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2009 J. Phys. B: At. Mol. Opt. Phys. 42 035701

(http://iopscience.iop.org/0953-4075/42/3/035701)

IOP Publishing Journal of Physics B: Atomic, Molecular and Optical Physics
J. Phys. B: At. Mol. Opt. Phys. **42** (2009) 035701 (4pp) doi:10.1088/0953-4075/42/3/035701

Self-alignment and conductivity of a glow discharge

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Received 3 October 2008, in final form 28 December 2008
Published 21 January 2009
Online at stacks.iop.org/JPhysB/42/035701

Abstract
A magnetically induced resonance of the conductivity is analysed within the frames of self-aligned atomic states in a hollow cathode discharge. The resonance $\Delta U(\boldsymbol{B}_0)$ arises when the magnetic induction applied $\boldsymbol{B}_0$ destroys the self-alignment. The value of $\Delta U(\boldsymbol{B}_0)$ characterizes the difference in the conductivity of both self-aligned and non-aligned atomic ensembles. Generally, all self-aligned atomic states contribute to the resonance measured. This study is an attempt to specify the contribution of NeI levels $1s_5$ and $1s_4$ to the resonance $\Delta U(\boldsymbol{B}_0)$. Selective light depopulation of these levels is accomplished by using irradiating $\lambda = 640.2$ nm and $\lambda = 638.3$ nm.

1. Introduction

One may acknowledge that the influence of strong magnetic induction $\boldsymbol{B}_0$ of the order of 1 T and more, over different plasmas is better studied than that of weak magnetic induction (~1 mT) sufficient to reveal the presence of specific quantum states of the ensembles of the plasmas' particles. Such states known as *Zeeman coherences*, or *alignment*, are inherent for many kinds of plasmas due to the self-sustained alignment, i.e. self-alignment. The latter arises because of the presence of *excitation anisotropy* of atoms in the plasma bulk.

The coherent states of a given ensemble of particles are manifested by the optical characteristics of their spontaneous emission or absorption. A weak magnetic induction directed in such a way that it destroys the excitation anisotropy causes a change in the intensity or polarization of the spontaneous emission or absorption. Such changes are resonant in nature. The width of the resonances is determined by the decay time of the particular kind of coherence. These phenomena are known as the magneto-optical effect (MOE) or Hanle effect [1]. Apart from the optical effects, the interfering atomic states were found to generate also a specific galvanic effect in the glow discharge. Hannaford and Series [2] observed a resonant change of the laser-induced galvanic (LIG) signal in a magnetic field, perpendicular to the **E** vector of the optical field. Taken alone a laser beam aligns one selected state. A magnetic field up to ten Gauss does not perturb the diffusion of the plasma electrons to the wall, but causes a splitting of the magnetic sub-levels of the atoms, which is in the order of the natural width of the excited states. Hence the observed galvanic resonance may be attributed to the magnetic destruction of the laser-induced alignment.

In this work, the galvanic reaction of any self-aligned states in a glow discharge to their magnetic disordering is reported. Dependent on the plasma conditions *excitation anisotropy* producing self-alignment may arise due to light re-absorption and/or electron excitation. The latter was studied by using magneto-optic (MO) methods [3, 4] and the anisotropy of the electron energy function distribution was found to generate self-alignment of the high-energy states. The sought galvanic reaction complements the MO information.

A glow discharge modification, i.e. a hollow cathode discharge (HCD), is studied. The fast electrons from the cathode dark space generate in a HCD a considerable second-order moment $f^{(2)}(v)$ in the velocity v space of the electron energy distribution function [5]. This moment characterizes

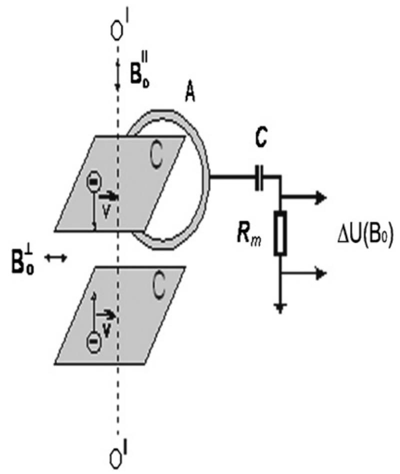

Figure 1. Schematic arrangement of the experiment with a two parallel net hollow cathode: A—anode, CC—cathode, $\boldsymbol{B}_0^{\mathrm{II},\perp}$—magnetic induction directed *along* and *normally* to the axes O′O′ of excitation anisotropy, *C*-decoupling capacitor, R_m-resistance.

