Atomic lifetime measurements with electron beam ion traps

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Abstract. Electron beam ion traps have been employed to measure very short (femtosecond) and long (microsecond to many millisecond) level lifetimes in highly charged ions. The lifetime measurement techniques reflect interesting properties of the apparatus. The measurement of very short lifetimes exploits the fact that the Doppler broadening in electron beam ion traps can be reduced to below the natural line width. For the measurement of long lifetimes (measured on electric-dipole forbidden transitions), the electron beam ion trap is switched periodically between electronic and magnetic trapping modes. It is then also necessary to learn about the charge exchange processes that limit long term ion storage. Investigations of the sources of systematic error as well as cross checks with heavy-ion storage ring techniques have confirmed that electron beam ion trapping techniques are capable of delivering accurate lifetime data. The best atomic lifetime data achieved with electron beam ion traps have reached uncertainties of less than one percent.

1. Introduction

Atomic line spectra reveal atomic structure and the fact that energy is quantized. Only transitions between the ‘fixed’ excitation levels of an atom are possible. However, not all combinations of levels occur in actual spectra, and not all spectral lines are of similar intensity. These observations point to selection rules (invoking parity, angular momentum, spin, etc.), and to the concept of transition probability, or the “A factor” \( A_{ki} \) for a transition from level \( k \) to level \( i \).

The mean life \( \tau \) that appears in the exponential decay law of an excited level is the reciprocal of the sum of all transition probabilities from a given level:

\[
\tau_k = \frac{1}{\Sigma (A_{ki})}
\]

Atomic lifetime measurements on electric dipole (E1) transitions yield information on atomic wave functions that supplements the insight gained from atomic energy levels alone. The E1 transition rate depends on the transition energy and an extra power of \( r \), because the electric dipole operator \( er \) explicitly depends on \( r \). Transitions between fine structure levels of a given term (“forbidden transitions”, magnetic dipole (M1) and electric quadrupole (E2) transitions) are supposedly insensitive to this, as they connect levels with similar radial wave functions. However, complex wave functions as well as relativistic effects in highly charged ions modify this simple picture.
Interpreting $\tau$ as the time constant of a damped oscillator, there are two ways to measure this parameter. Firstly, by the (Lorentzian) line width, or, secondly, by measuring the line intensity as a function of time and fitting an exponential curve to the data. (Lorentzian line profile and exponential decay curve are Fourier transforms of each other.) Classical spectroscopy is hardly sufficient to observe the natural line width of atomic levels. Narrowband laser spectroscopy, however, has achieved this goal. Also, with (nanosecond-) pulsed laser excitation, it is nowadays quite feasible to selectively excite and then measure the typical nanosecond lifetimes of most low-lying levels of neutral atoms and of some levels of singly charged ions. This option pertains to levels that decay by electric dipole (E1) radiation. E1 transition rates of transitions which involve a change of principal quantum number $n$ ($\Delta n \neq 0$) scale as $Z^4$. For multiply charged ions the level lifetimes therefore are much shorter than for neutral ions. They are out of the reach of lasers both because of the laser photon energy being insufficient to reach the excited levels and excite them selectively, and because the decay time usually is too short for classical electronic timing measurements. An alternative is provided by fast ion beams that experience excitation by being passed through a thin foil [1]. The ions in the beam lose a fraction of their energy, but apart from that, the ion beam leaves the foil largely unharmed and continues its trajectory. Distance of the ions from the rear side of the foil translates into time after the end of excitation. Therefore one can record the spatial decrease of the light intensity emitted by the ion beam as a function of distance from the foil and convert that to a time measurement in the picosecond to many-nanosecond range. Atoms with levels that are particularly short-lived may have a natural line width that is greater than the Doppler and instrumental line widths that are typical for beam-foil spectroscopy. If autoionization is a direct competitor to the radiative decay one observes, then the intensity of the radiative branch and thus the signal rate suffers, of course. Fortunately, there are cases in which the lower level of a transition autoionizes and thus broadens the final level, whereas the radiative signal benefits from an unbranched radiative decay. Given the typical autoionization rates of the order of $10^{14}$ s$^{-1}$, the typical lifetimes studied in this way are in the range of a few femtoseconds (for examples see [2, 3]). Electron beam ion traps intuitively suggest that lifetimes to be studied there would be long (else there would be no need for extended storage). We will discuss how such measurements of long lifetimes in the microsecond to many-millisecond range can be done with electron beam ion traps and electronic timing. We will also explain how short lifetimes (again in the femtosecond range) can be addressed by a line width measurement, and how all these techniques relate to other types of lifetime measurement, for example, by beam-foil spectroscopy. Reviews of measurements of long atomic lifetimes in various types of ion traps have been presented elsewhere [4, 5, 6, 7]. These reviews provide a more comprehensive literature survey than is intended for the present report that focuses on electron beam ion traps.

