SECTION I

LABORATORY PLASMAS AND FUNDAMENTAL EXPERIMENTAL DATA

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SPECTROSCOPY OF LABORATORY PLASMAS

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Abstract. Work under the heading of Laboratory Plasma Spectroscopy may be conveniently separated into three classes depending on the extent to which the interaction of the emitting atoms with their plasma environment is central to the investigation. Zero order, the longest established use of laboratory plasmas in connection with astrophysics, concerns the use of hot plasmas for the excitation, measurement, and identification of the spectra of highly-stripped ions. In such work the properties of the plasma itself are usually of secondary importance. In first-order, plasma spectroscopy is used to determine fundamental atomic data concerned with the interaction of an atom with a single particle, usually either a photon or an electron, i.e.: the determination of oscillator strengths and collision cross-sections. Finally, higher-order processes in which the plasma nature of the surrounding medium is most relevant concern the study of line-shapes, and related topics such as the excitation of satellite spectral features by plasma oscillations. Developments in plasma diagnostic techniques in the last five years have greatly extended the scope of the second and third categories and have yielded much astrophysically important information from laboratory studies. Recent advances in these areas are reviewed.

1. Introduction

The phrase, 'Spectroscopy of Laboratory Plasmas' – or less accurately 'Plasma Spectroscopy' – covers a wide area of work, varying from atomic structure through to straight plasma physics. It is therefore perhaps necessary to begin by making a subclassification, dependent on the degree to which the plasma nature of the source enters its Spectroscopy. To this end the work reviewed below will be classified under three headings, which are admittedly arbitrary, but which I feel contain some physical and practical content.

In *zeroth-order plasma spectroscopy* (Figure 1) – the use of plasmas as light sources for wavelength spectroscopy – knowledge of the plasma environment of the emitting atoms is entirely secondary to the purpose of the investigation, namely the identification of the energy level structure of the (usually) highly ionized species produced in the plasma. Plasma properties only enter in so far as it is necessary to prove (or postulate!) that stark and other plasma–induced wavelength shifts are negligible (see below). Whilst this oldest field of plasma spectroscopy is still very active and of great astrophysical importance, developments *in principle* rather than in detail depend primarily on the availability of new plasma sources. I shall review in outline the laboratory sources presently available, but will leave detailed discussion of progress in wavelength identification to other papers at this conference.

First-order plasma spectroscopy concerns those problems – f-values and cross-sections – where the emitting atom can be taken as interacting primarily with *one* other particle, namely a photon or a charged particle, usually an electron. Knowledge of plasma conditions, in this case number densities and electron temperatures or velocity distributions, is essential to the interpretation of the experiment. The data obtained – f-values and averaged cross-sections – however are taken as being parameters of the

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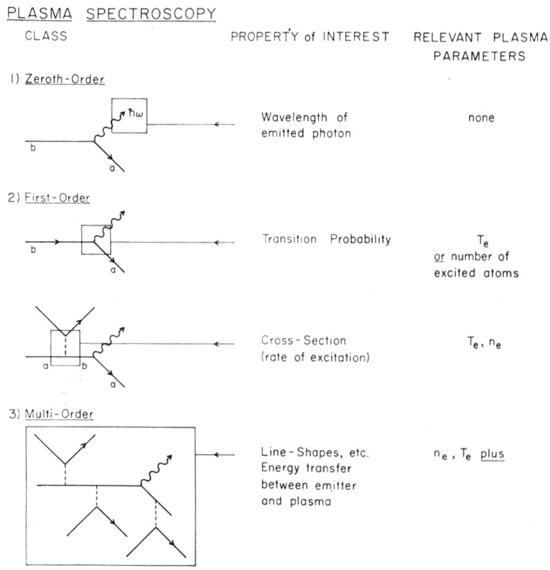

Fig. 1. Plasma spectroscopy, zeroth, first, and multi-order. Light boxes indicate the phenomena of interest. In zeroth-order only the photon wavelength is relevant. In first-order either the number density of excited atoms in state b and their rate of emission (f values) is relevant or the parameter of interest is the rate of those collisions occuring *immediately* prior to emission (averaged cross-sections). In multi-order the detailed history of the atom both prior to, and after, emission (i.e. upper and lower state interactions) determines the line-profile and related phenomena.

emitting atom rather than of the plasma, and *in principle* if not in practice could have been obtained by non-plasma methods; for instance, in the case of atomic lifetimes by beam-foil spectroscopy. Again, Dr Kunze will be reviewing plasma determinations of excitation rates in a later paper, and I shall confine myself to rather general comments, particularly with regard to the degree to which we can justify formally the interpretation of plasma data in terms of binary collision rates etc.

Multi-order plasma spectroscopy – true plasma spectroscopy – concerns the study of line-shapes and shifts, plasma satellite lines and other effects of plasma waves, series termination, and other phenomena which cannot *a priori* be written simply in terms of atomic properties. These effects occur only in a plasma – and thus are not properties of isolated atoms. In some cases, as with line-widths, it may be possible to reduce the problem theoretically and to make valid predictions over a limited range of densities in terms purely of binary collision cross-sections, and of plasma densities and temperatures. Nevertheless, the phenomena of interest could only be studied in a plasma. In other cases, or at other densities and temperatures, the plasma nature of the medium may dominate, and it may be necessary to know more about the plasma conditions than simply its density and temperature in order to predict spectroscopic properties accurately. Whilst the discussion of sources and diagnostics will apply more or less equally to all three types of work, I shall concentrate my attention later in this review largely on progress in the third area.

2. Plasma Sources and Diagnostic Techniques

The range of laboratory plasma sources suitable for spectroscopic purposes is now so large and so well known that it is neither possible nor necessary to review them all. Figure 2 is a density/temperature plot of most of the sources in common spectroscopic use. Included under each source are typical references, an approximate value for the plasma life-time, and a typical value of the maximum plasma dimension, the latter

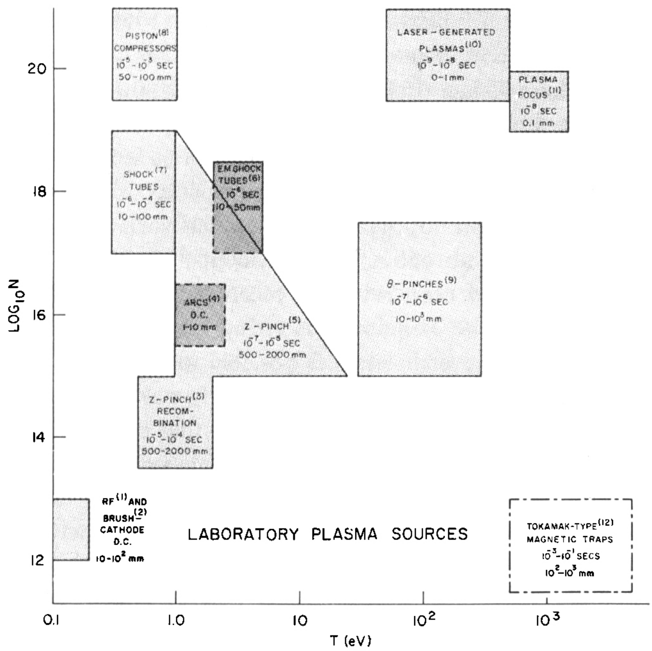

Fig. 2. Plasma sources presently used in spectroscopic experiments. Detailed references are given in Appendix A.

being important for diagnostic purposes (see below). It is interesting to note that spectroscopic studies of laboratory plasmas have now been made over some four orders of magnitude in temperature, and over at least nine orders of magnitude in density.

2. 1. Diagnostic techniques

The most important single advance in the last five years in fundamental spectroscopic experiments has been the incorporation of laser-based diagnostic methods for the measurement of densities and temperatures. There are two techniques of particular importance in this context. Observations of Thomson scattering and resultant Doppler shift of laser radiation by the free electrons in a plasma, potentially can give complete information on the spatial distribution of electron density and of both electron and ion temperature in a discharge. Optical-frequency interferometry provides an al-

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ternative probe of electron density. So flexible are these techniques that one or other, and in most cases both, have been applied in some form to every single plasma source listed in Figure 2. Both techniques are independent of atomic processes, and to an excellent approximation are free of corrections due to plasma effects.

Thomson scattering measurements, by far the more difficult of the two methods in view of the low efficiency in terms of scattered photons per incident photon ($<10^{-13}$), is nevertheless now a well-developed technique, and both principle and practice have been discussed in detail in a number of recent reviews by De Silva and Goldenbaum (1971) by Kunze (1968), and by Evans and Katzenstein (1969). The first applications of Thomson scattering to fundamental spectroscopic studies were in the determination of excitation rates, where T_e is a vital parameter, which could only be measured accurately in this way (e.g. Boland *et al.*, 1970). However, the technological problems are now overcome to the extent that a number of laboratories are making scattering measurements for other reasons. For instance we at Imperial College are now installing a system for the determination not of T_e, but of spatial variations of electron density in the plasmas used in our line-broadening experiments.

Optical interferometry had been reviewed recently by Jahoda (1971). Whilst less powerful in principle than the Thomson scattering method in that the same spatial resolution is not achieved, nevertheless it is possible to get precise determinations of n_e using very simple interferometric methods indeed. In particular with methods using gas lasers, the apparatus can be so cheap and simple that on several occasions at Imperial College we have installed and set up a complete system from scratch and obtained a determination of n_e to $\pm 5\%$ within a single afternoon. The gain in precision, and certainly of interpretation over traditional spectroscopic methods of measuring n_e is of great significance.

To these techniques, one should add that the advent of cheap tuneable lasers based on organic dye systems will undoubtedly have a major effect on plasma spectroscopy in the near future (e.g. Dimock *et al.*, 1969) even in so far as UV spectroscopy is concerned. As a simple example, by pumping a visible transition whose lower level is the upper level of a UV-resonance line one could in principle determine an absolute population density for the level in question, and hence deduce the f-value of the UV-resonance line independent of considerations of LTE and the like.

Because of these developments in laser-diagnostic techniques, there has been a very natural and marked fall-off in the development of new *spectroscopic* methods of measuring n_e and T_e. Some useful extensions of well-tried techniques have appeared – e.g. a considerable extension of the line-to-continuum method for T_e has been developed by Jenkins (1971), to pick just one example – but by and large the tendency has been to adopt one of two attitudes, depending on the particular experimental situation. Either spectroscopic *diagnostics* are dispensed with altogether for measurement of the plasma parameters critical to the experiment, or the classic spectroscopic techniques of many years vintage are used, but with a new confidence in that they have been themselves calibrated against non-spectroscopic methods. Thus, the use of Hβ profiles as a measure of n_e no longer rests purely on theory, but also on a long series of careful, independent experiments. The width of this line is therefore a calibrated secondary standard for n_e determinations.

