Suppression of the low-frequency decoherence by motion of the Bell-type states

Andrey Vasenko

School of Electronic Engineering,
Moscow Institute of Electronics and Mathematics,
Higher School of Economics

In collaboration with

Dmitri V. Averin, Stony Brook University, USA

STONY BROOK
STATE UNIVERSITY OF NEW YORK

Introduction/ outline

- **Main suggestion:** Motion of logical qubits in systems of physical qubits can be a useful tool for quantum information processing. In particular, it provides a convenient way to suppress the low-frequency dephasing.

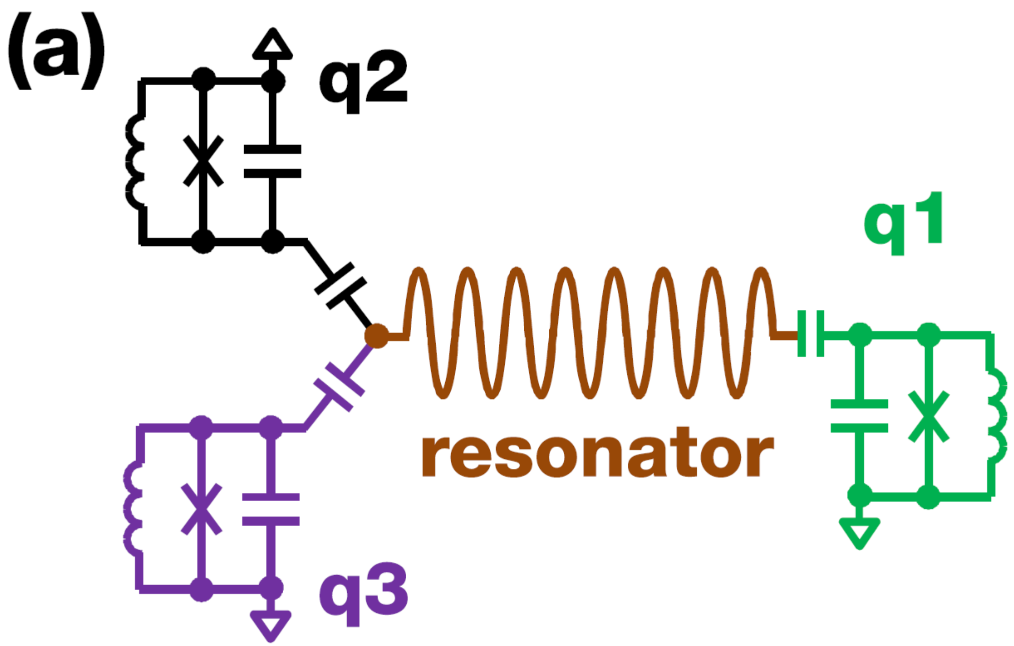
- **Few-qubit structures**. Enhancement of the dephasing time of the logical qubit with the number of physical qubits: theory and experiment.

- **Bell-type state motion.** The physical transfer of this state implements a dephasing-suppression protocol which automatically combines the motion-induced suppression of the low-frequency noise discussed previously with the simplest dynamic decoupling scheme, the spin-echo.

- **Carr-Purcell sequence** of single logical qubit motion.

Suppression of Dephasing by Qubit Motion in Superconducting Circuits

D. V. Averin,[1,*] K. Xu,[2] Y. P. Zhong,[2] C. Song,[2] H. Wang,[2,†] and Siyuan Han[3,‡]
[1]*Department of Physics and Astronomy, Stony Brook University, SUNY, Stony Brook, New York 11794-3800, USA*
[2]*Department of Physics, Zhejiang University, Hangzhou, Zhejiang 310027, China*
[3]*Department of Physics and Astronomy, University of Kansas, Lawrence, Kansas 66045, USA*
(Received 31 August 2015; published 8 January 2016)



$$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

The method of transferring logical qubits between different physical qubits is based on creating controlled qubit-qubit interaction through coupling to a common resonator bus.

It was shown that the logic qubit transfer suppress the low-frequency dephasing.

Motion-induced suppression of dephasing in few-qubit systems

The main origin of dephasing is the low-frequency noise.