2. Experimental techniques
Electron beam ion traps combine the Penning trap principle with a strong, extremely well collimated electron beam along the magnetic field (of typically 3 to 5 T field strength B), thus also defining an axis of symmetry. The electron beam is compressed by the field, to a diameter of about 50 $\mu$m. The “Penning” parts of the trap are completed by drift tubes on different potentials that keep ions in the trap volume axially confined. The electron beam serves several purposes: the electrons collisionally ionize atoms from the ambient gas or from a gas flow injected ballistically on purpose (for example, a neutral gas stream of a density corresponding to a pressure of as low as $10^{-10}$ mbar may be crossing the electron beam trajectory under UHV conditions ($<10^{-11}$ mbar)), or low-charge ions injected along the magnetic field lines from an external MeVVA ion source. These freshly produced ions are then confined by the trap fields and can be hit by fast electrons over and over again. If the electron-ion collisions are sufficiently
frequent (that is why the electron beam needs to be so tightly focused) and energetic, stepwise ionization to ever higher charge states can proceed. This process is moderated by the interplay of ionization, recombination and charge-changing collisions with the rest gas (this determines the need for ultrahigh vacuum (UHV)). The charge state limit is given by the electron energy and the increasingly high ionization potentials of highly charged ions. The second job of the electron beam is a compensation of the space charge of the cloud of positive ions that is being built up in the trap. Even with a strong magnetic field for radial confinement, the ions would repel each other and move away from the location of the electron beam, if the attractive potential of the beam electrons and the space charge compensation were absent.

2.1. Line width measurements
In beam-foil spectroscopic observations of ions after the interaction with the exciter foil, the spatial resolution of the detection system in combination with the finite solid angle of detection and geometrical constraints imposed by ion beam cross section and foil surface roughness, limit practical lifetime measurements to about one picosecond and above. A shorter time scale is provided by the time that the fast ions spend inside the thin exciter foil, which is of the order of $10^{-14}$ s. This is the same order of magnitude as the many-femtosecond lifetimes of K-vacancies in ions of the beam. Using foils of different thicknesses, Betz et al. have determined such K-vacancy lifetimes from the variation of the x-ray yield with foil thickness [8]. The accurate determination of such a foil thickness is a major and persistent problem, however.

In the aforementioned observation of radiative decays of autoionizing levels, the signal rate often is poor, because of the poor branching ratios (fluorescence yields). In beam-foil spectroscopy the situation is aggravated by the finite standing time of the thin exciter foils under ion bombardment. Next, the shape and then the width of these weak lines has to be measured, correcting for contributions to the width by instrumental effects. It is then no surprise that the lifetime results from such line broadening measurements may bear error bars of 10%, 30%, and sometimes even more. This is to be compared to a scatter of the lifetime predictions of autoionizing states that often reaches an order of magnitude for such levels (which are degenerate with continuum levels). The calculations involve the tracking of the outgoing electron from small to very large distances.

We find some of the same problems in the measurements at the electron beam ion trap. The determination of very short atomic lifetimes via a determination of the line width has not reached the accuracy of a precision tool yet, but it provides insight into EBIT physics besides an interesting estimate of an atomic property.

In the pilot experiment on this topic [9], Cs (Z=55) was introduced into EBIT as a vapour through a ballistic gas injector. Ions were easily trapped, charged up to the charge state of interest (Cs$^{45+}$), and excited. Under trapping and excitation conditions that maximized the signal, the crystal spectrometer line width of the decay of a short-lived 3d level appeared to be rather similar to that of a long-lived 3s level in the same ion. Evidently, instrumental and thermal (Doppler) contributions to the line width exceeded the natural lifetime contribution. Only when the ion trap was made shallow (by reducing the potential difference between the drift tubes to very low values or even to zero) so that evaporative cooling was encouraged, and when ion heating was minimized by lowering the electron beam current and thus the number of ions in the trap, the linewidths went down and revealed the lifetime differences between the upper levels (3s and 3d) of the transitions observed in Cs$^{45+}$.

