Decoherence in a sparse system of dipolarly coupled spins: application to isotope-enriched silicon

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Decoherence (specifically the decay of the spin echo signal) of a central spin coupled by contact hyperfine interaction to a bath of dipolarly interacting nuclear spins was successfully described in recent years using cluster-expansion-based methods [1]. The convergence of these methods was related to the fact that the intra-bath interaction (between the nuclear spins) is weaker than the central spin-bath spin interaction. On the other hand, the problem of decoherence of a spin coupled by dipolar interaction to a bath of spins of the same kind (e.g. an electron spin interacting with other electron spins), which was studied in the context of nuclear magnetic resonance for more than 50 years [2], is much harder to solve using the cluster expansion methods.

Recently we have applied a version of the cluster expansion method [3] to a problem of spins of the same kind coupled by dipolar interaction. Specifically, we have calculated the spin echo decay of the spin of the electron bound to a phosphorous donor in silicon [4], taking into account the finite concentration of such donors in experiments conducted in recent years [5]. In the paper [4] we have also included the previously studied effects of the presence of nuclear spins of ^{29}Si atoms on the electron spin coherence. We have studied the dependence of the spin echo decay time (T_2) on both the donor concentration and the nuclear spin concentration. For decreasing ^{29}Si concentration the T_2 time increases, and finally it saturates due to the dominant role of the donor-donor spin interaction. In this isotopically purified regime the decoherence is due to dipolar interactions between the electron spins. Interestingly, we predict a maximum of T_2 time at some concentration of ^{29}Si. This is due to the fact that the nuclei play a dual role: their dynamics is a source of decoherence, but their presence leads also to quasi-static energy offsets (due to Overhauser fields) between different donor spins. These offsets lead to suppression of dipolar flip-flopping between the electron spins, and thus diminish the decoherence due to the electron spin dynamics. The calculated spin echo decay times from [4] are in agreement with most recent measurements in high-purity silicon [6].

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