Determination of the quadrupole moment of the electron distribution function in a plasma

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The first physical evidence of a quadrupole moment of the electron distribution function in a plasma has been detected: The total angular momenta of the ensemble of excited particles become aligned and give rise to a partial linear polarization of the spontaneous emission.

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The first physical manifestation of a quadrupole ordering of the electron velocities in a plasma has been observed. The effect is a partial linear polarization of the spontaneous emission.

The electron kinetics in a plasma is characterized by the velocity distribution function $f(\mathbf{v})$, which is analyzed by making use of an expansion in spherical harmonics[1] $Y_q^{(\kappa)}(\mathbf{n})$:

$$f(\mathbf{v}) = \sum_{\kappa=0}^{\infty} \sum_{q=-\kappa}^{\kappa} Y_q^{(\kappa)}(\mathbf{n}) f_q^{(\kappa)}(v) , \tag{1}$$

where $\mathbf{n} = \mathbf{v}/|v|$ is a unit vector along the electron velocity, and $f_q^{(\kappa)}(v)$ is a multipole moment of the distribution function. The zeroth-order moment $f^{(0)}(v)$ represents the isotropic part of the distribution function and reflects the dependence on the velocity modulus, i.e., the energy distribution of the electrons. This multipole moment determines the excitation and ionization of the particles in the plasma and thus the emission spectra. The first-order moment $f^{(1)}(v)$ reflects the presence of a dipole ordering of the electron velocities in the ensemble, i.e., a drift of the electron gas. The multipole moments of higher orders are very small in magnitude, have not been observed experimentally, and have not been taken into account in the corresponding theory. The second-order moment of the electron distribution function represents a momentum flux of the electrons or a pressure.

We report here the first experimental observation of a physical effect caused by $f^{(2)}(v)$. We believe it is possible to determine this moment of the distribution function and to make use of the information embodied in it for diagnostics of laboratory and astrophysical plasmas.

The polarization characteristics of the spontaneous emission of an ensemble of excited particles are described in the representation of polarization moments of the atomic density matrix[2] $\rho_q^{(\kappa)}$:

$$I_{\mathbf{e}_\lambda} = A \sum_{\kappa, q} (-1)^q \alpha_\kappa \rho_q^{(\kappa)} \Phi_{-q}^{(\kappa)} (\mathbf{e}_\lambda) \tag{2}$$

where $I_{\mathbf{e}_\lambda}$ is the intensity of the spontaneous emission in a particular spectral line with polarization vector e_λ, A is a constant characteristic of the particular transition, $\Phi_q^{(\kappa)}(\mathbf{e}_\lambda)$ is the observation tensor, which determines the geometric and polarization characteristics of the linearly polarized emission which is observed, and α_κ is a constant. The linearly polarized emission of an ensemble of excited particles is determined by the alignment tensor $\rho_q^{(2)}(q = 0, \pm 1, \pm 2)$.

An electron beam causes an alignment of the total angular momenta of excited atoms, which emit linearly polarized light with polarization direction parallel to the velocity vector $\mathbf{v}$ of the exciting electrons.[3] In a coordinate system with OZ axis along the vector $\mathbf{v}$, the excitation by a beam of unpolarized electrons is cylindrically symmetric, and, according to Ref. 4, the polarization angular momenta are represented exclusively by an alignment tensor with $q = 0$. Its value in this coordinate system, ${}^{v}\rho_0^{(2)}(v)$, can be found theoretically or experimentally. Making use of the transformation of the polarization angular momenta as we transform to the laboratory coordinate system, and taking an average over all directions of the electron velocities, using the electron distribution function in the multipole-moment representation, (1), we find that if the particles in the plasma are excited by direct electron impact, the alignment tensor characterizing the ensemble of excited particles, $(\hat{\rho}_q^{(2)})$, can be written

$$\hat{\rho}_q^{(2)} = (-1)^q c \int_0^\infty dv\, v^2\, {}^{v}\rho_0^{(2)}(v) f_{-q}^{(2)}(v) \cdot \tag{3}$$

It follows that the alignment of the angular momenta of the ensemble of excited

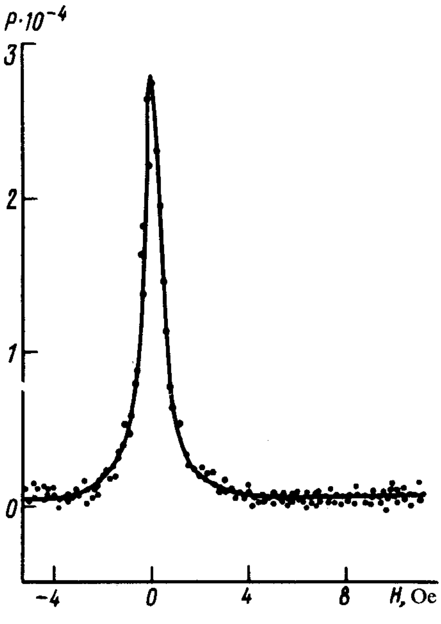

FIG. 1. Experimental alignment signal of the $7d\,[\frac{5}{2}]_3^0$ state of xenon detected in a low-temperature plasma in the positive column of a discharge. The signal corresponds to the transition $6p[\frac{3}{2}]_2 - 7d\,[\frac{5}{2}]_3^0(\lambda = 7393$ Å). The pressure is 14 mTorr, and the discharge current is 50 mA. The points reflect the experimental degree of linear polarization obtained by accumulating the signal in numerical form at a certain value of the external magnetic field. The signal accumulation time is 1 h.

particles in the plasma, $\hat{\rho}_q^{(2)}$, and thus the presence of a linear polarization of the spontaneous emission I_{e_λ} are determined by the quadrupole moment of the distribution function, $f_q^{(2)}(v)$.

This effect has been detected experimentally in highly excited states of inert gas atoms in a low-temperature gas discharge at pressures on the order of a few tens of millitorrs. Under these conditions, the primary mechanism operating to excite these states in the positive column of a dc discharge is the mechanism of collisions of the first kind with electrons. The alignment in the plasma was observed by making use of the Hanle effect: The alignment tensor is disrupted by a weak magnetic field, and the plasma emission is observed to become depolarized; this depolarization is the experimental signal. Figure 1 shows a typical recording of this signal for the $7d[\frac{5}{2}]_3^0$ level of xenon. The degree of linear polarization of the emission corresponding to this effect is on the order of 10^{-4}, reflecting the multipole-moment ratio $f^{(2)}/f^{(0)}$ in the plasma.

Returning to (2) and (3), we can analyze the possibility of polarization spectroscopy of plasmas. By solving the inverse problem—by working from the magnitude and spatial distribution of the degree of linear polarization of the spontaneous emission of the plasma for several atomic and ionic spectral lines corresponding to various excitation potentials—we can extract information about the quadrupole moment of the electron distribution function. Information of this sort lies beyond the reach of other known plasma diagnostic methods.

This effect may have some important astrophysical applications. By studying the alignment of excited atoms and ions in astrophysical entities[5]—this alignment is manifested by a linear polarization of the optical emission—one can reconstruct the characteristics of the velocity field of the exciting particles in the entities, e.g., in the solar atmosphere.

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