The low-frequency noise is typically produced by fluctuations in the form of impurity charges or magnetic moments localized in each individual physical qubit.

Then each qubit is coupled to a source of Gaussian fluctuations $\xi_j(t)$ of the energy difference between the computational basis states.

$$H_{\mathrm{dec}} = -\frac{1}{2}\sum_{j=1}^{n} \sigma_j^z \xi_j(t)$$

$$\langle \xi_j(0)\xi_k(t)\rangle = \int \frac{d\omega}{2\pi} S_{j,k}(\omega) e^{-i\omega t}$$

$S_{j,j}(w)=S_j(w)$ represents the spectral density of noise $\xi_j(t)$ in the jth qubit, $S_{j,k}(w)$ account for the noise correlations in different qubits ($j \neq k$).

Motion-induced suppression of dephasing in few-qubit systems

If a logical qubit is prepared at time t = 0 as an initial state of the *j*th physical qubit and is kept there for a period τ, it will decohere due to the noise $\xi_j(t)$. This decoherence process can be characterized quantitatively by the function F(τ). Experimentally, the function F(τ) is obtained by measuring the Ramsey fringes.

$$F(\tau) = \langle T \exp\{-i \int_0^\tau \xi_j(t) dt\}\rangle = \exp\{-\int_0^\tau dt \int_0^t dt' \langle \xi_j(t)\xi_j(t')\rangle\}$$

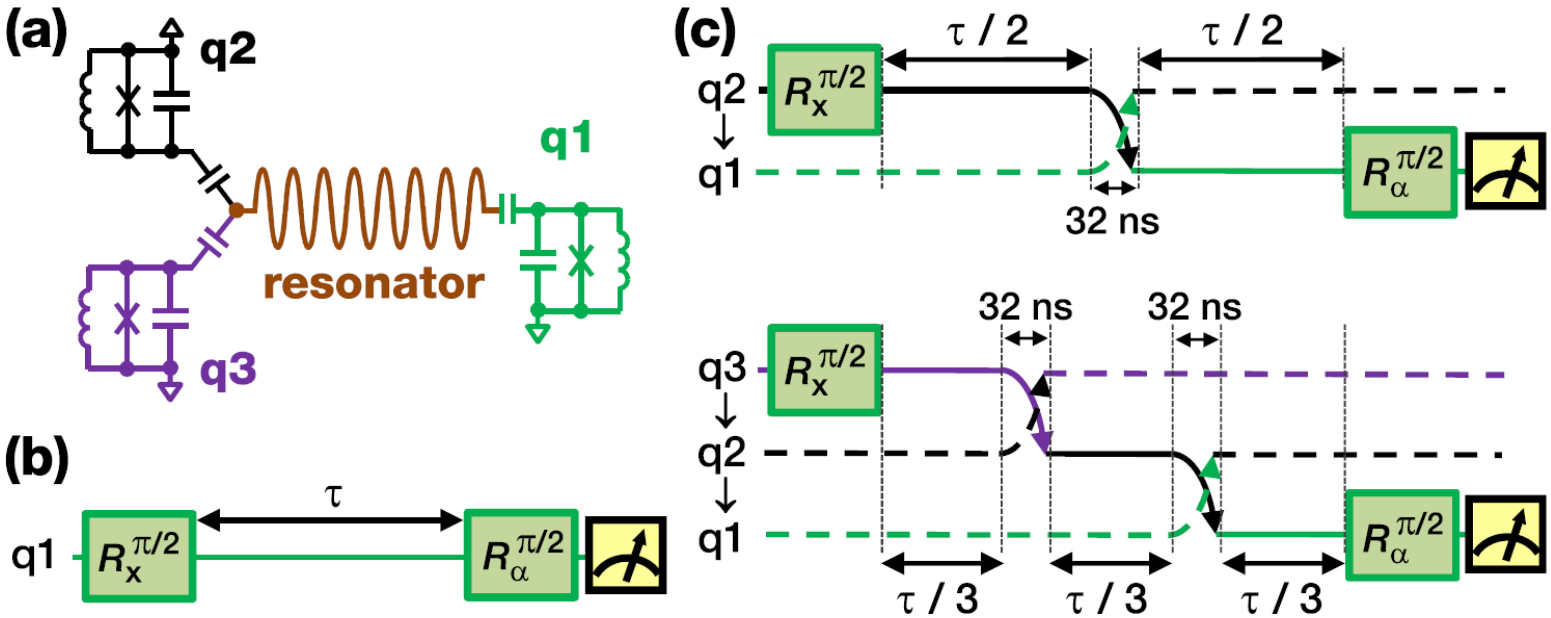
For the same qubit, but transferred successively from physical qubit 1 to n

