

Introduction

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1.1 What is Plasma Polarization Spectroscopy?

Plasma spectroscopy is one of the disciplines in plasma physics: a spectrum of radiation emitted from a plasma is observed and its features are interpreted in terms of the properties of the plasma. In conventional plasma spectroscopy, line (and continuum radiation) intensities and broadening and shift of spectral lines have been the subject of observation. Attributes of the plasma, e.g., whether it is ionizing or recombining, what are its electron temperature and density, are deduced or estimated from the observation. We can expand the ability of plasma spectroscopy by incorporating in our framework the polarization characteristics of the radiation.

Figure 1.1 is an image of a plasma; a helium plasma is produced by a microwave discharge in a cusp-shaped magnetic field and this picture shows the intensity distribution of an emission line of neutral helium. The symmetry axis of the magnetic field and thus of the plasma lies horizontally below the bottom frame of the picture; this picture shows the upper one third of the plasma. The magnetic field is mirror symmetric with respect to the vertical plane (perpendicular to the axis) located at the center of this picture, and the magnetic field on this plane is purely radial. An interference filter placed in front of the camera lens selects the emission line of HeI $\lambda 501.6\text{ nm}$ ($2^1S_0-3^1P_1$), and the intensity distribution of this line is recorded, as shown in this picture. Here, throughout this book, we adopt the convention for a transition that the lower level comes first and the upper level follows. A linear polarizer is also placed. From the comparison of the images for various directions of the transmission axis of the polarizer, the field view map of the directions and magnitudes of linear polarization is obtained; the result is shown with the direction and length of the bars. (The procedure to construct this picture is given in Chap. 14 later.) The meaning of the intensity distribution is rather straightforward; i.e., it shows the spatial distribution of the upper-level population of this line, i.e., He(3^1P) in this case, or even the shape of the plasma. What does the polarization mean, especially in relation with the characteristics of

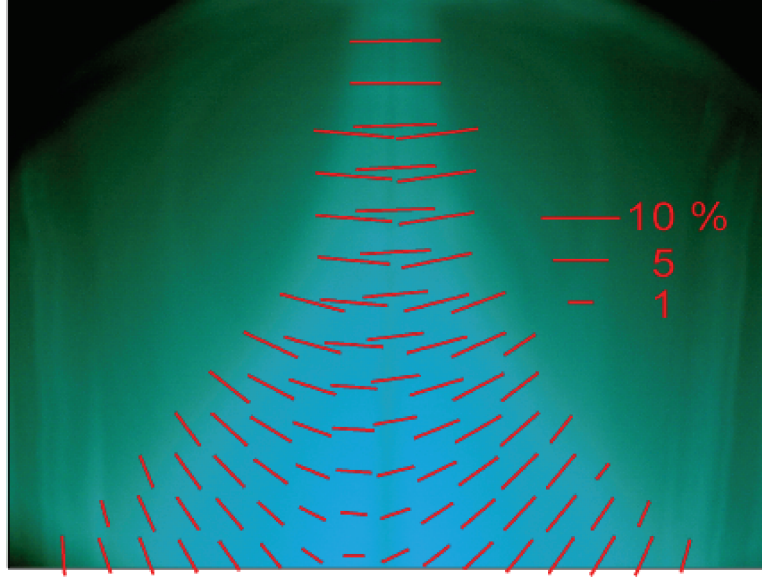


Fig. 1.1. The map of the intensity and polarization of the HeI $\lambda 501.6$ nm ($2^1S_0 - 3^1P_1$) line emitted from a microwave discharge plasma produced in a cusp-shaped magnetic field. The plasma axis lies horizontally below the bottom frame of the picture. The *short lines* indicate the magnitude and direction of linear polarization of this emission line

the plasma? This is the question to which *plasma polarization spectroscopy* (abbreviated to PPS henceforth) is to address.

As is obvious from the nature of polarization, the polarization phenomenon is related with spatial (more accurately, *directional*) anisotropy of the plasma. As a typical example of anisotropy, which will be important in PPS as discussed in more detail later in this book, we consider anisotropic electron impact on atoms. The most extreme example would be excitation of atoms by a beam of monoenergetic electrons. We discuss this collision process in a classical picture here.

