X-ray Emission from Charge Exchange of Highly-Charged Ions in Atoms and Molecules

J. B. Greenwood[1], I. D. Williams[1], S. J. Smith[2], and A. Chutjian[2]

[1] Physics Department, The Queen's University of Belfast, Belfast BT7 1NN, UK

[2] Atomic and Molecular Collisions Team, Jet Propulsion Laboratory/Caltech, Pasadena CA 91109

Abstract

Charge exchange followed by radiative stabilization are the main processes responsible for the recent observations of X-ray emission from comets in their approach to the Sun. A new apparatus was constructed at JPL to measure, in collisions of HCIs with atoms and molecules, (**a**) absolute cross sections for single and multiple charge exchange, and (**b**) normalized X-ray emission cross sections. The ions are produced by the JPL HCI Facility and passed through a neutral-gas target cell. The product charge states are analyzed by a retarding potential difference technique. Results are made absolute by measuring target pressure, and incident and product ion currents. X-rays emitted from the product ions are detected with a Ge solid-state detector having a resolution of approximately 100 eV. X-ray astronomy has taken major steps forward with the recent launch of the high-resolution satellites *Chandra* and *Newton*. The cross sections reported herein are essential for the development of the solar wind – comet interaction models inspired by these observations.

email addresses: j.greenwood@qub.ac.uk i.williams@qub.ac.uk steven.j.smith@jpl.nasa.gov a.chutjian@jpl.nasa.gov

1. Introduction

The discovery of X-ray emissions from comet Hyakutake by Lisse *et al.* [1] has initiated a fascinating field of X-ray spectroscopy through new observations using the *Chandra* and *Newton* X-ray orbiting spectrometers. The origin of the emissions was proposed by Cravens [2,3] to arise from charge-exchange of solar-wind ions (such as high charge states of C, N, O, Ne, Si, and Fe) with the comet's neutral gases, resulting in radiative cascading. Some of these neutral species are H_2, CO, H_2O and CO_2, and they are vaporized from the comet surface by solar sputtering and heating as the comet nears the Sun. Hence, one of the important quantities needed for modeling of the satellite-observed intensity and spectrum of the X-ray emissions are absolute charge-exchange cross sections for single and multiple electron transfer between the comet neutral species, and the major and minor components of the solar wind [4].

A new beam line was constructed at the JPL HCI Facility to measure both absolute charge-exchange cross sections for HCIs with neutral species; as well as the resultant spectrum of Lyman X-rays emitted in the collision. The experiment has been described previously [5,6]. By normalizing the X-ray emissions to the total cross sections, one may also obtain cross sections for the line emissions. The relative intensities of the X-ray transitions were also used to derive information about the initial distribution of the electron capture within *nl* levels.

For estimating HCI-neutral charge exchange cross sections in laboratory and astrophysical plasma it is often convenient to use the classical over-barrier model (OBM) [7,8]. The model also determines the principal quantum number *n* of the level into which charge exchange occurs. This information has been used to produce a synthetic spectrum of the X-rays from 1996 comet Hyakutake [9]. However, electron capture does not occur into a unique *n* level [10,11]. The OBM also gives no information on the detailed distribution of l states, but one may obtain an average angular momentum value $\langle l \rangle$ given by $\langle l \rangle = mvR$ (here, m is the electron mass, v the projectile-target velocity, and R the capture radius). This information is necessary to determine cross sections of photon emission from the excited product ion.

There are other aspects of charge exchange that can have a significant effect on the intensity of line emission from plasmas. Multiple charge-exchange cross sections can be large relative to single exchange [12], there are wide variations in the ratio of autoionization to radiative stabilization following multiple capture [13], and alignment of the excited states causes the emission to be non-isotropic [14]. For instance, in space observations from a comet, the sun-comet-earth angle can affect the intensity of the observed X-ray radiation.

2. Experimental Methods

Highly charged ions of charge state q are extracted from an electron-cyclotron resonance ion source at energy of $7q$ keV [15]. The desired mass/charge is selected by a high-resolution 90° double-focusing bending magnet. Isotopically enhanced gases are used to ensure that fully-stripped ions of C, N, O and Ne are well separated from the ever-present H_2^+ ion. The selected HCI beam is then electrostatically deflected into the charge-exchange beamline. There, it is collimated by a series of narrow apertures, and enters a collision cell with the gas target. The pressure inside the cell is determined with a temperature-stabilized capacitance manometer. It was kept low enough (typically less than 10^{-4} mbar) so that there was less than a 2% conversion of the primary beam to product ions, hence multiple collisions or extra-cell collisions could be neglected. The primary ion beam current is measured in a deep Faraday cup. To measure the current of ions undergoing charge exchange, a reflecting potential is used to remove the primary ions. By increasing this reflecting potential the current produced in single, double, and higher exchanges can be measured. We note that with this method one measures a final single- or double-capture cross section which may be the result of both true direct capture, as well as multiple captures followed by autoionization.