A further consequence of the development of laser-techniques (in my own view) may be a drift *away* from specifically VUV, or at least extreme VUV, spectroscopy in studies of laboratory plasmas. The classic argument that one should study plasmas at frequencies $h\nu \gg kT_e$, i.e. in the VUV, rested on two facts. Firstly, $h\nu = kT$ is usually the region of maximum emission. This is not usually a particularly serious consideration for laboratory work. Secondly, *diagnostic* measurements with $h\nu \gg kT_e$ are usually the most easily described theoretically in terms of straightforward atomic physics, binary excitation rates and the like. Hence, of spectroscopic methods for measuring n_e and T_e those at short wavelengths are the most free from plasma corrections which are difficult to handle theoretically. With the advent of laser diagnostics, the process is inverted and these plasma corrections themselves become the object of study – witness the continued explosive growth of line-broadening studies and other aspects of multi-order plasma spectroscopy. An important feature of such work is that the basic physics involved in studying in the laboratory, say, the shape of a visible region spectral line is just as relevant to e.g. astrophysical observations of VUV line-shapes as the study of these lines themselves. For this reason I shall not make too conscious an effort to restrict myself to reviewing only work in the UV region when I come to discuss multi-order plasma spectroscopy.

2. 2. Plasma sources

In so far as the plasma sources themselves are concerned, the only major change in recent years has been in zeroth-order spectroscopy, two types of source having been developed capable of producing very high ionization stages, but with a very small plasma volume. These have partially superseded Θ pinches and the like for wavelength spectroscopy. Laser-generated plasmas offer the possibility of producing high ionization stage spectra of almost any element, with extreme purity and freedom from low ionization stage contaminations. Such sources have been extensively used for line-identification work, notably at Culham Laboratory. The very small plasma volume, however, makes diagnostic measurements a study in themselves, and very little has been done to apply such sources to first or multi-order plasma spectroscopy. A notable exception is the work of Irons (1972) who has studied the broadening of C V and C VI lines in the plasma generated using a polythylene target (see below). Plasma-focus type machines presently seem capable of producing even higher ionization stages than laser-generated plasmas, but again their very small plasma volume and the consequent inhomogeneity have limited their use to zeroth-order purposes.

Theta-pinch plasmas have become standard spectroscopic light sources, special purpose machines having been constructed for excitation rate measurements at Maryland and at the ARU Culham, for line-broadening work at Imperial College, and for wavelength spectroscopy at a number of other laboratories. Since conduction cooling along the field lines limits the plasma temperature to about 400 eV, rather little is to be gained spectroscopically by large installations, and a common size is about 50 kJ bank energy. The theta-pinch plasma suffers from inflexibility in plasma parameters for a given coil geometry, and from severe plasma inhomogeneity in both the axial and radial directions. Nevertheless it remains the most practical source for electron temperatures above about 50 eV.

For temperatures below 50 eV the author's opinion is that by far and away the most flexible plasma source is still the simple unstabilized linear or Z pinch. Properly run, the mode of formation of a Z-pinch plasma gives excellent shot-to-shot reproducibility and freedom from impurity contamination. Plasma homogeneity is excellent in the axial direction, and at least comparable with other sources radially. Simple variations of bank voltage and filling pressure allow wide ranges of plasma conditions to be studied. At Imperial College we have now used several essentially similar Z-pinch devices with minor variations in capacitor bank voltage and energy to study line-broadening in H, He I, He II, Ar II, Ar III and in our latest experiment C IV, corresponding to a range of a factor of 5×10^4 in electron density and 10^2 in temperature. Moreover, the Z pinch provides a very long optical path is the plasma, 75 cm being standard in our machines, but 2 m being entirely feasible. This long optical path has already been of great importance in laser interferometric measurements of n_e, and has allowed us also in special cases to measure line-shapes in absorption as well as in emission. Measurements in absorption allow the use of a very small and hence extremely homogeneous central region of the plasma column (Burgess and Cairns, 1971) and we are presently setting up a tuneable dye laser system to extend the range of such absorption line-shape measurements in hot plasmas and possibly also to attempt resonance fluorescence measurements. Studies of a proven 100% homogeneous plasma may thus be a possibility, removing what is perhaps the biggest remaining experimental problem in such work.

One other future possibility seems worthy of mention. Until now the lower bound on electron densities in laboratory plasma spectroscopy has largely been set by available light levels together with limited plasma containment times. The new generation of toroidal magnetic traps of the so-called Tokamak type have such greatly extended containment times – fractions of a second – that this limitation may be removed. This may open up new possibilities for the study e.g. of partially forbidden lines, two-photon processes and the like in the laboratory. For this reason I have included such devices in Figure 2, although their application to fundamental plasma spectroscopic studies is still in the future.

3. 1. Zeroth-order plasma spectroscopy

The primary requirements of a plasma source for wavelength spectroscopy are (1) that it is capable of generating the spectrum of the element of interest, (2) that the plasma is hot enough and lasts long enough to produce the ionization stages of interest, and (3) that the lines emitted are unbroadened or shifted and that the spectrum is reasonably free from impurity contaminations or lines of low ionization stages.

The record for the highest ionization stage observed in the laboratory (Cu XXVIII, Fe XXV) is still held by a discharge source, namely the focussed vacuum spark used by

Lie and Elton (1971). Similarly the Plasma Focus device has been used by Peacock *et al.* (1969) to observe lines of Ar XVIII, and by Connerade *et al.* (1970 a,b) in observing Fe XVII and XVIII (although the identifications in the latter papers have been disputed recently by Fawcett *et al.* (1971)).

Nevertheless a cursory study of the literature quickly suggests that the advent of laser-generated plasmas is the most important development in the spectroscopy of high-ionization stages since the early exploitation of the vacuum spark by Edlen. The simplicity, flexibility and purity of the laser-plasma source have led to an unprecedented increase in the number of spectra studied, to the point where an overall review of progress becomes impossible. As an illustration, a single paper by Fawcett (1970) contained identifications of 239 lines in seven elements with ionization stages varying from VI to XIV. Experience to date has shown that a laser system with a peak power of between 500 MW and 1 GW is desirable, neodymium-glass being preferred to ruby on economic grounds. Densities in laser-generated plasmas are so high (10^{19}–10^{21} cm^{-3}) (Burgess *et al.*, 1967) that some approach to LTE occurs even for high ionization stages, and the spectrum is much more fully developed than, say, in θ-pinch plasmas where characteristically only those lines originating from levels strongly collisionally coupled with the ground state are intense. A limitation on the use of laser-plasmas for

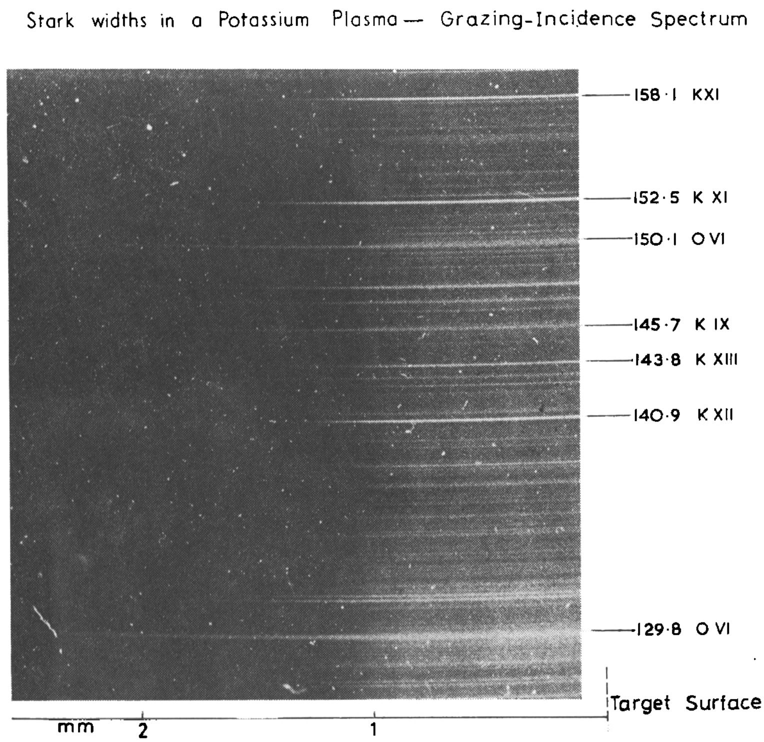

Fig. 3. Pressure-broadening of XUV lines from high ion stages in a laser plasma (Burgess *et al.*, 1967). See also Section 3.3.7.

wavelength spectroscopy arises from the high density and the possibility of sizeable Stark widths and shifts (see also discussion of plasma polarization shifts below). An extreme case is the 1Å width of the 129 Å$2p^2P^0$–$4d^2D$ line of O VI observed by Burgess *et al.* (1967), shown in Figure 3 (see Section 3.3.7). Large Doppler shifts also occur due to the plasma expansion, often varying with ionization stage, and Fawcett (1970) estimates a typical error in wavelength determination of 0.03 Å at a wavelength of 200 Å due to these causes. In addition, the plasma densities are sufficiently high that selfabsorption may occur, and may add to the broadening of some lines. Higher instrumental resolution than provided by a 2 m grazing incidence instrument is therefore probably not yet worthwhile for UV laser plasma spectroscopy.

Other laboratory plasma sourves for use in wavelength spectroscopy have been reviewed recently by Gabriel (1970). It remains to be said that by far and away the most physically interesting discovery in zeroth-order plasma work, is the identification of the 1-photon decay of 2^3s in He-like ions by Gabriel and Jordan (1969) which was not made using a laboratory source at all, but from the results of rocket observations of the solar spectrum.

3. 2. First-order plasma spactroscopy

The determination of f values and cross-sections from plasma spectroscopic experiments depends almost entirely on the measurement of spectral line *intensities*. As such two problems, one technical and one interpretative, arise in first-order spectroscopy which make the comparision of observations with theory harder than in the perhaps conceptually more difficult areas of multi-order spectroscopy. Firstly, for both f-value and cross-section work, intensity calibrations are required, both relatively over wide spectral ranges and absolutely, and often in very difficult spectral regimes. Such problems have been reviewed recently by Lincke (1968). Secondly, interpretation of observed line intensities depends on knowledge of level populations, and hence on questions of LTE/non-LTE in the plasma. Multi-order studies, such as line-shapes, on the other hand avoid both problems in that the spectral range to be covered is usually narrow, and population densities are either irrelevant or at least involve a very closely spaced group of levels.

