Supplementary Information for
Field Ionization of Cold Atoms Near the Wall of a Single Carbon Nanotube

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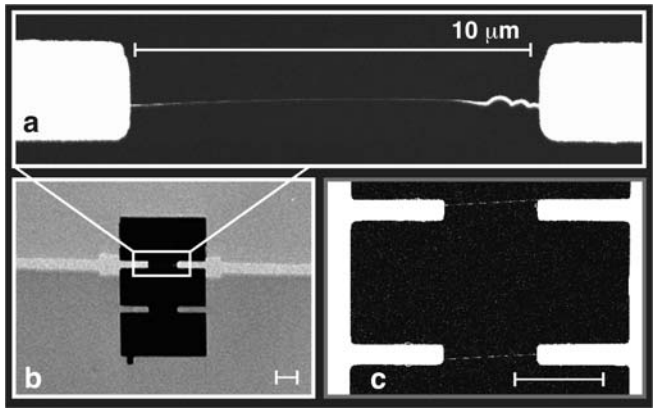
Preparation of samples with suspended nanotubes.

Single-walled carbon nanotubes, suspended across 10-μm gaps, are grown on silicon chips in a CVD oven. Each sample is 3mm x 3mm and cut from a 525-μm thick silicon wafer (p-type with resistivity of 10-20 Ωcm at 300K) with an overlayer of SiO_2 and low-stress Si_3N_x on both sides. After using photolithography and a reactive ion etch to selectively remove the bottom layer of Si_3N_x, we apply an anisotropic silicon etch that creates a free-standing 70 x 70 μm^2 membrane consisting of 2 μm of SiO_2 and 200 nm of Si_3N_x. A through-hole in the membrane, with a shape as shown in Supp. Fig. 1b, is milled with a focused ion beam (FIB). With a shadow mask we then e-beam evaporate catalyst pads, consisting of 1 nm Fe on top of 10 nm Al_2O_3, [25] at the ends of the long membrane arms (Supp. Fig. 1a).



Supplementary Figure 1. Suspended nanotubes for atom capture. The SEM images show the top surfaces of the nanotube samples. The chip structures are shown with suspended nanotubes and Ti/Mo electrodes that are insulated by SiO/SiN from the silicon substrates. The scale bar in all images is 10 μm. The sample shown in (a, b) yielded the data presented in the main text. Figure **a,** a single tube is suspended between rigid SiO/SiN arms, with metal evaporated on the arms and at the ends of the tube; **b,** thru-hole (dark) milled in the rigid, free-standing membrane, bridged by the tube shown above, and with narrow electrodes (pale) deposited after tube growth; **c,** sample with two parallel, suspended tubes shown before electrodes are evaporated (we use high contrast here to show the nanotube locations).

Nanotubes are grown – from the catalyst pads and between the arms – with chemical vapor deposition in an oven heated to 850C and with methane as the carbon source [1,13]. Often we observe several tubes on a sample as seen in Supp. Fig. 1c. We finally evaporate electrodes with 10 nm of Mo on top of 50nm of Ti. (No degrading of the electrodes is observed even after extended periods of exposure to rubidium). A shadow-mask stencil is milled with the FIB, mounted in a translatable holder with ~20 μm clearance over the silicon chip, and then aligned

under an optical microscope before electrode deposition in the e-beam evaporator [26]. While a wet-lithography process can cause contamination or damage for long suspended tubes, the post-growth electrode patterning we use leaves the tubes unharmed. The Ti/Mo strips cover the top surface of the membrane arms, creating well-defined 2-μm-wide electrodes, and wet the ends of the suspended tube for improved contact [27] (Supp. Fig. 1a, b). The strips are contacted to 2-mm-sized macroscopic pads (outside the field of view of the images), and a high voltage is applied with clip connections to the pads. The electrode design was optimized with numerical modelling based on a finite-element analysis with COMSOL Multiphysics® (a commercial software package by COMSOL AB). In the analysis we include the full three-dimensional structure of the chip and confirm that electric fields are determined entirely by the charge density on the nanotube and that shielding effects from the 2 -μm wide electrodes are negligible.

