Magnetic dipole transition rates from measured lifetimes of levels of Be-like and B-like argon ions

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The lifetimes of the $1s^2 2s2p\ ^3P_2$ level of Ar XV and $1s^2 2s^2 2p\ ^2P_{3/2}$ of Ar XIV have been measured using metastable Ar^{14+} and Ar^{13+} ions produced by an electron cyclotron resonance ion source, which were subsequently separately captured into a Kingdon ion trap. The lifetime results are τ(Ar XV, 2s2p $^3P_2$) $=13.4(7)$ ms and τ(Ar XIV,$2p\ ^2P_{3/2}$)$=9.12(18)$ ms. Transition rates derived from the measured lifetimes differ significantly from both relativistic and nonrelativistic calculations of the $2s2p\ ^3P_1 - ^3P_2\ M1$ transition rate of Ar XV, but are in reasonable agreement with calculations for the $2p\ ^2P_{1/2} - ^2P_{3/2}\ M1$ rate of Ar XIV. [S1050-2947(98)07108-X]

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I. INTRODUCTION

Few-electron ions are simple enough to treat with high precision, but still complex enough to provide a challenge for many-electron theory. Since relativity, electron correlation, and QED all may play a role, approximations to any Hamiltonian are required. It is a characteristic of transition rate calculations that accuracy is often difficult to assess in any well-defined manner. Although experimental results exist for some transitions of singly and doubly charged ions [1], for most magnetic dipole ($M1$) or electric quadrupole ($E2$) transitions between fine-structure terms in high charge states, there have been no experimental measurements. Consequently, comparisons between different calculations are often made to assess accuracy, with the assumption that the most elaborate calculation is the best reference value. Nevertheless, the importance of any particular approximation remains undetermined. Recently there have been several *ab initio* calculations of the $2s^2\ ^1S_0 - 2s2p\ ^3P_1$ intercombination electric dipole ($E1$) transition rate in Be-like ions [2–4]. The magnetic dipole ($M1$) transition rates between the $2s2p\ ^3P$ levels of Be-like ions [5], and the $2p\ ^2P_{1/2} - ^2P_{3/2}$ levels of B-like ions [6] have also been calculated using relativistic methods. The intercombination $E1$ rate has now been determined from a very high precision lifetime measurement for Be-like C [7]. Experimental lifetimes of levels in Be-like and B-like Ar are reported here, from which magnetic dipole rates are obtained.

B-like ions have been observed in a wide variety of plasmas, including solar flares [8], laser-produced plasmas [9], and tokamak plasmas [10]. The ground term transition rate can be used in conjunction with measured intensity ratios as a diagnostic of electron energies. Transitions from the $2s2p\ ^3P$ levels of Be-like ions are also used in plasma diagnostics of electron density, based on measured intensity ratios with $E1$ transitions [11]. The $2s2p\ ^3P$ level populations also depend on the $M1$ rates as well as on collisional mixing [12].

During the last few years, a general technique applicable to the measurement of many lifetimes of metastable levels of multiply charged ions has been developed. This technique is based on the capture and storage in a Kingdon ion trap of metastable ions produced in a multiply charged ion source such as the Electron Cyclotron Resonance Ion Source (ECRIS), found now in many laboratories. A ''Caprice'' ECRIS source located at the University of Nevada–Reno was used in the present measurements, to produce beams of Ar^{13+} and Ar^{14+}, with sufficient ions excited to metastable levels for measurements.

II. APPARATUS AND PROCEDURE

The general procedure for the present measurements [13] and for earlier measurements on lower-charged argon ions [14] are very similar, and are only outlined here. Details about apparatus and technique can be found in the references, and only major differences from the earlier apparatus [14] will be mentioned.

The Kingdon ion trap [13], which confines ions electrostatically, presently consists of a cylinder electrode perforated by four circular apertures symmetrically placed around the midplane, a concentric central wire, and two ''end cap'' electrodes. The whole trap structure is ''floated'' to an electric potential V_f to permit ion capture at relatively high values of the ion extraction voltage of the ECRIS. Additional positive voltages are applied to the cylinder, end caps, and central wire. Slowed beam ions pass into the trap through an electrostatic lens held at V_f and a midplane aperture in the cylinder, and are captured when the wire potential is suddenly (100 ns) reduced to zero by a fast electronic switch. About 6.6×10^6 ions per particle microampere are captured.

The confined ions then stably orbit inside the trap unless a collision with a neutral atom leads to electron transfer. The charged products of such a collision are likely to be unstable and leave the trap [15]. After a suitable storage interval, the central wire potential is slowly increased. Some ions leave the trap through another midplane aperture and are accelerated toward a microchannel plate ion detector. The number of ejected ions versus storage time is found to decrease with a single exponential dependence [13], with a time constant determined by electron capture collisions with residual gas molecules [14,15].

