Interaction of UV light with cold metastable helium atoms

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2004

citation for published version (APA)
Koelemeij, J. C. J. (2004). *Interaction of UV light with cold metastable helium atoms*. [PhD-Thesis - Research and graduation internal, Vrije Universiteit Amsterdam].

Summary

Since the first proposals in 1975 for manipulation of atoms with near-resonant laser light, laser cooling and trapping of atoms has resulted in many new developments in experimental physics. Perhaps the most exciting example is the field of Bose-Einstein condensation (BEC), which is firmly based on laser cooling and trapping techniques. BEC in a gaseous cloud of indistinguishable bosonic atoms occurs when the wavelength of the atomic wavepacket exceeds the interatomic distance. The atomic ensemble then obeys Bose-Einstein statistics rather than classical Boltzmann statistics, and the cloud exhibits macroscopic quantum-mechanical wave properties. The condition for BEC, a high (~ 1) phase-space density, translates to (sub)microkelvin temperature and $\sim 10^{14}$ cm^{-3} density for a gaseous sample of atoms. Over the years, laser cooling and trapping techniques such as the *magneto-optical trap* (MOT) have been refined to approach these conditions, although the final step towards BEC requires a purely magnetic trap or an off-resonant optical trap and evaporative cooling methods. The improvements in MOT density were partly based on knowledge obtained from *cold-collision* experiments. The study of cold collisions in the presence of near-resonant light exemplifies another branch of experimental physics which arose from the earliest laser cooling and trapping experiments.

The experiments described in this thesis involve laser cooling and trapping of triplet metastable helium (He*) atoms, which is usually done using 1083 nm laser light. The metastable state has an $\sim 8 \times 10^3$ s lifetime which is practically infinite on typical experimental timescales, while the large internal energy (19.8 eV) enables detection of single He* atoms by electron multipliers. One of the major goals of cooling and trapping metastable helium has been the achievement of BEC. In contrast to “common” BECs consisting of ground-state alkali atoms, BEC of He* is rather spectacular as the internal energy of the atoms exceeds the typical BEC energy scale by many orders of magnitude. However, aligning the spins of the He* atoms in the magnetic trap (*spin polarization*) suppresses the occurrence of Penning-ionizing collisions, during which the total energy of two metastables is released and both He* atoms are lost from the trap. It was demonstrated in 2001 by two groups in France that BEC in a spin-polarized He* cloud is indeed feasible. In the magneto-optical trap, however, spin polarization is not possible, and Penning ionization dominates the loss of metastables. Here, Penning ionization occurs mainly through two-body *photoassociative collisions*, in which two approaching atoms are excited by the MOT light to a bound molecular dimer state. In this molecular state, the two atoms experience an attractive force accelerating them towards the short internuclear distances where Penning ionization takes place. This process limits the density in the MOT, which is unfavorable for the further experimental steps towards BEC.

In an attempt to improve the density in a He* MOT, in this thesis laser cooling and trapping at 389 nm is investigated. Using 389 nm photons a three-times larger force than with 1083 nm can be exerted on the He* atoms, allowing for a substantial decrease of the trapping volume of the MOT. However, until then it had been unknown whether collisional losses in the presence of 389 nm light would be larger or smaller than in 1083 nm light. In case of small losses, the compression of the cloud might result in a large density.

For this experiment, a powerful 389 nm laser system was constructed and frequency stabilized to the 389 nm transition in helium. The laser setup, based on a frequency-doubled titanium:sapphire laser, produces 1 W of 389 nm light with a net conversion efficiency as high as 75% in the second harmonic generation process. The 389 nm laser is described in Chapter 2, together with modifications made to improve the stability and applicability of the system. Furthermore, a vacuum apparatus for production, laser collimation and Zeeman deceleration of a bright beam of He* atoms was build up. This part of the setup, which was built along the same lines as an existing He* BEC apparatus, operates with 1083 nm lasers. Both machines are described in Chapter 1. In the last part of the vacuum apparatus a prototype MOT at 389 nm was realized. The aim of the prototype experiment was to measure two-body and other losses, and to observe compression of a trapped He* cloud by 389 nm light. As described in Chapter 3, in the 389 nm MOT the volume of the trapped cloud was indeed considerably reduced. At the same time, the number of photoassociative collisions was significantly reduced as compared to a 1083 nm MOT, and an explanation for this was found in cold-collision theory. Small losses due to two-photon ionization were also measured and characterized. A final important observation was that the 389 nm MOT has an intrinsically small loading rate, which would ultimately limit the number and density of trapped atoms. The 389 nm MOT was therefore combined with a large 1083 nm MOT in the existing BEC apparatus. By running a sequence of a loading phase, during which the 1083 nm MOT was loaded with 10^9 He* atoms, followed by a 5 ms compression phase in a dedicated 389 nm MOT, the He* density could be increased to an unprecedented 5×10^{10} cm^{-3}, as described in Chapter 4. Making use of the many diagnostic tools of the BEC machine, the dynamics during the compression were observed in various ways. One method, detection of collisional loss products, provided a real-time monitor on this compression in the 389 nm MOT.

By comparing the temporal behavior of the Penning ionization rate and the production rate of fast metastable atoms (which find their origin in photoassociative collisions as well), some remarkable conclusions could be drawn. Firstly, the production rate of fast metastables in the 389 nm MOT turned out to be of the same order of magnitude as the Penning ionization rate. By contrast, in the 1083 nm MOT this production rate was of the order of a few percent compared to the Penning ionization rate. Secondly, the velocities and the abundances of fast metastables escaping from the 389 nm MOT and the 1083 nm MOT are explained by a hypothesis on the short-range behavior of the involved molecular dimer states. For the 1083 nm case this hypothesis was verified using existing *ab initio* data on the involved molecular states. However, for the 389 nm case the hypothesis cannot be verified as theoretical *ab initio* data on the relevant molecular states are not available yet.

In Chapter 5, a numerical treatment of the long-range interaction between He* atoms in the presence of either 1083 nm or 389 nm light is presented. The aim of the calculations was to find possibilities for photoassociation spectroscopy of *purely long-range bound states* in He* with 389 nm light, similar as previously done by others using 1083 nm light. The results for the 1083 nm case agree well with existing data, with an accuracy limited by approximations made in the calculation. The results for the 389 nm case, which had not been considered before by others, are shown to be valid only for sufficiently large interatomic distances, which is due to general difficulties encountered in calculations of the electrostatic interaction between atoms in more highly excited states, and the resulting divergence of the second-order perturbation theory. It remains therefore unclear what the prospects are for photoassociation spectroscopy at 389 nm of purely long-range bound states.