Relations connecting violation of any Bell inequalities and the complementarity between visibility and distinguishability in the interferometric experiments with different sources of decoherence are presented. A boundary of local-realistic explanation of the which-way complementarity is discussed in dependence on choice of independent or collective tests of nonlocality.

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I. INTRODUCTION

Quantum-mechanical nonlocality and complementarity between which-way information and visibility are well-known manifestations of the quantum-mechanical microworld. However, a nature of both the effects is identical: it is quantum entanglement shared between parts of total system. In the consequence, a natural question arises: what is a relation between complementarity and nonlocality in commonly used interferometric experiments? Consider a fact that there exist the states which are entangled however do not violate any Bell-type inequalities and that relation between visibility and distinguishability can be also assisted by classical correlations, it seems to be important to find a boundary for explanation of complementarity experiments in terms of local-realistic theories (LRT). Up to this boundary, no LRT cannot explain the complementary results of experiment, whereas below this boundary some LRT can exist. In addition, it is well known that multiple copies of entangled states, which do not violate Bell inequalities, could be distilled by the local operations and classical communications to produce a state violating the Bell inequality. Arising question is: how changes a connection between complementarity and nonlocality using the collective tests of nonlocality?

For the simplicity, we consider both the analysed effects based on the measurements of a bipartite system compounded from qubit $A$ and $B$ systems. It will be assumed that the measurements are performed by two different experimentalists (Alice and Bob) sharing state which arises from Bob’s monitoring of Alice’s system. Fortunately, for two-qubit systems the questions concerning to violating of any Bell inequalities, entanglement distillation and inseparability of mixed state have been solved completely. In addition, it was proved that necessary and sufficient condition for the local realistic description of two-qubit correlations is equivalent to condition on violating of any Bell inequality. Due to these important facts, a sharp boundary between LRT and quantum mechanical explanation of which-way complementarity could be proposed. In this paper, it is shown, on simply example of interferometric experiments, how nonlocality, entanglement and quantum information features are related to the complementarity under influence of different kind of decoherence in the system and meter. The most attractive are cases, where the complementarity effects could be explained only by quantum mechanics and not also some kind of local realistic theory. The individual and collective tests of nonlocality are discussed in this consequence.

II. DECOHERENCE-FREE CASE

To begin analysis, a decoherence-free case of interferometric experiment is shortly examined. At the input, the qubit $A$ is prepared in the state

$$|\Psi_A \rangle = \sqrt{r}|\uparrow\rangle - \sqrt{1-r}|\downarrow\rangle$$

which can be treated as the superposition of a possible “paths” in interferometer. The qubit $B$ is considered in the state $|\downarrow\rangle$. Commonly used nondemolition monitoring of the qubit $A$ by the qubit $B$ is considered to acquire an information about the individuality of the state in superposition

$$|\uparrow\rangle_A|\downarrow\rangle_B \rightarrow |\uparrow\rangle_A|\downarrow\rangle_B,$$

$$|\downarrow\rangle_A|\downarrow\rangle_B \rightarrow \sqrt{1-D^2}|\downarrow\rangle_A|\downarrow\rangle_B + D|\downarrow\rangle_A|\uparrow\rangle_B,$$

where $D$ is a measure of distinguishability due to nondemolition monitoring. Here, the distinguishability is independent on a possible measurement performed by Bob; it is considered rather as parameter of interaction between systems $A$ and $B$. After monitoring, an output state is given in the following form

$$|\Psi = \sqrt{r}|\uparrow\rangle_A|\downarrow\rangle_B - \sqrt{1-r}(\sqrt{1-D^2}|\downarrow\rangle_A|\downarrow\rangle_B + D|\downarrow\rangle_A|\uparrow\rangle_B)$$

and if one performs phase shift operation

$$|\uparrow\rangle_A \rightarrow \exp(-i\phi)|\uparrow\rangle_A, \quad |\downarrow\rangle_A \rightarrow |\downarrow\rangle_A,$$

and specific rotations on the qubit $A$. 

complementarity is completely assisted by the quantum-mechanical nonlocality. No local-realistic theory can explain these results. On the other hand, for this pure state case, we assume two different kinds of decoherence in the system and meter. These cases will proceed separately and general results are presented in the conclusion.