When a sample is placed in the vacuum chamber (10^{-9} torr), the silicon is grounded and the electrodes are charged to positive voltage to generate the atom-capturing field. The sample is mounted upside-down as shown in Fig. 2 of the main text. The cone-shaped sample holder, with the chip mounted at the apex, conforms to the geometry of our laser beams, and x-y-z translation stages allow continuous scanning of the sample in three dimensions. Using the wrapped-wire heater, the sample temperature is slightly elevated (100°C) to prevent the accumulation of rubidium on the nanotube chip.

MOT loading and launching.

We operate a 2D magneto-optical trap (MOT) in pulsed mode to cool, confine, and launch clouds of ^{85}Rb atoms [15]. We use four trapping laser beams and elongated current coils that generate magnetic gradients in the two horizontal directions. The MOT is vapor-loaded from an evaporable getter source for 1.25 sec, resulting in a trapped cloud with 1 million atoms and a temperature of 200 μK. To launch an atom cloud, we abruptly change the relative detuning δ between two pairs of laser beams and create a moving MOT. The launch velocity v is proportional to δ, with v/δ=(1 m/s)/(1.81Mhz). We chose a nominal launch velocity of 5.0 m/sec (δ= 9.06 Mhz), and the actual atom velocity was determined by time-of-flight measurements to be v =5.3 m/sec. (This difference is due to slight errors in optical beam alignment for the MOT). Importantly, the launch velocity was chosen to be much larger than the rms velocity of 20 cm/s of the atom cloud, and all atoms are therefore launched toward the tube with nearly the same velocity. Atoms arrive at the tube 4.2 ms after being launched. For each launch, the time-dependent optical density of the atom cloud is measured by a weak, resonant laser probe beam (size of 140 μm x 210 μm and power of 100nW) placed just below the nanotube chip, and we measure a peak density of $1.2\text{x}10^{9}$ atoms/cm^3 corresponding to a peak flux of $6.4 \text{ x } 10^{11}$ atoms/cm^2/sec. The size of the launched atom cloud in the horizontal plane at the sample position is 1100 μm by 800 μm (FWHM), which is measured with the nanotube by scanning it across the atomic beam profile.

Ion detection and time stamping.

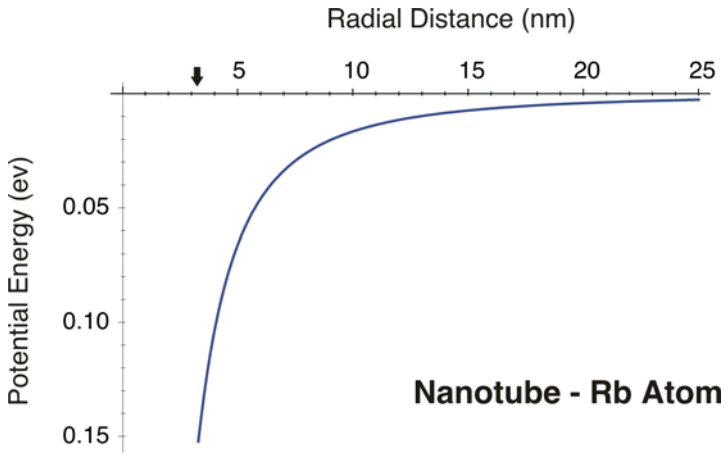
For ion detection, we use a single-channel electron multiplier (Channeltron® CEM, manufacturer Burle/Photonis) run in discrete pulse-counting mode. The funnel-shaped detector (main text Fig. 2) is charged to –2300V; the rim has a transverse diameter of 9.9 mm and is positioned 25 mm from the nanotube. Individual ions incident on the CEM generate discrete charge pulses that are input to a charge-sensitive amplifier (Amptek A121 discriminator/preamp

that requires a minimum pulse-to-pulse separation of 60 nsec). The timing of the output signals is digitally recorded with an accuracy of 14 nsec. For each launch we generate a list of time-stamps corresponding to every ion arriving during a 100 msec time window, including a 50 msec time interval both before and after atom launch.

