The lifetime of the helium anion

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Abstract. We report the result of a correction-free measurement of the lifetime of the metastable atomic negative helium ion. For all previous experimental investigations of the lifetime of the most long lived level of the He\textsuperscript{−} ion, 1s2s2p\textsuperscript{4}P\textsubscript{5/2}, it was necessary to correct for systematic effects of the experimental environment as magnetically induced mixing with more short-lived fine structure components and/or photo detachment by the thermal radiation. In the present experiment any such influence on the measured lifetime has been effectively eliminated by performing the measurement in a cryogenic electrostatic ion-beam trap. With this technique we have reached a higher accuracy than earlier obtained. Our result with one standard deviation error is \(\tau_{5/2} = (359.0 \pm 0.7) \mu s\).

1. Introduction

Ground state helium is a very compact and tightly bound system and has the smallest dipole polarizability of all neutral atoms [1]. It is therefore not surprising that it is impossible to bind an additional electron to a ground state helium atom to form a stable negative ion. Excited states of helium He(1snl) are much more readily polarized by an additional electron and indeed negative ions do exist in the state He\textsuperscript{−}(1s2s2p\textsuperscript{4}P\textsubscript{J}, \(J=1/2, 3/2, 5/2\)), which is bound by 77 meV with respect to the neutral metastable He(1s2s\textsuperscript{3}S\textsubscript{1}) state. Energetically, this state is embedded in the continuum of a ground state helium atom and a free electron and is therefore able to decay by autodetachment. This final state, however, has a total electronic spin of \(S=1/2\) while the initial state has \(S=3/2\). For this reason rapid—fs time scale—non-relativistic Coulomb autodetachment is forbidden and the system can decay only by slower alternative mechanisms. One such mechanism is relativistically induced Coulomb autodetachment. Relativistic spin-orbit coupling will open a decay path by inducing a small mixing of the \(J=1/2\) and \(J=3/2\) levels of He\textsuperscript{−}(1s2s2p\textsuperscript{4}P\textsubscript{J}) with the equivalent \(J\)-levels of the shortlived resonance state 1s2s2p\textsuperscript{2}P\textsubscript{J}. For \(J=5/2\) no equivalent resonance level is available to mix with and therefore this level decays only by direct relativistic, magnetic interactions between the two active electrons (spin-spin and spin-other-orbit) [2] (cf. figure 1). In part due to the lack of the relativistically induced Coulomb autodetachment channel and in part because of a weaker direct relativistic coupling, the \(J=5/2\) level has a considerably longer lifetime than the \(J=1/2\) and \(J=3/2\) levels. In [2] the lifetimes, \(\tau_{J}\), of the three fine structure levels were calculated to be \(\tau_{1/2} = 10.7 \mu s\), \(\tau_{3/2} = 11.8 \mu s\) and \(\tau_{5/2} = 405 \mu s\). The calculation for the \(J=5/2\)-level was later improved and constitutes to our knowledge the most recent theoretical result for the lifetime of the most long-lived and lowest energy level
Figure 1. Levels and decay paths for the He$^{-}$ ion. s-s and s-o-o are spin-spin and spin-other-orbit interactions, while the acronym RICA stands for Relativistically Induced Coulomb Autodetachment.

of the atomic helium anion: $\tau_{5/2}=(345\pm10)\mu s$.[3]

On the experimental side Blau et al. [4] performed a measurement with a very sophisticated experimental apparatus in which a Faraday cup could be moved along a magnetically confined beam of He$^{-}$ (and detached electrons) over a distance of the order of ten metres. The result of that challenging and pioneering experiment was $\tau_{5/2}=(345\pm90)\mu s$. A significant improvement in precision was obtained when Andersen et al. used a stored beam of He$^{-}$ in the ASTRID magnetic-confinement heavy-ion storage ring in Aarhus [5]. In that experiment [5] a short bunch of He$^{-}$ ions was stored in the storage ring and a detector was placed behind one of the dipole-bending magnets to collect all neutral helium atoms formed in the preceding straight section. The detector count rate as function of time after the injection yielded a decay curve from which a long lifetime component could be deduced and related to the lifetime of the $J=5/2$ fine structure level. This was a very efficient experiment in the sense that a significant fraction of the injected anions after autodetachment ended up at the single-particle counting detector and thus contributed to the signal, and therefore a very small statistical error could be obtained in a short time. There were, however, two systematic effects that needed to be corrected for and the uncertainty related to these corrections dominated the estimated error on the final result: $\tau_{5/2}=(350\pm15)\mu s$. The two systematic effects that both lead to a shortening of the measured lifetime were Zeeman mixing with the two shorter-lived fine structure components in the strong fields of the dipole bending magnets and photodetachment by absorption of photons from the thermal radiation.

