# Super-Zitterbewegung oscillations in monolayer graphene

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We consider the Zitterbewegung (ZB, trembling motion) in monolayer graphene in the presence of a monochromatic electric wave. In analogy to the Bloch oscillations in the presence of an electric wave [1] we call the considered effect the Super-Zitterbewegung (SZB). Within the dipole approximation the average velocities of delta-like and Gaussian wave packets are calculated as functions of time. The oscillating electric field gives rise to several new effects. First, for nonzero wave there appear two or more oscillating components of the motion, as compared to simple ZB [2]. For low field intensities the additional components have smaller amplitude than ZB, while for large fields they dominate. Second, in the presence of electric wave the motion of the packet exists in two directions. Third, the decay times of Gaussian wave packets in the presence of the wave are much longer than in the field-free case.

We start our analysis assuming weak intensity of the electric field $E_0$ and the wave frequency $\omega_D$ to be smaller than the ZB inter-band frequency $w_Z = 2u|k|$, where $u \simeq 1\times10^6$ m/s and $\boldsymbol{k}$ is the wave vector. The time-dependent Schrodinger equation is solved numerically and the average packet velocity is calculated for delta-like and Gaussian wave packets. Frequencies of ZB and of the satellite related to the external field vary with the field intensity. To find the resulting frequencies we used the Rotating Wave Approximation (RWA). The calculated frequencies are:

$$\omega_\pm = \omega_D \pm \sqrt{(\omega_D-\omega_Z)^2 + \left(\frac{eE_0u}{\hbar\omega_D}\right)^2}. \qquad (1)$$

Figure 1 compares the numerical results with $\omega_\pm$ obtained in Eq. (1) for $\omega_D = 2\times10^{15}s^{-1}$ and $\omega_Z = 2.31\times10^{15}s^{-1}$ for delta-like packet. The upper line describes ZB-related frequency, while the lower one the satellite frequency. If the driving frequency $\omega_D$ is larger than $\omega_Z$ the resulting frequency modes are reversed. For the delta-like packet the oscillatory motion has a permanent character in time. For larger electric fields, or for large differences between $\omega_D$ and $\omega_Z$, a multi-frequency motion appears suggesting that we deal with nonlinear wave phenomena. In that case the amplitude of ZB is comparable or smaller than that of the satellites.

For the Gaussian wave packets similar calculations give the motion decaying in time, but the decay times are more than order of magnitude longer than that for the simple ZB motion. We also calculated a time-dependent polarization of graphene $\boldsymbol{P}(t) \propto \langle\psi(t)|\boldsymbol{r}|\psi(t)\rangle$, which is, on one hand, proportional to the oscillations of position operator and, on the other hand, it can be measured

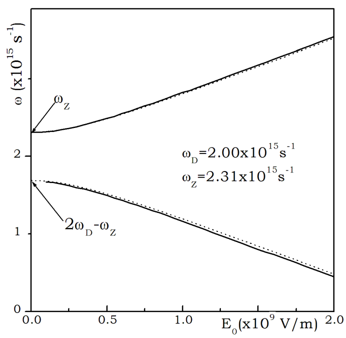


FIG. 1: Frequencies of the two calculated motion components delta-like wave packet in monolayer graphene in the presence of an electric wave versus the wave amplitude. Upper line: ZB-like component; lower line: satellite. Solid lines: the exact results, dotted lines: approximations given by Eq. (1).

in the time-dependent spectroscopy. The dependence of the mode frequencies on the externally controlled parameters $\omega_D$ and $E_0$ should allow one to measure more precisely the ZB frequency $\omega_Z$.

[1] E. Haller, R. Hart, M. J. Mark, J. G. Danzl, L. Reichsollner and H. C. Nagerl, Phys. Rev. Lett. **104**, 200403 (2010), arXiv:1001.1206.

[2] T. M. Rusin and W. Zawadzki, Phys. Rev. B **76**, 195439 (2007), arXiv:cond-mat/0702425.