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MAGNETIC TRAPS

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Magnetic trap for thulium atoms

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***Abstract*. For the first time ultra-cold thulium atoms were trapped in a magnetic quadrupole trap with a small field gradient (20 Gs cm^{-1}). The atoms were loaded from a cloud containing 4×10^5 atoms that were preliminarily cooled in a magneto-optical trap to the sub-Doppler temperature of 80 μK. As many as 4×10^4 atoms were trapped in the magnetic trap at the temperature of 40 μK. By the character of trap population decay the lifetime of atoms was determined (0.5 s) and an upper estimate was obtained for the rate constant of inelastic binary collisions for spin-polarised thulium atoms in the ground state ($g_{\text{in}} < 10^{-11}$ cm^3 s^{-1}).**

Keywords: *laser cooling of atoms, magnetic interaction, thulium atom, magnetic quadrupole trap.*

1. Introduction

Ultra-cold gases composed of strongly-magnetic atoms (Cr, Er, Dy, Tm) are unique physical systems because they allow direct observation of magnetic anisotropic long-range dipole – dipole interaction, which considerably differs from van der Waals interaction. This interaction can be controlled by external fields [1], which allows one to employ such strongly correlated atomic systems as a model of solid-state superconductors (see, for example, [2]). Dipole – dipole interactions are especially manifested in quantum condensates [3]. Bose-condensate of chromium atoms [4] exhibited quantum ferromagnetism [5, 6], and in rubidium atoms the phase metal – isolator transition was observed [7]. Magnetic interactions occur in non-condensed media as well, being responsible, for example, for anisotropic spread of a cloud of cooled dysprosium atoms [8].

For trapping atoms in magnetic traps (MTs), strong high-gradient magnetic fields are conventionally used [3, 9] combined with atom cooling. However, for some atoms from the lanthanide group, loading to MT is simplified due to the unfilled inner electron 4f-shell. Such atoms have a large magnetic moment in the ground state ($4\mu_{\text{B}}$ for Tm, $6\mu_{\text{B}}$ for Er, and $10\mu_{\text{B}}$ for Dy, where μ_{B} is the Bohr magneton), which makes them attractive in investigations of anisotropic magnetic interactions and synthesis of magnetic molecules [10 – 12]. In addition, close values of Lande g-factors for the levels involved in laser cooling make it possible to reach sub-Doppler temperatures directly in a magneto-optical trap (MOT) [13]. For example, in the USA, Er [14] and Dy [8] atoms trapped in a shallow MT formed by a quadrupole field of the MOT were investigated. The present work is aimed at investigating laser-cooled thulium atoms trapped in the MT with a small field gradient (20 G cm^{-1}).

For the first time, laser cooling of thulium atoms was demonstrated at the P.N. Lebedev Physics Institute in 2010 [15]. The interest to thulium atoms (the only stable isotope ^{169}Tm has the nuclear spin $I = 1/2$) is explained by specificity of the electron levels of lanthanides with an unfilled inner shell. So, a line width of the magneto-dipole transition at the wavelength of 1.14 μm between two sublevels of the ground state fine structure of ^{169}Tm is as small as ~ 1 Hz [16]. The transition is weakly affected by the static and dynamic Stark-effects [17], which makes it attractive for employing in the atomic clocks based on optical lattices [18]. By investigating atoms in the MT one may preliminarily analyse the rate of atom leak from the trap, which is important in solving a problem of Bose-condensation for lanthanides.