III. SYSTEM DECOHERENCE

First, we consider an additional observer (Eve), which non-demolitionally monitored the system $A$ in the following way

\[
\begin{align*}
|\uparrow\rangle_A \rightarrow |\uparrow\rangle_A - |\downarrow\rangle_A, \\
|\downarrow\rangle_A \rightarrow |\downarrow\rangle_A - |\uparrow\rangle_A,
\end{align*}
\]

then the visibility

\[
V = \frac{p_{\text{max}}(\phi) - p_{\text{min}}(\phi)}{p_{\text{max}}(\phi) + p_{\text{min}}(\phi)}
\]

of interference measured on the qubit $A$ is related to defined distinguishability $D$ and the predictability $P = |p_1 - p_\uparrow| = \sqrt{1 - 2r}$ in the following way

\[
\frac{V^2}{1 - D^2} + D^2 = 1.
\]

Using the overlap $O = \sqrt{1 - D^2}$ and the unpredictability $U = \sqrt{1 - P^2}$, the relation can be re-arranged to

\[
V = OU,
\]

where $V, D, O, U \in (0, 1)$. The predictability $P$ (and inversely unpredictability $U$) describes a priori information about “path” in the interferometer, whereas distinguishability $D$ (and overlap $O$) are rather connected with efficiency of path monitoring by the meter system $B$. By a decreasing of unpredictability in system $A$ and overlap in system $B$, the visibility of interference vanishes as can be seen in Eq. (8). For given predictability $P$, the relation (8) can be interpreted as a particular relation of complementarity between which-way information expressed by distinguishability $D$ and visibility $V$.

Recently Gisin [20,21] showed that any entangled pure state of a pair of qubits violates the Clauser-Horne-Shimony-Holt (CHSH) form of Bell inequalities. Particularly, in considered case of pure state (3), the dependence $V$ in (8) of interference measured on the qubit $A$, then the visibility $V$ in (8) of interference measured on the qubit $A$ is related to the distinguishability $D$ and the robustness $R$ in the following way

\[
\frac{V^2}{R^2} + D^2 = 1.
\]

It is similar to formulae (9), if the robustness $R$ is identified with unpredictability $U$, however the action is rather non-unitary here. Using the defined visibility $V_0 = \sqrt{1 - D^2}$ without decoherence for the same distinguishability, the robustness $R$ can be evaluated in the following form

\[
R = \frac{V}{V_0}.
\]

Thus, the robustness $R$ can be also interpreted as ratio between visibility with decoherence $V$ and decoherence-free visibility $V_0$. However, irrespective to formal analogue between (8) and (13), a question is still opened: is it possible to explain the complementarity by a hidden local-variable theory, i.e. can the complementary observations be predetermined before the measurement by an existing local element of physical reality. One possibility is to test the Bell inequalities on the state shared by Alice and Bob. To test it, a general CHSH form of the Bell-inequalities can be used for general state of $2 \times 2$ system. After calculations, it can be found that maximal value of the Bell parameter $B_{\text{max}}$ is
\[ B_{\text{max}} = 2\sqrt{R^2 + D^2}, \]  
\[ \text{where dependence of } B_{\text{max}} \text{ on robustness } R \text{ and distinguishes } D \text{ is depicted in Fig. 2. Contrary to an analogue between the complementarity relations} \] 
\[ \text{and Bell-CHSH inequality violation differs substantially in these cases. To overcome the maximal local-realistic correlations } B_{\text{max}} = 2, \text{ the robustness } R \text{ must be large than the overlap } O = \sqrt{1 - D^2} \text{ between Bob's states} \]
\[ R > O \]  
or equivalently, the relation
\[ D^2 + R^2 > 1 \]
must be satisfied. Particularly, for decoherence-free case \( R = 1 \), complete relation between visibility and distinguishability \( [12] \) can be explained only by the quantum mechanics and no local-realistic theory can be constructed. With decreasing \( R \), using Eq. (12), it can be found that for the visibility \( V \) it is sufficient to satisfy the following condition
\[ V > 1 - D^2 = O^2 \]
which cannot be explained by a local-realistic theory. On the other hand, there are the regions of complementarity which can be simulated by the local-realistic theory and are larger as \( R \) decreases, as is illustrated in Fig. 3. The inverse condition \( V \leq 1 - D^2 \) is a necessary and sufficient condition for a state to be described in terms of a local, hidden variable theory.

On the other hand, one can assume a generalized notion of nonlocality, based on the distillation procedure and classical communications. Generally, any inseparable mixed state of a two-qubit systems can be distilled \( [17] \) to a singlet form by using local operations and classical communications \( [18] \). Thus any nonseparable two-qubit system reveals nonlocal properties if the sequential measurements are considered collectively. Any inseparable mixed two-qubit state is nonlocal in this sense. However, the collective tests of nonlocality describe a different situation – one can argue that if collective measurement on \( n \) copies of state \( \hat{\rho} \) is needed to reveal nonlocality, then it is the state \( \hat{\rho} \otimes^n \) that is nonlocal rather \( \hat{\rho} \).

