Quantum Electronics **51** (6) 490–494 (2021)

https://doi.org/10.1070/QEL17580

Loss of atoms from a near-resonance hollow dipole trap

V.A. Vinogradov, K.A. Karpov, A.V. Turlapov

Abstract. **The lifetime of a gas of ^{6}Li atoms in a large hollow optical dipole trap formed by radiation with a frequency detuned by 4 or 2 GHz upward from resonance is measured. The trap has the shape of a thin-walled cylinder with flat bases and a volume of ~1 mm^3. The main mechanism responsible for the loss of atoms is heating due to Rayleigh scattering. The influence of collisions of atoms with the background gas and with each other on the measured lifetime is negligible.**

Keywords: *laser trapping and cooling, dipole force, lifetime of atoms in dipole traps.*

The capture of a gas of atoms in an optical dipole trap was first performed in 1986 [1]. Such traps can be used in the study of quantum gases [2–4] and atoms in Rydberg states [5, 6], for the implementation of quantum informatics algorithms [7–9], for creating frequency standards [10, 11], as well as for vacuum measurement [12].

The depth of the dipole trap potential is relatively small. To trap atoms in a dipole trap, they must be pre-cooled and localised, e.g., in a magneto-optical trap (MOT) [13]. The attainable depth of the potential and the spatial overlap of the MOT with the dipole trap limit the efficiency of transferring atoms from the MOT. For ^{6}Li atoms, a MOT was obtained that holds $N = 10^{10}$ particles in a volume of ~1 cm^3 at a temperature of 1.4 mK [14]. Large-volume dipole traps make it possible to intercept a significant fraction of atoms from the MOT [15].

After the trapping of atoms, their loss from the dipole trap can be due to several reasons: collisions of atoms with the background gas [12, 16], heating due to fluctuations in the intensity and position of the laser beam [17], collisions of atoms of the trapped gas with each other [18, 19], and heating due to Rayleigh scattering of light by atoms [13]. A pressure of ~10^{-11} Torr attainable in experiments with ultracold gases in a vacuum chamber determines the lifetime of atoms (a few minutes) [16]. The use of stable laser sources makes it possible to minimise heating due to intensity fluctuations, the effect of which limits the lifetime to values of ~2.3×10^4 s [20], while in the experiment the lifetime was 400 s. For ^{6}Li, it is possible to prepare atoms in a state resistant to pair collisions [19]. The frequency of Rayleigh scattering and, accordingly, heating decrease with an increase in the detuning of the frequency of the trap laser beams from the transition frequency in the atom [13]. For traps with large detuning, scattering is small, and the confining potential is conservative at times up to 1 h [16]. For a near-resonance hollow optical dipole trap described in Ref. [15], the Rayleigh scattering frequency is much higher. At the same time, traps with thin walls make it possible to reduce the Rayleigh heating in comparison with thick-walled ones [21].

In this work, the lifetime of ^{6}Li atoms in a hollow dipole trap is measured. The mechanisms of the loss of atoms that limit their lifetime are investigated. The hollow dipole trap used here has the form of a cylinder with flat bases. The region in which atoms are confined is formed by optical fields, schematically shown in Fig. 1. A vertical light tube with a ring-shaped cross section restricts the motion of atoms in the xy plane, and motion along the z axis is limited by flat walls (light beams). The transverse profile of a ring-shaped beam in the xy plane is shown in Fig. 2a, and the profile of the flat beam at $x = 0$ is shown in Fig. 2c. Light fields produce a repulsive dipole potential, since the laser radiation frequency ω is greater than the frequency ω_0 of the nearest electric dipole transition in the atom. The dipole trap for ^{6}Li was formed by radiation tuned in frequency by $\Delta_{D_2}/2\pi = (\omega - \omega_0)/2\pi =$ 4 GHz upward from the frequency of the D_2 line of the transition $2S_{1/2} \to 2P_{3/2}$ with a wavelength of 671 nm (hereinafter, the detuning is $\Delta_{D_2}/2\pi$). The fine splitting in ^{6}Li is 10 GHz, which is comparable to the detuning value. In this case, the potential $U(\boldsymbol{r})$ of the dipole force is related to the light intensity profile $I(\boldsymbol{r})$ as follows [13]:

$$U(\boldsymbol{r}) = \frac{\pi c^2 \Gamma I(\boldsymbol{r})}{2\omega_0^3}\left(\frac{2}{\Delta_{D_2}} + \frac{1}{\Delta_{D_1}}\right), \qquad (1)$$

where Γ is the inverse lifetime of the atomic excited state, and the detuning $\Delta_{D_1}/2\pi$ of the radiation frequency upward from the frequency of the D_1 line is 14 GHz.