A high-purity Ge crystal detector with large viewing solid angle is used to detect the spectrum of X-rays emitted at 90° to the incident HCI beam. A 7.5 μm-thick Be window separates the collision cell from the detector, and transmits X-rays of energy greater than about 500 eV.

3. Results

Shown in Fig. 1 are single charge-exchange cross sections as a function of charge state q for collisions in H_2O. These results are compared with predictions of the OBM. The discontinuities in the OBM are a result of a change in n level into which capture occurs. It can be seen that there is an overestimation of the cross sections by a factor of two to three. As there is no such structure in the measurements, this indicates that the capture is probably distributed among a number of n levels. As H_2O is a major constituent of comets, these results are important in analyzing the X-ray spectral emission intensity in the solar-wind interaction with comets.

X-ray spectra, uncorrected for transmission of the Be window of the detector, are shown in Figs. 2 and 3. The spectra were fitted with Gaussian profiles. They represent transitions to the ground state of the $q-1$ ion from np levels. It can be seen that the Ly-α $2p \rightarrow 1s$ transition has the greatest intensity, having been populated entirely by cascades from higher levels. Collisions of Ne^{10+} in H_2O demonstrate the existence of Ne^{8+} transitions generated from radiative stabilization of double capture, or autoionization following triple capture. Detector-corrected X-ray cross sections will be reported in a subsequent publication [16].

The relative intensities of the transitions are seen to change, depending on the target. This indicates that capture is occurring into different *nl* levels. From analysis of the branching ratios for an H-like ion it is clear that capture into states with higher *l* tends to result in population of the *2p* level, thus strengthening the Ly-α line. However, our results indicate that the intensity of the Ly-α lines is less than that expected from the assumption that the *l* levels are statistically populated. We find from Fig. 3 that the average value of the initial capture state $\langle l \rangle$ for O^{8+} is about 1.8, compared to a value 2.8 expected from statistical capture into $n= 5$. This result is broadly in agreement with the findings of Burgdörfer *et al.* [17] who developed the OBM to include effects of the classical angular momentum barrier of the captured electron with respect to the projectile. At our collision velocity of 0.35 au there is insufficient angular momentum for the electron to be captured into states with large *l*. It has been pointed out by Vernhet *et al.* [18] that the relative intensities of the Ly-α,β,γ transitions depend only on $\langle l \rangle$. We also point out that the process of multiple capture followed by autoionization could alter the relative intensities, with a tendency to enhance the Ly-α transition, hence lowering $\langle l \rangle$ even further [16].

In summary, we have demonstrated the ability to accurately measure total cross sections for charge exchange. Our results indicate that the OBM is not a reliable predictor of cross sections for charge exchange. The X-ray spectra show that Ly-α transitions dominate the X-ray emission; and that the relative intensities of these lines can be used to derive qualitative information on the initial *l* distribution. Because relative intensities of the Ly transitions generated by cascades are sensitive only to the average transferred angular momentum $\langle l \rangle$, the model of Ref. [17] could be a useful tool to help estimate X-ray line-emission cross sections. These data can be used in conjunction with laboratory X-ray emission spectra to obtain X-ray emission cross sections, in systems that are relevant to *cometary* charge-exchange and X-ray emission modeling. In addition, they may be used to model *other* astrophysical systems (such as planetary atmospheres, and circumstellar clouds) wherein solar or stellar winds may impinge on relatively dense atmospheres or plasma clouds.

Acknowledgments

This work was carried out at the Jet propulsion Laboratory, California Institute of Technology, ~~and was funded by~~ under a contract with the National Aeronautics and Space Administration.

References

[1] Lisse, C. M. *et al.,* Science, **274**, 205 (1996).

[2] Cravens, T. E., Geophys. Res. Letters, **24**, 105 (1997).

[3] Cravens, T. E., Adv. Space Res., **26**, 1443 (2000).

[4] Bochsler, P., Phys. Scripta, **T18**, 55 (1987).

[5] Greenwood, J. B., Smith, S. J. and Chutjian, A., Astrophys. J., **529**, 605 (2000).

[6] Greenwood, J. B., Williams, I. D., Smith, S. J. and Chutjian, A., Astrophys. J., **533**, L175 (2000).