$$F(\tau) = \exp\left\{ -\sum_{j=1}^{n} \int_0^{\tau/n} dt \int_0^t dt' \langle \xi_j(t)\xi_j(t')\rangle - \sum_{j<k} \int_0^{\tau/n} dt \int_0^t dt' \left\langle \xi_k\left(\frac{\tau}{n}(k-j)+t\right)\xi_j(t')\right\rangle \right\}$$

In the case of the 1/f noises of the same intensity uncorrelated on different qubits (and sufficiently low high-frequency cutoff)

$$F(\tau) = e^{-(\tau/\tau_d)^2}, \quad \tau_d = \sqrt{2n}/W\,, \quad W^2 = (A/\pi)\ln(\omega_h/\omega_l)\,.$$

Motion-induced suppression of dephasing in few-qubit systems



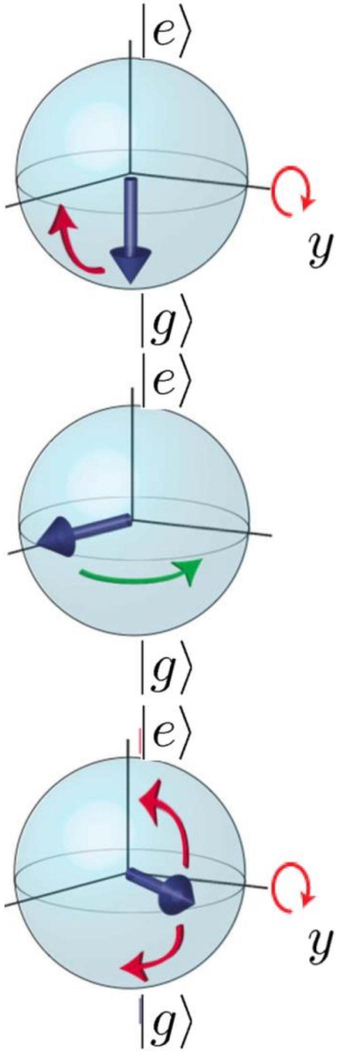
Logical qubit is transferred between physical qubits by two successive iSWAP gates involving resonator.

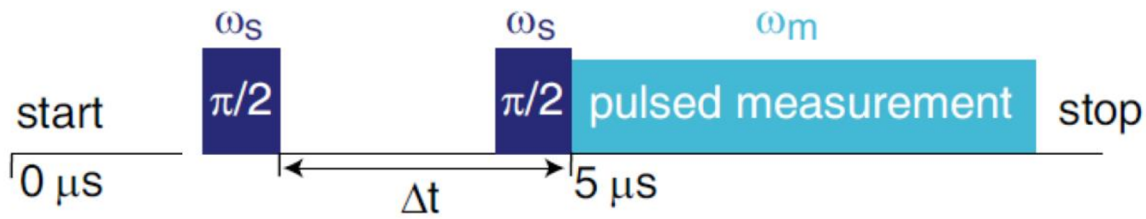
The dephasing time is obtained by the Ramsey fringe measurements.