The power of the ring-shaped beam is 50 mW, the full width of the ring-shaped walls (Figs 2a and 2b) at the half-maximum intensity level in the plane of the smallest thickness is 31 μm, and the diameter of the ring is 1 mm, which yields a potential height of 740 μK. Radiation beams with a power of

V.A. Vinogradov, A.V. Turlapov International Center for Quantum Optics and Quantum Technologies, Bolshoi bul'var. 30, stroenie 1, Skolkovo, 121205 Moscow, Russia; Institute of Applied Physics, Russian Academy of Sciences, ul. Ulyanova 46, 603950 Nizhny Novgorod, Russia; e-mail: turlapov@appl.sci-nnov.ru;
K.A. Karpov International Center for Quantum Optics and Quantum Technologies, Bolshoi bul'var. 30, stroenie 1, Skolkovo, 121205 Moscow, Russia; Institute of Applied Physics, Russian Academy of Sciences, ul. Ulyanova 46, 603950 Nizhny Novgorod, Russia; Moscow Institute of Physics and Technology (National Research University), Institutskii per. 9, 141700 Dolgoprudnyi, Moscow region, Russia; e-mail: kkarpov@appl.sci-nnov.ru

Received 4 March 2021; revision received 26 April 2021
Kvantovaya Elektronika **51** (6) 490–494 (2021)
Translated by V.L. Derbov

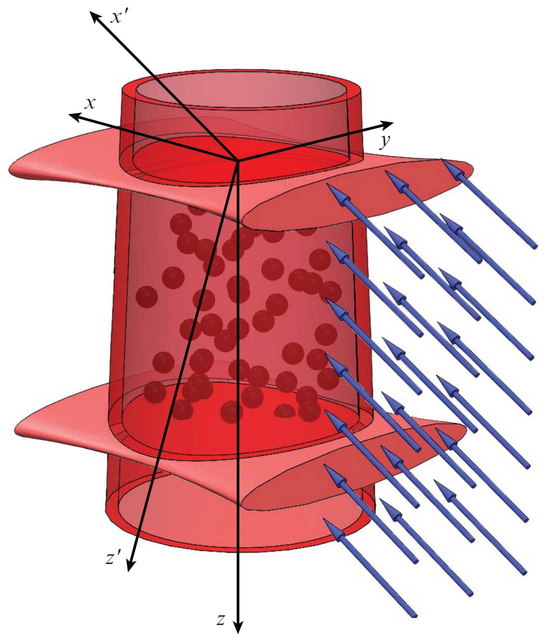

Figure 1. (Colour online) A gas of atoms (spheres) trapped in a space limited by beams of light (shown in shades of red), and resonant radiation for imaging (blue arrows). A ring-shaped beam propagates along the z axis; two flat beams, along the x axis; and beams for imaging, along the x' axis.

17 mW each, the distance between which is 1 mm, form the flat walls. The elliptical profile of the beams (Figs 2c and 2d) with full widths of 41 μm and 1.37 mm at a half-maximum intensity level produces barriers with a height of 410 μK.

In the experiment, the number of trapped atoms populating the $2S_{1/2}$ ($F = 3/2$) level was measured, depending on the confinement time, and from these data their lifetime was determined. To find the concentration distribution of atoms and their number, we used a method of absorption imaging [22, 23]. The gas in the trap was illuminated by a radiation pulse with a frequency resonant to the frequency of the transition $2S_{1/2}$ ($F = 3/2$) $\rightarrow$ $2P_{3/2}$. The radiation intensity was 0.2 mW cm^{-2}, and the pulse duration was 10 μs. Due to the absorption of part of the radiation by the atoms, a shadow region appeared. The transmitted radiation was projected onto a CMOS (complementary metal–oxide–semiconductor) matrix. Figures 3 and 4 show the spatial distributions of light absorption $f(y, z')$ by atoms in the MOT and in the hollow trap, respectively, immediately after switching the MOT beams off. The distributions $f(y, z')$ were calculated in the object plane as the intensity ratio of the absorbed light and the illuminating radiation. Part of the illumination (less than 10%) of the matrix from other sources, e.g., the dipole trap beams, can be taken into account using a background frame, i.e., a frame in the absence of illuminating radiation. This frame is subtracted from the images of both the transmitted

