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Scattering of light molecules from Al_2O_3 surfaces

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Abstract

Various light ions were scattered at grazing incidence from a highly polished Al_2O_3 single crystal and from a thin film of Al_2O_3 on graphite. The energy of incident particles was varied from 390 eV to 1200 eV. For scattered positive oxygen and carbon ions, negative ion fractions of up to 14% and 3%, respectively, were recorded. For scattered positive hydrogen ions, the negative ion fractions reached the percent level.

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1. Introduction

The interaction of atomic and molecular particles with insulating surfaces has been researched extensively in recent years [1–10]. Reports of relatively high fractions of negative ions resulting from scattering of positive atomic and molecular ions off insulating surfaces suggested possibilities for several new applications. Among these applications we use this process for efficient detection of 10 eV to 2 keV neutral particles in interplanetary and interstellar space [11–13]. The proof of concept for this detection technique has already been demonstrated in space with the IMAGE satellite mission [14]. The mass spectrograph used there is designed to detect low energy neutral atoms. It uses a conversion surface of volatile adsorbates on a highly polished, polycrystalline tungsten substrate to convert a fraction of the incoming neutral atoms to negatively charged ions [14,15]. For future missions, such as IBEX from NASA or BepiColombo from ESA, diamond-like carbon surfaces will be used as conversion surfaces because of their better long-term stability and higher negative ion yield [9,10]. For technical reasons, the conversion surfaces will be exposed to space from the very beginning of the mission on. During separation of rocket stages, a small amount of Al_2O_3 will be created and might be adsorbed on the spacecraft, including the conversion surfaces. Therefore, as a worst case scenario, we tested a rough film of Al_2O_3 on a graphite substrate for ionization efficiency and scattering properties. We found fractions of negative ions high enough to suggest the use of Al_2O_3 as a possible new material for a conversion surface. Since we observed very broad scattering cones we repeated these measurements with a highly polished Al_2O_3 single crystal.

Since interstellar gas is expected to consist mainly of H and He with traces of O, N, C and Ne [16] we focused our tests on these particles. In the case of hydrogen, molecular ions were used because they can be produced far more efficiently than atomic ions in our test system. The impact of using positively charged molecular ions on the results is discussed in detail below.

The measurements were done at moderate vacuum conditions, i.e. in the low 10^{-7} mbar range, which mirror the conditions within a typical particle sensing satellite instrument shortly after launch. From the European Space Agency's (ESA) ROSETTA mission it is known that several weeks after launch, the pressure in the vicinity of

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the spacecraft drops to the low 10^{-9} mbar range, and into the 10^{-10} mbar range after few months. The pressure inside space instruments with small openings to vent to the outside, such as most particle instruments, is expected to be at least an order of magnitude higher than the pressure outside the spacecraft. Because of internal outgassing, pressures in the 10^{-8} mbar range are expected to persist in space particle instruments more or less indefinitely.

2. Experiment

The surface tested first is a thin film of Al_2O_3 on a graphite substrate. Film thickness is approximately 500 nm, surface roughness a few hundred nm. The second tested surface is a highly polished Al_2O_3 single crystal with random orientation and a surface roughness of nm level.

Measurements were made with the ILENA apparatus at the University of Bern, Switzerland. The setup will be described briefly. More detail on the experimental setup can be found in [11,17]. Fig. 1 displays a sketch of ILENA. It consists of an ion source, a beam-filter and guiding system, a sample stage with housing and a detection unit. All these units are contained in a single vacuum chamber pumped by an ion pump. For the measurements reported here an impact angle of 8° with respect to the surface plane has been chosen. The reflected beam is recorded using a two-dimensional position-sensitive MCP detector with a viewing angle of ±12.5° in both azimuthal and polar directions, as demonstrated in Fig. 2. A retarding potential analyzer (RPA) consisting of three grids is mounted in front of the MCP detector. The detector unit, including the RPA, is shielded electrostatically and can be rotated independently from the converter surface around the same axis. The outer grids of the RPA are grounded to shield the inner grid, which can be biased to suppress positive ions. An additional grid in front of the MCP detector at negative potential with respect to the MCP detector serves to reject secondary electrons originating from the preceding grids and the converter surface. The MCP detector may be floated to a high negative voltage with respect to the converter surface in order to vary the transmission threshold for negative particles. After baking out the vacuum chamber at 80 °C overnight, a residual gas pressure of 5×10^{-8} mbar is achieved. During operation the pressure may rise into the low 10^{-7} mbar range as a result of test gas leaking into the ion source chamber.

The fraction of negative ions is determined by taking measurements with and without an applied floating voltage on the MCP. In the first case, only neutral particles are recorded, in the latter neutral particles and negative ions. The difference gives the fraction of negative ions.