$$\mathrm{SWAP} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

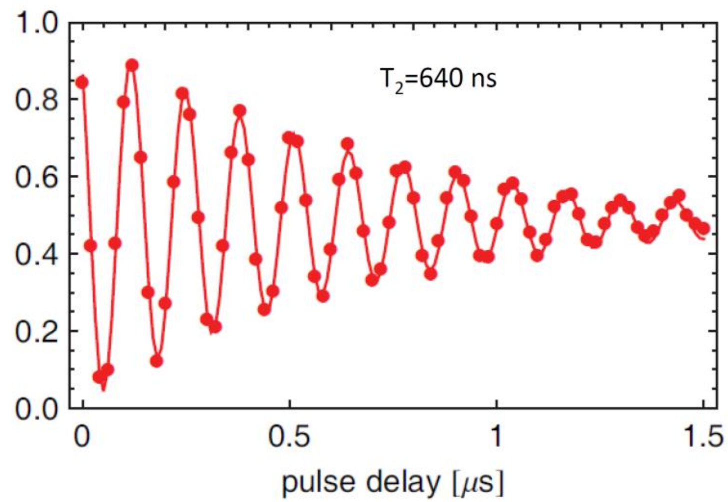
Ramsey fringes: dephasing time measurements

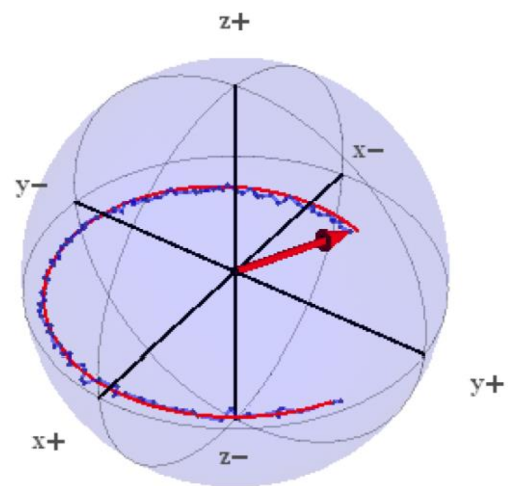
pulse scheme:



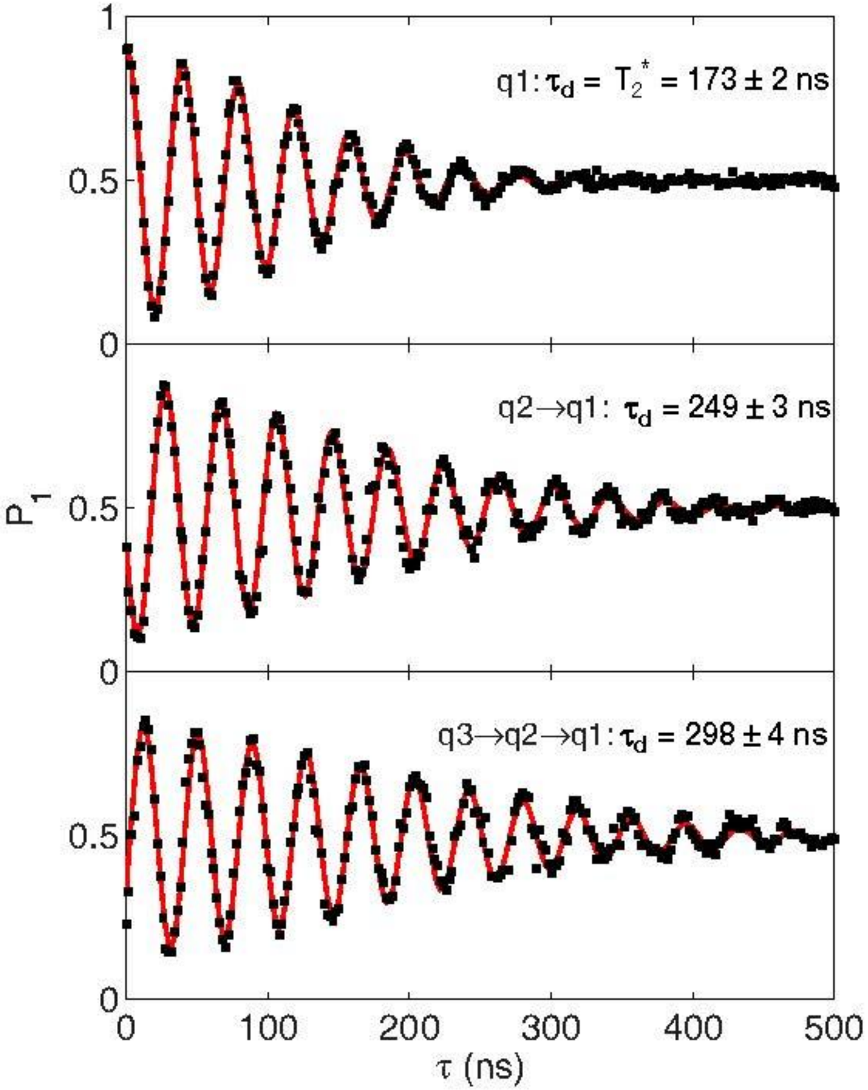


Ramsey fringes:





Enhancement of the dephasing time



1-qubit	T_2^* (ns)	2-qubit	τ_d (ns)	3-qubit	τ_d (ns)
q1:	173 (2)	q2→q1:	249 (3)	q3→q2→q1:	298 (4)
q2:	177 (1)	q3→q1:	243 (3)	q2→q3→q1:	295 (4)
q3:	176 (2)	q1→q2:	245 (3)	q3→q1→q2:	306 (4)
		q3→q2:	242 (3)	q1→q3→q2:	290 (5)
		q1→q3:	244 (2)	q2→q1→q3:	298 (4)
		q2→q3:	241 (3)	q1→q2→q3:	296 (4)
average:	175.3 (2.3)		244.0 (3.1)		297.2 (5.5)

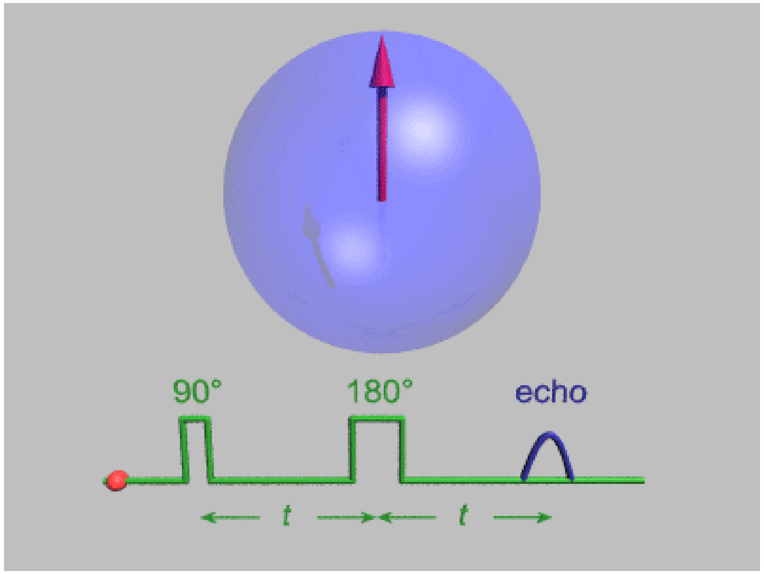
$$\tau_d = \sqrt{2},\ \sqrt{3} \cdot T_2^*$$

Bell-type state of two physical qubits

We consider one qubit of quantum information encoded into a Bell-type states of two physical qubits (entangled quantum states of two qubits).

The physical transfer of this state implements a dephasing-suppression protocol which automatically combines the motion-induced suppression of the low-frequency noise discussed previously with the simplest dynamic decoupling scheme, the spin-echo.

$$|\psi\rangle = \alpha|01\rangle + \beta|10\rangle$$



The combination of the two approaches should provide a qualitatively stronger suppression of the low-frequency decoherence than each of them individually.

In direct implementation of the spin-echo technique, a single π-pulse inverting the qubit state is applied in the middle of a time interval the logical qubit spends on the physical qubit, cancelling the phase accumulated due to the low-frequency noise.

