Preserving quantum states in a subspace using the super Zeno effect on an NMR quantum computer

Harpreet Singh[1] * Arvind[1] † Kavita Dorai[1] ‡

[1] *Department of Physical Sciences, Indian Institute of Science Education & Research (IISER) Mohali, Sector 81 SAS Nagar, Manauli PO 140306 Punjab India.*

Abstract. We experimentally demonstrate the preservation of a quantum state in a subspace on a two-qubit NMR quantum information processor, using the super-Zeno effect. The super-Zeno effect[1] uses a set of inverting radiofrequency pulses punctuated by pre-selected time intervals for state preservation, and has been shown to be more efficient than the standard Zeno schemes. Efforts are underway to use these super-Zeno pulses to arrest the decoherence of a maximally entangled state such as the Bell state in a two-qubit system. Our results have important implications for decoherence mitigation in multi-qubit entangled states.

Keywords: NMR, Superzeno,Destructive interference

1 Introduction

Quantum computation is more powerful than classical computation as it uses the inherent advantages of superposition, entanglement and quantum interference to achieve computational speedup. The destructive interference of quantum amplitudes can be used to cancel out the amplitudes of undesired states. We wish to apply this general strategy to the problem of state preservation in a quantum subspace i.e., how to limit the system evolution to remain confined within the desired subspace. The quantum Zeno effect has been used to suppress the evolution of a quantum state within a multidimensional subspace[5]. It relies on the fact that frequent measurements can preserve a quantum state.

We consider a quantum mechanical system described by a two-dimensional Hilbert space $H = \{|00\rangle, |01\rangle, |10\rangle, |11\rangle\}$, which is a direct sum of two orthogonal subspaces P and Q. A two-qubit NMR system is described by the Hamiltonian:

$$H_o = \omega_1.I_{z1} + \omega_2.I_{z2} + 2\pi J_{12} I_{z1} I_{z2} \tag{1}$$

where the first two terms describe the free precession of spins 1 and 2 about the strong static magnetic field B_o in the z direction and the third term represents the scalar spin-spin coupling J_{12} between the two spins. The unitary operator corresponding to evolution for a time interval t is given by $U_o(t) = e^{-iHt}$.

When the system is subjected to a very short duration external rf pulse, we assume that the effect of the pulse can be represented by a unitary operator J. If the system is initially in the state $|\psi\rangle$, after being subjected to the pulse, its state will change to $J|\psi\rangle$, J is the inverting pulse $J = Q - P$, where P and Q are the projection operators for the subspaces P and Q respectively. Clearly $J|\psi\rangle = -|\psi\rangle$, if $|\psi\rangle \in P$, and $J|\psi\rangle = |\psi\rangle$, if $|\psi\rangle \in Q$.

*harpreetsingh@iisermohali.ac.in

†arvind@iisermohali.ac.in

‡Kavita@iisermohali.ac.in

When the two-qubit NMR system is subjected to a sequence of N inverting pulses, the evolution operator is given by:

$$W_n(t) = U_o(x_{n+1}t) \cdots J.U_o(x_3 t).J.U_o(x_2 t).J.U_o(x_1 t) \tag{2}$$

If the initial state is $|\psi\rangle \in P$, then the effect of unitary operator $W_n(t)$ is to prevent the leakage of the quantum state in the subspace P to the subspace Q.

2 Results

The Super Zeno algorithm can be used to preserve a state when the subspace P consists of just the intial state. We wish to achieve preservation of a general state within the subspace P, with the subspaces P and Q of the two qubit Hilbert space being $P = \{|11\rangle\ , |00\rangle\}$, and $Q = \{|01\rangle, |10\rangle\}$ respectively. As an example, we consider preserving the state $|11\rangle$ using the set of super-Zeno pulses.

The inverting pulse for protecting $|\psi\rangle\ \epsilon\ P$ is given by:
$J = I - 2(|00\rangle\langle 00| + |11\rangle\langle 11|\ )$
In Matrix Form it is:

$$J = \begin{bmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}$$

The state preserving sequence of rf pulses takes the form:

$$\begin{aligned} W_4(t) &= U_o(x_5 t).J.U_o(x_4 t).J.U_o(x_3 t).J.U_o(x_2 t).J.U_o(x_1 t) \\ \{x_k\} &= \{\beta, 1/4, 1/2 - 2\beta, 1/4, \beta\} \\ \beta &= \frac{(3-\sqrt{5})}{5} \end{aligned}$$

The plot between number of pulses and Relative Intensity, plotted for time interval t=0.00004 sec, shows the results of state preservation.

