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RECOIL EFFECT IN LASER SPECTROSCOPY OF ALKALI METAL ATOMS

Abstract

We have analyzed the influence of the mechanical momentum acquired by atoms when interacting with resonant laser radiation (atomic recoil effect) in the spectroscopy of alkali metal atoms. Direct quantitative measurements are done using a sodium atomic beam setup. A 1.3 mm deflection of atoms on a distance of 890 mm downstream the beam was detected with 7.5 mW power of deflection laser radiation, corresponding to ≈ 300 cm/s transversal recoil velocity acquired by atoms. Power dependence of deflection exhibited square-root low caused by the Doppler walk-off of the resonance frequency with the increase of the lateral velocity. The possible influence of recoil effect in high-resolution atomic spectroscopy is discussed. The obtained results are used to evaluate the case of interaction of laser radiation with gaseous media. Corresponding estimates are done for the laser spectroscopy of nanocells containing atomic vapor of alkali metals, where the strongest impact of recoil phenomenon is expected.

Keywords: *atomic recoil; laser spectroscopy; fluorescence; resonant interaction; Doppler effect; atomic beam; alkali atoms; optical nanocells.*

Introduction

Resonant interaction of continuous-wave laser radiation with atomic media (notably, an atomic vapor of alkali metals) underlies numerous important applications in sensing, metrology, laser technology, chemical reaction control, and elsewhere. This interaction can be influenced by several extensively studied factors, among which are laser radiation intensity effects (saturation, optical pumping), flight-time (the flight time of an atom through the laser beam), scanning rate of laser radiation frequency across atomic resonance, velocity distribution of atoms (Doppler effect), presence of a buffer gas or anti relaxation coating, etc. Besides, there are yet other processes the contribution of which can be revealed only in specific conditions of interaction. Among those is a deflection of atoms by spontaneous emission force.

The essence of this effect, which can be considered as a mechanical action of laser radiation (flux of photons) on atoms, is as follows. Under absorption of radiation quantum, the atom acquires a momentum equal to $2\pi\hbar/\lambda$ in the direction along the wave vector of laser radiation $\mathbf{k}$ (λ being the resonant radiation wavelength). Upon subsequent spontaneous emission by an atom, this momentum is transferred to the emitted photon. Since spontaneous emission may occur in any direction within the 4

π solid angles, after averaging over many absorptions and emission cycles, the atom acquires an additional velocity component in direction of exciting radiation, undergoing mechanical deflection.

This process, which is conventionally termed as "recoil effect", is successfully used in laser cooling techniques [1,2], but because of the low impact, it did not find proper attention in the studies of the interaction of laser radiation with atoms in vapor cells. Meanwhile, current progress in atomic spectroscopy with nanometric thickness vapor cells and their numerous applications (see e.g. [3-5] and references therein) stipulate for renewed interest towards recoil effect, which may straightforwardly reveal itself in atomic spectra.

The peculiarity of the interaction of laser light with atoms in optical nanocells is mostly caused by a strong anisotropy for atoms with different thermal velocity components. The interaction behaviour for atoms flying across the laser beam (parallel to the cell windows, atoms marked "1", "4" in Fig.1) is similar to the case of an "ordinary" cell, where the atom-light interaction time is determined by the flight time of atoms through the laser beam (typically about D = 1 mm). For room-temperature conditions, the mean thermal velocity of alkali metal atoms forming the vapor is ~ 250 m/s, thus flight time is ~ 5 μs, long enough for multiple cycles of resonant absorption and emission of light. Dramatically different is the contribution of atoms flying along the laser beam (across the windows, atoms marked "2", "3" in Fig.1). For a typical L ~ 500 nm thickness of nanocell, the window-to-window flight time is only 2 ns, after which atom experiences quenching collision with the window. As the typical absorption/emission time on the first resonant transitions of alkali atoms (so-called D-lines) below the saturation intensity is 15 – 30 ns, as a result, the longitudinally-flying atoms do not have time to interact with light and do not contribute to the recorded absorption/fluorescence signals. This is the main reason for sub-Doppler nature of spectra recorded with nanocells.

