A temperature dependent X-ray absorption characterization of test filters for the ATHENA mission X-IFU instrument

Luisa Sciortino*[1], Ugo Lo Cicero[2], Salvatore Ferruggia Bonura[1,2], Elena Magnano[3,4], Stefano Nannarone[3], Konstantin Koshmak[3], and Marco Barbera[1, 2].

1 Università degli Studi di Palermo, Dipartimento di Fisica e Chimica, Palermo, Italy
2 INAF, Osservatorio Astronomico di Palermo G.S. Vaiana, Palermo, Italy
3 IOM-CNR, Trieste, Italy
4 Department of Physics, University of Johannesburg, PO Box 524, Auckland Park, 2006, Johannesburg, South Africa

Abstract In order to work properly, the X-ray Integral Field Unit of the ATHENA mission requires a set of thermal filters that block the infrared radiation, preventing it to reach the detector. Each filter will be mounted and thermally anchored onto a shield of the multistage cryostat and will be kept at the specific temperature of the stage. On the other hand, the filters partially absorb X-rays, and their transmittance has to be carefully characterized. The effect of temperature on the absorption edges of the elements that make up the filters has not been investigated yet. Here, we report the results of a preliminary run on the optical transmission data around the edges of C, N, and O at different temperatures for a selected test sample with 500 nm of polyimide and 100 nm of aluminum.

Keywords ATHENA • thermal filters • K-edge • X-IFU

1 Introduction

The ATHENA mission [1] will be a large X-ray space observatory that will offer both spatially resolved X-ray spectroscopy and deep wide field X-ray spectral imaging necessary to address the ESA science theme "Hot and Energetic Universe". Such a mission will greatly exceed the performances of the current X-ray observatories like Chandra [2] and XMM-Newton [3].

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The Athena spacecraft will be equipped with three key elements: a X-ray telescope with a focal length of 12 m and an effective area of ~ 2 m^2 at 1 keV, a Wide Field Imager (WFI) for large field of view imaging with moderate spectroscopic resolution [4], and a high spectral resolution energy dispersive instrument named X-ray Integral Field Unit (X-IFU) [5].

The X-IFU detector is a large array of Transition-Edge Sensor microcalorimeters that will be sensitive in the 0.2 keV - 12 keV energy range, with 2.5 eV energy resolution at 7 keV. To achieve such a high-energy resolution the detector operates at ~ 50 mK inside a sophisticated multistage cryostat, and requires a set of filter filters to attenuate the infrared (IR) radiative heat load onto the microcalorimeters and thus avoid energy resolution degradation due to photon shot noise, in this context we refer to the filters as thermal filters (TF). The TF will close the X-ray entrance aperture in the cryostat thermal shields and thus shall be highly transparent in X-rays. The choice of polyimide and aluminum as the current selected filter materials to achieve good IR reflection, high X-ray transmission, and good mechanical properties [6] comes from the experience of previous X-ray missions such as Chandra and Astro-H. Beside playing a crucial role in the reduction of the thermal load onto the low temperature detector, the filters provide protection from low energy particles and contamination.

The chemical elements (C, N, O, and Al) that make up the filters show X-ray absorption edges in the X-IFU energy range [7, 8]. The oscillations above the edges may be sensitive to the changes of temperature [9, 10]. Since the X-IFU will have a high spectroscopic resolution, a detailed understanding of the change in filter transmission with temperature is mandatory to formulate a robust calibration plan. Performing high spectral resolution transmission measurements of thin filters at very low temperatures is not straightforward. Here, we present preliminary measurements of the K-edge of the C, N, and O elements on a test filter in the soft X-ray energy range at two different temperatures, ~230 K and 300 K, here named low temperature (LT) room temperature (RT), respectively.

2 Materials and methods

Polyimide provides mechanical support to the aluminum thin film which is highly reflective in the IR, furthermore, being made of light elements allows to achieve a high X-ray transmission.

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We purchased a prototype test filter by LUXEL Corporation consisting of a polyimide membrane with nominal thickness of 500 nm coated by an aluminum (purity 99.999%) film, with nominal thickness of 100 nm. The filter is provided by the company mounted on an anodized aluminum frame.

