Contributed paper

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# Excitation space anisotropy, coherence and coherent conductivity in hollow cathode discharge

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*Based on the excitation space anisotropy a partial polarisation of the spontaneous emission is found in hollow cathode discharge. This polarisation is ascribed to existing spontaneous coherence, i.e., self-alignment of the excited states. The aligning factors are the beam-like fast electrons from the cathode dark space. An expression for observed signal of the spontaneous emission magnetic depolarisation is obtained. Within the frames of the ordinary opto-galvanic effect a separate coherent conductivity is analysed. A poor coherent conductivity due the self-aligned states is detected.*

**Keywords:** hollow cathode discharge, excitation space anisotropy, coherence, self-alignment, opto-galvanic effect and coherent conductivity.

## 1. Introduction

The unique sputtering-excitation properties have lately traced much interest to hollow cathode discharge (HCD) within modern spectroscopic investigations. In particular, HCD extends the application field of absorption spectroscopy, opto-galvanic (OG) spectroscopy, spectroscopy of interfering excited states. The interfering quantum states are known to enrich the conceptions about the atom system. The latter manifests itself as a more dynamic one in this kind of experiments [1]. HCD adds high lying states as well those of the sputtered atoms to the above fields.

A variety of interfering states are the degenerated magnetic ones; here the interference manifests itself as polarisation $P$ of their spontaneous emission. The necessary condition, i.e., coherence may be introduced (alignment, orientation) or spontaneous (self-alignment) but it is always based on the space anisotropy of the excitation. Spontaneous coherence enlarges the objects of, so-called, zero magnetic field level crossing technique: a magnetic field $\boldsymbol{B}$ applied to the coherent ensemble of atoms destroys its coherence depolarising the emission if $\boldsymbol{B}$ direction is orthogonal to the (self-) alignment axes and a Magneto-Optic (MO) resonance of magnetic depolarisation $P(\boldsymbol{B})$ may be detected.

On the other hand within the frames of light-induced coherence the absorbed light generates one more effect, i.e., light-induced conductivity (OG effect). The latter arises due to decrease of the efficient potential of ionisation and/or to the electron mobility change. Having laser-aligned degenerated magnetic states Hannaford [2] detected an OG analogue of the magnetic depolarisation $P(\boldsymbol{B})$.

In this report, the excitation space anisotropy in HCD is discussed as well the excited states self-alignment and their galvanic analogue.

## 2. Experimental data background

### 2.1. Excitation space anisotropy in HCD

The results of two separate investigations are the starting point of understanding spontaneous coherence, i.e., self-alignment in HCD. By using an electrical probe of rectangular shape Borodin and Kagan detected anisotropy of the electron velocity space in the Negative Glow (NG) of HCD; the higher buffer gas pressure reduces this anisotropy [3]. Another HCD diagnostic procedure was used in Refs. 4 and 5. By using a two-position Fabry-Perot interferogram the shift $\delta\nu$ of spectral line centre was observed along the radius. At the boundary NG-CDS, the value of $\delta\nu$ gives (3.0–3.7) kV/cm intensity of electric field. Later, these values were confirmed by OG way [6]. However, at $p < 0.2$ Torr we observed that the shift $\delta\nu$ takes place ($\delta\nu \neq 0$) in the NG too. It means that electric field penetrates into the NG and keeps the dominating radial velocity vector of the fast electrons here. Thus, this space anisotropy should (self-) align the excited states along the radius and plane polarised emission should be detected.

### 2.2. Illumination induces both additional conductivity and coherence simultaneously

Hanle was the first to observe magnetic depolarisation of the spontaneous emission originating from mercury optical transition irradiated by plane polarised resonant light [7,8].

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The latter aligns the degenerated magnetic sublevels distinguishing in magnetic number *m* as $\Delta m$ = 0, ±2, they emit light of the same polarisation. An external magnetic field decreases this polarisation degree by destroying the induced alignment. Later, this coherence was generalised as a result of the exciting process space anisotropy, i.e., as a difference between axial, radial and tangential light beams in a positive column of the discharge [9]. This kind of alignment realised in the discharge without any external action is called self-alignment. It is known to manifest itself only optically as polarisation of the spontaneous emission from (self-) aligned ensemble of atoms.

