Precision measurement of the lifetime of the $1s2s\ ^3S_1$ metastable level in heliumlike O^{6+}

J. R. Crespo López-Urrutia,[1] P. Beiersdorfer,[1] D. W. Savin,[2] and K. Widmann[1]
[1]Department of Physics and Space Technology, Lawrence Livermore National Laboratory, Livermore, California 94550
[2]Department of Physics and Columbia Astrophysics Laboratory, Columbia University, New York, New York 10025

(Received 29 December 1997)

The lifetime of the $1s2s\ ^3S_1$ level of the He-like O^{6+} ion has been measured using the Electron Beam Ion Trap in the magnetic trapping mode. A value of 956^{+5}_{-4} μs is found, which corresponds to a radiative transition rate of 1046^{+4}_{-5} s^{-1} for the magnetic dipole transition to the $1s^2\ ^1S_0$ ground state. This value is in excellent agreement with recent theoretical predictions and distinguishes among different treatments of negative energy states and correlation in multiconfiguration Dirac-Fock calculations. [S1050-2947(98)05307-4]

PACS number(s): 32.70.Cs, 52.70.La, 95.30.Ky

I. INTRODUCTION

Line emission from metastable levels that decay only via electric dipole-forbidden transitions, such as the $1s2s\ ^3S_1$ level in heliumlike O^{6+}, plays an important role in plasma diagnostics [1]. The metastable level will be collisionally depopulated when the electron density approaches a critical value, transforming the line emission into a diagnostic of electron density. Accurate knowledge of the radiative rate is, therefore, a requisite for inferring reliable electron densities from such lines. It is also important for testing calculations of atomic wave functions, as small inaccuracies may lead to large changes in the rates of forbidden transitions. Thus these rates are sensitive indicators of the accuracy of atomic calculations.

The $1s2s\ ^3S_1$ level is the lowest-lying excited level in the heliumlike system. It is forbidden to decay to the $1s^2\ ^1S_0$ ground level by an electric dipole transition. At low densities the level decays via a magnetic dipole transition to the $1s^2\ ^1S_0$ ground level. At sufficiently high collision rates, i.e., sufficiently high electron densities, the level is collisionally depopulated by transferring its population to the nearby $1s2p\ ^3P_1$ level. The intensity ratio of the $1s2s\ ^3S_1 \rightarrow 1s^2\ ^1S_0$ forbidden transition to the $1s2p\ ^3P_1 \rightarrow 1s^2\ ^1S_0$ intercombination line is, thus, sensitive to the electron density, as shown by several modeling calculations [2–4]. The density at which the electron collision rate rivals the predicted radiative decay rate of the $1s2s\ ^3S_1$ level is in the range 10^{10}–10^{12} cm^{-3}. This density range is typically found in active solar and stellar plasmas. High-resolution measurements of the O^{6+} K-shell line emission from the Sun have indeed shown this density dependence [5].

Early estimates of the $^3S_1$ radiative decay rate were provided by Gabriel and Jordan [6] using the relation

$$A_r = \frac{4.4\times 10^9}{\lambda^5}\ s^{-1}. \tag{1}$$

Their estimate yielded a value of 1.198 ms based on the transition wavelength $\lambda = 22.0977$ Å. This value was revised in many subsequent *ab initio* calculations [7–11]. Some of those predictions (e.g., Ref. [9]) are only byproducts of calculations testing methods to be applied to more complex atoms, and did not intend to reach the precision that could have been achieved when specifically applied to two-electron ions. The newer calculations provided values between 943 and 955 μs employing a variety of different theoretical approaches. One of these approaches, the multiconfiguration Dirac-Fock method, was recently shown by Indelicato [12] to provide significantly different values depending on whether and how correlations and the negative energy continuum are included in the calculations. The largest scatter among the different approaches was found in low-Z ions, i.e., for the smallest radiative rates. Similar differences were found by Johnson, Plante, and Sapirstein [11]. For low-Z ions such as oxygen, these authors calculated the radiative decay rate using the Hartree potential, as it produced more accurate results than using the Coulomb potential because of a significantly smaller need for negative energy corrections.

