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Limitations of the Beam-Foil Method in Lifetime Measurements

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Abstract

We have measured the decay time of the $1s^2 2p\ ^2P_{3/2}$ level of Li-like Ar^{15+} using beam-foil spectroscopy. The experiment was done at a beam energy of 2.6 MeV/u and with an Al foil instead of a C foil which is usually used in beam-foil experiments. The signal was recorded by means of a CCD detector system installed on a 2.2 meter grazing incidence spectrometer. This system allowed recording of the spectral line-profile decay. The result shows different decay times for different parts of the measured line profile, thereby corroborating our previous studies of the same transition in Ar^{15+} by using a C foil and the same energy. In the latter work some difficulties were revealed in determing reliable lifetimes for excited levels in highly charged ions. We discuss the causes of the uncertainties in decay time (hence lifetime) measurements and suggest a scheme for increasing the reliability of beam-foil lifetime experiments.

1. Introduction

Reliable experimental values of lifetimes and transition probabilities of highly charged ions provide important tests of atomic many-body theories in the relativistic regime. They have also applications in a number of fields, including astrophysical studies of the solar corona, solar flares and the atmospheres of hot stars, as well as the diagnostics of fusion plasma impurities.

Methods for measuring lifetimes of energy levels of highly charged ions fall into a number of catagories. Until some years ago, the beam-foil technique was the only method for such purpose [1, 2]. More recently valuable results have been obtained by using other methods, such as heavy ion storage rings [3, 4], or electron-beam ion traps [5, 6]. These novel techniques can be used to measure very long lifetimes (ms) [3–5] but also very short lifetimes (fs) [6], and they complement the beam-foil method which can be routinely applied in the 1 ps – 100 ns interval where many atomic and ionic lifetimes fall.

However, a systematic shortening of the experimentally obtained $3s3p\ ^3P_1$ lifetimes of Mg-like ions, in comparing with theoretical predictions, was noted in our recent beam-foil studies of the isoelectronic $3s^2\ ^1S_0 - 3s3p\ ^3P_1$ intercombination line strengths [7]. Similar lifetime shortenings have been noted in some earlier beam-foil studies [8, 9] dealing with the $1s^2\ ^1S_0 - 1s2s\ ^3S_1$ M1 transition in He-like ions, Lin and Armstrong [10] explained that this discrepancy was caused by contamination of quicker decaying unresolved Li-like satellite transitions. However no additional extensive or systematic studies of such problems have been reported. In order to understand the discrepancies, we recently made beam-foil experiments measuring the decays of the lines $2s\ ^2S_{1/2} - 2p\ ^2P_{3/2,1/2}$ in Li-like Mg^{9+} and Ar^{15+} ions [11]. These cases were selected because theoretical f-values for transitions in Li-like ions are quite accurate. In the Mg case measurements were done at 3 different beam energies, and we found that the decay times of the $2p\ ^2P_{3/2,1/2}$ levels varied with beam energy. This somewhat unexpected result was explained as being caused by $2snl$-$2pnl$ satellites in Be-like ions which could blend the resonance lines of the Li-like ions. Only at the highest beam energy when the fraction of Li-like ions was much larger than that of Be-like ions did the experimental decay times agree with theoretical predictions. In the Ar case the experiment was done at a fixed beam energy, 2.6 MeV/u, and with good spectral resolution. At this energy there are approximately equal amounts of Li-like and Be-like ions after the foil. Here we found that the extracted decay time changed with wavelength within the measured line profile. These findings which indicate the presence of unresolved satellites propose a serious question about the reliability of the beam-foil method for lifetime measurements. The present work is a continued study of such problems. We have now measured the decay of the $2s\ ^2S_{1/2} - 2p\ ^2P_{3/2}$ line of Ar^{15+} at the same energy as in previous work [11]. However, instead of the exciter foil C we now used a thin Al foil, which may result in different populations of the Be-like satellite levels, and may lead to a factor of 2 or so increase in light intensity [12].

2. Experiment

The experiment was carried out using the RILAC heavy ion accelerator at RIKEN. Here the beam-foil set up has been previously described by Ando *et al.* [13]. Beams of highly charged Ar ions were extracted from an ECR ion source and then accelerated to the final energy (2.6 MeV/u) using the RILAC. The accelerated ions were further stripped and excited using a thin Al foil (27 $\mu g/cm^2$). The VUV photons produced by decay of the excited states were dispersed and observed using a 2.2 meter Nikon/McPherson grazing incidence spectrometer employing a 1200 lines/mm grating. In the experiments desribed in [7] photon detection was done using single channel techniques (Ceratron electron multilpier). The results reported in the present paper are obtained using a CCD detector system, see [14]. The CCD was supplied by the X-ray astronomy group at the University of Leicester. The mounting of the detector on the grazing incidence instrument was not along the Rowland circle as would be expected. For reasons of intensity the chip was instead mounted so that its center was perpendicular to the incoming photons. As discussed in [14] this leads to some distortion of the spectral line shapes away from the center of the CCD. However this does not lead to any problems in the present case as the line was positioned close to the center of the CCD.

