

Quantum theory of flicker noise in metal films

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Abstract

Flicker ($1/f^\gamma$) voltage noise spectrum is derived from finite-temperature quantum electromagnetic fluctuations produced by elementary charge carriers in external electric field. It is suggested that deviations of the frequency exponent γ from unity, observed in thin metal films, can be attributed to quantum backreaction of the conducting medium on the fluctuating field of the charge carrier. This backreaction is described phenomenologically in terms of the effective momentum space dimensionality, $\mathcal{D}$. Using the dimensional continuation technique, it is shown that the combined action of the photon heat bath and external field results in a $1/f^\gamma$ -contribution to the spectral density of the two-point correlation function of electromagnetic field. The frequency exponent is found to be equal to $1 + \delta$, where $\delta = 3 - \mathcal{D}$ is a reduction of the momentum space dimensionality. This result is applied to the case of a biased conducting sample, and a general expression for the voltage power spectrum is obtained which possesses all characteristic properties of observed flicker noise spectra. The range of validity of this expression covers well the whole measured frequency band. Gauge independence of the power spectrum is proved. It is shown that the obtained results naturally resolve the problem of divergence of the total noise power. A detailed comparison with the experimental data on flicker noise measurements in metal films is given.

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1. Introduction

As is well known, power spectra of voltage fluctuations in all conducting media exhibit a universal low-frequency behavior—for sufficiently small frequencies f they scale as $1/f^\gamma$ —with the frequency exponent γ about unity. This asymptotic behavior is a manifestation of the so-called flicker noise present in any system containing free-like charged particle states [1]. Although the value of γ and an overall proportionality factor in this power law depend on many factors such as sample material and sample geometry, system temperature, etc., there are some important characteristic properties possessed by all flicker noise power spectra. Namely, it is well established experimentally that the noise produced by a biased sample is proportional to the voltage bias squared, and roughly inversely proportional to its volume. The enigmatic property of the

$1/f$ -spectrum is its unboundedness. Flicker noise is present in the whole measured frequency band covering more than 12 decades. Experiments show no flattening of the spectrum for frequencies as low as 10^{-6} Hz. Although on the opposite side of the spectrum the $1/f$ -component is dominated by other types of noise (it compares with thermal noise usually at $f \sim 1$ Hz), it has been detected at frequencies as high as 10^6 Hz.

Despite numerous models suggested since its discovery 80 years ago [2], the origin of flicker noise still remains an open issue. There is a widespread opinion that this noise arises from resistance fluctuations, which is quite natural taking into account its dependence on the applied bias. It has been proposed that the resistance fluctuations possessing the other properties of flicker noise might result from temperature fluctuations [3,4], fluctuations of the charge carrier mobility [5–9], or of the number of charge carriers [10–16]. All these models, however, have restricted validity, because they involve one or another assumption specific to

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the problem under consideration. For instance, assuming that the resistance fluctuations arise from temperature fluctuations, one has to choose an appropriate spatial correlation of these fluctuations in order to obtain the desired profile of the power spectrum. In addition to that, some models involve artificial normalization of the power spectrum, needed to come up with the observed noise level.

Perhaps the main difficulty for theoretical explanation is the unboundedness of flicker noise spectrum. There are many physical mechanisms that generate noise whose power spectrum has the $1/f$ -profile in some frequency domain. But these domains are so narrow in comparison with the whole measured band that the corresponding mechanisms cannot be considered as the general mechanisms of flicker noise generation. For instance, according to Ref. [17], defect motion in carbon conductors generates noise with power spectrum close to the inverse frequency dependence in the frequency range 10^3 – 10^4 Hz, while outside this interval it switches to $1/f^2$. At the same time, the omnipresence of flicker noise and high universality of its properties suggest that there must exist an equally universal reason for its occurrence.