Penning was the first to detect another property of the gas discharge, i.e., its added light-induced conductivity [10]. Having absorbed a light portion at any optical transition, the discharge changes its current/voltage due to light-induced population transfer. These galvanic variations turned out to be more easily and precisely measurable than the absorbed light. A new technique known as OG spectroscopy is based on these considerations. Here, the discharge cell plays the role of OG detector illuminated by a light beam.

OG effect provokes a new aspect of spontaneous coherence manifestation. Really any OG arrangement predetermines coherent excitation of the irradiated transition [1,9]. Does the self-aligned state possess proper coherent conductivity?

## 3. Experiments and results

### 3.1. Polarisation and magnetic depolarisation of spontaneous emission in HCD

The (self-) aligned state manifests itself in the plane polarisation *P* of proper spontaneous emission. Our results in Refs. 4 and 5 provoke polarisation measurements. The measured intensity in two orthogonal polarisation, i.e., along the radius $I_r$ and orthogonal $I_h$ gives the degree of polarisation $P = (I_r - I_h)(I_r + I_h)^{-1}$ in a cylindrical HC. However, the latter complicates the polarisation analyse. Figure 1(a) illustrates the used two parallel nets – HCD. The axis OX coincides with the fast electron velocity vector and it is the only axis of excitation anisotropy. Indeed, Fig. 1(b) shows a top polarisation close to the cathode-net where the polarisation $I_r \parallel OX$ is maximum and decreases vs. distance. One is to note that polarisation signal-to-nonpolarised emission ratio is $\approx 10^{-3}$. The orthogonal polarisation keeps constant. The buffer gas pressure *p* destroys this polarisation at $p > 0.5$ Torr.

Generally, the observed intensity of polarisation $\vec{e}$ i.e., $I(\vec{e})$ at the transition $J_1 \rightarrow J_2$ (*J* – angular moment) may be described in the terms of the statistical tensor $\rho_q^k$, the tensor of excitation $\boldsymbol{F}_q^k$, the coherence decay time-constant $\Gamma_2$ and the emission -polarisation tensor $\boldsymbol{F}_{-q}^{k}(\boldsymbol{e})$ [1]

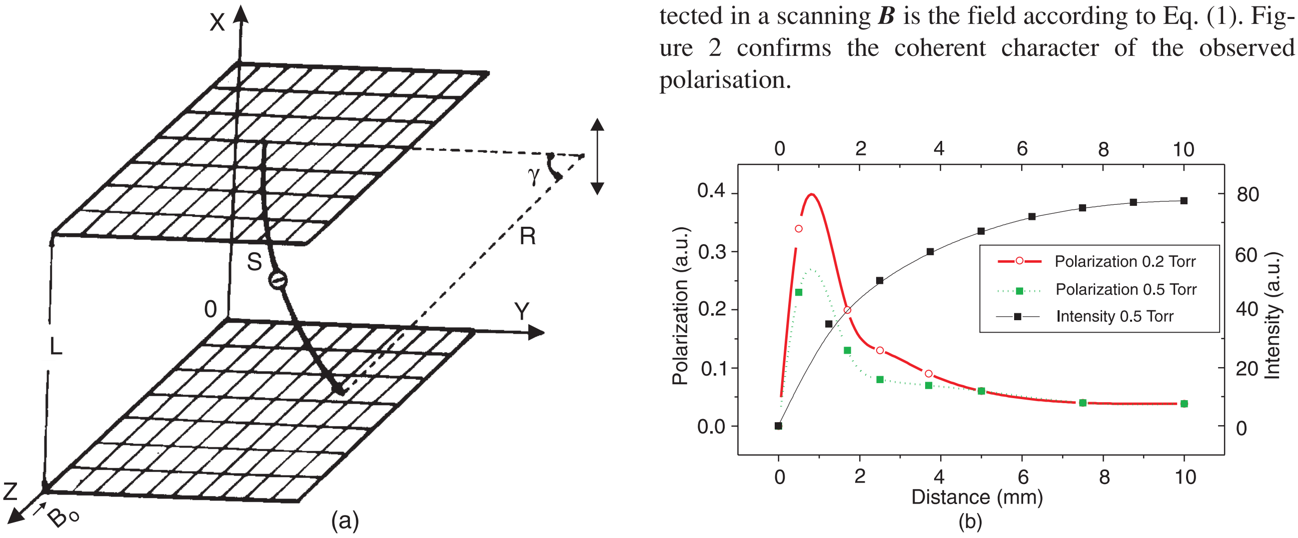
$$I(\vec{e}) = (-1)^{J_1+J_2} I_0 \sum_k (2k+1) \times$$
$$\times \left[ \begin{Bmatrix} 1 & 1 & 0 \\ J_1 & J_2 & J_2 \end{Bmatrix} \rho_0^0 \boldsymbol{\Phi}_0^0 + 5 \begin{Bmatrix} 1 & 1 & 2 \\ J_1 & J_1 & J_2 \end{Bmatrix} \times , \right. \qquad (1)$$
$$\left. (\rho_0^{(2)} \boldsymbol{\Phi}_0^{(2)} + \rho_{-2}^{(2)} \boldsymbol{\Phi}_2^{(2)} + \rho_2^{(2)} \boldsymbol{\Phi}_{-2}^{(2)}) \right]$$

