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Conversion surfaces for neutral particle imaging detectors

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Abstract

Low-energy neutral particles must be ionized before they are analyzed by mass spectrometric means. Within the limitations regarding space, weight and power consumption onboard a spacecraft surface ionization has been identified as the only viable ionization technique. In the study presented here molecular oxygen and hydrogen ions were scattered at grazing incidence from several diamond-like carbon (DLC) surfaces in the energy range from 190 to 2400 eV. Most surfaces were hydrogen terminated. For incident positive oxygen and hydrogen ions, scattered negative ion fractions of up to 28% and more than 6%, were measured, respectively. These values are among the highest ever reported, especially for oxygen. Furthermore, though these surfaces are amorphous, due to improved polishing techniques angular scattering distributions of the scattered beam have been observed, which were comparable to distributions of scattering experiments with single-crystal surfaces. Therefore, these DLC surfaces are strong candidates to work as conversion surfaces in a neutral particle imaging detector for the BepiColombo mission.

Keywords: Diamond-like carbon; DLC; Neutral particle imaging; Particle scattering; Surface ionization; Tetrahedral amorphous-carbon

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1. Introduction

Interaction of atomic and molecular projectiles with insulating surfaces has gained considerable attention in recent years (Scheer, 1999a; Scheer et al., 2003; Auth et al., 1995; Stracke et al., 1997; Deutscher et al., 1999; Roncin et al., 1999; Borisov and Esaulov, 2000; Souda, 2000; Winter, 2002). Reports of relatively high fractions of negative ions resulting from scattering of positive atomic and molecular ions off insulating surfaces were quite unexpected, but suggested possibilities for several new applications. Among these applications we propose to use this process for efficient detection of 10 eV to 2 keV neutral particles in interplanetary and interstellar space (Wurz et al., 1997; Wurz, 2000; Wieser et al., 2002). Interstellar gas is expected to consist mainly of H and He with traces of O, N, C, and Ne (Geiss and Witte, 1996); for magnetospheric applications, mostly H, He and O are of interest. We therefore tested diamond-like carbon surfaces using H and O molecules, since a diamond surface has already demonstrated high yield (Scheer, 1999a; Wurz et al., 1998). The proof of concept for this detection technique has already been proven in space. The mass spectrograph on the IMAGE satellite mission, designed to detect low energy neutral atoms, uses a conversion surface of volatile adsorbates on a polished, poly-crystalline W substrate to convert a fraction of incoming neutral atoms into negatively charged ions (Wurz et al., 1995; Moore et al., 2000). For future missions, including interplanetary missions like Chandrayaan and BepiColombo, a conversion surface with better controlled long-term stability and higher yield is desired. A natural diamond surface would be an excellent

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candidate for such purposes (Scheer, 1999a; Scheer et al., 1999b; Wurz et al., 1998), if there were not its disadvantages of limited availability and extremely high price.

In the tests presented here, positive molecular oxygen and hydrogen ions were scattered off tetrahedral amorphous-carbon (ta-C; a subset of diamond-like carbon, DLC) surfaces with and without hydrogen termination. Molecular ions were used because they can be produced far more efficiently than atomic ions in our systems. The impact of using positively charged molecular ions upon the results is discussed in detail below. Results from these tests are presented here regarding ionization efficiencies, i.e., negative charge state fractions and scattering properties, i.e., angular scattering distributions of the scattered beam.

The measurements were performed at moderate vacuum conditions, i.e., in the low 10^{-7} mbar range, which simulate the conditions within a typical particle detector shortly after launch. For the European Space Agency's (ESA) ROSETTA mission, for example, the pressure in the vicinity of the spacecraft dropped to about 10^{-9} mbar range severel weeks after launch, and to 10^{-10} after a few months. The pressure inside space instruments with small external openings, such as most particle instruments, is expected to be at least an order of magnitude higher than that around the spacecraft. Due to internal outgassing, pressures of the order of 10^{-8} mbar are expected to persist in space particle instruments more or less indefinitely. To ensure that the observed effects were not induced by adsorbates on the surfaces, which is inevitable at pressures of 10^{-8} mbar, additional measurements were done at ultra high vacuum (UHV) conditions with another apparatus with a base pressure in the low 10^{-10} mbar range.