In order to experimentally test and distinguish among the calculations, a measurement with an accuracy better than a few percent is needed. However, only recently have methods been developed that allowed measurements of the long-lived $1s2s\ ^3S_1$ level in heliumlike ions. Radiative lifetimes in the millisecond regime have become accessible to experimental scrutiny in storage rings [13]; measurements of radiative lifetimes in the microsecond regime were demonstrated at the Electron Beam Ion Trap (EBIT) facility at Livermore [14,15]. The latter facility used an electron beam to confine the ions and excite the transition of interest, and adjustments for collisional effects had to be made.

Recently, a new mode of operation, dubbed the magnetic trapping mode, has been developed [16]. This mode dispenses with the need to account for electron collisions when making radiative lifetime measurements on the EBIT facility. The magnetic mode allows the measurement of the decay of much longer-lived metastable levels than before and with higher accuracy. The method relies on the observation that ions produced in EBIT remained trapped for many seconds after the electron beam was turned off [16–18]. In the absence of the electron beam, the fluorescent decay of metastable levels can be observed without collisional perturbations. This has been illustrated in a measurement of the $1s2s\ ^3S_1$ level in heliumlike N^{5+}, which has been measured with a 3% accuracy [16]. In the following we use the capability provided by the magnetic trapping mode method to

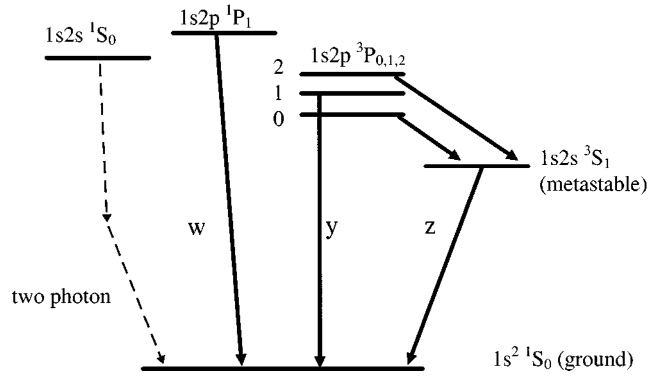

FIG. 1. Schematic level diagram of the $n=1$ and $n=2$ levels of heliumlike O^{6+}. The prominent decay paths are indicated.

measure the radiative lifetime of the $1s2s$ $^3S_1$ level in heliumlike O^{6+} within a 0.5% accuracy.

II. EXPERIMENTAL ARRANGEMENT

The measurement was carried out at the Livermore EBIT facility. Oxygen was introduced into the trap by injecting a molecular beam of CO_2 into the trap. We used a continuous injection of CO_2 at a gas injector pressure of 10^{-7} torr, giving a neutral CO_2 density of roughly 10^6 cm^{-3}, or 10^{-11} torr in the trap. The beam energy was 1.2 keV, and the current around 25 mA. The beam dissociated and ionized the CO_2 molecules. Although the beam energy was above the threshold to strip oxygen completely, it was necessary to choose such a high energy given the nonequilibrium, transient ionization conditions of the measurement to produce sufficient amounts of heliumlike oxygen ions.

Similar to our earlier measurement of N^{5+} and Ne^{8+} [14,16], we measured the total intensity of the $K\alpha$ emission with a lithium drifted silicon Si(Li) detector mounted side-on in EBIT. The advantage of the low resolution Si(Li) detector lies in a high counting efficiency, which is essential for achieving good statistics.

