Visualizing a quantum crystal: Imaging the electronic Wigner crystal in 1-D

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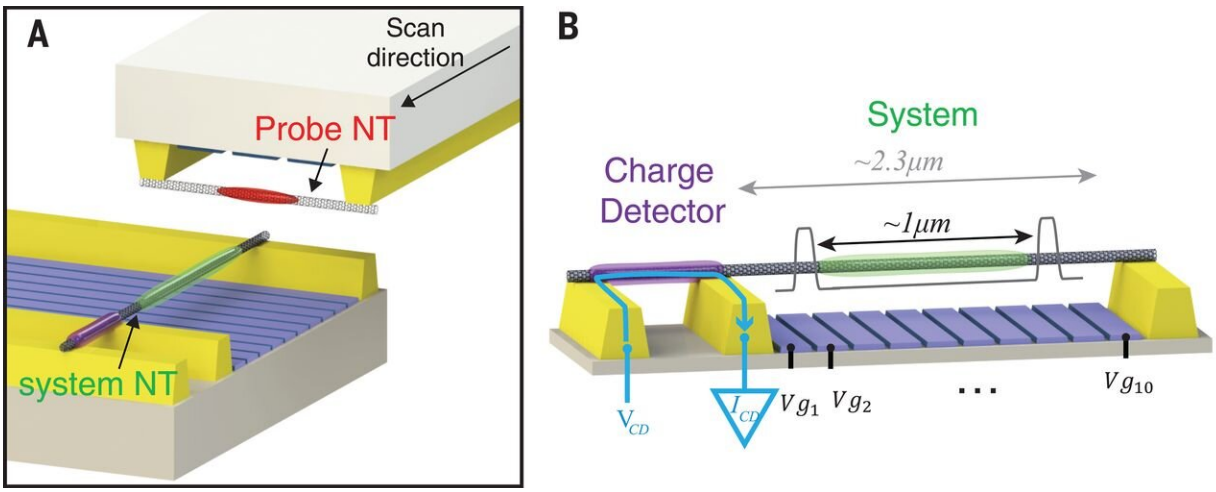
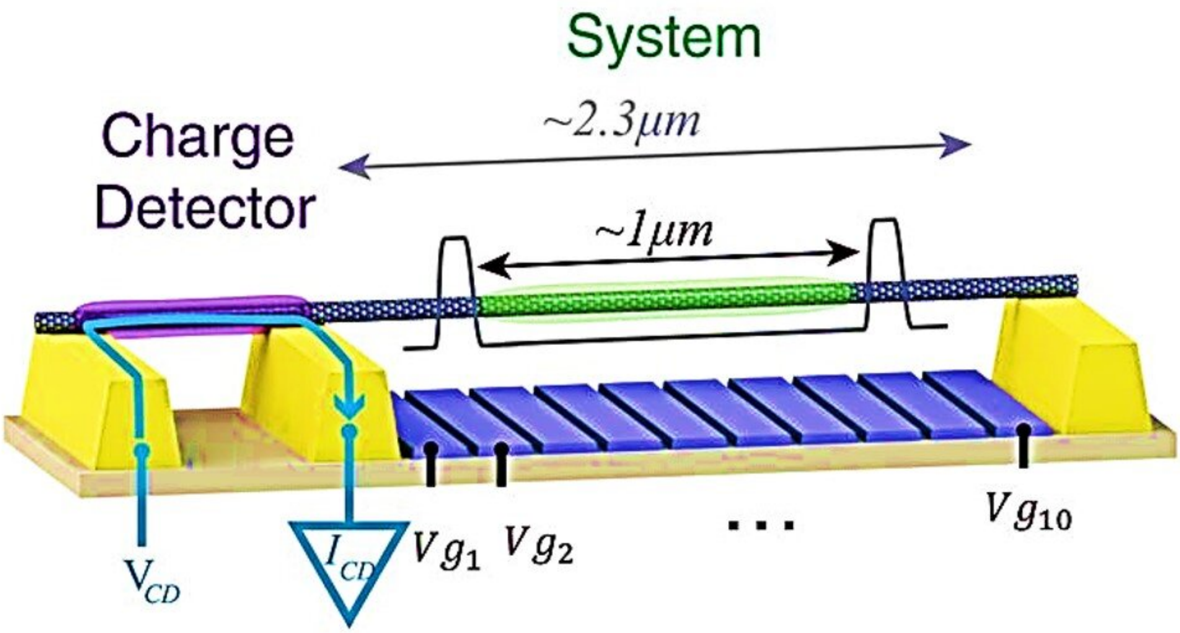


