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Abstract. Xenon ions are present in stellar atmospheres and in astrophysically interesting plasmas on the ground. Atomic spectra of xenon ions induced by the beam-foil interaction have been recorded in the far-ultraviolet region between 30 and 120 nm. From the relative intensities of Xe \textsc{ii} to Xe \textsc{x} lines that appear in our spectra, we have deduced the first experimental charge state distribution of xenon ions at the exit of a carbon foil target for energies ranging from 0.2 to 1.9 MeV. Our results differ from the predictions of different theoretical models and indicate that xenon is two times easier to ionize than what was predicted by existing models.

1. Introduction

Xenon ions are present in stellar atmospheres and in astrophysically interesting plasmas on the ground. The ionization rate of xenon ions in a hot plasma is directly related to its temperature and that process is itself closely related to the charge state distribution of a xenon beam in matter or gas. In this paper we report measurements of charge state distributions of xenon ions interacting with a solid carbon foil. No previous measurement exists for xenon in the energy range considered in this paper.

Several models have been proposed to describe equilibrium charge state fractions of heavy ions having passed through a solid. At low and medium energies, the Gaussian model of Bell [1] does not correctly describe the data [2], and it has been shown that the \( \chi \)-square model of Baudinet-Robinet et al. [3] is better suited [4]. The complicated expressions proposed in [2] fit well the large data set considered by the authors but, as they are based on polynomial fits, the parameters cannot be easily interpreted.

In this paper we have used an analytical model derived from the \( \chi \)-square model that is better suited to fitting the new data. With that model, the fraction of charge state \( i \), \( Q_i \), is given as a function of the emergent ion energy \( E \) by the relation

\[
Q_i(E) = A_i \left[ \frac{E}{m_i} e^{\left(1 - \frac{E}{m_i}\right)} \right] \left(\frac{m_i}{\sigma}\right)^2
\]  

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The charge state fraction, \( Q \), may be described by the distribution \( Q(E) = \alpha E^n e^{-kE} \). The maximum, \( \alpha \left(\frac{m}{\sigma}\right)^n \), of that distribution is reached when \( E = \frac{m}{k} \) and the distribution width, \( \sigma \), is given by \( \frac{m}{\sigma} \). By setting \( m = \frac{1}{k} \) and \( A = \alpha \left(\frac{m}{\sigma}\right)^n \), we deduce relation (1).
That expression only depends for each $i$ on three parameters that have direct physical meaning: the maximum amplitude of the distribution $A_i$, the position of its maximum $m_i$ and the width of the distribution $\sigma_i$. Moreover, as the maximum and the width vary slowly with the energy, it is possible to easily compute the experimental mean charge and the standard deviation of the charge state distribution.

2. Experiment

The charge state fractions of an ion beam travelling through a solid target reach very rapidly an equilibrium that is only dependent on the ion speed (or energy) and the target material [5, 6]. For xenon ions of a few MeV in carbon the equilibrium is always reached after less than 2 $\mu$g/cm$^2$ of carbon [6]. Different techniques have been used to measure charge state fractions at the exit of a solid target. An electrostatic or magnetic analyzer that separates the different charges allows to measure the charge fractions at different beam energies [4, 7, 8, 9, 10, 11, 12]. It is well known [13] that the excitation functions of all terms within a given charge state follow closely the probability of that charge state being formed. Thus, the beam-foil line intensity varies as a function of the beam energy and that variation is strictly correlated with the charge fraction of the ion from which the line is issued [3, 14, 15] so that it is possible to deduce relative charge state fractions from spectroscopic measurements.

Charge state fraction measurements for xenon were obtained from beam-foil line intensity measurements. A $\text{Xe}^+$ beam of $\sim 0.15 \mu$A was produced by the 2 MeV Van de Graaff accelerator of Liège equipped with a RF source. The beam was projected through a thin home-made foil of carbon ($\sim 20 \mu$g/cm$^2$) having a diameter of 6 mm. The light produced by the beam-foil interaction was observed at right angle with a Seya-Namioka type spectrometer equipped with a 1 m radius 1200 l/mm concave grating coated with platinum for improved reflectivity in the ultraviolet. The line width (FWHM) was about 0.12 nm (slit width 120 $\mu$m). With this mounting, the efficiency of the grating has its maximum around 60 nm. The width of the portion of the ion beam (diameter 5 mm) viewed by the spectrometer was 0.15 mm corresponding to a time resolution of 0.1 ns for 1 MeV xenon. To measure the weak signal, the exit slit was removed and replaced by a thin, back-illuminated, liquid nitrogen cooled CCD detector specially developed for far-ultraviolet measurements. The CCD was tilted to an angle of 125$^\circ$ relative to the spectrometer exit arm axis in order to be tangential to the Rowland circle. Under that geometry, it has a dispersion of 0.02 nm/pixel and detects light over a 20 nm wide region with a fairly constant resolution. The CCD detector system was supplied by the Universities of Leicester and Lund. It is based on a EEV CCD15-11 chip of 27.6x6.9 mm$^2$ (1040x280 of 27x27 $\mu$m square pixels) specially conditioned for UV light detection [16, 17]. The CCD images were transferred to a networked computer and analyzed by a specially written software. The XY image was transformed by binning the horizontal lines into a file containing a list of numbers representing the light intensity as a function of the wavelength. The calibration of the spectra and the identification of the lines were based mainly on the recent compilation of xenon lines [18], available also on the NIST web site [19]. The light measurements were normalized to a fixed amount of charge entering the electrically isolated excitation chamber acting as a Faraday cup. The current was measured with an Ortec 439 current digitizer, and the chamber was held to a potential of +90V to reduce secondary electron loss through the chamber apertures. The whole system worked under vacuum ($10^{-5}$ Torr). The line intensities have been measured by recording spectra at different energies. To evaluate a line intensity, the portion of the CCD spectrum surrounding the line was fitted with a Gaussian in order to subtract the background, and the amplitude of the Gaussian was used as a measurement of the line intensity. As the foil was moved 0.2 mm upstream from “zero” position (to reduce the possible influence of foil surface irregularity) the intensity at the foil exit was calculated by extrapolating the measured intensity at 0.2 mm to the “zero” position along the observed decay curve recorded at 1 MeV
and corrected for other energies by a speed factor (see [15] for a description of the method).

