ion is driven by an identical field and chose the phase appropriately, the interaction corresponds to a single collective spin of value $j = N/2$ precessing around the $\hat{J}_y$ direction due to an applied field.

By appropriate choice of Raman lasers it is possible to realise the conditional displacement operator for the i'th ion[9,5]

$$H = -i\hbar(\alpha_i a^{\dagger} - \alpha_i^{*} a)\sigma_z^{(i)}. \tag{1}$$

If the ion is in the excited (ground) state this Hamiltonian displaces the vibrational mode by a complex amplitude α (α). In the case of N ions with each driven by identical Raman lasers, the total Hamiltonian is

$$H = -i\hbar(\alpha a^{\dagger} - \alpha^{*} a)\hat{J}_z . \tag{2}$$

By an appropriate choice of Raman laser pulse phases we can then implement the following sequence of unitary transformations

$$U_{NL} = e^{i\kappa_x \hat{X}\hat{J}_z} e^{i\kappa_p \hat{P}\hat{J}_z} e^{-i\kappa_x \hat{X}\hat{J}_z} e^{i\kappa_p \hat{P}\hat{J}_z} \tag{3}$$

where $\hat{X} = (a + a^{\dagger})/\sqrt{2}$, $\hat{P} = i(a\ a^{\dagger})/\sqrt{2}$. Noting that

$$e^{i\kappa_p \hat{P}\hat{J}_z} \hat{X} e^{-i\kappa_p \hat{P}\hat{J}_z} = \hat{X} + \kappa_p \hat{J}_z \tag{4}$$

it is easy to see that

$$U_{NL} = e^{-i\theta \hat{J}_z^2} \tag{5}$$

where $\theta = \kappa_x \kappa_p$ which is the unitary transformation generated by a nonlinear top Hamiltonian describing precession around the $\hat{J}_z$ axis at a rate dependant on the z component of angular momentum. Such nonlinear tops have appeared in collective nuclear models[1] and form the basis of a well known quantum chaotic system.

It should be noted that the transformation in Eq. (5) contains no operators that act on the vibrational state. It is thus completely independent of the vibrational state and it does not matter if the vibrational state is cooled to the ground state or not. However Eq. (5) only holds if the heating of the vibrational mode can be neglected over the time it takes to apply the conditional displacement operators. In itself the unitary transformation in Eq. (5) can generate interesting states. For example the highly entangled state

$$|+\rangle = \frac{1}{\sqrt{2}}\left(e^{-i\pi/4}|j,j\rangle_x + (1)^j e^{i\pi/4}|j,j\rangle_x\right) \tag{6}$$

Such states have been considered by Bollinger *et al.*[10] in the context of high precision frequency measurements, and also by Sanders.[11]

Using a sequence of conditional displacement operators that does distinguish different ions we can simulate various interacting spin models. As interacting spins are required for general quantum logic gates, these models may be seen as a way to perform quantum logical operations without first cooling the ions to the ground state of some collective vibrational mode.

Suppose for example we wish to simulate the interaction of two spins with the Hamiltonian

$$H_{int} = \hbar\chi\sigma_z^{(1)}\sigma_z^{(2)}. \tag{7}$$

The required pulse sequence is

$$U_{int} = e^{i\kappa_x \hat{X}\sigma_z^{(1)}} e^{i\kappa_p \hat{P}\sigma_z^{(2)}} e^{-i\kappa_x \hat{X}\sigma_z^{(1)}} e^{i\kappa_p \hat{X}\sigma_z^{(2)}}$$
$$= e^{-i\chi\sigma_z^{(1)}\sigma_z^{(2)}}. \tag{8}$$

If we choose the parameters as random variables and average the Ising model undergoes quantum phase transitions with long range order,[12] which indicates significant quantum entanglement over the ions.

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QMD2 (Invited) 11:00 am

Atoms in cavities

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A central theme over twenty years of my interactions with Professor D. F. Walls was the radiative processes of atoms in cavities. His leadership played a critical role in the establishment and advancement of the modern field of cavity quantum electrodynamics.

QMD3 (Invited) 11:30 am

Entanglement purification of Gaussian continuous variable quantum states in quantum optics

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One of the key elements of quantum communication is the generation of maximally entangled states between distant nodes of a quantum network.[1] The usual way to create maximally entangled states consists of two steps: (i) generating partially entangled states between distant sites based on quantum optical communication, and (ii) using entanglement purification protocols to distill more useful maximally entangled states from the partially entangled states. In contrast to the familiar case of qubits we consider here a communication protocol which generates *partial continuous variable entanglement* through transferring *two-mode squeezed light.*[2,3] Entanglement has been made useful in the recent experiment demonstration of continuous variable teleportation.[2]

In the present work, we present an entanglement purification scheme which generates maximally entangled states in finite Hilbert spaces from the continuous two-mode squeezed states. With high probabilities, we get a more entangled state, and the entanglement in the continuous partially entangled state is transferred to the maximally entangled states with high efficiency. Furthermore, in several practical cases this purification protocol can be readily extended to distill maximally entangled states from the mixed Gaussian continuous states. We know that a two-mode squeezed state will inevitably evolve into a mixed Gaussian continuous state due to the unavoidable loss in light propagation. A small alternation of the protocol also provides a method for preparing the free Greenberger–Horne–Zeilinger states in high dimensional Hilbert spaces. Our purification scheme relies on a local quantum non-demolition (QND) measurement of the total excitation number of several entangled pairs. Possible experimental implementations of the scheme are discussed.

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QME 10:15 am–12:00 pm
Room 220–226

Photonic Band Gaps—Resonators

Joseph Wendel Haus, *Univ. of Dayton, USA, Presider*

QME1 10:15 am

Light manipulation with polymeric thin-film photonic crystals

T. Maka, S.G. Romanov, C.M. Sotomayor Torres, M. Müller,* R. Zentel,* *Inst. of Materials Science and Department of Electrical Engineering, Univ. of Wuppertal, 42097 Wuppertal, Germany; E-mail: romanov@uni-wuppertal.de*

The photonic energy band structure provides means for light moulding and spontaneous