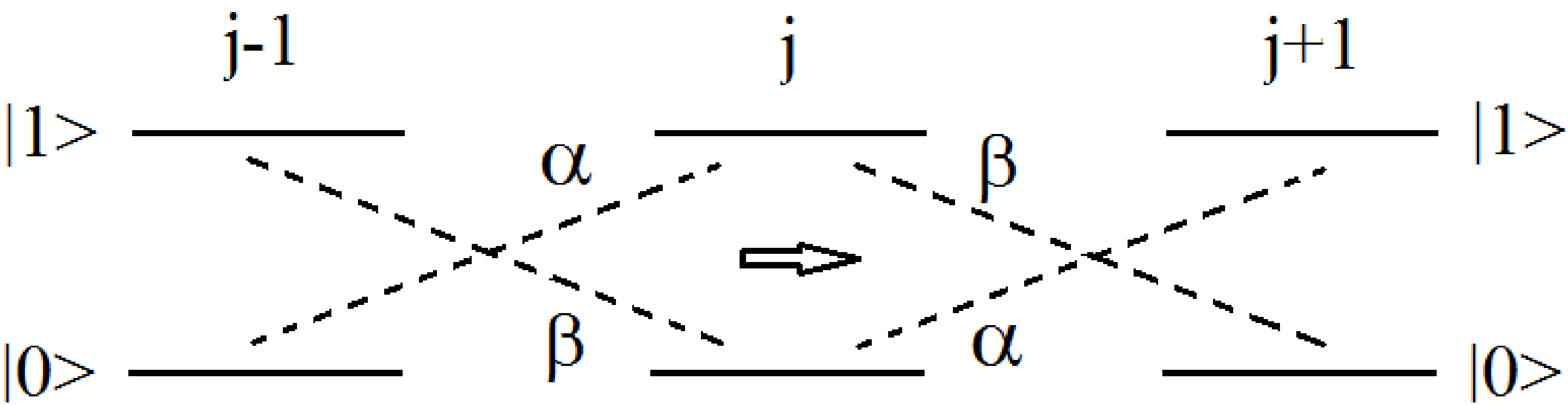
Bell-type state motion

No π-pulse is necessary! Its role is automatically played by the transfer of the logic state by one step in an array of physical qubit.

The contributions of the noise of the *j*th physical qubit to the phase difference between the parts α and β during the two steps cancel one another in a same way as in the spin-echo technique.

In addition to this cancellation, the motion of the logical Bell-type state suppresses the effect of the low-frequency noise in a same way as for the motion of the individual logical qubits.

$$|\psi\rangle = \alpha|01\rangle + \beta|10\rangle$$



Quantitative description

The total decoherence factor F accumulated during the propagation of the Bell-type state through the array of physical qubits can be represented by the product of decoherence factors produced by the noise of the j physical qubit ($\tau/2$ is the time the Bell-type state spends on each physical qubit):

$$F = \prod_j F_j \qquad F_j = \langle \exp\{ i \int_0^{\tau/2} [\xi_j(t) - \xi_j(t+\tau/2)] dt \} \rangle$$

For the experimentally relevant 1/f noise with same noise intensities A for all qubits we have:

$$S_j(\omega) = A_j/|\omega| \equiv A/|\omega| \qquad F = \exp\{-\frac{A\tau^2 \ln 2}{2\pi} n\}$$

For large arrays of physical qubits, $n >> 1$, it is natural to consider the dephasing in the continuous approximation, $t = k\tau$.

$$F = e^{-\gamma t}, \qquad \gamma = \frac{A\tau \ln 2}{2\pi}$$

Carr-Purcell noise suppression protocol

The noise suppression protocol of Bell-type state motion can be implemented also for individual logical qubits. In this case the motion does not implement automatically the spin-echo cancelation and it should be enacted directly by a π-pulse flipping the state of the logical qubit in the middle of the time interval τ the logical qubit spends on the physical qubit.