An electron traveling in the z -direction collides with an atom located at the origin. This classical atom consists of an ion core and an electron that is attracted to the core with a harmonic force. In the case that the incident electron has an energy just enough to excite the atom and the collision is head on, the electron would give up the whole of its momentum and energy to excite the atom, and it stops there. The atomic electron begins to oscillate in the z -direction. This excited atom is nothing but a classical electric dipole, and it emits dipole radiation. If observed in the x - y plane, the radiation is polarized in the z -direction, or it is the π light, the electric vector of which oscillates in the z -direction. See Appendix A. Figure 1.2 shows an example of experimental observations on real atoms; helium atoms in the ground state

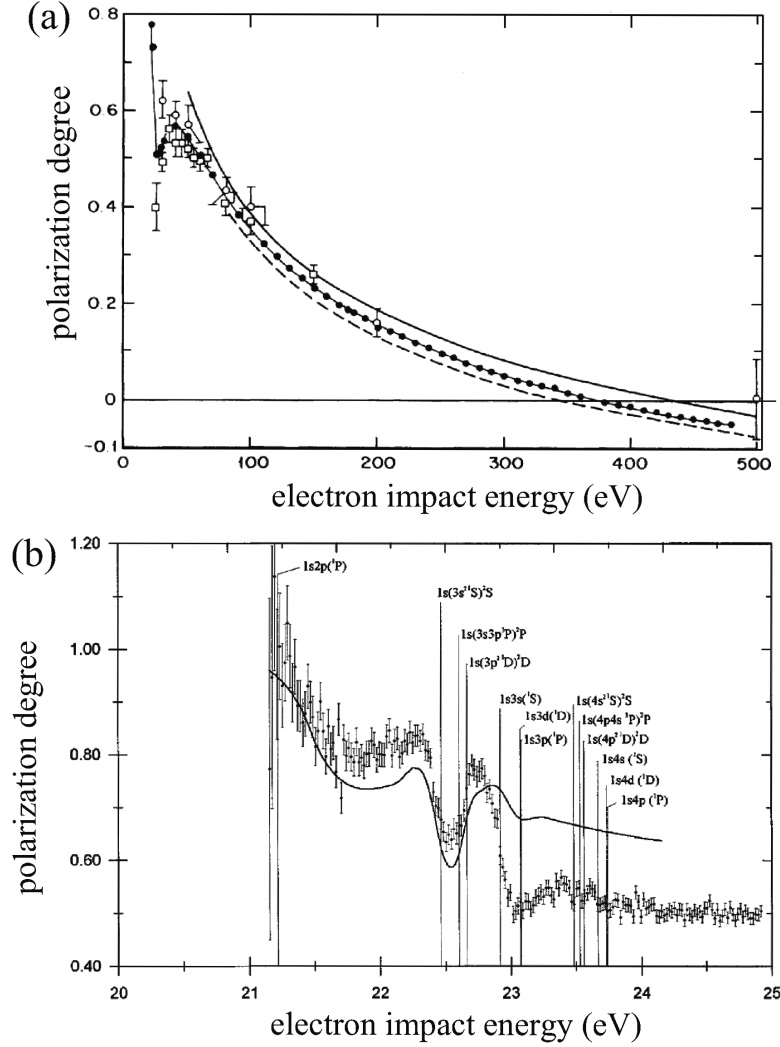


Fig. 1.2. Polarization degree of emitted radiation of neutral helium upon excitation from the ground state by an electron beam. (a) $1^1S \rightarrow n^1P$ with $n \geq 2$ for a broad energy region. (Quoted from [1], with permission from The American Physical Society). (b) $1^1S \rightarrow 2^1P$ close to the excitation threshold at 21.2 eV. The *full curve* represents the result of calculations convoluted with a 0.16 eV Gaussian function. In the figure, the positions of doubly excited levels are given near 22.5 eV and 23.5 eV; the former levels give rise to a structure because of the resonance effects. Singly excited level positions are also marked near 23 eV and 23.7 eV. The substantial deviation of the experimental polarization degree from the theoretical values in the higher energy region is obviously attributed to the cascading effects from these higher lying levels (Quoted from [2], with permission from The American Physical Society.)

(1^1S_0) are excited by a beam of electrons to one of the n^1P_1 ($n \geq 2$) levels and a transition line ($1^1S_0 - n^1P_1$) emitted by these atoms is observed [1, 2]. The degree of linear polarization $P = (I_\pi - I_\sigma)/(I_\pi + I_\sigma)$ is determined, where I_π is the intensity of the π light, and I_σ is that of the σ light, the electric vector of which oscillates in the x - y plane. Figure 1.2a shows the overall feature and Fig. 1.2b is the detailed structure just above the excitation threshold, 21.2 eV, for the resonance line ($1^1S_0 - 2^1P_1$) excitation. Toward the excitation threshold, the polarization degree tends to 1, in agreement with our above discussion in the classical picture.