In 1999 Wolf et al. measured the He$^{-}$ lifetime in an experiment at the Weizman Institute
in Israel, which conceptually was very similar to the ASTRID experiment [5], but using a much smaller electrostatic ion-beam trap [6]. As no significant magnetic fields were present in that measurement, the photodetachment by photons of the black-body radiation was yielding the only major systematic uncertainty, and a slightly smaller error than found in the ASTRID experiment [5] resulted. The final result of the experiment by Wolf et al. was $\tau_{5/2}=(343\pm10)\mu s$ [6]. Soon after this, the He$^-$-lifetime was measured in the all electrostatic ion-storage ring ELISA in Aarhus [7]. Also in that experiment, no Zeeman-mixing correction was needed and further, the measurement was performed at different temperatures in the range 215-295 K, where the lower temperatures were reached by pouring liquid nitrogen over the entire storage ring. This resulted in a smaller influence of the thermal radiation on the final result of the measurement; $\tau_{5/2}=(365\pm3)\mu s$ [7]. The results of these two measurements [6, 7] are on the limit of agreement. If the true lifetime were 360 $\mu s$, both experiments would be within two standard deviations of that.

Here, we discuss an experiment in which He$^-$ ions are stored in a compact electrostatic ion-beam trap, ConeTrap [8, 9], which is cooled to a temperature of only 10 K. This experiment yields the first correction-free result for the $J=5/2$ level: $\tau_{5/2}=(359.0\pm0.7)\mu s$[10].

2. Experiment
An overview of the experimental setup is shown in figure 2. A beam of 2.5 keV He$^+$ ions was extracted from a plasma ion source and selected by a 90° analyzing dipole magnet. The He$^+$ beam was then steered through a cesium vapor cell in which a small fraction of the ions underwent

Figure 2. Schematic of the experimental setup as described in the text.
two sequential charge-transfer processes to form helium anions in the 1s2s2p $^4P_J$ levels. After the Cs cell the mixed beam was charge separated by a set of parallel-plate deflectors and the negative ions were directed towards a cryogenic vacuum chamber.

This vacuum chamber, which is built for cryogenic testing of components and detectors [11] for the double electrostatic ion-storage ring, DESIREE [12, 13], consists of two separate vacuum volumes: An aluminium vacuum chamber is mounted inside another vacuum chamber made from stainless steel. The inner chamber is connected to the second (colder) stage of a two-stage Sumitomo closed-helium circuit cryogenerator. Between the two chambers a thermal shield made from copper is installed. This shield is cooled by the first stage of the cryogenerator. The lowest temperature of the inner chamber was 10 K and by applying ohmic heating at the coldhead any temperature between this value and room temperature could be reached. The cryogenic vacuum chamber was pumped by a turbomolecular pump and a titanium sublimation pump. In spite of two stages of differential pumping the main gas load came from the injection-line vacuum system at $10^{-7}$ mbar. At a room temperature extension to the cryogenic chamber a pressure of $10^{-10}$ mbar was measured and this constitutes the upper limit to the pressure in the cold trap during cryogenic operation.

When the ions entered the cold chamber they were again deflected by 20° before entering the electrostatic ion-beam trap, ConeTrap [8, 9]. These deflector plates were contained in an aluminium housing with 4 mm diameter beam entrance and exit apertures. The housing and deflector plates were in good thermal contact with the walls of the inner chamber and thus it was ensured that no warm surfaces were at the line-of-sight from any position inside the cold electrostatic trap. The ConeTrap itself is shown in figure 3. This simple ion trap consists of only three electrodes. Two conical electrodes are facing each other and are separated by a cylindrical middle electrode. In the standard configuration the middle electrode is grounded while the
Figure 4. The number of counts in every 1 µs channel accumulated for about 5 million injections as function of the time after injection in ConeTrap. The full curve is the result of a fit to the sum of two exponential functions and a constant background to account for detector dark counts. This data set was recorded with a trap temperature of 10 K.