3. Results and discussions

The wavelength of the $2s\ ^2S_{1/2} - 2p\ ^2P_{3/2}$ line in Ar^{15+} is 353.87 Å and the theoretical lifetime of the upper level is 0.653 ns [15]. We measured the whole line profile of the transition at different time after excitation. Figure 1 shows three typical such recordings. From these spectra we extracted a range of values for the $^2P_{3/2}$ decay time. The form of the decay depended very much on which section of the line profile was taken to compose the decay curve. Fig. 2 shows decay curves obtained by integrating the counts over three channels at long wavelength side, top part and short wavelength side on the line profile. The extracted decay times are also given in Fig. 2. The slopes of the three decay curves are very different. The short wavelength side decays slowest, and with some kind of growing-in, whereas the long wavelength side decays fastest. This wavelength dependence of the extracted decay time agrees with the results from our previous studies [11]. We consider that the non-unique value of the decay time is caused by contamination from 2s*nl* - 2p*nl* satellite transitions where n can be quite high. Satellites from levels of low *n*, of course, will not influence the measured decay curves as they move well outside the line profile.

Satellites from the highest possible *n* values lie closest to the primary line and the satellite levels decay via different channels, either as 2s*nl*-2p*nl* transitions or to a lower satellite level, i.e. 2p*n′l′* - 2p*nl*. According to our superposition of configurations (SOC) calculations by using the Cowan code [16], the rates of the unresolvable satellite transitions are nearly the same as the primary transition. However, the decay times of the 2p*nl* satellite levels are shorter than the decay of the 2p primary level, because of the additional 2p*n′l′*-2p*nl* decay channels. So the contamination of satellite transitions will always cause a shortening of the decay of the top part of the measured transition line profile. Satellite levels 2p*nl* of relatively lower *n* which have short lifetimes can also be fed by higher lying satellite levels. Considering the slight difference in wavelength of satellites from different *n*, the satellite contamination can cause the decay time variation with wavelength within the measured line profile.

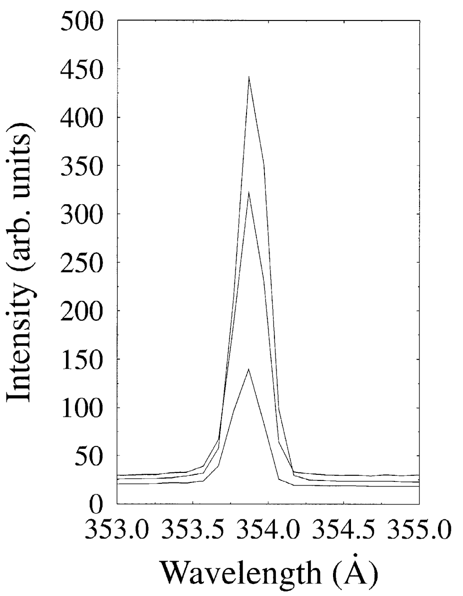

Fig. 1. The $1s^22s\ ^2S_{1/2} - 1s^22p\ ^2P_{3/2}$ line in Li-like Ar^{15+} recorded at 0.15, 0.36 and 0.80 ns after excitation.

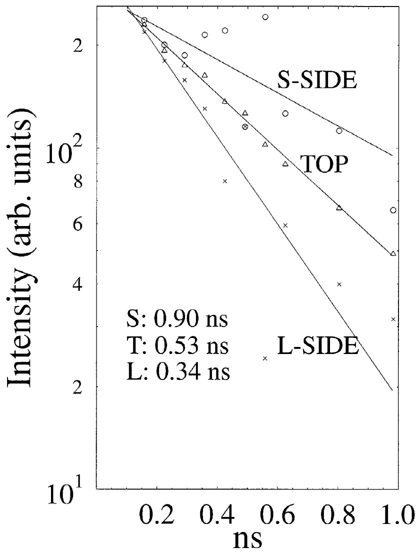

Fig. 2. The decay curves composed by integrating the counts over three channels at long wavelength side, top part and short wavelength side on the measured line profile of the transition $1s^22s\ ^2S_{1/2}–1s^22p\ ^2P_{3/2}$.

In some recent work by Ishii *et al.* [17] satellite lines have also been discussed for beam-foil spectra recorded in the visible region. We can note here that satellite levels with very high values of *n* may not influence the measured decay curves as they will have an autoionisation channel and hence decay mostly by electron emission. For Li-like Ar^{15+} the satellite levels (Be-like) become autoionizing for *n* greater than 10.

In our previous work for measuring the decay of the similar transition of Mg^{9+} [11], we found that at higher beam energy extracted decay time is closer to theory, that corroborates our explanation of satellite contamination. So we suggest to use a beam energy as high as possible to get more reliable lifetime by means of the beam-foil method. In the Ar^{15+} case, the ion energy should be around 5 MeV/u.

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