where

$$I_0 = k(2J_1+1)^{-1/2} \left| J_2 \| d \| J_1 \right|^2, \rho_q^k = \boldsymbol{F}_q^k (\Gamma_2 - iq\boldsymbol{\Omega})^{-1},$$

and $\boldsymbol{\Omega}$ is the frequency difference between the interfering states. The terms containing $\rho_0^0$ give the emission mean intensity (i.e., the population), which is the background to the interference terms containing $\rho_0^2$ and $\rho_{\pm 2}^{(2)}$ – the contribution of the coherence.

If the observed polarisation [Fig. 1(a)] is due to (self-) aligned state, the magnetic field ***B*** applied orthogonally to the (self-) alignment axis OX should destroy this coherence (the second term) and a MO resonance *P(**B**)* may be detected in a scanning ***B*** is the field according to Eq. (1). Figure 2 confirms the coherent character of the observed polarisation.



(a) (b)

Fig. 1. Scheme of the analysed two-plate hollow cathode (a). Spectral line HeI 501.6 nm, intensity and polarisation *P* distribution along the normal to the cathode surface (b).

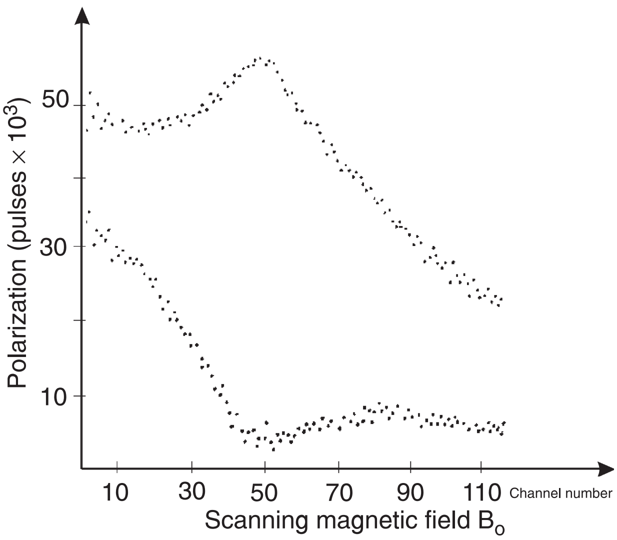


Fig. 2. Signal of self-alignment of level HeI $3p^1p^0$ detected by accumulation in two orthogonal polarisations of spectral line HeI 501.56 nm ($p_{He}$ = 0.15 Torr, 10 mA).