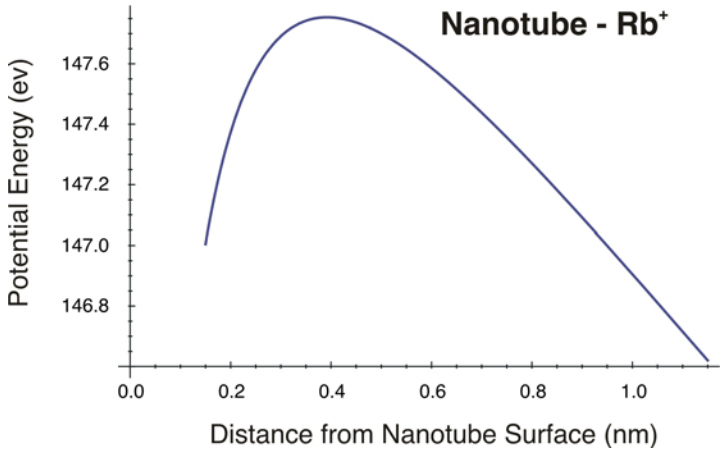
To produce Fig. 4a (in main text), we distinguish those ions which correspond to captured cold atoms from background ions by counting only the ions that arrive within a 2.6 msec time window ($3.0 \leq t \leq 5.6$ msec) determined from the histograms of ion arrival times. Counts from ionization of the background rubidium vapor are accumulated in the time window before the launch ($-50 \leq t \leq 0$ msec). The background rate is ~ 0.5-3.0 ions/sec, increasing with voltage, so the contribution is negligible during the short time window of the cold-atom pulse and background subtraction is unnecessary.

Interaction potentials between a carbon nanotube and neutral or singly charged rubidium.

In Supp. Fig. 2 we show the attractive $1/r^2$ potential [11] that governs the motion of a neutral rubidium atom in the electric field from a charged carbon nanotube. In Supp. Fig. 3 we show the interaction potential between a rubidium ion and a charged carbon nanotube. The potential is a combination of the image potential induced by the ion [19] and the repulsive potential from the positively charged tube. When the atom ionizes within the potential barrier at 0.4 nm, the ion is trapped near the surface as described in the main text.



Supplementary Figure 2. Attractive $1/r^2$ potential for a neutral rubidium atom around a carbon nanotube charged to 150V. The arrow indicates the surface of the 3.3 nm radius nanotube used in the experiments. The polarizability of Rb is 47 $Å^3$.



Supplementary Figure 3. Potential for a Rb^+ ion in proximity to a charged carbon nanotube wall. This is a combination of the ion's induced image potential and the repulsive potential from a nanotube positively charged to 150V. The nanotube radius is 3.3 nm. From the measurements of nanoscale interaction dynamics (main text Fig. 4b, c) we estimate repulsive interactions (not shown) to be dominant for distances below 1.5 Å. An ion, created at this tube voltage by field ionization of a captured rubidium atom, is trapped in the resulting potential minimum for roughly a millisecond.

Supplementary References

[25] K. Hata. *et al.,* Water-assisted highly efficient synthesis of impurity-free single-walled carbon nanotubes. Science **306**, 1362 (2004).

[26] M. M. Deshmukh, *et al.*, Nanofabrication using a stencil mask. Appl. Phys. Lett. **75**, 1631 (1999).

[27] Y. Zhang, *et al.*, Metal coating on suspended carbon nanotubes and its implication to metal-tube interaction. Chem. Phys. Lett. **331**, 35 (2000).