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PLASMA PHYSICS

DEMONSTRATION OF THE PENNING EFFECT

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The Penning effect has been confirmed in a neon–sodium gas–vapor mixture. An apparatus and method are described for performing an experiment demonstrating a lowering of the discharge ignition voltage in a neon lamp caused by introducing sodium into its envelope.

Experimental confirmation of the Penning effect in a course on "Gas Discharge Physics" is usually achieved using a vacuum apparatus equipped with a system for preparing and dispensing Penning mixtures utilizing rare gases (neon or argon). This test takes a long time, the method is complex, is accessible for a small group of students, and involves considerable financial expenditure. An experiment demonstrating a lowering of the discharge ignition voltage in a neon lamp as a result of introducing sodium into its envelope is considered below.

We shall demonstrate a change in the discharge ignition voltage of an apparatus filled with a rare gas when sodium is introduced into it by an electrolytic method [1]. The ignition voltage U_1 in a discharge in a rare gas with no admixture, for plane-parallel electrodes formed by a lamp cathode and molten sodium nitrate (Fig. 1), is [2]

$$U_1 = \frac{Q_0 P d U_i}{\ln Q_0 P d - \ln\ln(1+\gamma^{-1})}, \tag{1}$$

where Q_0 is the total effective elastic collision cross-section, P is the gas pressure, U_i is the ionization potential of the gas, and γ is the ion–electron secondary emission coefficient.

After introducing a small concentration of sodium vapor into the apparatus, the electrons will mainly collide with rare gas atoms during a discharge. The rare gas atoms then become excited to metastable levels. The concentration of the metastable atoms is high due to their long lifetime of $\sim 10^{-4}$ sec. When a metastable atom of a rare gas such as neon encounters a sodium atom the latter becomes ionized on account of the energy of the metastable state:

$$Ne^M + Na \to Ne + Na^+ + e, \tag{2}$$

where Ne^M is the metastable neon atom.

The rate of ionization of the neon atoms is considerably lower than the rate of excitation to the metastable level since ionization requires a considerably greater energy than excitation (U_i = 21.47 V, U_m = 16.57 V).

It is possible to lower the discharge ignition voltage as a consequence of the Penning effect if each event of exciting a rare gas atom to a metastable level results in ionization of the admixture. This process is most probable when the average time τ_d for diffusion of an excited rare gas atom from the middle of the discharge gap to an electrode considerably exceeds the average time τ_c between collisions of the gas atoms with those of the admixture, that is

$$\tau_d \gg \tau_c. \tag{3}$$

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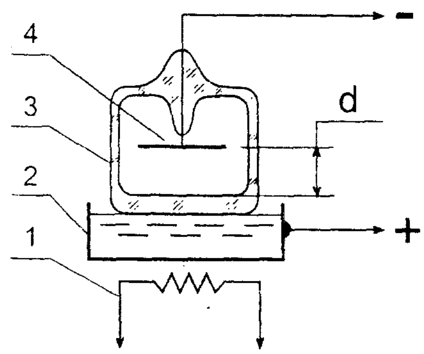

Fig. 1. Introduction of sodium into a lamp by the electrolytic method: *1*) heater; *2*) dish with sodium salt; *3*) lamp envelope; *4*) cathode.

The average diffusion time of a rare gas atom from the middle of the discharge gap to the walls of the lamp is

$$\tau_d = d^2/8D. \quad (4)$$

Here d is the interelectrode separation and D is the diffusion coefficient.

Taking into account that

$$D = \frac{\lambda_1 \bar{v}}{3P}, \quad (5)$$

we obtain

$$\tau_d = \frac{3d^2 P}{8\lambda_1 \bar{v}}, \quad (6)$$

where P_1 and λ_1 are respectively the pressure and mean free path of a rare gas atom, and v is the average velocity.

The average time between collisions of the rare gas and admixture atoms is proportional to the mean free path λ_2 of the admixture atoms

$$\tau_c = \frac{\lambda_2}{P\bar{v}}. \quad (7)$$

Taking expressions (6) and (7) into account, the inequality (3) assumes the form

$$\frac{3d^2 P}{8\lambda_1} \gg \frac{\lambda_2}{P}. \quad (8)$$

The discharge ignition voltage U_2 between the electrodes in the presence of the Penning effect is also determined by formula (1) in which the potential ionization U_i of the rare gas atoms is replaced by the potential U_m for its excitation to the metastable level:

$$U_2 = \frac{Q_0 d U_m P}{\ln Q_0 Pd - \ln \ln (1+\gamma^{-1})}. \quad (9)$$

Taking expressions (1) and (9) into account, the relative change in the discharge ignition voltage is

