The decay of quantum correlations between quantum dot spin qubits and the characteristics of its magnetic-field dependence

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Abstract – We address the question of the role of quantum correlations beyond entanglement in the context of quantum magnetometry. We study the evolution of the rescaled variant of the geometric quantum discord of two electron-spin qubits interacting with an environment of nuclear spins via the hyperfine interaction. We have found that quantum correlations display a strong magnetic-field sensitivity which can be utilized for decoherence-driven measurements of the external magnetic field. The discord-based measurement is sensitive to a wider range of magnetic-field values than the entanglement-based measurement, including very small fields which are inaccessible via entanglement.

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Introduction. – Entanglement represents correlations that cannot be explained in any classical terms (see ref. [1] for a review), meaning that an entangled state cannot be created from a product of quantum states via classical randomness shared by multiple observers. However, there are quantum correlations that go beyond entanglement (for a review see ref. [2]). They are represented by separable states, but reflect non-commutativity of quantum physics, since the product states in the probabilistic mixture are eigenvectors of more than one mutually non-commuting observable. This is responsible for the fact that such correlations, although much weaker than entanglement, may outperform classical resources in some quantum information tasks. Recently they have been utilised in retrieving classical information encoded in quantum correlations [3], remote state preparation\textsuperscript{1} [4,5], and recovering quantum resources in the absence of system-environment back-action [6].

The most popular measures of quantum correlations beyond entanglement are the quantum discord and the quantum deficit. Recently geometric versions of the quantum discord attracted much attention because of their increased computability [7–9]; some measures can now be computed for arbitrary two-qubit density matrices [7,10,11]. It must be stressed that geometric objects cannot be treated as measures exactly (see ref. [12]); they serve as indicators of quantum correlations. Also, the application of the quantum discord to a quantum task of purely information theoretic character may be subject to some limitations and may require some care interpretation-wise (see footnote \textsuperscript{1}). Here, we propose to use it as an indicator that can help in the estimation of a physical parameter in a well-defined physical model.

Systems of electron spins confined in semiconductor quantum dots (QDs) are appealing for the study of inter-qubit quantum correlations. Firstly, because of the naturally occurring, long-lived qubit of spin-up and spin-down. Secondly, because of the high level of the experimental

\textsuperscript{1}The corresponding effect on the ground of remote state preparation was found in ref. [4], where the experiment was reported together with theoretical evidence for the surprising superiority of quantum correlations of separable states over entanglement. A later comprehensive approach [5] has shown its limitations, yet leaving space for the expected superiority in cases of restricted observer’s decoding abilities.
state of the art, which allows for a wide range of initializable states and measurement possibilities [13–16]. A flagship example of the experimental possibilities is the recently demonstrated quantum state tomography performed on two singlet-triplet qubits (four electrons in four quantum dots) [17]. The main decoherence mechanism here is the hyperfine interaction (see refs. [18,19] for a review). This interaction leads to pure dephasing at moderately high magnetic fields, but to a more involved decoherence process at lower fields.

Since correlation decay is so strongly dependent on the magnetic field, a variant of quantum magnetometry can be proposed with much weaker requirements than quantum entanglement. To this aim, we study the decay of quantum correlations between two-electron-spin-in-a-QD qubits for two classes of pure initial states. Firstly, the Bell states which are convenient for the study of the magnetic-field dependence of the evolution. The dependence is complex and it turns out that the more general quantum correlations provide a means to measure the magnetic field in a wider value range than entanglement-based schemes. All magnetic-field sensing results can be reproduced using separable non-zero-discord states, such as the Werner states. Secondly, we study the entangled initial states with all density matrix elements finite. Their discord evolution is more complex and exhibits both indistinguishability points and a dependence of the decay on the inter-qubit phase, which are not observed for Bell-diagonal states.

Electron spin in a quantum dot system. – The system under study consists of two electron spins confined in two, well-separated lateral GaAs QDs. Each electron spin constitutes a qubit, with its spin-up (spin parallel to the applied magnetic field) and spin-down (anti-parallel) components indicated as the |0⟩ and |1⟩ states. We take into account the hyperfine interaction of each electron spin with the spins of the nuclei of the surrounding atoms.

