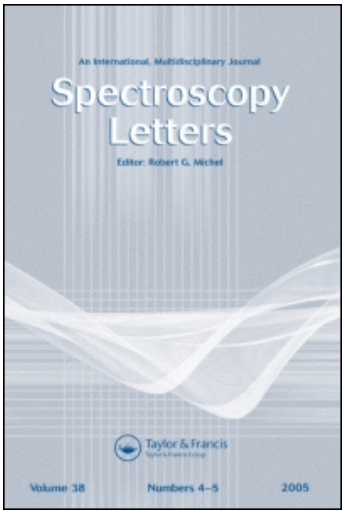

Spectroscopy Letters
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713597299

Electron Energy Function Distribution in Hollow Cathode Discharge at Resonant Irradiation

S. N. Khvorostovsky[a]; D. Z. Zhechev[b]
[a] Department of Physics, Hydrometherological Institute, Leningrad, USSR [b] Institute of Solid State Physics BAS, Sofia, Bulgaria

To cite this Article Khvorostovsky, S. N. and Zhechev, D. Z.(1990) 'Electron Energy Function Distribution in Hollow Cathode Discharge at Resonant Irradiation', Spectroscopy Letters, 23: 7, 911 — 921
To link to this Article: DOI: 10.1080/00387019008054469
URL: http://dx.doi.org/10.1080/00387019008054469

SPECTROSCOPY LETTERS, 23(7), 911-921 (1990)

ELECTRON ENERGY FUNCTION DISTRIBUTION IN HOLLOW CATHODE DISCHARGE AT RESONANT IRRADIATION

Key Words: Hollow Cathode Discharge, Electron Energy Function Distribution, Resonant Irradiation

S.N.Khvorostovsky
Hydrometheorological Institute, Department of Physics, av.Malookhtensky 98, 195196 Leningrad, USSR

D.Z.Zhechev
Institute of Solid State Physics BAS, Blvd.Lenin 72 1784 Sofia, Bulgaria

ABSTRACT

The behaviour of electron energy function distribution in hollow cathode discharge at resonant light irradiation is analyzed.The function is calculated for energies near and higher than the energy excitation $\mathcal{E}_1$ of the hellium metastable levels.It turns out that the electron energy function distribution is essentially influenced in the vicinity of point $\mathcal{E}_1$.

INTRODUCTION

The photoresonance plasma state can not be described correctly if the electron kinetics reaction in respect to light irradiation has been neglected or unproperly taken into account.In particulary stressing on level po-

pulation ballance only, a contemporary aspect of the photoresonance plasma, namely the optogalvanic effect(OGE) is modeled incompletly.This is particularly important in relation to hollow cathode discharge(HCD) since it is widely used as optogalvanic detector.On the other hand, the analysis of specific electron energy function distribution(EEFD) is very difficult from OGE stand point although EEFD determines the spectroscopical advantages of HCD.[1]We intend to discuss in turn the channels of OGE formation in HCD.Generalizing the consideration in ref.(2 ÷ 5) here as a first step we analyse the EEFD at discharge illuminating by resonant light.

We have adopted the designations as follows: $\mathcal{E}_e$ - average energy of the electron, $\mathcal{E}_1$-threshold energy of excitation, $\mathcal{E}_o = eU_k$ - energy acquired by the electron over the darc cathode space (e - charge of the electron, U_k- cathode fall potential), $\mathcal{E}_i$, $\mathcal{E}_n$ - energy of ionization ($\mathcal{E}_i$) and excitation ($\mathcal{E}_n$) of the level "n", $f(\vec{v},\vec{r})$- electron energy function distribution ($\vec{v}$ and $\vec{r}$ - velocity and coordinates of the electron), S^{*}_{ea}, S_i, S_{ea} - operators of electron-atom unelastic, ionizing and elastic interaction, $q_n(\mathcal{E})$, $q_i(\mathcal{E})$ - cross-sections of the excitation and ionization of level "n", q^k_m - cross-section of collisions of II type for level "k", $\sigma_i(\mathcal{E}',\mathcal{E})$ - differential cross-section of the atomic ionization by electron with energy $\mathcal{E}'$ and appearence of a secondary electron with energy $\mathcal{E}$, $\sigma_n(\mathcal{E}',\mathcal{E})$- differential cross-section of the n-level excitation by electron, changing its energy from $\mathcal{E}'$ to $\mathcal{E}$, $q_{tr}(\mathcal{E})$ - the transport cross-section of elastic collisions, N - normal atoms concentration, N_k - quantity of atoms in the whole cathode hole, excited to k -level, $n_e(\mathcal{E})$ - concentration of the slow-speed electrons, m and M- mass of electron and atom, $I(\mathcal{E})$ - number of the electrons with energy $\mathcal{E}$, apearing in the cathode, I_o - number of the electrons apearing in the cathode per unit time, z - number of the valence electrons, z_i- number of the ionizations in the volume.

