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## Abstract

## Full Text

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# ON THE POSSIBILITY OF REDUCING THE MAGNITUDE OF IONIZATION FLUCTUATIONS IN GASES

As is known, the magnitude of the fluctuations of ionization produced by ionizing particles determines the limiting resolving power in ionization methods of measuring nuclear particles. In Fano' s theoretical work ([1]), the following expression was obtained for the root-mean-square fluctuation $\delta_N$ of the number of ion pairs $N$, at a fixed energy of the ionizing particles, which produce on average $N_0$ ion pairs:

$$\delta_N^2 = \frac{\overline{(N-N_0)^2}}{N_0^2} = \frac{F}{N_0}. \tag{1}$$

An analytical expression for the coefficient $F$ will be given below. According to Fano' s estimate, for the case of ionization in gases $F = 0.3 \div 0.5$. Measurements we recently carried out of the magnitude of ionization fluctuations in argon showed that $F = 0.22$. This means that, for example, the limiting value of the half-width of an $\alpha$-line in an ionization $\alpha$-spectrometer is 14 keV at an energy $E_\alpha = 6.0$ MeV.

Analyzing the results of Fano' s calculations, one can show that the magnitude of ionization fluctuations is determined mainly by the redistribution of the number of ionized and excited atoms. Their total number, apparently, fluctuates considerably less. This leads to the idea that in an ionization spectrometer it is necessary to record precisely the sum of ionized and excited atoms, which can be accomplished, for example, in the following way. It is known that in atoms of noble gases the lowest excitation level is metastable and that, when such excited atoms collide with molecules of an admixture whose ionization potential is smaller than the energy of the metastable state, ionization of these molecules occurs (additional ionization) ([2]). Obviously, if the probability of additional ionization is large, then the magnitude of the total ionization recorded in the spectrometer will be equal to the sum of the initially ionized and excited atoms.

## Magnitude of the fluctuations of total ionization

In calculating the magnitude of the fluctuations of total ionization we shall use the method developed by Fano ([1]). Repeating Fano' s reasoning completely, one may obtain the following expression for the relative root-mean-square fluctuation $\delta_J$ of the total ionization $J$:

$$\delta_J^2 = \frac{\overline{(J-\bar{J})^2}}{\bar{J}^2} = \frac{\bar{N}^l}{\bar{J}^2}\left(n_k - \frac{E_k}{W}\right)^2, \tag{2}$$

where $n_k$ is the number of ion pairs formed in the $k$-th collision accompanied by a loss of energy $E_k$ by the ionizing particle; $\bar{J}$ is the mean value of the total ionization ($\sim$ the number of ion pairs); $W = E_\alpha/\bar{J}$ is the mean energy for the formation of one ion pair; $\bar{N}$ is the mean number of inelastic collisio-

···collisions. (Here and below, by inelastic collisions we mean collisions leading to a loss of energy of the ionizing particle. These include collisions with atoms of the medium both by the particle itself and by $\delta$-electrons, but do not include collisions of molecules with excited atoms.)

Let us introduce the following notation: $P_k^i$ is the fraction of inelastic collisions leading to excitation with an energy loss $E_k^i$; $P_k^e$ is the fraction of inelastic collisions leading to excitation with an energy loss $E_k^e$; $\sigma$ is the probability that excitation is removed with the formation of additional ionization; $P = \sum P_k^i$ is the total probability of ionization in an inelastic collision; $W_i = \sum P_k^i E_k^i/P$ is the mean energy loss over all collisions leading to ionization; $W_e = \sum P_k^e E_k^e/(1-P)$ is the mean energy loss over all collisions leading to excitation.

Using the quantities introduced, it is easy to obtain the following equalities:

$$W_0 = W_i + W_e\frac{1-P}{P}; \tag{3}$$

$$W = W_0\frac{1}{1+\sigma\frac{1-P}{P}} = W_0 A; \tag{4}$$

$$\bar{N} = N_0/P; \qquad \bar{J} = N_0/A. \tag{5}$$

where $N_0$ and $W_0$ are the mean number of ion pairs and the mean energy of formation of an ion pair in the absence of additional ionization.

Substituting (5) into (2), we obtain:

$$\delta_J = \frac{1}{N_0}\frac{A^2}{P}\overline{\left(n_k - \frac{E_k}{W}\right)^2} = \frac{F}{N_0}. \tag{6}$$

In calculating $F$, all inelastic collisions may be divided into three groups.

A. Collisions leading to ionization. This includes both primary ionization and ionization by $\delta$-electrons, and it is assumed that the ratio of the cross sections of the different inelastic collisions does not depend on the nature and energy of the ionizing particle.

B. Collisions leading to excitation of atoms with subsequent removal of this excitation with the formation of additional ionization.

