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Variations of Carbon Foil Lifetimes Under Bombardment by N^+, Ne^+, Ar^+ and Zn^+ Ions

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Abstract

Studies of the useful lifetime of 2–5 $\mu g\,cm^{-2}$ carbon stripper foils have been made using 225 keV heavy ion beam bombardment. The foils were self supporting and were mounted both in a standard and a tension-slackened manner. In determining the quality of the foil during ion bombardment several techniques were used, in particular beam-foil spectroscopy. Here the intensity of the light emitted by the foil-emergent beam was measured as a function of bombardment time. The measured lifetime before foil failure for standard foils was found to agree well with a semiempirical model proposed by Auble and Galbraith, and the slackened foils exhibited usable lifetimes 3–4 times longer than the normal foils. The properties of ordinary and slackened foils were compared under realistic conditions. It is concluded that the slackened foils are very well suited for studies of atomic spectra and meanlives of excited states using beam foil excitation methods.

1. Introduction

Carbon foils are often used to obtain a distribution of charge states in a beam of monoenergetic fast ions. The useful lifetime of conventional carbon-arc evaporated stripper foils can be a serious limitation in many types of experiments. One such example involves the measurement of the atomic properties of the excited states of ions produced by the sharply defined interaction at the foil. Another example involves the use of a foil to provide multiply ionized beam atoms by electron stripping, which are subsequently accelerated further in, e.g., high voltage terminals of tandem accelerators.

In studies of atomic spectra and meanlives [1] using beam-foil spectroscopy degradation of the foil can cause many problems. Signal normalization, to compensate for beam current fluctuations etc, is frequently altered by foil breakage. Changes in the properties of the foil can distort the shape of the decay curve in atomic meanlife measurements. If the foil lifetime is less than the time needed to record a complete decay curve, atomic meanlife measurements are severely complicated. Thus the experimental parameters (beam current and profile, beam energy, foil thickness, etc.) must be carefully chosen, see. e.g., Berry and Hass [2].

In beams from tandem accelarators, the efficiency of high-charge state production decreases as the stripper foil deteriorates due to partial breakage. One alternative often applied to circumvent the short lifetime of the stripper foils in heavy ion accelerators, particularly in the case of the heaviest ions, is the use of gas stripping rather than foil stripping. However, foils are generally preferable as electron strippers, since they produce higher mean charge states. With foil strippers one also avoids some of the operational difficulties that can be expected from the use of gas stripping. Small tandems (such as the 3 MV Pelletron tandem accelerator at the University of Lund) are not normally equipped with terminal pumping. The increased pressure along the accelerating tube when using gas stripping leads to a less stable voltage, and hence to a higher energy spread in the beam. In addition, this pressure causes increased risk of damage to the accelerating tube and a higher X-ray level near the accelerator. Another approach would be to increase the number of externally selectable foils in the stripper assembly. While an increase by a factor of two or three is often possible, in most machines space limitations impose restrictions. The stripper assembly in the Lund Pelletron has recently been rebuilt to accommodate 100 foils instead of the earlier 50, and in this way we have proportionately decreased the number of foil mounts per year down to 2 or 3. For these reasons, much attention has been devoted to the improvement of the usable lifetime of the foils through a variety of methods, see for example the introduction of Ref. [3].

For some time introductory foil tests have been carried out in the terminal of the Lund Pelletron. However, the difficulties in obtaining reproducible ion optics, vacuum conditions, ion currents, etc. without diagnostic instruments in the terminal have complicated this work. The desire to directly compare carbon foils under reproducible conditions motivated the use of the University of Toledo Heavy Ion Accelerator. This accelerator provides a beam which is very stable in energy, current and beam profile, and the accelerator is also equipped for energy-resolved and time-resolved photon spectroscopy. With this accelerator systematic studies of the useful lifetime of carbon stripper foils, mounted both in a standard and a tension-slackened manner, were made using 225 keV ions of N^+, Ne^+, Ar^+ and Zn^+. The quality of the foil was determined by monitoring the intensity of light emitted by the foil-emergent beam as a function of bombardment time. This technique provides a very sensitive check of foil degradation. Furthermore, atomic spectra and meanlives were measured both using normal and slackened foils so as to test the suitability of the latter to atomic structure measurements.