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Metastable ions produced in the ion source reach the trap if their lifetimes exceed about 50 μs. Charge states are chosen that have metastable transitions with calculated lifetimes exceeding 1 ms, and having wavelengths in the visible or ultraviolet range. Once confined, fluorescence from the decays of these metastable ions is collected with quartz optics, wavelength-analyzed with an interference filter, and detected with a photomultiplier tube (PMT). This procedure is carried out over many measurement cycles, with the pulses collected in a multichannel scalar. In the present measurements, the detected PMT pulses versus ion storage time can be fitted by two exponentials plus a constant background, the latter due to dark counts. The first exponential has low amplitude and a time constant ≅1.2 ms. It is observed in all decays, and is thought to be due to ion settling in the trap following capture. The second exponential depends on the measured transition, and is associated with the metastable level decay.

The present measurements were carried out on few-electron argon ions. To verify the performance of the present trap system, measurements on the $2p^5\ ^2P_{3/2}-^2P_{1/2}$ transition of Ar X near 553 nm, which were carried out in the earlier version of the Kingdon trap [14], were repeated. These earlier lifetime measurements were performed as a function of Ar pressure, since Ar was the dominant residual gas, which significantly quenched the metastable level by collisions [14]. The slope of these measurements, when plotted against pressure, determined the quenching rate, and the intercept at zero pressure determined the metastable lifetime. It was separately determined that the quenching could be dominantly attributed to electron capture collisions [15].

In the present apparatus, the vacuum was sufficiently good to make quenching a small effect. Several separate fluorescence measurements were made, and the average of the results computed. The average storage time constant for Ar^{9+} ions in the trap was measured to be $\tau_{st}=750(23)$ ms, in the superior vacuum of the new system. The ion loss rate was well fitted by a single exponential, so this result was used directly to correct the level lifetime measurement for quenching by electron capture ion loss. Measurements of the fluorescence were fitted to yield a time constant for level decay $\tau_u=8.60(37)$ ms. The corrected result was $\tau(\text{Ar X},2p^5\ ^2P_{1/2})=8.70(37)$ ms, obtained using the expression $\tau^{-1}=\tau_u^{-1}-\tau_{st}^{-1}$. This result can be compared to the one obtained with the original apparatus by extrapolation versus pressure, $\tau(\text{Ar X},2p^5\ ^2P_{1/2})=8.53(24)$ ms. The two results agree well within their uncertainties, indicating that the current procedures with the new trap system yield consistent results. The relationship to theory is discussed in the earlier publication [14]. Three theoretical calculations lie between 9.43 and 9.52 ms.

The present measurements on higher argon ion charge states were made using an EMI 9862QA/350 PMT cooled to −23 °C, lowering the dark rate to a few counts per second. The ECRIS was operated at 14.4 GHz, with about 400 W of power. An oxygen support gas was also used in the source. About 3 μA of B-like Ar^{13+} was obtained from the ion source, corresponding to about 1.5×10^6 ions stored per cycle. The fine-structure level diagram of the ground term for this ion is shown in Fig. 1. Since the metastable level is in the ground term, it is estimated that about 2/3 of the ions were initially in the upper level. Data sets were collected over several hours on each of two days using an interference filter with a transmission of 45% near 441 nm. The storage time constant for these ions on both days was nearly identical, and was measured to be $\tau_{st}=665(84)$ ms. This result does not follow the expected linear charge-dependent scaling [16] from the Ar^{9+} storage data, since the residual pressure varied between measurements on different charge states, which were not carried out sequentially. The uncorrected time constant of the fluorescence decay shown in Fig. 2 was fitted to be $\tau_u=9.00(16)$ ms. The resulting corrected lifetime was $\tau(\text{Ar XIV}\ 2p\ ^2P_{3/2})=9.12(18)$ ms.

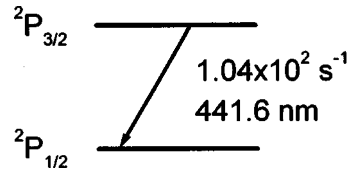

FIG. 1. Fine-structure level diagram for the ground term of B-like argon. The wavelength and transition rate are calculated values taken from Ref. [20].