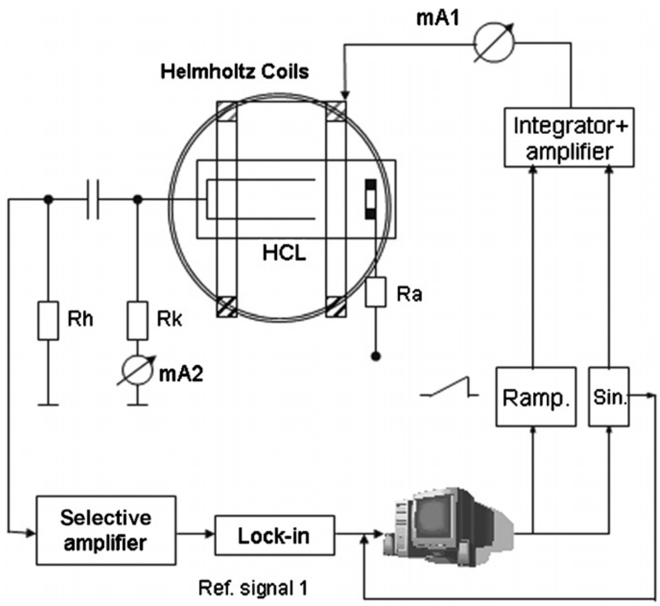

Figure 2. Experimental set-up: R_a—ballast resistance, R_k—cathode resistance, R_h—gauge resistance, HCL—hollow cathode discharge lamp.

the electron momentum flow and creates space anisotropy in the electron–atom excitation [6]. The galvanic contribution of NeI levels $1s_5$ and $1s_4$ is specified.

2. Experimental details

Figure 1 illustrates the essence of the measurements. The voltage variation $\Delta U(\boldsymbol{B}_0)$ across the discharge is searched without external irradiation or any other perturbation except the scanning magnetic induction $\boldsymbol{B}_0$ (Helmholtz coils) changed in the limits of about 10 G.

The value of $\Delta U(\boldsymbol{B}_0)$ is detected as variation of the voltage drop over the resistor in a R_mC circuit parallel to the discharge (figure 1). Two tubes of different HC geometry are used, i.e. conventional (cylindrical) in a commercial HCD lamp, and one consisting of two parallel plates (20 × 20 × 20) mm (figure 1). This HC design is used to identify a single relation between $\Delta U(\boldsymbol{B}_0)$ and *self-alignment*. Here the velocity vector $\vec{v}$ of the fast electrons from cathode dark space is characterized by a single axis **O′O′** of excitation anisotropy. The axis determines the self-alignment direction due to the fast electrons. Then the magnetic field $\boldsymbol{B}_0^{\perp}\perp\mathbf{O'O'}$ destroys the coherence. The cube-shaped plasma bulk minimizes the optical anisotropy in this HCD geometry.

An accumulating system was used in searching for and measuring the functions $\Delta U\left(\boldsymbol{B}_0^{\perp}\right)$. A distance of 20 mm within the cathode surfaces allows stable mode for operation at low enough pressure p_{Ne} (≈3 × 10^{-2} Torr) of the buffer gas Ne. Because of the disordering role of the collisions of atom–atom the lower the pressure the higher the self-alignment degree.