2. Foil damage

The response of arc-evaporated carbon foils to ion-bombardment is well-known and the foil lifetime is limited by various processes. During irradiation, carbon stripper foils thicken in the irradiated area. The thickening is due both to radiation damage and to carbon build-up from the cracking of hydrocarbon vapour within the vacuum system by the ion beam. Correlated to the thickening, a shrinkage of the foils occurs during ion irradiation. Radial stress lines appear at an early stage around the beam spot as the foil contracts, while the foil surface at the beam spot assumes a mirror-like appearance. Gradually the stress lines become more prominent and accumulated mechanical stresses eventually cause the foil to rupture. The rupture usually takes place near the edge of the foil, outside the bombardment area.

Several approaches have been attempted to overcome the shrinkage which is attributed to the rearrangement of the atoms in the amorphous foil. Sørensen [4] measured spectra and meanlives using a sliding adhesive of vacuum pump oil to bond the foil to its mounting. Bukow *et al.* [5] have found that foil lifetimes can be prolonged by heating the foil with a CO_2 laser. An improvement by a factor of 3 to 4 in foil lifetime has been obtained by providing a sufficient slackening in the foil tension at the production stage [6]. In this way an increased amount of shrinkage is possible before the foil becomes ruptured. Measured improvements appear to be relatively insensitive to the beam parameters such as energy, mass, atomic number, current density, etc. [7]. No obvious dependences of the lifetime on foil thickness have been observed. The technique of compressing an aluminium ring with its mounted foil was orginally developed by Armitage *et al.* [8, 9]. This slackening procedure is used today in many laboratories, although the method is time consuming. Often the efficiency (unbroken/total) of slackening is low, at least for the thinnest foils unless an organic backing such as Formvar is used.

3. Experimental

3.1. *Foil preparation*

The foils used in lifetime experiments with N^+, Ne^+ and Ar^+ beams had a thickness of 4–5 $\mu g\,cm^{-2}$, whereas the studies using a Zn^+ beam were made with 2 $\mu g\,cm^{-2}$ foils. To simplify the handling, most of the foils used were supported on a thin film of Fomvar [10], as described in Ref. [11]. The carbon foils to be slackened are mounted on soft aluminium rings that are 1.5 mm thick and 11.5 mm inside diameter and 14.0 mm outside diameter. (It is of course important that the two diameters are concentric to avoid buckling of the ring.) The diameter of the aluminium rings is reduced by means of crimping jig and a tapered die. The jig is made of nylon and the die is made of steel with a polished internal taper. To avoid damage to the foil during the compression, the die must be capable of slow steady operation under, for example, a hydraulic press. It is also necessary to provide adequate means for the escape of air from the die during the compression. The die is tapered from 14.0 mm to 12.5 mm. The relative slackening $(b-a)/a$ as defined in Ref. [6] is in our case 15%. The constants a and b are the diameters of the freestanding area after and before the slackening. In some preliminary runs an earlier version of the die was used. By this the relative slackening was 9%. The compressed aluminium rings with their Formvar and carbon foils are glued on to standard foil frames. The efficiency, i.e., unbroken/total, of our slackening method including mount of Formvar and foil is for a skilled person about 50%.

3.2. *Experimental setup*

The measurements were made at the University of Toledo Heavy Ion Accelerator, which consists of a Danfysik 30 kV isotope separator with a 0–300 kV post accelerator. The detection station used is equipped with a beam foil target chamber with translatable foil wheel holding 23 foils. The beam is collimated onto the foil aperture, and post foil current is collected in a Faraday cup. A 1 meter normal incidence Acton vacuum monochromator views the light at a variable distance from the foil and a fibre optic link monitors light at a fixed distance downstream from the foil. All light detection uses single photon counting with either a photomultiplier tube or a channel electron multiplier. In all measurements a beam energy of 225 keV was used. The beam current was, with the help of a raster sweep, uniformly distributed over a 5.6 mm diameter collimator. The collimator preceded the self supporting foils which were mounted perpendicular to the beam axis. Figures of the experimental set up and the electronics used in this experiment can be found in [12].

