

# High Resolution Photoemission Spectroscopy on Single-Walled Carbon Nanotubes

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## INTRODUCTION

The rich and unusual physics of one-dimensional electronic systems, e.g. nanotubes, is a very important current topic, and is fully contained in the single-particle spectral function of many-body theory of electrons. Therefore, angle-resolved photoemission spectroscopy on nanotubes is a highly desirable goal, given that it has provided detailed information on the single-particle spectral function of other important materials such as high temperature superconducting cuprates [1]. So far, no such study has been reported on nanotubes, mainly due to the difficulty of obtaining clean, homogeneous and ordered surfaces of nanotubes. We hope that we can do such a study soon, using highly aligned nanotubes, and we are making progress in sample preparation. However, it should be noted that even angle integrated photoemission data on nanotubes is scarce and needs improvement, e.g. temperature dependence. Here, we report our first angle integrated photoemission data on single-walled nanotubes as a starting point of our nanotube program.

## EXPERIMENTAL

This experiment was carried out at the beam line 12.0.1.1 using the photoemission end station equipped with an SES 100 electron analyzer. Single-walled nanotubes were deposited on a Si substrate coated with  $\sim 2000$  Å of Pt. The dimension of the Si substrate was 5mm x 5mm. For cleaning the sample, we used annealing at a temperature of  $\sim 550$  C in the analysis chamber. The pressure of the analysis chamber was  $\sim 3e-11$  Torr during measurements and went up to  $\sim 5e-10$  Torr during the annealing. A flowing He cryostat using either liquid nitrogen or liquid helium controlled the sample temperature during the measurement. The spot size of the photon beam on the sample was about 100  $\mu$ . For the position of the Fermi energy ( $E_F$ ) and the experimental energy resolution, spectra taken on clean Au surface were used.

## RESULTS

Fig. 1 shows an example angle integrated spectrum on single-walled carbon nanotubes. For this spectrum taken with photons of 35 eV, the combined energy resolution of the monochromator and the electron analyzer was dominated by the monochromator line width and was given by 55 meV. This spectrum was recorded after 27 hours of annealing. The annealing made peaks sharper compared to those measured on “as-is” surface. The spectra show characteristic peaks in the valence band similar to, but not exactly the same as, those known in the literature [2]. Specifically, the binding energies are lower in our data, which may mean more metallic nanotube sample in our case.

In view of the theoretically predicted Luttinger liquid (LL) [3] state, a paradigm non-Fermi liquid, of one-dimensional electrons, it is interesting to look at the detailed line shape near  $E_F$ . We find that the line shape near  $E_F$  is non-FL, i.e. not described by the Fermi edge line shape. Instead, when compared with the T dependent LL spectral function [4], the line shapes within 200 meV below  $E_F$  gives an approximate power law behavior with the exponent (“anomalous dimension [3]”)  $\alpha \approx 0.5$ .

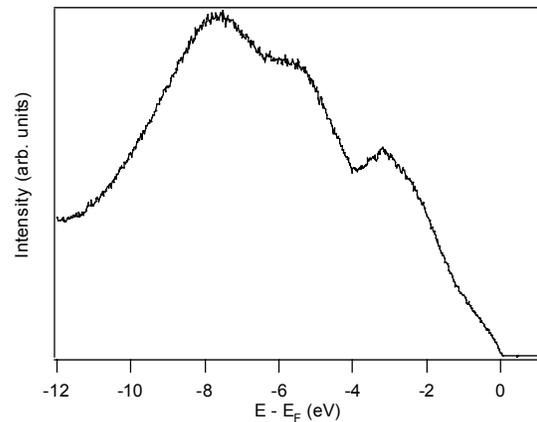
## DISCUSSION

While our study is preliminary and requires more measurements, it is already interesting to compare our  $\alpha$  value with the values obtained by a tunneling conductance study of nanotube ropes [5]. In the latter,  $\alpha = 0.3 \sim 0.4$  was reported for tunneling from leads into the bulk of nanotubes and  $\alpha = 0.6 \sim 0.9$  was reported for tunneling from leads into the ends of nanotubes. In the same work, theoretical values of  $\alpha \approx 0.24$  and  $\alpha \approx 0.65$  were estimated for tunneling into the bulk and the end of the nanotubes, respectively. In fact, the boundary condition imposed by an impurity or an open end is known [6] to give a distribution of  $\alpha$  values between the bulk and the end values as a function of position. The current photoemission spectrum would then be interpreted as a space average of the power law spectral line shapes with these different  $\alpha$  values, and this would give a qualitative explanation as to why our  $\alpha$  value comes between the bulk and the end values.

We have only begun to investigate nanotubes using photoemission, and we are gaining experience in preparing suitable sample for photoemission. Although we think that a reasonably clean sample surface was obtained for the data shown in Fig. 1, we still need to accumulate more data on differently prepared, and likely better, samples. On the current sample, photoemission signal from foreign element (Na) co-existed with that from carbons. The origin of this foreign element is tentatively attributed to the cleaning solution used in the final stage of the sample growth. The signal from this foreign element was very small, but not zero, even for the best spot. Noticeable changes in the  $E_F$  line shapes were observed as the photon spot was moved slightly from the best position. Therefore, the macroscopic cleanliness of the sample is an important continuing issue for our future studies of nanotubes, such as temperature dependence and angle dependent studies of aligned multi-walled nanotubes.

## REFERENCES

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**Fig. 1** Valence band spectrum of single-walled carbon nanotubes taken with photons of 35 eV at  $T = 88$  K.

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