Similarly to this Ne-like ion species, Graf et al. [10] have evaluated EBIT measurements of the He-like ion Fe$^{24+}$. Here the resonance line ‘w’ was investigated in comparison to the intercombination line ‘y’ and the forbidden line ‘z’.

Common to all these evaluations is the need of a good determination of the line shapes. Unfortunately it is not good enough to approximate the line shape for all lines by a Gaussian.
Such a shape may be appropriate for a line that is dominated by statistical fluctuations or by the instrumental line width. For the line of primary interest, the proper shape is a Voigt profile, with maybe a Gaussian-dominated center, but also with Lorentzian wings that are essential for the very determination of the natural line width part. A Voigt profile can be fitted reliably to these wings only if the signal-to-background ratio is sufficiently high in the range where the wings show, that is, away from the bright part of the line profile.

In both of the EBIT measurements using this technique, the deviation from theoretical lifetime prediction is less than a factor of two, but it is not yet clear which one needs to be improved, theory or experiment, or both.

2.2. Magnetic trapping

For lifetime measurements that follow the decrease of the emission signal after the excitation stops, two approaches have been tried. In the first, the electron beam energy is modulated above and below the production/excitation threshold [11]. In this way, the ion cloud is minimally perturbed, because the electron beam is present at all times. However, in order to avoid complications that are possibly arising from interactions of the ion cloud with the electron beam (for example, by recombination), the electron beam can be shut off completely. This then is the magnetic trapping mode [12] in which EBIT acts as a Penning trap. The ion cloud does expand somewhat when the electron beam is switched off (this has been visualized at the NIST EBIT [13]), but trapping is still effective for many seconds (as has been ascertained by ion cyclotron resonance frequency observations at LLNL) [12, 14]. This operational mode has become the standard technique for lifetime measurements in the range from a few microseconds to many milliseconds. All of the further examples discussed below use this technique.

2.3. Ion loss measurements / CX

In all ion trap lifetime measurements, it is of paramount importance to determine the ion storage time (the inverse of the loss rate). The observed optical signal decay rates represent the sum of the true atomic decay rate and of all other loss processes, notably the loss of ions from the stored sample. Only when the loss rates are known, can the radiative transition rate be determined from the apparent decay rate. This task is most easily dealt with in heavy-ion storage rings, where only ions of a single charge state are being stored, so that a measure of the change of ion beam current is at the same time a measure of the change of ion number.

In an electron beam ion trap, in contrast, ions of several species (elements and charge states) usually are stored at the same time. If by a collision with a residual gas atom a stored ion gains an electron (or more), it may well remain trapped. In this way there can, both, be losses of the charge state species of interest as well as gains resulting from the recombination of more highly charged ions. Examples of the latter effect have been shown in lifetime experiments on He-like Ne ions [15]. Evidently it is best to have the charge state of interest as the highest one produced (which can be regulated by the electron beam energy).

The actual loss rate due to charge exchange (CX) is less simple to determine. The electron captured in a CX reaction often populates a high n, high ℓ state. This excited ion will decay eventually, often in many steps. It is difficult to selectively observe the photons from typical steps along the decay chains, because the number density of CX-excited ions is small, and narrowband optical detection of spontaneous emission is fairly inefficient. Only if the decay chain reaches the x-ray range, energy dispersive detectors of large detection solid angle become applicable. For a variety of ions, however, the optical determination of the CX loss rate is simply not practical. Assuming that the CX processes largely reflect the density of the residual gas, one instead resorts to storing more highly charged, few-electron ions under the same vacuum conditions, and uses their x-ray emission to determine the CX loss rate.
This immediately raises the question of cross sections. The collisional cross sections of ground state one- or two-electron ions with residual gas particles may be considered sufficiently well known, but the corresponding cross sections of excited many-electron ions (on which the actual lifetime measurements are done) are not. At present only estimates can be made. One of these is based on the observation that the CX cross sections at the low collision energies of present concern vary linearly or quadratically with the ion charge; simple scaling then interconnects the CX loss rate of more highly charged ions with that of the lower charge states of primary interest for a given atomic lifetime measurement. It is not clear, however, whether the scaling may be transferred from K-shell ions to, say, L-shell ions. As long as the CX ion loss rates are several orders of magnitude lower than the atomic transition rates to be measured, the uncertainty of the scaling process remains of secondary importance.

