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The EBIT Quest for Better Transition Probabilities of Forbidden Lines

E. Träbert,* P. Beiersdorfer and S. B. Utter

Department of Physics and Space Technology, Lawrence Livermore National Laboratory, Livermore, CA 94551, U.S.A.

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Abstract

Electron beam ion traps (EBIT) lifetime measurements on forbidden lines in the visible spectrum have reached a precision of only about 5%, whereas some EBIT lifetimes measured on X-ray transitions are good to 0.5% already. Scientific and technical problems encountered when trying to improve on these limits are discussed.

1. Introduction

Electron beam ion traps (EBIT) offer spectroscopical access to highly charged ions practically at rest, just by using a room-sized apparatus with some auxiliary equipment. Of particular interest are the so-called forbidden transitions that cannot proceed by emission of electric dipole (E1) radiation, but only by the normally much less probable magnetic dipole (M1) or electric quadrupole (E2) radiation. X-ray lifetime measurements on M1 transitions using EBIT have reached a precision much better than 1% [1,2]. In the visible range, however, lifetime measurements on forbidden transitions between fine structure levels of a given term so far are at uncertainties of 6.5% (Xe^{32+} [3]), 6% (Ar^{13+} [4]), 9% (Kr^{22+} [4]) or 5% (Kr^{22+} [5]). The first three data are from the NIST (Gaithersburg) EBIT, and the last is from LLNL's SuperEBIT. All these measurements used the same magnetic trapping mode [6], that is, operating EBIT in a steady-state mode to create the desired ionization state, then switching off the electron beam and using the device as a Penning trap. (The same level in Ar^{13+} has also been studied by Moehs and Church [7], capturing ions from an electron cyclotron resonance ion source (ECRIS) into a Kingdon-type electrostatic ion trap. Those authors quote lifetime uncertainties as low as 2% in this case.) Why are some of these EBIT measurements better than the others, and why aren't they all as good as the X-ray data? What is there so different with the experimental working conditions that it might explain this behaviour and point at ways for improvement?

2. State of the art

Atomic lifetime measurements with EBIT have been done in two very different lifetime ranges, femtoseconds (by a line-broadening measurement on Ne-like Cs^{45+} [8]) and milliseconds. Here we discuss only the latter. In the first of such investigations, the fairly isolated 1s2s $^3S_1$ level in the two-electron ion Ne^{8+} was studied [9]. The electron beam energy was modulated between values above and below the excitation threshold energy. A large solid angle X-ray detector monitored the time behaviour of line radiation from the level of interest for a number of cycles. With frequent cycling, it was possible to collect data of very good statistics and, a property of the good pulse height discrimination in X-ray spectroscopy, low background. After separating the data recorded above and below threshold, lifetimes in the range of 90 μs and (for heavier ions) below [9,10] were extracted. The measurements have since been developed toward better statistics and better control of systematic errors, nowadays completely shutting off the electron beam during the time interval of decay curve measurement (the aforementioned magnetic trapping mode) [6,11] (Fig. 1). The latest two of these experiments, on O^{6+} [1] and Ne^{8+} [2], have reached uncertainties as low as 0.45%.

3. Signal detection

In contrast to that X-ray work, precise lifetime measurements in the visible / ultraviolet (uv) regime are limited by detector performance. The quantum efficiency of X-ray diodes can be fairly high, and electronic noise and cosmic events can be discriminated against. In contrast, photomultipliers for visible light usually are both less efficient and much more noisy, even when cooled. CCD cameras promise lower backgrounds, but need a fast framing-mode read-out to cope with lifetimes in the millisecond range. Alas, such CCDs are expensive and, because of the lengthy read-out process, not readily compatible with the specific need of fast cycling; low-noise photomultipliers (preferably in event mode) have to be used instead.

With suitable optics, a large solid angle of observation can be reached in the visible and near ultraviolet ranges [3,12,13]. However, in the search for the lines of possible interest (of which EBIT spectra are rich), the combination of flexibility and precision that is offered by a grating spectrometer comes

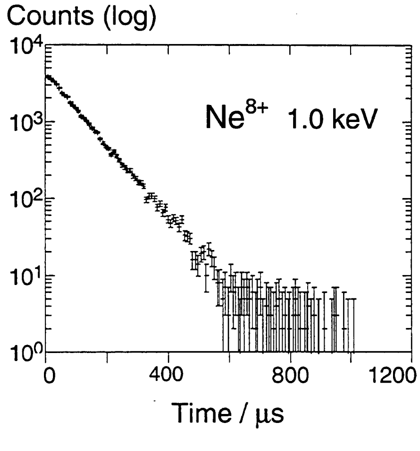

Fig. 1. Example of X-ray data curve. Decay $1s^2\ ^1S_0 - 1s2s\ ^3S_1$ in Ne^{8+} [2].

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*Experimentalphysik III, Ruhr-Universiatät Bochum, Germany at the cost a limited light path and additional reflective and diffractive light losses. Low signal rate and non-neglibible dark rate result in poorer signal dynamics, as is evident in typical decay curves (Fig. 2).