For two qubits, inseparability of state shared by Alice and Bob can be theoretically tested by the positive partial transposition criterion \( [13,14] \). After tracing out Eve’s states and some calculations, a partially transposed density matrix has three positive eigenvalues and one is negative for \( D \neq 0 \) or \( R \neq 0 \). Thus except a total decoherence \( (R = 0) \) or no distinguishability \( (D = 0) \), Alice and Bob share an inseparable state which can be distilled to maximal entangled state violating any Bell-CHSH inequality. Even an imperfect complementarity with Eve’s intervence cannot be explained by the hidden local-variable theory, if the distillation procedures are assumed. This “hidden nonlocality” changes the boundary of local-realistic explanation of the complementarity.

To quantificate an information acquired by Alice’s monitoring, the mutual information \( I_{AB} = S_A + S_B - S_{AB} \), where \( S_A, S_B \) and \( S_{AB} \) are von Neumann entropies of particular Alice’s and Bob’s subsystems and total system, can be used \( 22,24 \). After trace out the Eve’s states, the mutual information can be evaluated by the particular entropies:

\[ S_{AB} = -\frac{1 + R}{2} \ln \left( \frac{1 + R}{2} \right) - \frac{1 - R}{2} \ln \left( \frac{1 - R}{2} \right), \]
\[ S_A = -\frac{1 + R \sqrt{1 - D^2}}{2} \ln \left( \frac{1 + R \sqrt{1 - D^2}}{2} \right) - \frac{1 - R \sqrt{1 - D^2}}{2} \ln \left( \frac{1 - R \sqrt{1 - D^2}}{2} \right), \]
\[ S_B = -\frac{1 + \sqrt{1 - D^2}}{2} \ln \left( \frac{1 + \sqrt{1 - D^2}}{2} \right) - \frac{1 - \sqrt{1 - D^2}}{2} \ln \left( \frac{1 - \sqrt{1 - D^2}}{2} \right) \]
and is depicted in Fig. 4. For \( R = 1 \), the mutual information varies in interval \((0, 2 \ln 2)\) in dependence on \( D \), whereas for \( R = 0 \) in interval \((0, \ln 2)\).

Without decoherence and for \( D = 1 \), Bob shared with Alice an additional “quantum” ebit, in a comparison with the maximal decoherence case. This additional ebit can be used in quantum “erasure” procedure and revealing of the visibility: one bit of information is damaged by Bob’s erasing procedure and the other is send to Alice to distinguish between “fringes” and “antifringes” in the interference effect. Of course, for \( R = 0 \) one bit of information is on Eve’s side and thus by performing same procedure by Bob, the visibility cannot be revealed. The violation of any Bell-CHSH inequalities can be simply expressed in terms of mutual information: the acquired information is sufficient to nonlocality exhibition if \( I_{AB} \) is larger than a boundary value \( \hat{I} \).

\[ \rho_{mn,m'n'}^{T_2} = A \langle m|B(n|\rho^{T_2}|n')B|m' \rangle_A = \rho_{mn,m'n'}. \]  
\[ \text{Clearly, the matrix } \rho^{T_2} \text{ depends on the basis, but its eigenvalues do not. Hence one can check separability using an arbitrary product orthonormal basis in Hilbert space of two qubit system.} \]
\[ I = -\frac{1 + R^2}{2} \ln \left( \frac{1 + R^2}{2} \right) - \frac{1 - R^2}{2} \ln \left( \frac{1 - R^2}{2} \right). \]  

(20)

For given robustness \( R \), the distinguishability must achieve some threshold value in order to the Alice’s information was sufficient to exhibit the nonlocality, as can be seen in Fig. 4. For almost unit robustness, only a small Bob’s acquired information is need to assist a nonlocal relation between Alice and Bob. On the other hand, for strong decoherence (small robustness), the nonlocal character of mutual information can be considered if the distinguishability is almost perfect.