As an alternative, the residual gas density in the trap can be varied, by adding a buffer gas or by switching off pumps. This can have marked effects on the apparent atomic lifetime [16] and may well explain why some earlier measurements at various ion traps had the unsatisfactory results that were reported. It is difficult, however, to determine the density changes to the residual gas except by resorting again to CX processes, the only probe that is in the very place (the trap volume) where also the wanted ions are [16].

2.4. UV/vis Spectrometer / Stovepipe

The first optical lifetime measurements were reported from the NIST EBIT [17, 18]. There, light from the trap was collected and made parallel by a large aperture ratio lens, transported away from EBIT, and focused onto the entrance slit of a grating monochromator. For spectral observations, the monochromator was tuned to different wavelengths; for lifetime measurements, the monochromator was set to match a desired spectral line, and then the signal of the photomultiplier at the exit slit was recorded as a function of time in a cycle that alternated between ion trapping with the electron beam on and off (electronic and magnetic trapping modes as dubbed at Livermore [12]) (see Figure1). The set-up demonstrated that the arrangement was able to yield meaningful lifetime data.

At Livermore, instead of using a monochromator, an interference filter was inserted into the light path. The resulting ‘Stovepipe’ instrument has been described elsewhere [19]. Although this is a somewhat less flexible approach (most lines need a special filter), the light yield was excellent, and the high statistical quality of the data soon showed a need to better understand the systematics and to measure the ion loss due to charge exchange as a major source of systematic error for atomic lifetimes in the millisecond range. Benefiting from these improvements, two of the three NIST EBIT lifetime measurements were revised considerably, and many others measured for the first time [20, 21, 22, 23]. A direct comparison with a measurement of the same ion in a heavy-ion storage ring [16] demonstrated that both measurements suffer from different systematics, but can yield coincident, reliable results, if the systematic effects are properly corrected for.

The available data on B-like and F-like ions, obtained at electrostatic ion traps, at various EBITs, and at the Heidelberg heavy-ion storage ring, indicate (Figure2) underestimated errors in the early electrostatic ion trap [24] and NIST EBIT [18] measurements, whereas EBIT work at Oxford [26], Livermore [16, 20, 22], and Heidelberg [27] as well as the storage ring work [16, 28] have yielded consistent results. The recent measurement of the M1/E2 transition rate in B-like Ar XIV [27] carries an error bar of only 0.21%. At this precision, the result disagrees with some of the calculations (see [29, 30] for recent examples) of this rate that scatter by about 0.6% even after adjusting to experimental transition energies. Evidently these new data with their extraordinarily small error bars mean a new challenge to theory.

A Livermore EBIT study of the green corona line (Al-like Fe XIV) was the first optical EBIT lifetime measurement that produced a result with an uncertainty of less than 1% [31]. This
Figure 1. Timing pattern of a measurement with the ‘stovepipe’ spectrometer (from [19]).

Figure 2. Lifetime data for the $2s^22p^2P_{3/2}$ level in the ground state of B-like ions from Cl$^{12+}$ through Ti$^{17+}$. The data are normalized to the theoretical results given by Galav´is et al. [29], which include a semi-empirical correction for experimental transition energies. A number of other theoretical results are within 0.6% of these values (see [16]). The experimental data are from an electrostatic Kingdon trap (EKT) [24], from the NIST, LLNL, and Heidelberg electron beam ion traps [16, 18, 20, 22, 27], and from the heavy-ion storage ring TSR [28].
Figure 3. Transition rate data for the $3s^23p^2\,{}^2P_{3/2}$ level in the ground state of the Al-like ion Fe$^{13+}$. Note how most calculational results agree within a close interval with each other, because they have been adjusted to match the experimental transition energy. The three older \textit{ab initio} theoretical results scatter notably (the one by Huang is based on too few configurations to be expected reliable). The electrostatic ion trap measurement by Moehs \textit{et al.} [32] caused some confusion, until the electron beam ion trap measurement by Beiersdorfer \textit{et al.} at Livermore [31] settled the case. The latest calculation, by Vilkas and Ishikawa [33] is the first that obtains close matches with experiment for both line strength and transition energy using \textit{ab initio} techniques. (The agreement of the earlier calculation by Huang with experiment must be seen as fortuitous, because the same type of calculations has a grossly deviant result for Fe X (see [46]).)

result superceded the systematically off-set value found in an experiment using an electrostatic ion trap [32]. It possibly also ended a long string of calculations of the astrophysically important transition rate that could not provide this number except by using the experimental transition energy. Figure 3 shows a time line of calculations and measurements. Since then, the first \textit{ab initio} calculation has been published that reproduces the experimental result with notable accuracy [33].

