Eur. Phys. J. D **21**, 101–104 (2002)
DOI: 10.1140/epjd/e2002-00175-2

THE EUROPEAN PHYSICAL JOURNAL D

Cross-section for collisions of ultracold ^{7}Li with Na

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Received 11 January 2002 / Received in final form 5 April 2002
Published online 24 September 2002 –

Abstract. In a magneto-optical trap (MOT) we are able to simultaneously trap and cool ^{7}Li and Na. We investigated the loading behavior of the cloud of Li atoms in presence of the overlapped cloud of cold Na atoms, and, by blocking the weak repumping beam for Na, compared it with the loading curve for Li atoms only. Out of these loading curves we calculated the collision cross-section of Na on Li to be 10^{-11} cm^3/s.

PACS. 32.80.Pj Optical cooling of atoms; trapping – 34.50.-s Scattering of atoms and molecules – 34.50.Rk Laser-modified scattering and reactions

1 Introduction

One of several applications of a magneto-optical trap (MOT) is the investigation of long-range homo- and heteronuclear molecules [1–7]. The first step towards heteronuclear LiNa molecules is the determination of the overall cross-section for collisions between excited and ground state ultracold lithium and sodium atoms. This work deals with this topic.

2 Experimental setup

We are using a standard MOT working with circularly polarized light, built for simultaneous use with Na and Li.

In principle, the optical arrangement is the same as used by other groups [9,10] and published earlier [8]. It can be seen in Figure 1. As light sources we use cw dye ring lasers, stabilized and locked to atomic transition frequencies using saturation spectroscopic setups, one for Na (589 nm), the other one for Li (671 nm). The Na cooling frequency is red shifted to the $3\,^2\mathrm{S}_{1/2}(F=2)$–$3\,^2\mathrm{P}_{3/2}(F'=3)$ transition by 10 MHz. From this position the repumping frequency (level like above, but from $F=1-F'=2$) is tuned to the blue by 1 720 MHz by means of an acousto-optical modulator (AOM). For Li, which has an inverse hyperfine level scheme in the $2\,^2$P state, the cooling frequency is red shifted relative to the $2\,^2\mathrm{S}_{1/2}(F=2)$–$2\,^2\mathrm{P}_{3/2}(F=3)$ transition by 25 MHz. Here the repumping frequency (again $F=1-F'=2$) is the blue sideband produced by an electro-optical modulator, running at 823 MHz.

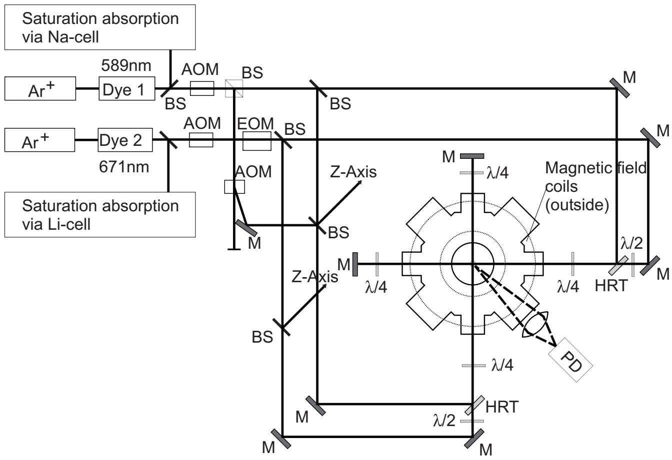

Fig. 1. Experimental setup of the Li Na MOT.

Before entering the trap, the red (Li) and yellow (Na) laser beams are divided into three beams, and then overlapped using dichroic mirrors. Quarter wave plates working for both wavelengths (produced for us by Halle, Berlin) are mounted directly in front of the entrance windows of the MOT chamber. They are generating the circular polarization. Each of the three mutually orthogonal beams is back reflected, passing two times another quarter wave plate. Typical parameters of the laser beams, their detunings, and the calculated fraction of atoms in the upper level are shown in Table 1. The detuning is noted negative, for it is to the red. It is relative to the transitions mentioned above. Due to our optical arrangement, the trapping beams for each of the two elements can separately be adjusted to the center of the trap. That makes it easy to overlap exactly the two atomic clouds.