The current extracted from the source for Be-like Ar^{14+} was 0.4 μA, corresponding to about 1.9×10^5 stored ions/cycle. An interference filter with a bandwidth of 35 nm and a transmission of 65% near 593 nm was used to isolate the decay. The level diagram of the $1s^2 2s2p\ ^3P$ levels, with the $M1$ transition indicated, appears in Fig. 3. The $2s2p\ ^3P_2$ level can decay by $E2$ transitions to the $2s2p\ ^3P_1$ and $2s2p\ ^3P_0$ levels, but these rates for Ar XV are negligible. The $2s2p\ ^3P_2$ level can also decay by a magnetic quadrupole ($M2$) transition to the $2s^2\ ^1S_0$ ground level. The rate for this branch has been recently calculated with some care for $Z<11$ [3], but for $Z=18$ only an older relativistic calculation seems to be available [17], which predicts a rate of 0.831 s^{-1}. This is sufficiently large to require a small correction to the decay rate obtained from the measured lifetime to obtain the decay rate for the $M1$ transition. The $2s2p\ ^1P_1$ level can decay by $M1$ transitions into the $2s2p\ ^3P$ levels,

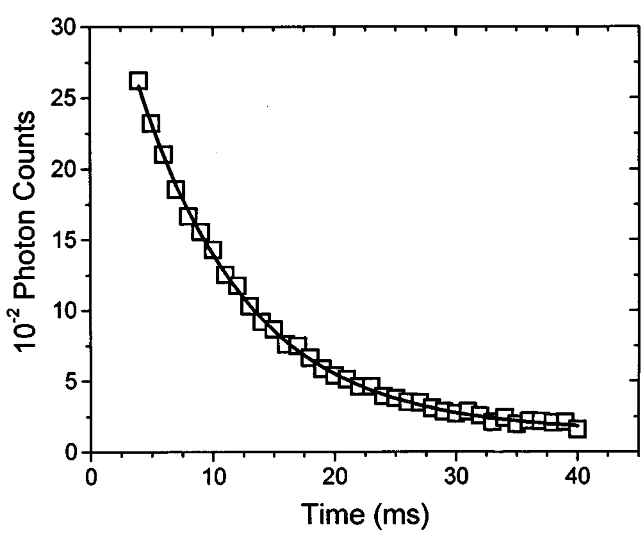

FIG. 2. Measured photon count data, fitted to a single exponential plus constant background, for the B-like argon ground term fine-structure transition. This plus other data were used to determine the lifetime of the $2p\ ^2P_{3/2}$ level.

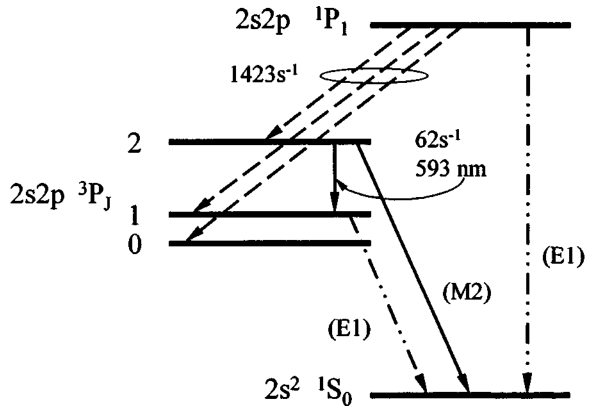

FIG. 3. Fine-structure level diagram for the $2s2p$ P levels of Be-like argon. The calculated wavelength and nonrelativistic transition rate for the $^3P_1$-$^3P_2$ $M1$ transition, and the calculated sum of transition rates for ^3P-^1P $M1$ decays are shown. The ^1P level is rapidly depopulated by $E1$ transitions to the ground level. The $2s2p$ $^3P_2$ level also decays to the lower ^3P levels by $E2$ transitions, but at negligible rates for Ar XV, and by an $M2$ transition to the $2s^2$ $^1S_0$ ground level with a calculated rate of 0.831 s^{-1}, resulting in a small correction to the $M1$ decay rate.

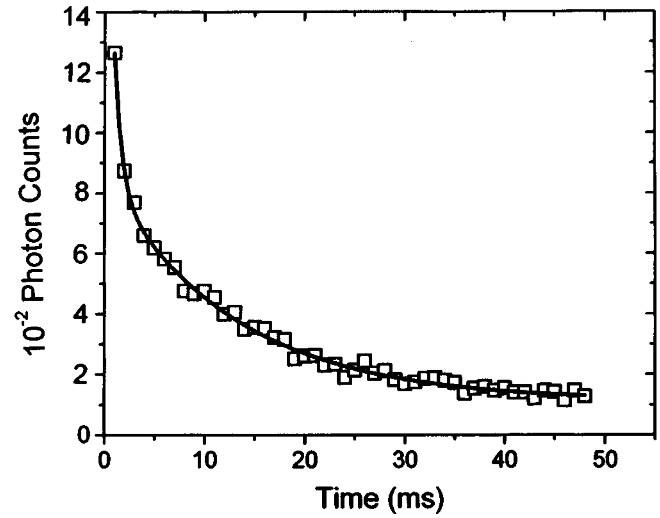

FIG. 4. Measured photon count data, fitted to the sum of two exponentials plus a constant background. The initial exponential (removed in Fig. 2) appears in all data, and is interpreted as due to ion settling in the trap. This plus other data were used to determine the lifetime of the $2s2p$ $^3P_2$ level of Ar XV.

but the population of the $2s2p$ $^1P_1$ level is rapidly emptied by the $E1$ transition from this level to the ground level. Consequently no long-lived cascades into the level of interest are anticipated.

