PHYSICAL REVIEW A, VOLUME 61, 051401(R)

Power-dependent loss from an ytterbium magneto-optic trap

T. Loftus, J. R. Bochinski, R. Shivitz, and T. W. Mossberg
Oregon Center for Optics and Department of Physics, University of Oregon, Eugene, Oregon 97403

(Received 4 November 1999; revised manuscript received 1 February 2000; published 7 April 2000)

Radiative decay of excited $^1P_1$ states to metastables is expected to limit attainable lifetimes in magneto-optic traps (MOTs) containing alkaline-earth-metal-like atoms. We present measurements of power-dependent loss from a $(6s^2)^1S_0$-$(6s6p)^1P_1$ ytterbium MOT, show that the observed power dependence is consistent with radiative decay from the $(6s6p)^1P_1$ excited state leading to population of lower-lying metastable states, and determine the $(6s6p)^1P_1$-to-metastable state decay rate. With weak excitation of the $(6s^2)^1S_0$-$(6s6p)^1P_1$ trapping transition, MOT lifetimes approaching 800 ms are observed.

PACS number(s): 32.80.Pj, 42.50.Vk, 95.30.Ky, 32.10.−f

Atomic ytterbium (Yb, $Z=70$) is ideally suited to studies of magneto-optic trapping involving coupled and narrow-linewidth transitions (see Fig. 1). Specifically, laser cooling resulting from two-color excitation of three-level V-type systems can be explored with the intrinsically simple 398.8-nm $(6s^2)^1S_0$-$(6s6p)^1P_1$ and 555.6-nm $(6s^2)^1S_0$-$(6s6p)^3P_1$ lines. Unlike Λ and cascade three-level atoms [1], the laser-cooling dynamics of this system have not been investigated. Additionally, the 555.6-nm transition is predicted to have a cooling limit (within an order of magnitude) [2] of the single-photon recoil temperature $T_r \sim 360$ nK, and may open new pathways for achieving ultralow temperatures and high spatial densities in a magneto-optic trap (MOT) [3,4]. With abundant bosonic ($A=168,170,172,174,176$) and fermionic ($A=171,173$) isotopes [5], Yb may provide opportunities for studying fermionic, bosonic, or composite systems. Trapped Yb has also been identified as an excellent system in which to explore optical frequency standards [6] and search for a permanent electric-dipole moment [7].

The $(6s^2)^1S_0$-$(6s6p)^1P_1$ 398.8-nm Yb transition (Einstein coefficient $A_E=1.76\times 10^8\ \mathrm{s}^{-1}$) [8] provides substantial cooling power [4,9] but is not radiatively closed. Some of the available upper-state decay channels terminate in metastable excited states. As a result, lifetimes for $^1S_0$-$^1P_1$ Yb MOTs are expected to depend on the excited-state fraction [4,10–12]. In this paper, we describe a quantitative study of Yb-MOT lifetime versus trapping-beam power. Our measurements confirm the dependence of trap lifetime on excitation level, clearly indicate that radiative decay to metastable levels is primarily responsible for this behavior, and allow us to estimate a value for the Yb $(6s6p)^1P_1$-to-metastable-state decay rate. Significantly, we find that for low trapping-beam power (low excited-state population) $^1S_0$-$^1P_1$ Yb MOT lifetimes approach 800 ms, a value that is four times longer than previously obtained with this Yb transition [4] and one to two orders of magnitude longer than similarly power-dependent lifetimes observed in strontium and calcium traps employing analogous transitions [3,10].

The Yb atomic beam used to load the MOT is generated with an effusion oven (2-mm nozzle diameter). Separate heaters maintain the oven body (nozzle) at 540 °C (780 °C), resulting in a measured flux of 10^{10} atoms/s through the trapping region (1-cm^2 cross section, located 90 cm from the nozzle). Fluorescence from this region is imaged onto a chilled photomultiplier tube (PMT) used in photon-counting configuration. The atomic beam is precooled in a 40-cm-long constant deceleration σ^- Zeeman slower [13] with a peak magnetic field of 270 G, corresponding to a capture velocity of 200 m/s.

