Metastable-ion lifetime studies utilizing a heavy-ion storage ring: Measurements on He^-

T. Andersen, L. H. Andersen, P. Balling, H. K. Haugen, P. Hvelplund, W. W. Smith,* and K. Taulbjerg
Institute of Physics and Astronomy, Aarhus University, DK-8000 Aarhus C, Denmark
(Received 8 September 1992)

The lifetime of the metastable autodetaching $1s2s2p\ ^4P_{5/2}$ level of the $^4He^-$ ion has been measured by a time-of-flight technique to be 350 ± 15 μs using a heavy-ion storage ring. Blackbody-induced photodetachment of this weakly bound level is shown to influence the decay rate by nearly 20%, an effect not discussed previously. The magnetic-field-induced mixing effects provide additional information about the lifetime of the close-lying $^4P_{3/2}$ level, yielding $\tau(^4P_{3/2})=12\pm2$ μs. The observed lifetimes are consistent with previous experimental values, but the accuracy of the $^4P_{5/2}$ lifetime is improved by a factor of 6, allowing a detailed test of theoretical predictions to be performed. The $^4P_{5/2}$ lifetime is significantly shorter than most recent advanced theoretical results, but in agreement with a multiconfiguration Hartree-Fock approach accurately describing the initial bound $^4P_{5/2}$ and the final continuum $^2F_{5/2}$ states.

PACS number(s): 32.70.Fw, 32.80.Dz

I. INTRODUCTION

He^- is the simplest unstable negative ion and represents an interesting three-electron system for fundamental studies in atomic physics. As such, it has received a great deal of experimental and theoretical attention since its discovery more than 50 years ago [1]. The He^- ion is a prototype of a class of long-lived negative ions which are metastable against decay via electron and photon emission. It is formed in the $1s2s2p\ ^4P$ state, which is bound with respect to the $1s2s\ ^3S$ state of helium by only 621 cm^{-1} [2,3]. The close-lying $J=5/2$ and $3/2$ levels are separated by 0.0275 cm^{-1}, with the $J=1/2$ level lying 0.2609 cm^{-1} above $J=5/2$, the lowest-lying level [4] (see Fig. 1).

He^- exhibits differential metastability with respect to autodetachment. The $^4P_{3/2,1/2}$ levels decay by the spin-orbit and spin-spin interactions, while the $^4P_{5/2}$ level decays only by the spin-spin interaction [5,6]. The coupling between the ^4P and ^2P levels of the same configuration, the latter of which are allowed to decay promptly by the Coulomb interaction, is responsible for the lifetimes of the $J=1/2$ and $3/2$ being decreased relative to the $J=5/2$ component. The coupling between the ^4P and ^2P levels complicates the theoretical predictions of the lifetime for the $J=1/2$ and $J=3/2$ components. For $J=5/2$, the interaction Hamiltonian is explicitly known, so that calculations of the lifetime of this metastable level are simpler. Several theoretical lifetimes for the $J=5/2$ level have been predicted. An overview of previously reported lifetimes, both experimental [5,7] and theoretical [8–13], for the $He^-(1s2s2p\ ^4P_{5/2})$ ion is presented in Table I. The most accurate measurement for $J=5/2$ of 345 ± 90 μs was conducted by Blau, Novick, and Weinflash [5], utilizing a direct beam line. The calculated values range from 266 to 550 μs and depend critically on the precise form of the wave function in both the initial and final state. For many years, the best calculation for the $J=5/2$ lifetime has been considered to be that of Estberg and LaBahn [12] (455 μs), a value in good agreement with the more recent calculations [11,13]. The lifetimes for $J=1/2$ and $3/2$ levels are much shorter. The data available are collected in Table II. The experimental and theoretical values reported so far for $J=3/2$ are in good agreement.

Recently, the newly constructed storage rings for atomic-physics experiments [16] have proved [17] to be a valuable tool for time-of-flight measurements of autoionizing lifetimes in the $\sim$10-μs–100-ms regime which usually is difficult to study by means of traditional beam techniques. Storage times in the range 1–5 s have been reported [18] for a number of stable negative ions, indicating that lifetimes of metastable ions such as $He^-(1s2s2p\ ^4P_{5/2})$, $Be^-(2s2p^2\ ^4P_{3/2})$ [17], or $Ca^-(4s4p^2\ ^4P_{1/2})$ [19] could be studied by this time-of-flight technique. The heavy-ion storage rings are equipped with a number of dipole and quadrupole mag-

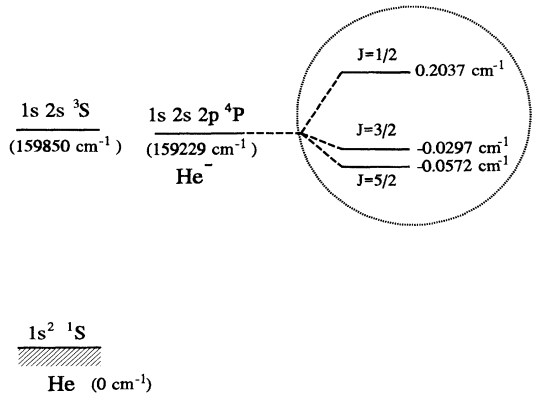

FIG. 1. Schematic energy-level diagram of He and He^- showing the fine structure of $^4He^-(1s2s2p\ ^4P_J)$.