Detailed investigations of multiqubit entanglement is an important field of research in QIP. Most entangled states are very fragile and prone to decoherence and we

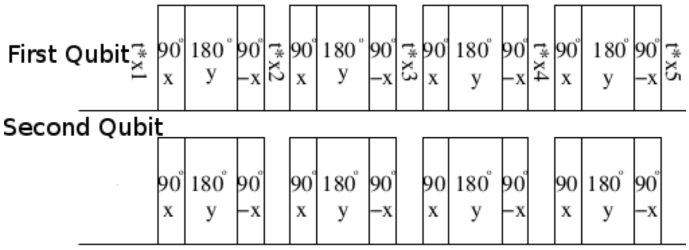

Figure 1: Preserving pulse sequence for the subspace $\{|00\rangle, |11\rangle\}$.

wish to use the super Zeno scheme described above to suppress decoherence of the Bell state. In this direction, we first created a Bell state from an initial pseudopure state and obtained a series of tomographs (shown in Figure 2) of how the state decays with time. The plot of the decay of the Bell state (of fidelity vesus delay time) shows how the state decoheres with time. Our aim is to use the super-Zeno pulse sequence to efficiently mitigate the decoherence of the Bell state. These experiments are currently being carried out.

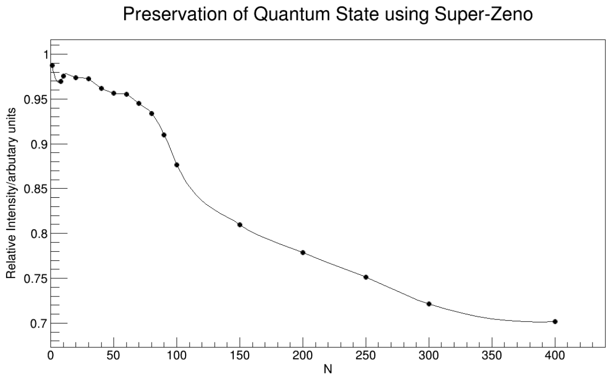

Figure 2: Plot depicting relative intensity as a function of the number N of inverting pulses.

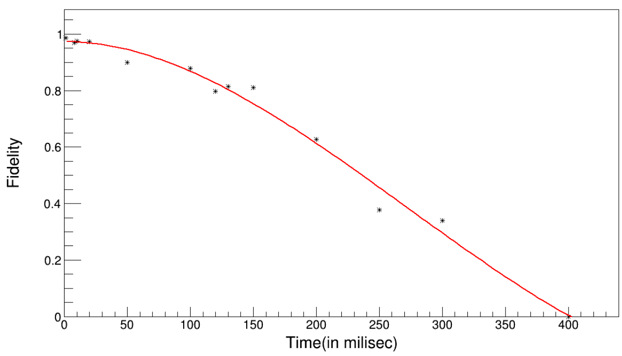

Figure 3: Natural decay of Bell state with time.

Experiments are in progress to use the super-Zeno pulse sequences described above to suppress the decoherence of a maximally entangled state such as the Bell state in two qubits. Our experimental schemes have important implications for the preservation of delicate en-

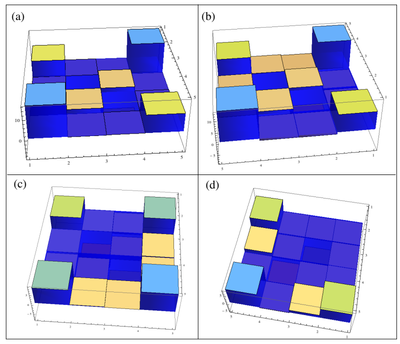

Figure 4: Tomography of the decay of the entangled Bell state $\frac{1}{\sqrt{2}}(\{|00\rangle + |11\rangle)$ at different delay times (a) 0 sec (b) 100 msec (c) 200 msec and (d) 250 msec.

tangled states and for the mitigation of decoherence in multiqubit systems.

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