Each data-point results from a series of successive measurements, which allows the detection of possible ion beam instabilities and surface charging during each measurement series. Surface charging was only noticed while scattering from the Al_2O_3 single crystal. The experimental setup was slightly modified to compensate for this effect. With the MCP detector, we cannot distinguish between negatively ionized primary particles and sputtered negative ions. Therefore, measurements with incident positive noble gas ions of comparable mass were done, e.g. Ne^+ for O^+, and the negative ion fractions recorded there were taken as upper limit for the sputtering background of the previous measurements.

The detection efficiency of the MCP is taken from [18,19], where an identical detector was used.

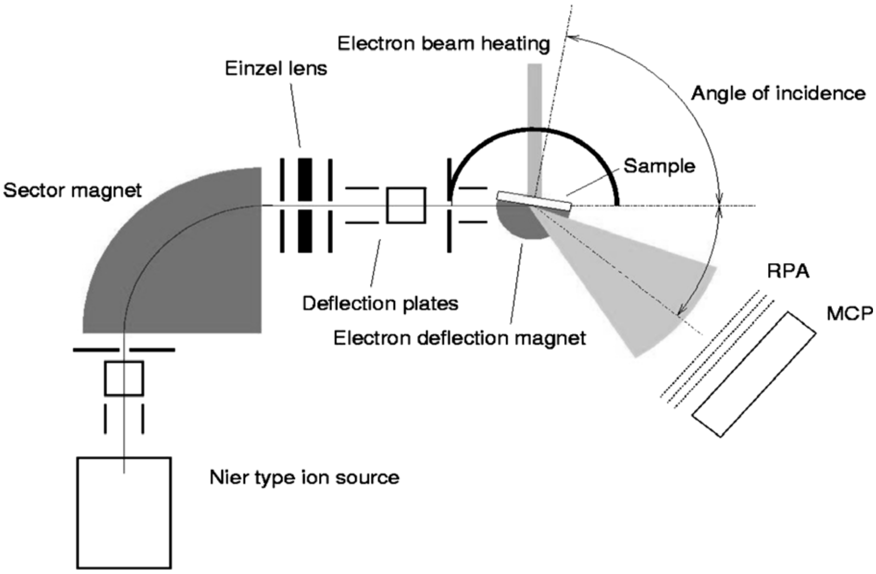

Fig. 1. Schematic representation of the ILENA experiment at the University of Bern. Positive ions are extracted from a Nier type ion source and after being mass-analyzed scattered from a sample-surface under grazing angles of incidence. The distribution of scattered particles gets recorded with an SSL-detector. An electron deflection magnet holds back electrons which are emitted during the scattering process. See text for further details.

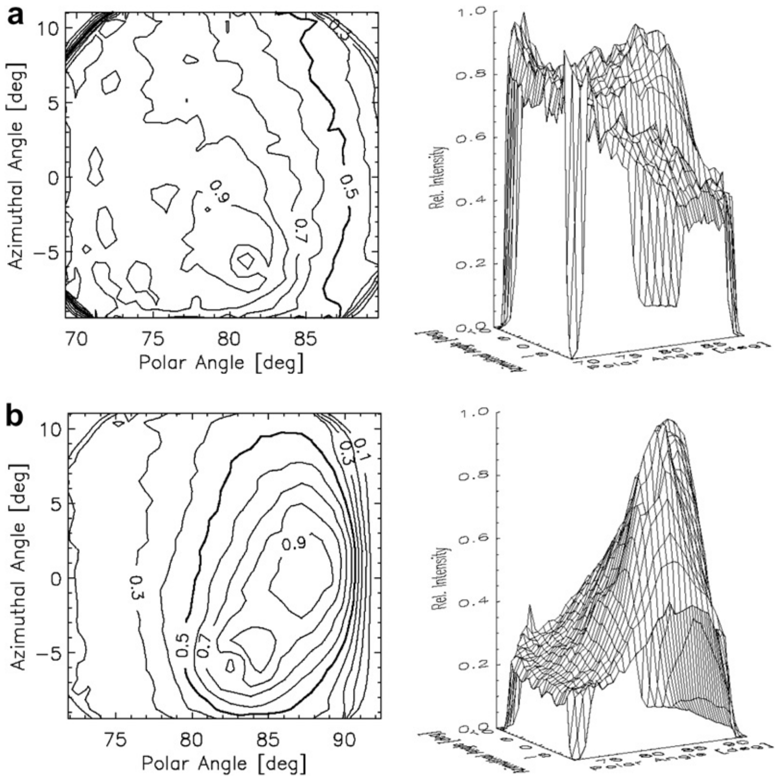

Fig. 2. Comparison of angular scattering distributions of 1000 eV H_2^+ scattered from a thin film (a) and from a single crystal of Al_2O_3 (b). The higher surface roughness of the film causes a broader distribution of scattered particles, which is clearly seen.