The atoms travel 40 cm beyond the slower before entering the trapping region where water-cooled anti-Helmholtz coils produce an axial field gradient B_z' of 60 G/cm. To prevent Yb from coating the window opposite the atomic beam, the window is heated to 200 °C.

We produce 60 mW of 398.8-nm light by resonantly doubling a Ti:sapphire laser in an external buildup cavity whose resonance frequency is locked to the Ti:sapphire output frequency. The resulting 398.8-nm light is offset locked to the $(6s^2)^1S_0$-$(6s6p)^1P_1$ trapping transition via saturated absorption and feedback to the Ti:sapphire laser. A portion of the 398.8-nm beam is acousto-optically down-shifted by 500 MHz and used to precool the atomic beam in the Zeeman slower. The balance of the 398.8-nm light, with total power P_T, is expanded to a $1/e^2$ diameter of 1.5 cm and split into three pairs of mutually orthogonal retroreflected beams that, after being appropriately polarized, intersect in the center of

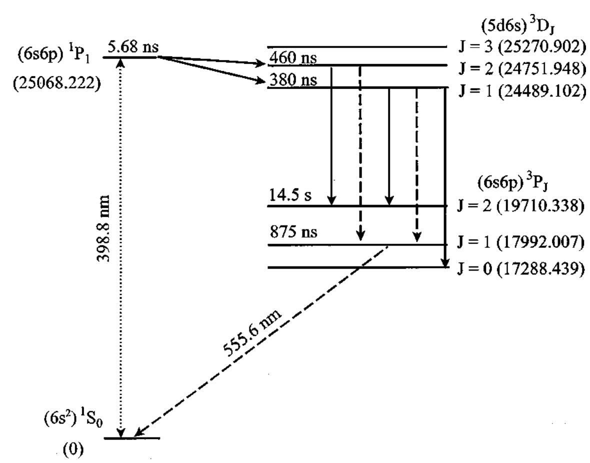

FIG. 1. A partial energy-level diagram for ^{174}Yb. Level energies (in cm^{-1}) are given in parentheses and lifetimes are shown next to the corresponding transitions. Decays denoted by solid lines terminate in metastable states, leading to trap loss.

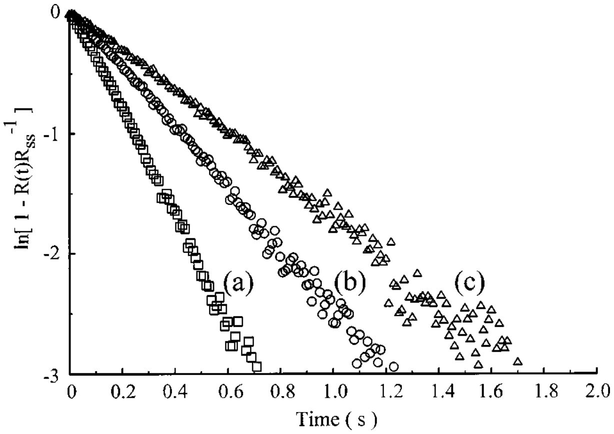

FIG. 2. Photocount rate from a ^{174}Yb MOT as a function of time after turning on the trapping beams for fixed Δ (-30 MHz) and p (6×10^{-9} Torr) and three different values of P_T. P_T is (a) 24 mW, (b) 14.5 mW, and (c) 8 mW.

