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# Microscopic parameters of a stochastic system and variance of physical quantity

## (ideal gas, electric current, thermal radiation of a black body)

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**Abstract.** It is shown that the variance of a random physical quantity F can be expressed and directly calculated with the help of a microscopic parameter which under certain conditions may be called the invariable intrinsic «micro-quantity of chaos» (MQC). MQC is a self-sufficient concept that characterises a physical system or a stochastic process. The following statement is proposed: if a random physical quantity F is additive and its fluctuations are statistically independent, then its variance $<\Delta F^2>$ can be expressed as the product of the mean value $<F>$ and the corresponding value of the MQC = $q_F$, i.e., $<\Delta F^2> = q_F.<F>$. Physical situations are considered in the frame of which this statement has been substantiated. The MQC concept is demonstrated for fluctuations in the ideal gas. Expressions of MQC are proposed for fluctuations of black body radiation, electrical and photocurrents. Arguments for usefulness of the MQC concept are presented.

**Keywords**: random physical quantity, macro parameter, micro parameter, variance, electric current, radiation, thermal noise, shot noise, generation-recombination noise.

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### 1. Introduction

Previously, this problem had been touched on [1, 2 ] in connection with a possibility of immediate calculation of the variance of a macroscopic physical quantity using the measured mean value of this quantity and a well known microscopic parameter $q_F$ .The latter mirrors the macroscopic physical quantity in the microscopic scale of the appropriate physical system. This microscopic parameter $q_F$ shows up in the form of a small invariable quantity (e.g. electron's charge **e**, Boltzmann's constant **k,** etc.) or a statistically defined small quantity (e.g. the most probable thermal energy per single particle **kT** and the like).

The formulation of the above-mentioned possibility is already involved in the general expression for variance

$$<\Delta \mathbf{F}^2> = \mathbf{q}_\mathbf{F}.<\mathbf{F}> \qquad (1)$$

in a number of cases, independently of the specific statistics.

It is well known (see e.g. [3, 4, 5]) that *u n i f o r m*, *b i n o m i a l*, *g e o m e t r i c*, *h y p e r - g e o m e t r i c*, *P o i s s o n's*, *e x p o n e n t i a l* and some other distributions of probability have the structure that can be rewritten in terms of variance according to (1). Meanwhile, rigorous determination of the variance requires more or less cumbrous experimental procedures and calculations to be performed with the help of statistical characteristics and methods.

The most popular characteristics of a random physical quantity **F** are the correlation function $\mathbf{K}_\mathbf{F}(\tau)$, spectrum of fluctuations $\mathbf{S}_\mathbf{F}(\omega)$, and variance $<\Delta \mathbf{F}^2>$. The latter is related to $\mathbf{K}(\tau)$ and $\mathbf{S}(\omega)$ by the folowing equations:

$$<\Delta \mathbf{F}^2> = \mathbf{K}_\mathbf{F}(0) = \int \mathbf{S}_\mathbf{F}(\omega) d\omega.$$

Thus, measuring $<\Delta \mathbf{F}^2>$ involves a more or less complicated work. However, it turns out that the variance $<\Delta \mathbf{F}^2>$ of a random physical quantity **F** can be evaluated in a different way.

We try to answer the following question: what kernel involves the quotient $\mathbf{q}_\mathbf{F}$ of $<\Delta \mathbf{F}^2>$ by $<\mathbf{F}>$ and is applicable for stochastic physical phenomena?

