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Kramers versus Kramers makes a stable qubit

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In a gate defined quantum dot in Bernal bilayer graphene, a combination of spin and valley protection diminishes spin relaxation drastically and yields a lifetime of 38 seconds.

Graphene, a two-dimensional sheet of carbon atoms arranged in a hexagonal lattice, has many properties that astound: strength greater than steel or diamond, but also high flexibility, transparency, conductivity, and lightness. Even twenty years after the manuscript by Novoselov et al.[1] kickstarted the current two-dimensional (2D) materials revolution by applying adhesive tape to graphite, graphene has not ceased to delight quantum researchers. Few-layer graphene sheets, with and without a small rotation angle between individual sheets, have shown a host of unusual properties such as superconductivity or the fractional anomalous quantum Hall effect. The current revolution owes much to another 2D material, the dielectric hexagonal boron nitride (hBN). hBN allows for the encapsulation of the graphene sheet into a heterostructure, which enables gating and more complex device geometries. One of the hopes of this newfound ability to precisely form and control gate structures such as quantum dots is a long-lived qubit, with inherent stability stemming from the clean material, the low nuclear spin density, and the unique bandstructure of graphene. Now, writing in *Nature Nanotechnology*, Denisov et al.[2] demonstrate hints of this protection by measuring the qubit relaxation time of a Kramers qubit. They find that a unique spin-valley blockade mechanism leads to a two-orders-of-magnitude prolonged relaxation time (T_1) of 38 seconds, compared to the purely spin-blocked case.

In the field of semiconductor spin qubits, many advancements in qubit coherence have stemmed from material improvements. For example, the ability to isotopically purify silicon to ^{28}Si heralded long coherence times[3] and advances in scalability for silicon qubits. Apart from a similar potential for purification, graphene possesses a two-fold valley degeneracy, allowing for the encoding of a qubit in the joint spin-valley subspace. In Bernal bilayer graphene (BBG), the Kane–Mele spin–orbit coupling lifts the four-fold single-particle degeneracy, and an out-of-plane magnetic field can split the ensuing Kramers doublets. The lower-lying Kramers doublet, $|K^-\uparrow\rangle$ and $|K^+\downarrow\rangle$, now constitutes a qubit known as a Kramers qubit. This qubit is encoded in both the spin and valley quantum numbers, and therefore holds promise for protection against two types of noise.

The researchers based their platform on BBG encapsulated in hBN and employed overlapping-gate technology, which has allowed for the development of complex architectures in silicon[4] and germanium[5] quantum dot arrays. Its application to graphene could enable sophisticated devices to explore qubit architectures as well as condensed-matter physics. Denisov and co-workers implemented electrodes made from overlapping gate layers to confine the qubit and sensor quantum dots (Fig. 1). A graphite back-gate adds tunability, specifically the ability to add a displacement field that opens a band gap and decouples the quantum dot from its reservoirs, aiding a long T_1. Previous experiments in BBG[6] employed its peculiar property of trapping electrons and holes alongside each other to show near-perfect particle–hole symmetry in a double quantum dot and predicted long relaxation times. Denisov et al. have now gone a step further and demonstrated spin readout for the Kramers qubit, a key ingredient in a qubit architecture, using the Elzerman scheme. They use pulsed operation while measuring the current running through the sensor and find a strongly enhanced T_1 time in the expected magnetic field range, where the two lowest energy states in the single-particle spectrum are spin-valley blockaded.

These experiments light up a clear path forward for graphene qubits, of which encapsulated Bernal bilayer graphene is emerging as the frontrunning contender. It also establishes a key direction of research incorporating pulsed operation and temporally resolved readout for graphene and other 2D materials. The techniques used by the researchers are broadly applicable to van der Waals heterostructures, where more sophisticated devices incorporating sensitive probes of energy, charge and temporal dynamics could be highly impactful. However, several challenges remain on the path towards a graphene qubit. A glaring problem is that the relaxation time (T_1) and the coherence time (T_2) are different beasts entirely; other materials such as GaAs have succeeded in showing stable T_1 times[7], but T_2 times for GaAs remain discouraging. In principle, graphene's exceptional bandstructure and its atomically flat, clean environment when encapsulated do not rule out long coherence times.

Additionally, Denisov and co-workers measured T_1 in a favourable regime where the quantum dot was closed off to its leads. Faster initialization and readout schemes required for a qubit architecture may require a more open system, which could erode the T_1 achieved. Readout will similarly have to improve to remain high-fidelity in a regime where the integration time is necessarily low, and will have to incorporate state-of-the-art techniques such as radio-frequency reflectometry or dispersive readout. Finally, it is not yet established how one can drive the Kramers qubit and measure its coherence, as coherent manipulation of the valley degree of freedom is not straightforward. The researchers propose a possible drive mechanism for future work, which involves an induced finite spin-valley mixing term, but the gate speed is unknown. With such a demonstration, an even more exciting era for graphene could commence.

