provides the empirical basis for these conclusions, though originally Popper discussed the experiment in a different context.

Quantum entanglement swapping [22] is understood within this frame work by noting that Bell state measurements choose subensembles of particle pairs that show a particular joint outcome. Particles entangled independently with the pair of particles that are subjected to the Bell state measurement will show a joint outcome consistent with swapped entanglement due to the correlation encoded in the internal variable. *But the Bell state measurement does not collapse the distant particle into a definite state.* Yet all correlations are correctly reproduced. This has important implication to the interpretation of quantum teleportation [6]. The present nonlocal interpretation of quantum teleportation is not correct.

3.2 Comparison of different formalisms and summary

The following table summarizes the locality and reality properties in various approaches to quantum correlations:

Theory/ Formalism	Basic quantity	Locality	Reality	Determinism	Predictions
Quantum mechanics	Multiparticle wavefunction	NO	NO	NO	Correct
Local Realistic theories with hidden variables	Eigen values	YES	YES	YES	Incorrect
Present formalism	Amplitudes	YES	Yes (for phase)	NO	Correct

In conclusion, the long standing puzzle of nonlocality in the EPR correlations is resolved. There is no nonlocal influence between correlated particles separated into space-like regions. There is no more any conceptual conflict with special relativity. The solution has new physical and philosophical implications [23] regarding the nature of reality, measurement and state reduction in quantum systems. It also reveals new interpretations for entanglement swapping and quantum teleportation. The solution presented here has empirical support from the results of the Popper's experiment. It is the concept of wave-particle unity, advanced by de Broglie, which formed the core of quantum phenomena, that resolves the EPR puzzle sixty five years after it was first discussed.

References

[1] A. Einstein, B. Podolsky, and N. Rosen, *Phys. Rev.*, **47**, 777, (1935).

[2] J. S. Bell, Physics, **1**, 195, (1965).

[3] A recent resource for exhaustive search is the book, *The Einstein, Podolsky, and Rosen Paradox in Atomic, Nuclear and Particle Physics*, A. Afriat and F. Selleri, (Plenum Press, New York and London), 1999.

[4] See for example, R. Penrose, *Emperor's new mind*, pp 370-371, (Vintage, UK, 1990).

[5] C. S. Unnikrishnan, *There is no spooky action-at-a-distance in quantum correlations: Resolution of the EPR nonlocality puzzle*, quant-ph/0001112, (2000).

[6] C. S. Unnikrishnan, *The resolution of the nonlocality puzzle in the EPR paradox*, *Current Science*, in press, (2000).

[7] C. S. Unnikrishnan, quant-ph/0005103, to appear in the proceedings of the International Conference on Quantum Optics, Minsk, Belarus (May, 2000).

[8] A detailed equivalent analysis of the EPR problem in terms of the local single particle wavefunctions with suitable constraints and phase coherence will be presented elsewhere.

[9] D. Bohm, *Quantum Theory*, (Prentice Hall, Englewood Cliffs, NJ (1951).

[10] C. S. Unnikrishnan, to be published; The geometric phase associated with spin rotations can be obtained directly from a generalization of the usual dynamical phase $\int p_i dx^i$, to include the spin as one of the momenta p_i and the angular coordinate as the corresponding dx^i.

[11] D. M. Greenberger, M. Horne, and A. Zeilinger in *Bell's Theorem, Quantum Theory and Conceptions of the Universe*, Ed. M. Kafatos, (Kluwer, Dordrecht,1989), pp 73-76 ; N. D. Mermin, *Phys. Today*, June 1990, p 9-11; D. M. Greenberger, M. Horne, A. Shimony, and A. Zeilinger, *Am. J. Phys.* **58**, 1131 (1990).

[12] C. S. Unnikrishnan, *Three-particle GHZ correlations without nonlocality*, quant-ph/0004089, (2000).

[13] P. Hariharan, J. Samuel, and Supurna Sinha, *J. Opt. B: Quantum Semiclass.Opt.*, **1**, 199 (1999).

[14] L. Hardy, *Phys. Rev. Lett.*, **71**, 1665 (1993).

[15] R. Hanburry Brown and R. O. Twiss, *Nature*, **178**, 1447, (1956).

[16] L. Mandel, in *Progress in Optics*, Vol II, 183-248, (Ed. E. Wolf, North-Holland Publishing Company, Amsterdam, 1963).

[17] C. S. Unnikrishnan, *Separability of probability is not a good criterion for locality*, TIFR preprint, to be published (2000).

[18] C. S. Unnikrishnan, *When is a quantum measurement? Lessons from the Popper's experiment and the EPR experiment*, TIFR preprint, to be published (2000).

[19] K. R. Popper, in *Open Questions in Quantum Physics*, Eds. G. Tarozzi and A. van der Merwe, (D. Reidel Publishing Co., 1985).

[20] C. S. Unnikrishnan, *Found. Phys. Lett.*, **13**, 197, (2000).

[21] Y-H. Kim and Y. Shih, *Found. Phys.*, **29**, 1849, (1999).

[22] C. H. Bennet *et al*, Phys. Rev. Lett., **70**, 1895 (1993); M. Zukowski, A. Zeilinger, M. A. Horne, and A. Ekert, *Phys. Rev. Lett.*, **71**, 4287 (1993); J-W. Pan, D. Bouwmeester, H. Weinfurter and A. Zeilinger, *Phys. Rev. Lett.*, **80**, 3891 (1998).

[23] Some of the philosophical implications of the results presented here will be examined in a detailed monograph in preparation.

(Manuscrit reçu le 7 juillet 2000)