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Effects of Foil Aging Properties on the Intensities of Atomic Transition Lines Following Ion-Foil Interaction

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Abstract

In this work we measured the time dependence of the light intensity of the $1s^22s\ ^1S_{1/2}$–$1s^12p\ ^1P_{3/2}$ resonance transition in Li-like Al ions after passing through a $10\ \mu g/cm^2$ carbon foil. The measurements were done at beam energies of 0.8 MeV/u and 2.5 MeV/u. Also, the 1s5g–1s6h transition in He-like Al ions, after passing through the same thickness carbon foil, at 2.5 MeV/u was investigated. The results show very obvious decreases of the light intensity for the Li-like transition with beam exposure time of the foil at both beam energies, while a slow increase was observed for the He-like line intensity. In this work several different foil aging effects on line intensities are discussed and a new normalization scheme is proposed to improve the reliability of beam foil spectroscopy method in lifetime measurements.

1. Introduction

The stripping of heavy ions by thin foil is used in many branches of physics. The uses range from stripping ions in the center of a tandem accelerator (for further acceleration) to ionization and excitation of ions for spectroscopic applications in Beam-Foil Spectroscopy (BFS). It is known from early work on BFS and other fields that foils tend to break quickly for low energy heavy ion passage. However at higher energies foils tend to last for longer periods of time, e.g. at energies of 2 MeV/u for ions of medium Z elements foils can last for a few days. At these higher energies it is often considered a rule of thumb that a fresh foil should be exposed for some time (e.g. 1 h, depending on the foil and beam parameters) to the ion beam of interest before starting a spectral recording. It should be anticipated that foils change their character (in other words, age) as a function of exposure time before finally breaking. Auble *et al*. considered that the aging is caused mainly by radiation damage induced foil structural change [1]. Sorensen discussed various problems in low energy beam-foil lifetime measurements [2], including foil aging effects. Hellborg *et al*. studied carbon foil lifetime under bombardment of heavy ions at energies of few hundreds keV [3], and found line intensities decreased with ion exposure time before foil rupture, which was also reported in Sorenson's work [2]. In the work of Ref. [3], they found the ratio of the line intensities of different charge states from the same beam remained unchanged with foil age, so concluded that foil aging would not change the charge state balance.

The measurement of atomic energy level lifetimes using the beam-foil technique relies heavily on normalization of the signal recorded as a function of the foil-detector separation. Changes in the foil properties could affect the normalization and hence have serious consequences for such lifetime measurements. This is an important consideration in beam-foil lifetime measurements and various normalization schemes have been considered. In low energy experiments where the foil aging problems are very severe, both the ion current collected in a Faraday cup and visible light intensity directly after the foil have been used [4]. In most medium to high energy beam-foil experiments current normalization has dominated, only in few cases the visible light intensity was used for the normalization [5] as mentioned above. In a recent work we found a divergence for the $3s^2\ ^1S_0$–$3s3p\ ^3P_1$ Mg-like transition rate for a number of high Z ions away from the theoretical values [6]. To establish if this divergence was due to experimental or theoretical problems, we studied the decay of the $2s\ ^2S_{1/2}$–$2p\ ^2P_{1/2,3/2}$ Li-like resonance lines where we know theory to be more reliable and accurate. We again found disagreement between experiment and theory and so established the problem to be experimental. Part of the experimental problem has been shown to be caused by blending by the close lying satellite lines to the line of interest [7,8]. However a second problem was found to be caused by the changing properties of the foil during the data collection time (often around 15 hours for a decay curve). To investigate this problem we collected data at a fixed foil position over periods of time equivalent to those used to obtain decay curve data. We have found, in the measurements to be described below, that foil aging can cause some lines to increase and some to decrease in intensity as a function of time. This brings into doubt the methods of normalizing experiments where foils were used.

In this work the possible causes of line intensity variations during the time an ion beam impinges on a C foil are discussed and a new normalization scheme is proposed.

