Lifetime measurement of He^- using an electrostatic ion trap

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The lifetimes of the metastable $1s2s2p\ ^4P_{5/2}$ level of He^-, as well as the lifetime of the average of the $^4P_{3/2}$ and $^4P_{1/2}$ levels, have been measured using a new type of ion trap that stores keV ion beams using electrostatic fields only. The use of a pure electrostatic field avoids the complication of magnetic-field-induced mixing effects, which can interfere with the measurement of the spontaneous decay. The measured lifetime for the $^4P_{5/2}$ state, after correction for decay induced by blackbody radiation, is 343 ± 10 μs. This value is consistent with previous experiments, and in excellent agreement with the most recent theoretical calculations. The average lifetime of the $^4P_{3/2}$ and $^4P_{1/2}$ is 8.9 ± 0.2 μs, which is about 20% lower than the weighted theoretical value. [S1050-2947(99)09501-3]

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I. INTRODUCTION

The physics of negative ions has attracted extensive experimental and theoretical attention during the past decades. The experimental progress has been very much linked to the introduction of new techniques, which allow for detailed study of the negative ion structure and lifetime. During the past decade, storage rings have been an important tool for such studies [1] as they have made possible the long-time storage of heavy-ion beams stored at energies between tens of keV to a few MeV. For negative ions, the storage time is governed by the neutralization due to collisions with the residual gas, setting an upper limit of a few seconds. For weakly bound systems (tens of meV), the decay induced by blackbody radiation represents another major restriction on the storage time, which is very much dependent on the value of the binding energy, but can be as short as a few hundred microseconds [2]. Such storage enables the study of lifetimes of metastable negative ions in the range of 10 μs–100 ms. However, one of the main drawbacks of the heavy-ion storage ring technique is the presence of magnetic fields that can mix the magnetic substates from the different, but close-lying, fine-structure components with the same magnetic quantum number.

One of the simplest negative metastable negative ions is He^-, which is known to be formed in the $1s2s2p\ ^4P$ state, and is bound by 77 meV relative to the first excited state $1s2s\ ^3S$ of helium. This ion has received a great deal of attention, both theoretically [3–8] and experimentally [9–15]. The He^- is known to be metastable and the decay of the three fine-structure components ($^4P_{5/2}$, $^4P_{3/2}$, and $^4P_{1/2}$) is due to spin-orbit or spin-spin coupling [9]. Calculations and experiments have shown that the $^4P_{3/2}$ and $^4P_{1/2}$ have much shorter lifetime than the $^4P_{5/2}$, as the decay mode of the latter is induced by spin-spin interaction only.

Theoretical calculations for the $J=5/2$ have been carried out using various methods, predicting a lifetime ranging from 266 to 550 μs (see Table I). On the other hand, only one set of values for the $J=3/2$ and 1/2 has been theoretically calculated, with lifetimes of 11.8 and 10.7 μs, respectively (see Table I). On the experimental side, the most accurate measurement of the $^4P_{5/2}$ was made by Andersen *et al.* [14] using the heavy-ion storage ring ASTRID. As pointed out above, the ring is equipped with a number of dipole and quadrupole magnets to store the beam. In order to correct for the effect of magnetic fields, Andersen *et al.* [14] have measured the lifetime of He^- at different beam energies, thus sampling different values of the magnetic field. The data were then extrapolated to zero magnetic field using

TABLE I. Experimental and theoretical lifetimes of the three different states of He^-. The values in the column headed ''Average'' are the average of the $J=1/2$ and 3/2 lifetimes.

	Lifetime (μs)				
Determination	$J=1/2$	Average	$J=3/2$	$J=5/2$	References
Theory				266	[3]
				303	[4]
				345 ± 10	[8]
	10.7		11.8	405	[5]
				455	[6]
				497	[7]
				550	[4]
Experimental	16 ± 4		10 ± 4	500 ± 200	[10]
			12 ± 2	350 ± 15	[14]
		11.5 ± 5		345 ± 90	[9]
		18.2			[11]
		$9\pm^5_3$			[12]
		16.7 ± 2.5			[13]
		8.9 ± 0.2		343 ± 10	present work

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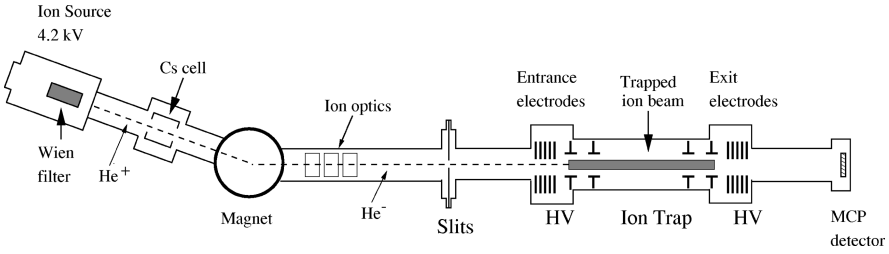

FIG. 1. Experimental setup.

a two-parameter fit based on a theoretical function, which takes into account the Zeeman mixing in the dipole magnetic field. Although the presence of a magnetic field makes the direct measurement of the $^4P_{5/2}$ lifetime difficult, it has, as pointed out by Andersen *et al.* [14], the advantage of providing information on the lifetime of the short-lived $^4P_{3/2}$ state through the fitting procedure.