**IV. METER DECOHERENCE**

In opposite to previous case with a decoherence in the system, one can consider that Eve monitors the meter in analogous way to (14). Then the state arising in the total system can be considered in the following way

\[ \frac{1}{\sqrt{2}} \left( |\uparrow\rangle_A |\downarrow\rangle_B |\downarrow\rangle_E - |\downarrow\rangle_A (\sqrt{1 - D^2} |\downarrow\rangle_B |\downarrow\rangle_E + \right. 
\]

\[ \left. + D |\uparrow\rangle_B \times (R |\downarrow\rangle_E + \sqrt{1 - R^2} |\uparrow\rangle_E) \right), \]  

(21)

where \( R \) is a measure of Bob system robustness against Eve’s decoherence. For \( R = 1 \) an information about path is extracted by means of shared quantum entanglement between Alice and Bob, whereas for \( R = 0 \) only classical correlations are used to monitoring procedure. After action of a phase shift (4) and the specific rotations (5) on the qubit \( A \), the visibility \( V \) in (6) of interference is related only to the distinguishability \( D \)

\[ V^2 + D^2 = 1 \]  

and is completely independent of the robustness \( R \) of the meter. The complementarity relation (22) is completely identical to decoherence-free one (6) with \( P = 0 \). Thus based on this relation, one is not able to distinguishing between classical and inherent quantum monitoring of the path. On the other hand, the maximum of Bell-CHSH factor depends significantly on the robustness

\[ B_{\text{max}} = 2\sqrt{(1 - R^2)(1 - D^2)^2} + R^2 + D^2, \]  

(23)

as it can be seen in Fig. 5. Even if the complementarity relation is same as for idealized case without decoherence, any Bell-CHSH inequality are violated for \( D \neq 0 \) and \( R 
eq 1 \) if

\[ 1 - D^2 < \frac{R^2}{1 - R^2}, \]  

(24)

and for \( R = 1 \) for every \( D \neq 0 \). For \( R \geq \frac{1}{\sqrt{2}} \), the violating Bell-CHSH inequality occurs for every \( D \neq 0 \), whereas for \( R < \frac{1}{\sqrt{2}} \), a boundary is given by (24). There is a different character of the boundary in comparison with previous system decoherence. Under this boundary, the complementarity can be assisted by a state non-violating any Bell-CHSH inequality. Especially, if the complementarity is assisted by classical correlations (\( R = 0 \)), no Bell-CHSH inequality violation occurs. Thus, the results of complementarity experiment can be simulated by local-realistic theory. Irrespective to this, all the states are entangled for \( D \neq 0 \) and \( R \neq 0 \) as can be proved using the PPT criterion of separability. Thus it contains a “hidden nonlocality” in sense of collective tests of non-locality, as it pointed above. To compare an amount of Bob’s acquired information with previous case, the mutual information \( I_{AB} = S_A + S_B - S_{AB} \) can be determined from the particular entropies:

\[ S_{AB} = -\left( \frac{1}{2} + \frac{1}{2} \sqrt{1 - D^2(2 - D^2)(1 - R^2)} \right) \times \]

\[ \times \ln \left( \frac{1}{2} + \frac{1}{2} \sqrt{1 - D^2(2 - D^2)(1 - R^2)} \right) \]

\[ - \left( \frac{1}{2} - \frac{1}{2} \sqrt{1 - D^2(2 - D^2)(1 - R^2)} \right) \times \]

\[ \times \ln \left( \frac{1}{2} - \frac{1}{2} \sqrt{1 - D^2(2 - D^2)(1 - R^2)} \right), \]

\[ S_A = -\left( \frac{1 + \sqrt{1 - D^2}}{2} \ln \left( \frac{1 + \sqrt{1 - D^2}}{2} \right) - \right. \]

\[ - \left. \frac{1 - \sqrt{1 - D^2}}{2} \ln \left( \frac{1 - \sqrt{1 - D^2}}{2} \right), \right. \]

\[ S_B = -\left( \frac{1}{2} + \frac{1}{2} \sqrt{(1 - D^2)^2(1 - R^2)} \right) \times \]

\[ \times \ln \left( \frac{1}{2} + \frac{1}{2} \sqrt{(1 - D^2)^2(1 - R^2)} \right) \]

\[ - \left. \frac{1}{2} - \frac{1}{2} \sqrt{(1 - D^2)^2(1 - R^2)} \times \right. \]

\[ \times \ln \left( \frac{1}{2} - \frac{1}{2} \sqrt{(1 - D^2)^2(1 - R^2)} \right), \]  

(25)

and their dependence on the parameters \( D \) and \( R \) is depicted in Fig. 6. From the boundary (24), the condition on the violation of Bell-CHSH inequality can be found in terms of information in following form

\[ I > I = \left( \frac{1}{2} + \frac{1}{2} \sqrt{\frac{2R^2}{1 - R^2}} \right) \ln \left( \frac{1}{2} + \frac{1}{2} \sqrt{\frac{2R^2}{1 - R^2}} \right) - \]

\[ - \left. \left( \frac{1}{2} - \frac{1}{2} \sqrt{\frac{2R^2}{1 - R^2}} \right) \ln \left( \frac{1}{2} - \frac{1}{2} \sqrt{\frac{2R^2}{1 - R^2}} \right). \right. \]  

(26)

From Fig. 4 and Fig. 6, it can be found that in terms of information the Bell-CHSH inequality violation boundary has seemingly similar character, however the system
decoherence generates an information boundary for any $R$, contrary to the meter decoherence where the information boundary occurs only for $R < \frac{1}{\sqrt{2}}$.

