University of Pécs

Doctoral School of Physics

Coherent acceleration of rubidium atoms using multiphoton adiabatic transfer

PhD Theses

Varga-Umbrich Károly

Supervisor
Dr. Kedves Miklós Ákos
senior research fellow

Wigner Research Centre for Physics

Pécs, 2022.

1. Overview

Resonant laser radiation can be used to manipulate more than just the internal state of the atom. An excitation or spontaneous or induced emission can also affect the motion of the whole atom due to the photon momentum absorbed or emitted. In this way, atoms can be selectively slowed down or accelerated, cooled and trapped.

The coherent manipulation of atoms is only possible through induced processes (excitation and stimulated emission) - spontaneous emission destroys the coherence of the quantum state. Laser pulse induced processes can be used to manipulate the motion of atoms in a variety of ways (e.g. deflection or focusing of atomic beams) and in many cases offer the possibility to preserve the coherence of the atomic wave packets. In order to preserve the coherence it is important to accomplish complete population transfer. Adiabatic passage techniques offer an efficient and robust solution to this problem [1] [2] [3] [4] [5] [6] [7]. These methods often use two counterpropagating laser pulses that interact with the atom (during the spontaneous lifetime of the atom) to force the atom to undergo a population transition (e.g. from the ground state to an excited state and back). With one photon absorption the atom is transferred to the excited state, and it acquires $\hbar k$ momentum. If the atom interacts with another similar laser pulse coming from the opposite direction, it undergoes stimulated emission, thereby gaining an additional quantum of $\hbar k$ momentum in the same direction as the first one. The second interaction must happen within the spontaneous life time, to avoid the spontanous emission. The system will acquire in total $2\hbar k$ momentum [8] [9] [10].

An important effect is produced when the counterpropagating laser pulses interact with the atom simultaneously, rather than separately, partially overlapping each other. Simulation models have shown that the atom, instead of the expected $2\hbar k$, can receive an integer multiple of that [11] [12] [13]. This is possible if the process is adiabatic, which implies strict conditions on the interaction parameters (such as laser intensity, pulse length, frequency sweep, pulse overlap). Accelerating atoms in this compact way can result in important practical benefits.

2. Aims and methods

In this thesis, the aim was to implement and study coherent excitation and adiabatic population transfer between atomic quantum states. The transitions were induced by frequency-modulated laser pulses, in which the frequency sweeps across the frequency of the atomic transition during the pulse, causing adiabatic population transfer. In order to reach and maintain the required laser radiation parameters, specific methods had to be developed, which may find applications in other spectroscopic fields. The motivation is to show how the particular adiabatic phenomenon obtained by theoretical calculations is realized in experiments [11]. The multiphoton adiabatic transfer results in the acceleration of the atom, and the aim of the present studies was to demonstrate this phenomenon and to achieve as high efficiency of momentum transfer as possible.

I have carried out experiments to accelerate cold rubidium atoms initially collected in a magneto-optical trap, by measuring the displacement of the atomic cloud. With the inclusion of the actual experimental parameters, numerical simulations have been performed to describe the results of the measurements.

The required nanosecond laser pulses are cut out from a continuous wave, frequency-modulated laser beam. The pulse slicing must occur at the appropriate part of the frequency sweep. In order to avoid unwanted frequency modulation during the process, attention is required to detect and eliminate unwanted effects of the modulators performing the pulse slicing. In addition, stabilisation of the centre frequency of the modulated laser may be necessary to reduce frequency fluctuations or drift.

This thesis aims to explore this phenomenon from a theoretical and experimental point of view, and to present and solve the problems that arise in the process.

3. Theses

1. Using an analogue spectrum analyser, I have developed a simple and practical method to reduce the drift and fluctuation of the centre frequency of a frequency modulated diode laser. By displaying the beat signal of the beam of the laser to be stabilized and a reference laser on the spectrum analyzer, the modulated laser can be stabilized to the electronically output signal of an arbitrary sideband of the beat spectrum [S1]

2. I have shown that a few-nanosecond-long laser pulse with good contrast and no additional frequency modulation can be cut out from continuous wave laser radiation using two different Mach-Zehnder type amplitude modulators with appropriate timing. To monitor the frequency parameters of the resulting pulse, I have developed a method whereby, together with the pulse shape, the beat signals of the diagnostics beams with a reference laser are also continuously recorded, from which the parameters of interest can be determined by fitting a mathematical formula. [S1]

3. I have carried out acceleration experiments using pairs of overlapping chirped laser pulses on rubidium atoms collected in a magneto-optical trap. I have shown that an average momentum transfer in excess of $2\hbar$k can be measured with the experimental parameters presented here. This implies that multiple photon exchange occurs during the interaction [S2].