When the incident electron is very fast and passes by our classical atom, it exerts a pulsed electric field on the atom. This field is, roughly speaking, directed within the x - y plane. This pulse may be approximated as a half cycle of an electromagnetic wave propagating in the z -direction. It is noted that a beam of radiation lacks the electric field in its propagation direction. The “photo”-excited atomic electron will oscillate within this plane, and this atom again emits dipole radiation. This time, the radiation is the σ light. As Fig. 1.2a suggests, within our picture, the polarization degree would go to -1 at very high energy.

Thus, an excited atom or ion keeps the memory of the direction of the collision by which it was produced and presents its memory in the form of polarization of the light it emits.

Since an atom (or an ion) in a plasma could be affected by various atomic interactions in its excitation and subsequent time development, the direction that the atom remembers may not be limited to that of the electron velocity. Atom and ion velocities, external fields, a radiation field, all these entities can enter into the memory of an atom and thus can be reflected in the polarization characteristics of the radiation it emits. Even recombination of electrons having an anisotropic velocity distribution could make the recombination continuum polarized and, in the case of recombination to an excited level, subsequent line emissions to still lower-lying levels are polarized, too. Only in the case when these atomic interactions are random in direction, or they are isotropic, we can expect the radiation to be unpolarized. In the conventional plasma spectroscopy, which we may call *intensity* spectroscopy, we implicitly assumed this situation. In the present context, the intensity spectroscopy provides information only of how *many* atoms were excited. The intensity distribution of the emission line in Fig. 1.1 gives us this information.

The above arguments constitute the starting point of PPS. If we utilize the polarization characteristics of radiation in interpreting the plasma, we should be able to deduce information of *how* these atoms or ions were excited in the plasma. Determination of anisotropic, therefore nonthermal, distribution function of electrons is an immediate example. As will be discussed in the subsequent chapters, atom collisions, electric and/or magnetic fields, a radiation field or even electromagnetic waves also affect the polarization characteristics of emission lines. All of these aspects are included in the framework of PPS.

1.2 History of PPS

The history of PPS may be traced back to 1924 when Hanle [3] reported a change of the polarization characteristics of the fluorescence light from a mercury vapor against applied magnetic field; the photo-excited atoms in a magnetic field perform Larmor precession, and the initial memory of excitation anisotropy is modified by the magnetic field during the lifetime of the atoms. See Appendix D for a more detailed explanation. In investigating the newly found Stark effect (see Chap. 2) by using a canal ray, Mark and Wierl [4] found that the intensity distribution among the polarized components of the Stark split Balmer α line depends on whether the ray passes through a low-pressure gas or a vacuum. This polarization may be interpreted as due to anisotropic collisional excitation of the canal ray atoms.

On the basis of the experimental and theoretical investigations of polarization of emission lines upon collisional excitation of atoms by electron impact [5], much progress was made in the 1950s in developing the theoretical framework, by which these excited atoms are treated in terms of the density matrix [6, 7]. The density matrix is briefly discussed in Appendix C. The studies in the 1970s of interactions of photons with atoms, especially optical pumping [8, 9], founded the theoretical basis of PPS.

Modern PPS research started in the middle 1960s. Spontaneous polarization of emission lines from plasma was discovered by three groups. The first was the observation of polarization of neutral helium lines from a high-frequency *rf*-discharge by Lombardi and Pebay-Peyroula in 1965 [10]. A little later, Kallas and Chaika [11], and Carrington and Corney [12], almost simultaneously, reported their observations of the magnetic-field dependent polarization of neutral neon lines from DC discharge plasmas. Interestingly, they had little knowledge of other groups' work. This new phenomenon was named *the self alignment*. The polarization shown in Fig. 1.1 may be regarded as an example of self alignment. In these early observations, the origin of polarization of light, or of the alignment (this term will be explained in Chap. 4) in the upper-level "population", was attributed to directional collisional excitation by electrons, as mentioned later and discussed in Chaps. 5 and 6 in detail, or to radiation reabsorption in the anisotropic geometry, which will be discussed in Chap. 7.