Hydrogen termination is an important issue for tests with diamond-like surfaces, for two reasons. First, it is known from previous measurements that hydrogen termination of a pure diamond surface increases its yield of negative ions significantly (Scheer, 1999a). This is explained by a change of the surface electronic structure from positive electron affinity (PEA) (Pate, 1986) to negative electron affinity (NEA), when hydrogen terminated (Himpsel et al., 1979; Bandis and Pate, 1996), making more electrons available for the electron transfer process. Secondly, the DLC surfaces used here are tetrahedral amorphous-carbon (ta-C) thin films with a high 4-fold content (fraction of C atoms displaying sp^3 bonding). At the surface, each carbon atom is bonded to only three other carbon atoms leaving one free bond, theoretically orientated perpendicular to the surface and called dangling bond (Pate, 1986; Evans, 1992; Kern et al., 1996). These bonds are very reactive to adsorbates. H termination saturates dangling bonds with hydrogen atoms, and the resultant C–H bonds are even stronger and more inert than the C–C bonds at the surface, providing the advantage of a tough and durable surface, which is of advantage in the harsh space environment. This is particularly desirable for space applications where decontamination of conversion surfaces at elevated temperatures is not feasible during the mission for power and thermal reasons.

2. Experiment

The Si wafers used as substrates for the ta-C films are 1 mm thick with the ⟨100⟩ face exposed, and boron doped for conductivity in the 1–20 Ω-cm range. Cut and polished wafer surfaces were measured to be within 0.13° of the actual ⟨100⟩ lattice plane. Tetrahedral amorphous-carbon (ta-C) thin films were prepared by pulsed laser deposition (PLD) using an excimer laser (248 nm, Lambda Physik Compex® 150 configured in the power oscillator power amplifier mode) at high fluence (~100 J/cm^2) to ablate a pyrolytic graphite target in vacuum (<10^{-6} mbar). Under these conditions the ablated carbon flux is highly ionized with a broad energy distribution ranging from 20 to 300 eV. The carbon ions penetrate and implant in the near surface region (called subplantation (Lifshitz et al., 1989)) causing densification and buildup of stress, ultimately leading to high 4-fold (i.e., sp^3 hybridization) content measured at ~80% (Alam et al., 2003) of the amorphous films. The subplantation also suppresses surface diffusion, which is thought to be one reason why these films are so smooth. Electrical conductivity (Sullivan et al., 1998a; Sullivan and Friedmann, 1998b) depends sensitively on the amount of 3-fold (i.e., sp^2) coordinated carbon present, and the degree of clustering and/or chain formation. The electron conduction is accomplished by hopping from 3-fold clusters mediated by the cluster size and spacing. Typically, resistivities of 10^6 Ω-cm are found for high 4-fold content films, but resistivities have been measured down to 10 Ω-cm in annealed films with slightly lower 4-fold content. The hydrogen termination process, when applied, occurs at approximately 450 °C in 27 mbar of pure hydrogen, with 700 W of microwave power applied for 60 s. It is important to note the importance of surface smoothness in minimizing scattering losses in the downstream particle collection and analysis system of any test apparatus or instrument. The exceptional smoothness of these ta-C samples, approaching perfect smoothness (<1 Å rms) when processed optimally, was an important criterion in selecting this material. An overview of the properties of the different surfaces is given in Table 1.

Table 1
Surface properties of the samples tested in this study are tabulated. L47 is the only sample without H termination, and L81 is made of purely amorphous carbon

Sample number	Film material	Film thickness (Å)	Surface roughness (Å rms)	H termination	Substrate
L31	ta-C	181	4.5	Yes	Si
L38	ta-C	78	5	Yes	Si
L45	ta-C	1050	3	Yes	Si
L46	ta-C	1075	0.7	Yes	Si
L47	ta-C	1075	1	No	Si
L81	–	–	25	Yes	Amorph C

Measurements were made in part at the University of Bern, Switzerland, and in part at the University of Duisburg-Essen, Germany. The two setups will be described briefly. More detail on both experimental setups can be found in (Wurz et al., 1997; Jans et al., 2001; Willerding et al., 1984), respectively. The experiment ILENA at the University of Bern 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 iongetter 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 direction. 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. The base gas pressure is 5×10^{-8} mbar, which may rise during operation into the low 10^{-7} mbar range as a result of test gas leaking into the ion source chamber.