3. Results and discussion

Figure 4 shows a decay curve recorded at 10 K. The decay curve is accumulated for 5 hours corresponding to about 5 million injections. The high and rapidly decreasing rate measured...
The un-corrected results of all measurements of the $J=5/2$ lifetime using electrostatic storage devices as function of the temperature of the storage device (ring or trap). The squares are results from the present work at $T=10$ K, $T=50$ K, and $T=293$ K. The results of the ELISA experiment [7] are shown as triangles and a filled circle denotes the result of the room-temperature measurement using the Weizman Institute’s electrostatic ion-beam trap [6]. The diamond at $T=0$K is the result of the calculation by Miecznik et al. [3]. Finally, the full curve results from adding to our measured decay rate, $1/\tau_{5/2}$, the rate of photodetachment by photons of the Planck distribution according to the photodetachment cross sections of [16].

shortly after injection corresponds to the decay of ions populating the two shortlived fine structure levels $J=1/2, 3/2$ with lifetimes of the order of 10 $\mu$s. The dominating contribution to the signal in the time range of 100 $\mu$s - 2 ms is due to decay of metastable He$^-$ ions populating the 1s2s2p $^4P_{5/2}$ level, while at still longer times a non-negligible contribution from detector dark counts is seen. The full curve through the data points is a fit to a function consisting of the sum of two exponentials and a constant background. Ideally three exponentials should be used, but even if the statistical quality of the data is high, it is not sufficient to separate the $J=1/2$ and $J=3/2$ contributions. In order to extract a $J=5/2$ lifetime that is independent of this problem, we used only the data after 200 $\mu$s, where only that longlived level was populated and made a fit to a sum of one exponential and a constant representing the detector background. The resulting lifetime from this fit was $\tau_{5/2}^{10K}=(358.8\pm0.7)\mu$s. We measured also at $T=50$ K and an equivalent analysis gave $\tau_{5/2}^{50K}=(362\pm2)\mu$s, and as we will discuss below, the effect of photodetachment by black-body radiation is negligible for $T \leq 100$ K and we give the weighted average of the values found at $T=10$ K and $T=50$ K as our final result: $\tau_{5/2}=(359.0\pm0.7)\mu$s.

In figure 5 we show the un-corrected results of all measurements of the lifetime of He$^-(1s2s2p$ $^4P_{5/2}$ performed with electrostatic storage devices and therefore not subject to the effect of Zeeman-mixing. All these measurements are made under ultra-high vacuum conditions so that collisional effects are negligible. Further, effects of the electric fields can be shown to be of no significance [14, 15]. It can therefore be assumed that the only significant effect
of external influence on the measured lifetimes in all these cases is the photodetachment by the thermal Planck radiation. The contribution—at a given temperature—to the decay rate from photodetachment by absorption of black-body radiation photons can be calculated by convoluting the photon-energy dependent cross section [16] with the Planck distribution. This photodetachment rate is shown as function of the temperature in figure 6 and should be compared to the autodetachment rate deduced from our measurement of 1/τ_{5/2}=2786 s\(^{-1}\). At T=100 K the resulting photodetachment rate is 0.3 s\(^{-1}\) and thus for our measurements at 50 K and 10 K we may safely neglect also this effect. Therefore unlike all previous measurements of τ_{5/2}, our result is not affected by the accuracy of the cross section used, and furthermore, we are not sensitive to variations of the temperature of the apparatus as long as all parts are well below 100 K.

To compare the different experimental results shown in figure 5 we have added the full curve, which is the resulting lifetime obtained by adding the autodetachment rate corresponding to our final result and the black-body radiation induced photodetachment rate calculated from the cross sections of Liu and Starace[16]. Plotted in this way it is seen that all the experimental results and the photodetachment cross sections are in relatively good agreement. The theoretical result[3] also agrees rather well if the error stated in that work is to be interpreted as a one-standard-deviation error. We hope that the availability of this much improved experimental value of the lifetime of He\(^-\)\((1s2s2p \ ^4P_{5/2})\) level will spur renewed theoretical interest in this problem to establish an equally accurate theoretical value for comparison.

4. Conclusions and outlook
By using a cryogenic electrostatic ion-beam trap, we have performed the first correction-free measurement of the lifetime τ_{5/2} of the most longlived fine structure level of the metastable helium anion. The final result, with a relative error of only 2 \%, is τ_{5/2}=(359.0±0.7)\,\mu s. Our
result is consistent with other measurements at higher temperatures when the photodetachment rate due to the thermal radiation is considered in those measurements. The most recent theoretical result that we know of is from 1993 and has an uncertainty which is 14 times larger than our experimental uncertainty. An improved calculation yielding an accuracy comparable to the experimental one would be very interesting.

To the best of our knowledge the work presented here and in [10] was the first demonstration of operation of an electrostatic ion-storage device at cryogenic temperature though more such demonstrations have followed [9, 17]. The demonstration of the elimination of thermally induced detachment of loosely bound systems is of principle importance for future cryogenic ion-storage rings currently under construction [12, 18].

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