This source is naturally expected to have a quantum origin. Although some of the models suggested so far do consider various quantum effects as underlying mechanisms of flicker noise (such as, for instance, trapping of charge carriers), it may well be that its origin is to be sought at the most fundamental level. Namely, it is plausible that the phenomenon of flicker noise has its roots in the very quantum nature of interaction of elementary charges with electromagnetic field. From this point of view, the problem has been attacked by Handel [18], who suggested that flicker noise is the result of low-energy photon emission accompanying any scattering process, and is related to the infrared divergence of the cross-section considered as a function of the energy loss. Later, the argument was modified and the so-called coherent quantum $1/f$ effect described [19], which is connected with the infrared properties of the dressed electron propagator. Although Handel's theory has been severely criticized in many respects [20], it has found support in independent investigations of Refs. [21,22].

An essentially different quantum approach to the problem was proposed recently in Refs. [23,24]. In this approach, flicker noise is treated as originating from quantum fluctuations of individual electric fields of charge carriers. As was shown in detail in Ref. [24], spectral density of the two-point correlation function of the Coulomb field produced by a charge carrier exhibits the above-mentioned characteristic properties of flicker noise. Namely, the low-frequency asymptotic of the spectral density is $1/f$, the noise intensity induced by external electric field is proportional to the field strength squared, and inversely proportional to the spatial separation between the field producing particle and the observation point. In application to the case of a conducting sample, the low-frequency asymptotic of the voltage fluctuation

power spectrum is found to be

$$C_U(f) = \frac{\eta}{2\pi} \frac{U_0^2}{f}, \quad \eta = \frac{2\alpha^2}{3ec} g\mu T, \quad (1)$$

where U_0 is the voltage bias, T the system temperature, α the fine structure constant, μ the charge carrier mobility, c the speed of light in vacuum, and g a geometrical factor which is roughly inversely proportional to the sample size. The range of validity of this result turns out to be notably wide: The term “low-frequency asymptotic” means that for a given T , Eq. (1) is valid for frequencies satisfying $f \ll 10^{11} T$ Hz, with T expressed in K. Covering well the whole band where flicker noise has ever been observed, this condition in particular sets no low-frequency cutoff, implying that the $1/f$ -spectrum extends down to zero. The fact that the found asymptotic does not require a low-frequency cutoff is the consequence of its oddness with respect to frequency. As discussed in Ref. [24], appearance of such contributions to the spectral density is related to the inhomogeneity in time of fluctuations produced by individual charge carriers, and provides a natural resolution to the problem of divergence of the total noise power.

It was demonstrated in Ref. [24] that Eq. (1) is in agreement with the experimental results of $1/f$ -noise measurements in metals. Naturally, in this comparison only genuine $1/f$ noise data were used, i.e., the data that fit the law $1/f^\gamma$ in which $\gamma = 1$, within experimental error. Experiments show, however, that generally power spectra follow the one-over- f law only in sufficiently thick samples, while in thin samples (films, whiskers) large deviations of γ (up to $\gamma = 1.5$) are often observed. The purpose of this paper is to show that these deviations can be described within the developed theory by taking into account backreaction of the conducting medium on the fluctuating electric field produced by a charged carrier. Staying within the one-particle picture of flicker noise generation, developed in Refs. [23,24], this backreaction can be described as an effective reduction of the momentum space dimensionality. It turns out that this reduction can be naturally realized using the well-known techniques of dimensional continuation [30]. It will be shown that the power spectrum of electromagnetic fluctuations, continued in this way to $\gamma > 1$, adequately describes the observed properties of flicker noise spectra in metal films.

The paper is organized as follows. The effect of the backreaction on photon propagation in a conducting film is discussed in Section 2.1. In Section 2.2, the influence of the heat bath on quantum propagation of electromagnetic and charged field quanta is considered, and the contributions relevant in the low-frequency regime are identified. The power spectral functions of the Coulomb field and voltage fluctuations are defined in Section 2.3, and written down in the form convenient for explicit calculations. Power spectrum of electromagnetic fluctuations in the presence of external electric field is evaluated in Section 3. The low-frequency asymptotic of the voltage power spectrum is found to obey the $1/f^\gamma$ -law with $\gamma = 3 - \mathcal{D}$,

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