2. Experiment

Beams of highly charged Al ions were obtained from the RILAC linear accelerator at RIKEN. The ions were first extracted from an ECR ion source and then accelerated to the final energy by the RILAC. In this work we used 0.8 MeV/u Al^{7+} and 2.5 MeV/u Al^{6+} beams. Beam currents were around 300 electrical na. The ions were directed towards the RIKEN beam-foil set up which is described in detail in [5]. The ions are sent through a thin carbon foil

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($10\,\mu g/cm^2$) where they are further ionized and also excited. The VUV photons from the excited ions are studied using a 2.2 meter grazing incidence Nikon/ McPherson spectrometer. The VUV photon detection is accomplished by a CCD detector mounted directly on the Rowland circle of the spectrometer [9]. This system has been mainly used in the past to measure decay curves of excited atomic states following the ion-foil interaction. Spectral data was recorded at 2 mm downstream of the C foil. This was done to avoid high background close to the foil from beam-related X-rays, see [10]. The energy resolving properties of the CCD can of course be used to discriminate away the X-ray background, however close to the foil a significant background still prevails.

Foils of many materials can be used to strip swift ion beams, however the most commonly used are those made from carbon. The foils used in the present experiments were obtained from "Atomic Energy of Canada Limited, Research Company, Chalk River Nuclear Laboratories".

3. Results and discussions

Figure 1 shows the foil age dependence of line intensities of Li-like $1s^22s\,^2S_{1/2}$–$1s^22p\,^2P_{3/2}$ resonance transition measured at beam energies of 0.8 and 2.5 MeV/u and of He-like 1s5g–1s6h transition measured at 2.5 MeV/u. From Fig. 1 we can see that the Li-like line intensity decreased by about 40% at 0.8 MeV/u, and about 50% at 2.5 MeV/u after 20 h ion beam impinging. We made single exponential fits for the Li-like line intensities versus foil age, and got decay times of 34 h and 23 h, respectively, for 0.8 and 2.5 MeV/u ion beam impinging on a $10\,\mu g/cm^2$. The "time" here means the time since the ion beam impinged on the carbon foil, or the "age" of the foil since its first exposure to the ion beam. The exponential fits were more to provide a number for discussion purposes. The He-like line increases slightly with the foil age. We consider that the foil aging affects line intensities in the following ways:

(a) The foil may thicken during the time the beam impings on the foil. The thickening being caused by depositing of carbon onto the foil from residual hydrocarbons etc. This effect is important when the foil has less than equilibrium thickness.

(b) The foil structure may change due to radiation damage. This can leave pinholes in the carbon foil, through which beam ions can have free passage [3]. In most cases this will reduce the fraction of excited ions in the charge state of interest. Only the fractions of the ions, whose charge state is the same or very close to incident ions, could be increased by this effect.

(c) Foil deformation caused by the beam impinging on the foil, beam pressure, and shifting the center of the foil towards the spectrometer slits. This will lead to an increase in line intensity. The increase is larger for the line transition from the shorter lifetime upper state. From our observations, the displacement of the center of the beam spot on the foil can be 0.1–0.3 mm towards the beam direction.

In the 0.8 MeV/u case, charge state equilibrium will be reached after passing through a $10\,\mu g/cm^2$ thick C foil. So the foil thickening effect would not influence the line intensity obviously. The upper state lifetime of the Li-like transition is 1.27 ns, according to the result of the SOC code of COWAN [11]. Hence foil deformation could cause the intensity of the line to increase by around 2% at most, which cannot be responsible for the observed 40% decrease. We consider that the intensity decrease in this case was caused by structural changes to the foil by radiation damage.

