A study of the characteristics of a collisional photoionization spectrometer
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The characteristics of a spectrometer, designed to determine the spectral composition and absolute intensity of radiation, have been studied. The working spectral range was determined from the region of atomic photoionization of the gas being used. In recording the photoelectron current, the threshold sensitivity of the device was \(-10^9\) quanta/(cm²s).

The spectrometer is designed to measure the spectrum and absolute intensity of radiation in the photoionization region of the gas atoms being used.

The spectrometer consists of a closed volume located in a magnetic field. The volume is filled with gas and has a window to introduce radiation in the form of a microchannel plate. Inside the volume two dynodes are located opposite one another with electrodes consisting of equidistant rectangular plates. A device to select electrons according to energy and an anode are located behind each dynode. The radiation ionizes the gas in the space between the dynodes. The photoelectrons, magnetized along the axis of the dynodes, diffuse in the gas between them by colliding with the atoms. After each collision with an atom the photoelectron, with probability \(\rho_{1i}\), penetrates the dynode, with probability \(\rho_{2i}\), undergoes an inelastic collision with an atom and leaves the analyzable energy interval, with probability \(\rho_{3i}\), it is lost on the dynodes, and with probability \(\rho_{4i}\) it leaves the analyzable interval of energies due to elastic collisions. The dependence of the anode current \(I\) [electrons/sec] on the retarding potential of the dynodes \(U\) [eV] for monochromatic radiation with a quantum energy \(E\) [eV] and intensity \(I\) [quanta/(cm²sec)] is given by the expression

\[
I = I_{n_0} = \sum_i Q_i \frac{1}{\sum_i t_i} \left( \sum_i t_i \right),
\]

where

\[
t_i = \frac{1 - \exp \left( -\frac{n_i E}{\sigma_i} \right)}{n_i E_i} \left( \frac{U}{E_i} \right)^{\frac{1}{2}}, t_{1i} = Q_i / Q_{1i}, t_{2i} = \frac{\mu_i}{\mu_{1i}},
\]

\[
t_{3i} = 4.3 \times 10^{-4} \left[ 2.2 \times 10^{-4} (1 - U/E_i) + 1.35 \times 10^{-3} U/E_i \right]
\]

\[
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\]

Here \(n_i\) [cm⁻³], \(T\) [K], \(\mu\) [arb. units] are the concentration, temperature, and mass of the gas atoms; \(\sigma\) [cm²] is the area of the dynodes; \(L\) [cm] is the distance between them; \(a\) [cm] is the extent of the illuminated region along the their axis; \(Q_{1i}\) [cm²] is the photoionization cross section of the gas atoms for the \(i\)th energy level; \(E_i = E - A_i\) [eV] is the initial energy of the photoelectrons; \(A_i\) is the ionization energy of the atom from the level \(i\); \(H\) [G] is the magnetic field strength; \(R\) [cm] is the distance between the plates of the dynodes; \(Q_{2i}\) [cm²] and \(Q_{4i}\) [cm²] are the overall scattering cross sections and the overall cross section of inelastic scattering of electrons with energy \(E_i\) on gas atoms, respectively; \(K_i\)
is the transmission coefficient of the selector for these electrons. The signal $I$ of the spectrometer depends significantly on the energy of the photoelectron and $n_t$. The expression

$$I = n_t e Q_0 Q_{11} K$$

(2)

describes the signal for photoelectron energies which are less than the excitation potential of the gas atoms ($Q_0 = 0$) and greater than the magnetic fields, for which $p_{21} < 0.2 p_{20}$ with $n_t < 0.2 Q_{21}$ and $p_{21} > n_t$. The obtained expression determines the unambiguous connection between the spectrometer signal and the radiation spectrum. The signal from various lines is in the form of steps, whose heights determine the absolute intensity of the radiation lines from the photoionization cross section and the concentration of gas atoms. The start of the steps determines the energy of the radiation quanta from $A_{11}$. Differentiation of signal gives a linear spectrum with a half-width on the order of $7.0 \times 10^{-3} E_{11}/\mu$ [eV]. With an increase in the concentration of gas atoms to values greater than $3/LQ_{21}$, the signal in the vicinity of the lines is described by the following expression:

$$I = 4.54 \times 10^{-15} \frac{Q_0}{Q_{21}} \left(1 - \frac{U}{U_{0}}\right).$$

(3)

As a consequence of the square dependence of $I$ on $E_{11} - U$, one gets the impression that, when recording the spectrum with an actual device, the signal close to $E_{11}$ is equal to zero. This phenomenon is called line shift. The maximum value of the shift $\Delta U$ [eV] at the 0.01 level of the signal

$$\Delta U = 4.7 \times 10^{-9} \frac{E_{11}}{\sqrt{Q_{21}}}.$$

(4)

In Fig. 1, the arrows $a$ and $b$ indicate the shift of the beginning of the line associated with an increase in the xenon pressure in the volume of the spectrometer from $1.2 \times 10^{-4}$ to $1.2 \times 10^{-2}$ Torr (this corresponds to a change in $n_t$ from $4.0 \times 10^{13}$ to $4.0 \times 10^{14}$ cm$^{-3}$) for the electron line with an energy of 7.8 eV. As is obvious from Fig. 1, the shift is equal to 65 mV. The studies were carried out in a spectrometer with an ionization volume length of 35 cm and an area of the exit window of 7.0 cm$^2$. For a xenon pressure of $10^{-2}$ Torr at the 73.5-nm line of Ne, the quantum output of the spectrometer was $\geq 20\%$, but in this case the resolution decreased to 3 nm according to Eq. (4), and the gradualism in energy becomes nonlinear and depends on the gas pressure.