The distinction between entanglement and classical correlations, used to monitoring, seems to be crucial for the understanding of quantum complementarity nature. Due to entanglement nature, the intrinsic quantum complementarity experiments has a “reversible” character: an information obtained by monitoring can be erased in proper way to restore the visibility of interference by postselection. Similar procedure cannot be performed in classical case and the complementarity experiments has an irreversible character. The reason is that an entanglement shared between Alice and Bob cannot be understand in a classical realistic sense.

V. SUMMARY AND CONCLUSION

A complementarity between measurement outputs need not be inherently quantum mechanical and can be given by a local hidden-variable theory: meter monitors the system in the classical sense of “measuring”: finding out what the state is. On the other hand, if one assumes that the complementarity is a pure quantum mechanical feature and cannot be explained by the some realistic hidden-variable theory, the mutual relation between distinguishability and interference must be treated carefully under the influence of decoherence.

Summarizing both the decoherence cases, we assume the system and meter decoherence simultaneously. The decoherence effects in the system and meter are described by the system $R_S$ and meter $R_M$ robustness. Then the visibility only depends on system robustness $R_S$

$$\frac{V^2}{R^2_S} + D^2 = 1$$

and maximal violation of any Bell-CHSH inequalities is expressed in following form

$$B_{\text{max}} = 2\sqrt{D^2(1 - R^2_M)(D^2 - R^2_S) + D^2R^2_M + R^2_S}.$$  \hspace{1cm} (28)

Any Bell-CHSH inequalities are violated only if distinguishability $D$ satisfies the condition

$$D^2 > \frac{\alpha}{2} + \sqrt{(\alpha/2)^2 + \beta},$$

$$\alpha = R^2_S - \frac{R^2_M}{1 - R^2_M},$$

$$\beta = \frac{1 - R^2_S}{1 - R^2_M}. \hspace{1cm} (29)$$

The boundary on distinguishability (29) is depicted in Fig. 7 in dependence on meter and system robustness. Then, one can be sure that the complementary results of measurements cannot be predetermined by an element of physical reality and the quantum mechanics must be used to their correct description. These conditions are another expression of the quantum-mechanical nonlocality (in sense of the Bell-inequality violation) in the terms of complementary variables for the imperfect interferometric experiments.

In addition, the quantum complementarity is differently related to a nonlocality, if the measurements are performed separately on each qubit pair or collectively on several qubit pairs at once. Separate imperfect measurements can lead to some nontrivial bound on the violation of any Bell-CHSH inequalities for the system-meter state. Apart from this, question about their local-realism remain open. They do not violate this inequality but might violate some other inequality. On the other hand, in all the considered cases the system-meter state can be distilled to pure maximal entangled state and thus the nonlocality can be revealed even for the imperfect complementarity experiments.

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FIG. 1. Decoherence-free case: maximal violation of the CHSH-Bell inequalities in dependence on distinguishability $D$ and unpredicability $U$.

FIG. 2. System decoherence: maximal violation of Bell-CHSH inequalities in dependence on the overlap $O$ and the robustness $R$.

FIG. 3. System decoherence: visibility of interference $V$ in dependence on the distinguishability $D$ and the robustness $R$; The thick-line establishes a boundary of an explanation of the complementarity by the local-realistic theory.

FIG. 4. System decoherence: mutual information between Alice and Bob under influence of Eve’s system decoherence in dependence on the distinguishability $D$ and robustness $R$; thick line is boundary for a violation of Bell-CHSH inequalities.

FIG. 5. Meter decoherence: maximal violation of Bell-CHSH inequalities in dependence on the robustness $R$ and distinguishability $D$.

FIG. 6. Meter decoherence: mutual information between Alice and Bob under influence of Eve’s meter decoherence in dependence on the distinguishability $D$ and robustness $R$; thick line is boundary for a violation of Bell-CHSH inequalities.

FIG. 7. Meter and system decoherence: lower bound of distinguishability $D$ leading to violating of any Bell-CHSH inequality in dependence on the system and meter robustness $R_S$, $R_M$. 
local-realistic theory

quantum mechanics

$V$ vs $D$
Bell-CHSH inequality violation
Bell-CHSH inequality violation