On a quite different note, there are interesting atomic physics systems that pose persistent challenges to theory so that experimental lifetime data might help to locate and identify the problems. There is a fine structure transition in Ti-like heavy ions that happens to vary very little in wavelength over a wide range of nuclear charges (for references, see [34]). A single lifetime measurement on such a transition [17] agrees with various calculations within its 6% error bar. A number of calculations have tried with limited success to match the trend of the experimental wavelength data. Several calculations show discontinuities of atomic parameters in one section of the isoelectronic sequence. Further lifetime measurements might help elucidate the exact position of the discontinuity and provide a check on the validity of the chosen wave functions in the same range [35].
2.5. X-ray diodes

Practically each EBIT set-up is equipped with an x-ray diode for monitoring the ions in the trap. Such solid state detectors (Si(Li) or intrinsic Ge (IGLET)) detectors offer a large solid angle and a good x-ray detection efficiency. Spectra from such detectors are of sufficient resolution to derive a rough charge state balance, and to detect characteristic emission from certain ionization stages of heavy ions (for example, H-like, He-like, Ne-like ions). With the trap operated in a cyclic mode, x-ray signal counts can be time stamped and thus sorted by both energy and time into two-dimensional spectra. Cuts along the time axis can be extracted as decay curves, while cuts along the energy axis yield information about possible line blends. The signals of such energy-dispersive devices can be well discriminated against noise.

In contrast to the excitation process in beam-foil spectroscopy, the electron beam in an EBIT does not excite ions from the ground state to high-lying, high angular momentum levels. If nevertheless a decay curve should feature a tail (which may lead to systematic errors in the lifetime determination), then this usually indicates the presence of repopulation by charge exchange (CX) with the (electrically neutral) residual gas particles. Consequently it is wise not to produce ions in charge states higher than the one of interest, if it can be avoided [15].

Early Livermore EBIT decay curve measurements on He-like ions - the M1 decay of the lowest triplet level, 1s2s 3S₁, is of particular interest in astrophysics and plasma physics - have used a beam energy modulation technique in which the electron beam energy was periodically lifted above and dropped below the threshold for reaching the level of interest [11, 36]. Since then, it has been found that it is not necessary for continued ion trapping to maintain the electron beam, and the latter has been switched on and off fully ever since [12, 37, 38, 39]. By fast switching techniques, the Livermore measurements have reached the nanosecond lifetime range (in unpublished work on S and Ar), whereas at low nuclear charge Z the measured lifetimes reached into the millisecond range. With error bars down to 0.5%, the results are in excellent agreement with the trend of lifetime data (at lower Z) from the Heidelberg storage ring, and with extensive nonrelativistic (but relativistically corrected) and some fully relativistic calculations [40, 41, 42] (Figure 4). This He isoelectronic sequence is one of the longest that has been studied by experiment (with level lifetimes varying over 15 orders of magnitude). In terms of meaningfully small errors, we note that the storage ring and EBIT lifetime measurements in their ranges of applicability have single-percent errors, whereas the techniques that are available in the other ranges of nuclear charges (very long and rather short lifetimes) have typical errors rather in the ten-percent range.

2.6. Microcalorimeter

In recent years, microcalorimeters have entered the stage of x-ray detection. Working by different principles and material combinations, they all involve small material samples (much below 1 mm³) at very low temperatures. Measuring the heat from the absorption of an x-ray photon in such a small physical pixel, however, permits energy dispersive spectroscopy at a spectral resolution that, while not as good as that of a crystal spectrometer, is much superior to a classical solid state x-ray detector. Present-day microcalorimeters have line widths below 10 eV, and, in order to increase the detection solid angle, they are mounted in arrays. Pixel arrays offer the additional benefit of revealing cosmic rays, because those usually affect more than one pixel. Filtering routines thus can clean up spectra quite notably.