3. Results and discussion

Although we eventually want to use neutral atoms to study surface ionization, for the hydrogen measurements we used positive molecular ions because they can be produced far more efficiently, and with much better energy, intensity and angle control in our system than can neutrals. But the charge and mass of the positive molecular ions must be justified.

From previous experiments with several other insulating surfaces (polycrystalline diamond [11], single-crystal diamond [20,21] and MgO [12]) it has been established that incident hydrogen and oxygen ions are effectively neutralized upon scattering. These previous measurements were done with both incident positive ions and with incident neutral particles and they revealed the same negative ion fractions in both cases. As a result, we can assume complete memory loss of the incident charge state after scattering.

The use of molecules instead of atoms is justified as follows. A molecule has many more electronic states than an atom, so we cannot expect the charge exchange process while scattering to be identical. But according to [10,11], more than 80% of molecules with energy in the 300–1000 eV range, when scattered off a polycrystalline diamond surface, dissociate shortly before reaching the surface, on the incoming stage of the trajectory. That means that the final charge state fraction is determined mainly by charge exchange processes between the surface and dissociated atoms. Therefore, we conclude that the use of molecules causes a negligible change to the charge state fractions measured in this study.

3.1. Angular scattering

The two key requirements for successful conversion surface performance in a space instrument are high ionization yield and low angular scattering, the latter to minimize scattered particle loss in downstream detection systems. The component of angular deviation from specular scattering that resides in a plane containing the incoming trajectory and normal to the surface is defined as polar scattering, with zero indicating a true specular reflection. The component of specular scattering normal to the polar angle plane is defined as azimuthal scattering. Fig. 2 shows angular scattering distributions for both surfaces. The observed asymmetric profile is caused by the roughness of the surfaces, which inevitably leads to a certain fraction of scattered particles, which do not undergo specular reflection. As a result, the beam profile is broadened, and the increase of this effect with higher surface roughness is clearly demonstrated. In this example, the FWHM of azimuthal and polar scattering angles of the Al_2O_3 single crystal are 19° and 11°, respectively, whereas for the Al_2O_3 film the FWHM of both the azimuthal and polar scattering angles are outside the detection area. Therefore, only FWHM of scattering angles of the Al_2O_3 single crystal are shown in Fig. 3. The lines indicate the general trend

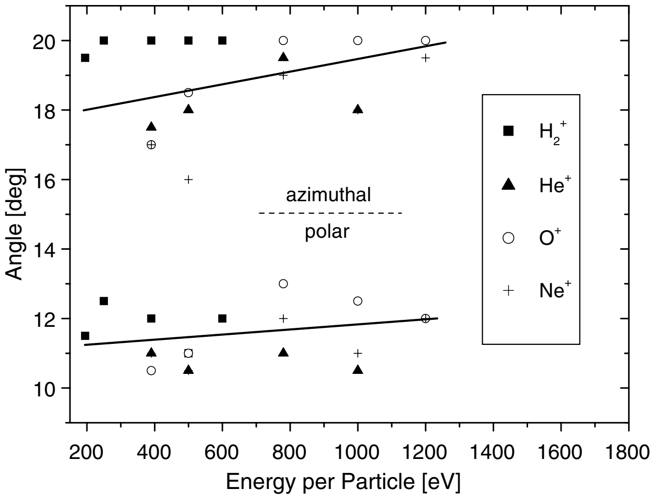

Fig. 3. Energy dependence of FWHM of angular scattering resulting from various positive ions scattered from an Al_2O_3 single crystal. The presented data are FWHM of scattering cones in polar (values smaller than 15°) and azimuthal (values larger than 15°) direction. The lines are to guide the eye.

of increasing angular scattering with increasing incident energy. This trend can be understood because higher particle energies probe the surface potential at deeper levels where the corrugation of the potential is larger, resulting in a larger angular scattering distribution. Moreover, angular scattering in the polar direction is about a factor of two smaller than in the azimuthal direction.

3.2. Ionization yield

Fig. 4 compares the negative charge state fractions measured for scattering of several ions from both surfaces. In the case of oxygen ions scattered from the Al_2O_3 single crystal (Fig. 4(b)) we found increasing negative charge state fractions with increasing energy of the incident ions. Similar findings have been reported for other insulating surfaces like MgO [12], LiF [8] and $BaZrO_3$ [22], and we agree with the interpretation, that higher energies cause smaller distances of closest approach between scattered ions and surface atoms, which results in higher probabilities for charge exchange processes and thus yields higher fractions of negative ions.

The situation is different for oxygen ions scattered off the Al_2O_3 thin film (Fig. 4(a)). Here, within the error bars of ±1%, the negative charge state fractions have a constant value of about 12%. This is explained by the very high surface roughness of this film, which leads to similar distances of closest approach for incident ions within the energy range used here.

