

Master 2 Internship/PhD offer 2026/2027

Laboratory: **Laboratoire de Physique de l'ENS**

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Using Graphene to Probe Strong-Field Quantum Electrodynamics

Scientific project: The goal of this internship is to test the predictions of strong-field quantum electrodynamics on a chip, using the relativistic electrons of graphene.

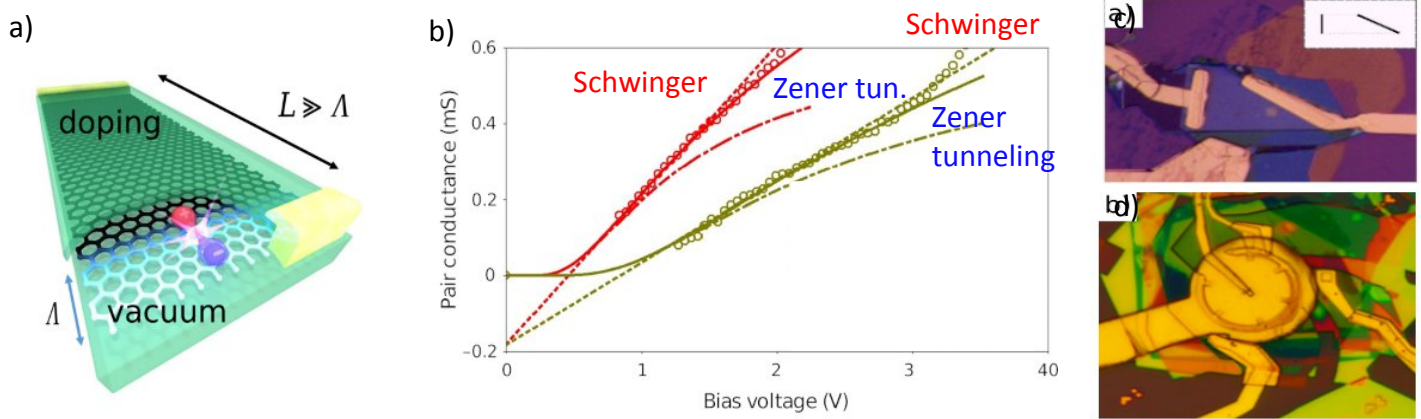


Figure 1 – a) Artistic representation of the fermion-antifermion pair creation near the drain electrode of a hBN-encapsulated graphene field-effect transistor. b) Excess pair conductance associated with the Schwinger current for two different channel doping. The dashed lines are the models for the Schwinger current and the Zener tunneling current, respectively. c and d) Two examples of advanced hBN-graphene heterostructures fabricated at LPENS clean room to study how and where the Schwinger effect nucleates in graphene transistors.

Quantum electrodynamics (QED) is the most precisely verified theory in physics — but only in its low-energy sector. Its strong-field regime, where the vacuum itself becomes unstable and decays into particle–antiparticle pairs (the Schwinger effect), requires electric fields about 10^{18} V.m^{-1} . This is far beyond the largest fields experimentally accessible using petawatt lasers, and direct observation is not expected before the 2060s.

Graphene offers a way around this: its electrons behave as massless Dirac fermions moving at $v_F = c/300$. With the substitution $c \rightarrow v_F$ and the bare electron mass energy $mc^2 \rightarrow E_F$, the Schwinger field drops from $\sim 10^{18} \text{ V.m}^{-1}$ in vacuum to $\sim 10^6 \text{ V.m}^{-1}$ in graphene, bringing strong-field QED within reach of a table-top device. [1] In 2023, our team achieved the first quantitative observation of the 1D Schwinger effect in a graphene transistor at room temperature, which was revealed by a universal excess current, captured by a the Schwinger formula involving only fundamental constants. [2] We also discovered that high-mobility graphene transistor response present other surprizing emergent behaviour when submitted to strong fields. [3]

This internship, leading to a PhD, will take place in the starting phase of a 4-year ANR project (QEDene, Feb 2027 - Jan 2031) with the following goals : (i) understand *where and how* the Schwinger effect nucleates inside the graphene transistor channel using local scanning probes, specifically designed transistors, and

photodetection means, and (ii) push the platform towards testing new strong-field QED predictions — the photo-assisted Schwinger effect, Schwinger luminescence, and the nonlinear "vacuum boiling" regime.

We are looking for candidates with a M2 in condensed matter physics or quantum physics, a solid grounding in quantum mechanics, a taste for hands-on experimental work, basic Python skills, and working English (B2). Prior experience in nanofabrication, RF or optics is a plus — all specific techniques (cleanroom processing, RF measurements, optical spectroscopy) will be taught during the internship. Feel free to reach out for enquiries about the project.

[1] R. Robinett, *Quantum fields from dimensional analysis*, Am. J. Phys. **93.4**, 344 (2025) — an accessible introduction to the underlying ideas of QED analogs.

[2] A. Schmitt *et al.*, *Mesoscopic Klein-Schwinger effect in graphene*, Nature Physics **19.6**, 830 (2023).

[3] L. Abou-Hamdan *et al.*, *Electroluminescence and energy transfer mediated by hyperbolic polaritons*, Nature **639**, 909 (2025).

Methods and techniques: The work will be done at LPENS in Paris under the supervision of Emmanuel Baudin, with the support of Vincent Blavy (PhD student) who will pass on the experimental activity to you. You will join the mesoscopic physics group of LPENS, which leads the QEDene consortium and includes Institut Langevin (Yannick De Wilde team) for scanning probe microscopy (SGM/KPFM) and mid-IR near-field imaging, LPS Orsay for theory and numerical simulations (Chunxiao Liu and collaborators). The experimental work includes :

- The nanofabrication of state-of-the-art hBN-encapsulated graphene transistors (mobility $> 10 \text{ m}^2/\text{V/s}$) in the ENS cleanroom, with the support of cleanroom engineers;
- The measurement of DC and RF transport (up to 67 GHz), under vacuum and/or at cryogenic temperature (4 K);
- The probing of the Schwinger regime under mid-IR illumination and the measurement of devices' NIR–visible emission and Raman response;
- The data analysis, transport and optoelectronic modelling, and exchange with the theory partners (LPS Orsay, ENS Lyon, Sorbonne Université) on a regular basis.

Internship duration: 5 months (March–July 2027), gratification: ~600 €/month

Possibility to go on with a PhD ? Necessary

Envisaged fellowship ? ANR, ED