TABLE I. Experimental and theoretical lifetimes of the $He^-(1s2s2p\ ^4P_{5/2})$ level.

Determination	Lifetime (μs)	Reference
Experiment	345±90	[5]
	500±200	[7]
	350±15	This work
Theory	266[a]	[8]
	303[a]	[9]
	354[b]	[10]
	405[b]	[11]
	455[b]	[12]
	497[c]	[13]
	550[b]	[9]

[a]Single-state initial configuration wave function.
[b]Configuration-interaction calculations based on the golden-rule formula.
[c]Configuration-interaction calculations using the saddle-point complex-rotation method.

netic fields to achieve and control the storage of the charged particles. The presence of these magnetic fields may have a significant influence on the time-of-flight data, particularly for negative ions with small fine-structure splittings such as He^-. For ions such as $Be^-(2s2p^2\ ^4P)$, with a fine-structure splitting approximately a factor of 20 larger than for He^-[1], recent storage-ring experiments [17] have yielded an accurate determination of the lifetime of the long-lived $Be^-(^4P_{3/2})$ level, but also provided additional information on the decay rates of the short-lived $J=1/2$ and $5/2$ levels from studies of the magnetic-field-induced quenching effects. For the He^- ion (see Fig. 1) it should be possible by studying the magnetic-field-induced quenching effects to determine the intrinsic lifetime of the $^4P_{5/2}$ level and, in addition, to obtain sufficient information about the $^4P_{3/2}$ level to allow a determination of its lifetime, whereas the influence from the $^4P_{1/2}$ level on the decay rate of the $^4P_{5/2}$ level will be negligible.

Blau, Novick, and Weinflash [5] performed the direct beam-line measurement of the lifetime of the $^4He^-(^4P_{5/2})$ level in a 10-m-long drift tube, equipped with a solenoid magnet capable of providing a static axial magnetic field up to 1500 G. The bulk of their data was taken with a 100-eV beam at 400 G, a magnetic field strong enough to induce a significant Zeeman mixing between the $M_J=3/2$ or $1/2$ sublevels, respectively, belonging to the $J=5/2$ or $3/2$ levels, whereas interactions with the $J=1/2$ level were assumed to be negligible. Blau, Novick, and Weinflash assumed that the magnetic field could be considered free from inhomogeneities which could lead to mixing of all the M_J sublevels. Later [20], however, it was recognized that minor inhomogeneities of $\sim\frac{1}{4}$ G in the magnetic field had been present, but the associated magnetically induced mixing effects were considered too small to change the published lifetime (345±90 μs). The possible influence on the $J=5/2$ lifetime from blackbody-induced photodetachment of $^4He^-(1s2s2p\ ^4P)$ during the 10-m flight path was, however, not discussed [5]. Blackbody-induced photodetachment of weakly bound negative ions such as Ca^-, which has an electron affinity in the $(4s^24p\ ^2P)$ ground state of only 18 meV [21], has recently [19] been shown to have a significant effect on the lifetime of a Ca^- beam in a storage ring. With an electron affinity of ~77 meV [2,3], blackbody radiation can also be expected to influence the lifetimes of the $He^-(1s2s2p\ ^4P)$ ion.

The present lifetime study of the $He^-(1s2s2p\ ^4P_J)$ levels was initiated in order to test previous experimental and theoretical data since it should be possible by means of the heavy-ion storage-ring technique (using storage times much longer than the lifetime) to obtain a much more accurate $^4P_{5/2}$ lifetime value than reported earlier [5], but also to explore the influence of the magnetic-field-induced quenching effects and of the blackbody radiation on time-of-flight experiments performed with weakly bound negative ions in a heavy-ion storage ring.

TABLE II. Experimental and theoretical lifetimes of the $He^-(1s2s2p\ ^4P_{3/2}$ and $^4P_{1/2})$ levels.

	Lifetime (μs)		References
Determination	$J=1/2$	$J=3/2$	References
Experimental	18.2[a]		[14]
	11.5±5[a]		[5]
	$9\pm^{5}_{3}$[a]		[15]
	16±4	10±2	[7]
	16.7±2.5[a]		[6]
		12±2	This work
Theory	10.7	11.8	[11]

[a]Average of the two lifetimes.