Measurements of f values have been concentrated almost entirely in those laboratory plasmas in which LTE exists, and hence in which level populations are known with some certainty. For this reason, laboratory determinations using plasma sources are still more or less restricted to lines of low ionization stages. These restrictions may be reduced somewhat, with the possibility of direct measurements of level population using tunable lasers as mentioned above. However, on the one hand the advent of beam-foil spectroscopy (Bashkin, 1970) has provided an alternative means of life-time measurements in ionized species, and on the other f values are much less important than cross-sections in the coronal or statistical equilibrium situations typical of highly-ionized species in hot plasmas.

For converse reasons measurements of excitation rates, i.e. averaged cross-sections have largely been concentrated on non-LTE low density laboratory plasmas. Much

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progress has been made in investigating the coupled sets of rate equations describing level populations in such experiments, and in investigating laboratory plasmas in this light. Such work had been reviewed in detail recently by Gabriel and Jordan (1971) and will not be discussed at length here.

The basis of both f-value and excitation rate determination is the interpretation of rate processes governing level populations and line intensities either in terms of the emission (or absorption) of a single photon, or due to collision with a single charged particle, usually an electron. It is very revealing, and somewhat disillusioning, to enquire about the rigour with which criteria for the validity of such binary descriptions are understood.

No problem arises for photon emission rates. Firstly, the interaction of the photon with the atom is weak, and the duration of this interaction is short. Secondly, photon-photon interactions are entirely negligible. Thus, the only processes involving one or two photons in de-exciting an atom are as shown in Figure 4(a) and 4(b), and it is straightforward to compare them and establish rigorous conditions on the intensity of the radiation field etc. for (a) to dominate, i.e. for one photon processes to dominate two photon rates.

On the other hand, in the entire literature of plasma spectroscopy, both laboratory and astrophysical, I have never seen a rigorous statement of the conditions under which binary collisional processes should dominate excitation and ionization rates. At worst (and usually) this 'fact' is simply assumed or asserted. At best an argument is used

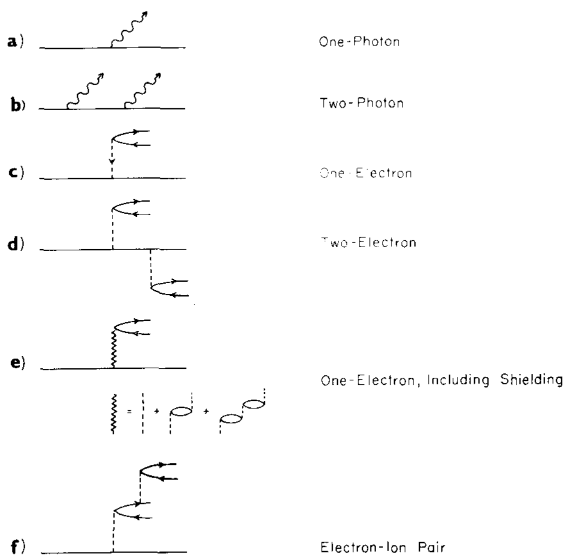

Fig. 4. Excitation and de-excitation processes due to non-interacting (photons) and interacting (electrons and ions) particles, showing types of binary and non-binary interaction. (a) 1-photon, (b) 2-photon, (c) binary collisional, (d) close-range non-binary collisional, (e) screened (binary) collisional, (f) long-range non-binary collisional.

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which is quite unsound and illogical. Essentially this reduces to the claim that when the rate in question (binary collisions) is vanishingly small it is therefore dominant! The argument runs that binary collisions involved in, say, excitation, such as that shown in Figure 4(c) usually correspond to impact parameters much smaller than interparticle separations. Hence, it is asserted that the probability of two particles coming close to the emitter at the same time is negligible. This is certainly true, and explains why two step non-binary excitations such as that shown in Figure 4(d) are indeed negligible under most circumstances. This process is just the analogue of the 2-photon process 4(b). What is ignored is that if the two particles are interacting, neither need approach to distances comparable to that of the binary collision in the first place. Indeed, simple considerations of energy and momentum transfer suggest that for *large* energy exchanges two perturbers will be much more effective than one. The major problem in the transfer of a large amount of energy to or from a single light particle such as an electron, as in a binary excitation collision, is conservation of momentum, the momentum transfer being inversely proportional to the classical impact parameter. With two *interacting* particles, one light and one heavy, the total momentum transferred to the atom for a given energy transfer can be considerably reduced, and hence effective impact parameters are larger.

For small energy transfer we know what happens. Classical impact parameters are large and we must dress the interaction by using a shielded potential (Figure 4(e)). However, it is only in this limit – the so-called Random Phase Approximation – that we have any justification for assuming that the energy transfer is ultimately to a single particle, i.e. that (apart from the correction of using a density dependent potential) we can assume that processes of interest are binary. For *large* energy transfer the RPA fails, and then we need to consider processes such as 4(f). Here, there is only one interaction with the atom, but it is with an interacting electron – ion pair. This is a non-binary process, which for large enough energy transfer, i.e. small enough binary collision cross-section, will dominate binary excitation processes such as in Figure 4(c, e).

There is certainly no experimental evidence that such ion-electron pair excitation rates are important at laboratory densities, even when binary excitation cross–sections are very small, but until the problem is treated in more detail (which is non-trivial) it remains that the *only* justification for the use of binary collision cross-sections is empirical.

3.2.1. *f values*

The most notable recent determinations of f values using plasma light sources have used either the aerodynamic shock tube, which can produce a transient but homogeneous plasma, or the wall-stabilized arc where the DC nature of the source permits accurate spatial resolution of density and temperature variations via Abel inversion procedures.

Recent work is well exemplified by studies of f values in neutral iron, which, as is now well known, have produced large corrections to the data published by Corliss and Bozman (1962), and have finally reconciled the photospheric and coronal Fe abundances. A wide range of plasma diagnostic techniques have been used in these experiments and they form an adequate survey of techniques used in nearly all f-value work. Thus the Harvard College Observatory group have measured f values in absorption on a shock-tube using a line reversal technique for temperature measurement (Huber and Tobey, 1968; Grasdalen *et al.*, 1969). This group have also obtained Fe I f values using the anomalous-dispersion hook technique on the same shock-tube (Huber and Parkinson, 1970). A typical 'hook' photograph together with absorption spectra is shown in Figure 5. The basic hook technique has been reviewed by Marlow (1967) and

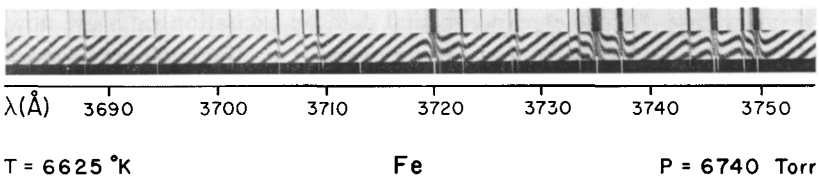

Fig. 5. Absorption and hook spectra photographed simultaneously through a shock-heated gas (Huber and Parkinson, 1971).

by Huber (1971). A group at AFCRL have used a somewhat similar shock tube to obtain Fe I f values from emission measurements, but using both reversal temperature measurements, and a unique ultrasonic technique to measure the velocity of sound in the gas and hence the temperature (Wares *et al.*, 1970). [Other applications of emission shock-tube spectroscopy to f-value determinations have been made by Wilkerson and his group at Maryland, e.g. Bengston *et al.* (1970).] Garz and Kock (1969) used a wall-stabilized arc run in argon to determine Fe I f values, temperatures being determined from a Boltzmann plot for Ar I lines of known oscillator strength, and the Fe I 3719 line of known f value being used to provide an absolute calibration. Recently Bridges and Wiese (1970) have performed a similar and very comprehensive experiment with an improved wall-stabilized arc. Given the diverse nature of these various sources, the agreement in measured f values between all these experiments, as discussed by Bridges and Wiese (1970), is extremely impressive.

However, it is already clear that the advent of beamfoil spectroscopy will increasingly affect the future of plasma determinations of f values, both by providing accurate lifetime values for resonance transitions as calibration standards in plasma experiments, and for the complex transitions by providing accurate level lifetimes. Future plasma experiments therefore probably will concentrate more and more on branching ratio and relative f-value determinations, which are difficult to perform with the lifetime techniques, or on the measurement of absolute f values for those systems where cascades interfere with beam-foil measurements.

3.2.2. *Averaged Cross-Sections*

A considerable volume of work has now been published on measurements of averaged cross-sections (excitation rates) via the determination of relative and absolute intensities of VUV transitions in coronal plasmas. All these experiments are notable for their use of the most advanced diagnostic techniques, in the form of laser scattering observations, for the determination of the parameter of most interest, the electron temperature, T_e. The primary limitation on the range of such studies is that for only a few lines of simple ion species can the intensities be described in terms of a single excitation rate, and in most cases many competing rate processes control the observed intensities. Elton (1971) has reviewed collisional processes in plasmas, and Gabriel and Jordan (1971) have written a comprehensive review of processes controlling spectral intensities in low density plasmas.

The primary cases for which experimental data on excitation rates are now available are N v (Boland *et al.*, 1970), C v, O viii (Kunze *et al.*, 1968), Ne vii (Tondello and McWhirter, 1971), N v, O vi, Ne viii (Kunze and Johnston, 1971). Data on ionization rates (deduced from spectral line time-histories in time-varying plasmas) has been derived by Hinnov (1966, 1967) for various stages of Ne, and by Kunze (1971) for C iv, N v, O v, O vi, Ne vii.

Detailed discussion of the results of such experiments will be left to Dr Kunze's paper. Two observations are worthwile.

Firstly, the results of experiments so far have been in sufficient agreement with theory (at least allowing for the rather large errors inherent for the more complex atoms in both theory and experiment) that not a great deal of theoretical controversy has arisen. This contrasts with the situation for both theory and experiment in so far as the cross-sections relevant to line-broadening studies are concerned (see below).

Secondly, some of the complexities of the analysis of the experimental data arise from the relatively high density of the plasma sources used, and the consequent need to include collisional rates other than from the ground state. These problems may be alleviated if and when measurements are made on the much lower density but longer lived plasma sources such as Tokamak machines.

3.3. Multi-order plasma spectroscopy

Turning now to multi-order processes, we are dealing with phenomena which cannot be attributed solely to the properties of isolated atoms. That is to say – despite the popular fiction of damping 'constants' – the emission from the plasma is not a priori described just by a statement of densities and temperatures and an adequate knowledge of cross-sections and f values. At the least we need also a theory of the process-line-broadening or whatever – to reduce the complex plasma physics involved to something calculable over the desired density and temperature ranges. In other cases – particularly plasmas with non-thermal levels of electron plasma wave excitation – a simple statement of density and temperature will not be adequate to specify the spectroscopic problem entirely.