**Table 1.**

| Physical quantity - **F** and its mean value <**F**> | Variance <$\Delta F^2$> with reference [...] | Variance <$\Delta F^2$> in the form of (1) | Quotient of <$\Delta F^2$>/<**F**> = = MQC = $q_F$ |
|---|---|---|---|
| Thermal energy: **E**, <**E**> = $T.C_v$ | <$\Delta E^2$> = = $kT^2.C_V$ [4,5] | <$\Delta E^2$> = = **kT**.<**E**> | **kT** |
| Free energy: **F**, <**F**> = -$\mu$.**N** | <$\Delta F^2$> = = $\mu^2$. **N** [5] | <$\Delta F^2$> = = $\mu$.<**F**> | $\mu$ |
| Preasure: **P**; <**P**>=**N.kT/V** | <$\Delta P^2$> = = **N**(**kT**/<**V**>)$^2$ [5] | <$\Delta P^2$> = = (**kT/V**).<**P**> | **kT/V** |
| Temperature: **T**; <**T**> = = **dE/dS** | <$\Delta T^2$> = = **k**<**T**>$^2$/$C_V$ [5] | <$\Delta T^2$> = = (**k**<**T**>/$C_V$) <**T**> | 2.<**T**>/**N.f**, because $C_V$=**N.f.k/2** |
| Heat capacity: $C_V$; <$C_V$> = = **N.f.k/2** | <$\Delta C_V^2$> = =**N.f.k**$^2$**/4** [5] | <$\Delta C_V^2$> = =**k/2**.<$C_V$> | **k/2** |
| Volume: **V**; <**V**>= **N.kT/P** | <$\Delta V^2$> = =<**V**>$^2$/**N** [5] | <$\Delta V^2$> = =(<**V**>/**N**).<-**V**> | <**V**>/**N** |
| Entropy: **S**; **S** = -(**dF/dT**)$_v$ | <$\Delta S^2$> = $k.C_p$ [4] | <$\Delta S^2$> = =**k.<S>** | **k** |

## 2. Identification of $q_F$

We start from fluctuations of thermodynamic characteristics, e.g. energy – **E**, free energy – **F**, pressure – **P**, volume – **V**, temperature – **T**, heat capacity – $C_v$ and other parameters used in the ideal gas model.

We have deliberately chosen more or less explicable cases to establish a rule which is supposed to exist. The following denotement is used below: **h** is Plank constant, **f** is number of degrees of freedom, **N** is number of particles, $\mu$ is chemical potential, **C** is light velocity.

For fluctuations of thermodinamical parameters of an ideal gas from [4, 5] one has (See Table 1) .

It can be seen that the «quotients» $q_F$ may be considered as physically (or mathematically) defined *c o n c e p t s* that have adequate natural images in the observed phenomena. Under predetermined physical conditions (**P, V, T**), $q_F$ manifests itself in the chaos much like an invariable intrinsic "*m i c r o - q u a n t i t y  o f  c h a o s*" (MQC). Quantities similar to $q_F$ are well defined in irreversible thermodynamics [6] as small parameters used to solve the kinetic equations by violation methods.

Proceeding from the Table 1 and following the above logic, we venture to propose the following list of definitions of MQC's:

- **- 1,** *unity*, e.g. a single particle out of **N** particles of a physical system; then **<$\Delta$N²> = 1.<N>.**
- **- e,** *minimum charge* of the whole one **Q**; then **<$\Delta$Q²> = e.<Q>.**
- **- k/2,** **k / 2** is the *least heat capacity* ($C_V$) related to a single degree of freedom; then **<$\Delta C_v^2$> =(k / 2) <$C_v$>.**
- **- kT** is the *most probable thermal energy of a single particle* of the system; then **<$\Delta$E²> = kT.<E>;**
- **- 2<T> / f.N** is the mean «*temperature*» related to a single degree of freedom of a single particle of the system; then **<$\Delta$T²> = (2<T> / f.N) <T>.**
- **- V/N** is the *intrinsic volume*, i.e., the mean volume occupied by a single particle of the system; then **<$\Delta$V²> = = (<V> / N) <V>.**
- **- $\mu$** is the *single-particle chemical potential*, i.e., the free energy of the system (at constant **V** and **T**) related to a single particle ; then **<$\Delta\Phi^2$> = $\mu$.<$\Phi$>.**
- **-kT/V** is the *minimum pressure*, i.e., the pressure related to a single particle inside the volume **V**; then **<$\Delta$P²> = (kT / V).<P>;**
- **-i = e / $t_i$** is the *elementary random single-electron current* calculated as appropriate for a particular physical phenomenon. This "*intrinsic*" current is measured during the characteristic time $t_i$ that will be discussed below.
- **-k** is the *minimum variation of entropy* **$\Delta$S** of a system (ideal gas !) as a result of the transition of this system between the states $W_{eq}$ and $W_{fl}$ which differ from one another in entropy by a factor of **k** or in free energy **$\Phi$** by the amount of **kT**. Here, $W_{eq}$ is the probability function of the equilibrium state, $W_{fl}$ is the probability function of the state with a fluctuation occurring. Then we ventured to write down **<($\Delta$S)²> = = k.<S>**