2. Obtaining ultra-cold atoms

The first step towards obtaining ultra-cold atoms is creating a MOT [19], in which atoms may usually be cooled to a temperature corresponding to the Doppler limit [20]. The Doppler limit for the strong transitions involved in primary laser cooling is a fraction of millikelvin. In alkali atoms most frequently used in laser cooling, sub-Doppler cooling in the MOT and, consequently, reaching lower temperatures are blocked by a residual magnetic field [21, 22]. Thus, usually a special sub-Doppler cooling cycle is used, capable of cooling atoms almost to the recoil limit (the temperature, which is determined by the recoil effect where an atom absorbs a photon), which is several μK. During the cycle, the gradient magnetic field of the MOT is switched off, the holding force vanishes, and the atomic cloud spreads. At the cycle end, the atoms are re-trapped in either an optical dipole [23], or magnetic [24] trap, which holds the cooled atoms. Ultra-cold atoms trapped in such traps are used in a wide range of problems: in obtaining quantum condensates, study of collisions, optical clocks, etc. As it

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was mentioned in Introduction, specific features of some lanthanides allow one to escape a special cycle of sub-Doppler cooling.

In our experiments, approximately 4×10^5 of thulium atoms were cooled and trapped in the MOT that operated on the $4f^{13}6s^2\,(J = 7/2) \rightarrow 4f^{12}5d_{3/2}6s^2\ \ (J = 9/2)$ transition at the wavelength of 410.6 nm [15]. Laser cooling and atom trapping were performed by means of a three-dimensional system of specially prepared magnetic and light fields [19]. The magnetic field in the MOT has the quarupole configuration produced by two coils in anti-Helmholtz configuration with a vertical axis. The field axial gradient at the trap centre was 20 Gs cm^{-1}. In a thulium MOT, the sub-Doppler cooling is observed [13] down to the temperature of 25 ± 5 μK, with the efficiency depending on the detuning of laser radiation frequency from that of cooling transition and on laser field intensities. In the experiments described in the present paper, the temperature of atoms in the MOT was 80 ± 10 μK.

The magnetic trap was formed by the same magnetic field that was used in the MOT. Since a three-dimensional minimum of the magnetic field is produced at a centre of the trap the only atoms whose potential energy rises with an increase in the field may be captured by the trap [25]. At the characteristic MT dimension of approximately 1 cm, its depth for thulium atoms is dozens of millikelvin, which provides trapping of the atoms that are in certain (see below) quantum states directly from the MOT.

Note that in an active MOT the atom continuously absorbs and emits photons with various polarisations moving around the three-dimensional minimum of a magnetic field. This leads to total mixing of magnetic sublevels and the atoms cannot be confined in the MT. As soon as light is switched off, the atoms stop scattering and some of them are trapped in the MT. The trap retains only those atoms for which the magnetic force is greater than gravity, which in our experiment is only valid for the atoms with the magnetic quantum numbers of the ground state $m_F = 2$, 3, 4. In view of the fact that initially atoms are distributed over nine equally populated magnetic sublevels of the ground state ($F = 4$), the MT traps at most one third of the atoms from the MOT.

For studying the MOT and MT we used the ballistic spread method. After the MOT is completely loaded, the light beams are switched off for a time interval Δt. Then the cloud is irradiated by a short-duration resonance light pulse and the luminescence is collected onto a CCD camera with magnification 1 : 1. Figure 1 presents the photographs of the atomic cloud spread with an active and inactive quadrupole magnetic field in the MOT. In Figure 1a, the cloud isotropically spreads and falls in the gravity field. In a time interval of ~ 10 ms, the signal from the cloud cannot be distinguished on the noise background. One can see that with the active gradient field, the fraction of MOT atoms is trapped for a time interval that is substantially longer than the characteristic time of atomic spread from the MOT. These are spin-polarised thulium atoms trapped in the MOT.