For carbon we recorded negative charge state fractions of about 2.5% and for hydrogen about 1.5%. No increase of charge state fraction with increasing energy could be found, which may be caused by the limited resolution of our detection system for low charge state fractions. However, regarding the negative electron affinities of oxygen, carbon and hydrogen, which are 1.46 eV, 1.27 eV and 0.75 eV, respectively, one should expect for higher negative electron affinities higher negative charge state fractions, which explains the higher negative ion yield for oxygen than for hydrogen and can be clearly seen in Fig. 4. Of course, this simple approach does not explain the large difference between oxygen and carbon ions. Detailed quantum mechanical analysis of this topic might be needed, but this is beyond the scope of this paper.

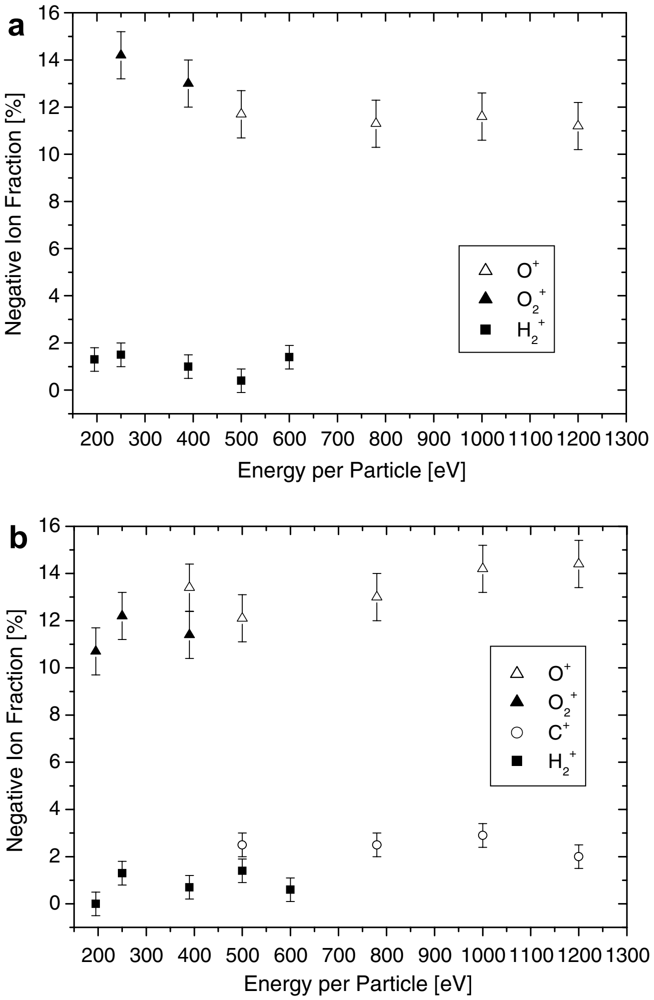

Fig. 4. Negative charge state fractions resulting from various positive ions scattered from a thin film of Al_2O_3 (a) and from an Al_2O_3 single crystal (b).

It has yet to be explained how charge exchange happens when particles scatter off an insulating surface. According to [23,24], the width of the band gap of Al_2O_3 is about 9 eV. As mentioned before, the negative electron affinity levels of H and O are 0.75 eV and 1.46 eV below the vacuum level, respectively. The valence band is filled and there is no electron mobility in an insulator. So one does not expect, that charge exchange would be possible. But it has been found, that for ionic crystals such as, for instance, LiF, charge exchange proceeds via capture of electrons from the anionic sites of the surface in a binary ion–atom interaction [25–27]. And once the negative ion is formed it cannot be destroyed by resonant electron loss (as in the case of metals) because of the band gap of the ionic crystal. It is safe to expect a similar behaviour here. In addition, the probability for a particle to be negatively charged increases with increasing effective number of collisions, and thus at grazing incidence angles.

4. Conclusions

The initial motivation for this study was the question, whether a conversion surface with an Al_2O_3-overlayer would still work. The negative ion fractions we found were about a factor of two lower compared to diamond-like carbon surfaces [10], which is the material we use today for neutral particle sensing instruments. That means, that the instruments would still work with an Al_2O_3-overlayer on the conversion surfaces, but with reduced detection efficiency.

For missions where high particle fluxes are expected, i.e. high transmission of the instrument is not a crucial requirement, Al_2O_3 surfaces could be candidates for conversion surfaces in new neutral particle sensing instruments due to their availability, durability, surface flatness and low price. At the moment, the observed surface charging of the Al_2O_3 single crystal and the roughness of the Al_2O_3 film preclude their use. To get over these problems, for future measurements we are looking for both smoother films and possibly doped single crystals with sufficient surface conductance.

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