Experimental platform for imaging strongly interacting electrons. (A) Scanning probe setup consisting of two carbon nanotube (NT) devices—a system-NT device (bottom) that hosts the electrons to be imaged (green ellipse) and a probe-NT device (top) containing the probing electrons (red). In the experiment, the probe NT is scanned along the system NT (black arrow). (B) The system NT is connected to contacts (yellow) and is suspended above 10 gates (blue) used to create a potential well (shown schematically in gray) that confines a few electrons to the middle part of the suspended NT (green), away from the contacts. The addition of these electrons is detected using a charge detector—a separate quantum dot formed on a side segment of the same NT (purple). The detector is biased by a voltage, VCD, applied on an external contact, leading to a current, ICD, flowing only between the contacts of the charge detector (blue arrow), such that no current passes through the main part of the system NT. Credit: Science, doi: 10.1126/science.aat0905

When electrons that repel each other are confined to a small space, they can form an ordered crystalline state known as a Wigner crystal. Observing the fragile crystal is tricky, since it requires extreme conditions including low temperatures and densities, as well as noninvasive imaging probes. To overcome the challenging conditions of imaging, I. Shapir and a research team in the departments of Physics and Condensed Matter Physics in Israel, Romania and Hungary created conditions in a carbon nanotube (NT) to house the electrons. They followed this experimental step by using a second nanotube as a probe (called "probe NT") to scan the first nanotube (termed "system NT"). The physicists measured the electronic densities and showed their consistency with theoretical predictions to demonstrate small Wigner crystals of up to six electrons in one dimension (1-D). The results are now published in *Science*.

More than 80 years ago, physicist Eugene Wigner predicted the quantum crystal of electrons, which remains one of the most elusive states of matter. In the present work, Shapir and co-workers developed a technique to directly image the Wigner crystal in 1-D by imaging its charge density in real space. They obtained images of a few electrons confined in 1-D that matched the theoretical predictions for strongly interacting crystals. The scientists viewed the quantum nature of the crystal using collective tunneling through an electric potential barrier confined with electrically independent gates. The work provided direct evidence to the formation of small Wigner crystals, paving the way to study fragile interacting states of electrons by imaging their many-body density in real space.

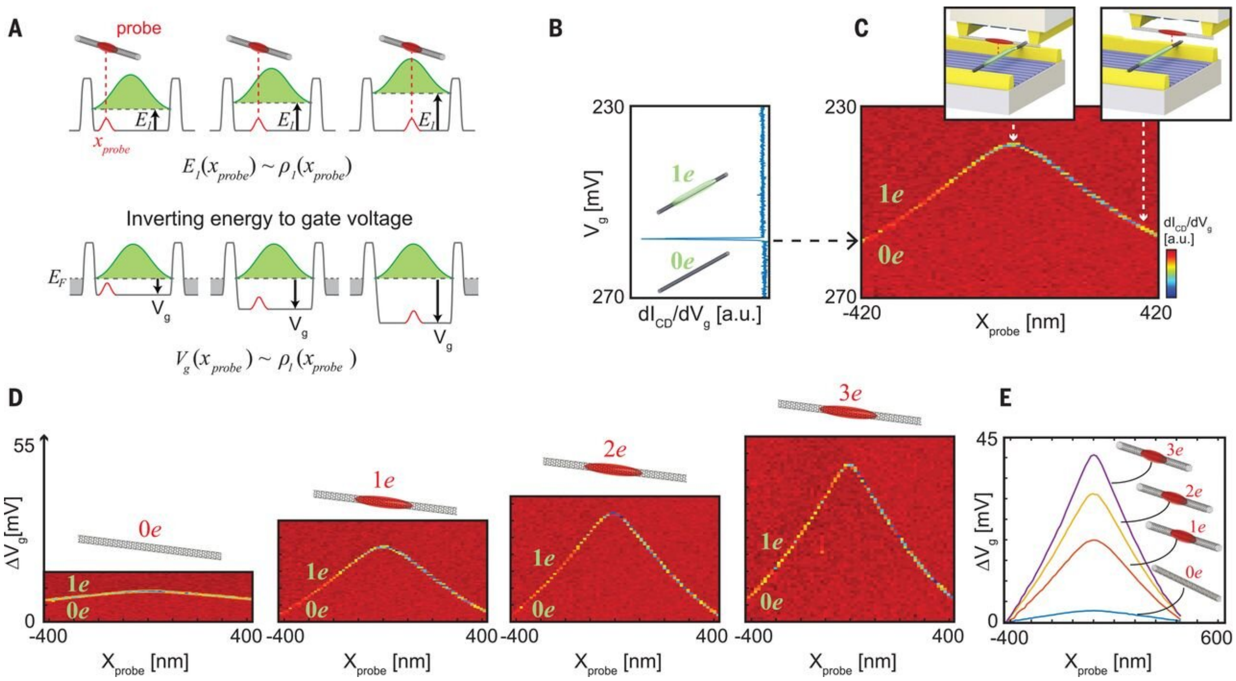
In his 1934 paper, physicist Eugene Wigner predicted that when long-range Coulomb interactions in a system of electrons dominated the kinetic energy and disorder, they would emerge in a crystalline ground state. Where the electrons were kept apart irrespective of their quantum number . Experimental physicists began to search for this quantum [crystal in the cleanest available electronic systems thereafter, including liquid helium] and low-dimensional semiconductor heterostructures.