II. LIFETIME MEASUREMENTS

A. Experimental techniques

Our experiments have been conducted with the newly constructed storage ring ASTRID (Aarhus Storage Ring in Denmark) which has been described by Møller [22]. Figure 2 shows a schematic diagram of the storage-ring setup for lifetime measurements. The ring has a circumference of 40 m and is kept at a vacuum of $\sim 3\times10^{-11}$ torr. The magnetic lattice confining the negative ions consists of four pairs of bending magnets and 16 quadrupole magnets. The beam position can be measured by 16 electrostatic pickup systems. Ions are injected at kilo-electron-volt energies and can be postaccelerated by rf cavities, in the case of protons (or H^-) up to ~150 MeV. The beam is chopped with an electrostatic chopper to match the ring circumference and is injected into the ring with a magnetic system and an electrostatic kicker. Up to $\sim10^9$ singly charged ions can be stored this way when the rf device is not inserted. In the present experiment, positive helium ions are extracted from an ion source, accelerated to an energy between 7 and 35 keV, mass- and charge-state analyzed, and passed through a 4-cm-long Na vapor cell where $\leq 1\%$ ($\sim$20

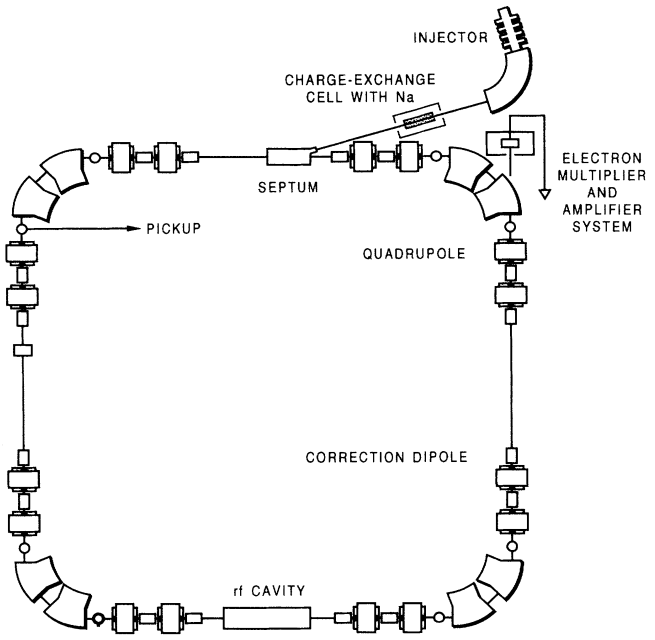

FIG. 2. The storage-ring setup, showing ion injector, charge-exchange facility, and the particle-detection system.

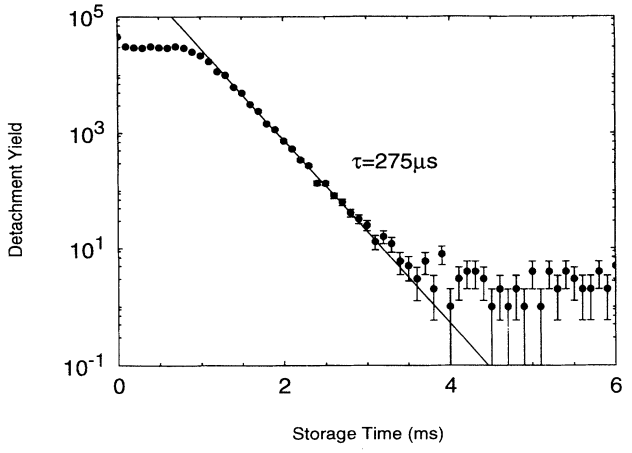

FIG. 3. Typical neutral-atom signal from tandem-channel-plate detector as a function of time following ion-beam injection.

nA) of the ions are charge exchanged to He^- and finally injected into the ring. A fraction of the ring, typically $\sim 25\%$, is filled. The autodetaching decay of He^- ions is studied both by nondestructive monitoring of the circulating current with capacitively coupled pickup plates, or through the detection of energetic neutral-decay particles, utilizing either a 2.5-cm-diam tandem channel-plate detector or an 8-mm-diam discrete-dynode electron multiplier. The first approach facilitated measurements over two He^- lifetimes, while the second allowed neutral-atom measurements over four orders of magnitude in the ion-beam intensity. The two detection techniques yielded consistent results, but the statistical uncertainty in the neutral signal was smaller. With a 20-nA beam, as used conventionally [17], the detector is saturated initially due to a high count rate, but after several revolutions in the ring, particle measurements without pileup can be performed. The experimental conditions with respect to the He^- beam can be varied as far as, e.g., beam energy, beam intensity, rest-gas pressure in the ring (factor of ~ 100), and temperature of the ring are concerned. The ring is equipped with a heating system, allowing experiments to be performed under conditions where half the ring is heated to temperatures between ~ 20 and $\sim 120\,^\circ C$.

B. Experimental data

Figure 3 shows a typical neutral-atom signal versus time for $^4He^-$. Initially, the detector is saturated due to a high count rate, but after several revolutions in the ring (where only particles, which are well confined to the near-harmonic-oscillator potential, remain circulating), single-particle measurements without pileup can be performed. The experimental data in Fig. 3, which cover an elapsed time following beam injection of 1–4 ms, can be described by means of a single-exponential decay process, using an initial time delay after loading the ring which is chosen to be insensitive to saturation effects. The ability to obtain a good signal-to-noise ratio out to ~ 10 lifetimes allows a determination with low statistical uncertainty and effectively averages betatron oscillations (with an amplitude of ~ 10–15 mm) in the ring [17–19]. Moreover, slit scattering, which could lead to significant systematic effects on direct beam lines, is virtually nonexistent after a couple of revolutions in the ring.