[7] Ryufuku, H., Sasaki, K. and Watanabe T., Phys. Rev. A, **21**, 745 (1980).

[8] Niehaus, A., J. Phys. B., **19**, 2925 (1986).

[9] Wegmann, R., Schmidt, H. U., Lisse, C. M., Dennerl, K. and Englehauser, J., Planet. Space Sci., **46**, 603 (1998).

[10] Cassimi, A., e*t al*., Phys. Rev. Letters, **76**, 3679 (1996).

[11] Kharchenko, V. and Dalgarno, A., J. Geophys. Res., **105 (A8)**, 18351 (2000).

[12] Sakaue, H. A., *et al*., Physica Scripta, **T73**, 182 (1997).

[13] Martin, S., Bernard, J., Chen, L., Denis, A. and Desesquelles, J., Physica Scripta, **T73**, 149 (1997).

[14] Vernhet, D. *et al.,* Phys. Rev. A, **32**, 1256 (1985).

[15] Chutjian, A., Greenwood, J. B. and Smith, S. J., Applications of Accelerators in Research and Industry (eds. J. L. Duggan and I. L. Morgan, AIP Conf. Proc. 475, New York, 1999) p. 881.

[16] Greenwood, J. B., Williams, I. D., Smith, S. J. and Chutjian, A., unpublished results.

[17] Burgdörfer, J.,Morgenstern, R. and Niehaus, A., J. Physics B, **19**, L507 (1986).

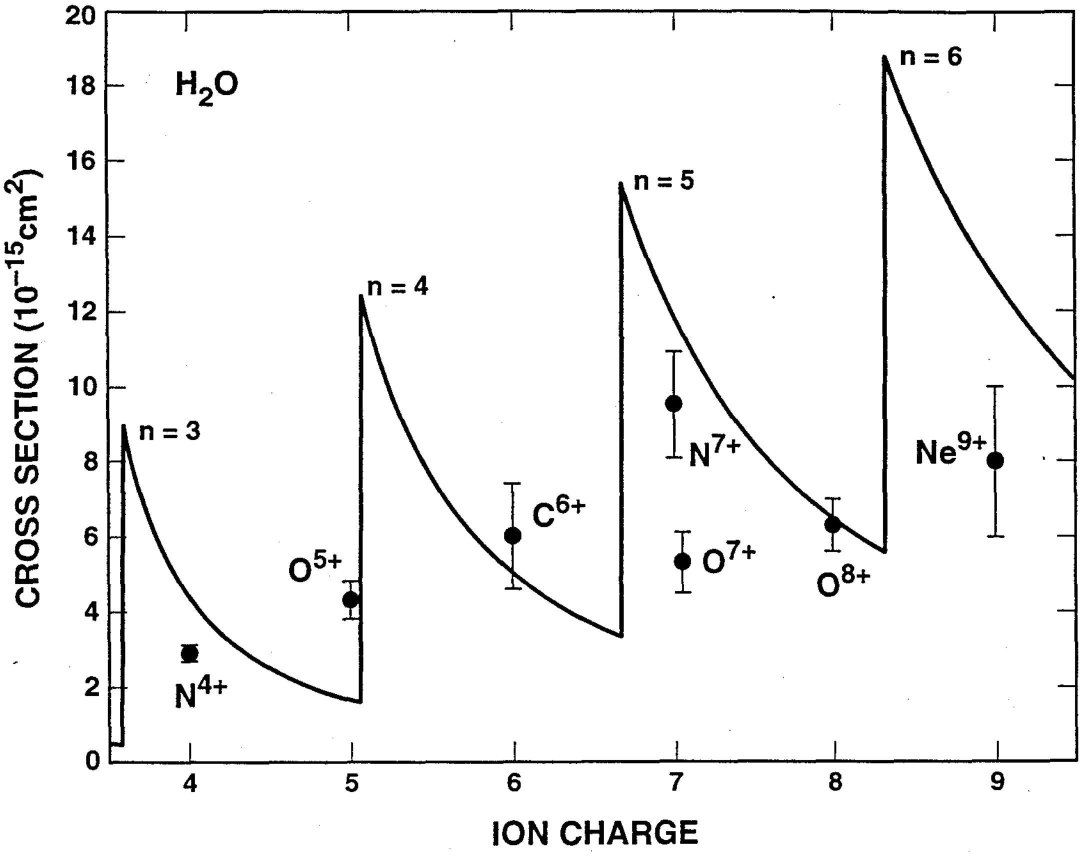
[18] Vernhet, D., *et al.*, J. Physics B, **21**, 1349 (1988).

