Nanostructures stabilise one- and two-dimensional quantum systems

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Helium adsorbed on and in nanotubes is predicted to form exotic quantum states of matter. In particular, helium on the surface of nanotube bundles is predicted to form a one-dimensional (1D) fluid or solid. Using neutrons, we have made the first measurements of the structure of helium on nanotubes. At low coverage, ^{4}He indeed forms 1D lattices along the grooves between two nanotubes on the surface of the bundles. At higher coverages, ^{4}He forms a 2D incommensurate monolayer on the bundle surfaces, thus exhibiting 1D to 2D cross-over. These measurements show that 1D and 2D quantum systems can be reliably created using ^{4}He on commercially available nanotubes, and their properties investigated using neutrons [1].

Single-wall carbon nanotubes (SWNTs) are sheets of carbon atoms rolled into a seamless cylinder 1-2 nanometres in diameter and thousands of nanometres long forming a nearly one- dimensional (1D) system. These tubes typically self assemble into bundles or ropes containing 50 or more tubes. The tubes in the bundle have a hexagonal structure, as depicted in ***figure 1***. Gases adsorbed on the surface of these 1D bundles may themselves become 1D systems.

Interest in 1D systems has a long and rich history. In 1936, Tonks first investigated a 1D gas of hard spheres, now denoted a Tonks gas. In 1960, Girardeau showed that this interacting 1D gas of Bosons was identical to a non-interacting gas of Fermions, with Fermi statistics assuming the role of interaction. Many subsequent exact results have been obtained, and superfluidity and smeared Bose-Einstein condensation in 1D have been predicted [2]. Electrons in 1D represent a strongly correlated system [3].

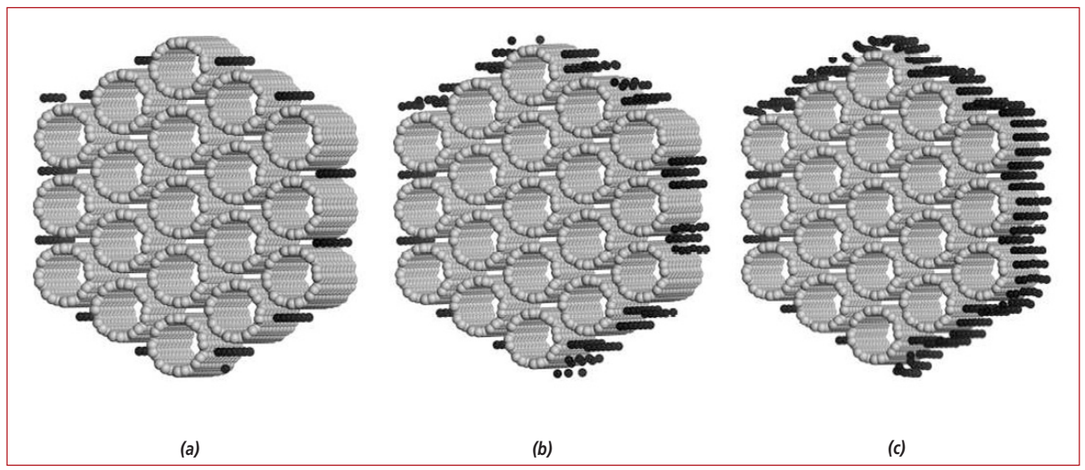

Figure 1: *Structure of ^{4}He atoms adsorbed on the surface of a single-walled nanotube (SWNT) bundle:* ***(a)*** *one-dimensional lines of ^{4}He in the grooves between two nanotubes,* ***(b)*** *three lines of ^{4}He in the grooves, the '3-line' phase,* ***(c)*** *monolayer coverage of the surface.*

Recent Monte Carlo calculations show that isolated ^{4}He in 1D forms a dilute, weakly interacting liquid with an average inter-atomic spacing of approximately 35 Å and energy per atom of approximately 10^{-3} Kelvin. The 1D liquid is highly compressible and when compressed supports phonon-roton-like excitations as observed in 3D. In 1D or 2D a crystal lattice is not stable at any finite temperature. However, a 1D lattice might be stabilised by interaction with the nanotubes, with the corrugation in the nanotube potential determining the lattice spacing [4].