The contribution of NeI levels $1s_5$ and $1s_4$ is studied in a commercial HCD lamp Ne/Si ('Narva') by using the set-up in figure 2. It is a multifunctional scheme allowing automated recording of $\Delta U(\boldsymbol{B}_0)$ signals, laser-induced galvanic (LIG) signals, *I*–*V* curves (U/I) and their derivatives $\mathrm{d}U/\mathrm{d}I$. The laser system (not shown in figure 2) consists of a temperature-stabilized single longitudinal mode Fabry–Perot diode laser with central wavelength of operation 640 nm. The central wavelength was tuned by means of the temperature to coincide exactly with the investigated transition. A fine wavelength tuning was performed using computer control of the laser current. The specially developed software allows fine-tuning across the investigated transition as well as step positioning on and off the transition centre. Phase-sensitive detection (PSD) was used in the registration system to increase the signal-to-noise ratio.

3. Results and discussion

3.1. Conductivity of self-aligned and non-aligned ensembles of atoms in a HCD

Two kinds of galvanic reactions are detected below the region $\boldsymbol{B}_0 \in [-5, 5]\, G$ (figure 3).

In geometry $\boldsymbol{B}_0^{\mathrm{II}}\|\mathbf{O'O'}$, the magnetic field destroys no coherence, and no resulting voltage resonance has been detected (figure 3(b)). The values $U\left(\boldsymbol{B}_0^{\mathrm{II}}\right)$, measured across the HCD, describe the total influence of the induction $\boldsymbol{B}_0^{\mathrm{II}}$ on the conventional HCD conductivity. The function $U\left(\boldsymbol{B}_0^{\mathrm{II}}\right)$ manifests itself as a background in MO measurements. In contrast, in the magnetic field $\boldsymbol{B}_0^{\perp}\perp\mathbf{O'O'}$ destroying the self-alignment, a voltage variation with a sharp peak $\Delta U\left(\boldsymbol{B}_0^{\perp}\right)$ was detected (figure 3(a)). The peak parameters depend on the operating {*I*, p_{Ne}} point. The peak amplitude decreases at any $\boldsymbol{B}_0$ deviation from $\boldsymbol{B}_0^{\perp}$ and p_{Ne} rising (from 7 × 10^{-2} to 1.8 × 10^{-1} Torr). The half-width is in direct proportion to p_{Ne}. Earlier, in the same HCD modification these correlations were observed for the Hanle signal, i.e. magnetic depolarization $\Delta P\left(\boldsymbol{B}_0^{\perp}\right)$ of the spontaneous emission from any self-aligned state [6, 7]. Therefore, the measured change $\Delta U\left(\boldsymbol{B}_0^{\perp}\right)$ may be considered as galvanic manifestation of

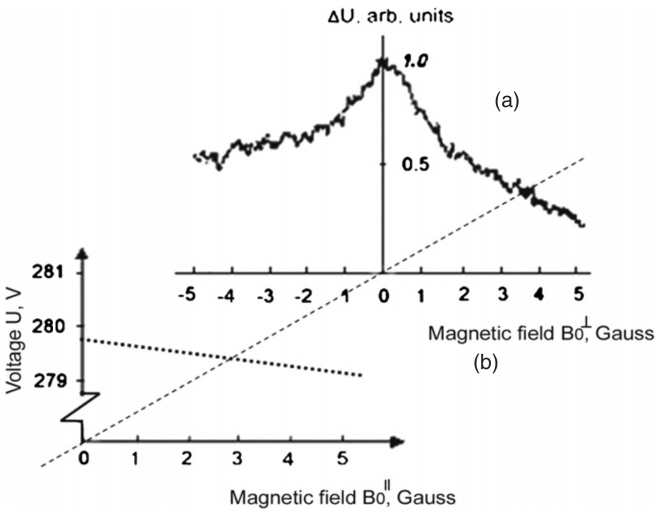

Figure 3. Galvanic reaction of the HCD in figure 1 versus magnetic induction $\boldsymbol{B}_0$: (a) resonance $\Delta U(\boldsymbol{B}_0^{\perp})$, (b) voltage drop $\boldsymbol{U}(\boldsymbol{B}_0^{\mathrm{II}})$ ($p_{\mathrm{Ne}} - 1.0 \times 10^{-1}$ Torr, dc. 5 mA).