The measured $K\alpha$ emission comprised three $2\rightarrow 1$ transitions. These were the transitions $1s2p$ $^1P_1 \rightarrow 1s^2$ $^1S_0$, $1s2p$ $^3P_1 \rightarrow 1s^2$ $^1S_0$, and $1s2s$ $^3S_1 \rightarrow 1s^2$ $^1S_0$, labeled w, y, and z in standard notation, as illustrated schematically in Fig. 1. To observe the fluorescent decay of the electron population in the $1s2s$ $^3S_1$ metastable level, we turned off the electron beam for periods of 10 ms by switching off the power supply used for the anode extraction potential of the electron gun. The beam was then turned on again for another 10 ms.

Upon turning off the beam, direct electron-impact excitation immediately ceased. Transitions w and y have transition rates that are many orders of magnitude larger than z. Their emission thus ceased almost instantaneously, as is indicated by the steep drop in the recorded $K\alpha$ emission shown in Fig. 2. This drop is slightly rounded by the finite time resolution of the detector electronics. By contrast, the decay of the $1s2s$ $^3S_1$ level produced emission that was seen to last well into the excitation-free period.

The time scale was calibrated to the ppm level with the help of a calibrated signal generator. Since the rate of data accumulation was on the order of a few counts per cycle, pulse pile-up and dead time effects can be totally neglected.

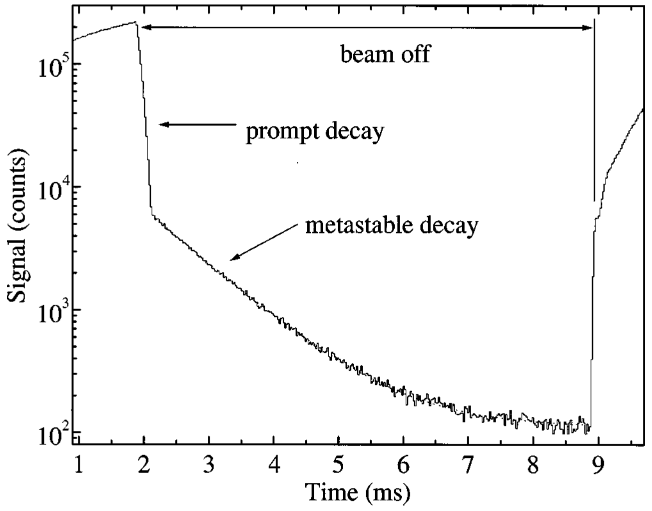

FIG. 2. $K\alpha$ emission from heliumlike O^{6+}. The emission drops immediately after the electron beam is turned off, revealing the fluorescent decay signal of the $1s2s$ $^3S_1$ level.

III. RESULTS

We fitted the temporal evolution of the $^3S_1$ fluorescent decay to a single exponential with statistical weighting and a constant background, as shown in Fig. 3. The resulting lifetime is $\tau = 955.9$ μs. The statistical uncertainty is 3.5 μs. Fits of double exponentials have been attempted but failed to describe the data.

Systematic errors might arise from ion loss from the trap during the magnetic trapping mode. Previous experiments, however, have shown that ions remain trapped on the order of seconds [16–18]. The dominant loss mechanism is charge exchange reactions with neutral background gases. Since we

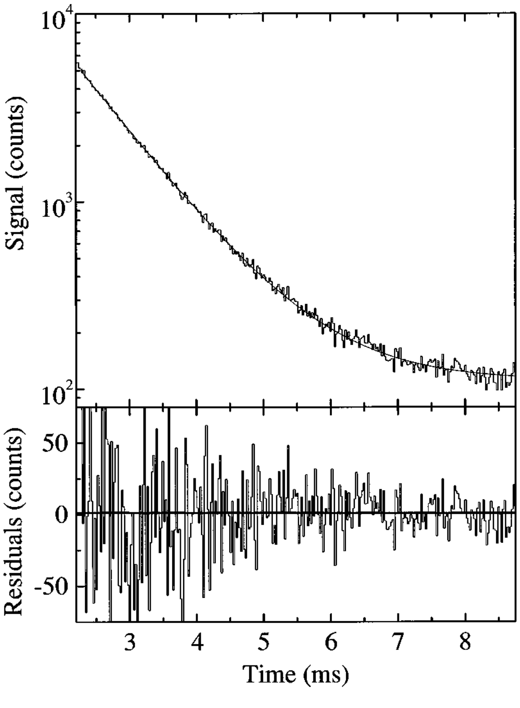

FIG. 3. Fit of a single exponential to the x-ray emission measured during the magnetic trapping mode (top). Residuals of the fit are given below.