Several checks were performed on the integrity of the data. Degradation of the vacuum by a factor of ~ 3.5 reduced the lifetime by less than 1%. This result is consistent with simple estimates from known collisional detachment cross sections. For example, at a vacuum of $\sim 10^{-10}$ torr and assuming a detachment cross section of $\sim 1.5\times 10^{-5}$ cm^2 (Ref. [23]), the collisionally limited lifetime is ~ 2s. The influence of the ion-beam density was also explored since at high currents (≥ 1 μA), particle ejection can occur on a millisecond time scale [18]. Our typical injected current, however, is only ~ 20 nA. It has been varied between ~ 1 and ~ 40 nA via control of the Na-vapor density without observing any influence on the experimental lifetimes. Moreover, data are acquired out to several lifetimes of the circulating beam. Tests for potential systematic effects comprise storage at several energies and the comparison of current and neutral-particle measurements.

In order to study the magnetic-field-induced effects on the lifetime, measurements have been conducted over an energy range from 7 to 35 keV, corresponding to dipole fields in the range from ~ 200 to ~ 500 G. The lower-energy limit was set by the stability of the steering system of the magnets. The ring is designed for injection at ~ 100 keV. The upper limit was set by the cross section for double charge exchange of positive helium ions in sodium vapor. Figure 4 shows the decay rates plotted versus beam energy. The solid curve represents the func-

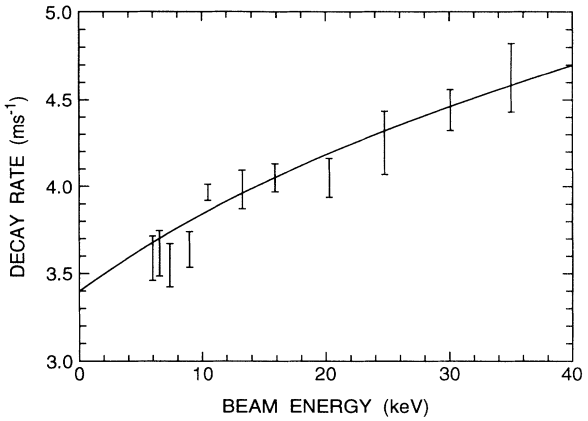

FIG. 4. Measured He^- decay rate vs ion-beam energy. Each point represents the average of several independent measurements, and the error bars indicate the statistical uncertainty of the mean value. The solid line is a two-parameter fit to the data points. The zero-field decay rate should be corrected for the blackbody-radiation effect in order to obtain the lifetime $\tau(^4P_{5/2})$.

$$\Gamma(E)=\Gamma_{BB}+\Gamma_{5/2}+(\Gamma_{3/2}-\Gamma_{5/2})Z_{3/2}(E)\ , \tag{1}$$

where the natural decay rates $\Gamma_{5/2}$ and $\Gamma_{3/2}$ are treated as constant fitting parameters, while $\Gamma_{BB}=0.534\ ms^{-1}$ and represents the contribution from photodetachment due to blackbody radiation, as discussed in Sec. II C. The function $Z_{3/2}(E)$ is the probability for mixing the $J=\frac{5}{2}$ manifold with the $J=3/2$ manifold due to Zeeman mixing in the dipole magnets. The form of $Z_{3/2}(E)$ depends, as discussed in Sec. II D, upon the coherence properties of the beam and in particular upon the way the depolarization effect due to the Larmor precession in the quadrupole magnets is modeled. Using a functional form of $Z_{3/2}(E)$ which corresponds to a $He^-(^4P_J)$ beam that remains in a statistical mixture of magnetic substates throughout the entire decay process, we determine the natural decay rates by a least-squares procedure. The corresponding lifetimes are $\tau(^4P_{5/2})=350\pm10$ μs and $\tau(^4P_{3/2})=12.0\pm1.5$ μs.

C. Influence of blackbody radiation

In order to investigate blackbody-radiation effects on $^4He^-(1s2s2p\ ^4P)$, the temperature dependence of the apparent $J=5/2$ lifetime was tested. By heating one-half of the storage ring to 389 K, the observed lifetimes were consistently reduced at all beam energies. For example, for a 20-keV He^- beam, the lifetime was reduced from 250 to 218 μs. The temperature rise degrades the vacuum by a factor of ~10, which will reduce the lifetime only by less than 1%. The observed change in the lifetime can be compared with the theoretical predictions based upon the photodetachment cross section for the $^4He^-$ ion [24–26]. The recently calculated photodetachment cross section by Saha and Compton [26] is in excellent agreement with the most accurate experimental cross sections available [27,28] to date. By folding the Planck radiation distribution with the theoretically calculated photodetachment cross sections by Saha and Compton, a numerical integration calculation has yielded blackbody-radiation-induced decay rates of 518 s^{-1} at 293 K and 1803 s^{-1} at 389 K. Taking into consideration that only one-half of the storage ring was heated, a simple estimate yields that the effective decay rate at the elevated temperature would be the average of the two rates mentioned above, i.e., 1161 s^{-1}. Eliminating this contribution from the measured lifetimes, one obtains a zero-temperature experimental lifetime of 287 and 291 μs, respectively, on the basis of the two measurements. These two lifetimes are equal within the experimental uncertainty. Thus it is reasonable to assume that the blackbody-induced photodetachment can be well described as a constant contribution to the measured decay rates. At room temperature, this effect reduces the measured $^4P_{5/2}$ lifetime by $\sim20\%$. If the less accurate photodetachment cross sections calculated by Hazi and Reed [24] were used for determining the lifetimes, the $\tau(^4P_{3/2})$ value would still be 12.0 ± 1.5 μs, but the $\tau(^4P_{5/2})$ value would be 371 ± 11 μs. Taking the uncertainty in the photodetachment cross sections into account and in addition incorporating an estimate of potential systematic uncertainties, our final result for the $J=5/2$ lifetime is 350 ± 15 μs, with the $J=3/2$ lifetime being 12 ± 2 μs. The uncertainties quoted represent 1 standard deviation.