the coherence of self-alignment type. Taken alone the value of $\Delta U\left(\boldsymbol{B}_0^{\perp}\right)$ characterizes the difference in the conductivity between both *self-aligned* and *non-aligned* ensembles of atoms. This difference may be identified as a *specific* (magnetic field dependent) *conductivity*, *i.e. a magnetic resonance conductivity* (MRC). The manifestation of MOE as a light emission depolarization assigns it to a concrete quantum transition. In contrast, many excited (self-aligned) levels contribute to the MRC, which is an integral characteristic and there is an uncertainty about the assignment of the aligned quantum states responsible for the effect. We emphasize once more that the MRC is regarded only as a manifestation of self-alignment destruction, which changes the ionization rate [8, 9].

3.2. Contribution of levels Ne I 1s$_5$ and Ne I 1s$_4$ to the MRC

To check the influence of the population and/or alignment of Ne I levels 1s$_5$ and 1s$_4$ on the formation of the MRC signal, an empirical approach based on the selective light perturbation of the transitions 1s$_5$–2p$_9$ ($\lambda = 640.2$ nm) and 1s$_4$–2p$_8$ ($\lambda = 638.3$ nm) is applied. The chosen wavelength λ is synchronously modulated (alternate communication 'on'/'off') with the ramp frequency of the magnetic field. Thus the signal $\Delta U(\boldsymbol{B}_0)$ measured is recorded in both irradiated and non-irradiated states. The corresponding maximum LIG signal is an indication of the resonant irradiation.

A correlation of MRC–LIG signals is of particular interest since the LIG influences strongly the charge carrier producing levels and the population of these levels depends on the interaction with different plasma components and on the electron density.

Figures 4 and 5 illustrate MRC signals $\Delta U(\boldsymbol{B}_0)$ in the Ne/Si HCD lamp under a discharge current of 2.6 mA and laser irradiation with either 638.3 nm or 640.2 nm. The induction $\boldsymbol{B}_0$ is directed along the axis of the cathode cylinder. Like the induction $\boldsymbol{B}_0^{\perp}$ (figure 1) here $\boldsymbol{B}_0$ destroys the self-alignment due to the fast electrons from the cathode surface,

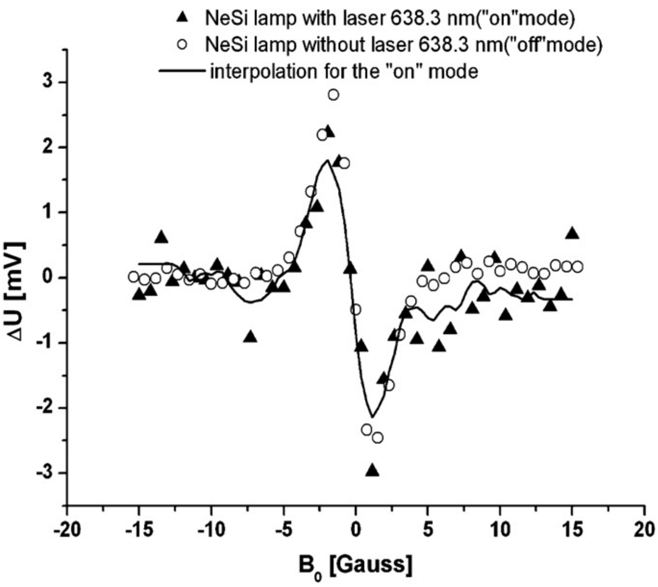

Figure 4. MRC signal in Ne/Si HCD lamp ('Narva') at 638.3 nm irradiating and discharge current 2.6 mA.