Experimental platform to image the Wigner crystal. The system NT is connected to contacts (yellow) and is suspended above 10 gates (blue) used to create a potential well (shown schematically in gray) that confines a few electrons to the middle part of the suspended NT (green), away from the contacts. The addition of these electrons is detected using a charge detector—a separate quantum dot formed on a side segment of the same NT (purple). The detector is biased by a voltage, VCD, applied on an external contact, leading to a current, ICD, flowing only between the contacts of the charge detector (blue arrow), such that no current passes through the main part of the system NT. Credit: Science, doi: 10.1126/science.aat0905.

Physicists had previously conducted measurements in two-dimensional (2-D) electronic systems relative to transport, microwave fields, nuclear magnetic resonance, optical, tunneling and bilayer electron systems to indicate the existence of a crystal at high magnetic fields. Observing a crystalline state in one-dimension (1-D), in an infinite system is unexpected, since thermal and quantum fluctuations can destroy long-range order. However, in finite systems, physicists had studied the theoretical one-dimensional Wigner crystal state since the quasi-long-range order produced crystalline correlations. Experimental physicists followed this observation with experimental probing via transport measurements, but the experiments could only probe macroscopic properties of this state.

In principle, a suitable imaging tool is required to observe the unambiguous fingerprint of a Wigner crystal in its real-space structure. Scientists therefore used scanning probe experiments, although they could only image the non-interacting state or show invasive gating by the probe. The measurements highlighted the inherent difficulty of imaging electron interactions with conventional scanning methods. To individually resolve and identify electrons, a macroscopic, metallic or dielectric tip should approach the electrons closer than their mutual separation. Nevertheless, such tips and their interactions can strongly distort the state being studied. Scientists therefore required a different scanning probe to image an interacting state or electron system.