By far the largest area of such activity, and the one with (until now) the most astrophysical consequences, is the study of line-broadening processes. To explain the popularity of this type of work, one might comment that current work on line-broadening processes on plasmas involves amongst other things studies of near-threshold elec-

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tron collision cross-sections for atoms and ions (Griem and Bely, 1970; Barnes and Peach, 1970), heavy particle collisions (Burgess and Grindlay, 1970), irreversible statistical mechanics (Fano, 1963), plasma kinetic theory (Chappell *et al.*, 1970), Debye shielding (Burgess, 1970a), plasma wave observation (Kunze and Griem, 1968) and excitation (Burgess *et al.*, 1971), quite apart from all the well-known practical, but less fundamental applications to astrophysics (e.g. Leckrone, 1971).

3.3.1. *Pressure-Broadening*

In understanding the very considerable volume of theoretical literature published on pressure-broadening in recent years, it is perhaps useful to note that the word 'theory' is used somewhat loosely in this context. There are rather *few* distinct theories in the sense of formal developments capable of predicting new phenomena *a priori*, or of greatly extending the range of physical parameters over which line-shapes are understood (such theories are however represented e.g. by Baranger (1958), Fano (1963), Ross (1966), Bezzerides (1966)). Most line-broadening 'theories' are in fact developments in the sophistication with which certain parameters can be *calculated*, 90% lying entirely within the common conceptual picture originally developed by Baranger (1958) and by Griem and Kolb (1958). Very many of these theories are not alternative *line-broadening* theories at all, but different treatments for calculating the *atomic scattering amplitudes* needed in the Baranger framework (e.g. Griem, 1964; Cooper and Oertel; 1969; Griem, 1968; Sahal-Brechot, 1969). Thus, these papers offer no extension of the basic regimes within which line-broadening is understood, but instead provide an increased accuracy or flexibility within that regime. A smaller percentage of papers attempt to increase the range, whilst staying within the same framework, by adding phenomena, such as non-thermal plasma effects (Baranger and Mozer, 1961; Griem, 1970), Debye shielding (Chappell *et al.*, 1969; Burgess, 1970a), perturber-radiation field interactions (Burgess, 1969) and the like. Whether recently published, and essentially identical, papers claiming unified lineshapes, making neither impact nor static approximations (Bezzerides, 1969; Smith *et al.*, 1969; Voslamber, 1969) constitute new theories , or simply extend computational sophistication is still a matter of some conflict (Lee, 1971), and is largely beyond the scope of this review, although a matter of great importance to the development of the subject.

3.3.2. *Isolated Lines*

The simplest case in line-broadening theory constitutes a line well-separated from any transition which originates from levels involved as intermediate states in the line-broadening calculation. Then, the basic Baranger formula applies for the electron impact broadening width W, and shift d. In the case of no lower state broadening: –

$$W = \left\{ \tfrac{1}{2} n_e V \left[\sigma_{\text{inelastic}} + \iint \sin\theta \, d\theta \, d\phi \, |f(\phi, \theta)|^2 \right] \right\}_{\text{Av}} \tag{1}$$

Here $\sigma_{\text{inelastic}}$ and $f(\theta, \phi)$ are the inelastic scattering cross-section and elastic scattering amplitude for the upper state of the line and the average is over perturber velocities. The ions on the other hand are usually treated either in the quasi-static approximation, or in the phaseshift impact limit (Griem *et al.*, 1962). The origin of the scattering amplitudes in the Baranger formula is easily understood in the one-perturber limit by realizing that the purpose of the plasma in this case is to supply or absorb sufficient energy to return the atom to the energy shell after absorption of an off-resonance photon (Figure 6). Two routes exist (Figure 7) corresponding (for small

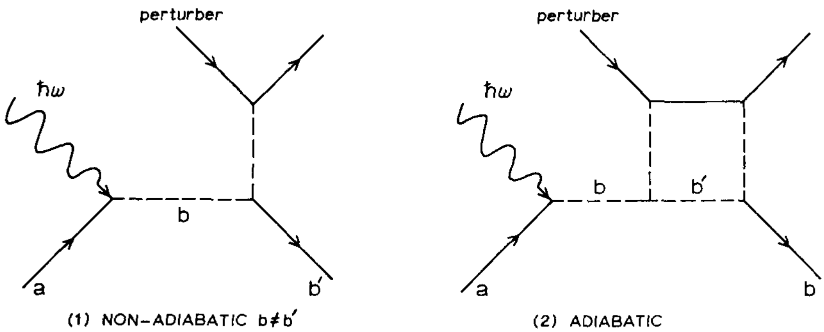

Fig. 6. Single-perturber interactions leading to absorption or emission of an off-resonance photon ($h\nu \neq E_{ab}$) by an atom or ion (i.e. line-broadening). Dotted lines represent virtual intermediate states. In each case the perturber acts to conserve energy overall via the transfer of energy to and from the absorbing atom. In the first case the atom is left in a state other than the upper state of the line of interest (i.e. an 'inelastic' collision). 'Elastic' collisions (second diagram) are of higher order because of the selection rules inherent in the $d \cdot E$ interaction with the perturber.

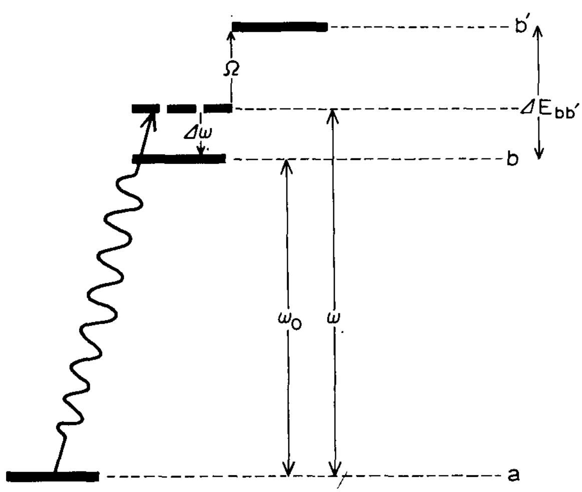

Fig. 7. Three-level system illustrating the general situation in the impact broadening of an isolated line. The photon at frequency ω is absorbed into a virtual state $\Delta\omega$ away from the unperturbed line-frequency. Absorption occurs via the transfer of energy $\Delta\omega$ or Ω to and from the plasma. The mechanism of energy transfer may be via either single-particle collisions or collective plasma effects. In the case of electron collisions the 'inelastic' process with energy transfer Ω dominates the elastic process (energy transfer $\Delta\omega$) for $E_{bb'} \ll kT$ even if $\Delta\omega$ is small. Note that for the photon frequency shown there would be *no* absorption in the purely static limit (since static fields split states b and b′).

frequency separations from line centre) to inelastic and elastic scattering processes in so far as the atom is concerned.

A number of cases exist even in this simplest possible situation.

$E_{bb'} \ll kT$ (Figure 7). In this case a single collision can be treated in the Born approximation. However, since effective impact parameters are then usually larger than interparticle separations, the basic problem is the justification of a binary model (Baranger, 1958).

Helium is by far and away the most important case for a neutral atom, both in the laboratory and astrophysically. A wide range of theoretical predictions are available (Griem *et al.*, 1962; Griem, 1964; Cooper and Oertel, 1969) including very careful treatments of angular averages, quadrupole interactions and the like. All of these calculations are basically numerical sophistications of the Baranger theory. The latest tabulations by Jenkins (1971a) treat 16 He I lines, using improved numerical procedures and including revised treatments of Debye shielding. A range of experiments have been performed on isolated lines of He I including recent and very accurate work both at high and intermediate electron densities (Greig and Jones, 1970; Jenkins and Burgess, 1971) and at low densities on the allowed lines of allowed-forbidden line pairs (Burgess and Cairns, 1971). As far as allowed line widths are concerned, all these experiments show excellent agreement with theory (but cf. 'discussion of forbidden components' below). Jenkins (1970) in surveying a wide range of experiments concluded that for isolated He I lines the mean agreement between theory and experiment is now $\pm$ 1% with discrepancies for individual lines usually not exceeding 5%.

Shifts are not yet so satisfactory, experimental values tending to fall systematically low with increasing density (Greig and Jones, 1970; Jenkins, 1970) even in comparison with theoretical treatments including the revised estimates of Debye shielding suggested by Chappell *et al.*, (1969) and by Burgess (1970a) which affect the shift more than the width, (see also discussion in section 3.3.4 below).

$E_{bb'} > kT$. For $E_{bb'} > kT$, the Born approximation is no longer valid in calculating the effects of a single collision. As a consequence the line-width, as given by the Baranger formula, is no longer dominated by inelastic collisions, but elastic scattering becomes of comparable importance. Equally, it is usually argued that the binary approximation is better for $E_{bb'} > kT$, binary collisions effective in causing line-broadening then corresponding to smaller impact parameters. The speculations in Section 3.2 apply equally here – indeed it might be argued that the success of the Baranger theory for helium (albeit with screened interactions,) is a demonstration that the binary approximation is essentially valid for *low* energy transfers. However there is certainly no experimental evidence yet that non-binary collisions are important for $E_{bb'} \gg kT$. Within the binary picture there are two possible theoretical approaches. One is to develop semi-empirical formulae by comparison with the known behaviour of cross-sections, so that by the use of an effective Gaunt factor, a single formula will accurately predict line-widths for a wide range of transitions (e.g. Griem, 1968;

Roberts, 1970). The other is to attempt thorough-going quantum mechanical computations of relevant scattering amplitudes for specific transition (e.g. Griem and Bely (1970) for Mg^+, Barnes and Peach (1970) for Ca^+).

There are also two distinct cases, in so far as whether the line of interest is of a neutral or ionized species. In the former case the inelastic scattering cross-sections go to zero at threshold. In the latter, the Coulomb interaction between the emitter and the perturbing electron means that not only are inelastic scattering cross-sections finite at threshold, but below threshold allowance must be made for the possibility of capture (virtual or real) of the perturber into a doubly excited state of the neutral species.

3.3.3. *Isolated Lines of Neutral Species other than He*

Quite a large volume of experimental work has now been done on widths of lines of neutral atoms. This includes recent work in the VUV region by Moo-Young *et al.*, (1970), on the resonance lines of neutral Ar and Ne, and by Morris and Garrison (1969) on O I and O II. In the visible and quartz UV a wide range of transitions of C, O, Ne, Si, P, S, Cl and Ar have been studied by Miller and Bengston (1970). Numerous authors have studied other neutral atom lines, (e.g. Oettinger and Cooper, 1970; Nubbemeyer *et al.*, 1970), earlier papers being discussed in the review by Wiese (1966).