Since the qubits are well separated (there is no inter-qubit interaction and no overlap between the environments), the Hamiltonian of the whole system is of the form \( H = H_1 \otimes 1_2 + 1_1 \otimes H_2 \), where \( H_i \) are single QD Hamiltonians (\( i = 1,2 \) distinguishes between the dots), and two-qubit evolution may be inferred from single dot evolutions. The Hamiltonians are given by

\[
H_i = -g\mu_B S_i^z B + \sum_k A_{k,i} \mathbf{S}_i \cdot \mathbf{I}_{k,i},
\]

where the magnetic field \( B \) is applied in the z-direction. The first term describes the electron Zeeman splitting, where \( g \) is the effective electron g-factor, \( \mu_B \) is the Bohr magneton, and \( S_i^z \) is the electron-spin component parallel to the magnetic field. The second term describes the hyperfine interaction, where \( \mathbf{I}_{k,i} \) is the spin of nuclei k and \( \mathbf{S}_i \) is the electron spin in dot i. The coupling constants, \( A_{k,i} \), depend on nuclear species and on the location of each nucleus with respect to the electron wave function (see ref. [20] for details).

In general, finding the QD evolution described is an involved task, because the interaction can be regarded as small with respect to the electron Zeeman splitting only at moderately high magnetic fields [18,19]. The problem simplifies when the initial state of the whole system is a product of the double QD state and the states of both nuclear baths, \( \sigma(0) = \rho_{\text{DQP}}(0) \otimes R_1(0) \otimes R_2(0) \), and the initial states of the nuclear baths are described by infinite-temperature density matrices. The baths are well described by such states when the nuclear Zeeman energies are very small with respect to the thermal energy \( k_B T \) [21,22]. Although typical temperatures for spin-in-QD experiments are sub-Kelvin, the Zeeman splitting for gallium and arsenate are \( \approx 0.1 \, \text{meV/T} \) and the condition is met for the whole range of magnetic fields. In this case, all coupling constants can be assumed to be equal, \( \alpha_i = \sum_k A_{k,i}/N_i \) (where \( N_i \) is the number nuclei in dot i) and the Hamiltonian can be diagonalized exactly. The model holds on short time scales, the limit of which is approximated by \( 1/\alpha_i \) [19] which is sufficient for the study of correlation decay.

We use parameters corresponding to identical lateral GaAs QDs. All isotopes found in GaAs carry spin I = 3/2 and the average hyperfine coupling constant for this material is 83 \( \mu \text{eV} \) [23]. The number of nuclei considered within each dot is \( N_i = 1.5 \times 10^8 \), so the limit of short times is \( \approx 1.2 \times 10^4 \, \text{ns} \). Set system parameters make the following discussion clearer, since the magnetic-field and time dependences can be specified, but the discussion is qualitatively valid for any QDs that are susceptible to hyperfine–interaction–induced decoherence. For more universal plot scalings, the B-dependence should be rescaled to dependence on \( g\mu_B B \) and t-dependence to \( t/\alpha \)-dependence.

In the high magnetic-field regime, \( B > 3 \, \text{T} \) for the parameters used, the evolution is of pure dephasing character and the coherence decays proportionally to \( \exp(-t^2/T_2^*) \), with \( T_2^* = \sqrt{N_i}/(\sqrt{N} \mathcal{A}) = 12.36 \, \text{ns} \) (as predicted in ref. [22]). The B-dependence is then limited to the frequency of the unitary oscillations of the spin, which do not influence quantum correlations. At lower magnetic fields, oscillations of the QD occupations accompany the dephasing process. The amplitude of these oscillations is damped with growing magnetic field, while their frequency increases. For more details see the appendix of ref. [20]. The mathematical model of the interaction has been used to model magnetic sensing in some biochemical systems (see ref. [24] and references therein).

Rescaled discord. – The geometric discord [7] is the first quantum discord measure for which the lower [7] and upper [10] bounds can be found given any two-qubit density matrix. Regrettably, it is susceptible to increase under local non-unitary evolution, and hence is an unreliable quantum discord measure [12]. A solution of this problem has been proposed in ref. [11]. To diminish the measures sensitivity to the purity of the studied state, it suffices to
normalize it by its Hilbert-Schmidt norm. For a two-qubit state the rescaled discord is given by

$$D(\rho) = \frac{1}{2} \left(1 - \sqrt{\frac{3}{2}} \right) \left[ 1 - \sqrt{1 - \frac{D_S(\rho)}{2\text{Tr}\rho^2}} \right],$$

where $D_S(\rho)$ is the geometric discord and $\text{Tr}\rho^2$ is the purity of the studied state. Hence, there is a straightforward relation between the rescaled discord and the geometric discord, and the bounds on the former can also be calculated.