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Table 1. Experimental parameters. Typical values, single values differ by some %.

	Li	Na
I_{cool}	80 mW/cm^2	145 mW/cm^2
I_{repump}	27 mW/cm^2	30 mW/cm^2
λ_{Laser}	670.776 nm	588.995 nm
$\Delta\nu_{\mathrm{cool}}$	−25 MHz	−10 MHz
$\Delta\nu_{\mathrm{repump}}$	−15 MHz	−3 MHz
$\Pi^{(\mathrm{e})}$	0.17	0.46

The magnetic field is produced by anti-Helmholtz coils situated outside the vacuum chamber. The magnetic field gradient is 2 mT/cm in axial direction.

In the chamber there is a pressure of 3×10^{-9} mbar. The vapor of the alkali metal from which loading occurs is produced by dispensers.

The fluorescence of the clouds of trapped Li and/or Na atoms is detected by photo-diodes with edge filters for red and yellow light. The density of the clouds is determined using a CCD camera.

The arrangement is described more detailed in reference [8].

3 Measurement

We have studied the influence of the presence of a cloud of cold Na atoms on the loading curve of a cloud of Li atoms, since the number of lighter atoms should be changed more by collisions than the number of the heavier atoms.

First we determined the parameters of the trapped Li and Na atoms clouds separately in the usual way. The number N of cold atoms in the cloud is given by:

$$N = \frac{I}{\eta\hbar\omega\Gamma\Pi^{(\mathrm{e})}} \tag{1}$$

where I is the power of the cloud's fluorescence detected by the photodiode, η the spatial angle of the imaging system, $\hbar\omega$ the energy of a resonant photon and Γ the linewidth of the resonant transition. $\Pi^{(\mathrm{e})}$, the fraction of excited atoms, is calculated from the known laser intensity and the frequencies for both kinds of atoms.

The number $N(t)$ is fitted with

$$N(t) = N_0(1 - \mathrm{e}^{-\gamma_0 t}) \tag{2}$$

leading to the steady state number of trapped atoms N_0 and the decay rate γ_0.

Assuming the cloud of the MOT being elliptically symmetric with a Gaussian profile, we can calculate the center density n_0:

$$n_0 = N_0/(r_x r_y r_z \pi^{3/2}) \tag{3}$$

r_i is the 1/e-radius of the cloud along the i-axis. The radial radii r_x and r_y are $\sqrt{2}\,r_z$, the axial radius in the symmetry of the anti-Helmholtz coils.

Table 2. Cloud properties. T is the temperature of the cloud, N_0 the equilibrium number of trapped atoms, $N_{0+\mathrm{Na}}$ is N_0 of Li with the Na-cloud overlapped, γ_0 the decay rate, n_0 the density. All single values are within ±5% of the noted numbers.

	Li	Na
T	> 300 μK	> 240 μK
N_0	5.8×10^5	7.3×10^5
$N_{0+\mathrm{Na}}$	4.7×10^5	—
γ_0	0.75 s^{-1}	—
n_0	1.7×10^{10} cm^{-3}	2.2×10^{10} cm^{-3}

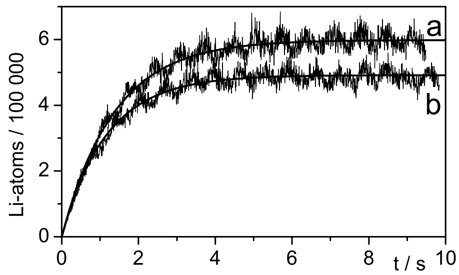

Fig. 2. Loading curves of Li without (a) and with (b) coinciding Na-cloud and fits. The modulation comes from an interference of the data-acquisition frequency with background light. The curves are the mean values over 10 data points of our raw data.

