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Abstract

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MEASUREMENT OF FLUCTUATIONS OF IONIZATION PRODUCED BY α-PARTICLES IN ARGON

At the present time, methods for measuring the energy of nuclear particles by the magnitude of the ionization they produce have become widely used. In this connection, the question of fluctuations in the number of ion pairs formed as a result of ionization acquires special importance, since the magnitude of these fluctuations sets the limit of the attainable resolving power in ionization methods.

This question was considered in Fano' s theoretical work (^{1}). He obtained the following expression for the mean-square fluctuation δ_N of the number of ion pairs N at a fixed energy of the ionizing particles (^{2}):

$$\delta_N^2 = \overline{(N - N_0)^2} = FN_0; \tag{1}$$

$$F = \frac{(1-p)W_i^2}{p^2 w^2} + \frac{1}{w^2 p}\left[\sum_{\text{ion.}} p_k^{(i)}\left(\omega_k^{(i)} - W_i\right)^2 + \sum_{\text{exc.}} p_k^{(e)}\left(\omega_k^{(e)} - W_e\right)^2\right]. \tag{2}$$

Here N_0 is the mean number of ion pairs formed as a result of ionization; p_k is the fraction of inelastic collisions accompanied by an energy loss ω_k, where the indices i and e refer respectively to the processes of ionization and excitation; $p = \sum_k p_k^{(i)}$ is the total probability of ionization; W_i is the mean energy loss over all collisions leading to ionization; W_e is the mean energy loss in collisions leading to excitation of the molecules of the substance; w is the mean energy expended in the formation of one ion pair.

Fano' s formula is convenient for estimating the upper limit of the values of δ_N; a more accurate determination of δ_N is difficult, since exact data on the quantities entering formula (2) are usually lacking. In addition, in Fano' s calculations it was assumed that the probability ratios of different inelastic processes are independent of the nature and energy of the ionizing particles. This assumption is not entirely correct and may significantly alter the results of the calculations.

Fig. 1. α-spectrum of Ra^{224}

Figure 1: Fig. 1. α-spectrum of Ra^{224}

Therefore numerical calculations carried out using Fano' s formula are only approximate in character. According to these calculations, the values of F for different gases lie within the limits $1/2 \div 2/3$.

An experimental determination of the magnitude of ionization fluctuations has in fact not been carried out up to now. One can only point to the work (^{3}), in which the fluctuation of pulse magnitudes in a proportional counter filled with argon was investigated for ionization by low-energy electrons. From these measurements, in agreement with Fano' s conclusions, it follows that $F < 1$. However, obtaining more definite data on the value of F in this case does not appear possible, since the mean-square fluctuation of the counter amplification factor is a rather uncertain quantity. On the other hand, in work (^{4}) it is asserted that, for ionization of argon by α-particles, $F \cong 15$; the erroneousness of this assertion is beyond doubt.

Experimental determination of δ_N in argon.

To measure the fluctuations of ionization produced by α-particles in argon, a pulsed ionization chamber with a grid was used. The ionization produced by α-particles of Ra^{224} ($E_\alpha = 5.681$ MeV) and Fr^{221} ($E_\alpha = 6.336$ MeV) was measured. The chamber was filled with chemically pure argon (99.96%). To reduce the electron collection time, 1.5% CH_4 was added to the argon. With this filling, a regime could easily be obtained in the chamber in which the recombination effect was completely eliminated, the passage of electrons through the grid was ensured, and “attachment” of electrons to neutral impurity molecules was absent. To improve the quality of the spectrum, electron collimation was introduced, sharply reducing the influence on the resolution of the thickness of the source layer, the transparency of the grid, and the pulse rise time. The necessary stability of the apparatus was provided by a circuit stabilizing the gain coefficient of the amplifying tract. Special attention was given to improving the signal-to-noise ratio. This improvement was achieved by reducing the input capacitance ($C_{\text{in}} = 10\ \mu\mu$F) and by selecting the operating regime of the first tubes of the preamplifier. The rms fluctuation δ_{sh} of the pulses at the output of the amplifier, due to radio noise, could be measured directly from the spectrum of generator pulses applied to the input of the preamplifier. According to these measurements, $\delta_{\text{sh}} = 4.7$ keV. In terms of the charge acting at the input of the amplifier, this amounts to $175\,e$ (e is the electron charge), which is considerably lower than the noise level obtained in similar installations (5–7).