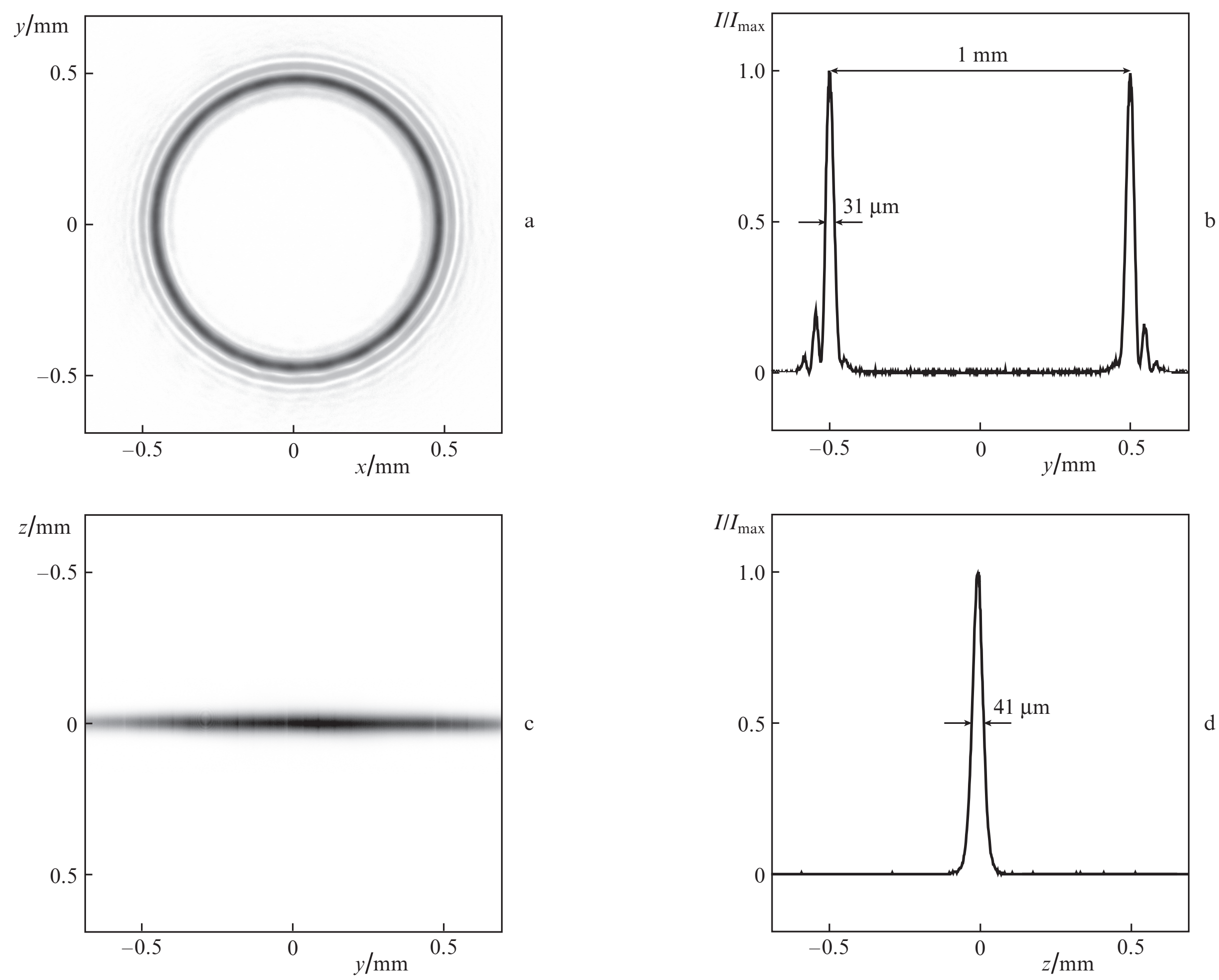

Figure 2. (a) Section of the ring-shaped beam in the xy plane, (b) section of the beam a by the y axis, (c) section of the flat beam in the yz plane and (d) section of the beam c in the z axis.

light and the illuminating radiation, which propagates along the x' axis (see Fig. 1). The x' axis lies in the xz plane and makes an angle of 30° with the x axis. The z' axis is chosen orthogonal to the yx' plane. The yz' plane corresponds to the plane of the object in Figs 3 and 4. The upper and lower boundaries of the trap in Fig. 4, formed by flat beams, look blurry, since the shooting is executed at an angle.