The outcome of such experiments is that in most cases line-widths are in broad agreement with theoretical predictions made using the semi-empirical formula of Griem (1968). In particular no very obvious trends attributable to *other* than the atomic physics of the perturber-emitter interaction have been distinguished, so that at least within the rather limited density range over which results have been obtained, the use of measured or theoretical widths as a means of obtaining damping constants valid at other densities appears justified.

3.3.4. *Isolated Lines of Ionized Species*

Isolated lines of ionized species have remained a topic of theoretical and experimental interest ever since the discovery of substantial discrepancies between the original calculations of Griem (1964) and the results of experiments (Popenoe and Shumaker, 1965; Jalufka *et al.*, 1966; Roberts, 1966). Many experiments since have confirmed similar discrepancies for lines of various ions. These discrepancies are a consequence of the failure of the Born approximation and of the importance of the emitter-perturber Coulomb interaction for near threshold collisions.

Theoretically, the semi-empirical effective Gaunt factor formula suggested by Griem appears to work to an accuracy of $\pm$ 50% (i.e. very much better than straight line classical path calculations) for a wide range of transitions. Within the experimental and theoretical scatter it is perhaps difficult to distinguish any systematic trends, although Konjevic *et al.* (1971) have recently claimed the existence of a systematic overestimation of widths by Griem's formula for lines with upper states close to the ionization potential of the species concerned.

More interesting from the fundamental standpoint are the attempts at thorough-

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going quantum mechanical calculations of line-widths by Griem and Bely (1970) and Barnes and Peach (1970). Unfortunately, to date it is impossible to make any clear statement about the accuracy of such attempts. In the case of Ca^+, where several experiments have been performed (Chappelle and Sahal-Brechot, 1970; Yamamoto, 1966; Roberts and Eckerle, 1967) the scatter in the experimental linewidths is relatively large. No systematic deviation, either from the binary collision theory predictions or from a linear dependence of the line-width on density, is observable so that the speculations of Section 3.2 appear irrelevant, at least at the densities studied. Griem (1971) has recently pointed out that a correction term should be added to the Baranger formula for systems where resonances in the neutral atom may be important. Detailed numerical studies of this correction remain to be made. However, Hildum and Cooper (1971) have recently performed a very careful experiment on Ca^+ in a rail-gun shock tube which confirms the result of Chappelle and Sahal-Brechot and and hence is in good agreement with the theoretical work of Peach and Barnes, thus suggesting that for Ca^+ at least the original theoretical formulation is adequate.

3.3.5. *Hydrogen and Hydrogenic Line-Broadening*

Historically, hydrogen line-broadening has been one of the strongest motivations for (and the most widely used test of) line-broadening theory. Indeed, Baranger's original treatment was specifically developed for hydrogen, where the energy-level degeneracy immediately suggests that nonadiabatic effects will be important. Hydrogen line-broadening is important both astrophysically and in the laboratory, where the relatively large widths of eg: the Balmer lines at modest electron densities make their profiles a very useful primary or secondary method of measuring electron densities. The success of line-broadening calculations in respect of $H\beta$ has been such that the width of this line has become a very reliable standard for n_e determinations (see below).

Whilst the complexity of the broadening mechanisms for hydrogen lines is such that the level of agreement of experiment with a priori calculations can only be rated as extremely impressive, hydrogen lines are *not* necessarily the most useful fundamental test of line-broadening theories. The strong ion broadening of the profiles, which can be treated very accurately in the quasistatic approximation, obscures much of the detail of the electron impact broadening. The degeneracy of the interacting levels removes one independent frequency parameter, namely that describing the energy transfer between the atom and the plasma, this characteristic frequency being always identical with the frequency separation from line-centre (cf: the situation eg: for HeI lines). Finally, whilst the practical need for a truly 'unified' line-broadening theory making neither impact or static approximations is strongest for hydrogen lines, because of the large line-widths and hence extended line-wings, hydrogen lines may not be the most sensitive test for such theories, a more stringent test perhaps being the profiles of forbidden components, eg: of HeI lines (see below).

For the most widely studied line, $H\beta$, the comparison of many careful experiments at densities between about 10^{16} cm^{-3} and 3×10^{17} cm^{-3} (Mclean and Ramsden, 1965; Hill and Gerardo, 1967; Popenoe and Shumaker, 1968; Morris and Krey, 1968

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and the most recent calculations (Kepple and Griem, 1968) suggests overall agreement for the line-profile and line-width of something on the order of 5%. Results at lower density ($2 \times 10^{14} - 10^{15}$ cm^{-3}) for the half-width only (eg. Burgess and Cairns, 1971) suggest that the accuracy of the theory in this density range is still $\pm$ 10% (Figure 8).

Other Balmer lines have not been treated in such detail, but the basic agreement with theory is still relatively satisfactory (e.g. Hill and Gerardo, 1967, Hill *et al.* (1971), Bengston *et al.*, 1969). The consistently observed asymmetries in the peaks of those

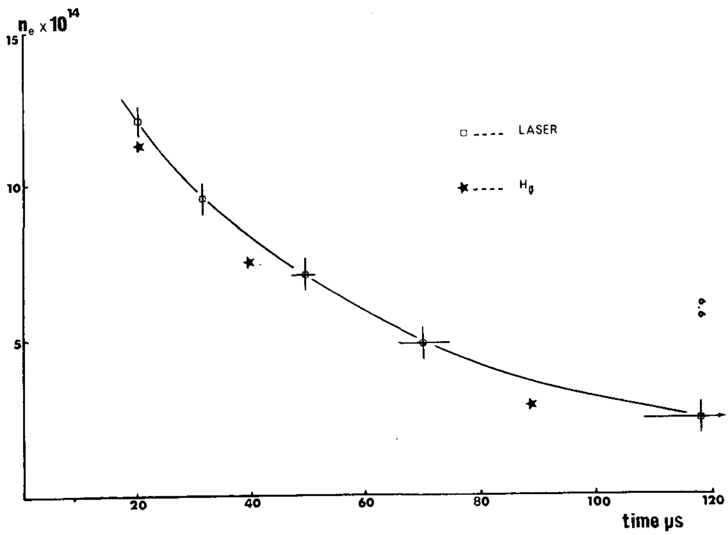

Fig. 8. Comparison of electron densities measured interferometrically with values deduced from observed $H\beta$ widths (reproduced from Burgess and Cairns, 1971).

lines having no central component ($H\beta$, $H\delta$, etc) and the tendency for the theoretical intensity at line-centre to be lower than experiment have been considered by a number of authors (Kudrin and Sholin, 1963; Nguyen-Hoe *et al.*, 1964; Sholin, 1969). Higher Balmer lines have been considered recently by Bengston *et al.* (1970).

For the Ly-α and Ly-β lines, the disagreement between two experiments (Elton and Griem, 1964; Boldt and Cooper, 1964) has not been entirely resolved, although Moo-Young *et al.* (1970) have obtained relative Ly-α and Ly-β results which appear to support the Elton and Griem observations. The Lyman lines have been one of the strong incentives for the theoretical developments recently published under the perhaps misleading heading of 'unified' line-broadening theories (Smith *et al.*, 1969; Voslamber, 1969; Bezzerides, 1969). These theories attempt to bridge the gap between the impact and static regimes (ie: the line-centre and line-wings) for electron broadening but within the limitations of a binary collision approximation. The two essential extensions of the usual impact approximation made by the authors quoted above are the inclusion of strong collisions and the retention of the frequency dependence of the

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line-broadening operator. The calculations thus essentially correspond to a binary t-matrix approximation for the appropriate self-energy parts describing the propagation of an emitting atom in a plasma, a model which has been discussed very thoroughly by Ross (1966). Similar calculations for a number of Balmer lines have also been made by Vidal *et al.* (1971), who claim improved agreement with experimental profiles in comparison with results of calculations of Bengston *et al.* (1970). (This conclusion is a matter of some dispute.) Without doubt improved treatments of the collision-broadening operator should increase the accuracy of calculations, but to the present author's mind the fact remains that the so-called 'unified' theories are in essence collisional (impact) treatments, as is the t-matrix theory of Ross (1966); and how or why such theories make a transition to the static wing even in the nearest neighbour limit, which is not simply a binary approximation in the sense implied by the unified theories, remains obscure. As an illustration of the collisional nature of the unified theories, their effective broadening operator remains linear in the perturber density. Much simplified derivations of the same result are possible, e.g. C. Bottcher (private communication) but a basic problem remains which is akin to the difference between the expansions used in obtaining the scattering (corresponding to the impact approximation) and bound-state forms of the Bethe-Salpeter equation (e.g. Roman (1965), p 391). The situation is further confused by purely semantic difficulties raised by the use of the classical path approximation in two of the theories. Lee (1971) has attempted a general assessment of the present theoretical situation.

For lines of HeII there is also some doubt on the present situation, in this case involving discrepant results of several experiments (Bogen, 1970; Eberhagen and Wunderlich, 1970; Jenkins and Burgess, 1971; Jones and Griem, 1971). Jones and Griem (1971) also claim that the effective identity of perturbing and emitting ions may cause a difference between absorption and emission line-shape for HeII resonance lines (see also comment by H. Griem on the paper by S. Volonté in this volume).

Jones and Griem's experiment also constitutes a measurement of profiles for the first 4 '$n\alpha$' lines of HeII (1–2, 2–3, 3–4, 4–5). For hydrogen such $n\alpha$ lines at much higher quantum numbers (n = 100–250) are very important in the radio region emission from gaseous nebulae. In this astrophysical case disagreement still seems to esist between measured line-widths (e.g. Menon and Payne, 1969) and theoretical work (G. Peach, 1972).

Partially for this reason, and partially because the underlying theory is particularly complex for $n\alpha$ lines where the upper and lower states of the line are closely similar, two experiments are attempting direct laboratory observations of $n\alpha$ lines of hydrogen (for n of the order of 20), one at the University of Maryland using a pulsed source and grating spectrometry, the other at Imperial College using a DC source and Fourier spectroscopy. The relevance in this case of these far IR lines to UV spectroscopy is that physically similar transitions can be seen in the UV in the $n\alpha$ lines emitted by high ionization stages, for instance in laser-generated plasmas, where such transitions may be very broad indeed. Irons (1972) has performed the difficult experiment of obtaining detailed photoelectrically-recorded time resolved profiles from a laser generated plasma and has compared results for the C V λ 2982 (5–6), λ 4945 (6–7), and C VI λ 3434 (6–7), λ 5290 (7–8) transitions with theoretical estimates obtained by scaling predictions originally made for hydrogen. His experimental line-widths differ from theory by a factor of two. More detailed theoretical calculations for this type of situation are being undertaken by G. Peach at University College, London.