It seems timely to emphasise at this point that the search for MQC has to be started from ascertaining the «*c o n c e p t i b i l i t y*» of the MQC itself.

## 3. MQC = $q_F$ for electric current noise

### *3.1. Thermal noise of a resistor*

Derive the MQC for the case of «thermal electric current» = $I_{th}$ which corresponds to the thermal noise. We assume that $q_{th}$ is the current of a single electron which moves with the most probable thermal velocity $V_{th}$ = = $(2kT/m_e)^{1/2}$ inside a resistor having the resistance **R = L/e$\mu_e$ <N>** (here **L** is the length of the resistor, $\mu_e$ = = $\tau_{re}$.**e** / $m_e$ is the mobility, $m_e$ is the effective mass, **<N>** is the number of electrons, $\tau_{re}$ is the electron momentum relaxation time). Between the collisions (time interval is $t_C$) such electron induces a random *current - impetus* = **e** / $t_C$ resulting in a measurable random *current - impulse* $i_{th}$ = = $MQC_{th}$ in the external circuit within the same time interval $t_C$. The concept of a "single electron current " had been used also in [7] for a more exact derivation of thermal noise.

Using the equation the electric dipole momentum conservation in the entire circuit in the form

$$e.|V_{th}|.\,t_C = Q_{th}\,.\,L \qquad (2)$$

(here $Q_{th}$ is the charge induced in the external circuit), one can write for the absolute value of | $i_{th}$ | the following expression

$$| i_{th} | = | Q_{th} / t_{re} | = e.|V_{th}| / L = e / T_t . \quad (3)$$

$T_t$ –is the electron *transit* time between the terminals of the resistor.

There is a reason to believe that the mean value of the «thermal voltage» across the resistor is equal to $<|U_{th}|> = kT / e$ ; then, the «mean value of the thermal current» of **N** electrons is

$$<|I_{th}|> = 2.kT / eR. \quad (4)$$

The factor **2** appears because the two directions of current $I_{th}$ are taken into account. Constructing the product of $2<|I_{th}|>\cdot| i_{th} |$ for the variance of $I_{th}$ according to the above conjecture, we have

$$<\Delta I^2_{th}> = (2kT / eR)e / T_t = (2kT / R) T_t^{-1}. \quad (5)$$

It turns out that (5) can be brought to quite a good agreement with the classic Nyquist-Johnson formula [5, 7 ] by using the expression (1) and assuming $T_t^{-1} = 2\Delta f$ in accordance with the Bracewell theorem [8].

If $\Delta f$ is the frequency band of the measuring circuit, limited by the time constant **RC** (where **C** is the capacitance of the circuit), then, obviously, MQC $\cong$ **e / RC**.

### *3.2. Shot noise*

The formula for variance of current $<i_{SN}>$ in the presence of shot noise is well known (e.g. see [7]) :

$$<\Delta i^2> = 2< i_{SN}>e\Delta f. \quad (6)$$

It can obviously be written in the manner of (1) as well. Assuming the MQC to be a *single-electron random current pulse* (pulse duration is $t_C$) under the external voltage **U** = = **E.L** (**E** is the field strength), one has

$$<i_{sn}(1)> = <e.\mu_e E / L > = e/T_{de} . \quad (7)$$

Here $T_{de} = L/\mu_e E$ is the *drift* time of electron between the terminals (compare with (3)). If $T_{de}^{-1} = 2.\Delta f$ [8], one can get (6) merely by multiplying (7) by $< i_{SN} >$.