In the 1970s–1980s, the self alignment phenomena of various origins were discovered and investigated vigorously on various discharge plasmas, mainly in the former Soviet Union. Gradually, it became recognized that PPS is a promising new technique, which would provide us with valuable information about the plasma, i.e., its anisotropy, to which no other ordinary techniques have an access. Thus, the target of PPS observations expanded to a variety of plasmas, and this trend continues now. These developments until a decade ago are summarized in Fujimoto and Kazantsev [13]. In astrophysical observations, polarization has been an important source of information about the magnetic

field, the sprathermal electrons, and so forth in the solar atmosphere. Several monographs have been published recently [14–17].

An element always important in the PPS research is the instrumentation. For stationary discharge plasmas, an observation system based on the Hanle effect was developed, which was capable of determining polarization degrees as low as 10^{-4} [18]. For a variety of discharge conditions, self alignment produced by anisotropic electron impact, or by radiation reabsorption was observed, and even self alignment due to the ion drift motion was discovered [19]. By the use of the Hanle effect method, the lifetime of excited atoms and the alignment destruction rate coefficient (cross-section) by atom collisions were determined for many atomic species. Various possibilities of plasma diagnostics were demonstrated: obtaining the quadrupole moment of the electron velocity distribution [20], determining the energy input in a high-frequency discharge [21], determining the electric field [22]. The term *Plasma Polarization Spectroscopy* was first introduced by Kazantsev et al [23]. An interesting observation was on an atmospheric-pressure argon arc plasma; ionized argon lines showed polarization and this was quantitatively interpreted as due to the distorted Maxwell distribution of electron velocities [24].

An important target of PPS is the solar atmosphere; Atoms in the solar prominence is illuminated by the light from the solar disk, and the photoexcitation is anisotropic. The alignment thus produced is perturbed by the magnetic field present there. From the direction and the magnitude of the observed polarization of a helium emission line, for example, the direction and the strength of the magnetic field were deduced [25, 26]. Solar flares, in which anisotropic excitation of ions by electrons having a directional motion would produce alignment, were also a subject of PPS observation [27].

In laboratories, vacuum sparks and plasma focuses were also the target of PPS observations. Polarization was found on helium-like lines in the x-ray region [28]. However, the difficulty stemming from the observation geometry sometimes makes the interpretation complicated, and efforts to improve the instrumentation are being continued [29]. The z -pinch and the so-called X-pinch are being investigated vigorously [29–32].

The first PPS observation on a laser-produced plasma was made by Kieffer et al on helium-like aluminum lines [33, 34]. They interpreted the polarization as due to the anisotropic electron velocity distribution, which was caused by the nonlocal spatial transport of hot electrons from the underdense plasma to the overdense plasma. Another observation was performed by Yoneda et al. [35] on helium-like fluorine lines. The intensity distribution pattern of the resonance-series lines ($1^1S_0 - n^1P_1$) and the presence of the recombination continuum ($1^1S_0 - \epsilon^1P_1$) clearly indicate that the observed plasma was in the recombining phase (see Chap. 3). Interesting findings were that the recombination continuum was polarized, and that the resonance-series lines were also polarized. The first fact indicates that the velocity distribution of the low-energy electrons that make radiative recombination is anisotropic: more directional to the direction of the target surface normal. This is against the

general understanding that low-energy electrons are thermalized very rapidly. The second point indicates that owing, probably, to the anisotropic elastic collisions by electrons, n^1P_1 upper-level atoms are aligned: i.e., among the $M = 0, \pm 1$ magnetic sublevels, the $M = 0$ level is more populated. Here M means the magnetic quantum number of the level having the total angular momentum quantum number J . J is 1 in the present case. No interpretation of this experiment has been made so far, except for the discussion [36], which will be presented in Chap. 6 later in this book. A new experiment is performed [37]. Kawachi et al. [38] examined polarization of the neon-like germanium X-ray laser line of 19.6 nm. The transition was $2p^53s - 2p^53p$ ($J = 1 - 0$), so that the spontaneous emission of this line is never polarized. The observed polarization was ascribed to the alignment of the $2p^53s$ lower-level population, which was due to anisotropic radiation trapping, $2p^6 \leftrightarrow 2p^53s$. This experiment will be introduced in Chap. 10.