Most calculations of hydrogen line-broadening neglect quadratic Stark effect contributions (due to levels of principle quantum number other than the upper and lower states of the line) and quadrupole interactions (e.g. Kudrin and Sholin, 1963). Both effects will cause line-shifts not otherwise expected for hydrogen or hydrogenic lines. In addition other effects (see plasma polarization shift Section 3.3.7 below) could also cause shifts. An interesting recent observation is that of Wiese and Kelleher (1971), who have measured red shifts for the low Balmer lines. These shifts are such that, if scaled for appropriate density changes, a significant contribution (15%) to the supposed gravitational shift in white dwarf stars would in fact be due to pressure effects. However, Wiese and Kelleher do not discuss whether their measured shifts are plausibly accounted for by e.g. quadratic Stark effects, or whether other more fundamental corrections to the theory appear necessary. Their shifts, however, do appear to scale more or less linearly with density suggesting that corrections purely to the atomic physics of the calculation may be adequate. This contrasts with the situation for helium mentioned above, and discussed by Jenkins (1970) where the non-linear behaviour of experimental shifts with increasing density suggests inclusion of further quadratic terms *cannot* account for the observations.

3.3.6. *Lines with Forbidden Components*

The broadening of those astrophysically important lines exhibiting nearby forbidden components ($\Delta L = 0, \pm 2$) induced by the plasma microfield, whilst rather little studied until recently, was greatly stimulated by recent and very detailed calculations for He I lines by Barnard *et al.* (1969) and Griem (1968), and by a more approximate but extensive treatment for higher principal quantum numbers by Gieske and Griem (1969). The outcome of several experiments, Barnard and Nelson (1971), Burgess and Cairns (1970), (1971), Burgess (1970b), Jenkins and Burgess (1971), Birkeland *et al.* (1971), Greig and Jones (1970), Burgess and Mahon (unpublished), provides a cautionary tale in so far as applications of line-shape calculations to astrophysical situations. Firstly, it illustrates that, for complex phenomena such as line shapes or 'damping constants' (as opposed to true atomic constants such as f values), there is danger in assuming that good agreement between experiment and theory under one set of density and temperature conditions implies equal success for densities differing by as little as say one order of magnitude. Secondly, it underlines the fact that some 'well-understood' criteria in line-broadening theory may well be much less rigorous than expected!

The astrophysical importance of He I lines with forbidden components in e.g. O and B type stars has long been realized (e.g. Snyder and Underhill, 1970; Leckrone, 1971). Early observations in the laboratory by Wulf (1958) appeared to be in reasonable agreement with theory (Griem *et al.*, 1962). Stimulated partially by the need for profiles for model atmosphere calculations, detailed predictions for the HeI $2p^3P^0 - 4d^3D$ λ 4471 transition were made by Griem (1968), and for both λ 4471 and the equivalent singlet line λ 4921 by Barnard *et al.* (1969). These authors compared their prediction with the earlier results of Wulf (1958), at an electron density of about 3×10^{16} cm^{-3}, and found good agreement.

The discovery that whilst predicted allowed line-shapes for the HeI 4471 line were in excellent agreement with experiment at low densities the experimental shape of the forbidden component differed from theory by much more (30% at peak intensity) than expected theoretical errors was made by Burgess and Cairns (1970) (Figure 9).

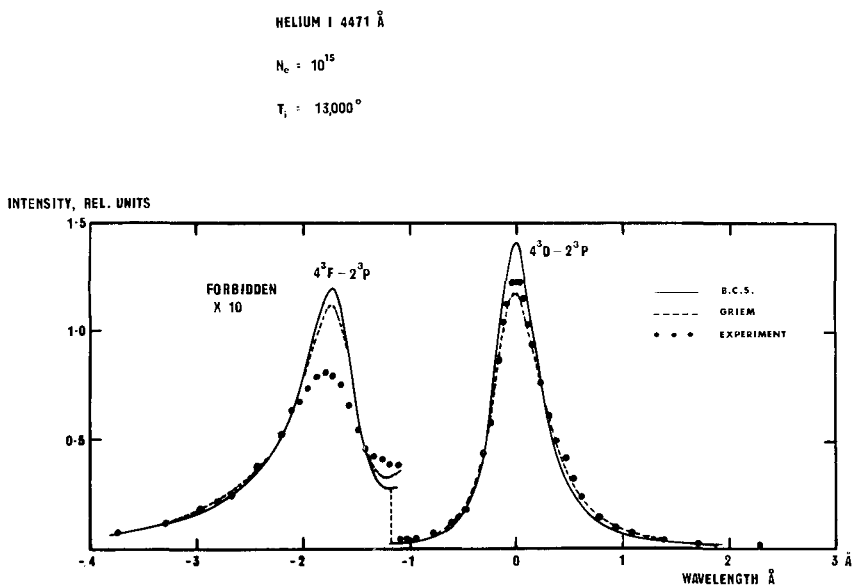

Fig. 9. Theoretical and experimental profiles for HeI λ4471 at low electron densities (reproduced from Burgess and Cairns, 1970).

Extensions of this work to other densities and to the λ 4921 transition in what is still the only experiment at astrophysically relevant densities ($3 \times 10^{14} - 10^{15}$ cm^{-3}) have also been described (Burgess and Cairns, 1971). A similar, but somewhat smaller discrepancy, at rather higher densities and in a quite different source has been reported by Birkeland *et al.* (1971). Barnard and Nelson (1971) have claimed a rather different type of discrepancy at much higher density (3×10^{16} cm^{-3}) involving the whole forbidden line-wing, although this result has been disputed by Jenkins and Burgess (1971) who, working at $10^{16} - 3 \times 10^{16}$ cm^{-3}, found only slight discrepancies in the peak of the forbidden line.

The present author pointed out the source of the problem (Burgess, 1970b), namely the invalidity of the 'usual' criterion for the quasi-static approximation for the ions,

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which had been accepted without comment until then and formed the basis of the theoretical calculations quoted above. To date, two attempts to include ion dynamics in calculations have been published. One (Griem, 1971) assumes that the total intensity of the forbidden component is given correctly by the usual static theory, but calculates the *shape* of this component by treating ions and electrons on an equal footing in the usual second-order (i.e. inelastic) impact approximation. (Experimentally, the question of the *total* forbidden component intensity is much harder to resolve, there being marginal evidence for about 10% reduction below the quasistatic prediction (Burgess and Cairns, 1971). The other treatment, a so-called adiabatic theory (Chappell *et al.*, 1970), has yet to be used for quantitative predictions. This latter theory despite its name may in fact include some contributions normally classified as non-adiabatic (J. Cooper, private communication), which are likely to be essential to any accurate treatment (see below). Both theories make the binary approximation, which is probably much more dubious for ion contributions to the forbidden component profiles than for electrons. Lee at Imperial College is currently attempting a different calculation based on a more formal separation of static and dynamic effects for the ions.

The question of non-adiabatic contributions is important, since a separate consequence of the failure of the quasistatic approximation is that the usual phase-shift approximation valid for the ions at the centre of an allowed line (Griem *et al.*, 1962), fails at the centre of a forbidden line (Burgess, 1970b). A nice experimental illustration of the importance of this correction is the HeI 4026 $2^3\,p^0 - 5^3\,D$ transition. Experimental profiles of this line have recently been obtained at low electron densities by Miss Rita Mahon at Imperial College, and are shown in Figure 10. The important

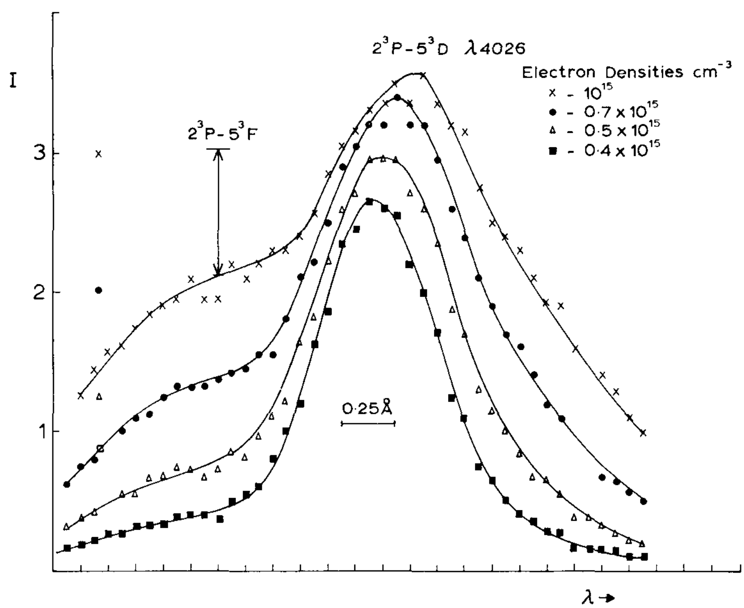

Fig.10. Experimental profiles for HeI λ4026 (Rita Mahon and D.D. Burgess, unpublished).

feature in this case is that the 5^3F level is sandwiched between $5^3D,G$ (cf. λ 4471) and hence the Stark coefficient for this level is very small. Thus, not only do theories based on the static approximation (Gieske and Griem, 1970; Shamey, 1971) predict a forbidden line much narrower than the allowed line, but, equally, so would any attempt to use the phase-shift limit for the ion broadening. Whilst the theoretical profiles currently available consist of too few points to make accurate comparisons possible, they clearly show a relatively sharp forbidden line flanking the allowed transition. Experimentally (Figure 10) quite the reverse is true, the forbidden line being the broader. This can only be explained by the inclusion of non-adiabatic contributions to the ion broadening, as suggested in my earlier theoretical paper.

3.3.7. *Spectroscopic Effects of Plasma Waves*

A subject related to the problem of electric-field induced forbidden lines is that of satellite spectral lines produced by the coupling due to bound electrons of the high-frequency EM-field and the low frequency longitudinal plasma waves. This coupling generates satellite lines separated by the plasma frequency, ω_p, or harmonics thereof, from ordinary optical frequency spectral lines.