The temperature T was estimated by fitting the fraction of atoms remaining in the trap dependent on the shut off time of the cooling lasers. A systematic error comes from the fact that we cannot switch off the magnetic trapping field fast enough. Typical values can be seen in Table 2.

As far as we could estimate, the clouds of Li and Na atoms are produced in the temperature-delimited regime. Nevertheless, we are using approximations belonging to the density-delimited regime for higher simplicity. Comparing fits of the measured loading curves assuming an arbitrary regime, we find the difference made by assuming the other regime negligible. Some curves are even fitted better with the formulas of the density-delimited approximation.

In Figure 2 a set of Li-loading curves is shown without (Fig. 2a) and with (Fig. 2b) presence of a coinciding Na-cloud, and fitting curves assuming the density-delimited case. Even to compare the temperature-delimited fit is not shown here, because the fits match so good that they are not to distinguish, even in higher resolutions of the figure.

To maximize the effect of Na on Li we worked only with the highest accessible number of atoms and the highest possible density. For this reason all the other measurements look similar, and are not shown here.

In preliminary measurements some time ago we could not see any influence of one atomic species on the cloud of the other one, so we had to assume that the interaction cross-section is very small. The next step was to improve the vapor pressure by one order of magnitude to achieve longer loading times, and to assure the overlapping of the clouds more exactly. One of the main tasks during the measurements was then to avoid any influence on the loading curve by changed conditions within the MOT. Every parameter should be the same, the only change should be the formation of a cloud of Na atoms. Therefore, during all the measurements the Li- and Na-dispensers were operating with constant current to keep the influence of the background-gas constant. The Li cooling and repumping and the Na cooling laser beams are kept unchanged, too. We switched only the weak Na repumping beam on or off to trap or not a Na-cloud. This Na repumping beam has about 1/3 of the intensity of the cooling beam, so we keep all influences constant, except the interaction of the cold Na atoms on Li.

The experimental procedure was to record a loading curve for Li alone, and then a Li loading curve in presence of trapped Na. Then the number of atoms and the density of the Na cloud were determined. This procedure is to compensate slow drifting of the results, and is repeated several times. We observe constant parameters for the Na cloud, so we are working with mean values $N_{0,\mathrm{Na}}$, $n_{0,\mathrm{Na}}$ in the further evaluation.

When describing the temporal evolution of the number of trapped Li atoms in presence of a cloud of cold Na atoms, we had to add additional trap losses caused by the interaction between the two species of cold atoms. The temporal evolution of the number of trapped Li atoms, N_{Li}, is therefore given by:

$$\frac{\mathrm{d}N_{\mathrm{Li}}}{\mathrm{d}t} = L_{\mathrm{Li}} - \alpha N_{\mathrm{Li}} - \beta \int n_{\mathrm{Li}}^2(\mathbf{r})\mathrm{d}V - \beta' \int n_{\mathrm{Li}}(\mathbf{r}) n_{\mathrm{Na}}(\mathbf{r})\mathrm{d}V \quad (4)$$

L_{Li} is the loading rate for Li, α the collision rate of cold Li atoms with hot background gas, β the collision rate between cold Li atoms, β' the collision rate between cold Li and cold Na, and n the densities of atoms. Corresponding variables for Li and Na are indexed.