The experimental system JUSO (Willerding et al., 1984) at the University of Duisburg-Essen is an UHV system with an achievable base pressure of 3×10^{-10} mbar. For the measurements reported here the base pressure was 1×10^{-9} mbar and remained in the low 10^{-9} mbar range during the measurements. Ions are extracted from an ion plasma source and are mass analyzed by a 90° sector field magnet. Using an electric deflection system in front of the analyzing magnet, the primary beam can be pulsed to allow time-of-flight (TOF) measurements. The scattering surface is mounted onto a three-axis manipulator equipped with thermocouple-controlled electron beam heating. Downstream from the scattering surface, a collimating tube providing 1.2° full field of view and a microsphere plate (MSP) detector are mounted under a fixed scattering angle of 10° with respect to the incident beam. The angle of incidence is fixed at 5° from the surface plane to assure specular scattering conditions. After the scattering surface a post-acceleration voltage can be applied to separate ions from neutrals. For reasons mentioned above, the measurements at JUSO have been made with a hydrogen terminated DLC surface. The sample was heated to 600 °C, which may have slightly decreased the smoothness after removing most of the adsorbates (Peng et al., 2001). The hydrogen termination remained unaffected since thermal desorption of hydrogen does not occur below 700 °C (Su and Lin, 1998). Target cleanliness was verified continually by the TOF technique (looking for recoil ions) throughout all JUSO tests. Negative charge state fractions were measured at both facilities. Angular scattering distributions were measured only in the ILENA, and energy distributions only in the JUSO apparatus.

3. Results and discussion

Although we eventually want to use neutral atoms to study surface ionization, for these experiments we used positive molecular ions because they can be produced far more efficiently, and with higher energy and intensity, and better angle control in than neutrals. The choice of charge and mass of molecules is justified in the following.

From previous experiments with a polycrystalline diamond surface (Wurz et al., 1997) and a diamond single-crystal surface, it was established that incident hydrogen and oxygen ions are effectively neutralized while scattering off diamond-like surfaces (Scheer, 1999a; Scheer et al., 1999b; Wurz et al., 1998). This is supported by the fact that we found very low positive charge state fractions for oxygen (below one percent) and hydrogen (several percent) with the measurements reported here, indicating effective neutralization upon scattering. Furthermore, these values are in good agreement with results for scattering experiments using an MgO crystal (Wieser et al., 2002) (which is like diamond an insulator with an even wider bandgap) where both neutrals and ions were used as incident particles. As a result, we can assume complete memory loss of the incident charge state after scattering.

For the use of molecules instead of atoms, the situation is different. 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 Wurz et al. (1997), more than 80% of molecules with energy in the 300–800 eV range, when scattered off a polycrystalline diamond surface, dissociate just 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. Analysis of the JUSO spectra (energy range: 850–2500 eV) revealed molecular survival fractions of about 10% for both hydrogen and oxygen, decreasing with increasing incident energy, which fits well with those data. Therefore, we conclude that use of molecules causes a negligible change to the charge state fractions measured in this study.

3.1. ILENA measurements

Table 1 lists the structural properties of the samples. The hydrogen terminated surfaces are of three of film thicknesses, <100 Å, ~200 Å, ~1000 Å, applied to samples L38, L31, and (L45, L46), respectively. They are all tetrahedral amorphous-carbon (ta-C) surfaces, but they were supplied by three different manufacturers and could have had somewhat different scattering properties. For comparison one solid amorphous carbon surface, instead of a film, L81, and one ta-C surface without hydrogen termination, L47, were also tested. All the samples were fabricated with the same standard processes (Friedmann, 2004) in order to ensure consistency and reproducibility. This is an important issue because the conversion surface area needed for typical, neutral particle sensing space instruments may reach 500 cm^2. The two key requirements for suitable conversion surfaces are high ionization yield and low angle scattering, the latter to minimize scattered particle loss in downstream detection systems. The component of angle 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. 1 shows an example of an angular scattering distribution measured with the ILENA apparatus. Here FWHM azimuthal and polar scattering angles are 18° and 10°, respectively. For all surfaces under investigation, the measured FWHM scattering angles resulting from incident hydrogen and oxygen molecular ions with various incident energies are shown in Figs. 2 and 3, respectively. The general trend is toward increased angular scattering with increasing incident energy. Moreover, angular scattering in the polar direction is about a factor of two smaller than in the azimuthal direction. The four hydrogen terminated ta-C surfaces display similar performance, and the ta-C surface without hydrogen termination, L47, performs almost as well, with the exception that the scattering is worse at the lowest incident energies. No explanation has been found for this behaviour at low energies yet. Note that for natural diamond the best performance was also achieved with H termination (Scheer, 1999a). Fig. 4 compares AFM scans, provided by a supplier, of a DLC surface, L46, and an amorphous carbon surface, L81. The difference in surface roughness is clear to see, the measured values for these surfaces for DLC and amorphous carbon