Another important correction for laboratory measurements of the lifetime of a weakly bound system is the influence of blackbody radiation. This radiation field can photodetach the weakly bound electron so that even a stable system would have a finite lifetime at nonzero temperature. For the $^4P_{5/2}$ state of He^-, such a correction amounts to about 20% of the measured value [14]. This can be determined by measuring the temperature dependence of the lifetime while cooling or heating the experimental system.

II. EXPERIMENTAL PROCEDURES AND RESULTS

In the present experiment, we have measured the lifetime of He^- using a new type of electrostatic ion trap [16,17], thus avoiding altogether the presence of magnetic fields. The experimental setup is shown in Fig. 1. A He^+ beam is produced by an electron impact ionization source, accelerated to an energy of 4.2 keV, selected by a Wien filter, and subsequently passed through a windowless target cell filled with cesium vapor, produced by a small oven. It is well known that He^- can be efficiently produced from He^+ by double-charge exchange with cesium atoms at keV energy [18]. In the present case, about 0.25% of the He^+ was transformed to He^-, resulting in a beam of ≈ 0.4 nA. The beam was mass and charge selected with the help of a magnetic field and directed toward the ion trap.

This ion trap stores the beam between two electrostatic mirrors. A complete description of its principle of operation and characteristics has already been given [17]. In short, the trap is made of two sets of electrodes (the ''entrance'' and ''exit'' electrodes) between which the ions bounce back and forth. On injection, the ''entrance'' electrodes are at zero potential, and the ''exit'' electrodes are at a potential, which is high enough to reflect the ions. The voltages on the ''entrance'' electrodes are then rapidly switched on to the same potentials as those of the ''exit'' electrodes, in a time that is much shorter than the oscillation time of the particles in the trap. The ions are then trapped between the two mirrors. The focal length of the mirrors is determined by the geometrical configuration of the electrodes and by the electric field strength. As theoretically proved and experimentally demonstrated [17], the trap is stable for a specific range of focal lengths. In such a case, the storage time of stable ions is limited mainly by collisions with the residual gas. The trap length is 407 mm, and for 4.2-keV He^-, the oscillation period is about 2 μs. The pressure in the trap is about 2×10^{-10} Torr. The central part of the trap is a field-free region, as the innermost electrodes are grounded.

Neutral particles, which are produced either by collisions with residual gas or because of the autodetachment process, exit the trap through the ''entrance'' or ''exit'' electrodes so that 50% of these particles hit a microchannel plate (MCP) located downstream (see Fig. 1). Injection and trapping are performed at a repetition rate of 30 Hz. For each injection, the rate of particles hitting the MCP is measured as a function of storage time. Figure 2 shows this time dependence for a total of about 50 000 injections. The spectrum can clearly be divided into three different components: two exponential decays, and a constant. The spectrum was fitted with such a function, with a total of five free parameters, and the resulting fit is shown as a solid line in Fig. 2. We have assigned the fast decay to the lifetime of the weighted average of the $^4P_{3/2}$ and $^4P_{1/2}$ states of He^-, and the slow decay to the $^4P_{5/2}$ state. The flat background at times greater than 1.5 ms is consistent with the noise in the MCP detection system. The lifetimes obtained with the fitting procedure as described above are $\tau_{\langle 3/2,1/2\rangle}=8.8\pm0.1$ μs for the mean value of the $^4P_{3/2}$ and $^4P_{1/2}$ states and $\tau_{5/2}=290\pm2$ μs for the $^4P_{5/2}$ level.

The lifetimes were measured also after changing the ion trap pressure by a factor of 2 (to 4×10^{-10} Torr) and no differences were observed in the lifetimes. For reference, the