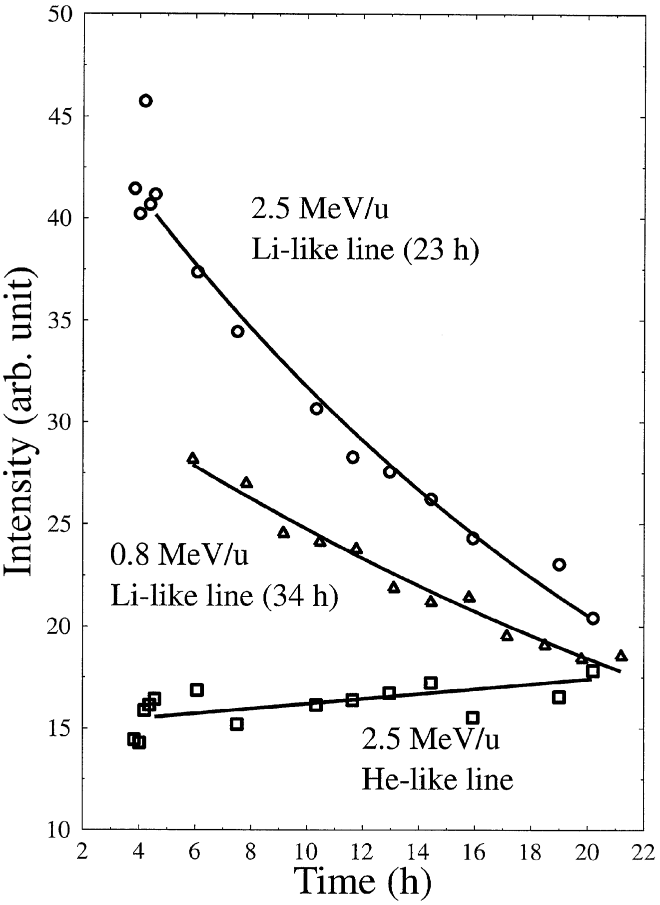

Fig. 1. Foil age (in hours) dependence of line intensities of Li-like Al ions $1s^22s\,^2S_{1/2}$–$1s^22p\,^2P_{3/2}$ transitions at beam energies of 2.5 MeV/u and 0.8 MeV/u, and 1s5g–1s6h He-like transitions at 2.5 meV/u. For convenience in comparison, single exponential fits for Li-like line intensities were made, and the decay times are indicated in brackets.

In the case of 2.5 MeV/u, the Li-like line intensity decreased faster than in the case of 0.8 MeV/u. This appears to be in conflict with the idea that foils age faster at lower energy beam bombardment. However, as $10\,\mu g/cm^2$ carbon foil is not thick enough for charge state equilibrium at this beam energy, the deposition of carbon onto the foil will cause the charge state balance to evolve towards its equilibrium distribution. At 2.5 MeV/u, the equilibrium distribution gives the highest fraction of He-like Al ions, and the maximum of Li-like charge state appears at foil thicknesses lower than the equilibrium thickness. So the thickening of the foil towards the equilibrium thickness may cause a decrease in line intensity of the transitions from Li-like ions. We consider that the faster decreasing of the Li-like line at beam energy of 2.5 MeV/u was caused by the united effect of foil radiation damage and foil thickening. At this beam energy, the foil deformation would lead to at most an insignificant 1% increasing of line intensity.

The He-like 1s5g–1s6h transition line increased about 16% through foil aging effects. As mentioned above, He-like is the most probable charge state at equilibrium for 2.5 MeV/u Al ions passing through a sufficiently thick carbon foil, so the deposition of carbon on to the foil can cause the He-like line intensity to increase. At the same time, foil deformation of 0.1–0.3 mm can cause this He-like line to increase in intensity by roughly 20%–60%, because the lifetime of the upper level of the transition is very short, 0.029 ns according to the result of the SOC code mentioned above. Combining these two effects, the He-like line intensity should increase by more than 20% at the lowest. However, radiation damage effects could play an important role in offsetting the increase and reduce it to the observed 16%.

4. Conclusion

In this work we studied the effects of foil aging on line intensities of atomic transition. We conclude that the effects can come from radiation damage of the foil, foil thickening by carbon deposition, and foil deformation. Which of these plays the key role would depend on the case in question, in some cases all of these effects are important, and in some case only one of them may dominate. The foil aging effects really brings into double the methods of normalizing experiments where foils are used. There are of course schemes where this problem can be minimized, i.e. by scanning the foil up and down stream quite quickly and recording the foil position for each arriving photon, although this scheme has rarely been used in most published beam-foil work. Here we propose a simple but efficient way in diminishing the foil aging effects: The foil aging effects can be measured as discussed in this work, so one can create a correction curve during lifetime measurements, e.g. alternatively measure the data points for the line decay caused by de-exitation and the line decay by the foil aging. This scheme corrects not only for the charge state but also for the population of the level of interest, and would be more reliable for obtaining lifetimes by beam-foil measurements.

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