4. I have developed a new extended model for the numerical simulation of the multi-photon adiabatic transition on rubidium atoms, since numerical

simulations with previous theoretical models deviated significantly from experimental results. This model includes elements that are essential for the experiment - the effects of spontaneous emission and repumping lasers, and the Doppler effect due to the motion of the atoms. The numerical solutions of the new model describe the experimental results approximately well [S2].

4. List of publications related to the thesis

[S1]. **K. Varga-Umbrich**, J. S. Bakos, G. P. Djotyan, P. N. Ignácz, B. Ráczkevi, Zs. Sörlei, J. Szigeti and M. Á. Kedves, „Stabilization and time resolved measurement of the frequency evolution of a modulated diode laser for chirped pulse generation,” *Laser Physics,* vol. 26, p. 055006, 2016.

[S2]. **K. Varga-Umbrich**, J. S. Bakos, G. P. Djotyan, Z. Sörlei, G. Demeter, P. N. Ignácz, B. Ráczkevi, J. Szigeti and M. Á. Kedves, „Coherent manipulation of trapped Rb atoms by overlapping frequency-chirped laser pulses: theory and experiment,” *The European Physical Journal D,* vol. 76, p. 70, 2022.

5. Other list of publications and patents

[K1]. M. Aladi, J. Bakos, I.F. Barna, A. Czitrovszky, G. Djotyan, P. Dombi, D. Dzsotjan, I. Földes, G. Hamar, P. Ignácz, M. Kedves, A. Kerekes, P. Lévai, I. Márton, A. Nagy, D. Oszetzky, M. Pocsai, P. Rácz, B. Ráczkevi, J.

Szigeti, Zs. Sörlei, R. Szipöcs, D. Varga, **K. Varga-Umbrich**, S. Varró, L. Vámos, Gy. Vesztergombi, „Pre-excitation studies for rubidium-plasma generation”, *Nuclear Instruments and Methods in Physics Research A*, vol. 740, p. 203, 2014.

[K2]. G.P. Djotyan, J.S. Bakos, M.Á. Kedves, B. Ráczkevi, D. Dzsotjan, **K. Varga-Umbrich**, Zs. Sörlei, J. Szigeti, P. Ignácz, P. Lévai, A. Czitrovszky, A. Nagy, P. Dombi and P. Rácz, „Real-time interferometric diagnostics of rubidium plasma,” *Nuclear Instruments and Methods in Physics Research Section A,* vol. 884, p. 25, 2018.

[K3]. G.P. Djotyan, J.S. Bakos, P. Ignácz, M.Á. Kedves, B. Ráczkevi, N. Sándor, Zs. Sörlei, J. Szigeti, **K. Varga-Umbrich** „Koherens kontroll fázismodulált rövid lézerimpuzusokkal: alkalmazása magasabbrendű harmonikusok keltésnél és részecskegyorsításnál,” *Kvantumelektronika 2014: VII. szimpózium a hazai kvantumelektronikai kutatások eredményeiről. Helyszín: Budapest, Magyarország*, 187p. pp. 66-67. 2014.

[P1]. G.P. Djotyan, J.S. Bakos, G. Demeter, Zs. Sörlei, D. Dzsotjan, N. Sándor, M.Á. Kedves, B. Ráczkevi, **K.**

Varga-Umbrich, „Coherent control of quantum states: From atoms to high-order harmonics generation and acceleration of particles” *Wigner 111 Symposium* (2013)

[P2]. M. Aladi, J. Bakos, I.F. Barna, A. Czitrovszky, G. Djotyan, P. Dombi, D. Dzsotjan, I. Földes, G. Hamar, P. Ignácz, M. Kedves, A. Kerekes, P. Lévai, I. Márton, A. Nagy, D. Oszetzky, M. Pocsai, P. Rácz, B. Ráczkevi, J. Szigeti, Zs. Sörlei, R. Szipöcs, D. Varga, **K. Varga-Umbrich**, S. Varró, L. Vámos, Gy. Vesztergombi, „The Wigner RC contribution to the CERN AWAKE experiment” *Wigner 111 Symposium* (2013)

[P3]. M. Aladi, J.S. Bakos, I.F. Barna, A. Czitrovszky, G.P. Djotyan, P. Dombi, P.N. Ignácz, M.A. Kedves, I. Márton, A. Nagy, D. Oszetzky, M.A. Pocsai, P. Rácz, B. Ráczkevi, J. Szigeti, Zs. Sörlei, D. Varga, **K. Varga-Umbrich**, L.Vámos, „Experimental Studies for Rubidium-Plasma Generation by Femtosecond Laser Pulses” *2nd European Advanced Accelerator Concepts Workshop* (2015)