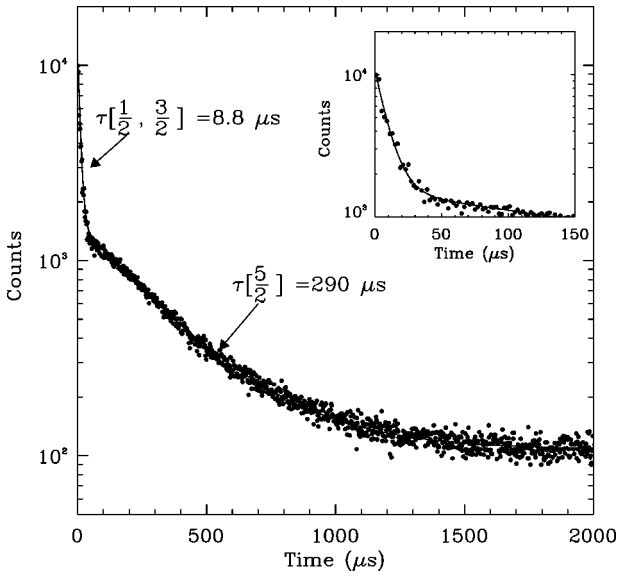

FIG. 2. Neutral He signal from the channel-plate detector as a function of time. The solid line is the fit to the data as described in the text. The two lifetimes $\tau_{\langle 1/2,3/2\rangle}$ and $\tau_{5/2}$ are not corrected for blackbody radiation-induced decay. Inset: expanded scale for short times

lifetime of a H^- beam at the same energy and same pressure is about 65 ms. Also, the lifetimes were left unchanged when the voltages of the electrostatic mirrors were set to a different value in order to change their focal lengths. There was no possibility to change the temperature of the ion trap (295 K) to test the sensitivity to blackbody radiation. However, the influence of blackbody radiation can be readily estimated using photodetachment cross sections as calculated by Saha and Compton [19], which are in very good agreement with available experimental data [20,21]. A numerical integration of the decay induced by blackbody radiation has already been performed by Andersen *et al.* [14], and yielded a decay rate of 0.534 ms^{-1} at room temperature. Subtracting this decay rate from the measured values, the lifetime of the $^4P_{5/2}$ increases to $\tau_{5/2}=343\pm10$ μs, where the error bar is mainly due to the uncertainty in the blackbody radiation cross section. The mean lifetime for the $^4P_{3/2}$ and $^4P_{1/2}$ states changed by only 0.1 μs: $\tau_{3/2,1/2}=8.9\pm0.2$ μs.

The identification of the decay curves as being related to the $J=5/2$ for the slow decay and a weighted average of $J=3/2$ and 1/2 for the fast decay can be reinforced by analyzing their relative populations. It is expected that after production by double-electron capture, the population of the three different J states will be related to their statistical weights. Based on this argument, the population after capture should be 50% in the $J=5/2$ states and 50% in the $J=3/2$ and 1/2 states together. From the data shown in Fig. 2, corrected both for the time of flight from the cesium target to the trap (4.8 μs) and for the delay between the moment the voltages on the entrance electrodes are raised and the initialization of the data acquisition (8 μs), one obtains a relative population of $50.7\pm0.1\%$ for the $J=5/2$ state, which is in excellent agreement with the above assumption. If one of the lifetimes of the $J=1/2$ or 3/2 states would have been very short so that the population of one of these states would have been lost between the cesium cell and the trap, the relative population would have been 2/3 for $[J=3/2]:[J=5/2]$, or 1/3 for $[J=1/2]:[J=5/2]$. Thus, it is highly probable that the fast decay in Fig. 2 is due to the weighted average of the $J=3/2$ and 1/2 states, and that their lifetimes are not very different from each other, a result that is in agreement with theoretical calculations [5] (see Table I).

The results for the lifetimes are presented in Table I, and are compared with previous experimental data, as well as theoretical values. For the $J=5/2$ state, the present result is in very good agreement with the previous measurement done with the ASTRID storage ring, which includes corrections due to magnetic-field effects. Our result also agrees with the two other experimental values, although as pointed out by Andersen *et al.* [14], the value measured by Blau, Novick, and Weinflash [9,10] was not corrected for the decay induced by blackbody radiation. On the theoretical side, a very large range of values has been calculated, and our result agrees extremely well with the most recent calculation done by Miecznik, Brage, and Fischer [8].

For the $J=1/2$ and 3/2, a direct comparison is more difficult, as only the average value has been obtained. Assuming that all the experimental values shown in Table I have been measured with an He^- in the same relative population for the $J=1/2$ and 3/2, the results shown in Table I display a relatively large variation from 8.9 to 16.7 μs. Since the relative populations of the long- and the short-lived components in our experiment are in perfect agreement with statistical argument, one can safely assume that the relative population of the $J=1/2$ and 3/2 states can be estimated on the same basis so that $[J=1/2]:[J=3/2]=1/2$. Thus, the value of 8.9 μs measured in the present experiment can be directly compared with the weighted average of the theoretical values [9] that yield 11.4 μs, a value that is higher by about 30% than the experimental lifetime. More theoretical calculations as well as experiments are needed, where the lifetimes of the two short-lived states can be measured separately in order to come to a final conclusion.

The present results demonstrate the power of the small electrostatic ion trap capable of trapping fast ion beams. The absence of magnetic fields allows for unperturbed measurement of lifetimes for states where mixing can occur. Because of the small size of the trap (about 50 cm) the whole system can be cooled to low temperature in a controlled way, allowing the elimination of blackbody radiation. Such a cooling system will be added to our system in the near future.

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