Drift self-alignment of ions in a plasma

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(Submitted 28 October 1986)
Pis'ma Zh. Eksp. Teor. Fiz. **45**, No. 1, 15–17 (10 January 1987)

A self-alignment, specifically, a spontaneous quadrupole orientation, of the angular momenta of the electron shells of ions drifting in a plasma has been detected for the first time. This self-alignment stems from the anisotropic nature of collisional relaxation.

In this letter we report the first detection of a self-alignment of the angular momenta of ions in a plasma as a result of their drift. A self-alignment of this sort was hypothesized in Ref. 1, where a theoretical study was made of an anisotropic collisional relaxation of the order of the angular momenta of ions due to a predominant direction for their collisions with neutral atoms: antiparallel to the drift.

The present experiments were carried out in a gas discharge in a hollow cathode (3 cm in diameter and 5 cm long) in argon at a discharge voltage of 100–400 V. A magnetic polarization spectrometer, which operates by virtue of the Hanle effect, was used to measure signals representing the intensities of the spontaneous emission polarized linearly along the drift axis (I_z) and in the perpendicular direction (I_y), for various lines of atomic and ionized argon in the direction of the symmetry axis of the cathode. The sensitivity of the instrument was such that it was possible to reliably detect a degree of polarization at the level of 10^{-3}–10^{-4} at a data acquisition time on the order of 20 min.

A measure of the self-alignment of the angular momenta of the excited states of the emitting particles is the intensity difference $I_z - I_y$, while the sum of the intensities, $I_z + I_y$, is proportional to the populations of these states. Clearly defined signals of the intensity difference $I_z - I_y$, which definitely indicate an alignment of the higher-lying levels of the ion transitions under study, were detected in Ar^+ lines corresponding to transitions from levels belonging to blocks of fine-structure states closely spaced along the energy scale. These signals were detected in the narrow pressure interval 0.1–0.5 torr and at discharge currents of 10–60 mA. The spatial distribution of the self-alignment and of the populations of the excited states inside the hollow cathode has the typical radial profile shown in Fig. 1. The maximum alignment $I_z - I_y$ is observed near the boundary of the cathode dark space, while the maximum population of the level occurs in the central part of the negative glow. An important point is that in the negative glow, where the density of fast electrons, which excite and ionize atoms, is at its maximum, the self-alignment signal is at a minimum. This result means that direct electron-impact excitation[2] is not the reason for the observed self-alignment of the ion states. This conclusion is supported by an analysis of the widths of the experimental lines of the signals in the Hanle effect: If the self-alignment were induced by a mechanism which was independent of the pressure, an extrapolation of the widths

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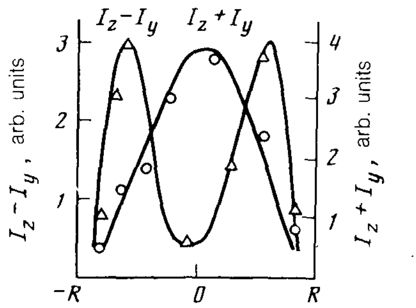

FIG. 1. Radial profiles of the self-alignment $I_z - I_y$ and of the population $I_z + I_y$ of the $4p^2P^0_{3/2}$ level of Ar^+ ($\lambda = 4764$ Å) in a discharge in a hollow cathode ($p = 0.3$ torr, $i = 30$ mA).

of the signals to zero pressure would yield the radiative lifetime of the upper level for the given transition. Experimentally, we observe a substantial difference between the results of such an extrapolation and the level lifetimes found in independent measurements. Consequently, the observed self-alignment of ion states is strongly related to collisions of these ions with gas atoms.

The most direct evidence for a drift mechanism for the alignment of the ions comes from a comparison of the signals $I_z - I_y$ for the extremely bright lines of neutral atoms and for the weaker ion lines of argon. These signals are an order of magnitude (or more) weaker for the atomic lines than for the ion lines. It must then follow that the drift of the ions in the plasma, which leads to the anisotropic collisional relaxation of ordered angular momenta of the excited ions, is in fact the reason for the observed self-alignment of ion states.