An important result was obtained by us for the region of photoelectron energies which exceed the first excitation potential of the gas atoms. For a specific case in the region of a line the signal, with an increase in concentration starting from a given value, ceases to depend on $n_t$ and is described by the following simple expression:

$$I = \frac{1}{2} \frac{Q_0}{Q_{21}} \frac{E_{11}}{L} \left(1 - \frac{U}{U_{0}}\right).$$

(5)

As is obvious from Eq. (5), the connection between the absolute radiation intensity and the current of the dynodes only depends on the constant and the dependence on $n_t$ disappears; the measurement error for $n_t$ can be significant. The results of experimental verification of Eq. (5) are illustrated in Fig. 1, where the differentiated dependence of the current of the dynodes on the retarding potential, under photoionization of xenon by the 58.4-nm resonance line of He $\lambda$, is shown. Two lines of the photoelectron-energy spectrum are formed with energies of 9.1 and 7.8 eV. The energy of the first of these exceeds the excitation potential of Xe atoms, and electrons of the second line are scattered elas-
ally in the gas. The distance between the dynodes of the spectrometer is 10 cm, the distance between the shielding plates of the dynodes is 1 cm, the magnetic field is 400 Oe. Curve 8 was obtained for a xenon pressure of $1.2 \times 10^{-4}$ Torr. As is obvious from Fig. 1, the line with an energy of 9.1 eV exceeds by a factor of two the value of the 7.8 eV line, which agrees well with the known relation of these line values. For a pressure of $1.2 \times 10^{-4}$ Torr the 9.1-eV line essentially no longer exceeds the 7.8 eV line. Further increase in the pressure do not raise the intensity of the 9.1-eV line, while the 7.8-eV line increases in proportion to the gas pressure. In this case if the absolute value of the intensity is known, then using Eq. (5) one can determine the inelastic scattering cross section of the electrons on the gas atoms. We carried out similar measurements in the 13-16-eV photoelectron-energy range for xenon and other gases. In this case the spectrometer was illuminated by a discharge of neon in a capillary. Measurement of the absolute values of the line intensities was carried out by filling the spectrometer with neon or helium, for which these lines are found in a region of elastic scattering of the photoelectrons. The results of the study are presented in Table I.

The obtained data agree satisfactorily with the cross section $Q_{\alpha} = 3.2 \times 10^{-3}$ cm$^{-2}$ for $E_i = 20.0$ eV, from Ref. 3, which speaks well of the applicability of the method of measuring cross sections.

The use of the spectrometer to determine the spectral composition and absolute intensities of radiation sources with a linear spectrum was illustrated in Fig. 2, where the differentiated signal of the spectrometer, with a relative step of 1%, from the discharge of helium in the capillary with a 2-mm diameter, 40 mm length for a 0.3-A discharge current and a 2.0 $\times$ 10$^{-4}$-Torr pressure is shown. The distance from the spectrometer to the capillary is 2 m. The spectrometer is filled with neon at a 2.6$\times$10$^{-2}$-Torr pressure. A complete spectrum for helium in the region from 23 to 53.4 nm was obtained. The absolute intensities were determined using Eqs. (2) and (5). The photoelectron-energy spectrum has an near linear form. A spectrum of such a form was obtained due to the action of the electron-energy selector, which is a collection of plates of height $d$ [cm]; the distance between the plates is $d$ [cm]. The selector is placed between the dynode and anode. Its transmittance is described approximately by the following formula:

$$K_1 = \exp \left( -\frac{\text{t.m.m}[d]}{\text{d}^{1/2}} \right). \quad (6)$$

For the spectrum presented in Fig. 2, $d = 2$ mm and $l = 25$ mm. The selector has a transmission equal to unity for electrons with zero energy and absorbs more energetic electrons due to their collisions with the gas atoms and entering onto the plates. From Fig. 2 it is obvious that in the region of elastic scattering of the electrons (for Ne from 0 to 16.6 eV), the quantum sensitivity is $\approx 85\%$, and for the region of inelastic scattering $\approx 10\%$. An estimate of the threshold sensitivity of the spectrometer when recording with an electron energy with a time constant of 15 sec. in the region of inelastic scattering of the photoelectrons--$10^{4}$ quanta/cm$^{2}$ sec), in the region of elastic scattering--$10^{3}$ quanta/cm$^{2}$ sec). The spectrum in Fig. 2 was obtained in 20 min.

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