Warszawa, June 15, 2023

Igor Bragar
Institute of Physics, Polish Academy of Sciences

ABSTRACT OF THE DOCTORAL DISSERTATION ENTITILED
"Dynamics of Entanglement of Spin Qubits Based on Semiconductor Quantum Dots"

The doctoral dissertation entitled "Dynamics of Entanglement of Spin Qubits Based on Semiconductor Quantum Dots" is of triptych form: apart from a short presentation of the scientific knowledge about the spin qubits, entanglement and reasons of its decay contained in Chapter 1 "Introduction: Entanglement and Spin Qubits", and auxiliary chapters such as Chapter 5 "Concluding Part", and Appendix, it consists of three main parts: Chapter 2 "Dynamics of Decay of Two Electron-Spin Qubits Entanglement", Chapter 3 "Retardation of Entanglement Decay of Two Spin Qubits by Quantum Measurements", and Chapter 4 "Dynamical Generation of Entanglement of Two Singlet-Triplet Qubits". All three main parts have a common subject of study—the decay of entanglement of two qubits based on spins of electrons which are localized on quantum dots (QDs) in a semiconductor nanostructure (e.g. gated QDs created in AlGaAs/GaAs heterostructure or self-assembled InGaAs QDs). At the same time, these chapters contain research pieces which are independent of each other.

In Chapter 1, I summarize the most important, from the point of view of the subject of the dissertation, scientific knowledge about the formal description of complex systems in quantum mechanics, define the entangled states, discuss approaches to quantification of the level of entanglement of a given quantum state and give explicit definitions of measures of entanglement used in the following chapters. I also sum up the information about a few experimental realizations of spin qubits in semiconductor QDs. In particular, I describe the design of a few types of such devices and the possibilities of electron spin manipulations they provide. I end the chapter with an overview of physical mechanisms that lead to decoherence of quantum states of spin qubits.

In Chapter 2, I present the theoretical analysis of the time evolution of two electron spin QD qubits. It is shown there how entanglement decays due to the interaction of electron spins with nuclear spin environment of QDs. The impact of various states of the latter has been considered (e.g. a thermal state, narrowed states, correlated states). It has also been examined the efficiency of application of a two-qubit echo procedure in order to revert dephasing of qubits and obtain back the entangled state of qubits. The existence of a cut-off strength of magnetic field below which echo procedure gives no effect has been demonstrated. Additionally, it has been shown that the amount of entanglement of two-qubit state which is undergoing the hyperfine-induced decay can be detected and quantified without

performing the two-qubit tomography. The amount of entanglement in such a case can be faithfully estimated by measuring a simple entanglement witness (projection on the initial two-qubit state). Moreover, this task can also be accomplished by measuring the averaged fidelity of quantum teleportation during which the analyzed state is consumed.

In Chapter 3, I develop further the study of the system of two electron spin QD qubits, namely, I investigate how one could counteract the decay of their entanglement. I show there that execution of a manipulation procedure based on joint evolution of qubits and their environments followed by quantum measurement of the qubits' subsystem may significantly retard the decay of qubits' entanglement. It turns out to be crucial to tune the parameters of the procedure (duration τ of free evolution of the system, number n of performed quantum measurements and their strength k) to maximize the effect of retardation of entanglement decay. It has been demonstrated that the effect can be achieved not only in the case of strong (projective) measurements but also for quantum measurements of moderate strength.

In Chapter 4, I concentrate on the dynamical creation of entangled states of two two-electron spin QD qubits. Motivated by the experimental realization of the procedure aimed at production of entangled states of two singlet-triplet (S-T_0) qubits, I analyze the impact of factors which limit the maximal possible amount of entanglement created in that system operated in a regime when energy associated with the magnetic field gradient ΔB_z is an order of magnitude smaller than the exchange energy J between singlet and triplet states. First, I study theoretically a single S-T_0 qubit in free induction (FID) and spin echo (SE) experiments. I have obtained the analytical expressions for averaged values of the components of S-T_0 qubit as functions of the procedure duration for quasistatical fluctuations of ΔB_z and quasistatical or $1/f^{\beta}$-type dynamical fluctuations of J. Next, I consider the impact of fluctuations of these parameters on the efficiency of the entangling procedure. In particular, I have obtained the analytical expressions for the density operator of two-qubit state which account for $1/f^{\beta}$-type fluctuations of J_1, J_2 and the degree of correlation of the noises. These expressions indicate the maximal possible level of entanglement that can be generated by performing the entangling procedure. The theoretical estimates deliver also an evidence that in the analyzed experiment, S-T_0 qubits were affected by uncorrelated $1/f^{\beta}$ charge noises.

Results presented in Chapter 2 are published in the scientific journal Physical Review B, 91:155310 (2015) "Dynamics of entanglement of two electron spins interacting with nuclear spin baths in quantum dots" (doi:10.1103/PhysRevB.91.155310), while results contained in Chapters 3 and 4 have not been published yet.

Igor Bragar

author's signature