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DARK MATTER IN COSMOLOGY
CLOCKS AND TESTS OF FUNDAMENTAL LAWS

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QUANTUM MECHANICALLY CORRELATED STATES AND ATOMIC CLOCKS

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ABSTRACT

Correlated states of atomic particles can be exploited to increase quantum-limited signal-to-noise ratio in spectroscopy. It may be possible to produce maximally correlated "EPR" states of N electrodynamically trapped ions by entangling the collective motion state of the ions with the internal (spin) states of the ions. As steps toward this goal, we report the cooling of a trapped ion to the zero-point energy, and the realization of a coherent exchange between an external vibrational energy level and the internal spin state of a trapped ion.

The concept of quantum-mechanically correlated particles is well-known through the famous thought experiment of Einstein, Poldolsky, and Rosen[1]. Several experiments have exploited "EPR-type" correlations between particles (primarily photons) to disprove local hidden-variable theories and show violations of Bell's inequality[2]. Recently, EPR states have been proposed as a vehicle for atomic state teleportation[3] and quantum cryptography[4]. In this paper, we show that correlated "EPR" states of atoms may provide increased signal-to-noise in spectroscopy[5], and investigate a method for preparing EPR states in a system of trapped ions.

Consider a two-level atom ($|\downarrow\rangle, |\uparrow\rangle$) with transition frequency ω_0. "Population spectroscopy" on the atom involves applying radiation at ω and monitoring the population of one of the atomic states, or equivalently measuring the value of the Pauli spin operator $\hat{\sigma}_z$ on the corresponding spin-½ system[6]. A spectroscopic figure-of-merit is the frequency inaccuracy

$$\Delta\omega = \frac{\Delta\bar{O}}{\left[\frac{\partial \langle\bar{O}\rangle}{\partial\omega}\right]} , \qquad (1)$$

where the operator $\bar{O}$ is the observable ($\hat{\sigma}_z$ in population spectroscopy on a single atom), $(\Delta\bar{O})^2 = \langle\bar{O}^2\rangle - \langle\bar{O}\rangle^2$ is the usual quantum-mechanical variance of observable $\bar{O}$, and $\partial\langle\bar{O}\rangle/\partial\omega$ is the sensitivity of the mean value of $\bar{O}$ to the applied radiation frequency. All other sources of noise are assumed negligible compared to the quantum-mechanical fluctuations $\Delta\bar{O}$; a situation which can be realized in a system of trapped ions[7]. Ramsey's method of separated oscillatory fields[8] exhibits the narrowest linewidths and hence provides the largest sensitivity for a given interaction time T. For a single atom, Ramsey spectroscopy with $\bar{O} = \hat{\sigma}_z$ yields a frequency inaccuracy of $\Delta\omega = 1/T$.

If N identical atoms are prepared in the uncorrelated state $|\downarrow_1\downarrow_2\cdots\downarrow_N\rangle$ (or $|\uparrow_1\uparrow_2\cdots\uparrow_N\rangle$), Ramsey spectroscopy on the sum observable $\bar{O} = \Sigma\hat{\sigma}_z$ can be shown to yield a frequency inaccuracy $\Delta\omega = 1/(T\sqrt{N})$ [5,7]. If, on the other hand, N identical atoms are prepared in one of the maximally entangled "EPR-like" states $[|\downarrow_1\downarrow_2\cdots\downarrow_N\rangle \pm |\uparrow_1\uparrow_2\cdots\uparrow_N\rangle]/\sqrt{2}$, Ramsey spectroscopy using the product observable $\bar{O} = \Pi\hat{\sigma}_z$ yields a frequency inaccuracy of $\Delta\omega = 1/(TN)$ [9]. Thus by using correlated atomic states, a factor of $\sqrt{N}$ can be gained in signal-to-noise ratio. Equivalently, the integration time required to reach a given inaccuracy can be reduced by a factor of N by using these maximally correlated states. By considering the time-energy uncertainty relation, it can be shown that $\Delta\omega = 1/(TN)$ is in fact the lowest possible inaccuracy

given T and N [9].

A method for creating EPR-like correlated states of trapped ions is to entangle a collective motional state of trapped ions (collective by virtue of the Coulomb interaction) with the internal spin states of the ions. Cooling trapped ions to the zero-point energy of the confining potential and thereby minimizing fluctuations of their motional state is a crucial prerequisite to this method for creating EPR states. For a harmonic ion trap, this involves cooling a collective motional degree of freedom of the ions (such as the center-of-mass) to the n=0 level, where the energy of the motion is $E = \hbar\omega_v(n+\frac{1}{2})$.