Once the wavelengths of the lines are known and nearby foreign lines can be excluded, a better detection efficiency than with standard spectrometers can be reached by the combination of efficient collection optics with interference filters. Also, a new type of high-efficiency wide-aperture transmission grating has been developed at LLNL which might improve on the overall detection efficiency problem in a somewhat limited wavelength range. First tests show both a high throughput and a higher spectral resolution than obtained with the previously employed prism and grating spectrometers.

4. EBIT operation

The above generic problems do not explain the differences of precision among visual lifetime data, some of which having even been done on the same transition. For this we need to look at EBIT operations in more detail. The highest charge state of an ion species reached in EBIT is determined by the available electron beam energy and the ionization energy sequence of the ions. EBITs are designed to work with highly charged ions. However, the ionization energies of moderately high charge states in heavy ions may be in the one to a few keV range. An electron energy of about 1 keV would, in fact, be appropriate and sufficient for many ions which are of interest to plasma and solar physics. That is clearly below the, say, 10 to 100 keV energies used for typical data production with highly charged ions. Consequently it can be difficult with these machines to study what in other contexts would be considered a highly charged ion, like Ar^{13+}, which is not really highly charged by EBIT performance standards.

However, while EBITs are not optimized to run at such low electron beam energies, SuperEBIT at LLNL is the machine not only capable of reaching the highest charge states by using the highest electron energies, 250 keV, but also the lowest (about 100 eV), because the trap region can be biased independently from the electron beam formation and acceleration toward the trap. However, at the lower electron beam energies the electron transmission through the trap region suffers, and that means that the signal will correspondingly be lower, too.

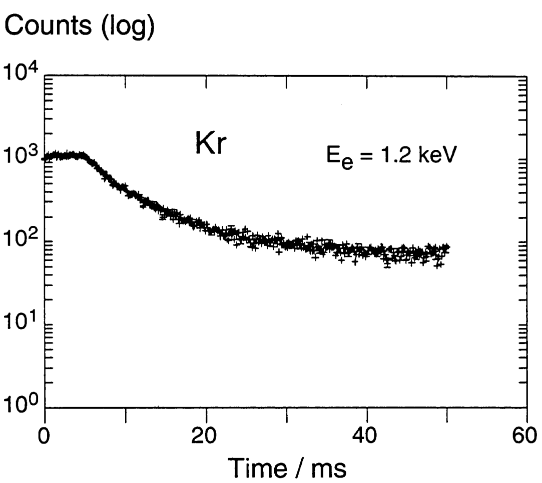

Fig. 2. Example of visual-light decay curve. Decay $3s^2\ 3p^2\ {}^3P_1{-}{}^3P_2$ in Kr^{22+} [5].

Aiming at ılowı charge states with regular EBITs therefore requires tricks, like an interruption of the stepwise ionization of Ar atoms at a time shortly after the start, so that the charge state distribution has not yet reached the final, steady-state equilibrium. The same incomplete ionization can be arranged for by worsening the ultra-high vacuum: More atoms are available for ionization and excitation by the electron beam, but the conditions of the experiment are less clean than wanted. For example, the data of Fig. 1 have been taken at an electron beam energy of 1 keV, not reaching any charge state higher than the wanted one. The result is a clean single-exponential decay with a time constant corresponding to a lifetime of (91.7±0.4) ms. At an electron beam energy of 3 keV, the electron beam current and consequently the signal rate are much higher, but also a second, much slower, decay component appears that might relate to recombination events of more highly charged ions. The worrysome problem lies in the fact that the primary decay then yields a lifetime of (91.1±0.1) ms (with an error estimate based on counting statistics only) that differs from the above value by more than the combined errors. Both results lie within the uncertainty range of the earlier measurement [9]. Apparently, the maximization of the signal rate by increasing the electron beam energy much beyond the excitation threshold introduces systematic errors that are not yet fully understood [2].

For the transition from steady−state conditions (with the electron beam "on") to the magnetic trapping mode (with the electron beam "off") one would ideally have a perfect switch that stops further excitation and ionization and also removes the remaining free electrons from the trap volume in order to prevent further recombination. In practice, the electron beam energy and the electron beam current are best both reduced to zero within about 0.1 ms. As most lifetimes measured on forbidden transitions in the visible are in the range of a few ms, such a switching time would be sufficiently fast. However, when the electron beam is being switched off, the trap potential changes and the ion cloud expands radially towards a new equilibrium. Also, the trap electrodes may react to the sudden field and load changes by "ringing". The dynamics of this change of geometry and the switching transients overlap in time, and it has not yet been possible to study this transition period in detail. As it is now, one has to truncate the early data points until a curve with a stable exponential behaviour is found.

5. Prospects

In conclusion, when aiming at high precision lifetime data, one will find the need for various trade-offs: At high electron beam energies, the electron current maybe high and result in a high signal rate, but also in the production of higher charge-state ions and in contributions from recombination. With an excitation energy just above threshold, conditions are cleaner, but the signal rate will be lower (in a recent run by one order of magnitude) because of a lower electron beam current. Precisions at the 0.1% level in X-ray work and at 1% for lifetime measurements in the visible seem within reach.

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