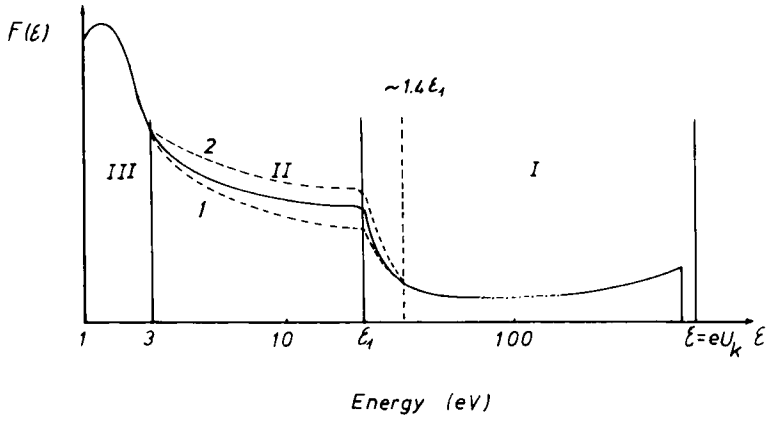

Fig. 1

STRUCTURE OF EEFD

Unlike the discharge positive columne, EEFD in HCD is formed due to elastic, unelastic and ionizing atom-electron interactions in the cathode hole.The electric field in the hole is practically concentrated inside darc cathode space.The size of this space allows the electrons emitted from the cathode to pass through, without unelastic interactions, acquiring energy $\mathcal{E}_o$.These electrons futher relax to energies $\mathcal{E}_1$.The EEFD can be considered consisting in three regions (FIG.1), i.e. $\mathcal{E}_1 \leq \mathcal{E} \leq \mathcal{E}_o$ (reg.I), $3eV \leq \mathcal{E} \leq \mathcal{E}_1$ (reg.II), $0 < \mathcal{E} \leq 3eV$ (reg.III).The high energy electrons relax to energy $\mathcal{E}_1$ in reg.I, in general.In frames of this model the kinetic equation for $f(\vec{v},\vec{r})$ can be written as:

$$\operatorname{div}\left[\vec{v}\, f(\vec{v},\vec{r})\right] = S^{*}_{ea}\left[f(\vec{v},\vec{r})\right] + S_i\left[f(\vec{v},\vec{r})\right] \quad (1)$$

This equation can be simplified integrating over whole cathode hole volume and space angle dO in the velocity

coordinates and introducing a function $F(\vec{v})$ determined as:

$$F(\vec{v}) = \iint f(\vec{r},\vec{v})d^3rd\Omega \qquad (2)$$

Physically, $F(\vec{v})$ function is given by the product $v^2F(v)dV$ determining the number of electrons in V,V+dV interval and in the whole cathode hole.[2] Introducing the argument $\mathcal{E} = mv^2/2$ and taking into account $F(\mathcal{E} > \mathcal{E}_0)=0$, equation (1) can be written as:

$$N\sqrt{2/m\mathcal{E}}\left[\int_{\mathcal{E}}^{\mathcal{E}_0}\sigma_i(\mathcal{E}',\mathcal{E})\mathcal{E}'F(\mathcal{E}')d\mathcal{E}' + \int_{\mathcal{E}+\mathcal{E}_i}^{\mathcal{E}_0}\sigma_i(\mathcal{E}',\mathcal{E}'-\mathcal{E}-\mathcal{E}_i)\mathcal{E}'F(\mathcal{E}')d\mathcal{E}' + \right.$$
$$\left. + \sum_{n=1}^{\infty}\int_{\mathcal{E}+\mathcal{E}_n}^{\mathcal{E}_0}\sigma_n(\mathcal{E}',\mathcal{E})\mathcal{E}'F(\mathcal{E}')d\mathcal{E}'\right] - N\sqrt{2\mathcal{E}/m}\left[q_i(\mathcal{E}) + \sum_{n=1}^{\infty}q_n(\mathcal{E})\right]F(\mathcal{E}) = -I(\mathcal{E}). \qquad (3)$$