To gain insight into the zero-point energy cooling mechanism and the creation of EPR states, we first consider the interaction of radiation with a single two-level 1-D trapped atom in the Lamb-Dicke regime[10]. The absorption spectrum consists of a "carrier" at frequency $\omega = \omega_0$, and frequency-modulation sidebands at $\omega = \omega_0 \pm \omega_v$ generated from the Doppler effect. The "carrier" corresponds to transitions $|\downarrow\rangle|n\rangle \rightarrow |\uparrow\rangle|n\rangle$, the "red" sideband at $\omega = \omega_0 - \omega_v$ corresponds to transitions $|\downarrow\rangle|n\rangle \rightarrow |\uparrow\rangle|n-1\rangle$, and the "blue" sideband at $\omega = \omega_0 + \omega_v$ corresponds to transitions $|\downarrow\rangle|n\rangle \rightarrow |\uparrow\rangle|n+1\rangle$. If the excited atomic state $|\downarrow\rangle$ has linewidth $\gamma << \omega_v$, then the sidebands are resolved from the carrier, and "sideband" cooling proceeds as follows[11]. Radiation is applied at the red sideband, driving the transition $|\downarrow\rangle|n\rangle \rightarrow |\uparrow\rangle|n-1\rangle$, and spontaneous emission recycles the atom primarily to the $|\downarrow\rangle|n-1\rangle$ state. Thus the vibrational energy level is on average reduced by one quanta per cooling cycle. Cooling proceeds until the atom's mean vibrational number in the harmonic well is given by $\langle n\rangle \simeq (\gamma/2\omega_v)^2 << 1$ [12]. As $\langle n\rangle$ approaches zero, the absorption spectrum exhibits a clear asymmetry in the red and blue sidebands, which allows determination of $\langle n\rangle$ [13]. This asymmetry occurs because once in the zero-point energy state, further reduction of n is impossible.

We report cooling of a single trapped ion to the n=0 zero-point energy with the technique of resolved-sideband Raman cooling[14]. A $^9Be^+$ ion is held in a strong rf (Paul) ion trap[15] with vibrational frequencies $(\omega_x,\omega_y,\omega_z)/2\pi \simeq (11.1, 18.0, 29.5)$ MHz. In the $^9Be^+$ system, the $|\downarrow\rangle, |\uparrow\rangle$ states are identified with the long-lived $^2S_{1/2}$ hyperfine ground states, separated by $\omega_0/2\pi \simeq 1.250$ GHz. Transitions between these states are driven by applying two counterpropagating laser beams tuned so that their difference frequency δ is very near ω_0. This two-photon stimulated Raman coupling is realized by detuning each beam sufficiently far (>5 GHz) from the $^2P_{1/2}$ excited state such that the $^2P_{1/2}$ state is practically never populated[16]. Sideband Raman cooling proceeds as follows[17]. The difference frequency is tuned to the red sideband ($\delta = \omega_0 - \omega_v$), and the ion is exposed to the Raman beams, driving the stimulated Raman transitions $|\downarrow\rangle|n\rangle \rightarrow |\uparrow\rangle|n-1\rangle$. The beams are switched off, and resonant "recycle" beams populate the short-lived $^2P_{3/2}$ state (radiative

linewidth $\gamma \simeq 19.4$ MHz), which immediately returns the ion predominantly to the $|\downarrow\rangle|n\text{-}1\rangle$ state via spontaneous emission. This process is repeated until steady-state is reached. By directing the Raman beams at oblique angles to all principal axis of the ion trap, all three dimensions can be cooled with this technique.

We measure the absorption spectrum after cooling by scanning the difference frequency of the Raman beams and monitoring the population of the $|\downarrow\rangle$ state. A spectrum of the red and blue sidebands of the x dimension after Raman cooling is shown in Figure 1 below. The clear asymmetry in the features indicates that the average vibrational quantum number is $\langle n_x \rangle \simeq 0.05$, or equivalently, that the ion is in the $n_x=0$ ground state 95% of the time. We have similarly applied sideband Raman cooling to all three dimensions, resulting in the ion being in the $n_x=n_y=n_z=0$ state $\simeq 70\%$ of the time.