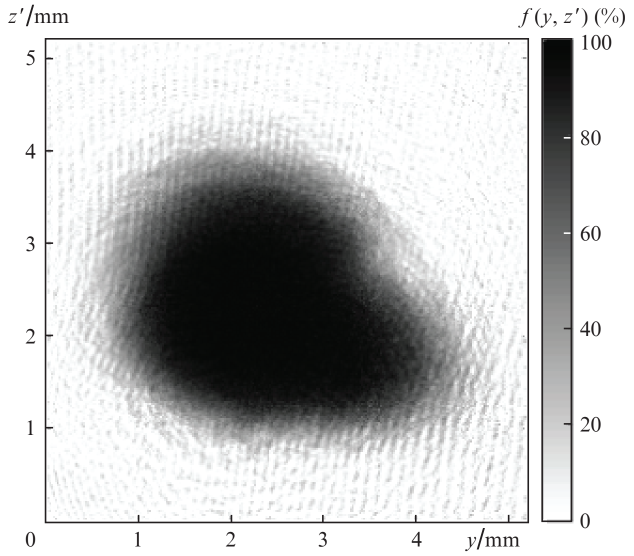

Figure 3. Distribution of light absorption by a cloud of atoms immediately after switching off the beams of the MOT in the absence of a dipole trap.

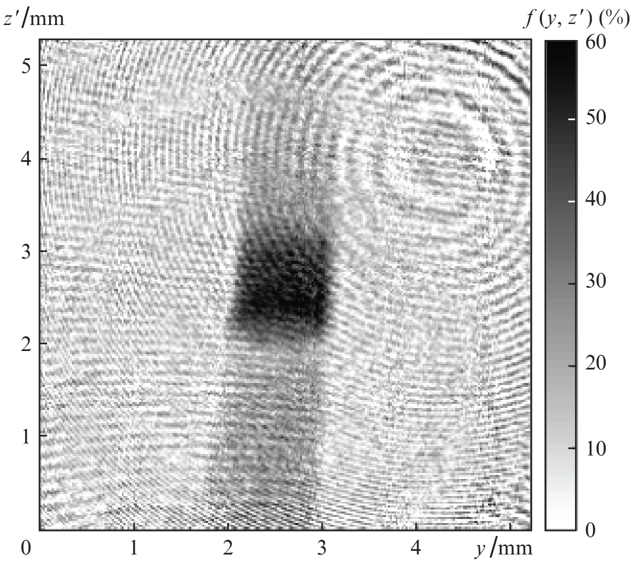

Figure 4. Distribution of light absorption by a cloud of atoms trapped in a hollow dipole trap 5 ms after switching off the MOT beams.

The number of atoms trapped in a dipole trap can be calculated from Fig. 4 by relating the fraction of absorbed light f with the concentration distribution n in the approximation of a two-level atom:

$$\ln(1 - f(y,z')) = -\sigma \int n(x',y,z')\,\mathrm{d}x', \qquad (2)$$

where $\sigma = \lambda^2/\pi$ is the cross section of the illuminating radiation scattering averaged over possible transitions. Some of the atoms (20%) populating the level $2S_{1/2}$ ($F = 1/2$) do not participate in the imaging process. Optical pumping of atoms in the MOT leads to a nonequilibrium population of the energy levels. Atoms in the MOT are affected by radiation consisting of two frequency components. One component is close to resonance with the transition $2S_{1/2}$ ($F = 3/2$) $\rightarrow$ $2P_{3/2}$, the second, with the $2S_{1/2}$ ($F = 1/2$) $\rightarrow$ $2P_{3/2}$ transition. The level populations depend on the ratio of the intensities of these components. The number of atoms populating the level $2S_{1/2}$ ($F = 1/2$) was found by measuring the absorption of radiation with a frequency resonant to the frequency of the $2S_{1/2}$ ($F = 1/2$) $\rightarrow$ $2P_{3/2}$ transition. The ratio of the populations of the levels $2S_{1/2}$ ($F = 1/2$) and $2S_{1/2}$ ($F = 3/2$) remains unchanged throughout the experiment.

The procedure for trapping atoms in the MOT is described in Ref. [15]. In the present paper, there is no additional cooling phase in beams with low intensity, and the components of MOT beams with different frequencies are turned off simultaneously. By the time they are turned off, a 3 mm cloud is formed (Fig. 3) containing 100 million atoms. The temperature determined from the ballistic expansion of the cloud is 1–3 mK. The optical dipole trap is turned on 10 ms before the MOT beams are turned off; the centres of the two traps coincide.