continuously injected CO_2 into the trap, charge exchange of O^{6+} ions with CO_2 was a possible loss mechanism in the present measurement. Moreover, charge capture of O^{7+} ions was a possible feeding mechanism of the heliumlike $^3S_1$ level.

Given the estimated neutral density of 10^6 cm^{-3} in the trap, an ion temperature of less than 1 keV [19], and charge exchange cross sections on the order of less than 10^{-14} cm^2 [20], an upper bound of less than 0.1 s^{-1} can be placed on the rate of charge exchange recombination losses. This is negligible compared to the measured radiative decay rate of about 10^3 s^{-1}. Similarly, population of the metastable level by charge exchange is also negligible.

As an upper limit on ion losses, we assume an ion storage time of 1 s, which is less than the shortest storage time measured in Fourier-tranform ion-cyclotron measurements [17,18]. Incorporating such a systematic error into our error limits, we find a lifetime of 956^{+5}_{-4} μs for the heliumlike $^3S_1$ level and a radiative transition rate of 1046^{+4}_{-5} s^{-1}.

IV. COMPARISON WITH THEORY

The measured radiative lifetime can be compared to various theoretical results. Using nonrelativistic wave functions, Drake [7] obtained a value of 957.9 μs. This value is within the uncertainty limits of our measurement. The relativistic calculation by Johnson and Lin [8] giving 950.6 μs is in slightly less good agreement. A very recent calculation employing exact relativistic wave functions by Johnson, Plante, and Sapirstein [11] yielded a value of 955.1 μs, which is in best agreement with our measured value.

By contrast, two other predictions based on relativistic wave functions yielded results that do not agree with our measurement. These are the value of 945.2 μs computed by Johnson and Lin [9] and the value of 943 μs computed by Lin, Johnson, and Dalgarno [10]. There is also poor agreement with the rates calculated with the single-configuration Dirac-Fock method by Indelicato [12], as illustrated in Fig. 4. However, the agreement clearly improves as correlation and negative energy states are included in the calculations.

Figure 4 also shows the predictions of Johnson, Plante, and Sapirstein [11] using exact relativistic wave functions. The present measurement is only the second measurement with a sub-1% uncertainty among low-Z ions and is clearly able to distinguish between the calculations of Johnson, Plante, and Sapirstein and the best multiconfiguration Dirac-Fock calculations from Ref. [12]. Our present measurement and that of C^{4+} by Schmidt *et al.* [13] are in excellent agreement with the predictions of Johnson, Plante, and Sapirstein, but differ significantly from multiconfiguration Dirac-Fock calculations.