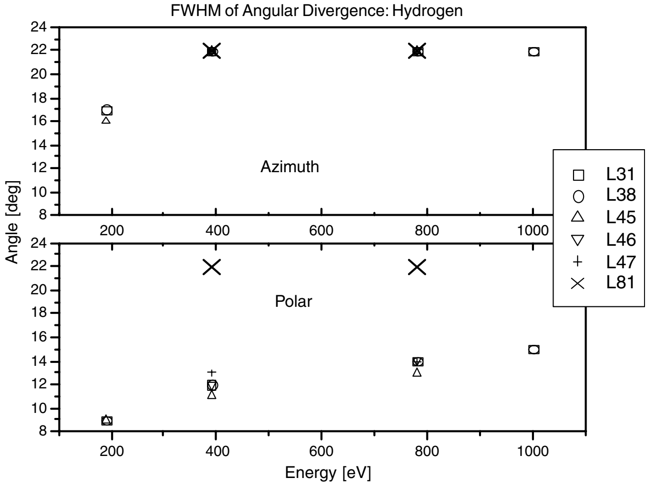

Fig. 2. Energy dependence of H$^-$ angular scattering with incident H$_2$$^+$. Errors are smaller than 1° in each direction. Measurements were taken with ILENA.

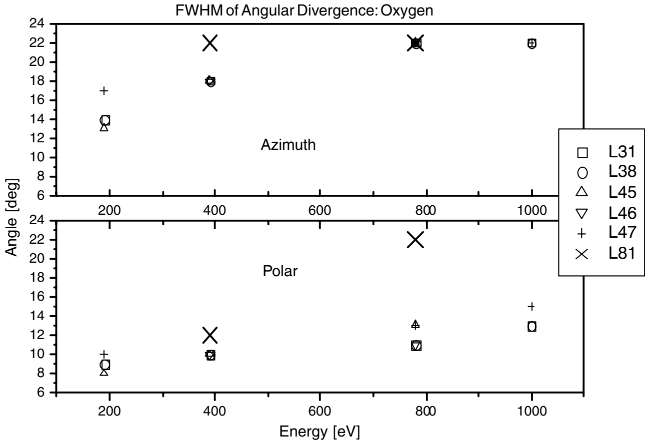

Fig. 3. Energy dependence of O$^-$ angular scattering with incident O$_2$$^+$. Errors are smaller than 1° in each direction. Measurements were taken with ILENA.

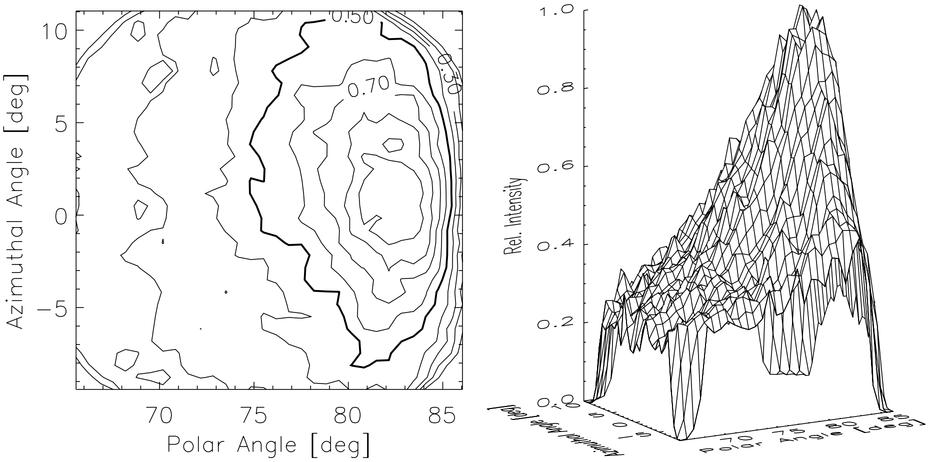

Fig. 1. Angular scattering distribution of O$^-$ ions with 390 eV O$_2$$^+$ incident on sample L45, a hydrogen terminated ta-C surface. FWHM angular scattering widths in the azimuthal and polar planes are 18° and 10°, respectively. Measurements were taken with ILENA.