A measurement campaign was performed at the IOM-CNR BEAR beamline [11] at the Elettra synchrotron (Trieste, Italy) in the 40 eV - 1470 eV in transmission geometry at normal incidence at basic pressure ~ 10^{-8} mbar (the residual gas is mainly composed by H_2 and water). The water condensation on the filter cannot be excluded, though it was not experimentally evaluated.

Here, we present only preliminary results of X-ray transmission around C, N, and O K-edges. The full range data will be presented in a forthcoming paper [ref. L. Sciortino et al. to be published]

The monochromator exit slit was set at 400 μm width providing a photon energy resolution E/ΔE ≈ 2000. The detector is a photodiode SXUV100 (8x8mm^2 active area) that is located at 160 mm from the focal point. The beam spot on the sample is 500x500 μm^2 (vertical x horizontal)

The transmission at a given energy was calculated according to the following expression:

$$T(\hbar\omega) = \frac{I(t1)(\hbar\omega) - I_d(t2)(\hbar\omega)}{\mathrm{I}_m(t1)(\hbar\omega) - I_{md}(t2)(\hbar\omega)} * \frac{I_{0m}(t3)(\hbar\omega) - I_{0md}(t4)(\hbar\omega)}{I_0(t3)(\hbar\omega) - I_{0d}(t4)(\hbar\omega)}$$

where I(t1) ($\hbar\omega$) and I_m(t1)($\hbar\omega$) are the sample transmitted current and the monitor current measured at time t1 with the shutter open and I_d(t2)($\hbar\omega$) and I_{md}(t2)($\hbar\omega$) are the relative dark currents measured at time t2 with the shutter closed; I_0(t3)($\hbar\omega$) and I_{0m}(t3)($\hbar\omega$) are the currents measured after removing the sample at time t3 and I_{0d}(t4)($\hbar\omega$) and I_{0md}(t4)($\hbar\omega$) are the relative dark currents measured at time t4.

In order to reduce the contribution of monochromator higher orders different setting (inclusion angle) of the optics of the plane-mirror-plane-grating monochromator were used together with a suite of filters according to the photon energy range. Different step sizes were used in the near edges regions according to the sharpness of the features (from 10 to 40 meV). Far from the edges a step size of 1 eV was used. The accuracy is of the order of 0.5 % over all the considered energy range. The evaluation of the error bar depends on the error on the eight quantities appearing in the expression of transmission. The measurements were carried on at RT (300 K) and at LT (~230 K). Sample was cooled down connecting the sample carrier through a copper braid to liquid nitrogen cooled cold finger (90 K). Sample carrier

temperature was calibrated off measurement run by a thermocouple and a Pt100 obtaining temperature values in the range from 120-190 K. The spread supposed to depend on the non-reproducibility of the carrier's thermal insulation from ground an aspect to be improved in the following runs. The sample is placed out of focus in order to avoid any radiation damage and moreover the defocusing allows investigating a larger area of the sample resulting in a spatially averaging of the obtained spectra.

3 Results and Discussion

In the current instrument baseline, five filters are expected to be used at five different temperatures corresponding to the cryostat shields temperatures of 300 K, 100 K, 30 K, 2 K, and 0.05 K [12]. In the current design each filter consists of a thin polyimide membrane (~ 45 nm thick) coated with aluminum film (~ 30 nm thick) attached to a hexagonal metallic mesh acting both as mechanical support and as radiofrequency attenuator [13].

To enhance any possible temperature effects, we employ a test specimen thicker than a baseline flight filter. Although such a sample is not fully representative, a larger thickness enhances the eventual changes in the transmission at energies close to the absorption edges since there are a larger number of absorbers (i.e. atoms) than in a thinner filter. The measured K-edges with the error bars of carbon, nitrogen, and oxygen at RT and LT are shown in figures 1, 2, and 3, respectively.

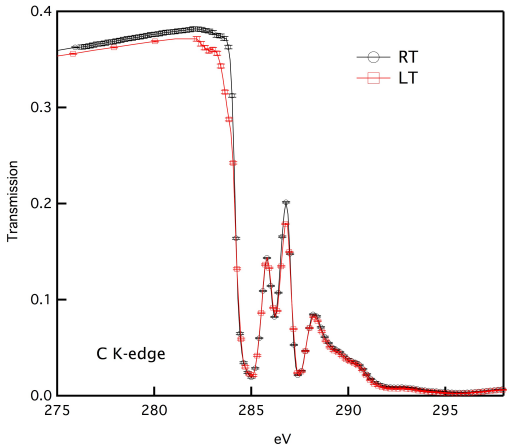

Fig. 1 Carbon K edge at two different temperatures: RT (*black circle and line*), and LT (*red squares and line*), the error bars are included. (Color figure online)

