Observation of the $^1S_0$–$^3P_0$ transition in atomic ytterbium for optical clocks and qubit arrays

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We report an observation of the weak 6 $^1S_0$–6 $^3P_0$ transition in ^{171,173}Yb as an important step to establishing Yb as a primary candidate for future optical frequency standards, and to open up a new approach for qubits using the $^1S_0$ and $^3P_0$ states of Yb atoms in an optical lattice. © 2005 Optical Society of America

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Optical clocks show great promise as the next generation of precision frequency standards due to the high frequency and correspondingly high line-Q of weakly allowed atomic transitions. Because of femtosecond comb technology,[1] clocks based on optical transitions in both single trapped ions and neutral atom clouds are poised to exceed the already very high precision set by microwave frequency standards.[2] A recent proposal combining the Lamb–Dicke confinement of single-ion frequency standards with the high signal-to-noise ratio of neutral atom clouds and exploiting a highly forbidden transition that is insensitive to external magnetic fields and trap light polarization has the potential to do even better.[3] The scheme makes use of the $^1S_0$–$^3P_0$ electric dipole transition in alkaline-earth atoms, weakly allowed in odd isotopes by the hyperfine interaction of the nuclear spin and completely forbidden by a single-photon process in even isotopes. Trapping the atoms in a Stark-free optical lattice will allow a large ensemble of atoms to exhibit a spectrum free of Doppler and recoil shifts, leading to an estimated accuracy of a few parts in 10^{18}.[4,5] As an additional application, the near absence of decoherence between the $^1S_0$ and $^3P_0$ states suggests forming a qubit from these states and creating an optical lattice array of such qubits for quantum information.[6,7]

Yb and Sr are both strong candidates for an optical lattice clock as well as for creating useful qubits. Both atoms have experimentally accessible optical transitions, allowing the atoms to be readily laser cooled and trapped, and in the case of Yb, Bose–Einstein condensed.[8] The Sr clock transition has been studied extensively, both in and out of an optical lattice.[9,10] The same transition in Yb also has attracted considerable recent interest,[5] but has thus far not been observed. Future work toward an Yb optical frequency standard will require detailed study of this transition.[5] Here we report the first step in this program, the direct excitation of the 578 nm $^1S_0$–$^3P_0$ transition in the odd isotopes ^{171,173}Yb.[11–13] We also discuss the possible application of this type of transition in making qubits for quantum computation.

The level structure of Yb is shown in Fig. 1. The experiment is performed on a sample of cold atoms collected in a magneto-optical trap (MOT) operating on the strong $^1S_0$–$^1P_1$ transition at 399 nm. To excite the clock transition, we irradiate the cloud of atoms with a 578 nm probe, continuously monitoring 399 nm fluorescence from the atom cloud. As the probe laser frequency is scanned over the clock transition, there is an observable decrease in MOT fluorescence as atoms are excited into the metastable $^3P_0$ state and escape the trap.

The experimental apparatus is diagrammed in Fig. 2. The 399 nm transition is used to decelerate an atomic beam in a Zeeman slower and then capture either ^{171}Yb or ^{173}Yb in the MOT. The 399 nm output of a frequency-doubled titanium:sapphire laser (Coherent 899-21) is locked to the atomic resonance with an adjustable detuning to prevent slow frequency drift. Further details of the MOT and Zeeman slower are discussed elsewhere.[14,15] To probe the clock transition, a ring dye laser (Coherent 899-21) is locked to a temperature-stabilized Fabry–Perot cavity. A small fraction of the laser's output is directed to an I_2 saturated absorption cell serving as a frequency reference. The main dye laser output is directed onto the MOT and its frequency continuously scanned from I_2 line 1852 through the Yb clock resonance. The MOT beams are chopped on and off at a rate of 2.5 kHz. Resonance data are taken with the probe and MOT beams chopped out of phase with each other. This procedure should completely avoid any shifts and broadening of the clock transition due to near-resonant 399 nm light while maintaining a steady-state MOT population. The MOT magnetic fields produce a negligible perturbation on the clock resonance because of the small g-factors of the $^1S_0$ and $^3P_0$ states.[5]

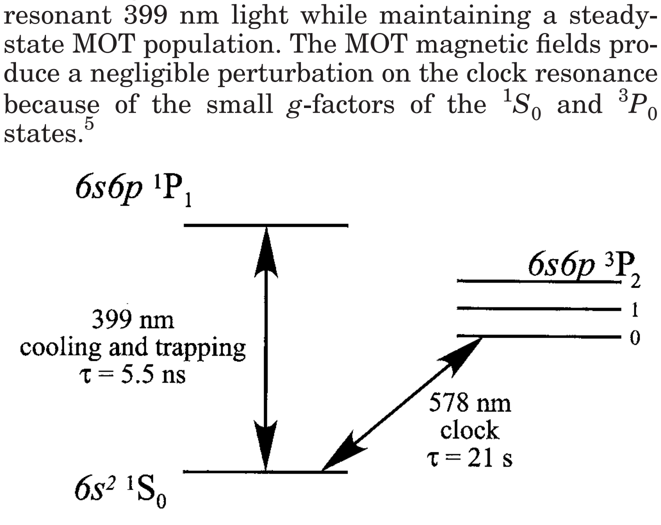

Fig. 1. Yb energy levels, transition wavelengths, and lifetimes.

