Lecture 8

Dienstag, 08. November 2011
14:57

iSWAP gate from virtual qubit-qubit coupling

$$H = \hbar J \left(\sigma_1^+ \otimes \sigma_2^- + \sigma_1^- \otimes \sigma_2^+ \right)$$

$$\sigma_1^+ \otimes \sigma_2^- = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \otimes \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}$$

$$\sigma_1^- \otimes \sigma_2^+ = \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix} \otimes \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}$$

$$H = \hbar J \left[\begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} + \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \right]$$

$$= \hbar J \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

0_2

$\tilde{\sigma}_x$

Basis: $|gg\rangle = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix}$ $\quad |ge\rangle = \begin{pmatrix} 0 \\ 0 \\ 1 \\ 0 \end{pmatrix}$

$|eg\rangle = \begin{pmatrix} 0 \\ 1 \\ 0 \\ 0 \end{pmatrix}$ $\quad |ee\rangle = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix}$

time evolution:

$$U = e^{-\frac{i}{\hbar} H t} = e^{-iJt \cdot \tilde{\sigma}_x} \oplus \overbrace{e^{-i 0_2 t}}^{\mathbb{1}_2}$$

$$= \left(\mathbb{1} \cdot \cos Jt - i \tilde{\sigma}_x \sin Jt \right) \oplus \mathbb{1}_2$$

$$= \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos Jt & -i \sin Jt & 0 \\ 0 & -i \sin Jt & \cos Jt & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$= |gg\rangle\langle gg| + |ee\rangle\langle ee| + \cos Jt \left[|eg\rangle\langle eg| + |ge\rangle\langle ge| \right]$$
$$- i \sin Jt \left[|eg\rangle\langle ge| + |ge\rangle\langle eg| \right]$$

effect on state $|eg\rangle = \begin{pmatrix} 0 \\ 1 \\ 0 \\ 0 \end{pmatrix}$:

$$U|eg\rangle = \cos Jt \begin{pmatrix} 0 \\ 1 \\ 0 \\ 0 \end{pmatrix} - i \sin Jt \begin{pmatrix} 0 \\ 0 \\ 1 \\ 0 \end{pmatrix} = \cos Jt\, |eg\rangle - i \sin Jt\, |ge\rangle$$

*) SWAP $|eg\rangle \leftrightarrow |ge\rangle$ for $t = \frac{\pi}{2J}$: $|eg\rangle \rightarrow -i|ge\rangle$ (iSWAP)

*) entanglement generation at $t = \frac{\pi}{4J}$: $|eg\rangle \rightarrow \frac{1}{\sqrt{2}}\left(|eg\rangle - i|ge\rangle\right)$ ($\sqrt{iSWAP}$)

maximally entangled state

*) phase shift for $t = \frac{\pi}{J}$: $|eg\rangle \rightarrow -|ge\rangle$

CPHASE gate from $|fg\rangle \leftrightarrow |ee\rangle$ coupling

$|fg\rangle$... state not in computational subspace

$$\text{coupling}: \tilde{H} = \hbar J_2 \left(|f\rangle\langle e| \otimes |g\rangle\langle e| + |e\rangle\langle f| \otimes |e\rangle\langle g| \right)$$

$$\hat{=}\ J_2 \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad \text{in basis} \quad |fg\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

$$|ee\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

$$\tilde{U} = e^{-\frac{i}{\hbar}\tilde{H}t} = \begin{pmatrix} \cos J_2 t & -i \sin J_2 t \\ -i \sin J_2 t & \cos J_2 t \end{pmatrix}$$

$$U_{phase} = \tilde{U}\left(t = \frac{\pi}{J_2}\right) = \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix}$$

$U_{phase}|ee\rangle = -|ee\rangle$

in standard 2-qubit basis: $\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} = U_{cPhase}$

$\Rightarrow$ <u>only</u> state $|ee\rangle$ obtains phase of π !