

## Lifetime measurement of $\text{Be}^-(2s2p^2\ ^4P_{3/2})$ using an electrostatic ion trap

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The lifetime of the metastable  $\text{Be}^-(2s2p^2\ ^4P_{3/2})$  state is measured using an electrostatic linear ion trap which stores keV-ion beams. Trapping using electrostatic fields avoids the complication of magnetic-field-induced mixing effects which can interfere with the measurement of the spontaneous decay. The result is found to be  $42.07 \pm 0.12\ \mu\text{s}$ , which is a factor of 40 better in accuracy than the previous result determined in a heavy-ion storage ring. The measured lifetime is found to be 30% longer than the most recent theoretical value. [S1050-2947(99)01008-2]

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Accurate measurements of the lifetimes of metastable negative ions allow for a direct probing of various correlation effects, such as electron-electron interaction, which sometime, can be as large as the electron affinity of such systems. Thus, these measurements can represent an excellent test of calculations on many-body systems in atomic physics [1]. However, precise experimental values are difficult to obtain as metastable negative ions are usually fragile, and need to be observed for a time scale up to a few milliseconds.

Among the best tools used so far for the measurement of lifetimes of metastable negative ions is the heavy-ion storage ring, where ions can be stored for several seconds, and decay of metastable species can be easily observed [1]. One of the main drawbacks of the large storage rings is the presence of the guiding magnetic fields, which are, in general, strong enough to mix magnetic substates from different fine-structure components [2–4]. Such a mixing might cause changes in the autodetachment lifetime, especially if energy splitting between the fine-structure component is small. On the other hand, it must be pointed out that the presence of such magnetic fields has also been used to extract the lifetime of the mixing states, even if they are not directly observed. Such a technique was applied to determine the lifetime of the three substates ( $J=1/2, 3/2, 5/2$ ) of the  $\text{He}^-(1s2s2p\ ^4P_J)$  and  $\text{Be}^-(2s2p^2\ ^4P_J)$  [3,4].

The  $\text{Be}^-$  ion is known to have three metastable states  $1s^22s2p^2\ ^4P$ ,  $1s^22p^3\ ^4S$ , and  $1s2s2p^3\ ^6S$ , of which only the  $^4P$  and  $^4S$  states have so far been observed experimentally [5–7]. The lifetime of the  $J=3/2$  component of the  $^4P$  state was measured by Balling *et al.* using a heavy-ion storage ring, yielding a value of  $45 \pm 5\ \mu\text{s}$ , after extrapolation to zero magnetic fields [3]. The lifetimes of the two other components (the  $J=1/2$  and  $J=5/2$ ) are much shorter, and were recently measured by Andersen *et al.* [5] who obtained the values of  $0.73 \pm 0.08\ \mu\text{s}$  for the  $^4P_{1/2}$  and  $0.33 \pm 0.06\ \mu\text{s}$  for the  $^4P_{5/2}$  states. The  $^4S$  state decays to the  $^4P$  state, with a lifetime of  $1.25 \pm 0.10\ \text{ns}$  [6].

On the theoretical side, the lifetime of the  $J=3/2$  state was calculated first by Aspromallis *et al.* [8] yielding a lifetime of  $2000\ \mu\text{s}$ , and by Brage and Froese-Fischer [9] who obtained a value of  $1290\ \mu\text{s}$  (this value is corrected from the value given in Refs. [3] and [9], as explained by Aspromallis *et al.* [10]). These theoretical values were in large disagreement with the experimental value of  $45 \pm 5\ \mu\text{s}$  measured by Balling *et al.* [3]. Using an Hartree-Fock calculation which incorporated electron correlation and interchannel coupling, Aspromallis, Sinanis, and Nicolaidis [10] reworked the problem, and calculated a new value for the  $J=3/2$  state,  $\tau_{3/2} = 33\ \mu\text{s}$ , in much better agreement with the experimental result of Balling *et al.* [3], although still outside the (one standard deviation) error bar. In view of these earlier large discrepancies, and the remaining difference between the last experimental and theoretical values, we have attempted to measure the lifetime of the  $J=3/2$  state of  $\text{Be}^-$  using a linear electrostatic ion trap.