D. Magnetic-field-induced effects

It is well known that a coherent superposition of degenerate magnetic sublevels of atoms or ions can be strongly affected when a weak external magnetic field is applied for a sufficiently long time (Larmor precession), and that closely spaced fine-structure components may be mixed by fields of sufficient strength (Zeeman mixing). Under the present experimental conditions, the magnetic field in the corner dipole magnets is strong enough to induce a significant Zeeman mixing of different J components in the $He^-(^4P_J)$ fine structure. Since the corresponding decay rates are very different, and since the Zeeman mixing fulfills the magnetic selection rule $\Delta M_J=0$, it is implicit that the $J=5/2$ level, which is the most long-lived component in the fine structure, will tend to align along the dipole-field axis because the $|M_J|=1/2$ and 3/2 magnetic sublevels decay with an increased rate due to the mixing with the shorter-lived $J=3/2$ and 1/2 levels. The alignment would accumulate during an undisturbed circulation in the ring and in principle lead to a beam consisting of only the $(J,M_J)=(5/2,\pm5/2)$ components. In practice, however, the alignment effect of the dipole fields competes with a corresponding depolarization effect due to the subsequent passage of the beam through the focusing field of the quadrupole magnets. In the steady-state situation, a distribution over magnetic sublevels results with population fraction P_M. We shall argue below that it is a reasonable assumption to consider that the $J=5/2$ subspace remains unpolarized throughout the entire decay process, i.e., that $P_M=1/(2J+1)=1/6$.

The field in the quadrupole magnets is so weak that

Zeeman mixing can be ignored, but it is strong enough to generate a significant Larmor precession of individual fine-structure levels. The polarization of the beam is accordingly affected. Note in this connection that the quadrupole field varies across the beam spot. The corresponding Larmor precession accordingly induces an incoherent mixing of magnetic sublevels when the ensemble of stored ions is considered. The depolarization effect due to the Larmor precession in the quadrupole magnets is in fact much more efficient than the weak polarization effect due to the Zeeman mixing in the dipole fields. To see this, we estimate the angle of precession during a passage of a single quadrupole magnet

$$\varphi=(g_J B_Q \mu_B/\hbar)(L_Q/v)\ , \tag{2}$$

where the first factor is the Larmor frequency, while the second factor is the time it takes to pass the quadrupole magnet. The Landé factor g_J is 8/5 for $J=5/2$, the length of the quadrupole, L_Q is 30 cm, while the quadrupole field B_Q varies from 0 to about 2 G across the beam diameter. The precession angle in Eq. (2) accordingly covers a range up to a few complete revolutions. It should be noted that the quadrupole magnets are used in pairs, and that the magnets are placed in such a way that the corresponding Larmor rotations tend to compensate each other. This compensation is, however, by no means perfect, and the net result is an appreciable, trajectory-dependent, rotation of the state of the considered ion.

A precise evaluation of the effect of the quadrupoles, however, is not possible since the distribution of trajectories through the set of quadrupole magnets is not well known. In the present context, it suffices to note that the depolarization effect of the quadrupole magnets is much more pronounced than the very weak polarization effect due to the M dependence of the decay rate in the dipole field. To see this, we recognize that a set of quadrupole magnets distorts the direction of polarization with a few degrees on the average. This implies that a completely polarized state would be fairly randomized after a couple of revolutions in the ring. It takes, on the other hand, about a lifetime of the considered metastable state, i.e., about ten revolutions at 40 keV in the ring, to reach an appreciable polarization in the beam due to the fields of the dipole magnets. The beam in the ring accordingly may be considered to remain in a completely statistically mixed state throughout the entire decay process. This understanding is essential for the following analysis of the field-induced contribution to the observed decay of metastable ions. Kristensen *et al.* [29] have recently demonstrated the same randomization of the atomic polarization during only one revolution of the ASTRID storage ring, a randomization which invalidated their attempts to observe coherent radio-frequency signals (Ramsay fringes) from successive interactions between the stored beam and the same rf field.