### *3.3. Generation-recombination (G-R) noise*

This kind of noise is typical for nondegenerated semiconductors where random events of generation and subsequent recombination of electrons and/or holes take place. Variance of the **G-R** current can be constructed in the same way as we have expressed the shot noise.

Examine the following situation: the electric charge is measured for a time $T >> \tau_{re}$. The total charge in the external circuit $Q_{Ex}$ consists of the sum of single-electron induced charges $Q_j(1)$. By analogy with (2), the equality $e.|E.et_c/m_e|.dt_C = dQ_j(1).L$ is fulfilled, which after integrating and averaging over collision times gives

$$<Q_{ex}(1)> = e.\tau_{re} / T_{de} . \quad (8)$$

Hence, if the number of $Q_{ex}(1)$- "pulses" over the measurement time **T** is approximately equal to $T/\tau_{re}$, then for the total external charge we have

$$Q_{Ex} = \Sigma\, Q_j(1) \cong (T/\tau_{re}) \cdot <Q_{ex}(1)>. \quad (9)$$

To collect the maximum charge in the external circuit, we assume that the time **T** of current measurement is equal to the drift time ($T_{de}$) for an equilibrium electron, and to the time of recombination ($\tau_{Re}$) for a nonequilibrium one. Then, we have

$$Q_{Ex}(T_{de}) = e \quad (9^*), \qquad \text{and} \qquad Q_{Ex}(t_{Re}) = e.t_{Re} / T_{de} . \quad (9^{**})$$

One can see from (9*) and (9**) that the charge gain $G_e = \tau_{Re} / T_{de}$ [9] takes place for a *nonequilibrium* electron only.

The expression for the *microscopic intrinsic chaotic current*, i.e. $MQC_{GR}$, in the external circuit can be found with the help of (8) and (9**)

$$MQC_{GR} =(e / T_{de}).(\tau_{Re} /\tau_{re}) . \quad (10)$$

Then, let us consider three examples.

1) Ordinary **GR**. According to (9**), $MQC_{GR}$ is equal to $G_e.(e / \tau_{re})$, where $G_e = \tau_{Re} /T_d$ is the above-mentioned gain. Keeping in mind that $2Df = \tau_{re}^{-1}$ [8], we can easily write down

$$<\Delta I^2>_{GR} = G_e (e / t_{re)} . <I_{GR}> = 2eG_e <I_{GR}>\cdot Df. \quad (11)$$

2) A strong electric field **E** is applied. Nonequilibrium carriers are extracted from the sample, and their lifetime $\tau_{Re}^*$ is decreased proportionally to $[1 - exp(-L / \tau_{Re}.m_e.E)]$. Thus, the current $I_{GR}$ of nonequilibrium electrons (e.g. those excited by light) will have the following variance:

$$<\Delta I^2_{GR}>= 2e.G_e^*.<I>.\Delta f.=$$

$$= 2e <I_{GR}> \Delta f.G_e.[1 - exp(-L/\tau_{Re}.\mu_e.E)]. \quad (12)$$

3) Bipolar conductivity, with photocurrent carried by electrons and holes. Then, for the bipolar micro-quantity of chaos $(MQC)_b = (MQC)_e + (MQC)_h$ we can write

$$(MQC)_b = (e/\tau_{re}).G_e + (e/\tau_h).G_h = e^2.E.t_{b.}(m_e^{-1} + m_h^{-1})/L$$

Here we assumed that $\tau_n = \tau_h = \tau_b$. Then, for the variance of *bipolar* $I_{GR}$ one has

$$<\Delta I^2_{GR}> = 2e.G_b.<I_{GR}>.\Delta f =$$

$$= 2e^2.<I_{GR}> \Delta f.t_{b.}(m_e^{-1} + m_h^{-1}).E / L. \quad (13)$$

The multiplier **4** (instead of **2** in formula (13)) can obviously appear when equality $m_e = m_h$ is satisfied. So, (11) and (13) are found to coincide with the well-known expression for the **G-R** noise [ 7, 10].

