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## Demonstration of the continuous quantum Zeno effect in optical pumping

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## Abstract

A continuous quantum Zeno effect is observed in optical pumping on the 3s  ${}^{2}S_{1/2}$ -3p  ${}^{2}P_{1/2}$  transition of the  ${}^{24}Mg^{+}$  ion. Independently of the strength of a magnetic field perpendicular to a circularly polarized light beam, optical pumping into the 3s  ${}^{2}S_{1/2}$ ,  $M_{J} = +1/2$  state can in principle be obtained without absorption. © 2000 Elsevier Science B.V. All rights reserved.

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Optical pumping has since its invention in the 50's been a versatile tool for producing spin polarized atoms (see, e.g., Ref. [1]). More recently, it was shown to be an essential ingredient in sub-Doppler laser cooling [2]. Optical pumping is normally associated with absorption of light with a specific polarization followed by spontaneous emission, often with a weak magnetic bias field *along* the chosen quantization axis. Recently, we [3] as well as Kitano et al. [4] have been analyzing the situation where optical pumping without absorption can be achieved even in the presence of a magnetic field *perpendicular* to the quantization axis of the optical pumping beam.

The scheme uses the simplest kind of electronic transition in atoms where both the states have Zeeman sublevels, namely, the  $J = 1/2 \rightarrow J' = 1/2$ transition shown in Fig. 1. If a resonant  $\sigma^+$ -polarized light beam of a fixed intensity is applied to such a system, it will be pumped into the  $M_1 = +1/2$  state and no further absorption will take place. If additionally a strong magnetic field is applied perpendicular to the direction of the light beam, absorption will reappear due to the precession of the atomic spin about the magnetic field axis leading to repopulation of the  $M_I = -1/2$  state. This precession can essentially be stopped without any absorption if the laser power is at a level where the corresponding effective Rabi frequency  $\Omega$  for the  $M_I = -1/2 \rightarrow M_{I'} = 1/2$ transition is much larger than the Larmor frequency

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Fig. 1. Level diagram of the  $J = 1/2 \rightarrow J' = 1/2$  transition.  $\Omega$  indicates the light-atom interaction while  $\omega_L$  and  $\omega'_L$  present magnetic field couplings. The spontaneous decay rates from the excited states are shown as well.

 $\omega_{\rm L}$  associated with the magnetic field precession in the ground state. This can be understood in terms of a continuous quantum Zeno measurement [5], where the magnetic field induced precession is inhibited by a *possible* absorption measurement of the applied light beam. Imagine that we tried to measure the photon flux in the light beam after its passage of an atom. If the atom was in the  $M_I = -1/2$  state, the measured photon flux would vary periodically with the Rabi frequency due to absorption and stimulated emission processes when neglecting spontaneous emission. Hence, if such variation is not observed, the atom *must* be in the  $M_I = 1/2$  state and a so-called null measurement has been made. Previously, discrete quantum Zeno experiments have been demonstrated inhibiting microwave field transitions [6] and continuous quantum Zeno effects due to collisions have been observed in otho-para convertion of nuclear spin isomers [7]. Very recently, quantum Zeno effects based on inhibition of photon polarization rotation have also been use in high-efficiency quantum interrogation measurements [8]

In this Letter we present the first experimental results on a continuous quantum Zeno measurement of the type discussed above using the 3s  ${}^{2}S_{1/2}$ -3p  ${}^{2}P_{1/2}$  transition of the  ${}^{24}Mg^{+}$  ion.

The experimental setup is sketched in Fig. 2. The ions in the experiments are trapped in a linear Paul

trap (see Ref. [9] for details of the trap). UV laser beams resonant with the transitions from the 3s  ${}^{2}S_{1/2}$ to the 3p  ${}^{2}P_{1/2}$  and  ${}^{2}P_{3/2}$  states of the  ${}^{24}Mg^{+}$  ion at 280 nm are made by two frequency doubled tunable dye lasers. One laser system is used for cooling the ions on the  ${}^{2}S_{1/2} - {}^{2}P_{3/2}$  transition down in the mK regime where they crystallize [9-11], while the other is used for optical pumping on the  ${}^{2}S_{1/2} - {}^{2}P_{1/2}$ transition. The beam profiles of the UV light from the doubling cavities has interference patterns. Since it is essential to know the intensity of the pumping beam, it is spatially filtered by focusing it through a pinhole. The obtained smoother beam is then stabilized to a fixed power level by using the first-order beam from an acousto-optic modulator (AOM) controlled by a feedback signal proportional to the power in that beam. To vary the pump laser power, an electro optic modulator (EOM) and a polarizing beam splitter cube (PBS) is used. The polarization of the light is controlled by a  $\lambda/2$  and a  $\lambda/4$  plate inserted into the beam path before focusing the beam along the z-axis onto the ion crystal. The FWHM of the beam intensity profile is  $146 + 8 \,\mu m$  and the laser detuning is less than one natural linewidth  $\Gamma$  below resonance ( $\Gamma = 2\pi \times 43$  MHz). The cooling laser is  $\pi$ -polarized in the direction of the applied magnetic bias field and propagates unfiltered along the y-axis. The fluorescence from the ions is imaged by lenses to an image intensifier that is optically connected to a digital camera. The cooling laser, which is detuned a few  $\Gamma$  below resonance, is chopped at 1 kHz by a mechanical chopper with equal light and dark peri-



