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Time of flight spectra of electrons emitted from graphite after positron annihilation

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Abstract. Low energy (~2 eV) positrons were deposited onto the surface of highly oriented pyrolytic graphite (HOPG) using a positron beam equipped with a time of flight (TOF) spectrometer. The energy of the electrons emitted as a result of various secondary processes due to positron annihilation was measured using the University of Texas at Arlington's (UTA) TOF spectrometer. The positron annihilation-induced electron spectra show the presence of a carbon KLL Auger peak at ~263 eV. The use of a very low energy beam allowed us to observe a new feature not previously seen: a broad peak which reached to a maximum intensity at ~4 eV and extended up to a maximum energy of ~15 eV. The low energy nature of the peak was confirmed by the finding that the peak was eliminated when a tube in front of the sample was biased at -15 V. The determination that the electrons in the peak are leaving the surface with energies up to 7 times the incoming positron energy indicates that the electrons under the broad peak were emitted as a result of a positron annihilation related process.

1. Introduction

Experiments using positron beams with energies in the range of a few eV have resulted in the discovery of novel processes of electron emission [1], and have helped provide a quantitative estimate of the intensity under the low energy tail [2]. In this paper we present the TOF Positron-Induced Auger Electron Spectroscopy (PAES) spectra from HOPG with a 2 eV positron beam. The aforementioned sample, HOPG, is a technologically important material which is used as a substrate for a variety of nanostructures [3]. In addition, the surface of HOPG is a suitable model of the 2D allotrope of carbon, graphene, and could help to understand positron interactions with graphene. These experiments were made possible by the ability of the spectrometer to acquire positron stimulated electron data with positrons incident on the surface at energies as low as 1.5 eV. At such low incident energies, all impact induced secondary electron emission is precluded and any electron emission must be due to annihilation related processes [2]. The use of this low incident positron energy allowed us to obtain the annihilation induced electron spectrum from C free of background from impact induced secondaries over a wide range of emitted electron energies from ~500 eV down to ~1eV. Our measurement revealed that in addition to the previously observed annihilation induced C KVV Auger peak at ~263 eV, the spectra included a second, larger peak in the annihilation induced electron spectrum which reached its maximum around 4 eV and extended as high as 15 eV.

2. Experimental Apparatus

The data were acquired using a Time of Flight (TOF) PAES system at UTA described previously [4]. The positrons were obtained by the decay of a 10 mCi Na^{22} source and then moderated using a thin tungsten foil. The moderator is biased to a positive voltage ($V_{moderator}$) with respect to the chamber (source tube) which houses the source. A grid that is connected to the source tube and kept in front of the moderator extracts the slow positrons into the axial magnetic field. Following moderation, a tungsten barrier collimates these positrons to a diameter of ~8 mm. The slow positrons are filtered from the moderated and collimated beam using mutually perpendicular magnetic and electric fields which are generated by a set of electrically biased plates (**EXB** plates) and the axial magnetic field. The potential difference between the first set of **EXB** plates bends the slow positrons upward through the offset aperture in the tungsten barrier. The fast positrons that are not bent sufficiently, as well as the gammas from the source, are obstructed by this barrier. The second set of **EXB** plates bends the slow positrons back onto the axis of the beam to enter the TOF spectrometer after traveling through a graded accelerator.

The system is equipped with a TOF spectrometer which is used for the measurement of the energy of electrons emitted after the interaction of positrons with the sample and the associated electronics are shown in Figure 1. The low energy positrons are bent around the micro-channel plate (MCP) electron detector using two pairs of **EXB** plates and finally reach the sample after travelling through the TOF tube. The electrons emitted from the surface of the sample after positron implantation travel through the TOF tube and subsequently get deflected into the MCP. These electrons are detected in coincidence with the 511 keV gammas produced as a result of the annihilation of positrons with the electrons of the sample which are detected by the BaF_2 detector. A NaI (Tl) gamma detector kept on the opposite side of the sample also collects the annihilation gamma spectrum.