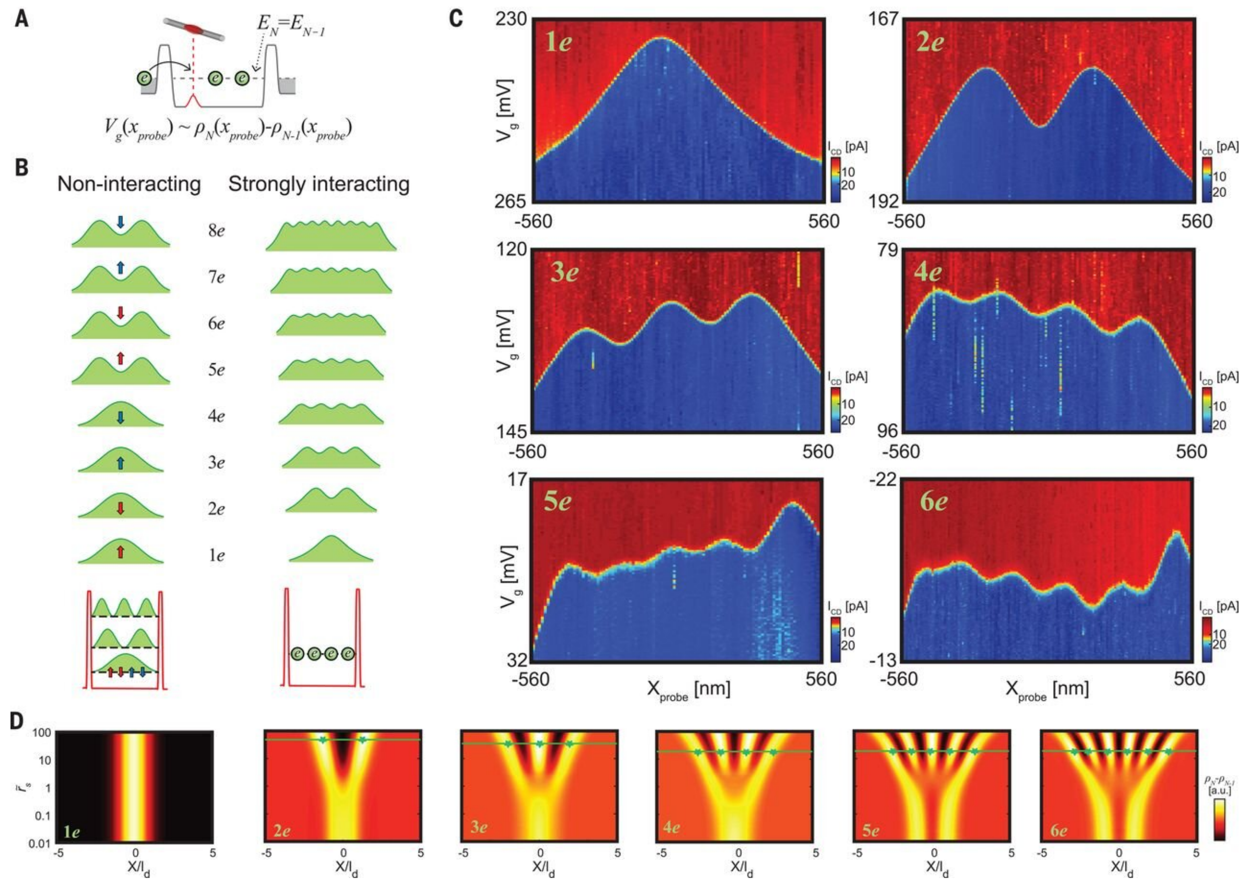


Real-space imaging of the density profile of a single confined electron. (A) To image the density distribution of a single electron confined in a potential “box” (gray), we place a fixed charge in the probe NT and scan it across the system NT. This charge creates a local perturbation at the probe position xprobe (red), which shifts the ground state energy of the system electron, E1 (top panels), proportional to the local density at the probe position E1(xprobe) ~ ρ1(xprobe). By measuring the global gate voltage, Vg, needed to keep the charging of this single electron in resonance with the Fermi energy of the leads, EF, for varying xprobe (bottom panels), the scientists effectively trace the profile of its charge distribution Vg(xprobe) ~ ρ1(xprobe). (B) The derivative of the charge detector current with respect to Vg, dICD/dVg, measured as a function Vg. The sharp charging peak corresponds to the first electron entering the system-NT potential well (in Fig. 3, the green and red labels indicate the number of electrons in the system and in the probe respectively). a.u., arbitrary units. (C) dICD/dVg as a function of Vg and xprobe. The charging resonance traces a curve that gives the charge density of the electron convolved with the point spread function of the probe. (Insets) Illustration of the system and probe devices for different measurement positions. (D) Same as in (C), but for different probe charges from qprobe = 0e to 3e. (E) The traces extracted from panel (D), plotted together. Credit: Science, doi: 10.1126/science.aat0905.

In the present work, Shapir et al. introduced a scanning probe platform that used a carbon nanotube (NT) as a highly sensitive, yet minimally invasive scanning probe to view the many-body density of strongly interacting electrons. The platform contained a custom-made scanning probe microscope operating at cryogenic temperatures (~10 mK) where two opposing NT devices could be brought in close proximity and scanned along each other. The scientists used one device to host the system NT as the 1-D platform under study, and the second device perpendicularly to that to contain the probe NT. They assembled the two devices using a nanoassembly technique to form pristine NTs suspended above an array of metallic gates.