These boring speculations are needed here only to emphasise that application of the MQC concept requires one to keep intra-correspondence in the hierarchy of characteristic times and quantities for each specific physical situation.

## 4. MQC for thermal emission of a black body (b.b.)

Fluctuations of the energy of b.b. emission involve two aspects: quantum and wave. Let us evaluate these fluctuations separately [1]. The energy of a single photon $h\nu$ can be accepted as $MQC_Q$ for the quantum mechanism of fluctuations. Then, for the b. b. emission with a mean energy $<E(\nu)>$

in the q u a n t u m range we, according to (1), have the variance

$$<\Delta E^2>_Q = h\nu.<E(\nu)>. \tag{14}$$

Next, for the w a v e range the quotient $<E(\nu)> / Z(\nu)\,\Delta\nu$ may also be interpreted as $MQC_W$, i. e. the mean radiation energy per one mode out of the whole number of modes [5] $Z(\nu).\Delta\nu = V.8\pi\nu^2.\Delta\nu/C^3$ (here **V** is the volume of b.b. cavity). Then, we have

$$<\Delta E^2>_W =<E(\nu)^2> / Z(\nu).\Delta\nu. \tag{15}$$

As we deal with a Bose gas, the total variance is written as the sum of (14) and (15)

$$<\Delta E^2>_{tot} = h\nu.<E(\nu)> + <E(\nu)>^2 / Z(\nu).\Delta\nu. \tag{16}$$

It can be rigorously shown [5] that fluctuations of b.b. photon numbers N within a frequency band from $\nu$ to $\nu+\Delta\nu$ is equal to

$$<\Delta N^2> = <N>.(1 + <n>). \tag{17}$$

Here $<n> = [\exp(h\nu / kT) - 1]^{-1}$ is the Plank distribution.

As a consequence of (16) and (17), we can add to the above-listed MQCs the following new ones for b.b. radiation:

$<E> / Z(\nu)d\nu$-is the mean radiation energy per single mode of b.b. radiation field,
$(1+<n>)$ - intrinsic photon number in b.b. emission,
$(1+<n>).\Delta\nu$ - intrinsic b.b. photon flow,
$(1+<n>).h\nu$ - intrinsic energy in b.b. emission,
$(1+<n>).h\nu.\Delta\nu$ - intrinsic b.b. photon flow power.

Thus, formula (1) works in the case of thermal b.b. radiation as well. This involves processes of interference (correlation) mirrored by the presence of the term $<n>$ which, within the quantum region of b.b. spectrum, can be considered as a first order small correction, following the terminology of [6, 11].

## 5. Conclusion

In the framework of the above consideration, the concept of variance takes on certain heuristic meaning directly connected with micro parameters of a stochastic physical system.

It seems that the following statement may be suggested in view of formula (1): if a random physical quantity **F** is additive and its fluctuations are statistically independent, then its variance $<\Delta F^2>$ can be expressed as the p r o d u c t of the m e a n v a l u e of $<F>$ by the m i c r o s c o p i c p a r a m e t e r, i. e. $MQC = q_F$, which corresponds to the physical e s s e n c e of **F.**

What is the utility of the MQC concept? The answer, as we suggest, is as follows:

1) an ordinary measurement of the mean value of **F** enables us to evaluate $<\Delta F^2>$ without measuring the fluctuation spectra $S_F(w)$ or correlation functions $K_F(t)$ in many practical situations if MQC is known *with certainty*;

2) comparison of $<\Delta F^2>_{exp}$ obtained by integration of experimental spectra $S_F(w)$ or by measuring $K_F(t)$ with $<\Delta F^2>_1$ which is «constructed» in accordance with the MQC-concept (i. e. formula (1)) provides information about adequacy of our notions concerning the physical details of the stochastic phenomenon under study.