Figure Captions

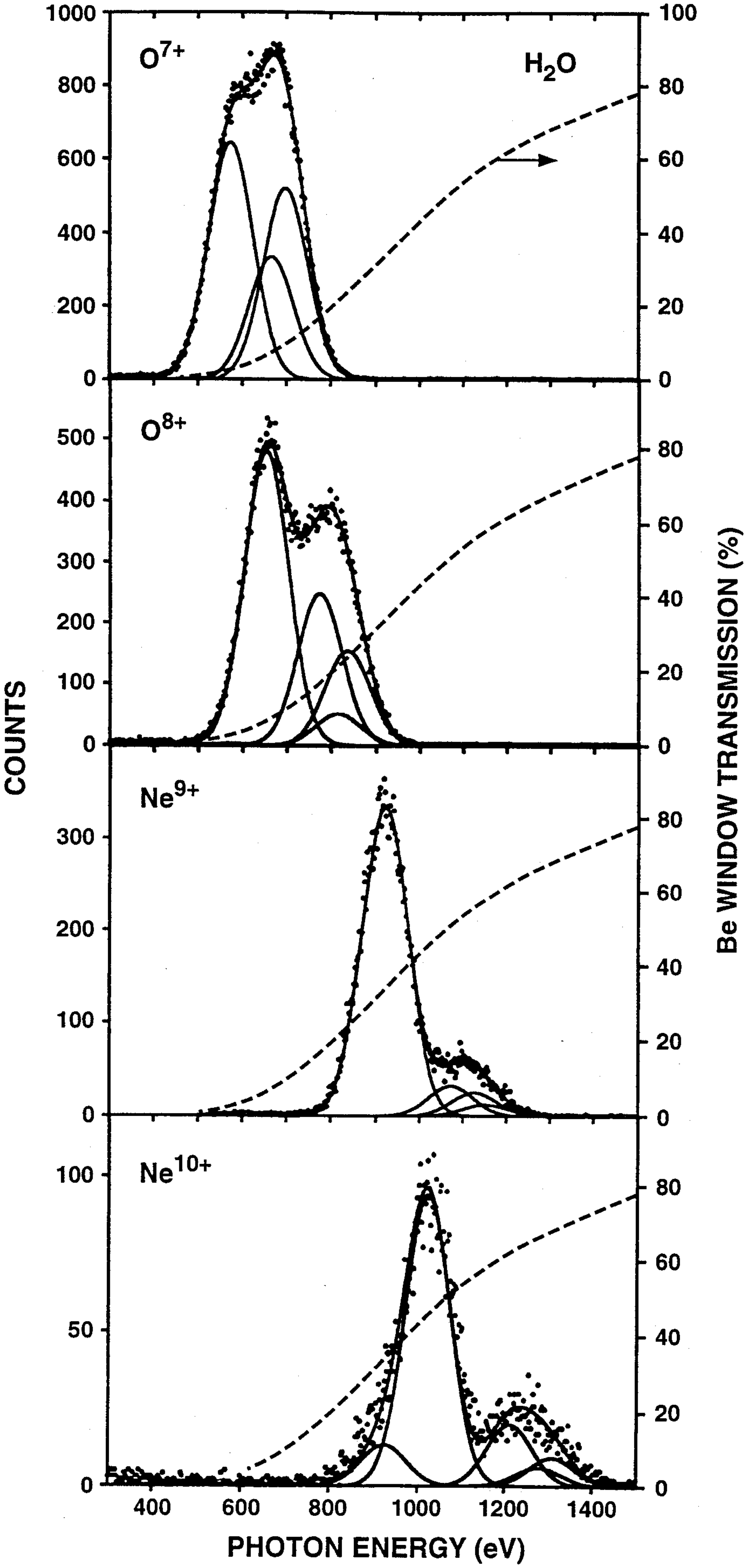
Figure 1 Single charge-exchange cross sections as a function of charge state for collisions in H_2O. Results are compared with predictions of the over-barrier model (solid line) [7].