3.3. *Collecting data*

Foil conditions were studied by means of electrical and optical measurements, of which the latter involved observation of total light emission as well as of individual spectral lines. Thus the measurements were carried out in three ways: (1) the post foil beam current was collected in the Faraday cup at the end of the chamber, (2) the intensity of undispersed light emitted by the foil emergent excited beam ions was measured with a photomultiplier tube viewing the beam via a fibre optic link. The end of the fibre optic bundle is viewing the beam approximately at a right angle, about 5 mm downstream from the foil, (3) in part of the experiment the intensities of two nitrogen spectral lines were measured simultaneously by rapidly stepping the monochromator back and forth between the two desired wavelengths. The digitized beam current and light intensity were measured continuously and the signals were accumulated and stored in an on-line computer. The beam current on the aperture and the time were also stored in the computer. As the current in the Faraday cup is affected by the quality of the foil, it is not possible to use the current as a monitor of the experiments. The correct monitoring quantity, the beam current hitting the foil, was not conveniently measurable in this configuration. However, the ratio of the current on the insulated aperture located just in front of the foil to the current in the Faraday cup, measured with an empty foil frame, was found to be very stable. Therefore the current on the aperture was used throughout the experiment as a monitor. The ratio of the two currents was checked regularly.

3.4. *Foil lifetime measurements*

The lifetime of a stripper foil is defined as the time (operationally the integrated beam current per beam area) required to produce some type of failure. The criteria for failure can differ among applications, i.e., using the foils as strippers in a tandem involves different standards than other uses such as applications in atomic physics experiments, stopping power studies etc. One definition of failure is that the intensity of the light emitted from the excited beam has decreased below a certain level (if the foil has not ruptured before that time). The decrease in intensity can depend on foil thickening, free passage of beam particles through foil pinholes and other

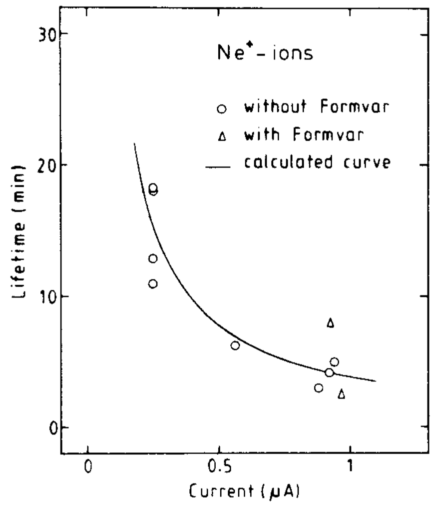

Fig. 1. Foil lifetime as a function of beam current for Ne^+ ions. The calculated curve is described in the text.

effects which reduce the beam of excited particles. In these measurements we have defined the lifetime as the time after which the light intensity has decreased to one-half of the initial value or the foil ruptures (whichever comes first). We observed a gradual decline in light intensity for all foils tested, although a short period of increasing intensity during the early exposure of a foil was sometimes observed. This may be due to the evaporation of volatiles from the foil surface, e.g., detergents/surfactants used to break the surface tension of the water used for floating the foils.

4. Beam test results

4.1. *Use of Formvar*

Tests with a low current ($< 0.25\,\mu A$) on several foils mounted on Formvar showed a curious result during the first few minutes of radiation before the Formvar was burned away. The ion current is apparently insufficient to immediately burn away the Formvar, and therefore little current in the Faraday cup and no light emission could be observed initially. With currents $> 1\,\mu A$ the Formvar seemed to burn away within a few seconds, and gave no problems. As it is necessary to use Formvar when slackening foils, and also important to burn away the Formvar immediately when measuring foil lifetimes, all such measurements with slackened foils were made with a N^+ beam of $1.5\,\mu A$. However in an atomic physics experiment with a Zn^+ beam of $0.1\,\mu A$, slackened foils supported with Formvar could be used after the Formvar was burned away, see Section 4.5 below.

4.2. *Lifetime of normal foils*

The lifetimes of normal foils were measured with three different types of ions: N^+, Ne^+ and Ar^+. To obtain a suitable lifetime for measurement (between a few minutes and one hour) different beam currents were used for each of the ions. Since the appropriate current for Ar^+ must be well below $1\,\mu A$, no foils supported by Formvar were used for this ion. As an example the results obtained for Ne^+ ions are shown in Fig. 1. The curve included in the figure is based on a simple calculation of the lifetime, which will be discussed in Section 5. In the same section additional results for normal foils will be compared with calculations.