The four quadrants of the ring are essentially identical. The effective decay rate of the beam may accordingly be determined as an average over such a segment. As discussed in Sect. I, it is consistent with the available information on lifetimes of the metastable states He^- to assign the observed long-lived component to the $^4P_{5/2}$ level since the $J=3/2$ and 1/2 levels in the fine-structure decay so fast that they are totally vacated after the first few revolutions in the ring. The effective decay rate for the $J=5/2$ state is composed of three contributions, the natural width, photodetachment by blackbody radiation, and the contribution from the Zeeman mixing during the passage of the beam through the dipole magnet. In principle, there would also be a contribution from nonadiabatic transitions from the 5/2 to the 3/2 or 1/2 manifold while the field is switched on and off at the entrance and exit of the corner magnets. The field gradient is, however, so small $[(1/B)dB/dl=\frac{1}{6}\ \mathrm{cm}^{-1}]$ that nonadiabatic effects can be ignored at the beam energies used in the present experiment. This conclusion is based on a simple Landau-Zener type estimate which shows that nonadiabatic effects remain negligible even if the beam energy were high enough that the level-crossing region was reached.

The Zeeman Hamiltonian and its matrix representation in the ^4P_J manifold are given in the Appendix. Since the coupling elements are linear in field strength, the Zeeman-mixing amplitudes are proportional to the magnetic-field strength provided first-order perturbation theory is applicable. A perturbation treatment is valid if the B field is much smaller than the characteristic Zeeman parameter B_0,

$$B \ll B_0=(1/G)(\Delta E/\mu_B)\ , \tag{3}$$

where ΔE is the fine-structure splitting and G is the corresponding coupling constant [listed in Eq. (A6) in the appendix]. In the present case, where $\Delta E\sim 0.027\ \mathrm{cm}^{-1}$ and $G\sim 3/5$, we find that B_0 is of the order of 300 G. Since the experiment covers the range from $\sim$200 to $\sim$500 G, the weak-field condition is violated, and a more exact treatment is accordingly needed.

To evaluate the Zeeman mixing in the dipole field, we diagonalize the Zeeman Hamiltonian to determine the mixing amplitudes in the adiabatic wave functions,

$$\psi_{JM}(B_D)=\sum_{J'} a_{J'M}(B_D)\psi_{J'M}(0) \tag{4}$$

with reference to a quantization axis along the dipole field $\mathbf{B}_D$ such that the $\Delta M=0$ selection rule is exploited. The effective decay rate of the $J=5/2$ state may then be written as

$$\Gamma_{5/2}(B)=\Gamma_{\mathrm{BB}}+0.81\Gamma_{5/2}+0.19\sum_M P_M \sum_J |a_{JM}(B)|^2\Gamma_J\ , \tag{5}$$

where Γ_{BB} and Γ_J are blackbody-radiation-induced and natural decay rates, respectively, and where it has been used that the dipole fields cover 19% of the ring circumference. Equation (5) is written for an incoherent probability distribution P_M over the magnetic sublevels belonging to the $J=5/2$ level. This is clearly a valid approximation, since any coherences between different M sublevels would be destroyed immediately by the strong dipole field. Equation (5) may be rewritten as

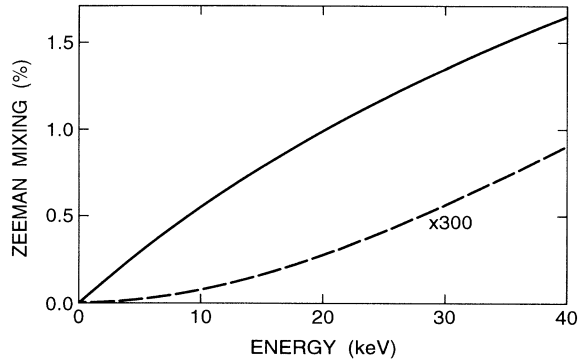

FIG. 5. The Zeeman-mixing coefficient $Z_J(E)$ for $J=3/2$ (solid line) and $J=3/2$ (dashed line). The latter is multiplied by a factor of 300 in the figure.

$$\Gamma_{5/2}(E)=\Gamma_{\mathrm{BB}}+\Gamma_{5/2}+\sum_{J\,(\neq 5/2)}(\Gamma_J-\Gamma_{5/2})Z_J(E)\ , \tag{6}$$

where the dependence on beam energy in place of dipole field is shown, and where the function

$$Z_J(E)=0.19\sum_M P_M|a_{JM}(B(E))|^2 \tag{7}$$

represents the fractional transient population of the other fine-structure components due to the Zeeman mixing in the dipole field. As discussed above, it is reasonable to assume that the $J=5/2$ manifold remains statistically populated throughout the entire decay process because of the stronger depolarization effect of the quadrupole magnets. Using $P_M=1/6$, we then obtain

$$Z_J(E)=\frac{0.19}{6}\sum_M|a_{JM}(E)|^2\ . \tag{8}$$

These $Z_J(E)$ functions ($J=3/2$ or $1/2$) are shown in Fig. 5. Note that $Z_{3/2}(E)$ is a linear function at low energies as expected from perturbation theory ($E\propto B^2$), while $Z_{1/2}(E)$ is a quadratic function reflecting that the dipole selection rule for the Zeeman coupling inhibits a direct coupling between the $J=5/2$ and $J=1/2$ components. In addition, $Z_{1/2}(E)$ is much smaller than $Z_{3/2}(E)$ due to the much larger fine-structure splitting to the $J=1/2$ level. Since $\Gamma_{3/2}$ and $\Gamma_{1/2}$ may be considered to be of the same order of magnitude, it is then clear that Zeeman mixing with the $J=1/2$ level is small enough to be totally ignored. Equation (6) then reduces to the form in Eq. (1) which was used in Fig. 4 to fit the data.