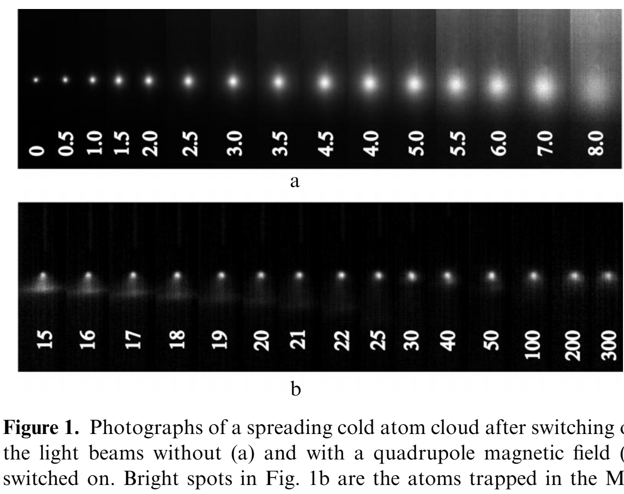

Figure 1. Photographs of a spreading cold atom cloud after switching off the light beams without (a) and with a quadrupole magnetic field (b) switched on. Bright spots in Fig. 1b are the atoms trapped in the MT. Numbers indicate the time Δt (in ms) passed since light switching off.

3. Spatial profile of concentration distribution and temperature of atoms in the MT

The spatial distribution of the atomic concentration in the MOT is easily determined from thermodynamic considerations. We may write the expressions for the potential energy of an atom around a zero quadrupole magnetic field (the axis of symmetry z is directed vertically) in the gravity field:

$$U(x, y, z) = \bar{\mu}\sqrt{x^2 b_x^2 + y^2 b_y^2 + z^2 b_z^2} + mgz, \qquad (1)$$

where $\bar{\mu}$ is the effective magnetic moment of the atom; $b_x = \partial B_x/\partial x$, $b_y = \partial B_y/\partial y$ and $b_z = \partial B_z/\partial z$ are the gradients of the magnetic field; m is the atomic mass; g is the gravitational acceleration acting along the z axis. The vertical (p_z) and horizontal (p_x) profiles of the atomic concentration in the MT are given by the expressions

$$p_z(z) = \int\int_{-\infty}^{+\infty} \exp\left[-\frac{U(x, y, z)}{k_B T}\right] dx dy,$$

$$p_x(x) = \int\int_{-\infty}^{+\infty} \exp\left[-\frac{U(x, y, z)}{k_B T}\right] dz dy,$$

where T is the temperature. The profiles along x and y axes coincide. The integrals are taken analytically:

$$p_z(z) = N_z \exp\left(-2\frac{|z|}{\tilde{z}} - 2\tilde{g}\frac{z}{\tilde{z}}\right)\left(1 + 2\frac{|z|}{\tilde{z}}\right),$$
$$p_x(x) = N_x \exp\left(-2\frac{|x|}{\tilde{x}}\sqrt{1 - \tilde{g}^2}\right)\left(1 + 2\frac{|x|}{\tilde{x}}\sqrt{1 - \tilde{g}^2}\right), \qquad (2)$$

where N_z and N_x are normalisation factors;

$$\tilde{z} = 2k_B T/(\bar{\mu} b_z); \quad \tilde{g} = mg/(\bar{\mu} b_z);$$
$$\tilde{x} = 2k_B T/(\bar{\mu} b_x); \quad \tilde{y} = 2k_B T/(\bar{\mu} b_y). \qquad (3)$$

The vertical profile of the atomic concentration in the MT measured in a time lapse $\Delta t = 100$ ms after switching off the light beams is presented in Fig. 2. The total profile half-height width is 430 ± 40 μm.

From the spatial profile of concentration one can find the atomic temperature in the MT. Indeed, (3) entails