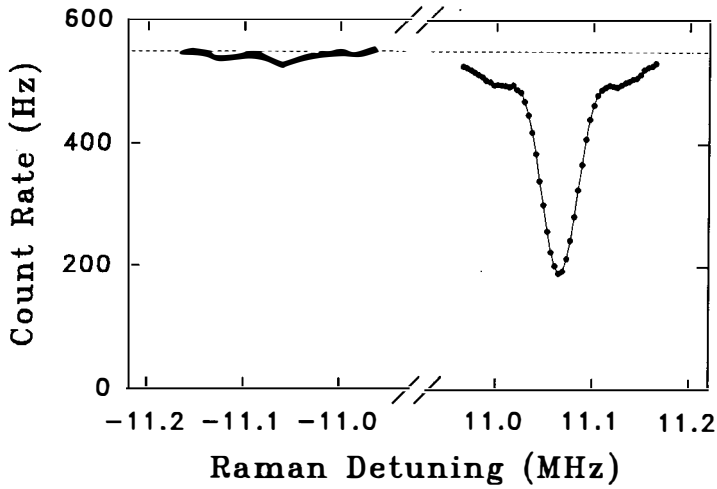

FIGURE 1. Raman absorption spectrum of the red and blue sidebands (at $\delta \simeq \mp 11.1$ MHz) after one-dimensional Raman cooling. Similar sidebands occur at $\delta \simeq \mp 18.0$ MHz and $\delta \simeq \mp 29.5$ MHz. The asymmetry in the sidebands indicates cooling to $\langle n_x \rangle \simeq 0.05$. The solid line connects the data points. The baseline corresponds to unity probability of the ion being in the $|\downarrow\rangle$ state.

The technique of sideband Raman cooling should also be applicable to more than one trapped ion. For instance, it should be possible to cool the center-of-mass motion of several harmonically trapped ions to the zero-point (all modes of collective ion motion are well resolved in

frequency[18]). The same coherent Raman coupling involved in the cooling may then be exploited to create entangled EPR states. Cirac and Zoller have earlier proposed closely related schemes for generating entangled states of free atoms traversing a high-finesse optical cavity[19], and for the demonstration of quantum logic gates on a system of trapped ions for use in quantum computation[18].

The simplest example of this scheme to create EPR states is for the case of N=2 ions whose center-of-mass degree of freedom is cooled to n=0. The initial state is then

$$\Phi_1 = |\downarrow\rangle_1 |\downarrow\rangle_2 |0\rangle_{cm} \quad . \tag{2}$$

To create a maximally-entangled EPR state from the pair, the Raman beams are centered on ion #2, and tuned to the blue sideband $\delta = \omega_0 + \omega_v$. The beams are applied for a time which is ¼ of a Rabi oscillation between the $|\downarrow\rangle_2|0\rangle_{cm}$ and $|\uparrow\rangle_2|1\rangle_{cm}$ states (a "$\pi/2$ pulse"). Ignoring phase factors, this results in the state

$$\Phi_2 = |\downarrow\rangle_1 \left[\frac{|\downarrow\rangle_2|0\rangle_{cm} + |\uparrow\rangle_2|1\rangle_{cm}}{\sqrt{2}} \right] \quad . \tag{3}$$

Next, the Raman beams are centered on ion #1 and tuned to the *red* sideband $\delta = \omega_0 - \omega_v$ for a time which is ½ of a Rabi oscillation between the $|\downarrow\rangle_1|1\rangle_{cm}$ and $|\uparrow\rangle_1|0\rangle_{cm}$ states (a "π-pulse"). The $|\downarrow\rangle_1|0\rangle_{cm}$ component remains unchanged in this step, and the EPR state is created:

$$\begin{aligned} \Phi_3 &= \frac{|\downarrow\rangle_1|\downarrow\rangle_2|0\rangle_{cm} + |\uparrow\rangle_1|\uparrow\rangle_2|0\rangle_{cm}}{\sqrt{2}} \\ &= \left[\frac{|\downarrow\rangle_1|\downarrow\rangle_2 + |\uparrow\rangle_1|\uparrow\rangle_2}{\sqrt{2}} \right] |0\rangle_{cm} \quad . \end{aligned} \tag{4}$$

It may be possible to extend this technique to more than two ions[18,19], requiring 2N-2 stimulated Raman operations to produce the maximally-entangled state $[|\downarrow_1\downarrow_2\cdots\downarrow_N\rangle \pm |\uparrow_1\uparrow_2\cdots\uparrow_N\rangle]|0\rangle_{cm}/\sqrt{2}$ from the initial uncorrelated state $|\downarrow_1\downarrow_2\cdots\downarrow_N\rangle|0\rangle_{cm}$.

It may be experimentally difficult to cool several trapped ions to the zero-point energy and at the same time individually address each ion. A geometry such as the linear rf trap[20] allows a

stable arrangement of ions along a line by making one of the trap dimensions relatively weak; however the vibrational energy levels are tightly spaced, and cooling to n=0 becomes more difficult. A further experimental difficulty is the unique addressing of individual ions with the Raman laser beams, since the ion-ion spacings in a linear trap is typically several micrometers. However, the light-shifts impressed upon individual ions will have a spatial dependence if the laser beams are strongly focused. Therefore, judicious tuning of the Raman beams may help isolate the laser interaction to select ions. An alternative geometry which may address these problems is an array of ion traps, each containing a strongly bound single ion.[21]

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