III. DISCUSSION AND CONCLUSION

The experimental lifetimes determined in the present study $\tau(^4P_{5/2})=350\pm15$ μs, $\tau(^4P_{3/2})=12\pm2$ μs are in good agreement with the more accurate of the previously reported values [5,7]. It should be pointed out, however, that our experiment differs from the earlier work of Blau, Novick, and Weinflash [5] in several important respects, which allows us to obtain a lifetime for $^4P_{5/2}$ with a much smaller uncertainty: (i) In our case, data can be extracted over a much greater range—out to several lifetimes—with a good signal-to-noise ratio; (ii) in the ring, slit scattering is essentially eliminated; (iii) the ultrahigh-vacuum conditions render collisional quenching entirely negligible; (iv) the intrinsic time structure of the ring allows rapid data acquisition and makes the results quite insensitive to low-frequency instabilities; (v) measurements can be performed on both the total He^- current and the neutral atoms formed from autodetachment. All these aspects represent an advantage in the storage-ring case. Blau, Novick, and Weinflash [5] did not discuss the effect of blackbody radiation in their measurement of the $^4P_{5/2}$ lifetime. Taking this into consideration, their lifetime would be $\sim 410\pm90$ μs, a value still in agreement with the present measurement due to its rather large uncertainty. The magnetically induced mixing effects caused by the quadrupoles may be considered a disadvantage for the ring technique with a view to obtaining the lifetime of the $^4P_{5/2}$ level, but these effects can be utilized as described above to obtain information on the lifetime of the other fine-structure levels, in this case of $^4P_{3/2}$.

The present lifetimes can be compared with theoretical predictions (see Tables I and II), showing a pronounced discrepancy between the experimental $^4P_{5/2}$ lifetime and the most recent advanced theoretical results [11–13]. For $^4P_{3/2}$, the lifetime is in good agreement with the calculation of Brage and Froese Fischer [11]. The present study has, however, initiated a new theoretical calculation [10] based on a multiple-configuration Hartree-Foch approach which accurately describes the initial bound $^4P_{5/2}$ and the final continuum $^2F_{5/2}$ states. The calculated value [$\tau(^4P_{5/2})=354$ μs] is in good agreement with the measured value.

It is generally observed that the nuclear spin only has a very small influence on the lifetime of an atomic level. Thus the lifetime of the $^4P_{5/2}$ level should, within the present experimental accuracy, be the same for $^4He^-$ and $^3He^-$. Due to the very large hyperfine splittings in $^3He^-$ (Ref. [20]) the influence of the magnetic-field effects will be very different for the two isotopes. We have performed a series of lifetime measurements using the $^3He^-$ isotope at beam energies ranging from 10 to 35 keV. The $^3He^-$ decay rate was much less dependent on the ion-beam energy than observed for $^4He^-$ (see Fig. 4), but the zero-field decay rate for $^3He^-$ was within 1% the same as obtained for $^4He^-$. In closing we note that the application of storage rings to the determination of autoionizing lifetimes should be applicable to a number of other negative and positive ions, including molecules and clusters. The magnetic-field mixing and depolarization effects discussed above for He^- will be less significant in other atomic systems of current interest such as $Li^-(1s2s2p^2\,{}^5P)$ and Be^- (Ref. [17]), but they will be important for the simple molecule He_2^-.

ACKNOWLEDGMENTS

We thank T. Brage and B. F. Davis for sharing their results prior to publication. Locally we have benefited from the technical support of the ASTRID staff

members, in particular N. Hertel, S. P. Møller, and V. Toft. The financial support from the Danish Natural Science Research Foundation (SNF) is gratefully acknowledged.

APPENDIX

The Zeeman Hamiltonian is given by

$$H' = (\mu_B/\hbar)\mathbf{B}\cdot(\mathbf{L}+2\mathbf{S}) , \tag{A1}$$

where μ_B is the Bohr magneton and **L** and **S** are orbital and spin angular-momentum operators. The expectation value of the Zeeman operator is given by the standard expression in *LS* coupling

$$E'_m = \mu_B B g_J M , \tag{A2}$$

where the quantization axis is taken along the dipole field, and g_J is the Landé factor. Explicitly, in the ^4P_J multiplet, we have

$$(g_{5/2}, g_{3/2}, g_{1/2}) = (8/5, 26/15, 8/3) . \tag{A3}$$

The off-diagonal elements of the Zeeman Hamiltonian,

$$\langle J_1 M_1 | H' | J_2 M_2 \rangle = \mu_B B \delta_{M_1 M_2} G(J_1, J_2, M) \tag{A4}$$

are restricted by the usual vector selection rules $\Delta M = 0$ and $\Delta J = \pm 1$ when the quantization axis is taken along the magnetic field **B**. The coupling constants are readily found in pure *LS* coupling,

$$\begin{aligned} G(J_1, J_2, M) &= G(J_2, J_1, M) \\ &= \sum_{M_S, M_L} M_S \langle L M_L S M_S | J_1 M \rangle \\ &\quad \times \langle L M_L S M_S | J_2 M \rangle . \end{aligned} \tag{A5}$$

For the ^4P term, we find explicitly

$$\begin{aligned} G(5/2, 3/2, \pm 3/2) &= -\sqrt{6}/5 , \\ G(5/2, 3/2, \pm 1/2) &= -3/5 , \\ G(3/2, 1/2, \pm 1/2) &= -\sqrt{5}/3 . \end{aligned} \tag{A6}$$

*Permanent address: Department of Physics, University of Connecticut, Storrs, CT 06268.