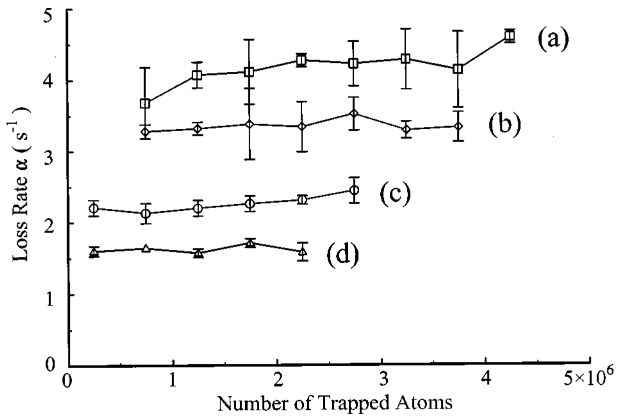

FIG. 3. Local decay slope α as a function of the absolute number of trapped atoms. Δ and p are -30 MHz and 6×10^{-9} Torr, respectively. P_T is (a) 24 mW, (b) 20 mW, (c) 14.5 mW, and (d) 8 mW.

the anti-Helmholtz field. The absolute trapping-beam energy density experienced by the atoms, μ_a, determines the excited-state population fraction. We determine μ_a through absolute measurement of P_T and modeling, based on measurement, of the trapping-beam profile as Gaussian with a 1.5-cm diameter ($1/e^2$ intensity points).

We have trapped all seven stable Yb isotopes, including ^{168}Yb (0.13% natural abundance), with maximum trap populations for the most abundant isotope, ^{174}Yb, of 10^7 atoms. In addition, we have successfully trapped five isotopes, ^{176}Yb, ^{174}Yb, ^{172}Yb, ^{171}Yb, and ^{170}Yb, without the use of Zeeman slowing, although in this case, trap populations are reduced by about 20. The remainder of this work will focus on MOTs containing ^{174}Yb that are loaded with the Zeeman slowed atomic beam.

We determined the spatial geometry of a ^{174}Yb MOT by translating a pinhole across an image of the atom cloud. During this measurement, P_T, and the detuning $\Delta=\nu_T-\nu_{174}$, where ν_T (ν_{174}) is the trapping beam (^{174}Yb $^1S_0-{}^1P_1$ transition) frequency, were 20 mW and -30 MHz, respectively. The atom cloud was approximately spherical with a diameter of 2.5 mm. Using the estimated number of trapped ^{174}Yb atoms, 4×10^6, we find an average trap spatial density of $\sim5\times10^8$ atoms/cm^3.

In Fig. 2, we study the filling rate of a ^{174}Yb MOT as a function of P_T. Specifically, we plot $\ln[1-R(t)R_{ss}^{-1}]$, where $R(t)$ (R_{ss}) is the instantaneous (steady-state) photocount rate and t is the time delay following abrupt switch-on of the trapping beams. At $t=0$, the trapping beams are switched on with a mechanical shutter (100-μs switching time). For each P_T, the plotted $R(t)$ is an average over 60 fill cycles. For all three traces, $\Delta=-30$ MHz.

It is clear that the trap fill (equivalently, the decay) rate increases with P_T over the P_T range studied. Various mechanisms for trap depopulation lead to characteristically different fill dynamics. Specifically, trap filling proceeds according to

$$dN/dt=\eta(P_T,\Delta,B_z')-[a_{2,0}f(P_T,\Delta)+p\gamma_c(f)+\xi(\Delta)P_T^3]\times N-\beta(f)N^2=\eta-\alpha(P_T,\Delta,N)N, \qquad (1)$$

where η is a loading rate, $a_{2,0}$ is the rate at which population in the $(6s6p)^1P_1$ state decays via radiative cascade into $(6s6p)^3P_{2,0}$ metastable states, p is the background gas pressure, γ_c is a background gas collision coefficient, ξ is a three-photon ionization coefficient, β is an Yb-Yb collision coefficient, N is the total number of atoms in the trap, and f is the fraction of trapped atoms in the excited state. f is given by $f=(s/2)[1+s+(2\Delta/\Gamma)^2]^{-1}$, where $\Gamma=A_E/2\pi=28$ MHz and s is the normalized energy density, $s=\mu_a/\mu_s$, where $\mu_s=1.93$ pJ/cm^3 is the $^1S_0$-$^1P_1$ saturation energy density and corresponds to the energy density of a 58-mW/cm^2 light beam. Note that the f dependence of γ_c reflects the unknown difference between ground- and excited-state scattering rates.