[P4]. G.P. Djotyan, M. Á. Kedves, B. Ráczkevi, **K. Varga-Umbrich**, J.S. Bakos, Zs. Sörlei, J. Szigeti, P.N. Ignácz, P. Lévai, I.F. Barna, A. Czitrovszky, P. Dombi, P. Rácz,

„Laser plasma source at Wigner Research Center for Physics” *ELI workshop* (2015)

[SZ1]. **K Varga-Umbrich**, B Jatekos, J.S. Gal, *„Dual purpose 3D image sensor integrated into automotive wing mirrors,* DE102019211033A1; publikálva: 2021.01.28.

[SZ2]. G. Friedmann, K.E. Horvath, **K. Varga-Umbrich**, „*Special light guide for illuminated rottary knob*”, DE102019209504A1; publikálva: 2020.12.31.

[SZ3]. **K. Varga-Umbrich**, B. Jatekos, „*Image generator unit quasi 3D laser projector-based head-up display system*”, DE102018211533A1; publikálva: 2020.01.16.

[SZ4]. **K. Varga-Umbrich**, Sz. Gemesi, B. Csato, „*Design holes as optical elements in the light guide to improve the light distribution*”, DE102018211527A1; publikálva: 2020.01.16.

[SZ5]. M. Baki, **K. Varga-Umbrich**, „*Method and device for determining an optical impairment of a camera*” DE102019218450A1; publikálva: 2021.06.02.

6. References

[1] N. V. Vitanov, T. Halfmann, B. W. Shore and K. Bergmann, "Laser - Induced Population Transfer By Adiabatic Passage Techniques," *Annual Review of Physical Chemistry,* vol. 52, p. 763, 2001.

[2] K. Bergmann, H. Theuer and B. W. Shore, "Coherent population transfer among quantum states of atoms and molecules," *Rev. Mod. Phys.,* vol. 70, p. 1003, 1998.

[3] M. M. T. Loy, "Observation of population inversion by optical adiabatic rapid passage," *Phys. Rev. Lett.,* vol. 32, p. 814, 1974.

[4] J. S. Melinger, S. R. Gandhi, A. Hariharan, D. Goswami and W. S. Warren, "Adiabatic population transfer with frequency-swept laser pulses," *J. Chem. Phys.,* vol. 101, p. 6439, 1994.

[5] B. Shore, "Picturing stimulated Raman adiabatic passage: a STIRAP tutorial," *Adv. Opt. Photon.,* vol. 9, p. 563, 2017.

[6] B. M. Sparkes, D. Murphy, R. J. Taylor, R. W. Speirs, A. J. McCulloch and R. E. Scholten, "Stimulated Raman adiabatic passage for improved performance of a cold-atom electron and ion source," *Phys. Rev. A,* vol. 94, p. 023404, 2016.

[7] B. W. Shore, K. Bergmann, A. Kuhn and J. Oreg, "Laser-induced population transfer in multistate systems: A comparative study," *Phys. Rev. A,* vol. 45, p. 5297, 1992.

[8] A. Goepfert, I. Bloch, D. Haubrich, F. Lison, R. Schütze, R. Wynands and D. Meschede, "Stimulated focusing and deflection of an atomic beam using picosecond laser pulses," *Phys. Rev. A,* vol. 56, p. 3354, 1997.

[9] J. S. Bakos, G. P. Djotyan, P. N. Ignácz, M. A. Kedves, M. Serényi, Z. Sörlei, J. Szigeti and Z. Tóth, "Interaction of frequency modulated light pulses with rubidium atoms in a magneto-optical trap," *Eur. Phys. J. D,* vol. 39, p. 59, 2006.

[10] I. Nebenzahl and A. Szőke, "Deflection of atomic beams by resonance radiation using stimulated emission," *Appl. Phys. Lett.,* vol. 25, p. 327, 1974.

[11] G. Demeter, G. P. Djotyan, Z. Sörlei, J. Szigeti and B. J. S., "Mechanical effect of retroreflected frequency-chirped laser pulses on two-level atoms," *Phys. Rev. A,* vol. 74, p. 013401, 2006.

[12] G. Demeter and G. P. Djotyan, "Multiphoton adiabatic passage for atom optics application," *Optical Society of America*, vol. 26, p. 867, 2009.

[13] G. Demeter, "Quantum control of multilevel atoms with rotational degeneracy using short laser pulses," *Phys. Rev. A,* vol. 82, p. 043404, 2010.