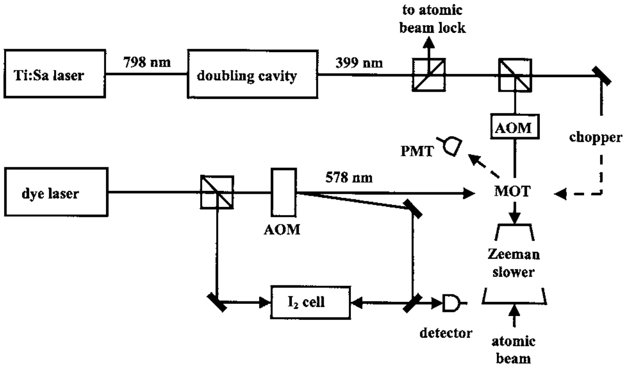

Fig. 2. Schematic of experimental setup: A frequency-doubled Ti:sapphire (Ti:Sa) laser is used for the MOT and the Zeeman slower. The Zeeman slower beam is detuned 300 MHz below the atomic resonance using a double-pass AOM. Its frequency scan is calibrated with an I_2 saturated absorption cell. The blue MOT fluorescence is detected by a photomultiplier tube (PMT).

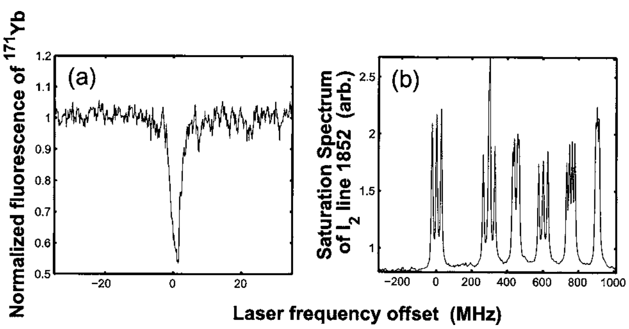

Fig. 3. (a) Normalized MOT blue fluorescence of ^{171}Yb and (b) saturation spectrum of I_2 reference line 1852 versus frequency offset of the probe laser. In (a) the probe laser is chopped out of phase with the MOT beams as discussed in the text. The frequency corresponding to zero offset in (a) is approximately 2.6 GHz below the zero shown in (b). The probe beam has a diameter of 4 mm and power of 0.04 W in (a).

The resonant absorption cross section for the $\lambda = 578$ nm photons may be written as

$$\sigma = (\sqrt{\ln 2/\pi}\lambda^2/2)(\Gamma/\Delta\omega)$$

for the case of a Gaussian line shape, where $\Delta\omega$ is the full width at half-maximum, and the natural decay rate of the $^3P_0$ state is $\Gamma \cong 5 \times 10^{-2}$ s^{-1}.[5] The fractional reduction in MOT fluorescence due to the clock transition is then

$$R = \sigma I/(\sigma I + \gamma_{\mathrm{MOT}}), \tag{1}$$

where I is the probe laser photon rate–area incident on the MOT and γ_{MOT} is the rate at which atoms are lost from the MOT in the absence of the clock transition. Typically, $\gamma_{\mathrm{MOT}} \cong 0.5$ s^{-1}. With a modest intensity Ihc/λ of 100 mW/cm^2 and a linewidth $\Delta\omega/2\pi$ of 3 MHz (which is the Doppler width at a MOT temperature of $\approx$10 mK), the value of R is $\approx$0.5. Thus, by contrast with a similar method in Sr,[9] we both expect and observe large fractional reduction in MOT fluorescence at the clock resonance.

The large MOT fluorescence reduction due to the clock resonance in ^{171}Yb is shown in Fig. 3(a). The probe laser frequency is calibrated by its detuning from a specific hyperfine resonance of the I_2 line 1852,[16] shown in Fig. 3(b). Using the data in Fig. 3(a) together with Eq. (1) yields a cross section $\sigma(\omega)$ of Gaussian shape with $\Delta\omega/2\pi = 2.7$ MHz FWHM, consistent with the expected Doppler width at a MOT temperature of 10 mK. Earlier time-of-flight measurements with this MOT yielded temperature estimates of $\approx$7 mK.[15] Further study is needed to fully quantify the sources of broadening in the clock resonance. The height of the clock resonance in Fig. 3(a) agrees to within a factor of 2 with estimates from Eq. (1), which is as good as expected considering the uncertain degree of overlap between the MOT cloud and the probe laser beam. A similar fluorescence reduction is also observed in the case of ^{173}Yb. The two clock transitions in ^{171}Yb and ^{173}Yb are approximately 2.6 and 3.9 GHz below the middle peak of the lowest frequency hyperfine component of the I_2 line 1852.

The large single-photon transition signals that occur even with relatively broad linewidths, as shown in Fig. 3(a), suggest the possibility of making controlled transitions between the $^1S_0$ and $^3P_0$ states, and hence using these long-lived states to form qubits with approximately 20 s inherent decoherence. Qubits, as basic elements in quantum computation, are extensively investigated to break through the limit of classical computers. Decoherence of atomic qubits, often caused by external magnetic fields and collisions, is generally believed to be the largest obstacle in the way of building quantum computers. Atom collisions can be reduced by trapping atoms in optical lattices and keeping low densities, and in fact methods for entangling qubits in lattices have been proposed.[6,7] However, magnetic field perturbations can be difficult and inconvenient to eliminate in experiments. Alkaline-earth atoms show intrinsic advantages in forming qubits in this respect because their metastable $^3P_0$ states and the $^1S_0$ ground states are insensitive to external magnetic fields. These states have negligible decoherence, and because of the reasonably large transition rate a qubit formed by a $^1S_0$ and a $^3P_0$ state can simply be flipped by a single-photon transition instead of more complicated two-photon Raman transitions as for alkali atoms.[6,7]

In conclusion, we have observed the weak $^1S_0$–$^3P_0$ clock transition in cold ^{171,173}Yb, which is an important step to establish Yb as one of the primary candidates for future optical frequency standards, and we have also discussed a new approach for qubits with this single-photon transition.

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