[1] J. W. Hiby, Ann. Phys. (Leipzig) **34**, 473 (1939).
[2] A. V. Bunge and C. F. Bunge, Phys. Rev. A **19** 452 (1979).
[3] B. Brehm, M. A. Gusinow, and J. L. Hall, Phys. Rev. Lett. **19**, 737 (1967); J. R. Peterson, Y. K. Bae, and D. L. Huestis, *ibid*, **55**, 692 (1985).
[4] D. L. Mader and R. Novick, Phys. Rev. Lett. **29**, 199 (1972).
[5] L. M. Blau, R. Novick, and D. Weinflash, Phys. Rev. Lett. **24**, 1268 (1970).
[6] R. N. Compton, G. D. Alton, and D. J. Pegg, IEEE Trans. Nucl. Sci. **NS-28**, 1198 (1981); G. D. Alton, R. N. Compton, and D. J. Pegg, Phys. Rev. A **28**, 1405 (1983).
[7] R. Novick and D. Weinflash, in *Proceedings of the International Conference on Precision and Fundamental Constants,* Natl. Bur. Stand. (U.S.) Spec. Publ. No. 343, edited by D. N. Langenberg and N. N. Baylor (U.S. GPO, Washington, D.C., 1970), p. 403.
[8] G. N. Estberg and R. W. LaBahn, Phys. Lett. **28A**, 420 (1968).
[9] C. Laughlin and A. L. Steward, J. Phys. B **1**, 151 (1968).
[10] G. Miecznik, T. Brage, and C. Froese Fischer (unpublished).
[11] T. Brage and C. Froese Fisher, Phys. Rev. A **44**, 72 (1991).
[12] G. N. Estberg and R. W. LaBahn, Phys. Rev. Lett. **24**, 1265 (1970).
[13] B. F. Davis and K. T. Chung, Phys. Rev. A **36**, 1948 (1987).
[14] D. J. Nicholas, C. W. Trowbridge, and W. D. Allen, Phys. Rev. **167**, 38 (1968).
[15] F. R. Simpson, R. Browning, and H. B. Gilbody, J. Phys. B **4**, 106 (1971).
[16] See, e.g., *Proceedings on the Workshop and Symposium on the Physics of Low-Energy Stored and Trapped Particles* [Phys. Scr. **T22** (1988)].
[17] P. Balling, L. H. Andersen, T. Andersen, H. K. Haugen, P. Hvelplund, and K. Taulbjerg, Phys. Rev. Lett. **69**, 1040 (1992).
[18] L. H. Andersen, T. Andersen, H. K. Haugen, N. Hertel, P. Hvelplund, S. P. Møller, and W. W. Smith, Phys. Lett. A **162**, 336 (1992).
[19] H. K. Haugen, L. H. Andersen, T. Andersen, P. Balling, N. Hertel, P. Hvelplund, and S. P. Møller, Phys. Rev. A **46**, R1 (1992).
[20] D. L. Mader and R. Novick, Phys. Rev. Lett. **32**, 185 (1974).
[21] C. W. Walter and J. R. Peterson, Phys. Rev. Lett. **68**, 2281 (1992); M-J. Nadeau, X-L. Zhao, M. A. Garwan, A. E. Litherland, Phys. Rev. A **46**, R3588 (1992).
[22] S. P. Møller (unpublished).
[23] J. Heinemeier, P. Hvelplund, and F. R. Simpson, J. Phys. B **15**, 2669 (1976).
[24] A. V. Hazi and K. Reed, Phys. Rev. Lett. **24**, 2269 (1981).
[25] L. V. Chernysheva, G. F. Gribakin, V. K. Ivanov, and M. Yu. Kuchiev, J. Phys. B **21**, L419 (1988).
[26] H. P. Saha and R. N. Compton, Phys. Rev. Lett. **64**, 1510 (1990).
[27] D. J. Pegg, J. S. Thompson, J. Dellwo, R. N. Compton, and G. D. Alton, Phys. Rev. Lett. **64**, 278 (1990).
[28] J. R. Peterson, M. J. Coggiola, and Y. K. Bae, Phys. Rev. Lett. **50**, 664 (1983); J. R. Peterson, Y. K. Bae, and D. Huestis, *ibid*, **55**, 692 (1985).
[29] M. Kristensen, J. S. Hangst, P. S. Jessen, J. S. Nielsen, O. Poulsen, and P. Shi, Phys. Rev. A. **46**, 4100 (1992).