Essentially, the existence of plasma waves means that the atom can transfer energy to or from the plasma in more or less discrete quanta with energies $h\omega_p$. Hence, absorption or emission of photons becomes possible at frequencies separated by $h\omega_p$ from optical transitions. In the narrow frequency range in which plasma waves exist, the probability of an atom emitting a quantum of the plasma wave (plasmon) is much higher than for the emission of a photon of the same frequency, in fact by about $(c/V_e)^3$ where V_e is the electron thermal velocity (Alekseev and Nikitin, 1966). However, since satellite-line formation involves a virtual transition, it is necessary for the

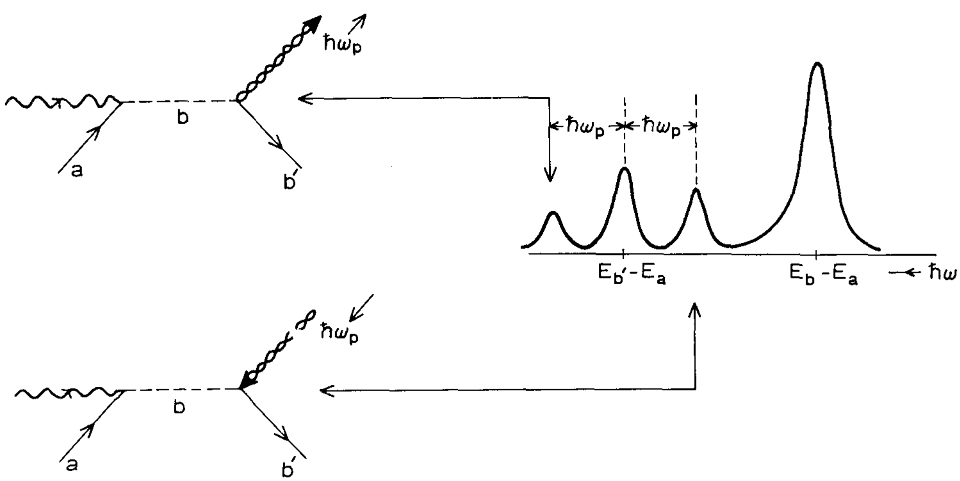

Fig. 11. Formation of 'near' and 'far' Baranger-Mozer satellite lines, corresponding to the emission or absorption of one quantum of energy of an electron plasma wave.

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plasmon density (i.e. energy density in the plasma wave) to be considerably higher than thermal before the satellite features approach the strength of ordinary optical transitions.

Historically such an effect was first pointed out theoretically by Baranger and Mozer (1961), who predicted ω_p satellites about forbidden ($\Delta L = 0, \pm 2$) optical transitions. The mechanism of formation of the Baranger-Mozer (BM) lines is shown in Figure 11 *. However, it took several years before such features were to be seen experimentally (Kunze and Griem, 1968). Since then a considerable body of experimental work has been done on such satellite lines (Kunze *et al.*, 1969; Cooper and Ringler, 1969; Ya'kobi and Bekefi, 1969; Ben Yosef and Rubin, 1971). Rather less theoretical progress has been made, what little that has been done concentrating on improving the treatment to second-order in the coupling with the plasma wave (Chappell *et al.*, 1970), rather than the perhaps more important problem of the non-linearities produced by higher orders in the wave-emitter coupling (Kunze *et al*, 1969; Burgess, 1971).

Along with the ω_p satellites of forbidden lines, 2 ω_p features exist about allowed ($\Delta L = 1$) lines and also about ($\Delta L = 3$) transitions (Figure 12), the separation of odd and even harmonics being due to the parity selection rule. (Simultaneous interaction of the emitter with a strong ion field would remove this restriction). Whilst the existence of such features is obvious from the microwave work of Townes and Schawlow (1955), no consideration had been given to their existence in plasmas until the present author pointed out that $2\omega_p$ satellites of allowed lines would almost

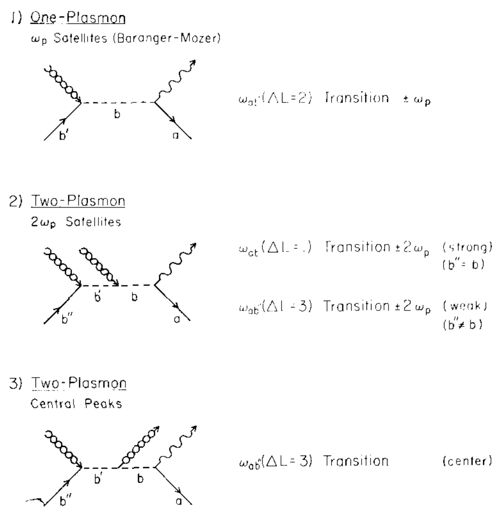

Fig.12. Types of plasma satellite lines – Baranger-Mozer and higher order features.

* Burgess *et al.* (1971) have proposed that this process may be reversed in order to *generate* electron plasma waves.

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always be as strong as the BM lines under plasma conditions in which either could be observed (Burgess, 1971).*

Finally, neither predicted nor observed prior to this paper is the fact that a central peak should be formed at the frequency of a ($\Delta L = 3$) transition (Figure 12) corresponding to one absorption and one emission of a plasmon. Notice that this essentially corresponds to the scattering, rather than the absorption or emission of a plasmon.

For ionized emitters there are further complexities. Thus the local polarization of the plasma by the ion makes it a very difficult problem to write down the effective coupling between the bound electron and the plasma wave. Very little has yet been done on observation of satellite features from ionized emitters, an exception being some previously unpublished work on C IV performed by J. E. Jenkins and myself at Imperial College. Diagnostic problems with the source, a 20 kJ theta-pinch, are one reason why this work is still tentative, and we are attempting a repeat experiment on a linear pinch source better adapted to accurate spatially resolved measurements of n_e. Nevertheless, we appear to have observed well defined satellite features of the $4d^2\ D - 5d^2\ D$ transition in C IV (Figure 13). The measured separation if identified

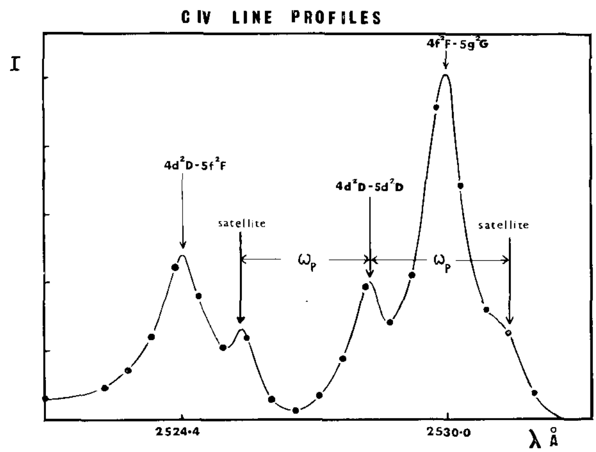

Fig. 13. Satellite features and anomalous forbidden component intensity in impact-broadened C IV spectra in a theta-pinch (J. E. Jenkins and D. D. Burgess, unpublished).

with ω_p corresponds to an electron density about a factor of 2 lower than that derived from laser interferometry or from predictions of allowed line-widths (J. E. Jenkins, unpublished). Neglecting plasma polarization effects, the intensities of these features correspond to a level of plasma wave excitation about 10^2 higher than thermal. More interesting is that the feature at the frequency of the $4d^2\ D - 5d^2\ D$ transition is itself about 10^2 stronger than that forbidden component is expected to be under our plasma

* The intensity of the $2\omega_p$ satellites relative to the ω_p BM lines was in fact *under-estimated* by a factor of 2 in my paper due to a neglect of the two possible time-orderings in the 2 plasmon case (Griem, private communication).

conditions. This raises the question of possible additional coupling mechanisms with the wave, present only for ionized emitters. One possibility is shown in Figure 14. Plasmons can be scattered by a bare ion with only a small change in the plasmon energy Likewise, a neutral atom will 'scatter' plasmons, this process corresponding to the ($\Delta L = 3$) transition discussed above (Figure 12). For an ionized emitter there is the possibility of a process midway between the two, Figure 14. This scatters a plasmon with a small energy charge (centred about zero), but with one unit change of angular momentum by the atom in the scattering. Hence it should give rise to a central peak at

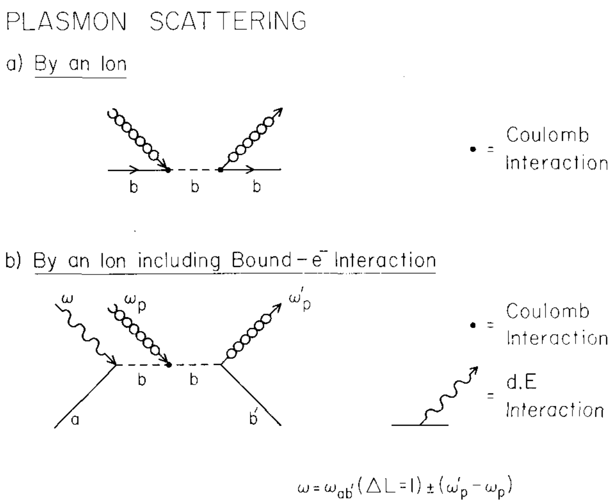

Fig. 14. Possible formation mechanism for anomalous forbidden component intensities in spectra of high ion stages.

the frequency of the ($\Delta L = 2$) forbidden line. This, however, will only be observed with ionized emitters, and the intensity will be proportional to the emitter charge squared. A numerical study of this process is being made by A. G. Richards at Imperial College.

Finally if the electric field associated with the plasma wave is strong enough that resultant Stark shifts are larger than ω_p, then lines will be broadened rather than satellites being generated. This effect has been observed by Kunze and Griem (1969) for HeII lines in an ultra-fast theta-pinch. The first suggestion theoretically of this effect was made by Wulf (1960) – indeed this was the first ever mention of any possibilities of spectroscopically observing plasma waves – and further theoretical work has been done by Lifshitz (1968) and Sholin (1971). Other observations of such effects for hydrogen lines have been made by Antanov *et al.* (1970) and by Zagorodnikov *et al.* (1971).

3.3.8. *Polarization Shift*

Turning now from those processes normally classified as pressure broadening, there remains one rather basic and controversial effect first proposed by Griem (1964), the so-called plasma polarization shift. This effect is interesting on the fundamental level because it is very definitely a many-body phenomenon in the interaction of an emitter with its plasma environment, and because in some ways it is intermediate between the statistical-mechanical effect of pressure broadening and those collective effects such as the effective lowering of the Ionization Potential to be used in Saha's equation, which are usually treated thermodynamically. On the practical level the polarization shift is important because it is likely to be the dominant plasma effect on the spectra of emitters of high ionization stage, and because it may be the ultimate restriction on wavelength accuracies in e.g. laser-generated plasmas (see below).