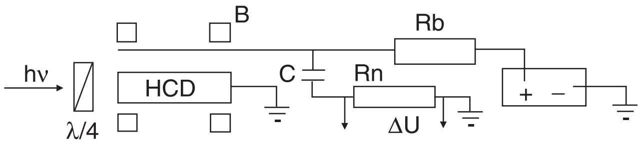


Fig. 3. Optogalvanic measuring circuit: $R_b$ is the ballast resistor, $R_m$ is the measuring resistor, $\Delta U$ is the optogalvanic signal. $B$ is the magnetic field (Helmholtz coils) in magneto-galvanic measurements.

The observed resonance in Fig. 2 may be described in the above mentioned electron beam – like approach [Fig. 1(a)] and continuous time excitation (power supply = $U$). Each electron-aligned level emits spectral line of intensity $I$, depending on the magnetic field $\boldsymbol{B}$

$$I = I_0 \int_0^\infty dt \exp(-\Gamma t) \cos^2(\omega t + \varphi),$$

where $\Gamma$ characterises the oscillator damping, $\omega = gB$ – its Larmor's precession frequency in $\boldsymbol{B}$, $\varphi$ is the angle between the self-alignment axis and the vector of the observed polarisation. At the end the intensity may be described by a Lorentzian lying on a decreasing background slope (Fig. 2)

$$I(2\gamma B/\Gamma) = I_0(2\Gamma)^{-1}\{R \arcsin L/R + L[1 + (2\gamma B/\Gamma)^2]^{-1} \times \\ \times [(1 - L^2/R^2)^{1/2} - L(2\gamma B/\Gamma)R^{-1}]\} \qquad (2)$$

where $L/R < 1$, $R = cB^{-1}(2mU_c/e)^{1/2}$, $c$ light velocity, $L$ is the distance $K$-$K$. Equation (2) contains coherent and noncoherent terms, corresponding to those in Eq. (1).

## 3.2. Coherent conductivity in HCD. Self-alignment and conductivity

The OG signals from aligned and oriented ensembles of atoms are detected and compared. A conventional OG measuring circuit is used (Fig. 3). The magnetic field $\boldsymbol{B}$ is off. Trademarks HCD lamps are irradiated by 632.8 nm laser line. A $\lambda/4$ –filter transforms the plane polarisation into circular. One should be taken in mind two circumstances:

- two compared OG signals belong to the same optical transition but different magnetic states: plane polarisation is absorbed at the magnetic transitions $m = 0 \rightarrow m = \pm 1$ (aligned ensemble) till circular polarisation at either $m = 0 \rightarrow m = 1$ or $m = 0 \rightarrow m = -1$ transition. Therefore the conductivity of aligned and oriented ensembles should be close,
- fact self-alignment $m = 0 \rightarrow m = \pm 1$ in HCD does not influence this comparison since the OG signals are detected at the frequency of laser beam modulation (485 Hz).

Figure 4 illustrates the measured OG signals. They suggest closeness and some differences of the OG reactions of aligned and oriented ensembles. The difference may be related to the specific proper coherent conductivity. In order the proper coherent conductivity of the self-aligned ensemble to be identified, the circuit of Fig. 3 is used at switched on scanning $\boldsymbol{B}$ – field and without any illumination. If an optical channel (plane polarisation filter – monochromator – multiplier – lock-in amplifier – recorder) has been added two resonances can be detected simultaneously. Besides