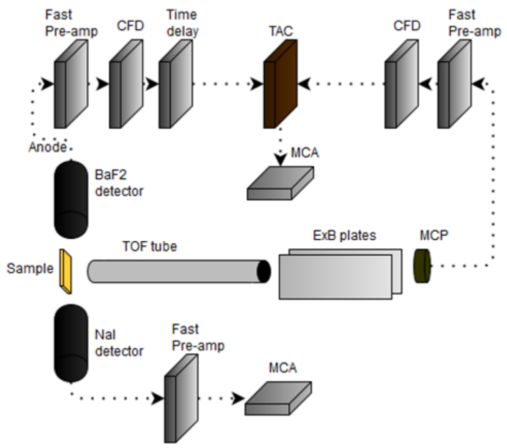

Figure 1. The TOF spectrometer and the associated nuclear electronics used to generate the PAES spectrum. The BaF_2 detector detects a gamma photon in coincidence with an electron detected by the MCP. The timing signal corresponding to the detection of gammas or electrons is produced by the corresponding constant fraction discriminators. The spectrometer is operated in reverse timing mode where the signal from BaF_2 detector is delayed and provided as the stop signal to the TAC. The start signal to the TAC is provided by the MCP detector.

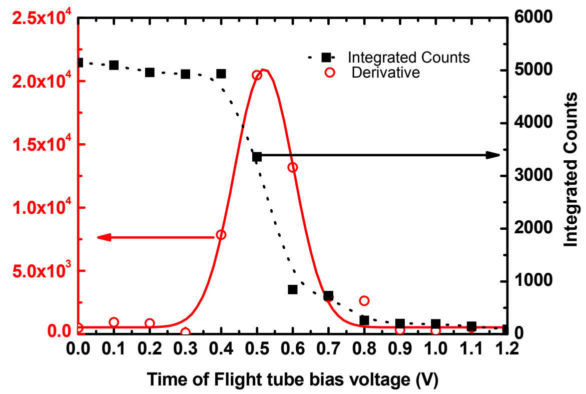

Figure 2. Positron beam energy profile Integrated coincidence counts vs. TOF tube bias (corresponding to positron energy), with the first derivative (red circles) providing the energy spectrum of the positron beam (Gaussian fit, x_c = 0.52, FWHM = 0.20). The sample was biased to -263 V and the total counts under the secondary electron peak are plotted as a function of the positive bias on the TOF tube. It can be seen that beyond ~ 1V, the coincidence count rate goes to near zero indicating that almost all positrons are reflected by the tube and do not reach the sample. The dotted line through the integrated counts is a guide to the eye. The solid line through the first derivative is a Gaussian fit.

2.1. Positron Beam Energy

The kinetic energy of the positrons hitting the sample was determined by measuring the positron energy distribution entering the TOF tube ($E_{ke,TOF}$) and then accounting for the potential difference between the TOF tube and the sample according to equation 1:

$$E_{KE} = -e \cdot V_{SB} + E_{KE,TOF} + \varphi^{-}{}_{sample} - \varphi^{-}{}_{chamber} \quad (1)$$

where e is charge of the positron, V_{SB} is the voltage on the sample, $E_{KE,TOF}$ is the kinetic energy of the positron entering the TOF tube, $\varphi^{-}{}_{sample}$ and $\varphi^{-}{}_{chamber}$ are the electron work functions of the sample and the chamber, respectively. The positron energy distribution entering the TOF tube was measured by using the TOF tube as a retarding field analyzer. For this experiment the sample was biased at -263 V (V_{SB}), which resulted in a strong secondary electron signal in the coincidence spectra when positrons were allowed to hit the sample. Applying a positive potential to TOF tube causes positrons to be reflected, resulting in fewer positrons reaching the sample. This reduces the intensity of secondary electrons detected at the MCP. Figure 2 displays the integrated coincidence counts under the secondary peak as a function of TOF tube bias, in addition to the first derivative of the integrated counts. It can be seen that nearly all of the positrons are reflected back with a positive bias of 1 V. Therefore, it can be concluded that the maximum kinetic energy of positrons travelling through the TOF tube is ~ 1 eV. The positron energy distribution given by the first derivative has a maximum at ~ 0.5 eV and a FWHM of 0.2 eV. In the data shown in Figure 3, the sample was biased at -1V, resulting in a maximum kinetic energy of positrons hitting the sample at ~2 eV.

3. Results and Discussion

The TOF-PAES spectra which were collected with a sample bias of -1 V, and with a positron energy distribution as shown in Figure 2, are given in Figure 3(a) – (d). Figure 3a shows the PAES spectra with 0 V bias on the TOF tube; allowing all of the electrons down to 0 eV to be detected at the MCP. The spectra in Figure 3(a) shows a broad low energy peak with a maximum around 4 eV and extending up to ~15 eV in addition to a peak corresponding to the annihilation induced KVV transition in carbon (~263 eV). This carbon sample was prepared by mechanically exfoliating HOPG in air and placing it in the sample chamber which was pumped down to a pressure of ~$1x10^{-10}$ Torr. In order to confirm that this peak was really due to low energy electrons and to find the maximum energy of the electrons under the low energy peak, we again employed the TOF tube as a retarding field analyser this time to measure the energy of electrons leaving the sample. The TOF tube was biased at a series of negative voltages, thereby reflecting electrons with energies lower than $-\boldsymbol{e} \cdot \boldsymbol{V_{TOF}}$, and preventing them from reaching the MCP. The results are shown in Figures 3(b) – (d). It can be clearly seen that most of the signal in the low energy peak is gone when -7 volts is applied to the TOF tube (Figure 3(b)) and that almost all of the signal is gone when -15 volts is applied (Figure 3(c)). These results show that the broad peak seen in Figure 3(a) was due to electrons with energies less than 15eV.