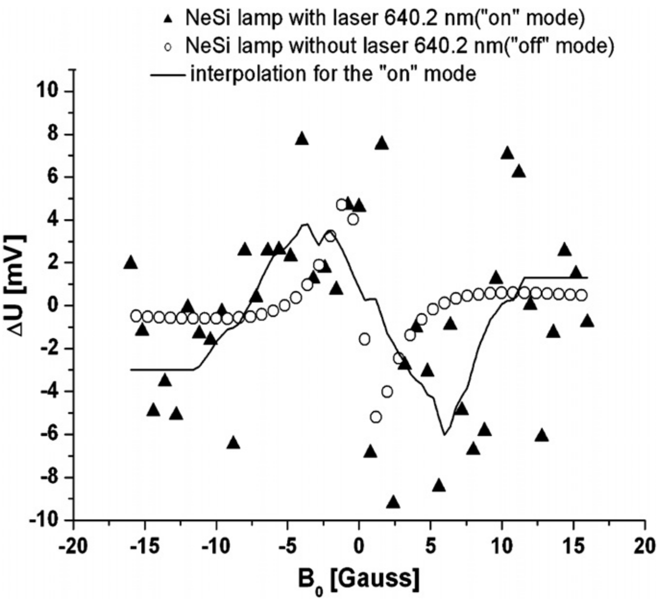

Figure 5. MRC signal in Ne/Si HCD lamp ('Narva') at 640.2 nm irradiating and discharge current 2.6 mA.

because of PSD the signal is close in shape to the first derivative $\partial U(B)/\partial B$. The 638.3 nm wavelength irradiating does not perturb the MRC signal (figure 2), including its width. Therefore, the contribution of the 1s$_4$ level in the MRC could be considered negligible within the frame of our experiment. In contrast, figure 3 illustrates the decisive participation of the 1s$_5$ level in the formation of the corresponding MRC. The light perturbation of the metastable dramatic perturbs the measured $\Delta U(\boldsymbol{B}_0)$ values and broadens essentially the MRC signal. Undoubtedly, the metastable 1s$_5$ contributes essentially to both destruction of the MRC signal and light-induced galvanic reaction. Moreover, light-induced extinction of a HCD was observed via 1s$_5$, but not via 1s$_4$ [10].

A key question is how the destruction of the aligned metastable state transforms to magnetically induced variation of the discharge current density j. It is known that the latter is proportional to the product of the electron number density n_e and electron drift velocity v_e. Therefore, one can write $\Delta j = c_1 \Delta n_e + c_2 \Delta v_e$. The second term can be *a priori* neglected in our case because the electron drift velocity is insensitive to the weak magnetic induction at which the MRC signal is observed. The first term is directly dependent on the ionization rate and for the considered plasma conditions the dominant ionization channel is through the neon $1s_5$ metastable state [6]. Therefore, the change of the current density due to variation of the magnetic induction will be evoked by the change of the ionization rate from the $1s_5$ metastable state. One must note that earlier the total ionization rate was found depending on the irradiating light polarization [11].

However, in the HCL, the $1s_5$ level may act on the MRC signal by a different means too, i.e. Penning ionization [12] of sputtered atom via this metastable. This process is a rule rather than an exception in a HCD due to the intensive cathode sputtering. If Penning ionization grows up to be dominating the step-like one, a section of negative dynamic resistance $\partial U/\partial I < 0$ arises on the I–V curve. The MRC signal was measured to be of lower signal-to-noise ratio in this section.

4. Conclusions

Magnetic destruction of self-alignment manifests itself as resonant change $\Delta U(\boldsymbol{B}_0)$ of the HCD conductivity. The peak parameters depend on both operating $\{I, p_{Ne}\}$ point and magnetic induction $\boldsymbol{B}_0$ like those of the Hanle signal $\Delta P(\boldsymbol{B}_0)$. Thus, the galvanic peak may be ascribed to the specific ionization from coherent states and characterizes the difference in the conductivity of self- and non-aligned ensemble of atoms. This difference may be designated as *magnetic resonance conductivity* and depends on the degree of self-alignment.

Generally, all self-aligned states contribute to the coherent conductivity. The essential contribution of the metastable $1s_5$ to the MRC is found using laser illumination at 640.2 nm.

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