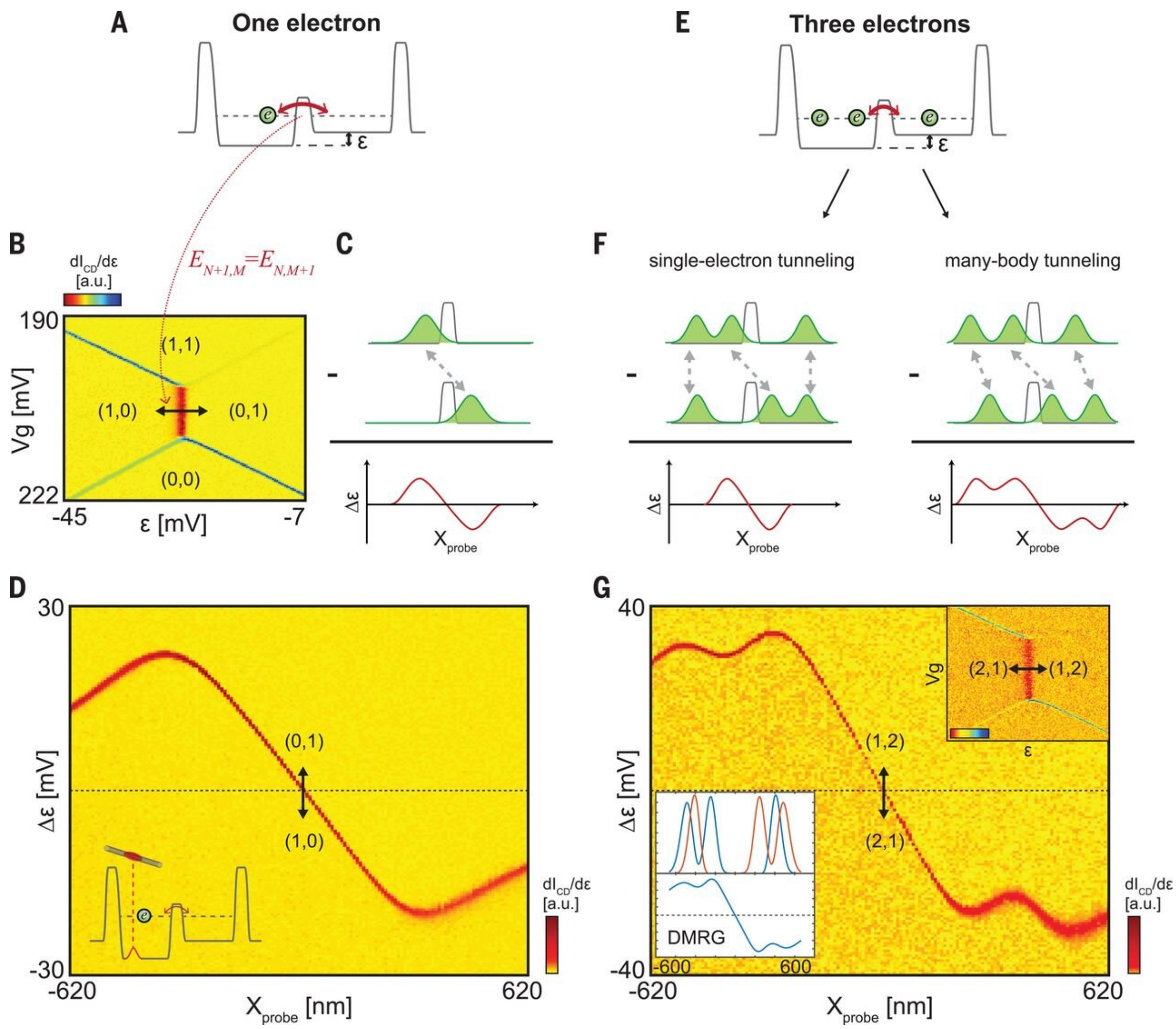
The scientists crucially maintained strong interactions and low disorder in the system to obtain a Wigner crystal by suspending the NTs far above the metallic gates at 400 nm. Then using 10 electrically independent gates they designed a potential that confined the electrons between two barriers 1 μm apart, localizing them centrally in a long suspended nanotube, away from contacts to prevent undesirable interactions.

Shapir et al. used highly opaque barriers to prevent hybridization of the confined electron's wave function with those of the electrons in the rest of the NT. Since transport in this situation was highly suppressed, the scientists probed the confined electrons using a charge detector located on a separate segment of the same NT. The probe NT device separately used in the study maintained an almost identical structure, which only differed by the suspension length of 1.6 μm and the number of gates (three).