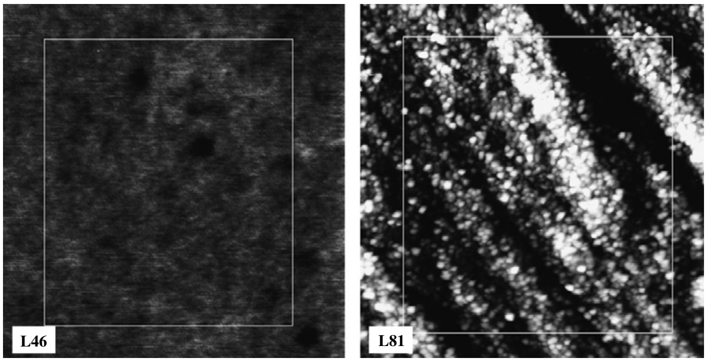

Fig. 4. AFM images of a hydrogen terminated DLC surface (L46, left), compared with a hydrogen terminated amorphous carbon surface (L81, right). The analyzed area is indicated by the white rectangle, and its size is 1 μm^2. The much higher surface roughness of the hydrogen terminated amorphous carbon surface is clearly seen.

are 0.7 Å rms and 27 Å rms, respectively. Accordingly, the amorphous carbon surface shows the largest angular scattering, as displayed in Figs. 2 and 3, and is therefore not the best candidate for a conversion surface at this time. If polishing techniques can be improved, this surface should be reconsidered.

Negative charge state fractions, i.e., ionization efficiencies, of all six samples tested are displayed in Fig. 5. With the detection system of the ILENA apparatus, atomic and molecular ions cannot be differentiated, but as mentioned above, the fraction of molecular ions is very low and will thus not have an impact on the results. Sample L81, amorphous carbon, shows good ionization efficiency, especially for oxygen. For the other surfaces, ionization efficiencies are comparable. Within the energy range investigated (190–1200 eV) ionization efficiency increases with increasing incident energy. Using hydrogen molecules as incident ions, ionization efficiencies vary between 2.5% and 5% for incident hydrogen, and vary between 11% and 22% for incident oxygen. These efficiencies are slightly higher than those reported for other insulating surfaces like MgO (Wieser et al., 2002) and BaZrO$_3$ (Jans et al., 2001). However no benefit appeared in ionization efficiencies due to hydrogen termination, as reported for natural diamond (Scheer, 1999a). This is most likely caused by the moderate vacuum conditions in the ILENA apparatus ($\approx 10^{-7}$ mbar), due to continuous adsorbate recontamination of the surface by residual gas, which obscures the effect of hydrogen termination.

Surfaces can be cleaned by heating up to several hundred degrees C, which is easily done in the laboratory, but is a great challenge in space. Regarding the limitations onboard of a satellite, no more than 80 °C surface temperature seems to be achievable. Therefore, measurements with unheated surfaces and with surfaces heated to 80 °C were done. The results for surface L47 are shown in Figs. 6 and 7. For clarity reasons, Fig. 6 displays only the results for incident O_2^+ but measurements with H_2^+ as incident particles had the same results. Neither the angular scattering FWHM nor the negative charge state fractions were noticeably affected by heating. The explanation is that for pure diamond surfaces much higher temperatures are needed to remove adsorbates, for more than 300 °C for oxygen and about 800 °C for hydrogen (Evans, 1992; Peng et al., 2001). Due to the high sp^3 amount of the DLC surfaces, a similar behaviour is not surprising. In addition, similar

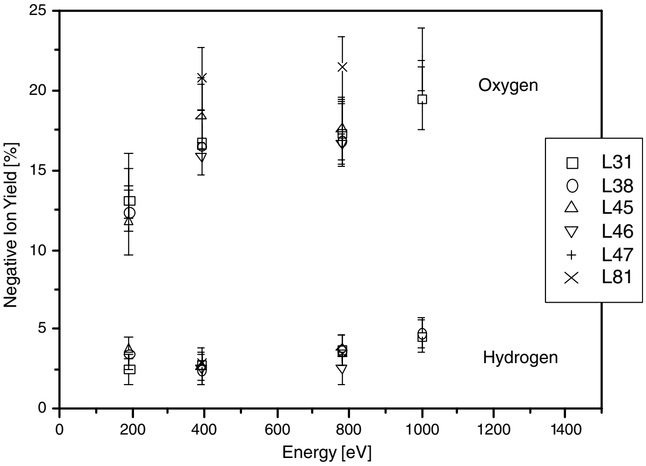

Fig. 5. Negative charge state fractions resulting from incident O_2^+ and H_2^+, larger than 10% for oxygen and below 10% for hydrogen. Measurements were taken with ILENA only.