Fig. 2. Sketch of the experimental setup including a picture of the ion crystal.

ods. The image intensifier gate was opened for 340  $\mu$ s per chopping cycle while the cooling laser is blocked off. This ensured good cooling as long as the absorption of the pump laser was not too high (see below). Spurious magnetic fields in the crystal region, were reduced by Helmholtz coils to about  $2\mu T$ , much weaker than the applied bias field along the *x*-axis ranging from 0.04 to 1.4 mT.

A data series, taken at a fixed magnetic field. consists of 70 pictures, each exposed for 1.67 s, while the pump laser intensity with the EOM is scanned at 10 mHz from about  $0.007I_{sat}$  to  $6.8I_{sat}$ , with the saturation intensity for the  $M_J = -1/2 \rightarrow$  $M_{I'} = 1/2$  transition  $I_{sat} = 1.1 \text{ W/cm}^2$ . A region of interest containing fluorescence light from about 15 ions is selected and the integrated intensity is measured. The variation in the laser intensity over this region is less than 5%. Due to charge exchange processes of the <sup>24</sup>Mg<sup>+</sup> ions with the background gas and collision losses, the number of  ${}^{24}Mg^+$  ions in the crystal decays with a time constant of minutes. This would lead to a dramatic change in the number of fluorescing ions if the fluorescence from the whole crystal was used. By pushing the  ${}^{24}Mg^+$  ions towards one end using a single cooling laser beam directed along the *y*-axis [12] and choosing a region of interest not too far from that end, such collisional effects can be drastically reduced. The relative laser intensity is found by integrating scattered laser light on the trap electrodes in each picture, while the absolute scale is set by measuring the maximum and minimum pump laser power with a calibrated photodiode. The background light level is determined from a data sequence without any ions in the trap.

Fig. 3 presents the experimental results for five different magnetic bias field settings. For low laser intensities, the four data series with non-zero bias field, show the same linear dependence on laser intensity. This agrees with the intuitive fact that as soon as the Larmor frequency  $\omega_L$  is larger than the effective Rabi frequency  $\Omega$ , the steady state population of the two ground state Zeeman sublevels will be equal and the absorption and the spontaneous emission rates will be proportional to the laser power. In particular for the two lowest values of  $\omega_L$  (open triangles and open squares), the fluorescence decreases relatively fast with increasing laser intensity, demonstrating the continuous quantum Zeno effect



Fig. 3. Integrated fluorescence from the ions in the region of interest shown in Fig. 1 as a function of the laser intensity for several Larmor frequencies  $\omega_1$ .

discussed above. The fluorescence level tends to equal that of the zero bias field data series (open circles in Fig. 3), which in the whole intensity range shows a nearly perfect linear dependence. This is probably due to a residual linear polarization component of the pumping beam. Since absorption of linearly polarized light is independent of  $\omega_1$ , a linear dependence in the fluorescence would be expected below saturation. Fig. 4 shows the observed fluorescence for  $\pi$ - and  $\sigma^+$ -polarized pump laser beams as a function of laser power for  $\omega_{\rm I} = 0.03 \Gamma$ . A nearly linear dependence is observed in a much larger regime for  $\pi$ -polarized light than for  $\sigma^+$ polarized light where the quantum Zeno effect is observed again. Even though the Clebsch-Gordan coefficients for absorbing  $\pi$ - and  $\sigma^+$ -polarized light differ by a factor of  $\sqrt{2}$ , the fluorescence signals are identical in the low intensity limit due to the fact that excitation by linearly polarized light can take place from both ground state sublevels, while the circularly polarized light can only excite from  $M_I = -1/2$ state.