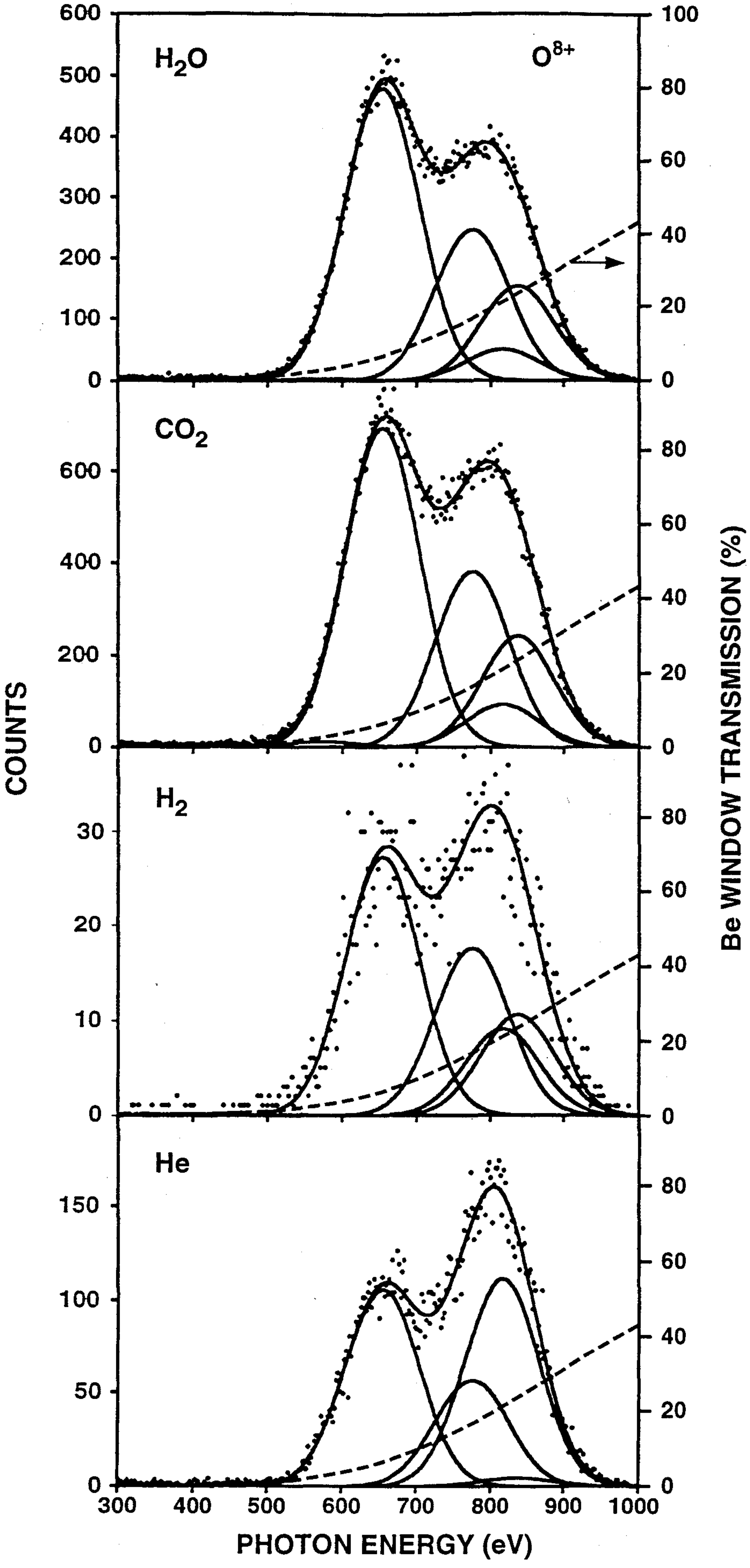
Figure 2 X-ray spectra for collisions in H_2O, uncorrected for the transmission of the Be window on the Ge detector (dashed line). Underlying curves are the Lyman transitions $np \rightarrow 1s$.

Figure 3 X-ray spectra for collisions of O^{8+} in He, H_2, CO_2, and H_2O. Underlying curves are the Lyman transitions $np \rightarrow 1s$.



H$_2$O
CROSS SECTION (10^{-15}cm^2)
ION CHARGE
0
2
4
6
8
10
12
14
16
18
20
4
5
6
7
8
9
n = 3
n = 4
n = 5
n = 6
N^{4+}
O^{5+}
C^{6+}
N^{7+}
O^{7+}
O^{8+}
Ne^{9+}


O7+
H2O
O8+
Ne9+
Ne10+
COUNTS
Be WINDOW TRANSMISSION (%)
PHOTON ENERGY (eV)
1000
800
600
400
200
0
500
400
300
200
100
0
300
200
100
0
100
50
0
100
80
60
40
20
0
400
600
800
1000
1200
1400


H$_2$O
O^{8+}
CO$_2$
H$_2$
He
COUNTS
Be WINDOW TRANSMISSION (%)
PHOTON ENERGY (eV)
0
100
200
300
400
500
600
0
200
400
600
0
10
20
30
0
50
100
150
0
20
40
60
80
100
300
400
500
600
700
800
900
1000