$$T = \frac{mg}{2k_B}\frac{\tilde{z}}{\tilde{g}}. \qquad (4)$$

Figure 3 shows the time dependence of the atomic

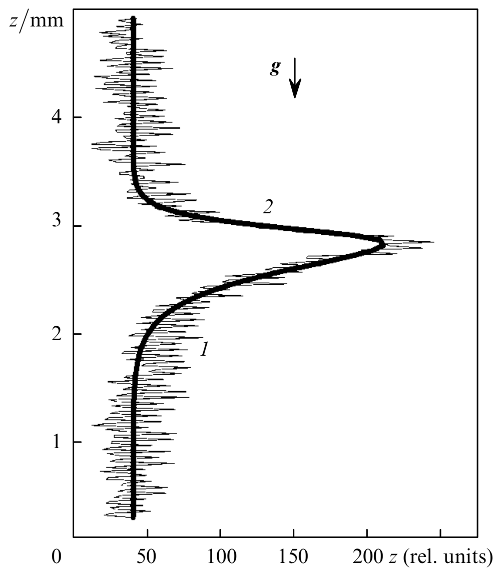

Figure 2. Vertical profile of an atomic concentration p_z in the MT (*1*) and its approximation (*2*) by formula (2) at $\tilde{z} = 203 \pm 15$ μm, $\tilde{g} = 0.5 \pm 0.1$.

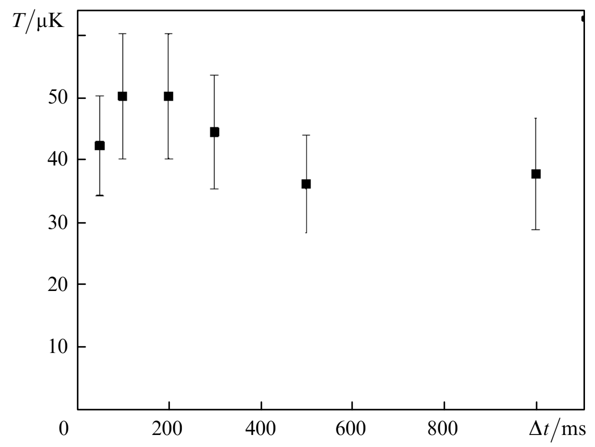

Figure 3. Atomic temperature in the MT versus time Δt passed since switching off the light sources.

temperature in the MT. The average temperature of atoms in the MT was 40 ± 10 μK, which corresponds to their root-mean-square velocity of ~ 10 cm s^{-1}. The initial temperature of atoms in the MOT was 80 ± 10 μK.

4. Number of atoms, atomic lifetime and collisions in the MT

The number of atoms trapped in the MT was determined by a signal of an absolutely calibrated CCD-camera. Figure 4 presents the dependence of the total number of atoms in the MT on the time Δt passed since switching off the light beams in the MOT. The greatest number of trapped atoms was 4×10^4, which is approximately 10 % of the atoms in the MOT. The atomic concentration at a centre of the MT was $\sim 10^9$ cm^{-3}. The relatively low atomic concentration and, consequently, low signal/noise ratio are explained by a small magnetic field gradient. The error of determining the number of trapped atoms related to

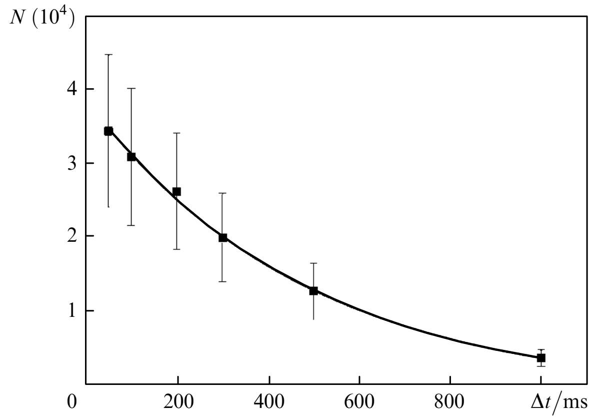

Figure 4. Dependence of the number of atoms in the MT versus time Δt (points) and its approximation by the exponent (solid curve) with the lifetime $\tau = 0.5$ s.

subtraction of the noise background from the images obtained in the MT was 15 %.