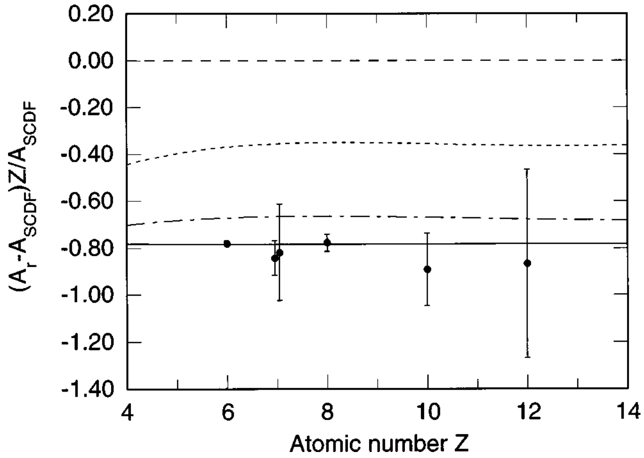

FIG. 4. Comparison of the measured magnetic dipole transition rate in O^{6+} with results from single-configuration Dirac-Fock calculations (dashed line), multiconfiguration Dirac-Fock calculations without (dotted line) and with taking negative energy states into account (dot-dashed line) from Ref. [12]. Also shown are the values calculated in Ref. [11] (solid line) using exact relativistic wave functions. All results are expressed relative to the single-configuration Dirac-Fock values. Previously measured values are from the following references: C^{4+}, Ref. [13]; N^{5+}, Refs. [13,16]; Ne^{8+}, Ref. [14]; Mg^{10+}, Ref. [15].

ACKNOWLEDGMENTS

This work was performed under the auspices of the U.S. Department of Energy by LLNL under Contract No. W-7405-ENG-48, and was supported in part by NASA's X-Ray Astronomy Research and Analysis Program under Work Order W-19127.

---

[1] C. de Michelis and M. Mattioli, Nucl. Fusion **21**, 677 (1981).
[2] R. Mewe and J. Schrijver, Astron. Astrophys. **65**, 99 (1978).
[3] R. Mewe and J. Schrijver, Astron. Astrophys., Suppl. Ser. **33**, 311 (1978).
[4] A. K. Pradhan and J. M. Shull, Astrophys. J. **249**, 821 (1981).
[5] G. A. Doschek, U. Feldman, P. B. Landecker, and D. L. McKenzie, Astrophys. J. **249**, 372 (1981).
[6] A. H. Gabriel and C. Jordan, Phys. Lett. **32A**, 166 (1970).
[7] G. W. F. Drake, Phys. Rev. A **3**, 908 (1971).
[8] W. R. Johnson and C. D. Lin, Phys. Rev. A **9**, 1486 (1974).
[9] W. R. Johnson and C. D. Lin, Phys. Rev. A **14**, 565 (1976).
[10] C. D. Lin, W. R. Johnson, and A. Dalgarno, Phys. Rev. A **15**, 154 (1977).
[11] W. R. Johnson, D. R. Plante, and J. Sapirstein, in *Advances of Atomic, Molecular, and Optical Physics Vol. 35*, edited by B. Bederson and H. Walther (Academic Press, San Diego, 1995), p. 255.
[12] P. Indelicato, Phys. Rev. Lett. **77**, 3323 (1996).
[13] H. T. Schmidt, P. Forck, M. Grieser, D. Habs, J. Kenntner, G. Miersch, R. Repnow, U. Schramm, T. Schüssler, D. Schwalm, and A. Wolf, Phys. Rev. Lett. **72**, 1616 (1994).
[14] B. J. Wargelin, P. Beiersdorfer, and S. M. Kahn, Phys. Rev. Lett. **71**, 2196 (1993).
[15] G. S. Stefanelli, P. Beiersdorfer, V. Decaux, and K. Widmann, Phys. Rev. A **52**, 3651 (1995).
[16] P. Beiersdorfer, L. Schweikhard, J. Crespo López-Urrutia, and

K. Widmann, Rev. Sci. Instrum. **67**, 3818 (1996).

[17] P. Beiersdorfer, B. Beck, R. E. Marrs, S. R. Elliott, and L. Schweikhard, Rapid Commun. Mass Spectrom. **8**, 141 (1994).

[18] P. Beiersdorfer, B. Beck, St. Becker, and L. Schweikhard, Int. J. Mass Spectrom. Ion Processes **157/158**, 149 (1996).

[19] P. Beiersdorfer, V. Decaux, S. Elliott, K. Widmann, and K. Wong, Rev. Sci. Instrum. **66**, 303 (1995).

[20] R. E. Olson, in *Electronic and Atomic Collisions*, edited by N. Oda and K. Takayanagi (North-Holland, Amsterdam, 1980), p. 391.