Our goal is to create 1D quantum systems with ^{4}He on nanotube bundles. With this aim we deposited ^{4}He on a large (2.7 gram) sample of commercially available nanotube bundles and observed the ^{4}He structure using the D20 diffractometer. At low coverage, we observed a net diffraction pattern from the ^{4}He characteristic of a 1D crystal lattice of inter-atom spacing a = 3.40 Å. Our simulations of ^{4}He on the bundles indicate that the lowest energy configuration at low coverage is a 1D lattice of ^{4}He along the grooves between two nanotubes on the bundle surface, as depicted in ***figure 1(a)***. As coverage is increased, the ^{4}He continues to show 1D lattice character, and simulations suggest that this is three lines of ^{4}He along the grooves on the bundle surface as depicted in ***figure 1(b)***, denoted the '3-line phase'. The 1D inter-atom spacing is surprisingly independent of coverage and our simulations reproduce the observed diffraction well [1]. Clearly, the ^{4}He-nanotube interaction is stabilising the lattice and compressing the 1D spacing from a = 3.5 Å to a = 3.40 Å.

As coverage is increased still further, the observed net diffraction pattern shows a shift from 1D to 2D character. The 2D diffraction character is reproduced in our simulation by a monolayer of ^{4}He, covering the bundle surface in a 2D triangular lattice as depicted in ***figure 1(c)***. At monolayer completion, the lattice spacing is 3.63 Å. The 1D to 2D cross-over in the diffraction intensity is shown in ***figure 2***. The lattice spacings are obtained from model fits to the data. The scattering intensity is broad, as shown in ***figure 2***, because there is a distribution of ^{4}He lattice spacings arising from a distribution of nanotube diameters in the sample. A 1D to 2D cross-over has also been inferred from recent specific heat measurements. The 2D triangular lattice appears to be incommensurate with the nanotube bundle surface.

The present measurements show that ^{4}He on nanotube bundles form 1D and 2D quantum solids at nearly constant lattice parameter largely independent of filling. These solids and the 1D-2D crossover can be reliably created using ^{4}He on commercially available nanotubes and reliably investigated using neutron diffraction techniques. Our next goal will be to reveal the nature of the excitations supported by these 1D and 2D systems using inelastic neutron scattering methods.

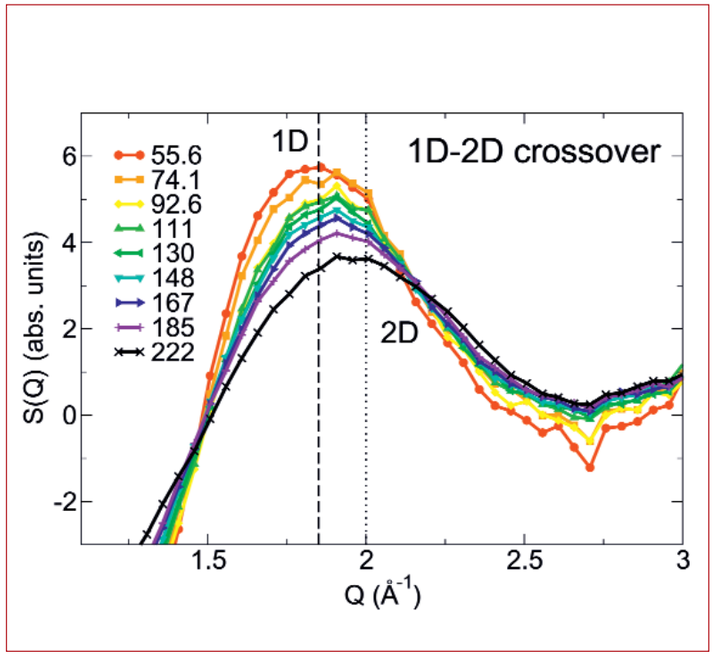

Figure 2: *Net S(Q) from ^{4}He absorbed on SWNTs per unit ^{4}He absorbed for coverages between the filled 'three line' phase (1D regime) to the nearly complete monolayer (2D regime). Shown here is the change of form of the line shape as the structure factor (intensity) per ^{4}He atom changes from 1D (55.6 cm^3/gram adsorbed) to 2D (222 cm^3/gram adsorbed). The dashed line shows the peak position expected for 1D, dotted line for 2D.*

References:

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