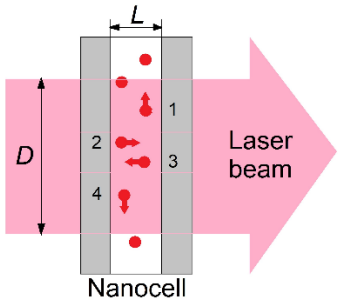

Fig 1 Schematic diagram of the interaction of atoms having different thermal velocity components with a laser beam in a nanocell.

As is described above, the predominant contribution to resonant absorption and fluorescence spectra in nanocell is provided by the atoms flying parallel to the cell walls, normally to the laser beam. After numerous absorption/emission cycles, these atoms will acquire mechanical momentum in a longitudinal direction, which will drive them towards the rear window of the cell with subsequent quenching of atomic

polarization. One may expect that thanks to the small cell thickness *L*, such a recoil-caused quenching may occur at moderate values of CW laser intensity, becoming a dominant factor limiting atom-light interaction time. We should note that because of the above discussed velocity-dependent contribution to atomic resonant spectra, atomic vapor nanocell can be considered as an effective two-dimensional atomic beam (a layer of atoms flying across the laser beam). For this reason, precise measurements, which are possible to perform with atomic beam configuration, can be very helpful for quantitative estimates of the recoil effects in nanocells. Below we describe such measurements done with the sodium atomic beam.

Recoil effect in an atomic beam experiment

We present below the results of studies directly showing that mechanical action of light can cause noticeable influence in atomic spectroscopy experiments. The most suitable configuration, which allows for the straightforward determination of this influence, is atomic beam experiment, where the recoil in transversal direction can be detected on a zero-velocity background.

The measurements have been done at Technical University of Kaiserslautern (Germany), on the atomic/molecular sodium beam setup schematically shown in Fig.2, with the following key characteristics: working length of collimated atomic beam is 129 cm; the velocity of Na atoms is $v = 2 \pm 0.12 \times 10^5$ cm/s (measured by the time-of-flight method [6]); the beam divergence is 0.15 mrad.

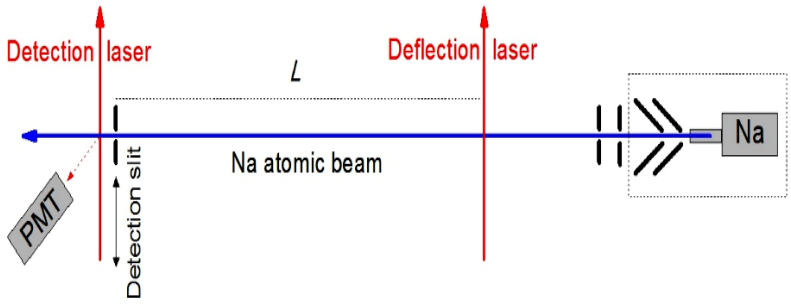

Fig 2 Schematic diagram of the experimental setup. The Na atomic beam with 0.15 mrad divergence angle is formed by the oven with a guiding pipe followed by two skimmers, and two collimation slits. Beam deflection is measured by lateral translation of a detection slit while recording fluorescence detected by a photomultiplier tube (PMT).

Before measurements, the spatial profile of the beam was tested using the following procedure. A 50 μm "detection slit" was installed downstream the beam, at the end of its working length. After passing the slit, the beam was transversely illuminated by a 25 μW power laser radiation tuned to one of the hyperfine components of the Na atomic D_2 line ($\lambda \approx 589.0$ nm). The detection slit was translated across the atomic beam while recording the emerging atomic fluorescence signal. The typical recorded beam profile is presented in Fig.3, showing 0.3 mm transversal width.

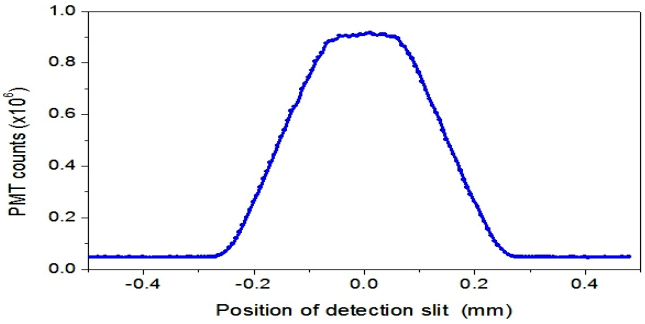

Fig 3 Typical downstream spatial profile of the atomic beam in the absence of the deflection laser. The full width at half-maximum is ≈ 0.3 mm.