After switching off the beams of the MOT, $N \approx 10^7$ atoms are retained in the hollow trap, which is 10% of the number of atoms in the MOT. The size of the MOT ~3 mm is larger than the size of the hollow trap, due to which a significant part of the particles is not trapped. On the other hand, the large size of the MOT makes it easier to combine it with a hollow trap. The concentration of atoms found from the images in Figs 3 and 4 is 3×10^{10} cm^{-3} in the MOT, and 10^{10} cm^{-3} in the dipole trap, i.e., about a third of the atoms trapped inside the dipole trap are trapped. This trapping efficiency corresponds to a temperature of 1 mK. The dependences of the number of atoms trapped in a hollow trap on the time elapsed from the moment the MOT beams were switched off are shown in Fig. 5. Each point was obtained by averaging five images. From the approximation (solid line) of the experimental data in Fig. 5 it follows that $N = 7.7 \pm 1 \times 10^6$ atoms were trapped, and the lifetime τ at the 1/e level is 6.7 ± 0.9 ms. In these experiments $\Delta_{D_2}/2\pi = 4$ GHz. When the cloud of atoms expands in the absence of confining radiation, the visible number of atoms in the region of the dipole trap (shown in grey in Fig. 5) decreases much faster, in 1 ± 0.3 ms.

The mechanism of the loss of atoms from the trap can be one- and two-particle. Since the level $2S_{1/2}$ ($F = 3/2$) is higher than $2S_{1/2}$ ($F = 1/2$), the process of inelastic collisions of atoms with each other is possible [19, 24], in which the atom acquires an energy of 10 mK and leaves the trap. In a zero magnetic field, the loss coefficient is 10^{-9} cm^3 s^{-1} [19], which at a concentration of 10^{10} cm^{-3} yields a lifetime of 100 ms. The absence of the two-particle process is evidenced by Fig. 5, which shows the exponential time dependence of the number of particles. Thus, inelastic collisions do not limit the lifetime of atoms in the trap considered.

The single-particle process can be Rayleigh scattering on walls or collisions with the background gas. The latter cannot lead to such a rapid loss of particles [12, 16]. At a pressure of ~10^{-11} Torr in the vacuum chamber, the lifetime limited by this mechanism is several minutes [12].

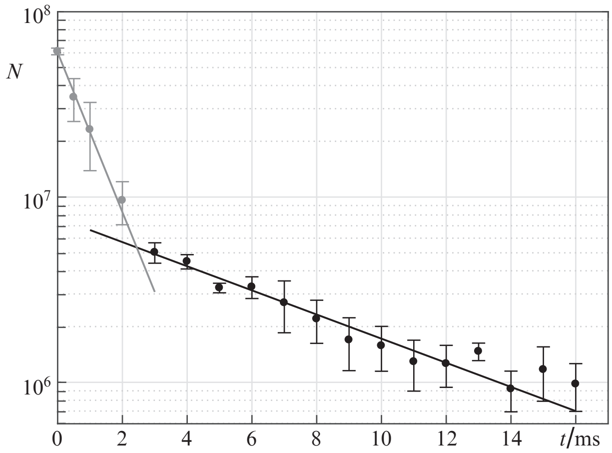

Figure 5. Time dependences of the number of atoms populating the $2S_{1/2}$ ($F = 3/2$) level in a hollow dipole trap. Black dots represent experimental data; solid line, approximation $N = 7.7\times10^6\exp(-t/6.7)$. The grey dots show the number of atoms in the region of the dipole trap in the absence of confining radiation, and the solid grey line shows the approximation $N = 6\times10^7\exp(-t)$. The moment of turning off the MOT beams was chosen as the reference point. Frequency detuning of the dipole trap beams is $\Delta_{D_2}/2\pi = 4$ GHz, and t is measured in milliseconds.