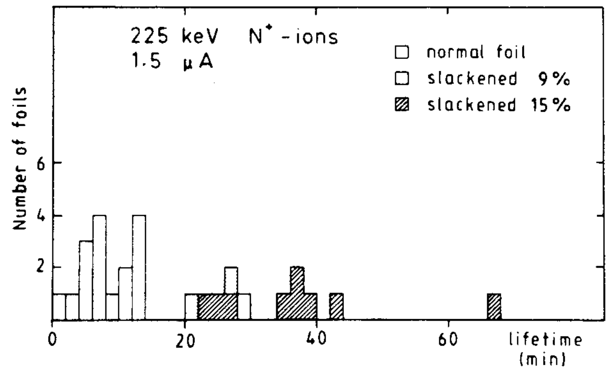

Fig. 2. Histogram of measured foil lifetimes of normal and slackened foils, $1.5\,\mu A$ N^+ ions.

4.3. *Lifetimes of slackened foils*

With a N^+ beam of $1.5\,\mu A$ several normal and slackened foils were irradiated. As was mentioned above two different values for relative slackening 15% and 9% were used. The results are found in Fig. 2. As is seen the normal foils have a lifetime between a few minutes and up to 13 min. Foils slackened 9% have a lifetime between 20 and 30 min and foils slackened 15% from 25 min up to 67 min.

4.4. *Light emission from N I and N III*

For N^+ ions the spectrum of emitted light was measured between 1100 and 1700 Å. A few different measurements were made. When the detector aperture was positioned just opposite the foil the spectra showed transitions in N I-N III as well as lines from H (e.g., Ly α at 1216 Å) and C I. When positioned one millimeter away, only nitrogen lines could be detected. Two lines were selected: N I 1200 Å and N III 1184 Å. The atomic meanlives of the upper levels of the two lines were measured and found to be close to published values. The intensities of these two lines were then measured simultaneously by rapidly stepping the monochromator between the two line positions. The results showed that the intensity ratio of these lines remained constant during foil irradiation, indicating that these charge states did not vary with foil aging.

4.5. *Spectra and atomic meanlife measurements with Zn^+ ions*

Both normal and slackened foils were tested in an atomic physics experiment using a beam of Zn^+ ions. The principal aim of this particular experiment was to measure meanlives of levels in Zn II and to investigate the beam-foil spectra of Zn in the region 1200–2500 Å. (These results will be reported elsewhere). However, a number of findings are of interest to the present study of foil properties.

For instance, we noted that Formvar was burnt away from the slackened foils after a surprisingly short bombardment time, about 3–4 min when the ion beam current was $0.1\,\mu A$. Thereafter the slackened foils could be used for atomic physics experiments. Detailed comparisons were made of spectra (1200–2100 Å) taken with normal and slackened foils. The spectra looked very similar, the only difference being due to the fact that several ordinary foils had to be used to record one spectrum, whereas a single slackened foil was sufficient. This result demonstrates the advantage of slackened foils – their long lifetimes practically eliminate intensity fluctuations in the emitted light caused by aging or breaking

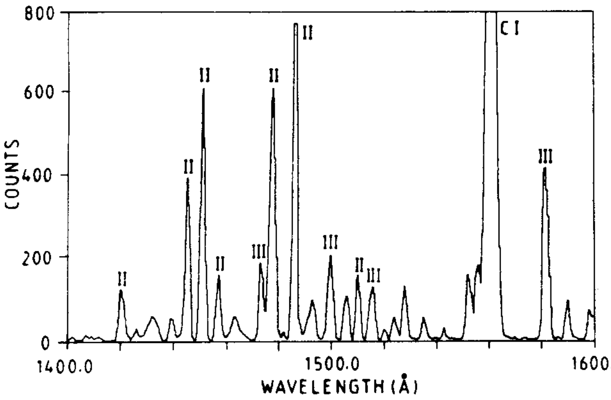

Fig. 3. Part of a Zn spectrum using a slackened foil.

of foils. Part of a Zn spectrum, registered using a slackened foil, is shown in Fig. 3. With the exception of a strong C I line all other transitions are well-known Zn II and Zn III multiplets.

We also tested the slackened foils in connection with an atomic meanlife study for Zn. The meanlife of the $4p\,^2P_{3/2}$ level in Zn II was measured both with ordinary and slackened foils and the preliminary results are identical, 2.40 ± 0.15 ns. This value is in excellent agreement with the latest theoretical result, 2.386 ns [13]. While this shows that slackened foils can be used in meanlife measurements, some care is still needed. For instance, the foil surface (and thus the point of excitation) is not as well defined as in the case of normal taut foils. This fact may lead to systematic uncertainties in determining very short meanlives (typically less than 2 ns). On the other hand, slackened foils could be useful in measuring long meanlives, up to a few hundred ns. In such cases the transitions of interest are usually weak and the recording of decay curves can be quite time-consuming. Foil breakage makes such measurements very difficult when ordinary foils are used, and slackened foils ought to be tried in future work.