The experiment on detection of atomic beam deflection by spontaneous emission force was performed in the following way. A 1 MHz-linewidth CW "deflection" laser beam resonant with $3S_{1/2}(F_g=2) \rightarrow 3P_{3/2}(F_e=3)$ transition of Na D_2 line was directed transversely onto the atomic beam, 89 cm upstream from the detection slit. The laser beam diameter (D_L = 6 mm) was chosen such that it fully covers the vertical size of a sodium beam (5 mm). The monitoring of beam deflection was done using the above-described technique for testing the beam profile.

Figure 4 summarizes the results of these direct beam-deflection measurements. As is seen from the figure, the strongest deflection rate is observable at low radiation power P_L of the deflection laser. As the power increases, the deflection rate decreases, and at P_L = 7.6 mW (I_L = 30 mW/cm^2) the absolute deflection on L_{beam} = 890 mm length reaches $\Delta x \approx$ 1.5 mm. Let us evaluate this result.

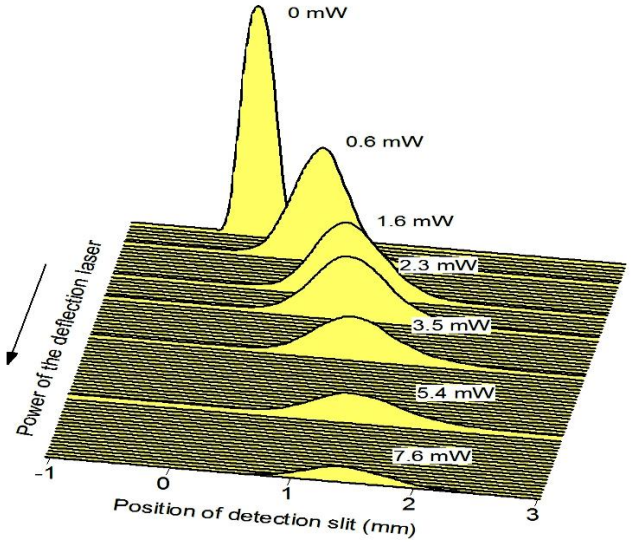

Fig 4 Transversal position Δx of atomic beam 89 cm downstream the interaction with deflection laser radiation depending on its power. The vertical scale shows the intensity of fluorescence excited by the detection laser.

At the maximum laser radiation intensity, the atoms acquire mean transversal velocity of $v_\perp = v\Delta x / L_{beam} \approx 340$ cm/s (dispersion of this mean velocity and, correspondingly, Δx are caused by the spontaneous nature of the fluorescence). Taking into account that the lateral velocity acquired by the atom in a single absorption event is $(2\pi\hbar)/\lambda / m_{Na}$ = 2.94 cm/s, and the mean number of absorption and emission cycles within the interaction time (time of flight) D_L / v = 3 μs is ≈ 120, the Doppler shift by the end of interaction time reaches $\Delta\nu_D = kv_\perp / 2\pi = v\Delta x / \lambda L_{beam} \approx$ 5.75 MHz, which is comparable with the natural linewidth of Na D_2 line (9.8 MHz). With this shift the atom practically gets out of resonance with the deflection laser radiation, thus preventing further deflection. In reality, the deflection does not completely cease as the laser radiation intensity increases, but its impact decreases according to $v_\perp / v \sim \sqrt{1 + P_L / P_s}$ dependence, where P_s is the saturation power of the atomic transition ($\sim \sqrt{P_L}$ at high laser intensity). The latter is caused by the power broadening of atomic transition in a strong radiation field [7]. The observed laser power dependence of the deflection (see Fig.5) is well described by a square root low in high-intensity case (the fitting done with y = 0.42 + 0.36 $\sqrt{x}$ dependence for the laser radiation intensity above the saturation power is shown by a solid line).

