Non-tunnelling Hartman effect, negative transit time and Fano resonances in electron transmission through graphene multilayers

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Attosecond dynamics of electron transmission through graphene multilayers is studied based on the concept of Wigner time delay implemented in an ab initio scattering theory. The character of the electron propagation through the multilayers is traced to the band structure of bulk graphite. In the forbidden gaps the wave packet transit time τ saturates with thickness, which establishes the Hartman effect at classically allowed energies. In the allowed bands τ oscillates following the transmission resonances (see Fig. 1a-c). Exact expressions for τ in both bands and gaps of a one-dimensional (1D) crystal are presented. In real crystals, the in-plane scattering brings about phenomena missing in 1D models and hitherto unknown: negative transit time is discovered in monolayers of graphene, h-BN, and oxygen. Moreover, the Wigner time delay is shown to diverge at the scattering resonances caused by the emergence of the secondary diffracted beams [1]. The in-plane scattering is also responsible for the N-resonances predicted in Ref. [2]. We show that they are closely connected with the resonances arising in the Fano theory. The N-resonance occurs when the lateral scattering couples the layer-perpendicular incident electron wave to a strictly bound state in the unoccupied continuum (Fig. 1d). A simple model is proposed [3] that manifests the above scattering features and leads to analytical expressions for the Fano parameters of the N-resonances and for the divergent time delay at the resonances caused by the emergence of the secondary beams.

References

[1] E. E. Krasovskii and R. O. Kuzian, arXiv:2404.19440
[2] V. U. Nazarov, E. E. Krasovskii, and V. M. Silkin, Phys. Rev. **B** 87 (2013) 041405(R)
[3] R. O. Kuzian, D. V. Efremov, and E. E. Krasovskii, Phys. Rev. Research 7(2025) 013180

Figures

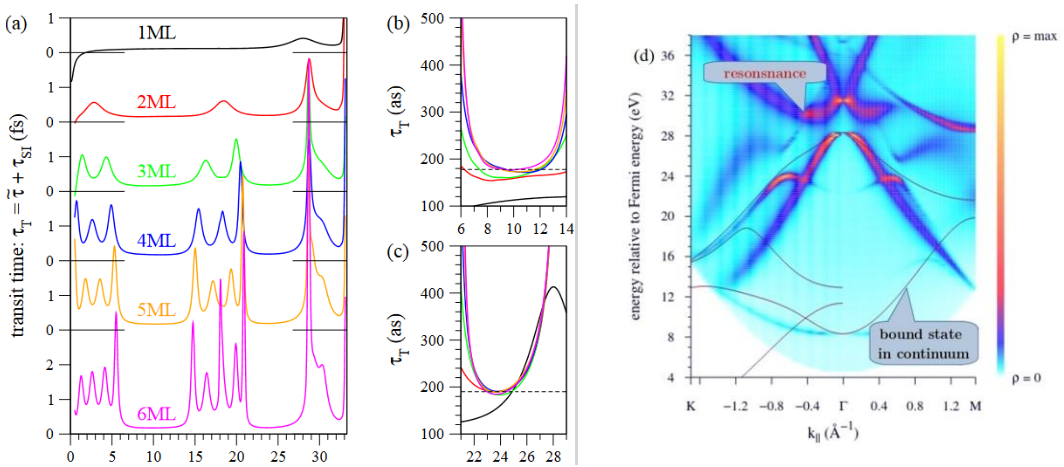

Figure 1: (a) Transit time through 1 to 6 graphene multilayers (ML) as a function of electron energy (in eV); (b), (c) Magnified view of two gap regions: the six curves are plotted in the same axes; (d) $\rho(E,\boldsymbol{k}_\parallel)$ characterizes the dwell time at the scatterer, which peaks at the resonances. The lines superimposed on the map show the dispersion of the strictly bound states.