The lower bound on the geometric discord is given by [7] $D_S^L = \frac{1}{3} \max_{q=x,y} (\text{Tr}[K_q] - k_q)$, where $k_q$ is the maximum eigenvalue of the matrix $K_q = |q\rangle\langle q| + T_qT_q^T$. Here, $|q\rangle$ denote local Bloch vectors and $T_x = T$, $T_y = T_T^T$, where $T$ is the correlation matrix (in the standard Bloch representation of a two-qubit density matrix). The upper bound is given by [10] $D_S^U = \frac{1}{3} \min_{q=x,y} (\text{Tr}[K_q] - k_q + \text{Tr}[L_q] - l_q)$, with $p = x, y$ and $p \neq q$. Here, $k_q$ are the maximal eigenvalues of the matrices $L_q = |q\rangle\langle q| + T_q|q\rangle\langle q|T_q^T$, and $l_q$ are the normalized eigenvectors corresponding to the eigenvalue $k_q$ of matrix $K_q$. The final step in acquiring the upper and lower bounds on the rescaled discord is inserting the geometric discord values into eq. (2).

**Bell states.**—Bell states are a natural choice for quantum correlation studies in a double spin-in-a-QD system (as in many other realistic scenarios), since they are initialized more easily than other entangled states. The singlet state is distinguished for spin qubits, since its preparation and the measurement of its fidelity have already been demonstrated experimentally in 2005 [14]. The evolution does not differentiate between the Bell states up to unitary single dot evolutions which are irrelevant for quantum correlations and have been omitted here. The evolution preserves the Bell-diagonal form [20], hence the density matrix is always of the form

$$\rho_{DQD}(t) = \begin{pmatrix} \frac{1}{2} - a(t) & 0 & 0 & 0 \\ 0 & a(t) & b(t) & 0 \\ 0 & b(t) & a(t) & 0 \\ 0 & 0 & 0 & \frac{1}{2} a(t) \end{pmatrix},$$

The initial conditions for all Bell states are $a(t) = 1/2$ and $b(t) = \pm 1/2$, with the basis states in the density matrix (3) arranged in the order $|00\rangle$, $|01\rangle$, $|10\rangle$, $|11\rangle$ for initial states $|\Psi^\pm\rangle = \sqrt{2/3}(|01\rangle \pm |10\rangle)$ and in the order $|01\rangle$, $|00\rangle$, $|11\rangle$, $|10\rangle$ for initial states $|\Phi^\pm\rangle = \sqrt{1/3}(|00\rangle \pm |11\rangle)$.

The lower and upper bounds on the rescaled discord coincide for any Bell-diagonal state, hence, they coincide throughout the hyperfine-interaction–induced evolution of any initial Bell state. Furthermore, analytical formulas for $D_S$ can be found for any instant in time, which can then be extended using eq. (2) to yield the value of $D$.
consider the singlet state, $|\Psi^\rightarrow\rangle$, and disregard any coherent oscillations, assuming $b(t) = b^\ast(t)$. The state resulting from the action of environmental noise, rewritten in the basis of projectors into the singlet $S_0$ and triplet $T_{-1}$, $T_0$, $T_1$ eigenstates of the total angular momentum of the two electron system (the subscripts correspond to the angular momentum projection into the z-axis), is always of the form $\rho_{DQD}(t) = \left(\frac{1}{2} - a(t)\right) (T_{-1} + T_{+1}) + [a(t) + b(t)] T_0 + [a(t) - b(t)] S_0$. When $B = 0$ there is no mechanism favouring the decay into any of the triplet subspaces and the evolved state fulfils $\frac{1}{2} - a(t) = a(t) + b(t)$ which is equivalent to the condition $g(t) = 1$.

On the other hand, high magnetic fields forbid spin transitions, as there is no first-order mechanism to diffuse the energy $2g_{12}S_z^2 B$. Therefore the dominating decay channel does not change angular momentum, meaning that $|b(t)|$ decays more rapidly than $a(t)$, and the Werner state degeneracy over triplet projectors is lifted. Figure 2 presents this by showing the time dependence of $g(t)$ at different magnetic fields. Hence, we have shown that for the singlet (this can be generalized to all Bell states) an indistinguishable evolution of the rescanned discord is impossible, since the entrance into the $g(t) \geq 1$ regime is forbidden by the energy conservation law.