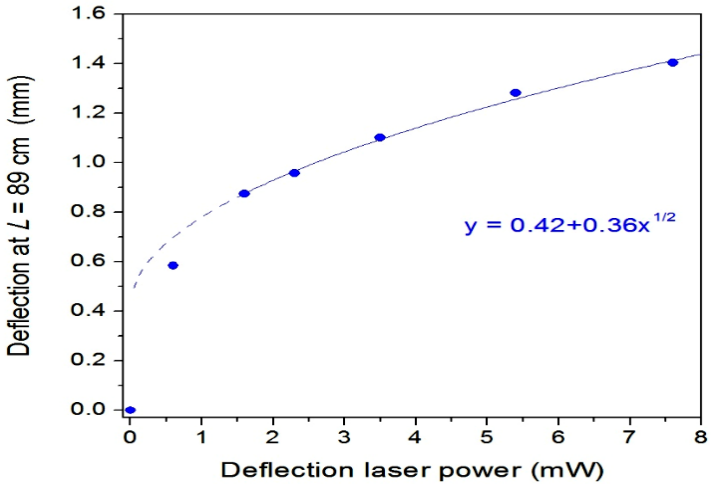

Fig 5 Deflection laser power dependence of the transversal position of atomic beam 89 cm downstream the interaction region.

It is spectacular that broadening of the beam profile with the increase of P_L is accompanied by a reduction of not only its amplitude but also the surface (see Fig.4). Such behaviour is caused by the following: because of acquired Doppler shift, the atom

is not anymore in resonance with the low-power narrow-band detection laser, thus resulting in an overall decrease of the fluorescence signal.

Discussion of the results and atomic recoil impact on nanocell spectroscopy

The obtained results demonstrate that the resonant laser radiation acting on an atom can drive the latter out of the resonance thus limiting subsequent interaction. One may suppose that this limitation should not apply to the atomic vapor with thermal (Maxwell) velocity distribution where within the inhomogeneous Doppler profile there will always be atoms resonant with laser radiation. But this statement is not applicable for all the resonant phenomena. In particular, such processes developing in dilute vapors as optical depopulation pumping, Zeeman pumping, coherent population trapping, electromagnetically induced transparency, etc. are in fact "single atom effects", and many absorptions and emission cycles by the same atom are required to build up a steady-state interaction regime. For these processes, consideration of mechanical action of laser radiation can be helpful for correct modeling of the particular problem.

Besides, the obtained quantitative results are of particular relevance and importance for the atomic spectroscopy with nanocells. As it was mentioned above, the recorded atomic signal is mainly contributed by atoms flying across the laser beam. These atoms will acquire intensity-dependent mechanical momentum from the resonant laser beam, i.e. longitudinal velocity component, which drives them towards the rear window of the nanocell, thus preventing further interaction with the laser radiation. In addition to this mechanical deflection, the acquired longitudinal velocity component can also result in a Doppler frequency shift, which may drive the atoms out of resonance. Let us evaluate these impacts for the case of sodium D_2 line quantitatively examined above.

The estimates are done for the typical conditions exploited in experiments: the nano cell thickness L = 500 nm, and temperature 150°C corresponding to the mean thermal velocity of Na atoms $\bar{V}$ = 620 m/s, laser beam diameter D = 1 mm, incident laser radiation power P_L = 10 μW, and radiation spectral linewidth ν_L = 1 MHz. For these conditions, a transversely-flying atom will obtain $v_\perp \approx 100$ cm/s longitudinal velocity component (derived from the results presented in Fig.5, taking into account the laser beam diameter in atomic beam experiment). The resulting window-to-window flight time will be ≈ 0.5 μs, which is less than the flight time of atom across the laser beam (1.6 μs). So, supposing slow enough scanning rate of laser radiation frequency, the real resonant atom-radiation interaction time is governed by recoil effect, corresponding to ≈ 30 elementary acts of absorption and emission per atom (the radiation lifetime for Na D_2 line is 16.2 ns). It should be noted that in the same conditions the Doppler frequency shift caused by recoil remains below the natural decay linewidth. The contribution from the recoil effect will become more significant with the increase of incident laser radiation intensity.

We above estimates have been done for Na atoms. Practical nanocell spectroscopy is mostly done with heavier atoms (Rb, Cs, K), where the recoil impact is less

pronounced. Anyway, it has to be taken into account, notably in the modeling of experiments requiring high radiation power.