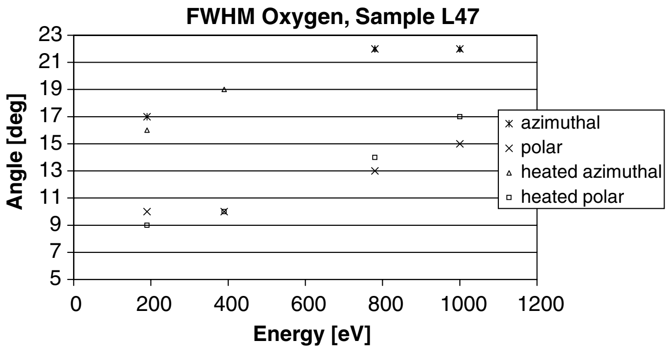

Fig. 6. Angular scattering FWHM resulting from O_2^+ scattered off sample L47, at room temperature and heated to 80 °C. Measurements were taken with ILENA.

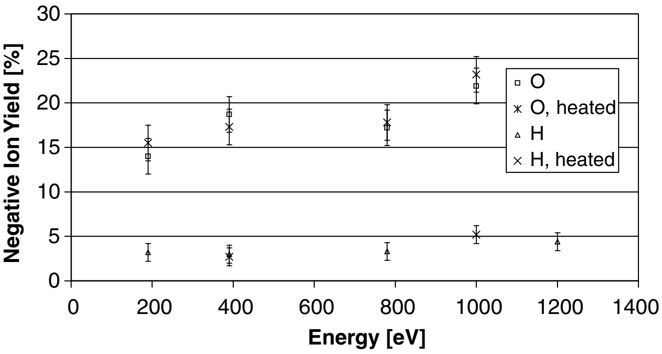

Fig. 7. Negative charge state fractions resulting from O_2^+ and H_2^+ scattered off sample L47, at room temperature and heated to 80 °C. Measurements were taken with ILENA.

measurements were done with unheated and heated hydrogen terminated surfaces, with similar results. No benefit is derived from heating to 80 °C.

3.2. JUSO measurements

For measurements under good UHV conditions, sample L45, a hydrogen terminated ta-C surface, was chosen, with a film thickness of 1050 Å. A typical energy spectrum is shown in Fig. 8, where time-of-flight (TOF) is converted into particle energy. The incident particles are O_2^+ molecular ions with a primary energy of 1801 eV. The large peak at low energy in Fig. 8 is a superposition of the distributions of neutral atoms (produced by dissociation) and of surviving neutral molecules. The molecules form a narrow peak on top of the broad distribution of the dissociated atoms. The fraction of neutral molecules is small in this energy range. See, for instance, Scheer et al. (1999b) for an example of a larger fraction of surviving molecules. Because of successive collisional energy losses in the scattering process, called energy straggling, the scattered neutral particle distribution falls mostly below the incident particle energy. This distribution exceeds partly the incident particle's primary energy because atoms gain energy in the dissociation process. This gain is further increased when converting from the centre of mass system, where the dissociation actually happens, to the laboratory system, where the process is observed, according to:

$$E = \tfrac{1}{2}E_0 + \tfrac{1}{2}E_D \pm \sqrt{E_0 \cdot E_D} \cdot \cos\alpha$$

Here E_0 is the incident particle energy, E_D the dissociation energy and α the angle between the molecule's axis and the incident beam direction. The higher energy peak in Fig. 8 shows the displaced distribution of negative atomic oxygen ions. Separation is accomplished by a post-acceleration voltage that shifts the ion peak to higher energies.