In the present experiment, we use a type of ion storage device [11,12], which allows us to trap ion beams of relatively low energy (keV's) under the influence of electrostatic fields only. The trap has already been used for the measurement of the lifetime of  $\text{He}^-$  [13]. In such a device, which is schematically represented in Fig. 1, the ion beam is produced in an external ion source and injected through a set of cylindrical electrodes (the ‘‘entrance electrodes’’). The ions are then reflected by a second set of electrodes (the ‘‘exit electrodes’’) and are trapped between the two ‘‘mirror’’ electrodes. During the injection, the voltages of the entrance electrodes are set to zero, and are then rapidly ( $\sim 100\ \text{ns}$ ) switched on in order to trap the beam. The stability of the system has been described in previous publications, where a detailed description of the system is given [11,12].

Once the ions are stored, they oscillate with a frequency which is a function of their velocity and the trap length. With a trap length of 40.7 cm, and with a beam energy of 4.2 keV, the oscillation frequency is about 330 kHz for  $\text{Be}^-$  ions. The trap is kept under ultrahigh vacuum using a cryopump, yielding a background pressure of  $2 \times 10^{-10}$  Torr. The main loss process of the stored ions is collisional detachment with the residual gas atoms in the trap. At the given pressure, and

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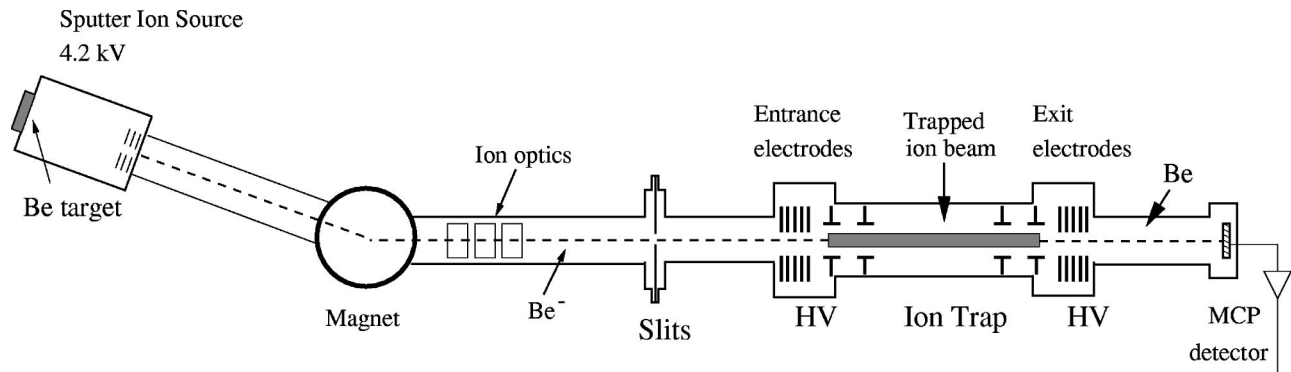


FIG. 1. Schematic view of the experimental setup. The  $\text{Be}^-$  ions are created in a sputter source, accelerated to 4.2 keV, mass selected by the magnet, and injected into the ion trap. The beam decay inside the trap is monitored by the MCP.

assuming a collisional detachment cross section of  $10^{-14} \text{ cm}^2$ , the expected lifetime for the beam inside the trap is on the order of a few hundred milliseconds. This was checked by storing stable beams of  $\text{H}^-$  and  $\text{O}^-$  which yielded lifetimes against destruction of 100 and 400 ms, respectively (the difference is mainly due to the different velocities of the ions, both being stored at 4.2 keV) [12].

Once a negative ion is neutralized (either by autodetachment or by collisional detachment) it exits the trap through the holes in the electrodes. If the neutralization event happens when the negative ion was moving in the forward direction (i.e., the original direction of the beam before trapping), the neutral atom will hit a microchannel plate (MCP) detector located downstream of the ion trap, and will be counted. The count rate measured by the MCP is thus proportional to the number of ions stored in the trap, and the time dependence represents the overall lifetime of the beam.

The  $\text{Be}^-$  ions were produced in a Cs sputter ion source, accelerated to 4.2 keV, and mass selected using a  $20^\circ$  magnet (see Fig. 1). About  $10^4$  ions were captured by the trap, and the decay rate of the ions was monitored using the MCP. The injection cycle was repeated at a rate of 50 Hz, and the data was accumulated over  $10^4$  injections.