To compare our obtained experimental results with theory, we calculated the steady state density matrix based on all four atomic sublevels and their interactions with the light and magnetic fields [3], but neglecting the motional degrees of freedom. Fig. 5 presents the calculated total population of the excited state sublevels  $M_{I'} = -1/2$  and  $M_{I'} = 1/2$ 



Fig. 4. Experimental data showing the dependence of the fluorescence on the pump laser beam polarization.

as a function of the laser intensity. The Larmor frequencies are as in the experiment and the laser light was chosen to be resonant. The total excited population is directly proportional to the experimentally observed fluorescence. At very low laser intensity the population increases linearly, independent of the strength of the applied magnetic field, as in the experimental data (Fig. 3). The excited state population reach a maximum at a certain laser intensity, depending on the exact Larmor frequency  $\omega_{I}$ . For higher intensities it decreases monotonically. In our cases where the Larmor frequencies  $\omega_{I}$  are much smaller than  $\Gamma$ , analytical calculations predicts that the total population of the excited states decreases as  $(\omega_{\rm I}/\Omega)^2$  or equivalently inversely proportional to the laser intensity [3]. In this limit, the population of the  $M_J = +1/2$  state approaches 1, as  $(1 + \frac{1}{2}(\Omega/\omega_{\rm L})^2)/(\frac{7}{2} + \frac{1}{2}(\Omega/\omega_{\rm L})^2)$ . Even when  $\omega_{\rm L}$  $\gg \Gamma$ , the population of the  $M_I = +1/2$  states converges to 1 as the laser intensity goes to infinity, which means that the quantum Zeno effect is not restricted by the rate of spontaneous emission.

Qualitatively the experimental data of Fig. 3 and the calculated curves of Fig. 5 agree very well. The quantitative differences can be due to several experimental problems. During the relatively long pumping period with the cooling laser blocked, the near-resonant pump laser introduces significant heating of the ions if the average degree of excitation is high. Comparing the experimental data and the calculated curves at low values of  $\omega_{\rm L}$  where the population of

the excited states is relatively low, good agreement is obtained. For the high values of  $\omega_1$ , where also a higher degree of excitation is present, the experimental data deviates from the theoretical results. The Doppler shifts connected with this heating will lead to reduced excitation and fluorescence. The effect of the Doppler shifts could be included in more time consuming simulations taking into account the motional degrees of freedom. In future experiments the heating can be reduced by shorter pump periods and by alternating cooling and pump beams. As discussed above, a small linear component of the pump beam is probably the reason for the linear increase in fluorescence with laser intensity observed for low values of  $\omega_{I}$ . This effect should be minimized by better control of the pump laser polarization. Due to the micromotion of the ions away from the trap axis [13], we estimate that some of the ions in the chosen region of interest experience an effective detuning variation of about one  $\Gamma$ . Such a variation should according to our simulations only lead to relatively small changes of the expected signal shapes [3]. By conducting the experiments with ions on a string, the effect of micromotion can essentially be removed. The background gas pressure of a few  $10^{-8}$  Pa leads to collisions changing the structure of the ion crystal at a rate of about  $1s^{-1}$ . Though these collisions can lead to changes in the spin states of the ions during the exposure of a single picture, the rate is too low to have any significant effect on the observed fluorescence.



Fig. 5. Calculated total population of the excited sub-states as a function of the laser intensity for various Larmor frequencies  $\omega_{1}$ .

Above we have exclusively been dealing with the  $J = 1/2 \rightarrow J' = 1/2$  transition, but similar quantum Zeno effects should be observed for any  $J \rightarrow J' = J$  transition when applying circularly polarized light. In the case of J = J' where J is an integer, optical pumping with linearly polarized light to the  $M_J = 0$  state without absorption can also be obtained in a transverse magnetic field. Such states are very often used in frequency standards since they have no first order Zeeman shifts. Quantum Zeno measurements of this latter kind could probably lead to less restrictive conditions regarding stray magnetic fields in such applications in the future.

We plan to make the experiment with a single ion, but several improvements have to be made, including more efficient fluorescence detection. With a pulsed rather than continuous pumping laser, discrete quantum Zeno experiments similar to [6] can be made with the discussed system.

In conclusion, we have demonstrated the continuous quantum Zeno effect in optical pumping without absorption. The  $J = 1/2 \rightarrow J' = 1/2$  transition is the simplest case where such an effect can be studied. This situation was realized by using the 3s  ${}^{2}S_{1/2}-3p {}^{2}P_{1/2}$  transition of the  ${}^{24}Mg^{+}$  ion. The demonstrated quantum Zeno scheme can be realized with any  $J \rightarrow J' = J$  transition, with the additional possibility of optical pumping to the  $M_{J} = 0$  state when J is an integer.

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