4. Conclusion

The energy spectra of positron induced electrons leaving a HOPG surface were measured for an incident positron kinetic energy < 2eV. A broad peak was observed with a maximum at ~4 eV and extending up to ~15 eV in addition to the annihilation induced KVV Auger peak at ~263 eV. The integrated peak intensity of the low energy peak was an order of magnitude larger than the KVV Auger. Considering that the incident positron energy is < 2 eV, energy conservation rules out non-annihilation processes from producing electrons in the energy range of the low energy peak, unless additional energy is made available through an annihilation process. We postulate that these electrons may be due to an Auger process initiated by the annihilation of an electron deep in the valence band of graphite. We are currently investigating the origin of this low energy peak, in addition to searching for its presence in other carbon allotropes, such as graphene.

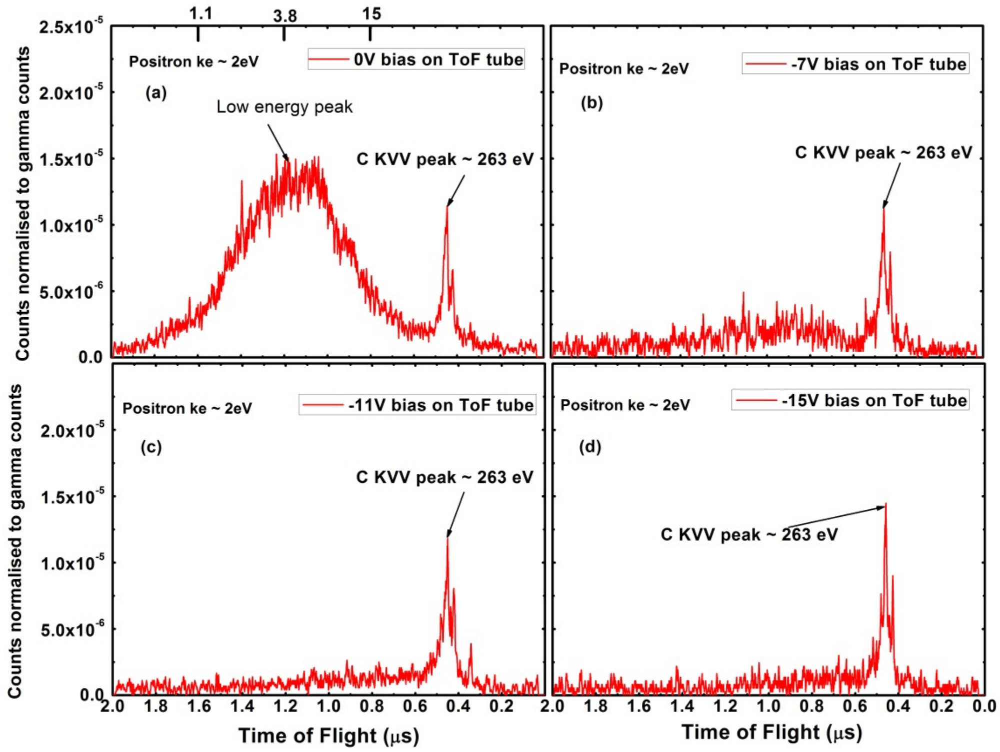

Figure 3. TOF PAES spectra from HOPG using positrons of kinetic energy < 2 eV. The indicated kinetic energy of the positrons does not correct for the additional energy due to the contact potential between the sample and the chamber. The TAC is set to observe a 2 μs time window. Pane (a) shows the PAES spectra with 0 V bias on the TOF tube. All of the spectra show the Auger peak corresponding to KVV transition in carbon at 263 eV. In the corresponding panes where the TOF tube is biased to different negative voltages, (b) -7 V (c) -11 V and (d) -15 V, it can be seen that the low energy peak is completely removed with a bias of -15 V. This indicates that the electrons under the low energy peak are < 15 eV.

Acknowledgments
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