**Measurement of small magnetic fields.** – The long-time discord behaviour shows strong magnetic-field dependence in the 0–5 mT range (see inset of fig. 1) and measuring the rescanned discord precisely would enable the detection of small magnetic fields. This is experimentally feasible, since measuring the discord is in this case equivalent to measuring the revival of interdcoherence. For sufficiently long times, $> 40\text{ ns}$, the specific choice of the measurement time is irrelevant (one should not wait too long). Hence, the sensitivity of a QD magnetic sensor can be extended to magnetic fields inaccessible via the entanglement-based procedure [20]. Moreover, entanglement is not a necessary resource for the measurements —any quantumly correlated Werner state will suffice, since its evolution displays asymptotics similar to the singlet.

Since the evolution always remains in the $g(t) \leq 1$ regime, where it is directly proportional to the amplitude of the single, non-zero coherence present in the system, measurements of this coherence are enough to determine the magnetic field. Therefore, the experimental realization of the discord-based magneto-measurement depends not on the ability to perform direct measurements of the asymptotic rescaled discord, but on the experimentally attainable precision of coherence measurements.

There are further possibilities of detecting small magnetic fields which take advantage of the rich characteristics of the decoherence-driven discord evolution. For instance, the evolution of the factor $g(t)$ (see fig. 2), $g(t)$ can be measured experimentally (although not directly), since $g(t) = \frac{\text{Tr}(\sigma_z \otimes \sigma_z \rho_{DQD}(t))}{\text{Tr}(\rho_{DQD}(t))}$, where $\sigma_i$, $i = x, y, z$, are the Pauli matrices. Although for $B = 0$ this function is constant, for higher magnetic fields it evolves with time and is very sensitive to small magnetic-field changes. The shape of $g(t)$ is a good indicator of the (small) magnetic-field value, but the depth of the minimum of $g(t)$ is a good indicator on its own in the range of 0–2 mT. Furthermore, from the inset of fig. 2, which shows the minimum and local maximum of $g(t)$ as a function of the magnetic-field, it is seen that registering the value of both parameters allows to determine the magnetic field in a wider range of small fields than using the entanglement-based scenario. This is because, although the minimal value is a non-monotonous function of the magnetic field, the value at the local maximum decreases monotonously with the field. The times at which the minimum and the local maximum occur are practically independent of the magnetic-field value at small magnetic fields which simplifies the measurement problem.

Again, let us stress that the proposed scheme does not require entanglement. The function $g(t)$ of Werner states, $\rho_{DQD}(0) = (1-p)1 + p S_0$, reproduces the behaviour shown in fig. 2 as long as $p \neq 0$, i.e. also for separable states which are parametrized by $0 < p \leq \frac{1}{4}$. This is because the amount of noise in the system scales both averages, $\text{Tr}(\sigma_x \otimes \sigma_x \rho_{DQD}(t))$ and $\text{Tr}(\sigma_z \otimes \sigma_z \rho_{DQD}(t))$, with the same ratio $p$.

Let us focus on the range $B > 10$ mT, for which the strong magnetic-field dependence of the entanglement-sudden-death time enables precise field sensing. We propose an indicator,

$$M(B) = \frac{1}{D(\rho_{DQD}(0))} \int_0^\tau D(\rho_{DQD}(t)) dt,$$

where $\tau = 20$ ns and the integration limits are arbitrarily chosen so that the rescaled discord values are reasonably high during the whole time under investigation, while the range of discord revivals for small $B$ is excluded. The second requirement is not necessary and was imposed only to obtain a monotonic increase of $M(B)$, which would otherwise attain a local minimum for small magnetic fields.
The measure is normalized with respect to the initial value of $D$. The $M(B)$ dependence on the magnetic field of an initially separable Werner state with $p = 0.33$ is shown in the left panel of fig. 3. It is clear that the magnetic field plays a sustainable role in keeping the presence of correlations beyond entanglement in the system during its evolution. The steep rise of $M(B)$ which makes it suitable for magnetic-field sensing is equivalent to the steep rise of entanglement-sudden-death time. Hence, entanglement is not necessary for decoherence-driven measurement of $B > 10$ mT magnetic fields (similarly as for lower fields).