5. Discussions and conclusions

A simple procedure for estimating foil lifetimes has been developed by Auble and Galbraith [14]. The method is based on the idea of estimating the number of displacements which occur per incident ion and then assuming that the foil lifetime is inversely proportional to the product of the number of displacements per incident ion and the fluence. The equation given by Auble and Galbraith for estimating the product of the current density and lifetime in real time, denoted here by T_{foil} (in units of pμA · min · mm^{-2}, where pμA stands for particle μA) is

$$T_{\text{foil}} = k_{\text{foil}} E_0 / (Z_1^2 M_1) \qquad (1)$$

E_0, Z_1 and M_1 are the kinetic energy (in eV), atomic number and mass number of the incident atoms. The proportionality factor, k_{foil} (in units of pμA · min · mm^{-2} · eV^{-1}), will depend on the detailed microstructure of the foils and will, therefore, be different for foils made by different techniques. For vapour deposited foils the empirically determined constant was found to be $k_{\text{foil}} = 0.0018$ [14]. This expression for lifetimes appears to yield a fairly good representation of foil lifetime over a large mass and energy range. This means that tests of foil lifetimes with ions of keV energies can be a good predictor of lifetimes at bombarding energies corresponding to the use of foils as strippers in tandem accelerators. In Fig. 4 are shown the measured lifetimes from section 4.2 (multiplied by $Z_1^2 \cdot M_1$) as a function of current density for normal foils bombarded with N$^+$, Ne$^+$ and Ar$^+$ ions, together with the calculation.

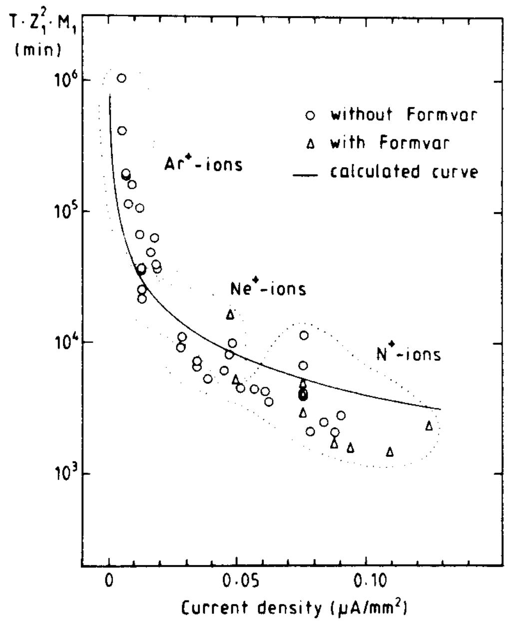

Fig. 4. Foil lifetime (multiplied by $Z_1^2 \cdot M_1$) as a function of current density, N$^+$, Ne$^+$ and Ar$^+$ ions. The calculated curve is described in the text.

Despite the fact that slackening can produce a longer lifetime of the stripper foil, this does not guarantee a stripper improvement, because foil thickening increases the small-angle scattering which reduces the ion transmission through a tandem accelerator, especially for heavy ions. The use of slackened foils as strippers in tandem accelerators is therefore of limited value.

In summary, we have made experiments with ordinary and slackened foils to compare the lifetimes during ion bombardment and to test the feasibility of slackened foils in various applications. When 225 keV N$^+$ ions are used (beam current 1.5 μA) the lifetime of slackened foils exceeds that of ordinary foils by about a factor of 3 (9% relative slackening) or 5–6 (15% relative slackening). This fact makes the slackened foils attractive in beam-foil spectroscopy experiments, particularly when foil breakage is a significant problem, i.e., in the case of heavier ions. From detailed comparisons we conclude that slackened foils are very useful in spectroscopic and meanlife studies, being superior to ordinary foils whenever high beam currents or long recording time are needed, for instance in measuring very weak lines or performing work at high spectral resolution.

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only use "meanlife" for the atomic case whereas the word "lifetime" refers to foil degradation under ion bombardment.

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