The dynamics of the atomic concentration n in the MT is described by the following equation

$$\frac{\mathrm{d}n(t,r)}{\mathrm{d}t} = -\frac{n(t,r)}{\tau} - g_{\mathrm{in}} n^2(t,r), \tag{5}$$

where τ is the atomic lifetime in the MT; $g_{\mathrm{in}} = \langle \sigma v \rangle$ is the rate constant for inelastic binary collisions of thulium atoms in the ground state with each other; σ is the collision cross section; v is the velocity of atoms. We assume that the collisions are due to the magnetic dipole–dipole interaction [26], which transfers thulium atoms to the states with lower m_{F} thus preventing them from participating in trapping to the MT. The first summand in (5) describes linear losses related, for example, to collisions of the trapped atoms with particles of a residual gas in a vacuum chamber and with atoms from the atomic beam or to Majorana spin flip [27, 28] (non-adiabatic motion of the trapped particles passing the zero-filed domain in the MT). An important role may play technical noises such as current fluctuations in coils and radio-frequency pickups, which also result in spin flips. To transfer from the atomic concentration n to the total number of trapped atoms N, we may integrate (5) over spatial coordinates. Then we obtain

$$\frac{\mathrm{d}N(t)}{\mathrm{d}t} = -\frac{N(t)}{\tau} - \frac{g_{\mathrm{in}} N^2(t)}{8} \frac{(1-\tilde{g}^2)^2}{\pi \tilde{x}\tilde{y}\tilde{z}}, \tag{6}$$

where

$$N(t) = \iiint_{-\infty}^{+\infty} n(t,r)\mathrm{d}^3 r. \tag{7}$$

Since the temperature T and the effective magnetic moment of atoms $\bar{\mu}$ are actually time independent, the parameters $\tilde{x}$, $\tilde{y}$, $\tilde{z}$ and $\tilde{g}$ may be considered constant. Then the solution to (6) will have the form

$$N(t) = N(0)\exp(-t/\tau)\times$$

$$\times\left\{1+\frac{g_{\rm in}}{8}\frac{(1-\tilde{g}^2)^2}{\pi\tilde{x}\tilde{y}\tilde{z}}N(0)\tau[1-\exp(-t/\tau)]\right\}^{-1}. \qquad (8)$$

Unfortunately, high linear losses and small atomic concentration have militated against observing inelastic binary collisions directly. Nevertheless, by approximating the time dependence of the number of atoms by formula (8) (see Fig. 4) we obtain an upper limit for the constant $g_{\rm in}$ in the case of thulium: $g_{\rm in} < 10^{-11}$ cm^3 s^{-1}, which agrees with the results of previous investigations performed at the temperature of 1 mK [9]. Note that the values of the rate constant $10^{-12} - 10^{-11}$ cm^3 s^{-1} were also obtained for other strongly magnetic atoms (Er [9], Dy [29, 8], Cr [26]). These values, seemingly, make impossible reaching Bose-condensation of atoms in the MT. For this purpose, one may employ an optical dipole trap, which allows trapping the spin-polarised atoms residing in a lowest magnetic sublevel of the ground state of Tm [4].

5. Conclusions

The MT for thulium atoms formed by a quadrupole field of the MOT was investigated, in which we succeeded to trap $\sim 4\times10^4$ of thulium atoms. The concentration of atoms at the trap centre was $\sim 10^9$ cm^{-3} with the lifetime $\tau = 0.5 \pm 0.1$ s. By analysing the atom leak from the MT we obtained an upper estimate for the rate constant of binary collisions for spin-polarised atoms in the ground state: $g_{\rm in} < 10^{-11}$ cm^3 s^{-1}. The temperature of atoms in the MT determined by their concentration distribution was found to be 40 ± 10 μK.

In further investigations of ultra-cold thulium atoms we plan to perform their secondary cooling on the weak transition at the wavelength of 530.7 nm, which may help cooling atoms down to the recoil limit and opens the possibility to load atoms to an optical dipole trap operating at the wavelength of 532 nm. In such a trap, it becomes possible to study interaction of spin-polarised atoms and the magneto-dipole metrological transition at the wavelength of 1.14 μm in more detail.

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