In order to complete analysis of the charge state fractions it was necessary to quantify the energy spectra and to include corrections for detector efficiency. The former was accomplished by use of an asymmetrical exponential fitting function as described in (Närmann et al., 1991). The latter, the detection efficiency, was determined by careful measurements of the energy-dependant probability of the detector to sense an incoming particle. Fig. 9 depicts negative charge state fractions, i.e., ionization efficiencies, for the entire energy range of 190–2400 eV, using the combined ILENA and JUSO measurements. It is important to mention that the measurements were done in different vacuum conditions. During operation the pressures were in the low 10^{-7} and 10^{-9} mbar range at ILENA and JUSO, respectively. While we cannot exclude effects induced by the presence of adsorbates for the ILENA measurements, in the JUSO apparatus particles were scattered off a

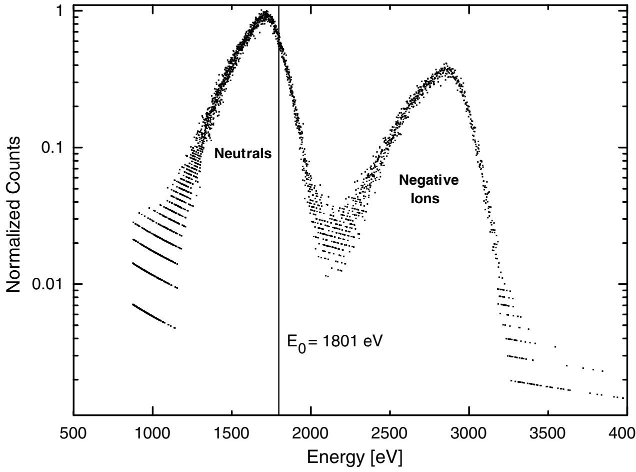

Fig. 8. Time-of-flight (TOF) spectra, in which time has been converted to particle energy and normalized. A positive post-acceleration voltage separates the ions from the distribution of the neutrals. The vertical line represents the nearly monoenergetic incident beam, before scattering, with primary energy E_0. The spectra shows relative O and O^- fractions resulting from 1801 eV O_2^+ scattered off a hydrogen terminated ta-C surface. Measurements were taken with JUSO.

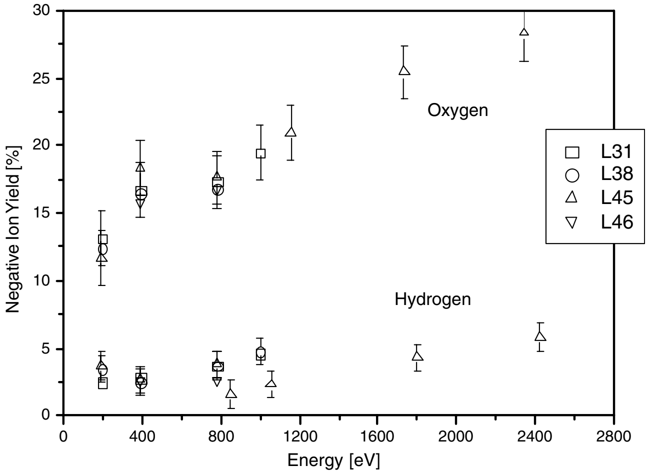

Fig. 9. Negative charge state fractions resulting from incident O_2^+ and H_2^+ scattered off hydrogen terminated ta-C surfaces, as measured in both ILENA (primary energy 190–1000 eV, L31–L81) and JUSO systems (primary energy 850–2400 eV, L45) combined. As in Fig. 5, values higher than 10% represent oxygen ions.

definitely clean surface, monitored by continuous search for recoil atoms, i.e., sputtered atoms from the surface. Lower negative charge state fractions with JUSO (compared to ILENA) would thus mean that data taken with ILENA were affected by surface contamination. We see in Fig. 9 that this is not the case.

3.2.1. Hydrogen

The negative charge state fraction increases with increasing incident particle energy from about 2% to 6% as shown in Fig. 9. The fractions measured with JUSO seem to be a little lower. However, within the error bars the agreement between JUSO and ILENA measurements is still quite good.

3.2.2. Oxygen

The negative charge state fraction increases with increasing incident particle energy from about 12% to 28% as shown in Fig. 9. These results fit very well to measurements taken with a hydrogen terminated surface of super-polished, natural diamond (Scheer, 1999a). Considering the differences in vacuum conditions between ILENA and JUSO, this similarity supports the thesis that hydrogen terminated surfaces strongly displace adsorbates.