3) determination of MQC for a new or inadequately studied stochastic phenomenon by applying formula (1) to $<\Delta F^2>$ obtained by integration of the fluctuation spectra $S_F(w)$, or from measurements of the correlation function $K_F(t)$, provides quantitative data about the micro parameters of stochastic system. This MQC can become a starting point for physical simulation of the phenomenon under study.

4) theoretical investigation of fluctuations by means of extracting the MQC from the subtleties of the physical nature of the phenomenon makes it easy to develop concepts of the essence of the stochastic phenomenon. These concepts could amplify the common «fluctuation formalism» with useful physical imagery.

Nevertheless, the following question is of most interest for us: why the microparameter multiplied by the mean value of physical quantity gives us the variance of this physical quantity ?

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## МІКРОСКОПІЧНІ ПАРАМЕТРИ СТОХАСТИЧНОЇ СИСТЕМИ І ДИСПЕРСІЯ ФІЗИЧНОЇ ВЕЛИЧИНИ (ІДЕАЛЬНИЙ ГАЗ, ЕЛЕКТРИЧНИЙ СТРУМ, ТЕПЛОВЕ ВИПРОМІНЕННЯ ЧОРНОГО ТІЛА)

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**Резюме.** Показано, що дисперсія випадкової фізичної величини F може бути виражена і безпосередньо підрахована за допомогою мікроскопічного параметра, котрий, при певних умовах, може вважатись незмінною притаманою цій F «мікро-кількістю хаосу» (МКХ). МКХ є самодостатнє поняття, що характеризує фізичну систему, або стохастичний процес. Пропонується таке твердження: якщо випадкова фізична величина F є адитивною, а її флуктуації статистично незалежні, тоді її дисперсія $<\Delta F^2>$ може бути виражена як добуток середнього значення $<F>$ і відповідного значення МКХ = $q_F$ , тобто $<\Delta F^2> = q_F.<F>$ . Розглядаються фізичні ситуації, в межах яких це твердження може бути підтвердженим. Поняття МКХ демонструються для флуктуацій в ідеальному газі. Пропонуються вирази МКХ для флуктуацій теплового випромінення АЧТ, електричних і фотострумів. Висловлюються аргументи щодо корисності поняття МКХ.

**Ключові слова**: випадкова фізична величина, макро параметр, мікро параметр, дисперсія, електричний струм, випромінення, тепловий шум, дробовий шум, генераційно-рекомбінаційний шум.

## МИКРОСКОПИЧЕСКИЕ ПАРАМЕТРЫ СТОХАСТИЧЕСКОЙ СИСТЕМЫ И ДИСПЕРСИЯ ФИЗИЧЕСКОЙ ВЕЛИЧИНЫ (ИДЕАЛЬНЫЙ ГАЗ, ЭЛЕКТРИЧЕСКИЙ ТОК, ТЕРМИЧЕСКОЕ ИЗЛУЧЕНИЕ ЧЕРНОГО ТЕЛА)

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**Резюме.** Известно, что дисперсия случайной физической величины F может быть выражена и прямо вычислена с помощью микроскопического параметра, который при определенных условиях может называться постоянная действительная «микро-величина хаоса» (MQC). Понятие MQC само-достаточное, которое характеризует физическую систему или стохастический процесс. Предлагается следующее утверждение: если случайная физическая величина F аддитивна и ее флуктуации статистически независимы, тогда дисперсия $<\Delta F^2>$ может быть выражена как произведение среднего значения $<F>$ и соответствующего значения MQC = $q_F$, т. е. $<\Delta F^2> = q_F<F>$. Рассматриваются физические ситуации, в рамках которых это утверждение может быть обосновано. Понятие MQC продемонстрировано для флюктуаций в идеальном газе. Выражения MQC предложены для флюктуаций излучения черного тела, электрического и фототоков. Представлены аргументы о полезности понятия MQC.

**Ключевые слова:** случайная физическая величина, макропараметр, микропараметр, дисперсия, электрический ток, излучение, термический шум, дробовой шум, шум генерации-рекомбинации.