Measuring how the total trap decay rate α varies with P_T, Δ, and N provides insight into trap depopulation mechanisms. Depopulation resulting from Yb-Yb collisions introduces telltale nonexponential filling dynamics whose signature, for the case of Fig. 2, is an increase in α with N [14]. There is no clear indication for this behavior in Fig. 2. In Fig. 3, we plot α (i.e., the local slope of $\ln[1-R(t)R_{ss}^{-1}]$) as a function of the absolute number of trapped atoms for several different values of P_T. The data of Fig. 3 are derived from multiple measurements, at constant Δ and p, like those shown in Fig. 2. According to Eq. (1), α will be constant during trap filling provided the trap parameters are held constant and Yb-Yb collisions introduce negligible trap depopulation compared to other loss mechanisms. The local slopes shown in Fig. 3 are essentially independent of N, indicating that Yb-Yb collisions play an insignificant role, certainly when compared to the observed variation in α with P_T.

In Fig. 4, we plot α as a function of P_T and P_T^3 when when p (6×10^{-9} Torr) and Δ (-30 MHz) are constant. For each P_T measurement, fits are performed to fill data under the assumption of constant α. As shown in Eq. (1), photoionization should produce a linear α versus P_t^3 plot [8,15]. In

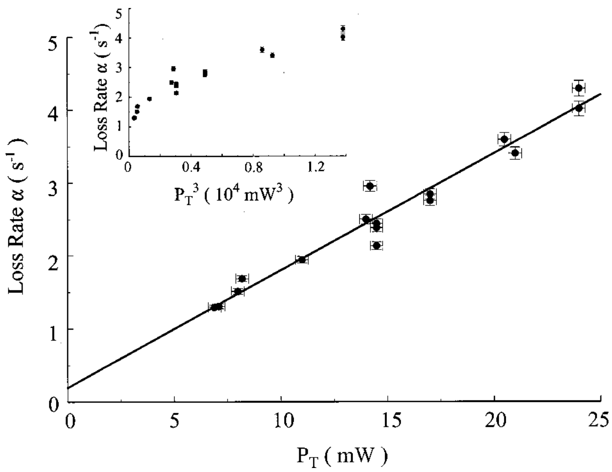

FIG. 4. Measured variation in α as a function of P_T. Observed values for α correspond to trap lifetimes τ of 200 ms$\leqslant\tau\leqslant$800 ms. The solid line is a least-squares straight-line fit. The inset shows α plotted as a function of P_T^3.

the α versus P_T^3 inset to Fig. 4, however, linearity is not observed, indicating that photoionization is not the dominant depopulation process. Measured values of α, however, do vary linearly with P_T, a behavior that is entirely consistent, in the weak excitation limit explored in Fig. 4, with depopulation proceeding via radiative decay of the $(6s6p)^1P_1$ excited state that cascades to the $(6s6p)^3P_{2,0}$ metastable states. Note also that the nonzero value of α obtained by extrapolating the α versus P_T plot to $P_T=0$ provides [according to Eq. (1)] a measure of trap depopulation resulting from Yb-background gas collisions.

The effect of background gas collisions is clarified in Fig. 5, where we plot α (again treated as a constant throughout the fill cycle) versus background chamber pressure for fixed $P_T=20$ mW and $\Delta=-30$ MHz. A linear variation of α with p is observed as expected from Eq. (1). Note that the extrapolated nonzero value of α at $p=0$ rules out the possibility that the dependence of α on P_T (see Fig. 4) results exclusively from differences in Yb ground- and excited-state scattering with background gas.