At Livermore, such a microcalorimeter was employed in a study of Ni-like Xe²⁶⁺ [43]. Ni-like ions have a ground state with a closed 3d¹⁰ shell, and the lowest excited levels (3d⁹ 4s) cannot decay by electric dipole radiation. The lowest order multipole decay of the J=3 level is by a magnetic octupole (M3) transition. This transition has been observed at the Livermore EBIT in Ni-like Th and U [44] before.

In measurements with a flat field spectrograph, the M3 decay in the Ni-like Xe ion was indeed
Figure 4. Iso-electronic trend of the transition rate data for the $1s^2 1S_0 - 1s2s^3S_1$ magnetic dipole (M1) transition in He-like ions. Out of the full range of experimental data, $Z=2$ to 54, only the low-$Z$ range $Z \leq 18$ is shown. Data points for $Z = 4$ to 7 are from the Heidelberg heavy-ion storage ring TSR, data for $Z = 7$ to $Z = 12$ have been obtained at the Livermore electron beam ion trap EBIT-II [36, 37, 38, 39]. Data on heavier ions are from the use of (mostly fast) ion beams. All experimental data have been scaled by normalization to the results of the fully relativistic calculation by Johnson et al. [42], and only the deviations from this prediction are displayed.

Figure 5. Decay curve extracted from a first set of microcalorimeter observations of the M3 decay of the metastable $3d^14s^3D_3$ level in the Ni-like ion Xe$^{26+}$ [43]. All delayed emission photons in the interval 570 to 610 eV were used (the M3 decay is at 590 eV [45]). These decay data yield a preliminary lifetime result near 11 ms, whereas predictions range from 14 to 19 ms.
Table 1. Examples of atomic lifetime results of EBIT measurements on ions with E1-forbidden decays.

| Ion   | Level | Lifetime $\tau$ | Trap type | Ref. | Comment |
|-------|-------|------------------|-----------|------|---------|
| He Sequence |       |                  |           |      |         |
| N$^{14+}$ | 1s$^2$ 3S$_1$ | (3.94±0.05) ms | LLNL EBIT [39] | x-ray M1 |
| O$^{14+}$ | 1s$^2$ 3S$_1$ | (956±5) $\mu$s | LLNL EBIT [37] | x-ray M1 |
| F$^{17+}$ | 1s$^2$ 3S$_1$ | (274±3) $\mu$s | LLNL EBIT [39] | x-ray M1 |
| Ne$^{15+}$ | 1s$^2$ 3S$_1$ | (91.7±0.4) $\mu$s | LLNL EBIT [38] | x-ray M1 |
| Mg$^{10+}$ | 1s$^2$ 3S$_1$ | (13.6±0.49) $\mu$s | LLNL EBIT [30] | x-ray M1 |
| Be Sequence |       |                  |           |      |         |
| Ar$^{14+}$ | 2s$^2$P$_{3/2}$ | (15.0±0.7) ms | Oxford EBIT [20] | 594 nm M1(M2) |
| K$^{17+}$ | 2s$^2$P$_{3/2}$ | (7.6±0.5) ms | LLNL EBIT [22] | 464 nm M1(M2) |
| B Sequence |       |                  |           |      |         |
| Cl$^{12+}$ | 2s$^2$P$_{3/2}$ | (21.0±0.5) ms | LLNL EBIT [16] | 574 nm M1(E2) |
| Ar$^{19+}$ | 2s$^2$P$_{3/2}$ | (8.7±0.5) ms | NIST EBIT [18] | 441 nm M1(E2) |
| K$^{14+}$ | 2s$^2$P$_{3/2}$ | (9.70±0.15) ms | LLNL EBIT [20] |         |
| F Sequence |       |                  |           |      |         |
| Ar$^{21+}$ | 2s$^2$P$_{3/2}$ | (9.32±0.12) ms | LLNL EBIT [20] | 553 nm M1(E2) |
| K$^{15+}$ | 2s$^2$P$_{3/2}$ | (4.44±0.10) ms | LLNL EBIT [22] | 426 nm M1(E2) |
| Al Sequence |       |                  |           |      |         |
| F$^{13+}$ | 2s$^2$P$_{3/2}$ | (16.74±0.12) ms | LLNL EBIT [31] | 532 nm M1(E2) |
| Si Sequence |       |                  |           |      |         |
| Kr$^{22+}$ | 3s$^2$P$_{2}$ | (5.7±0.5) ms | NIST EBIT [18] | 384 nm M1 |
| P Sequence |       |                  |           |      |         |
| Kr$^{21+}$ | 3s$^2$D$_{5/2}$ | (0.80±0.03) ms | LLNL EBIT [23] | 345 nm M1 |
| Ar Sequence |       |                  |           |      |         |
| Kr$^{18+}$ | 3s$^2$P$_{3/2}$ | (2.20±0.2) ms | LLNL EBIT [23] | 403 nm M1+M2 |
| K$^{18+}$ | 3s$^2$P$_{3/2}$ | (4.2±0.5) ms | LLNL EBIT [23] | 579 nm M1+M2 |
| K Sequence |       |                  |           |      |         |
| Kr$^{17+}$ | 3s$^2$P$_{3/2}$ | (22.7±1.0) ms | LLNL EBIT [23] | 637 nm M1 |
| Ca Sequence |       |                  |           |      |         |
| Kr$^{18+}$ | 3s$^2$P$_{3/2}$ | (8.4±1.2) ms | LLNL EBIT [23] | 545 nm M1 |
| Ti Sequence |       |                  |           |      |         |
| Xe$^{32+}$ | 3s$^2$D$_{5/2}$ | (2.15±0.14) ms | NIST EBIT [17] | 414 nm M1 |
| Ni Sequence |       |                  |           |      |         |
| Xe$^{36+}$ | 3d$^3$D$_{3}$ | (11.5±0.5) ms | LLNL EBIT [43] | 2.0 nm M3 |
| Cs$^{37+}$ | 3d$^3$D$_{3}$ | (8.2±2.0) ms | LLNL EBIT [43] | 1.9 nm M3 |
| Ba$^{38+}$ | 3d$^3$D$_{3}$ | (4.3±3.6) ms | LLNL EBIT [43] | 1.8 nm M3 |