The decay curves have been obtained by moving the foil target upstream along the ion-beam path. The displacement of the foil was measured with a resolution of 10 µm by a digital gauge (Mitutoyo 5 MQ65-5P). For a 1 MeV xenon beam, a speed of 1.15 mm/ns was used to convert all the distances to time (the energy loss inside the foil has been deduced [20]). The decay data were fitted with a model describing the whole curve as a growing part (close to the foil) followed by a multi-exponential decay to take into account the possible cascading process.

3. Results and discussion

For each charge state, the intensity of strong and well separated lines appearing in our spectra has been measured at different energies. The data have been corrected to get the relative charge state fraction at the exit of the foil, and these values have been fitted by the function describing the data (see (1)). Typical results are presented in Fig. 1 for lines of Xe II to Xe IX. In Table 1, the fitted values of $m_i$ and $\sigma_i$ are given for 19 lines. $T$ is derived from the slope of the decay curve recorded at 1 MeV. That value, which is related to the lifetime of the upper level of the considered transition, has been used to calculate the intensity at the exit of the foil.

| charge state $i$ | wavelength (nm) | $m_i$ (MeV) | $\sigma_i$ (MeV) | $T$ (ns) |
|-----------------|-----------------|------------|-----------------|--------|
| II              | 97.28           | 0.28       | 0.13            | 1.2    |
| II              | 105.19          | 0.28       | 0.13            | 0.73   |
| III             | 71.97           | 0.32       | 0.17            | 0.16   |
| III             | 77.91           | 0.42       | 0.21            | 0.25   |
| IV              | 61.40           | 0.66       | 0.51            | 0.08   |
| IV              | 62.65           | 0.63       | 0.33            | 0.12   |
| IV              | 64.75           | 0.57       | 0.34            | 0.16   |
| V               | 83.00           | 0.82       | 0.45            | 0.25   |
| VI              | 44.75           | 1.23       | 0.51            | 0.17   |
| VI              | 48.10           | 1.20       | 0.54            | 0.17   |
| VI              | 59.98           | 1.17       | 0.58            | 0.10   |
| VII             | 41.06bl         | 1.55       | 0.70            | 0.10   |
| VII             | 41.47           | 1.55       | 0.70            | 0.10   |
| VII             | 52.18           | 1.54       | 0.75            | 0.10   |
| VII             | 56.60           | 1.59       | 0.66            | 0.14   |
| VIII            | 56.25           | 1.90       | 0.66            | 0.14   |
| VIII            | 74.05           | 1.87       | 0.78            | 0.14   |
| IX              | 47.73           | 2.7        | 1.05            | 0.07   |
| IX              | 51.58           | 2.6        | 1.28            | 0.17   |

The values of $m_i$ quoted in Table 1 are very well described by the expression:

$$m_i = (0.0324 \pm 0.0005) \ i^2.$$  \hspace{1cm} (2)

A good approximation for $\sigma_i$, which increases slowly with $i$, is given by:

$$\sigma_i = (0.12 \pm 0.04) + (0.012 \pm 0.001) \ i^2.$$  \hspace{1cm} (3)
Figure 1. Line intensity variation of Xe lines issued from charge state II to IX as a function of the beam energy. The solid line is the best fit using (1).
From our measurements it is also possible to deduce the mean charge of a xenon beam at the exit of a carbon foil. The detail of the procedure is explained in [4]. For each energy:

$$\sum_i Q_i(E) = 1.$$  \hfill (4)

From the charge state fraction $Q_i(E)$ for charge $i$, the mean charge $\overline{Q}$ is defined as:

$$\overline{Q}(E) = \sum_i Q_i(E) i,$$  \hfill (5)

and its distribution width as

$$d(E) = \sqrt{\sum_i Q_i(E) [Q_i(E) - \overline{Q}(E)]^2}.$$  \hfill (6)

These values have been computed from our measurements as explained in [4] and we have obtained the following relations ($E$ in MeV):

$$\overline{Q}(E) = (5.30 \pm 0.07) E^{(0.58 \pm 0.02)}$$  \hfill (7)

$$d(E) \simeq (0.48 \pm 0.02) E^{(0.84 \pm 0.1)}.$$  \hfill (8)

Our results can be compared with two semi-empirical model predictions for the mean charge. From [21] one gets $\overline{Q}(E) = 2.44 E^{0.50}$ and from [2] $\overline{Q}(E) = 2.97 E^{0.5359}$. Those propositions differ strongly from our experimentally determined value. We conclude that xenon is easier to ionize than predicted by existing models. No simple explanation could be given to explain that behavior even if oscillations of the mean charge of ions in the solid have been observed [6, 22].

4. Summary

We have measured for the first time the charge state distributions of xenon ions in a carbon foil. Our values have been deduced from beam-foil population measurements at energies ranging from 0.2 to 1.9 MeV. We have verified that the $\chi$-square model describes our data very well. The expression for the mean charge of a xenon beam at the exit of a carbon foil deduced from our measurements indicates that xenon is almost two times easier to ionize than predicted by existing models.

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