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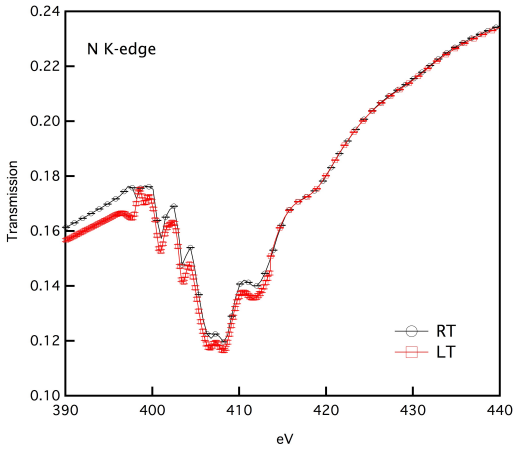

Fig. 2 Nitrogen K edge at two different temperatures: RT (*black circle and line*), and LT (*red squares and line)*, the error bars are included. (Color figure online)

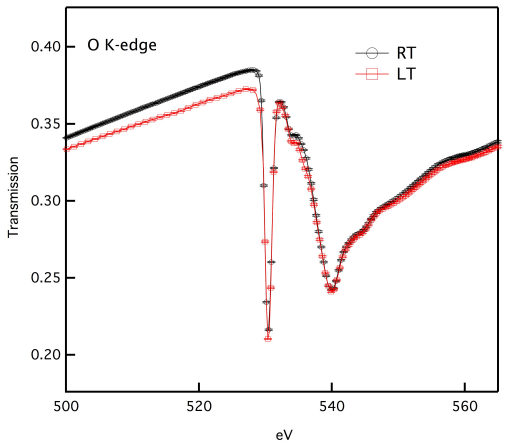

Fig. 3 Oxygen K edge at two different temperatures: RT (*black circle and line*), and LT (*red squares and line*), the error bars are included. (Color figure online).

Each edge is marked by a characteristic structure that is distinctive of the chemical state and the local geometry of the absorbing element. As expected most features of the showed spectra in figures 1, 2, and 3 are not modified by the change of temperature up to LT, meaning that there are no chemical transformations of the analyzed materials. Nevertheless, some

slight differences are noticeable between the two investigated temperatures, in particular in the pre-edge region of the K-edges. A reliable hypothesis may be the contamination by the residual water in the measurement chamber. Water condensation on the filter during low temperature measurements cannot be excluded. Consequently, this evidence, though preliminary, requires an in-depth study to verify if the same trend is valid at lower temperatures.

Considering that the thermal filters used for the X-IFU will be significantly thinner than the investigated sample, the preliminary results suggest that a reliable transmission of such a type of filters when operating at low temperatures might be carried out at room temperature by a correction algorithm derived by the temperature behavior of present or similar data. According to the Beer-Lambert's law the transmission decreases with an increasing number of absorbers, then, in principle, we can obtain a coefficient for the change of oscillation intensity for the investigated range of temperature, even though the edge structure might be slightly different for a thin film of 500 nm and a thin film of 100 nm because of a different degree of oxidation.

Summing up we demonstrated that a campaign to measure accurately C, N, and O K-edge can be carried out decreasing the temperature in vacuum. Our data suggest to perform new transmission measurements of filters in the low energy region (below 1500 eV) at even lower temperatures to verify if the reduction of transmission at decreasing temperature is confirmed. We point out that the slight decrease of X-transmission measured at lower temperature might be due to water contamination, and thus this contribution must be studied and quantified in more details in future experiments. The future measurements will be performed at least at 100 K and 30 K although we aim to perform further campaigns down to 10 K.

Acknowledgements
The research leading to these results has received funding from ASI (Italian Space Agency) through the Contract n. 2015-046-R.0 and from the European Union's Horizon 2020 Program under the AHEAD project (grant agreement n. 654215). Angelo Giglia and Javid Rezvani are acknowledged for their assistance in transmission measurements and useful discussions. Igor Píš is acknowledged for his contribution to the experimental set up. Federico Salvador is acknowledged for the fabrication of the sampleholder.

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