**Indifferentiability of the discord evolution.** – Indifferentiable evolutions [25,26] can be exhibited by the studied system, only if the initial state is appropriately chosen, since this requires a crossing between the two regimes of discord evolution, which are separated by the parameter line which fulfills $g(t) = 1$. This cannot happen for Bell states, is possible for “pre-decayed” Bell-diagonal states, which keep the form of eq. (3), and additionally satisfy $g(0) > 1$. An example of such an evolution of the rescaled discord at $B = 100$ mT is shown in the right panel of fig. 3, with $a(0) = 0.4$ and $b(0) = 0.4$ (red, solid line). Complementarily, the evolution of the function $g(t)$ is shown in the same plot (green, dashed line). Before the transition, the decay of quantum correlations is much slower and displays slight oscillations due to the redistribution of the spin occupations, which disappear after the transition.

**Other entangled states.** – To complete the study of the evolution of quantum correlations, it is necessary to study a non-Bell-diagonal state. We study the initial state $|\psi\rangle = \frac{1}{\sqrt{2}} [|00\rangle + |10\rangle + |01\rangle + e^{i\gamma}|11\rangle]$. This state is maximally entangled only for $e^{i\gamma} = -1$ and for $e^{i\gamma} = 1$ the state is separable and has zero discord. The dependence of initial $D$ on the phase parameter $\gamma$ is plotted in the inset of fig. 4.

Panels (a)–(d) of fig. 4 show the evolution of the rescaled discord of an initial state with $\gamma = \pi$ (red solid line) and $\gamma = \pi/2$ (blue short-dashed line) for four different magnetic-field values. Analogously, panels (e)–(h) show the evolution of the rescaled discord of initial states with $\exp[i\gamma] = (-1 + i)/\sqrt{2} \ (\gamma = 3\pi/2, \text{red solid line})$ and $\exp[i\gamma] = (-1 + 3i)/\sqrt{2} \ (\gamma = 7\pi/6, \text{blue short-dashed line})$. The evolutions are renormalized so that all discord evolutions start at 1/2. As seen, discord oscillations are much more pronounced than in the case of Bell-diagonal states. Although the time of the minima and maxima is unaffected by the phase factor $\gamma$, their amplitude is. Furthermore, the evolutions strongly vary depending on the initial phase if $B \neq 0$. This is in direct contrast with the evolution of entanglement, for which the same normalization would yield exactly overlapping curves.

The evolutions shown in the upper panels (a)–(d) always display matching lower and upper discord bounds. Contrarily, the evolutions in the lower panels (e)–(h) display a discrepancy between the lower and upper bounds after some level of decoherence is reached. The discrepancy...
appears earlier at higher magnetic fields. In accordance with ref. [27], this occurs in an abrupt manner, and is followed by a slow decay of the difference between the lower and upper bounds. The indifferentiable points in the evolution of the discord upper bound are also indifferentiable points in the evolution of the discord lower bound (the jump in the upper bound is accompanied by a transition between two decay curves in the lower bound).

Conclusion. — We investigated the evolution of quantum correlations quantified by the rescaled discord, in a system of two electrostatic non-interacting QDs. We have studied the magnetic-field dependence of the evolutions in the context of the usability of the decohering double QD system for the measurement of the applied magnetic field. We have found that the sensitivity of the discord to the magnetic field is of wider range than the sensitivity of entanglement in the same system. Firstly, it displays strong sensitivity to very low magnetic fields (in the range of 0–5 mT) for which the sensitivity of entanglement decay is negligible. This is quantified either by exploiting the properties of the evolution of the correlations revived in the system, or by a measurement of the extrema of the function \( g(t) \) which occur at short time scales. We have also shown that the rescaled discord provides good insight into the higher magnetic-field values for which entanglement sensitivity is optimal. It should be possible to extend the results to other quantum systems with a strong and non-trivial dependence of quantum correlations on the magnetic field [28,29].

We have also shown that, regardless of the magnetic-field regime, entanglement is not a necessary resource for strong magnetic-field sensitivity. Quantum correlations beyond entanglement can serve as a resource for magnetic-field sensing in higher magnetic fields, but the range of applicability of a QD sensor can be extended to low magnetic fields. In both regimes, and for all three methods of measuring the magnetic field, the results can be obtained using separable Werner states with non-zero discord.

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