EBIT Electron beam ion trap (at HD Heidelberg, NIST Gaithersburg, LLNL Livermore, Oxford)

observed [45], but only as a weak line, because a long-lived level like this (predictions range from 14 to 19 ms) is also depopulated by the electron beam. Nevertheless, in two-dimensional spectra (energy vs. time in the EBIT trapping cycle) this line showed up as the only one with a typical decay curve. H- and He-like oxygen lines (from a small fraction of oxygen in the residual gas) showed a practically constant delayed emission due to charge exchange even at long times after the electron beam and thus the excitation stopped. The Xe line was the only spectral feature with a decay curve time constant of the order of milliseconds (about 11 ms in this case). New measurements are under way to improve on the error bars. However, this is the first example
of an atomic lifetime measurement using a microcalorimeter, and in this the new device has already proven its unique properties.

3. Conclusion and prospects
Table I presents a selection of the (long) atomic lifetime measurements that have been done with electron beam ion traps. All transitions are electric-dipole forbidden, with actual multipole orders ranging from M1 to M3. The ions studied belong to isoelectronic sequences from He through Ni, that is from few-electron ions, for which accurate measurements test details of the theoretical description, to many-electron ions that require quite different calculational techniques and that cannot yet be treated by theory with the reliability expected for few-electron ions. The published measurements reach from microsecond lifetimes to many milliseconds, the wavelength ranges from the visible (several eV photon energy) to the x-ray range (near 2 keV so far). Having identified crucial measurement parameters like the ion loss rate due to charge exchange, the systematic errors are under good control for atomic level lifetimes up to a few dozen milliseconds. It appears quite feasible to extend this range to about 100 ms in the near future.

Looking farther forward, the selective excitation of ions that are stored in the electron beam ion trap, by laser, XFEL, or synchrotron light pulses, has been suggested and may some day be achieved. This would yet again offer a new window into atomic structure and dynamics.

Acknowledgments
The author appreciates thankfully the hospitality and support experienced at the Livermore EBIT laboratory. P. Beiersdorfer kindly provided advice on the manuscript. The work at the University of California Lawrence Livermore National Laboratory was performed under the auspices of the US Department of Energy under Contract No. W-7405-Eng-48.

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