C. Collisions leading to excitation of atoms and not accompanied by additional ionization.

Obviously, for collisions of types A and B, $n_k = 1$, whereas in case C $n_k = 0$. Bearing this in mind and using (6), we obtain:

$$F = \frac{A^2}{P}\left[\sum_{\text{ion}} P_k^i \left(1 - \frac{E_k^i}{W}\right)^2 + \sum_{\text{exc}} P_k^e \sigma \left(1 - \frac{E_k^e}{W}\right)^2 + \sum_{\text{exc}} P_k^e (1-\sigma)\left(\frac{E_k^e}{W}\right)^2\right], \tag{7}$$

where the summation extends over all collisions leading to ionization (the first sum) and to excitation (the second and third sums). Introducing into (7) $W_i$ and $W_e$ and using (4), we finally obtain

$$F = \Phi(\sigma) + \frac{1}{PW_0^2}\left[\sum_{\text{ion}} P_k^i (W_i - E_k^i)^2 + \sum_{\text{exc}} P_k^e (W_e - E_k^e)^2\right]; \tag{8a}$$

$$\Phi(\sigma) = \frac{1}{W_0^2}\left[(W - W_i)^2 + \sigma\frac{1-P}{P}(W - W_e)^2 + \frac{1-P}{P}(1-\sigma)W_e^2\right]. \tag{8b}$$

The last two terms in (8a), denoted below by $\Phi_i$ and $\Phi_v$, are due to fluctuations of energy losses in ionization and excitation and do not depend on additional ionization. $\Phi(\sigma)$ is determined by the redistribution of the number of ionized and excited atoms, as well as by fluctuations arising in the process of additional ionization. In the limiting case of absence of additional ionization ($\sigma = 0$), (8) becomes Fano' s formula

$$F = \frac{1-P}{P^2}\frac{W_e^2}{W_0^2} + \frac{1}{PW_0^2}\left[\sum_{\text{ion}} P_k^i (W_i - W_k^i)^2 + \sum_{\text{excit}} P_k^e (W_e - E_k^e)^2\right]. \tag{9}$$

In the case $\sigma = 1$, (8b) can be represented in the form

$$\Phi_{\text{lim}} = \frac{(W_i - W_e)^2}{W_0^2}(1-P) = \frac{(W_i - W_e)^2 (W_0 - W_i)}{W_0^2 (W_0 - W_i + W_e)}. \tag{10}$$

Fig. 1. Dependence of $\Phi/\Phi_0$ on the probability of additional ionization $\sigma$.

Figure 1: Fig. 1. Dependence of $\Phi/\Phi_0$ on the probability of additional ionization $\sigma$.

**Discussion of results. 1.** Figure 1 gives the calculated dependence of $\Phi(\sigma)/\Phi_0$ for argon and helium ($\Phi_0$ is the value of $\Phi(\sigma)$ at $\sigma = 0$). In the calculation, the ionization potential $I$ and the energy of the first excitation level $U_1$, respectively, were taken as $W_i$ and $W_e$. As is seen from the figure, with increasing probability of additional ionization the value of $\Phi(\sigma)$ decreases almost 30-fold in the case of argon and 100-fold in the case of helium. The values of $\Phi_{\text{lim}}$ for He, Ne, Ar, Kr, and Xe were found to be, respectively, 0.0038; 0.0083; 0.012; 0.014; and 0.016, whereas $\Phi_0 = 0.33 \div 0.38$. The quantity $\Phi_{\text{lim}}$, as follows from (10), is determined mainly by the difference $W_i - W_e$. Exact data on these quantities are not yet available. It is possible that the listed values of $\Phi_{\text{lim}}$ are somewhat lower than the real ones. Nevertheless, it may be asserted that, in the case of using light noble gases (He, Ne, Ar), with effective additional ionization it is possible to reduce the value of $\Phi(\sigma)$ to $0.01 \div 0.03$.

Fig. 1. Dependence of $\Phi/\Phi_0$ on the probability of additional ionization $\sigma$

**2.** It is possible to estimate the last two terms ($\Phi_i$ and $\Phi_v$) in (8a), assuming that the energy losses $E_k^i$ and $E_k^e$ are uniformly distributed in the energy intervals $I \leq E_k^i \leq 2I$ and $U_1 \leq E_k^e \leq I$. As follows from the estimate, in all the cases considered the quantity $\Phi_v$ is negligibly small, while the quantity $\Phi_i$ is approximately the same and equal to $\sim 0.03$. However, it must be taken into account that the assumption of a uniform distribution of $E_k^i$ is very crude and leads to a considerable increase in $\Phi_i$. Therefore one may expect that the real value of $\Phi_i$ is $0.01 \div 0.02$. Thus, there are grounds to believe that, with sufficiently effective additional ionization, it is possible to reduce the value of the coefficient $F$ to $0.02 \div 0.04$, i.e. by approximately a factor of 10, which in the case of an ionization $\alpha$-spectrometer means a reduction of the limiting half-width of an $\alpha$-line to $4 \div 6$ keV.

**3.** As follows from the above, the accuracy of measuring the energy of an ionizing particle is substantially improved when the total number of ionized and excited atoms is registered. Of course, the method of producing additional ionization through collisions of the second kind is not

the only one, although it also appears realistic ([2,3]). For these same purposes one may use, for example, photoionization of impurities added to noble gases.

Up to now we have spoken about the production and registration of additional ionization. It is obvious, however, that everything that has been said also applies to the case in which the number of excited atoms is registered, while the ionized atoms are converted into excited ones. Such a situation occurs, for example, in a gas scintillation counter under conditions of complete recombination of the ions. Consequently, the limiting resolving power of such a counter should be

very high.

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*Note: Figure translations are in progress. See original paper for figures.*