Fig. 1. α-spectrum of Ra^{224}

In Figs. 1 and 2 the α-spectra of Ra^{224} and Fr^{221} are shown. The half-width of

Fig. 2. α-spectrum of Fr^{221}

Figure 2: Fig. 2. α-spectrum of Fr^{221}

the α-line of Ra^{224} is 17 keV ($\delta = 7.2$ keV). The resolving power achieved is almost twice as high as the resolving power of existing ionization α-spectrometers (30–35 keV). The total rms deviation δ may be represented in the form

Fig. 2. α-spectrum of Fr^{221}

$$\delta = \sqrt{\delta_N^2 + \delta_{\mathrm{sh}}^2 + \delta_0^2}, \tag{3}$$

where δ_N, δ_{sh}, δ_0 are the root-mean-square fluctuations due respectively to fluctuations of ionization, radio noise, and all other causes. The analysis carried out showed that in the case of Ra^{224} one may neglect δ_0 in (3). Then from (3) it follows that $\delta_N(5.681\ \mathrm{MeV}) = 5.5$ keV. In the case of Fr^{221} it proves necessary to take into account the effect of the thickness of the source layer. The point is that Fr^{221} is formed as a result of α-decay of Ac^{225} present in the same source, the recoil energy of whose nuclei is 100 keV. In this case half of the recoil nuclei remain on the surface, and half penetrate to some depth into the backing. This leads to the fact that the observed α-line of Fr^{221} actually consists of two lines shifted by 2–3 keV, while the half-width of the line increases by 1.5–2 keV. Thus, the effective half-width of the α-line in the present case is 18 keV ($\delta = 7.7$ keV). Substituting this value of δ in (3) and neglecting δ_0, we obtain $\delta_N(6.336\ \mathrm{MeV}) = 6.0$ keV.

Discussion of the results

1. Since $\delta_N \sim \sqrt{E_\alpha}$, the measured values of δ_N may be reduced to one energy (6.0 MeV). After averaging over two measurements we obtain $\delta_N(6.0\ \mathrm{MeV}) = 5.8$ keV. Using this value, one may propose a formula for determining δ_N at different E_α

$$\delta_N(E_\alpha) = 5.8\sqrt{\frac{E_\alpha}{6.0}}, \tag{4}$$

where E_α is expressed in MeV, and δ_N in keV. Thus, in the ionization spectrometer the half-width of a line in the limiting case can be brought to ~ 14 keV at $E_\alpha = 6.0$ MeV (this value may turn out to be overestimated by 1–2 keV because we neglected δ_0 in (3)).

2. The results obtained can be used to determine F. Transforming (1) in such a way that δ_N is expressed in keV, and taking $w = 26.4$ eV (^{8}), we obtain $F_{\mathrm{exp}} = 0.22$.

Let us now determine the upper limit of the values of F (F_{lim}) from Fano' s formula. In the case of ionization of argon one may neglect in (2) the last two terms (^{2}). Further using the obvious relation

$$w = W_i + W_e \frac{1-p}{p} \tag{5}$$

and substituting in (2) and (5) instead of W_i and W_e, respectively, the values of the ionization potential (15.7 eV) and the energy of the first excitation level (11.5 eV), we obtain $F > F_{\text{lim}} = 0.33$.

Comparing F_{lim} with F_{exp}, one may conclude that Fano' s theory apparently describes the effect of ionization fluctuations in argon rather well. The magnitude of this fluctuation can be determined from formula (1) with the coefficient $F = 0.22$, or directly from formula (4).

In conclusion the authors consider it their pleasant duty to express their gratitude to M. F. Sobolevskaya for help in carrying out the measurements.

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