The triplet system is little populated by direct electron impact excitation since electron spin tends to be conserved in the collisions when the atomic number Z is low. However, formation of these ions by electron capture collisions of higher charge states should populate triplet and singlet systems approximately equally. Intercombination transitions to the $2s2p$ ^3P levels from a higher-lying ^1D level have also been observed [18], and other intercombination decays may occur. If it is assumed that half of the ions rapidly decay to the $2s2p$ ^3P levels, then from the statistical weights about 56% of those should initially be in the $^3P_2$ level. Based on a calibration of detection efficiency, the calculated rate of photon collection from this number of ions should be about 22 per second. The observed rate was about 3.4/s, indicating that only about 4.4% of the ions were in the $^3P_2$ level, and that the total population of the triplet system was about 8%. This is compatible with model data for Be-like Th [19], an ion with much higher Z, populated in the Electron Beam Ion Trap.

The Ar^{14+} storage time τ_{st}=307(34) ms, reduced due to relatively higher pressure in the apparatus, was measured. The metastable decay constant τ_u=12.8(6) ms was obtained from data including that shown in Fig. 4. When combined with the ion storage time constant, the corrected measured lifetime τ(Ar XV $2s2p$ $^3P_2$)=13.4(7) ms resulted. In this case, the magnitude of the storage time correction was comparable to the uncertainty of the measurement. The experimental $M1$ transition rate, obtained from the lifetime measurement corrected for the theoretical decay rate of the $M2$ branch given above, is 74(4) s^{-1}.

III. DISCUSSION

The $M1$ transition rate for B-like Ar has been calculated nonrelativistically by Bhatia, Feldman, and Seely [20] using the configurations $2s^22p$, $2s2p^2$, $2p^3$, $2s^23s$, $2s^23p$, and $2s^23d$. The resulting transition rate was A=106.8 s^{-1}. An early relativistic calculation tabulated by Kaufman and Sugar [21] yielded A=104 s^{-1} in good agreement. An extended average level multiconfiguration Dirac Fock (MCDF) calculation [6] also resulted in a rate A=104 s^{-1}. The measured lifetime of 9.12(18) ms corresponds to a transition rate near 110 s^{-1}, 3 to 5% higher than predicted. However, taking the uncertainty in the measurement into consideration, the measured result is within two standard deviations of the higher theoretical rate, indicating satisfactory agreement.

The $2s2p$ $^3P_1-^3P_2$ $M1$ transition rate was calculated nonrelativistically by the configuration-interaction method using the configurations $2s^2$, $2s2p$, $2p^2$, $2s3s$, $2s3p$, $2s3d$, $2p3s$, $2p3p$, and $2p3d$ [22]. The result was A=64.3 s^{-1} for Ar XV. Another nonrelativistic calculation in intermediate coupling tabulated by Kaufman and Sugar [21] yielded A=62 s^{-1}. Subsequently this transition rate was calculated relativistically by the MCDF extended average level method, using three nonrelativistic configurations $2s^2$, $2s2p$, and $2p^2$ [5]. Breit and QED effects were treated as first-order perturbations. The result for Ar XV was A=105 s^{-1} [5]. The experimental $M1$ rate of 74(4) s^{-1} falls about 30% below this calculation, but 15% above the closest nonrelativistic transition rate.

The precision of the present measurements is appropriate for these tests of theory, but is limited by the population of the metastable levels, the available beam current, and by the duration of averaging time. Precisions better than 1% have been achieved in similar measurements using this technique [13]. The precision of the present data is potentially subject to improvement in future measurements, if warranted by increased accuracy of the theory.

In summary, the present experimental lifetime results for the decay of the $2s2p$ $^3P_2$ level of Ar XV, and the $2p^5$ $^2P_{1/2}$ level of Ar X, yield experimental $M1$ transition rates. These rates lie above the nonrelativistic predictions by 10 to 16%, well outside the experimental error estimates, but in the case of Ar XV the $M1$ decay rate falls below the relativistic calculation by 30%. However, the lifetime measurement for Ar XIV is in satisfactory agreement with a nonrelativistic prediction, which differs only 2.7% from two relativistic calculations.

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