Finally, the question remains how charge exchange happens while positive ions scatter off an insulating surface. The valence band of diamond has a bandwidth of 21 eV, and the width of the bandgap is 5.47 eV. The hydrogen terminated diamond surface exhibits a negative electron affinity of 0.7 eV, i.e., the bottom of the conduction band exceeds the vacuum level by approximately 0.7 eV. The affinity levels of H and O are 0.754 eV and 1.462 eV, respectively, below the vacuum level. The valence band is formed by sp^3 hybridized C electrons, the bonds are absolutely covalent. The valence band is filled and there is no electron mobility. So all models using the conventional idea of resonant electron capture from the conduction band (as for metals) can be excluded from further discussion. It is important to mention that although the surfaces tested here are diamond-like carbon surfaces, their high sp^3 content ($\sim$80%) allows us to apply the same discussion as for natural diamond.

For ionic crystals (e.g. LiF) charge exchange proceeds via capture of electrons from the anionic sites of the surface (Auth et al., 1998; Meyer et al., 1997; Ustaze et al., 1997) in a binary ion-atom interaction. Once the negative ion is formed it cannot be destroyed by resonant electron loss (as in the case of metals) because of the bandgap of the ionic crystal. Diamond is not an ionic crystal, there is no such charge localization, but the latter conclusion applies to diamond as well. When an ion approaches a surface, its affinity level experiences a downward shift due to the image potential effect. According to Auth et al. (1995), in the case of LiF, with its bandgap of $\sim$14 eV, the shift is too small (1–2 eV) under grazing scattering to bring the ion's affinity level into resonance with the occupied states of the valence band. But for diamond, below a certain surface-ion distance charge transfer could be possible because of the smaller bandgap. Furthermore, the probability for a particle to be negatively ionized increases with increasing effective number of collisions, and thus at grazing incidence angles.

Maazouz et al. (1996, 1997, 1998) reported results of O^- and H^- fractions for scattering off Al, a jellium type metal, and off Si, a semiconductor with a bandgap of 1.1 eV. Surprisingly, despite the differences in electronic structures they found comparable ion fractions for both surfaces. The authors suggested, taking parallel velocity effects and dangling bonds into account, the presence of surface states at the Si surface to be responsible for their findings.

A theoretical approach is given by Lorente et al. (1997). Calculations for H^- formation while scattering off Al, Si and LiF showed comparable electron hopping probabilities for Al and Si. Furthermore, the parallel velocity of the projectile caused a smoothening of the surface density of states, SDOS, of Si to make it look like Al for the moving particle.

We can safely extend these arguments to diamond, which is very similar to Si. The observed higher fractions of negative ions in the case of diamond are then explained by a larger bandgap, which hinders electron loss on the outgoing trajectory. However, additional work is still necessary to fully understand negative ion formation induced by scattering off insulating surfaces.

4. Conclusions

The ionization and scattering properties of several diamond-like carbon (in our case: tetrahedral amorphous-carbon, ta-C) surfaces have been tested. High fractions of negative ions, 12%–28% for oxygen and 2.5%–6% for hydrogen, have been observed for scattering of O_2^+ and H_2^+ with incident energies of 190–2400 eV. These ionization efficiencies are among the highest ever reported (Willerding et al., 1984; Scheer, 1999a; Jans et al., 2001; Wieser et al., 2002) compared to those achieved with other insulating surfaces. The high ionization efficiencies of these surfaces are even more remarkable when compared to metal surfaces like W or Al, where negative charge state fractions of less than 5% were found for every kind of incident particle. Most tested surfaces were hydrogen terminated, but with the moderate vacuum conditions during operation of the ILENA apparatus (approx. 1×10^{-7} mbar) no benefit of hydrogen termination in terms of ionization efficiency and/or scattering properties could be observed. Scattering experiments off a hydrogen terminated diamond-like carbon surface with controlled surface cleanness at the JUSO apparatus confirmed the results for ionization efficiency found with ILENA for several different diamond-like carbon surfaces, especially in the case of O_2^+ as incident particles. This match of the data taken under different vacuum conditions supports the expectation that hydrogen terminated surfaces strongly displaces adsorbates. This statement is also supported by the fact that angular scattering spread from all tested ta-C surfaces was minimal. As a result, these surfaces are strong candidates for conversion surfaces in space borne neutral particle instruments and are therefore considered as the surfaces of choice for the BepiColombo mission. Finally, ta-C films applied to highly polished silicon wafers are readily available, are affordable for large sample sizes and provide consistently reliable results, all of which are of great importance for today's and future applications in space research.

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