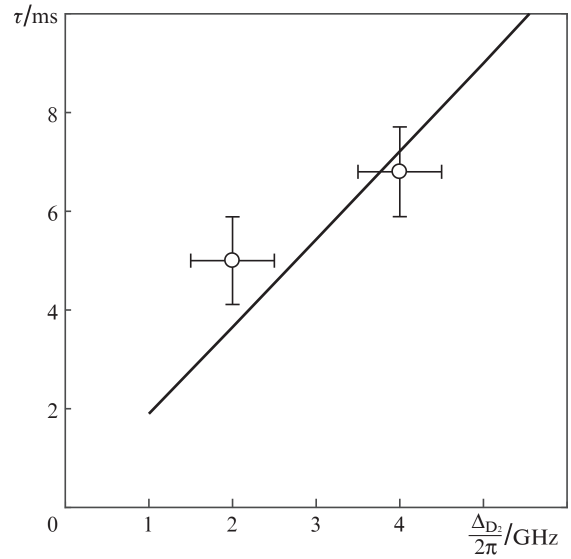

Figure 6. Dependence of the lifetime of atoms in a hollow trap on the detuning $\Delta_{D_2}/2\pi$, found using Eqn (5) for $T = 1$ mK; points are experimental data. The horizontal error is determined by the wavemeter used to measure the laser radiation frequency of the dipole trap, and the vertical error is the root-mean-square deviation.

Small frequency detuning, which allows a sufficiently high potential to be produced at a low radiation power, leads to intense Rayleigh scattering of light by atoms in contact with the walls. The Rayleigh scattering frequency is determined by the formula [13]:

$$\Gamma_{\rm R}(\boldsymbol{r}) = \frac{\pi c^2\Gamma^2 I(\boldsymbol{r})}{2\hbar\omega_0^3}\left(\frac{2}{\Delta_{D_2}^2} + \frac{1}{\Delta_{D_1}^2}\right). \qquad (3)$$

In a single scattering event, an atom acquires an energy $\hbar^2\omega^2/(mc^2)$, its fraction related to the velocity along the direction of beam propagation being greater than in transverse direction:

$$\Delta E_{\parallel} = \frac{7}{10}\frac{\hbar^2\omega^2}{mc^2}, \quad \Delta E_{\perp} = \frac{3}{10}\frac{\hbar^2\omega^2}{mc^2}. \qquad (4)$$

Scattering is more frequent on a ring-shaped beam, which occupies a larger volume and has a higher intensity. In this case, the atom heats up (acquires energy) mainly along the z axis, and easier overcomes the potential barrier of flat walls $U_{\rm fl}$, which is lower than the potential barrier at the ring-shaped beam wall. As a result, the lifetime of an atom in a trap is

$$\tau = \frac{U_{\rm fl} - \bar{E}_z}{\Delta E_{\parallel}\bar{\Gamma}_{\rm R}}, \qquad (5)$$

where $\bar{E}_z$ is the average kinetic energy of the atomic motion along the z axis at the initial moment of time; and $\bar{\Gamma}_{\rm R}$ is the rate of scattering on the ring-shaped beam wall averaged over the trap volume.

The dependence of the lifetime on the detuning is shown in Fig. 6. The solid line shows the values calculated using Eqn (5) for $T = 1$ mK, the dots mark the experimental data. It is seen that the measured lifetime correlates with the value obtained from Eqn (5): it decreases with decreasing frequency detuning of the dipole trap laser.

Thus, the short lifetime of atoms in the trap is due to the small detuning $\Delta_{D_2}/2\pi$. As follows from Eqn (1), a small detuning is necessary to produce a potential with a height sufficient to trap atoms from the MOT, which is required only at the stage of their reloading into a hollow trap. Further cooling of ^{6}Li is possible by applying optical molasses [21], as a result of which the temperature within 1 ms will decrease to a value not greater than 40 μK [25]. Thereafter, the detuning can be increased, which will reduce the heating due to Rayleigh scattering. In an external-cavity injection diode laser, a jump in lasing from one mode of the internal cavity to another allows the frequency to be changed by 100 GHz (0.15 nm). Frequency tuning can be executed in milliseconds by a piezoelectric element or in microseconds by changing the diode current. Near-infrared fibre lasers allow wavelength tuning by tens of nanometres in microseconds [26]. To lower the temperature further, evaporative cooling can be used [27]. The thin walls of the trap described in this work made it possible to limit the Rayleigh heating. With a wall thickness of the trap, as in Ref. [21], Rayleigh heating would lead to a lifetime of 1 ms.

Thus, the lifetime of atoms in the large hollow dipole trap was measured. The 1/e lifetimes were 5 and 6.7 ms for detunings $\Delta_{D_2}/2\pi$ of 2 and 4 GHz, respectively. The lifetime was found to be limited by Rayleigh scattering of light by atoms.

Acknowledgements. The authors acknowledge the support from Rosatom, the Russian Foundation for Basic Research (Project Nos 19-02-00585 and 19-29-11025) and the Ministry of Education and Science of the Russian Federation (State Assignment to IAP RAS No. 0030-2021-0002).

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