Futher, the classical expression for differential cross-section[2] is used:

$$\sigma_i(\mathcal{E}',\mathcal{E}) = a_i\frac{ze^4\pi}{\mathcal{E}'}\frac{1}{(\mathcal{E}+\mathcal{E}_i)^2}\ln\frac{\mathcal{E}'}{\mathcal{E}_i} \qquad (4)$$

$$\sigma_n(\mathcal{E}',\mathcal{E}) = a_n\frac{ze^4\pi}{\mathcal{E}'}\frac{1}{(\mathcal{E}+\mathcal{E}_n)^2}\ln\frac{\mathcal{E}'}{\mathcal{E}_n} \qquad (5)$$

where a_i and a_n are empirical constants, fitting so that the cross-sections calculated by

$$q_i(\mathcal{E}') = \int_0^{\mathcal{E}-\mathcal{E}_i}\sigma_i(\mathcal{E}',\mathcal{E})d\mathcal{E} \qquad (6)$$

$$q_n(\mathcal{E}') = \int_0^{\mathcal{E}_{n+1}-\mathcal{E}_n}\sigma_n(\mathcal{E}',\mathcal{E})d\mathcal{E} \qquad (7)$$

to coincide with the experimental data.Then, eq.(3) can be reduced to:

$$\varphi(x) = \frac{x}{x-1}\left[\frac{a^*}{a}\int_{x+1}^{x+x_i}\frac{(x')dx'}{(x'-x)^2} + \frac{a_i}{a}\int_{x+x_i}^{x_0}\frac{(x')dx'}{(x'-x)^2} + \int_{x+x_i}^{x_0}\frac{a_i}{a}\varphi(x')dx'\right] + \delta(x-x_0) \qquad (8)$$

where a is an empirical parameter selected in such a way that the excitation total cross-section coincides

with the experimental data, being analogical constant for unelastic loses $/q(\varepsilon)=q_i(\varepsilon) + \sum_{n=1}^{\infty} q_n(\varepsilon)/$, $x=\varepsilon/\varepsilon_1$, $x_i=\varepsilon_i/\varepsilon_1$, $x_o=\varepsilon_o/\varepsilon_1$, $\varphi(x)$ and $F(x)$ are connected as follows:

$$\varphi(x)= \frac{2\pi a e^4 N(x_o-1)}{m^2 I_o x_o} F(x)\ln x \tag{9}$$

At deriving eq.(8) it has been supposed that: (10)

$$I(\varepsilon)= \frac{m^{3/2} I_o}{\sqrt{2\varepsilon_o}} \delta(\varepsilon-\varepsilon_o)$$

The function (x), therefor F(x) too, diverges at x=1 between I and II regions.The reason is that the eq.(1) does not express correctly the electron relaxation in this region since at x=1, the cross-section of unelastic energy loses is zero.The evaluations carried out show that for correcting F(x) in the vicinity of x=1, the electron relaxation by elastic electron-atom collisions have to be taken into account. Thus, kinetic equation for EEFD near x=1 can be writen as

(11)

$$\mathrm{div}\left[\vec{v}f(\vec{v},\vec{r})\right] = S_{ea}\left[f(\vec{v},\vec{r})\right] + S_i\left[f(\vec{v},\vec{r})\right] + S_{ea}\left[f(\vec{v},\vec{r})\right]$$

Passing to $F(\varepsilon)$ function and transforming eq.(2) analogically to eq.(1) we obtain:

(12)

$$N\sqrt{\frac{2}{m\varepsilon}} \frac{d}{d\varepsilon}\left[2\frac{m}{M} q_{tr}(\varepsilon)\varepsilon F(\varepsilon)\right] + S(\varepsilon) - N\sqrt{\frac{2\varepsilon}{m}} q(\varepsilon)F(\varepsilon) + I_1(\varepsilon)=0$$

where $q(\varepsilon)=q_i(\varepsilon) + \sum_{n=1}^{\infty} q_n(\varepsilon)$, (13)

$$S(\varepsilon)=N\sqrt{\frac{2}{m\varepsilon}}\left[\int_{\varepsilon+\varepsilon_i}^{\varepsilon_o} \sigma_i(\varepsilon',\varepsilon)\varepsilon' F(\varepsilon')d\varepsilon' + \int_{\varepsilon+\varepsilon_i}^{\varepsilon_o} \sigma_i(\varepsilon',\varepsilon'-\varepsilon-\varepsilon_i)\varepsilon' F(\varepsilon')d\varepsilon' + \sum_{n=1}^{\infty}\int_{\varepsilon+\varepsilon_n}^{\varepsilon_o} \sigma_n(\varepsilon',\varepsilon)\varepsilon' F(\varepsilon')d\varepsilon'\right]$$