: Imaging the differential density of many-electron states. (A) In a charging transition from N – 1 to N electrons, the resonance occurs for EN = EN–1 and the gate voltage shift images the differential density Vg(xprobe) ~ ρN(xprobe) – ρN – 1(xprobe). (B) Illustration of the expected differential density of noninteracting (left) versus strongly interacting (right) electrons in a carbon NT. These sketches also include the finite resolution smearing. Noninteracting electrons occupy the particle-in-a-box wave functions, each being fourfold degenerate because of the spin and valley degeneracy (red and blue arrows). Consequently, the differential density of the first four electrons should be identical and single-peaked, and that of the next four should be double-peaked. For the strongly interacting case, the electrons separate in real space (bottom right), and each added electron will add one more peak to the differential density profile (top right). (C) Measurement of ICD as a function of Vg and xprobe, around the charging peaks of the first six electrons in the system. The curves directly trace the differential density of these many-electron states, showing that they are deep in the strongly interacting regime. (D) The differential density of the first six electrons, calculated with DMRG, which considers long-range electronic interactions as a function of the spatial coordinate x/ld and the effective strength of electronic interactions, r˜s, ranging from very weak (r˜s=0.01) to very strong (r˜s=100). Green stars mark the positions of the peaks measured in the experiment, and the green lines mark the calculated positions (with a single free parameter ld = 160 nm). Credit: Science, doi: 10.1126/science.aat0905.

The scientists demonstrated the working principle underlying the imaging technique known as the "scanning charge," starting with the simplest experiments on imaging the charge distribution of a single electron confined in a 1-D box. Shapir et al. measured the energetic response of the system to a scanned perturbation (agitation) and directly determined the system's density distribution. By measuring the system's energy as a function of the probe NT, the scientists directly resolved the electron's density profile. When measuring the energy, the scientists referenced it to the Fermi energy in the leads and credited the perturbation produced by the probes to the separation between the two NTs and to the confined charge within the probe NT.



Many-body tunneling of the few-electron state. (A) Illustration of the potential landscape, which now includes a central barrier through which an electron can tunnel (red arrow). The detuning voltage, ε, changes the relative height of the bottom of each well. (B) Charge stability diagram for 1e as a function of Vg and ε, measured using dICD/dε (color bar). The states (N, M) denote the charge N (M) in the left (right) wells. The vertical, wider line corresponds to an internal tunneling, occurring when EN+1,M = EN,M+1. (C) Schematic of the expected tunneling differential density for one electron (red "dipole", bottom), given by the difference between its density distribution before and after tunneling [ρ10(x) and ρ01(x)] convolved with the probe's point spread function (PSF). (D) Measured charge detector signal as a function xprobe and the difference in detuning relative to the unperturbed state, Δε. The red trace shows the

$\Delta\varepsilon$(xprobe) necessary to keep the tunneling in resonance (shown schematically in inset), giving the tunneling differential density. (E) Same as (A), but for three electrons in the trap. (F) Two scenarios for the tunneling: (Left) Only the central electron moves in the tunneling event; $\Delta\varepsilon$(xprobe) will show a single dipole, as in the one-electron case illustrated in (C). (Right) Many-body tunneling, in which the coordinates of all the electrons move coherently in the tunneling process; multiple dipoles are expected in the differential tunneling signal. (G) (Top inset) Charge-stability diagram of three electrons, with ICD/dε (a.u.) measured for −42 mV

Shapir et al. obtained six panels in the experiments to indicate the differential density of the six electrons added to the system NT. For minimal perturbations, they performed all scans with one electron in the probe NT. The imaged density profiles clearly differed from those predicted by single-particle physics yet matched those of a strongly interacting crystal. When Shapir et al. increased the number of electrons, the electron spacing reduced, although their overall speed increased to signify electrons confined in a "box" with soft walls. The resulting images provided direct, real-space observations of the electronic Wigner crystals.

To quantitatively understand the measurements, Shapir et al. performed density matrix renormalization group (DMRG) calculations and included long-range Coulomb interactions. The measured electron positions (viewed as green stars) agreed well with those predicted by DMRG, placing the observed crystals well within the strongly interacting regime in the experimental setup. To understand the quantum nature of the Wigner crystal, Shapir et al. measured the tunneling characteristics of the crystal and expected the correlations between the electrons in a crystal to cause the crystal to tunnel through a barrier collectively. They observed the tunneling differential density become more interesting in a system with more than one electron since it displayed direct fingerprints of collective motion.

In this way, Shapir et al. used a new method to directly image the spatial ordering of interacting electrons. Based on the results, they anticipate the possibility of addressing additional basic questions related to the quantum electronic crystal, including the nature of its magnetic ordering. The scanning platform developed by Shapir et al. will allow further exploration of a much wide range of canonical interacting electron states of matter that were previously beyond imaging reach.

More information: I. Shapir et al. Imaging the electronic Wigner crystal in one dimension, *Science* (2019). DOI: 10.1126/science.aat0905

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