In this case one can also consider more advanced noise-cancellation schemes like Carr-Purcell sequence, in which the single π-pulse is replaced by two π-pulses, at times τ/4 and 3τ/4.

$$F_j = \langle \exp\{ i \int_0^{\tau/4} [\xi_j(t) + \xi_j(t+\tau/2)] dt - i \int_{\tau/4}^{3\tau/4} \xi_j(t) dt \} \rangle$$

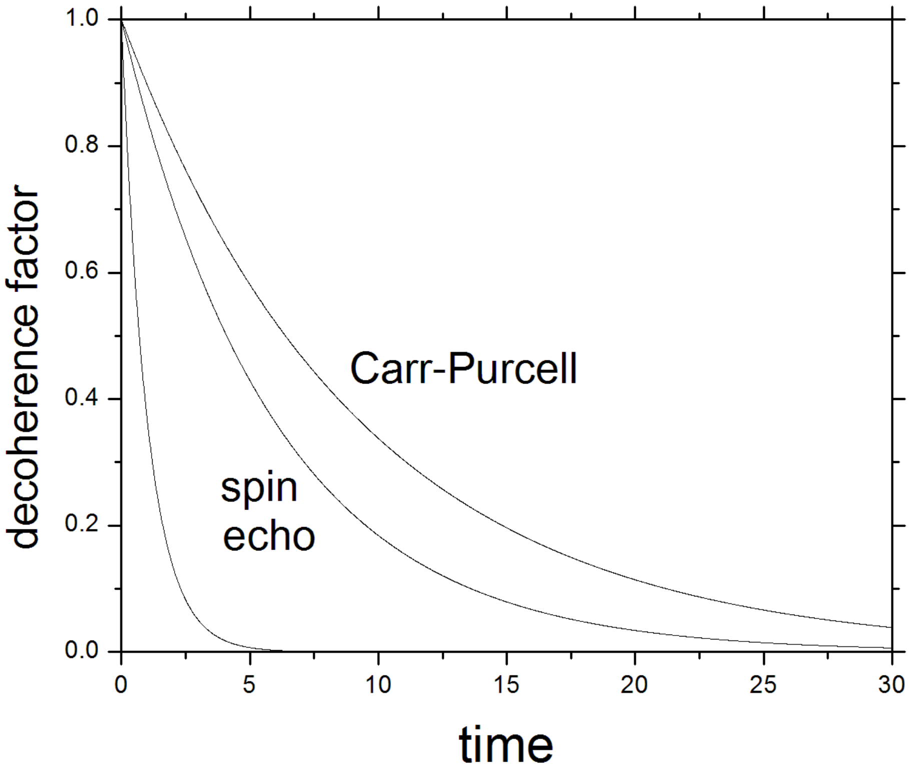
For the experimentally relevant 1/f noise with same noise intensities *A* for all qubits we have:

$$F_j = \exp\Big\{ -\frac{A\tau^2}{8\pi}\Big[\frac{9}{4}\ln(3) - \ln(2)\Big]\Big\}$$

Thus we obtain parametrically the same expression, but improve the numerical factor in it:

$$\ln 2 \simeq 0.69 \qquad [(9/4)\ln(3) - \ln(2)]/4 \simeq 0.44$$

Dynamic-decoupling-enhanced motional suppression of single-qubit decoherence



The upper curve correspond to the Curr-Purcell sequence protocol for the motion of one logical qubit.

The middle curve correspond to the spin-echo protocol for the motion of one logical qubit (π-pulses). It describes also the decoherence of the Bell-type state. The motion of such a state realizes automatically the spin-echo suppression of decoherence in addition to motion-induced suppression.

The lowest curve on the plot that is not labeled corresponds to simple motion of one logical qubit, without dynamic decoupling pulses ($\tau\omega_l = 1/30$).

The time on the horizontal axis of the plot is normalized in such a way that the lowest curve has the decoherence rate equal to 1.

Conclusions

- Motion of logical qubit in arrays of physical qubits leads to the increase of the dephasing time.
- Bell-type state motion combines the motion-induced suppression of the low-frequency noise with the simplest dynamic decoupling scheme, the spin-echo.
- Carr-Purcell sequence protocol for the motion of one logical qubit produces parametrically the same expression as the simplest spin-echo decoupling scheme, for the suppressed dephasing rate. It still improves the numerical factor in it.

Future plans

- A description of the state transfer process for some experimentally relevant physical qubits.
- A proposal/ description of some gate operation on moving states.
- To present our scheme as a general error-correcting approach.

Thank you!