The value $I_1(\varepsilon)$ differs from $I(\varepsilon)$ since in considered interval the electrons can be also producted by super-elastic collisions with excited atoms. Taking into account that in this region eq.(10) is equal to zero, we can write down:[4]

$$I_1(\varepsilon) = \frac{ne m^{3/2}}{\varepsilon_e^2 \sqrt{2\varepsilon_1}} \sqrt{8\varepsilon_e/m} \, (\varepsilon - \varepsilon_1) \exp.\left(\frac{\varepsilon - \varepsilon_1}{\varepsilon_e}\right) \sum_k N_k q_m^k \qquad (14)$$

We should note that the solution of eq.(12) essentially differs from that of eq.(3) in a small vicinity near $x=1$ ($\Delta x=0.46$). To solve eq.(12) it is admitted that:

i) cross-section $q(\varepsilon)$ can be presented as $q(\varepsilon)=q_0(\varepsilon) \cdot (\varepsilon-\varepsilon_1)$, where $q_0(\varepsilon)$ is a function less depending on ε;

b) in order to calculate $S(\varepsilon)$, the function obtained from eq.(5), should be used; at the same time, in this region the expression between the square brackets of eq.(13) is correctiy approximated by A/ε relation where A is a constant;

c) the cross-section $q_{tr}(\varepsilon)$ changes slightly in this range and we can write down: $q_{tr}(\varepsilon) \simeq q_{tr}(\varepsilon_1)$.

The solution of eq.(12) is:

$$F(\varepsilon) = F(\varepsilon_1+\Delta\varepsilon) \exp.\left[-\int_{\varepsilon}^{\varepsilon_1+\Delta\varepsilon} \frac{q_0(\varepsilon')(\varepsilon'-\varepsilon_1)d\varepsilon'}{2mM^{-1}\varepsilon' q_{tr}(\varepsilon')}\right] + \left\{\int_{\varepsilon}^{\varepsilon_1+\Delta\varepsilon} \left[\frac{1}{N}\sqrt{\frac{m\varepsilon'}{2}}\, S(\varepsilon') + \right.\right. \qquad (15)$$

$$\left.\left. + \frac{1}{N}\sqrt{\frac{m\varepsilon'}{2}}\, I_1(\varepsilon')\right] \exp.\left[\int_{\varepsilon'}^{\varepsilon} \frac{q_0(\varepsilon'')(\varepsilon''-\varepsilon_1)d\varepsilon''}{2mM^{-1}\varepsilon'' q_{tr}(\varepsilon'')}\right] d\varepsilon' \right\} (2mM^{-1} q_{tr}(\varepsilon)\varepsilon)$$

where $F(\varepsilon_1+\Delta\varepsilon)$ is a solution of eq.(3) in point $(\varepsilon_1+\Delta\varepsilon) = \varepsilon_1(1 + 0.46) = 1.46\varepsilon_1$. Eq.(15) can be presented in a form suitable for futher calculations:

(16)

$$F(x)=4.65\ x10^{6}\ \frac{i\,[mA]}{p\,[Torr]}\sqrt{\frac{q_o(1)}{q_o(x)}}\ \frac{1+\Delta x}{x^{3}\sqrt{\Delta x}}\ e^{t^{2}}\Big\{\mathrm{erf}\Delta t-\mathrm{erf}t+$$

$$+\frac{2(x_o-1)}{2.47x_o\sqrt{\pi}}\ \frac{n_e\sqrt{8\varepsilon_\varepsilon(m\pi)^{-1}}}{I_o}\ \sum_{\kappa}N_k q_m^{k}\ \frac{ax^{3/2}e^{a^{2}}}{x_e}\Big\{e^{-(t+a)^{2}}-$$

$$-e^{-(\Delta t+a)^{2}}-a\sqrt{\pi}\left[\mathrm{erf}.(\Delta t+a)-\mathrm{erf}(t+a)\right]\Big\}+\Big[1+\frac{x_o-1}{2.47x_o}\cdot$$