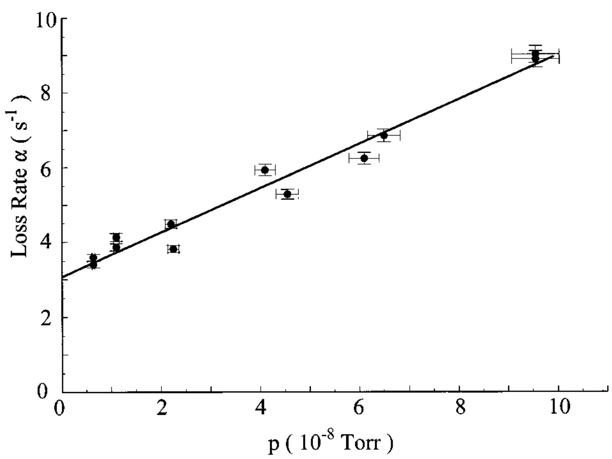

FIG. 5. Measured variation in α as a function of p. The solid line is a least-squares straight-line fit.

TABLE I. Summary of the results obtained by fitting α as a function of P_T (Fig. 4). For comparison, we include a_1 [4], and the theoretically predicted values for $a_{2,0}$, a_1, and $a_{2,0}/a_1$ [8,12]. Uncertaintites in the theoretical values were computed using the reported uncertainties in the matrix elements.

	This work	Previous work	Theory
$a_{2,0}$	23 (11) s^{-1}		6.6 (4.6) s^{-1} [a]
a_1		21.3 (2.6) s^{-1} [b]	5.2 (2.6) s^{-1} [a]
$a_{2,0}/a_1$	1.1 (0.5) [b]		1.25 (0.34) [a]

[a]References [8,11].
[b]Reference [4].

We conclude, on the basis of the measurements and analysis above, that radiative decay of the $(6s6p)^1P_1$ state, leading to population of the $(6s6p)^3P_{2,0}$ metastable states (see Fig. 1) is the dominant trap loss mechanism responsible for the observed power dependent fill rates. Using Eq. (1), we can estimate the value of $a_{2,0}$. To do so, we must make accurate estimates of the excited-state fraction f which depends on the absolute energy density μ_a and detuning Δ. Both of these quantities vary spatially throughout the MOT; the former due to the transverse profile of the trapping beams and their mutual interference and the latter due to the spatially varying magnetic field. As such, precise determination of f is difficult. In estimating f, we note that the trapping beams are relatively weak and thus replace the spatially varying value of μ_a with its trap-volume average. We also neglect magnetic-field-induced detuning variations. Overall, we estimate that our deduced value for f is accurate at the 50% level. Errors in f, therefore, are the dominant source of uncertainty in our estimate of $a_{2,0}$.

To obtain $a_{2,0}$ from the variation of α with P_T, we use the slope of the straight-line least-squares fit shown in Fig. 4, an approximation that is well justified in the weak excitation regime explored here. This result is summarized in Table I, where for comparison we include the recently measured value for a_1, i.e., the rate for decays from the $^1P_1$ state that lead to population of the $^3P_1$ state [4,8], and theoretically predicted values for $a_{2,0}$, a_1, and the ratio $a_{2,0}/a_1$. We note that Ref. [4] measured the ratio a_1/A_E, and was thus less sensitive to absolute errors in trapping beam power than is the case here. Theoretical values were determined by combining the reduced matrix elements reported by Porsev *et al.* [12], with experimental values for the relevant transition frequencies [8].

Interestingly the ratio $a_{2,0}/a_1$, determined from the present measurement and the measurement of Ref. [4], is consistent with the theoretically predicted value. Absolute values for $a_{2,0}$ and a_1, however, are larger than the theoretically predicted values by about 4. Investigation of both experimental and theoretical methods are required to determine the source of this discrepancy.

In conclusion, we have measured power-dependent loss from a ^{174}Yb $^1S_0$-$^1P_1$ MOT and shown that the observed power dependence results, at least in large part, from decays of the $^1P_1$ state that transfer population to metastable states.

Our measured rates are consistent with a related experimental measurement but deviate significantly from the theoretically expected values.

The authors with to thank D. Alavi for providing significant assistance with designing and constructing the resonant frequency doubler and D. McIntyre, P. Anandam, and C. Oates for many useful comments and suggestions. We gratefully acknowledge financial support from the National Science Foundation under Grant No. PHY-9870223.

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