Finally, twenty years after the discovery of graphene, the on-chip and industrial integration of this remarkable material, as well as other 2D materials, is still an open challenge. Silicon and to some extent germanium spin qubits have the advantage of being more easily able to exploit the behemoth that is the semiconductor fabrication industry. The Graphene Flagship (https://graphene-flagship.eu/), a scientific research initiative funded by the European Commission's Horizon Europe programme, aims to spearhead a similar industry-wide adoption of 2D material device fabrication, including a 2D experimental pilot line for graphene electronics[8]. We hope that the scaling up of graphene qubits can also proceed hand-in-hand with these efforts in future.

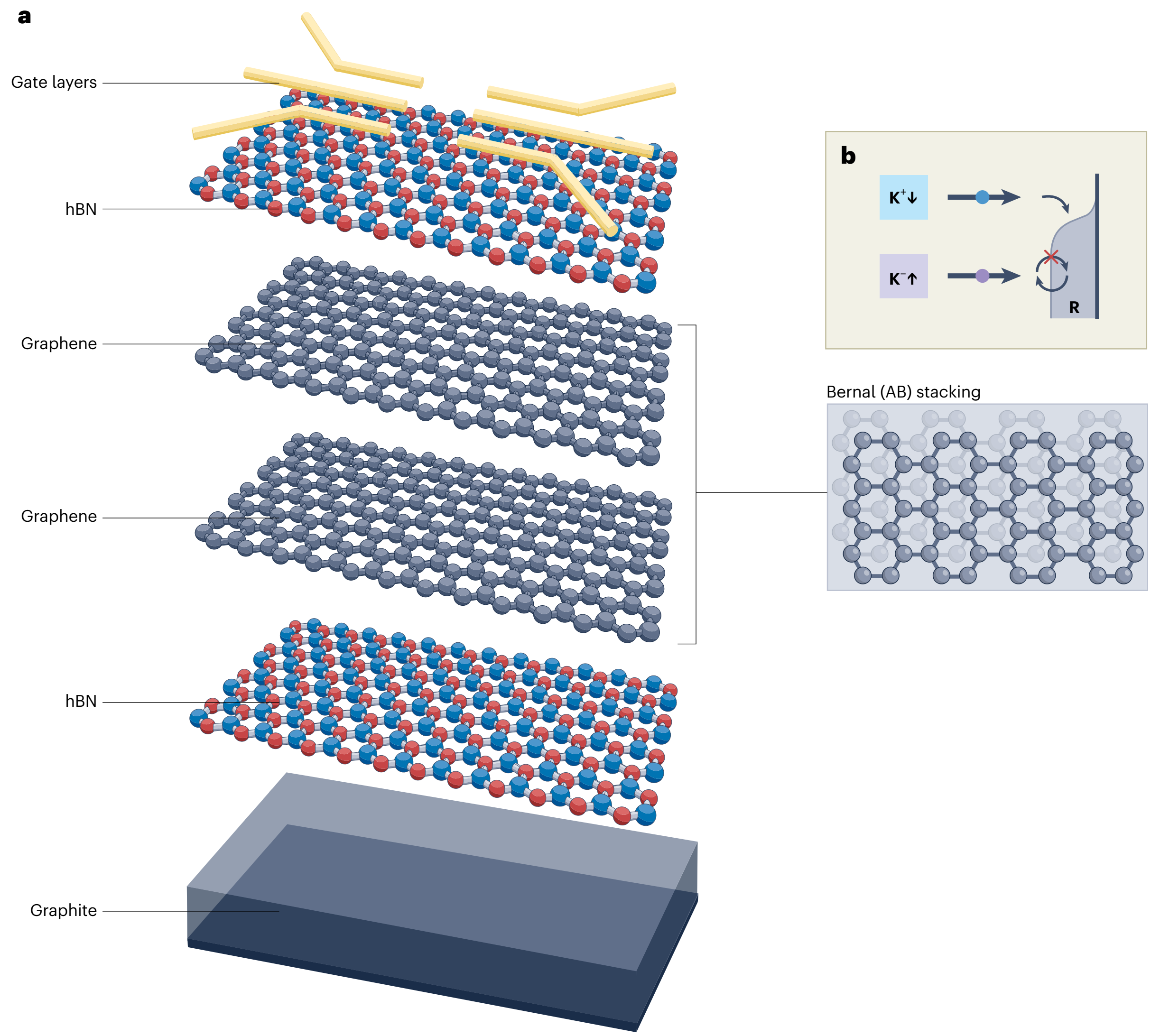

Fig. 1 | A Kramers qubit in Bernal bilayer graphene. a, Bernal bilayer graphene, with atoms in one sheet lying over the centre of a hexagon in the other sheet (AB stacking), is encapsulated in hexagonal boron nitride and forms a protected environment for a qubit encoded in the lowest-lying Kramers doublet. **b**, Such a qubit is encoded in both the spin and valley quantum numbers and can be read out with high fidelity via selective tunnelling into the reservoir (R).

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Competing interests

The author declares no competing interests.