Using equation (3) and

$$\gamma_0 = \alpha - 2^{-3/2}\beta n_{0,\mathrm{Li}} \quad (5)$$

equation (4) can be integrated to:

$$\frac{\mathrm{d}N_{\mathrm{Li}}}{\mathrm{d}t} = L - \gamma_0 N_{\mathrm{Li}} - \frac{2\beta'(n_{0,\mathrm{Li}} n_{0,\mathrm{Na}} N_{\mathrm{Li}} N_{0,\mathrm{Na}})}{\left((n_{0,\mathrm{Na}} N_{\mathrm{Li}})^{2/3} + (n_{0,\mathrm{Li}} N_{0,\mathrm{Na}})^{2/3}\right)^{3/2}}. \quad (6)$$

If there is no Na cloud present ($N_{0,\mathrm{Na}} = 0 = n_{0,\mathrm{Na}}$), equation (6) can be integrated to the well known equation (see also Eq. (2)):

$$N_{\mathrm{Li}}(t) = N_{0,\mathrm{Li}}(1 - \mathrm{e}^{-\gamma_0 t}) \quad \text{with} \quad N_{0,\mathrm{Li}} = L/\gamma_0. \quad (7)$$

Fitting the loading curves without Na atoms with this equation, we obtain L, $N_{0,\mathrm{Li}}$, and γ_0. These values, the densities, and $N_{0,\mathrm{Na}}$ are put into equation (6). This equation is integrated numerically with β' as a fit parameter. All other variables are known.

By means of the fit procedure, the interaction cross-section for β', describing the influence of cold Na atoms onto cold Li atoms, was found to be 10^{-11} cm^3/s $\pm$ 15%. This value is one order of magnitude smaller than for Cs on Rb, reported in reference [6] and is in agreement with predictions on interactions and Franck-Condon factors in reference [11].

Due to the conditions in a MOT, the cloud of trapped atoms consists of N atoms, the fraction $\Pi^{(\mathrm{e})}$ being in the excited state. We therefore have determined the interaction between $(1 - \Pi_{\mathrm{Li}}^{(\mathrm{e})})N_{\mathrm{Li}}$ ground state Li atoms and $\Pi_{\mathrm{Li}}^{(\mathrm{e})}N_{\mathrm{Li}}$ Li atoms in the $2^2\mathrm{P}_{3/2}$ state interacting with $(1 - \Pi_{\mathrm{Na}}^{(\mathrm{e})})N_{\mathrm{Na}}$ Na ground state and $\Pi_{\mathrm{Na}}^{(\mathrm{e})}N_{\mathrm{Na}}$ Na atoms in the $3^2\mathrm{P}_{3/2}$ excited state. At the moment we cannot distinguish, to which part the change in the Li loading curve is: due to a lower number of ground state atoms or if the change is mainly due to a loss of excited Li atoms. We also cannot tell if mainly Na ground state atoms or excited atoms are interacting. Hence, the cross-section we derived is a mixture of values belonging to collisions of excited and ground state Li and Na atoms. We hope to be able to discriminate the different values in further experiments.

4 Conclusion and outlook

We measured the overall collision cross section for ultracold ^{7}Li pushed by ultracold Na to be 10^{-11} cm^3/s. This value is one order of magnitude smaller than for Cs on Rb, reported in reference [6]. This difference may be explained by the small Franck-Condon factors reported in reference [11].

Distinguishing between the different contributions to the overall cross-section seems to be very difficult. One should study, for example, interactions with a dense cloud of Na atoms in their ground state. That means, for short time intervals the trapping laser for Na is switching off. After some ns only ground state Na atoms are present, but there is still a Na cloud for several 10 μs, decay time $\gamma_0 \leq 1$ s. During the time the Na atoms are reloaded with the trapping laser on, the overall cross-section, which is reported here, is valid. If the ratio between loading and dark-state time of the Na cloud is comparable, maybe one would be able to notice differences in the loading curves of Li.

If higher numbers of atoms are achieved with improved MOT conditions, a change of $\Pi^{(\mathrm{e})}$ of Na or Li could be induced by choosing different intensities of the cooling and/or repumping laser light. Out of changes in β' the contributions of the different species might be distinguished.

This work is funded by the Austrian Science Foundation FWF, project number P14645.

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