$$\frac{n_e\sqrt{8\varepsilon_\varepsilon(m\pi)^{-1}}}{I_o}\ \sum_{\kappa}N_k q_m\frac{x-1}{x_e^{2}}\cdot e^{-\frac{x-1}{x_e}}\Big]\cdot\frac{1}{\sqrt{\pi}}\ \frac{e^{-\Delta t^{2}}}{\Delta t}\Big\}$$

where

$$t=\frac{x-1}{0.022}\ \frac{\sqrt{x\Delta x}}{1+\Delta x}\sqrt{\frac{q_o(x)}{q_o(1)}}\ ;\quad a=\frac{0.011(1+\Delta x)}{x_e\sqrt{x\Delta x}}\sqrt{\frac{q_o(1)}{q_o(x)}};$$

$$\Delta t=\frac{\Delta x}{0.022}\ \frac{\sqrt{\Delta x(1+\Delta x)}}{\sqrt{1+\Delta x}}\sqrt{\frac{q_o(x)}{q_o(1)}}=\frac{\Delta x^{3/2}}{0.022}\sqrt{\frac{q_o(x)}{q_o(1)}}\ .$$

We have to note that F(x) function is known accuracy to constant I_o, determined by anode current i equation:

(17)

$$i=e(z_i+I_o+I_o')$$

where z_i are the electrons, appearing in the cathode hole per unit time as a result of the following processes: cathode electron emission at cathode bombardement by excited atoms (first of all metastable levels), photoeffect irradiating the cathode by UV light (first of all from resonant levels), mutual interaction of excited atoms $A^{*}+A\to A^{+}+e$, producing an electron and (molecular) ion. The electron number z_i can be determined using the calculated EEFD:

$$z_i = \frac{2N}{m^2}\int_{\varepsilon_i}^{\varepsilon_o} F(\varepsilon)\varepsilon q_i(\varepsilon)d\varepsilon + \sum_{\kappa}\frac{2N_k}{m^2}\int^{\varepsilon_o} F(\varepsilon)\varepsilon q_i^k(\varepsilon)d\varepsilon \qquad (18)$$

where the first term discribes the direct ionization number and the second, the step ionization number.In the typical conditions of HCD, the value I_o' and the step ionization are negligible, then eq.(17) determines I_o and further, $F(x)$ can be calculated in absolute units.FIG.1 demonstrates a schematic representation of EEFD.

EEFD AT PHOTORESONANCE IRRADIATION

Let a HCD is irradiated by $h\nu_{ki}$ photons corresponding to an optical transition which level i is the lower one.We assume level i to be metastable one taking into account the essential role of metastable levels in the ionization and EEFD formation processes.However this admitance concerning quantitavely the final result is not important.

If the transitions probabilities A_{ki} obey the inequality $A_{ki} < \sum_{\nu<i} A_{kr}$ the behaviour of EEFD at $h\nu_{ki}$ irradiation is identical with the case of destruction of the level i.The function $F(x)$ /$F(\varepsilon)$/ is calculated according to eq.(16) for HCD maintained by hellium.Three values N_m are used ($N_m=10^{13}$ cm^{-3}, 2.10^{13} cm^{-3} and $N_m=0$) at gas pressures p_{He}=1.5; 3 and 6 Torr and discharge current 100 mA.The data $n_e=10^{12}$ cm^{-3}, q_m= = 1.6 x10^{-16} cm^{-2} for the metastable levels 2^3S_1, 2^1S_o and ε_e=1.3 eV, 0.7 eV, 0.3 eV, corresponding to the p_{He} - values are used too.The effect of completely destructed ($N_m=0$) metastable levels is also calculated. FIG.2 represents the calculated functions $F(\varepsilon)$.

We would like to point out the significant change of the $F(\varepsilon)$ values in the vicinity of the point ε_i when the HCD plasma is irradiated.It is caused by the