Our experiments also confirm the validity of the more-detailed predictions of the theoretical model developed in Ref. 1. According to that model, the self-alignment that arises is strongly related to a collisional mixing of fine-structure sublevels of the ions, while the self-alignment signal stems from a deviation of the relative populations of these sublevels, N_1/N_2, from the ratio of their statistical weights, g_1/g_2. Direct measurements of the intensities of the fine-structure components of the lines revealed

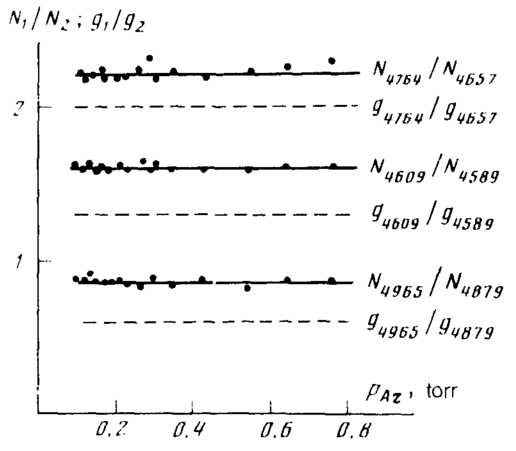

FIG. 2. Population ratio of the components of Ar^+ ion doublets versus the pressure in the discharge in the hollow cathode ($i = 40$ mA).

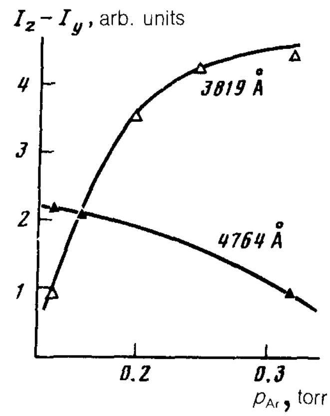

FIG. 3. Linear polarization of the ion lines of argon at 3819 Å and 4764 Å versus the pressure ($i = 30$ mA).

the population ratios N_1/N_2 for several ion doublets of argon. Some typical results are shown in Fig. 2. From this figure we see that at low pressures the population ratios of the sublevels of the doublets deviate significantly from the ratio of statistical weights. Finally, the model of a combined dispersive and ion-polarization-quadrupole interaction, which was proposed in Ref. 1, determines the splitting of the degenerate magnetic sublevels of an excited ion in its collision with a neutral atom. In that model it turned out that the collisional self-alignment of ion states depends nonmonotonically on the parameter

$$S = n_a \alpha_a^{-0.3} \left(\frac{3 \,|\, Z_e Q_e^2 \,|\, \alpha_a + C_{\parallel} - C_{\perp}}{\hbar} \right)^{0.4},$$

reaching a maximum at a certain optimum value S. Here n_a is the density of neutral atoms, α_a is their polarizability, Z_e and Q_e are the charged and electric quadrupole moment of the ion, and $C_{\parallel} - C_{\perp}$ is the anisotropy of the constants of the dispersive interaction of the ion with the atom.

Since Q_e and $C_{\parallel} - C_{\perp}$ depend on the electronic state of the ion, the drift self-alignment of the ion levels is selective: Different groups of fine-structure levels undergo a maximum self-alignment at different pressures, and at a given pressure the self-alignments of the different groups of levels are different. These predictions are confirmed by our experiments, as can be seen in Fig. 3, which shows some typical results on the self-alignment signals $I_z - I_y$ of Ar^+ doublets versus the pressure.

Taking all the experimental results into account, we can assert that these experiments have revealed a new phenomenon: a drift self-alignment of ion states in a plasma. The use of this phenomenon will expand the capabilities of polarization optical methods for plasma diagnostics, for a wide range of objects in the laboratory and in astrophysics.

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Translated by Dave Parsons