Magnetically confined plasmas including tokamak plasmas are also the target of PPS observations. MSE (motional Stark effect) is now a standard technique to determine the direction of the local magnetic field, and thus to determine the current distribution in the plasma [39, 40]. The Zeeman effect is also employed for plasma diagnostics [41]. The polarization resolved observation of the Zeeman profile of the Balmer α line was found quite useful [42]. Fujimoto et al. [43] first reported the polarization observation on carbon- and oxygen-ion emission lines from a tokamak plasma. They used a calcite plate incorporated into the spectrometer as the polarization resolving element. Anisotropic distributions of electron velocities were suggested as the origin of the observed polarizations. As shown in Fig. 1.1, magnetically confined plasmas are now a target of PPS observations. The full PPS formalism, which is described in [13] and also in Chap. 4 later, was implemented on the helium plasma in Fig. 1.1. An oblate-shaped distribution function was deduced from the intensity and polarization of several emission lines [44].

1.3 Classification of PPS Phenomena

As noted earlier, emission lines (and continua) can be polarized because of the anisotropy of the plasma. This anisotropy may be due to anisotropic collisional excitation as discussed in Sect. 1.1, or due to an external field, electric, or magnetic. Even electromagnetic waves could affect the polarization characteristics [45] as will be shown in Chap. 13. We classify the polarization phenomena into three classes:

Class 1: When an atom is placed in an electric field or a magnetic field it is subjected to the Stark effect or the Zeeman effect: an atomic level, and therefore a spectral line, is split into components and each of the components is polarized. When all the components are added together, the line is overall unpolarized. These phenomena are known for a long time and the formulation of these effects is well established. Still, new techniques are being

developed for plasma diagnostics on the bases of these classical principles. When both the electric and magnetic fields are present at the same time with arbitrary strengths and relative directions, the problem is rather involved, and a prediction of the line profile as observed from an arbitrary direction is less straightforward. When a time-dependent electromagnetic field is applied, especially when the frequency is resonant with the energy separation of the Zeeman or Stark split sublevels, a new polarization phenomenon may emerge. This aspect is not well explored yet. If the applied field is static but extremely strong, the effects may not be a small perturbation, and the spectral line may show a new feature, including an appearance of overall polarization.

Class 2: An external field is absent. Atoms are subjected to anisotropic excitation: the directional electron collisions, photo-excitation by a laser beam, reabsorption of radiation (resonance scattering) in an anisotropic geometry, and so on. For the first anisotropy, the key is the velocity distribution of plasma electrons that excite the atoms. We simply call that EVDF (electron velocity distribution function) in the following. In this case, the immediate objective of PPS diagnostics is to deduce the “shape” of EVDF of the plasma in the velocity space. The presence of a weak magnetic field would make the produced atomic anisotropy rotate around the field direction, or it even defines the local axis of axial symmetry. The phenomena of this class are one of the main subjects to be developed in this book.

Class 3: This is the combination of Class 1 and Class 2. Anisotropic excitation under an electric field or a magnetic field, or even both of them. This Class is very difficult to treat, but, from the practical standpoint of plasma diagnostics of, say, z -pinch plasmas, this class should be explored and its formulation should be established. If the electric field is extremely strong, the problem of EVDF and that of the anisotropic excitation of atoms may not be separated, and they have to be treated self-consistently in a single framework.

1.4 Atomic Physics

Plasma spectroscopy is, from its nature, based on various elements in atomic physics; see Chap. 3 of Fujimoto [46]. This strong correlation with atomic physics is even more true with PPS. This is because polarization of radiation is due to intricate properties of an atom and its interaction with colliding perturbors, and further, due to the interaction of atom with the radiation field. Therefore, atomic physics constitutes an important element, or even a half, of PPS research.

Among the elements of atomic physics relevant to PPS, the area that is still under development is the field of atomic collisions involving polarization of atoms. Other elements, e.g., the density matrix formalism, which plays important roles in PPS, are well established. For readers who are unfamiliar with these concepts, the outline will be given in Appendices A–C. Among the

collision processes, elastic and inelastic scattering of electrons on atoms or ions constitute the central problem. The classical picture introduced in Sect. 1.1 is too simplistic, and realistic theoretical treatments should be performed according to the particular problem that we face. For neutral atoms, studies of emission polarization upon electron or ion collisions have a long history. For ions as a target of collision experiment, experimental investigations have been quite limited for a long time because of the difficulty of producing enough number of ions. However, owing to the developments in the ion source technology, especially the invention of the device called EBIT (electron beam ion trap), the polarization study progressed substantially [47, 48]. On the theoretical side, thanks to the developments of computers, large-scale calculations have become possible, and calculations based on a new formalism are being made. Even so-called user-friendly codes, e.g., the FAC code, are becoming available [49]. Some workers put up their calculation results of cross sections on their home page, which is easily accessible. These circumstances are quite favorable for practicing PPS experiments on a variety of plasmas.