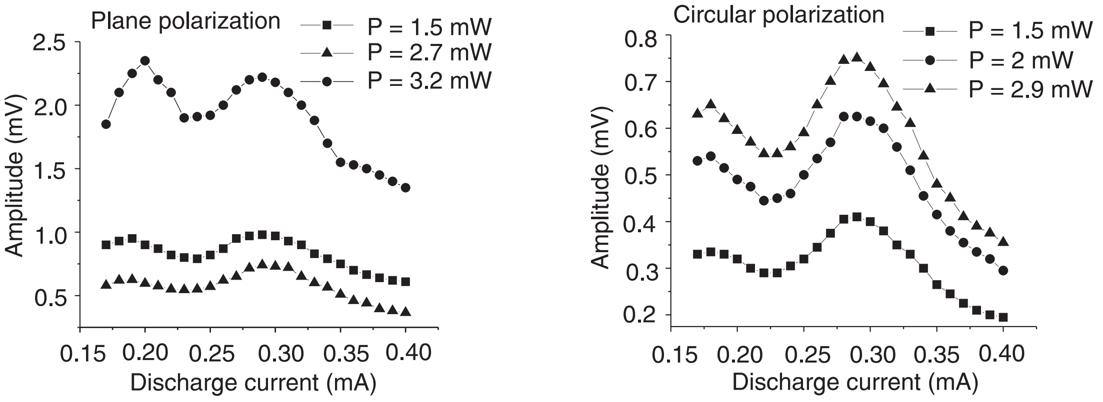


Fig. 4. OG signals from plane polarised (aligned ensemble) and circularly polarised (oriented ensemble) light.

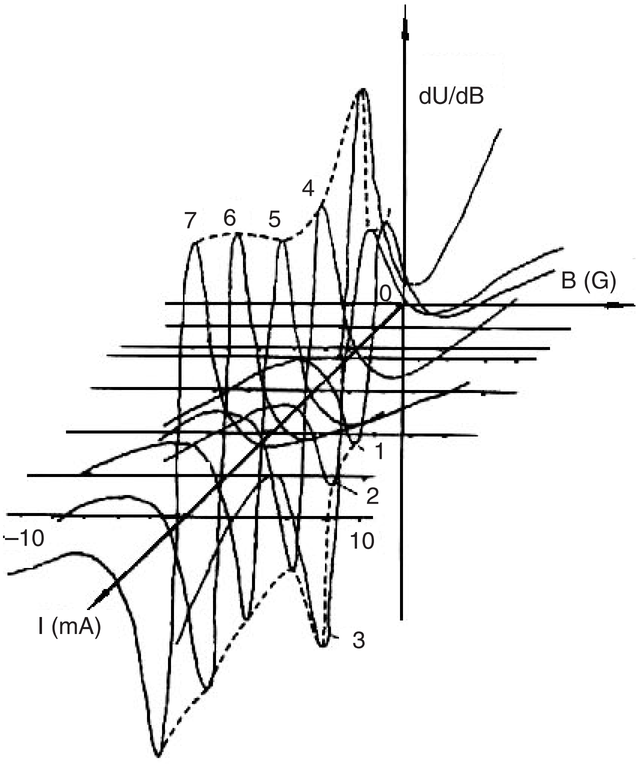


Fig. 5. Shape of magneto-galvanic resonance in Ne/Cu ("Narva") HCD lamp. Experimental signals at discharge currents: 1–0.5 mA, 2–1.0 mA, 3–1.25 mA, 4–2.0 mA, 5–3 mA, 6–4.0 mA, 7–5.0 mA. Magnetic field directed along the axis.

MO peak $P(\boldsymbol{B})$ for selected spectral line (Fig. 2) a galvanic signal $\partial U/\partial B$ with a shape close to the first derivative of voltage $U$ as a function of magnetic field, is detected by modulation of $B$ with an alternative component $\boldsymbol{B}_m$ (Fig. 5). We call this unknown up to date signal magneto-galvanic (MG) one. The two signals correlate in magnetic field direction, i.e. increase and decrease. This correlation means that the MO and MG resonances represent two manifestations of the same coherence, i.e., self-alignment. However MG peak is an integral galvanic indication of the coherent state.

## 4. Conclusions

Both the commensurability of the contact surfaces cathode ↔ cathode dark space ↔ negative glow and the electric field penetrating into NG predetermines strong electron excitation space anisotropy in HCD. This anisotropy (self-) aligns degenerated magnetic states along the normal to the cathode surface and their coherence manifests itself optically in partial plane polarisation of the spontaneous emission at low buffer gas pressure $p < 0.5$ Torr. The degree of polarisation $P$ increases near the NG. An external magnetic field destroys established self-alignment and an MO signal $P(\boldsymbol{B})$ is detected. Another analogue, i.e., galvanic one $\Delta U(\boldsymbol{B})$ of the self-alignment is also identified. This means that the coherent ensemble of atoms possesses proper coherent conductivity.

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