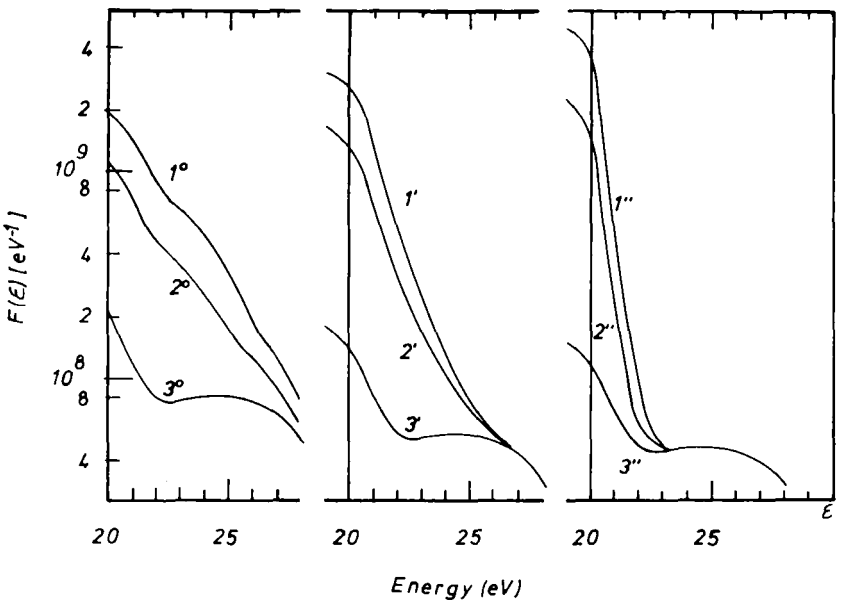

Fig. 2

additional superelastic collisions $He^{*} + e \rightarrow He + \vec{e}$. According to ref.4, the value $F(x)|_{x=1}$ is a boundery one for the function F(x) in reg.II ($x < 1$), $F(x<1) > F(x=1)$. Thus FIG.2 illustrates an essential change (decreasing) with one order in $F(\varepsilon)$ -values depending on irradiation power. It is a reason for variation in the step ionization number, therefor in the plasma conductivity too. On the other hand, the step ionization caused by the additionally populated levels n=3,4,... competes the abovementioned step ionization decreasing from n=2 due to its bigger cross-section for n>2. Besides, in the step ionization from levels with n>2, electrons from the slow Maxwell group whose $F(\varepsilon)$ values slightly depend upon illumination, take part too (reg.III).

The perturbed part of $F(\varepsilon)$ function in reg.I is negligible, its range $\Delta\varepsilon_1$ depends on p_{He} as $\Delta\varepsilon_1 \sim p_{He}^{-1}$. Practically, in this region the $F(\varepsilon)$ values are not affected by the resonance irradiation, therefore the number of directly ionized atoms does not change at illumination.

In some cases the resonance irradiation is able to stimulate the concentration of the metastable levels. Then in reg.II the $F(\varepsilon)$ -values are greater stimu - lating the step ionization and the plasma conductivity respectively.

In general, in the vicinity of point ε_1 the $F(\varepsilon)$- values depend essentially on the concentration N_m of the metastable atoms.The same conclusion should be valid in reg.II.A detailed computation of EEFD on reg.II as well as of N_m at resonance irradiation, including also the step ionization are in progress and will be published elsewhere.

CONCLUSION

1.In high energy region I of EEFD the resonance irradiation effect arizes in a narrow interval $\varepsilon_1 + 1.4\varepsilon_1$ close to the potential of the excitation ε_1.In the region II ($3<\varepsilon<\varepsilon_1$) the resonance irradiation causes essential EEFD reaction.The deviation of the EEFD at ε_1 allows an approximate evaluation of this reaction; the values of EEFD in region II change in direct proportion to deviation at ε_1.

2.Decreasing(increasing) the population of the metastable levels the resonance irradiation causes diminution(augmantation) of $F(\varepsilon)$ -values in region II.

3.The reaction of EEFD in region II and in region I partially does not influence on direct ionization but changes essentially the number of the step ionizations.

This investigation was sponsored by the State Committee of Science.

REFERENCES

1. Caroli S., ed. Improved Hollow Cathode Lamps for Atomic Spectroscopy, Ellis Horwood Limited Publ., Chichester,1985.

2. Kagan Yu. M., Lyagushchenko R.I. and Khvorostovsky S.N., Zh.Tekh.Fiz. 43, 1686(1972).

3. Kagan Yu. M., Lyagushchenko R.I.,Tarojan A.S. and Khvorostovsky S.N., Zh.Tekh.Fiz. 43, 1488 (1973).

4. Kagan Yu. M., Lyagushchenko R.I., Khvorostovsky S.N. and Hodorkovsky M.A.,Tekh.Fiz. 45, 1834 (1975).

5. Kagan Yu. M., Lyagushchenko R.I., Khvorostovsky S.N. and Hodorkovsky M.A., Zh.Tekh.Fiz. 45, 1839 (1975).

Date Received: 04/11/90
Date Accepted: 05/21/90