In the past PPS experiments, in many cases, polarization of virtually only one emission line was measured, and it was interpreted on the corona equilibrium assumption with a model anisotropic EVDF. However, intensity and polarization of several emission lines of atoms or ions in a plasma should give more comprehensive information about the plasma. A formulation for such an interpretation has been developed. This method is a generalization of the collisional-radiative (CR) model. The conventional collisional-radiative model has been the versatile tool in *intensity* plasma spectroscopy [46]. This new method is called the *population-alignment collisional-radiative* (PACR) model in [13]. This model will be introduced and discussed in Chap. 4.

Finally, the structure of the present book is outlined. Chapter 2 introduces the well-known effects of an electric or magnetic field on atoms, the Class 1 polarization. This chapter is intended for the reader to become familiar with these phenomena and, further, to be able to develop a new technique on the basis of the knowledge of these classical principles. Several recent examples of such developments are given. Chapter 3 is the summary of the collisional-radiative (CR) model. Neutral hydrogen is taken as an example of atoms and ions in a plasma. The objective of this chapter is twofold: the first is that the reader obtains the idea of what are the general properties of the excited-level populations in various situations of the plasma. The classification of plasmas into *the ionizing plasma* and *the recombining plasma* is introduced. The second objective is to establish the basis of the PACR model, which is to be developed in Chap. 4. As already noted, the PACR model is a generalization or an extension of the CR model. In Chap. 4, various cross sections relevant to the alignment are introduced, and the PACR formulation is established for the ionizing plasma and for the recombining plasma. In this chapter, the cross sections are treated semiclassically. Chapter 5 gives the quantum mechanical formulation of these cross sections. Chapter 6 discusses the physical meanings of various collision cross sections and rate coefficients introduced in

Chaps. 4 and 5. We also review briefly the present status of our knowledge of the cross section data. Chapter 7 deals with two polarization phenomena, which result from reabsorption of line radiation. They are creation and destruction of alignment. Both of the phenomena may be important in performing a PPS experiment on neutral atoms in a plasma in which radiation reabsorption is substantial. In Chap. 8, we review typical PPS experiments so far performed on plasmas that belong to the class of ionizing plasma, including discharge plasmas which have a long history of PPS research. Chapter 9 is devoted to the class of recombining plasma. In these chapters, we confine ourselves to the Class 2 polarization. Several other interesting facets of PPS experiments and formulation are introduced in Chap. 10. They are emission line polarization from a plasma confined by a gas, a polarized X-ray laser and an alternative approach to the PACR model. Chapter 11 is devoted to the problem of Class 3 polarization, i.e., anisotropic excitation in electric and magnetic fields. In Chap. 12, PPS observations of solar plasmas are introduced. Chapter 13 treats emission line polarization of hydrogen atoms under the influence of electromagnetic waves. In Chaps. 14 and 15, we look at several facets of instrumentation. In the visible-UV region, highly sophisticated devices have been developed. In the X-ray region, PPS experiments are extremely difficult, though information of anisotropy, e.g., the presence of beam electrons in a z -pinch plasma, is strongly needed. Several facets of instrumentation of X-ray PPS will be introduced. In Appendices, short summaries of the “tools” of PPS, e.g., the angular momentum, the density matrix, and the Hanle effect, are given for the purpose of convenience of the readers.

In the last decade, a series of international workshop has been held in every two-and-a-half years. These meetings are the forum among the researchers in plasma spectroscopy and in atomic physics, who are interested in PPS. The progress in PPS researches is reported and information exchanged. In the Reference section below, the Proceedings books of these workshops are given. An excellent review of PPS activities until the meeting of 2004 is given by Csanak [50]. The present book is, in a sense, an outcome from this series of workshop. A decade after the start of the workshops, it was felt that PPS has reached the stage of some maturity, and it was agreed among some of the participants that a monograph be published, which resulted in the present book.

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Proceedings of the series of international workshops provide a good perspective of the progress in this field:

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Proceedings of the third workshop 2001 (Eds. P. Beiersdorfer and T. Fujimoto)
Report UCRL-ID-146907 (University of California Lawrence Livermore
National Laboratory).

<http://www-phys.llnl.gov/Conferences/Polarization/> http://www.osti.gov/energycitations/product.biblio.jsp?osti_id=15013530

Proceedings of the fourth workshop 2004 (Eds. T. Fujimoto and P. Beiersdorfer)
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