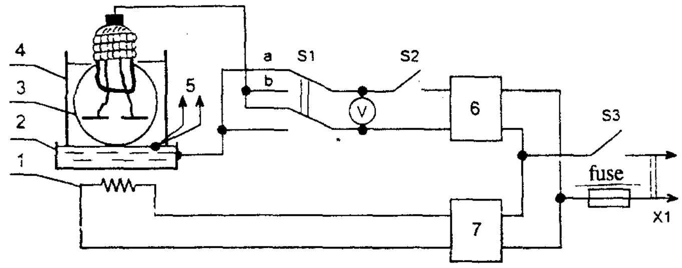

Fig. 2. Schematic diagram of the apparatus for demonstrating the Penning effect: *1*) heater; *2*) dish with sodium nitrate; *3*) neon lamp; *4*) heat screen; *5*) thermocouple; *6*) rectifier; *7*) laboratory autotransformer.

$$\delta = \frac{U_i - U_m}{U_i} \cdot 100\%. \tag{10}$$

Let us compare the experimentally measured change of the discharge ignition voltage in neon and in a gas–vapor neon–sodium mixture with that determined by calculation. Figure 2 shows a schematic diagram of the apparatus. It consists of a heater, a dish with sodium nitrate, a rectifier, and a neon lamp. Provision was made in constructing the apparatus for a cylindrically shaped heat screen in order to stabilize the thermal regime of the lamp.

With a negative potential of the dish relative to the anode, sodium was electrolytically removed from the envelope. A TN-20 indicator light with plane electrodes and filled with neon at a pressure of 20 torr was used as the neon lamp in the apparatus.

The discharge ignition voltage between the cathode and the molten sodium nitrate salt was measured at a constant temperature of 310°C. The ignition voltage U_1 of the lamp in neon, averaged over five lamps, was 210 V. After this the electrolytic method was used to introduce sodium into the apparatus over a period of 10-15 min. The averaged value of the discharge ignition voltage for the neon–sodium mixture was then measured to be 180 V.

With the tumbler switch *S*1 in position 1 the sodium was removed from the lamp envelope for repeated measurements of the discharge ignition voltage.

Let us estimate the lowering of the discharge ignition voltage on account of the Penning effect. The validity of calculations using Eq. (10) was confirmed by the low saturated vapor pressure of the sodium in the neon–sodium mixture and by the agreement with inequality (8) which occurs when energy is transferred from the metastable neon atoms to the sodium atoms.

The concentration of the neon atoms in the lamp operating at a temperature of 310°C exceeded that of the sodium atoms by more than four orders of magnitude (for neon it was $9 \cdot 10^{24}$ m^{-3} and for sodium it was $3 \cdot 10^{20}$ m^{-3}).

In the case considered the inequality (8) is satisfied for the values $d = 2.5 \cdot 10^{-2}$ m, $P = 26$ torr, $\lambda_1 = 1.16 \cdot 10^{-4}$ m, $\lambda_2 = 8 \cdot 10^{-5}$ m [3].

Consequently the calculated lowering δ_{calc} of the ignition voltage in the lamp is

$$\delta_{calc} = \frac{21{,}47 - 16{,}57}{21{,}47} \cdot 100\ \% \approx 23\ \%,$$

while the experimentally determined value was

$$\delta_{exp} = \frac{210 - 163}{210} \cdot 100\ \% \approx 22\ \%.$$

The calculated and measured changes in the discharge ignition voltage are therefore almost identical. This enables our proposed experiment to be used as a lecture demonstration confirming the presence of the Penning effect.

The method of performing the demonstration is as follows. The apparatus is connected to the electrical power line. After melting the sodium salt the lamp is smoothly lowered until its bulb comes into contact with the surface of the molten salt. When a constant melt temperature of 310°C has been established, as monitored with a thermocouple, the rectifier output voltage is smoothly raised and the discharge ignition voltage in the cathode–glass gap of the lamp at which the red–orange luminescence of the neon appears is measured using a voltmeter. It is 210 V. Then, while maintaining a constant rectifier output voltage, a visual observation is made of the propagation of a sodium luminescence front in the direction from the lamp bulb to the cathode, on a background of the rare gas emission lines. After a steady-state discharge has been established and the light flux is practically constant, the discharge ignition voltage is again determined for the neon–sodium mixture, and this is $U_2 = 160$ V.

In order to repeat the experiment the sodium is removed from the lamp by changing the polarity of the electrode voltage using the tumbler switch *S*1.

Thus, the introduction of sodium into the TN-20 neon lamp results in a 22% lowering of the discharge ignition voltage, and this confirms the presence of the Penning effect.

A TN-20 indicator lamp [4] was used in the apparatus. The $6\cdot10^{-2}$ m diameter $1.5\cdot10^{-2}$ m high cylindrical dish was made of steel. When performing an experiment the dish was filled with sodium nitrate whose melting point is 307°C. The $6\cdot10^{-2}$ m diameter 10^{-1} m high heat screen was made of $2\cdot10^{-3}$ m thick quartz glass. A VUP-2M rectifier was used. The heater power consumption was 150 W.

An RNShO-250 voltage regulator could be used as the laboratory autotransformer. The discharge ignition voltage was measured with a Shch4300 digital multirange meter.

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