Figure 2 shows the neutral-atom signal versus time. A

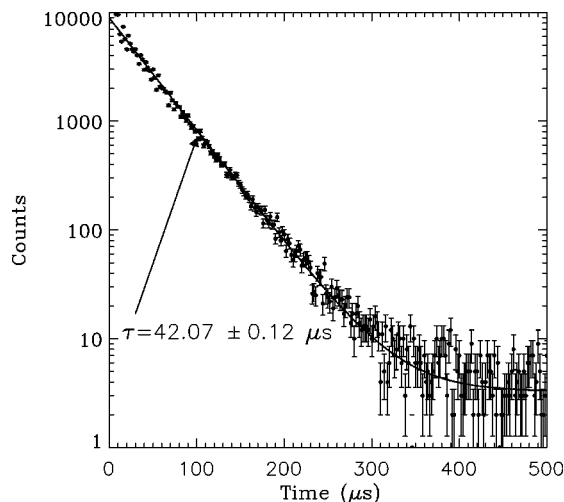


FIG. 2. Neutral Be signal from the channel plate detector as a function of time. The solid line is the fit to the data as described in the text.

small oscillatory behavior is visible at short times and is due to the fact that while raising the electrode potentials (on the entrance side) upon injection, a “hole” is created in the beam population, since the stability condition [11,12] is not respected during the switching time. Such a hole “oscillates” back and forth between the electrodes of the trap, at the same frequency as the ions, until it disappears due to the finite momentum distribution of the ions. When the hole moves forward (i.e., in the direction of the MCP), less ions are detected as the number of ions moving forward in the trap is also smaller. Thus the oscillations observed in the decay curve shown in Fig. 2 are directly related to the natural frequency of the ions in the trap. The time-independent rate measured for times greater than  $400 \mu\text{s}$  is due to background noise in the MCP. The data could be accurately fitted by a single exponential decay curve plus a time-independent background. The decay time of the exponential is directly related to the lifetime of the  $^4P_{3/2}$  state, as no magnetic fields are present in the trap. Also, the effect of black-body radiation can be neglected, since the  $\text{Be}^-$  is bound by 276 meV, with respect to the  $\text{Be}(^3P)$  threshold, and the lifetime is quite short. The value obtained from the fit is  $\tau = 42.07 \pm 0.12 \mu\text{s}$ . The influence of collisional detachment inside the trap can also be neglected, as the autodetachment lifetime is shorter by about four orders of magnitude than the collisional lifetime. The error bar quoted here is thus mainly due to the finite statistics, as measured in the present experiment.

Table I summarizes the results and compares the existing experimental and theoretical values for all  $J$  states. The present result is in excellent agreement with the value measured by Balling *et al.*, and represents a factor of 40 improvement in the experimental accuracy compared to the heavy-ion storage ring measurement. The main reason is the absence of magnetic fields, which allows for unperturbed evaluation of lifetimes for states where mixing can occur, as opposed to the storage ring experiment, where a measurement of the lifetime as a function of the beam energy (i.e., the magnetic field of the dipole magnet), including an extrapolation to zero energy (zero magnetic field) had to be performed. The best theoretical value is by Aspomallis, Sinanis, and Nicolaidis [10] who obtained  $33 \mu\text{s}$ . Although this value is well outside the error bar of the present experimental results, it can be considered to be in good agreement, and represents a significant improvement over previous cal-

TABLE I. Experimental and theoretical lifetimes of the three different states of  $\text{Be}^-$ .

Determination	Lifetime ( $\mu\text{s}$ )			References
	$J=1/2$	$J=3/2$	$J=5/2$	
Theory	0.08	2000	1.0	[8]
	0.8	1290	0.94	[9]
	0.5	33	0.43	[10]
Experimental	$\sim 10$	$\sim 100$	$\sim 10$	[7]
	$0.25 \pm 0.15^a$	$45 \pm 5$	$0.25 \pm 0.15^a$	[3]
	$0.73 \pm 0.08$		$0.33 \pm 0.06$	[5]
		$42.07 \pm 0.12$		present work

<sup>a</sup>These values are based on the assumption that the lifetimes of the  $J=1/2$  and  $J=5/2$  are identical.

culations, considering the difficulties which are present in the *ab initio* calculation of such properties. However, we believe that our result represents a new challenge to theoretical many-electron atomic physics, especially as it is difficult to obtain accurate measurements of negative ion properties.

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. On the

other hand, such magnetic fields, as present in the heavy-ion storage ring technique, have the advantages of allowing indirect determination of the short lived components of the lived time, as demonstrated by Balling *et al.* [3].

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