Conclusions

Summarizing, we have outlined and explored the importance of the recoil effect (mechanical momentum acquired by atoms when interacting with resonant laser radiation) in atomic spectroscopy. The direct quantitative study has been done using a sodium atomic beam setup, and the obtained results were further extended to atomic spectroscopy of gaseous medium (alkali metal vapor). It was shown by estimates that the most pronounced influence of recoil effect is expected for laser spectroscopy of nanocells containing atomic vapor of alkali metals.

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ԱՐԱՄ ՊԱՊՈՅԱՆ

ֆիզիկամաթեմատիկական գիտությունների դոկտոր, ՀՀ ԳԱԱ թղթակից անդամ

ՀԵՏԱՀԱՐՄԱՆ ԵՐԵՎՈՒՅԹԸ ԱԼԿԱԼԻ ՄԵՏԱՂՆԵՐԻ ԱՏՈՄՆԵՐԻ ԼԱԶԵՐԱՅԻՆ ՍՊԵԿՏՐԱՍԿՈՊԻԱՅՈՒՄ

Վերլուծվել է լազերային ճառագայթման հետ ռեզոնանսային փոխազդեցության ընթացքում ատոմի կողմից ձեռքբերած մեխանիկական մոմենտի (հետահարման երևույթ) ազդեցությունը ալկալի մետաղների ատոմների սպեկտրասկոպիայում: Ուղղակի քանակական չափումները կատարվել են նատրիումի ատոմական փնջի սարքավորման վրա: Շեղող լազերի 7.5 մՎտ հզորության դեպքում փոխազդեցության կետից 890 մմ փունջն ի վար գրանցվել է ատոմների 1.3 մմ շեղում, ինչը համապատասխանում է ատոմների ձեռքբերած ≈ 300 սմ/վ ընդլայնական հետահարման արագությանը: Շեղման կախումը հզորությունից դրսևորում է քառակուսի-արմատային

օրենք՝ պայմանավորված լայնական արագության մեծացմանը զուգընթաց տեղի ունեցող ռեզոնանսային հաճախության դոպլերյան վերալարումով: Քննարկվում է հետահարման երևույթի հնարավոր դերը բարձր լուծունակության ատոմային սպեկտրասկոպիայում: Ստացված արդյունքները օգտագործվել են գազային միջավայրերի հետ լազերային ճառագայթման փոխազդեցության դեպքի վերլուծության համար: Կատարվել են համապատասխան գնահատականներ ալկալի մետաղների ատոմական գոլորշի պարունակող նանոբջիջներում լազերային սպեկտրասկոպիայի համար, որտեղ սպասվում է հետահարման երևույթի ամենամեծ ազդեցությունը:

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ЭФФЕКТ ОТДАЧИ В ЛАЗЕРНОЙ СПЕКТРОСКОПИИ АТОМОВ ЩЕЛОЧНЫХ МЕТАЛЛОВ

Проанализировано влияние механического момента, сообщенного атомам при резонансном взаимодействии с лазерным излучением (эффект атомной отдачи), в спектроскопии атомов щелочных металлов. Прямые количественные измерения проведены с использованием установки атомного пучка натрия. При мощности отклоняющего лазера 7,5 мВт на расстоянии 890 см вниз по пучку зарегистрировано отклонение атомов на 1,3 мм, что соответствует приобретенной атомами поперечной скорости ≈ 300 см/с. Зависимость отклонения от мощности лазера описывается корневым законом, что обусловлено допплеровским уходом резонансной частоты при увеличении поперечной скорости. Обсуждается возможная роль эффекта отдачи в атомной спектроскопии высокого разрешения. Полученные результаты использованы для анализа случая взаимодействия лазерного излучения с газообразными средами. Проведены соответствующие оценки для лазерной спектроскопии наноячеек, содержащих атомарные пары щелочных металлов, где ожидается наиболее сильное влияние явления отдачи.

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ANALYSIS OF TRANSCRIPTOME CHANGES IN RESPONSE TO HEAVY METALS USING SELF-ORGANIZING MAPS

Abstract

In this study, we have performed self-organizing maps (SOM)-based clustering and functional annotation of gene expression in hepatoma cell lines exposed to cadmium, nickel and arsenic using publicly available microarray data. The results show that cadmium and nickel exposure is associated with overexpression of genes related to hypoxia and oxidative stress response, while arsenic causes up-regulation of