Griem has produced several differing estimates of the effect (Griem, 1964, 1966; and Greig *et al.*, 1970). All attempt to take account of two facts (Griem, 1971).

(1) The average environment of a charged emitter is not the same as the average over the plasma in general. Polarization of the plasma by the emitter charge produces (time-averaged) an excess of negative charge in its immediate neighbourhood.

(2) Some of this net charge density will lie within a given bound electron orbit. and hence will alter the energy level structure of the emitter.

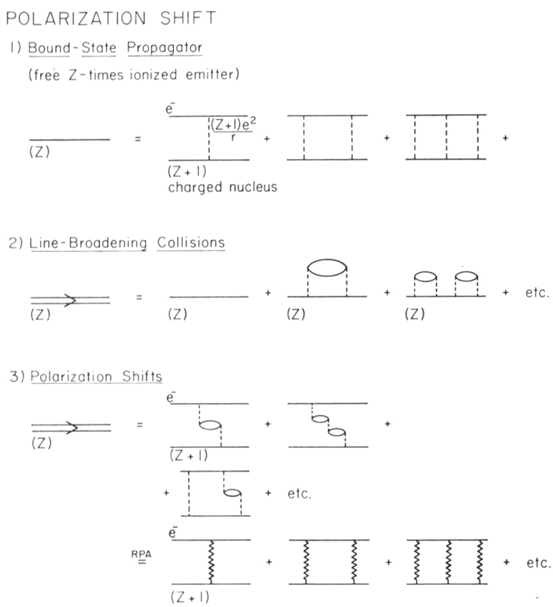

Fig.15. Diagrammatic representation of the distinction between processes normally included in electron impact broadening calculations, and those corresponding to 'plasma polarization shifts'. (1) shows the sum of ladder diagrams corresponding to the solution of the Schrodinger equation for the Z-times ionized emitter. (2) indicates the self-energy corrections to the resultant propagator corresponding to impact broadening. (3) shows modifications to the solution corresponding to polarization effects.

Before proceeding to comment in more detail on the calculation of resultant energy level shifts, one should note that the polarization shift is extremely complicated to treat in detail. Firstly, it constitutes an 'initial correlation' problem – effects of which are almost always neglected in line-broadening theory – i.e. an attempt to include the effect of particle correlations on the statistical equilibrium of the system. Secondly, whilst the effect is distinct from the interactions treated in most line-broadening calculations, an exact division between the two problems is impossible. Figure 15 attempts to illustrate diagrammatically what is of interest in the two cases. In view of the complexity of the problem, one should not treat comments made below on the validity of existing theoretical estimates as rigorous criticisms – the present theoretical estimates are as yet the *only* estimates. Present comments should be regarded more as possible indications of areas for future work on this interesting effect.

The salient points of the various theoretical estimates can be summarized as follows:

(1) Griem's (1964) and (1970) estimates obtain e.g. the net electron density at radius r from a Z times ionized emitter, $n_e(r)$, by writing it in terms of the average electron density n_{e0}, and a Boltzmann factor:

$$n_e(r) = n_{e0} \exp\left[eV(r)/kT\right]. \tag{2}$$

(2) Neither estimate uses a self-consistent field approach for $V(r)$, both using the bare Coulomb potential of the ion:

$$V(r) = Ze/r.$$

(3) The (1964) estimate linearizes the exponential – usually at the values of r of interest, this is invalid (i.e. $eV(r) \gg kT$). This linearization therefore underestimates the resultant shift.

(4) The (1970) estimate does not linearize the exponential, but in addition allows for the wave-nature of the electrons (and hence the spread in r), by limiting $V(r)$ to the ionization potential, χ, of the $(Z-1)$ times ionized species.

(5) The (1966) estimate derives the charge density by treating perturbing electrons as being in high bound states and using Saha's equation.

All the estimates then integrate the net charge density within a bound orbit, and treat this as a correction to the nuclear charge, hence deriving a level shift. In all cases the shift is to the blue.

The final result of the (1970) estimate for the shift of a level of principal quantum number in terms of the ionization potential of hydrogen, E_H, for a Z-times ionized emitter treated as hydrogenic is:-

$$\Delta E = \frac{8\pi}{3} \frac{n^4}{Z^z} E_H (a_0^3 n_e) \exp\left(\frac{\chi_{Z-1}}{kT}\right). \tag{3}$$

The experimental situation is complex. Griem's (1964) estimate was not borne out by two experiments, on singly charged ions, neither of which found any evidence for a polarization shift (Day and Griem, 1965; Burgess, 1964; Burgess and Cooper, 1965).

At Imperial College, Chowdhury (1969) continued the author's work on singly-ionized Argon, and he found *positive* evidence for Griem's (1966) revised estimate by comparing line shifts with impact broadening calculations made by Roberts (Chowdhury, 1969; Roberts, 1968). Chowdhury's experimental work covered a range of densities and temperatures. Greig *et al.* (1970) found a shift for the He II 303 Å line in a *T*-tube in good agreement with the formula above. This result is however questioned by the conclusions of the paper by Volonte in this volume, p.528. Finally, and to add some confusion, Peacock and I found evidence in spectra from laser-generated plasmas that for high ionization stages the value of ΔE given above is at least *ten times too large* (Burgess and Peacock, 1971). The spatially-resolved spectra shown in Figure 2, should have shifts for the O VI and K IX lines of between 1 and 3 Å if the estimate given above holds. Clearly, such shifts are not present, and detailed study sets much lower bounds. Indeed, if Equation (3) did hold, I think we would have already discovered most remarkable discrepancies in wavelengths from line-identification work performed using laser plasmas.

Theoretically, one can raise many problems, Foremost amongst these is the continuum treatment of the charge density at such small radii. As I commented some time ago (Burgess, 1964) the effect of a single electron penetrating an atomic orbit is enormous – a 'strong collision' in line-broadening terminology – and the result of the emitter charge and the consequent initial correlations should be a small increase in the line-width rather than a shift. Secondly, for high Z, I cannot distinguish the spirit of Griem's (1964) estimate from the problem of an electron interacting with the Debye-shielded field of a Z-times ionized emitter, apart from a trivial factor of (Z) or $(Z-1)$ and the fact that Griem does not use a self-consistent potential. Yet the Debye potential treated to the same approximation gives a *red* shift (this also agrees with the fact that satellites of resonance lines due to inner shell transitions in lower ion stages are usually to the red). This is suggested by a trivial expansion of the Debye potential:

$$\frac{Ze^2}{r}\exp\left(-r\lambda/_{\mathrm{D}}\right)=\frac{Ze^2}{r}-\frac{Ze^2}{\lambda_{\mathrm{D}}}+\frac{Ze^2r}{\lambda_{\mathrm{D}}^2}.$$

(The third term in the series is the first term affecting wavelength shifts.) One notes also the work of Nakayama and De Witt (1964) using a frequency dependent shielded field and of Theimer and Kepple (1970) using a self-consistent field, both of whom found much smaller shifts than given by the use of a static potential such as the Debye potential or equivalently the polarization effect. Finally, one notes that in most cases it is the exponential term in Equation (3) which makes the predicted effect of measurable magnitude. (For some high ions in laser plasmas this exponential is enormous.) Burgess and Peacock (1971) have queried this term, which derives from the Boltzmann factor for the electron density. Near to an emitting ion there is no thermal equilibrium of the perturber velocities, the kinetic energy of a perturber being directly related to the potential energy in the field of the ion, and the use of $\exp[eV(r)/kT]$ for r much less than an interparticle distance appears rather dubious.

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We must await further experimental results, and, hopefully, extended treatments before any firm conclusions can be drawn about this potentially interesting effect.

4. Other Plasma Spectroscopic Effects and Conclusions

The limits of this review have been set largely by space, and by attempts to limit discussion to the UV region (more or less!) as dictated by the Symposium title. This latter distinction appears to the present author to be becoming more and more artificial, at least in so far as laboratory work is concerned. In the context of the present review it has largely meant restriction to those areas of plasma spectroscopy in which atoms (or at least partially ionized species) are the ultimate radiators. Nevertheless, important work in plasma spectroscopy is being performed in regions far removed from the UV, and which does not involve atomic species at all, but which yet has direct relevance to some of the topics discussed above. Thus, as one example, nonthermal plasma wave-excitation, of importance to UV line-profiles, also leads to anomalous emission of IR radiation at ω_p and its first harmonic. Such emission (which is also important in solar radio bursts) has been studied recently in the laboratory by Chin-Fatt and Griem (1970). Similarly, the exclusion of radiation scattering measurements, which can also probe plasma wave excitations (Paul *et al.*, 1969), or even magnetic fields, from discussion of plasma spectroscopy is quite arbitrary. The final conclusion of this review perhaps is to contend that from the standpoint of multi-order plasma spectroscopy such developments now make an effective restriction of interest to any one spectral region impossible. From the point of view of zeroth and first-order plasma spectroscopy, where interest will remain largely in the UV region, the developments in understanding and technique (arising increasingly from multi-order work) mean the source and diagnostic problems are now largely solved, and that the application of laboratory plasmas to these purposes, ie: determination of atomic parameters, is only one of many methods which may be used as occasion dictates.

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Appendix A

References for Figure 2 (Typical but by no means exhaustive references are given. Where possible those chosen constitute typical spectroscopic work on the particular device, rather than the original plasma physics applications).

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DISCUSSION

H. R. Griem: In agreement with the speaker I would like to emphasize the importance of stark shifts of hydrogen lines, like H_γ. However, it may be of interest, especially to the astronomers here, that a very simple theory, namely that of Lindholm or Foley applied rather ad hoc to the ions, gives factor of ~ 2 agreement with new and old measurements. (See H. Griem, *Z. Physik* **2** (1954)). What is really needed here is of course an extension of the Holtsmark theory along the lines, eg.. of Kogan's work (*Plasma Physics and Contr. Fusion*, Vol. IV (ed. by M. A. Leontovich), 1958), but inclusive of quadratic Stark effect.

D.D. Burgess: Time did not permit me to discuss the situation for hydrogen lines as fully as I would have liked. If, as you say, the shifts observed earlier by yourself, and more recently by Wiese (*Astrophys. J.* **166** (1971), 162) can at least partially be accounted for by a phase-shift type of theory, then these shifts should also provide a very interesting experimental test of the Kogan type of theory you mention. I think Dr Gillian Peach at University College of London has been attempting some calculations along these lines, although I do not believe these are yet published in any form. In addition, of course, such shifts lead us on to the whole question of so-called 'unified' line-broadening theories (e.g. R. W. Lee, *J. Phys.* **4** (1971), 1640).

H.G. van Bueren: What is the effect of the repulsion by higher quantum number levels on the observed non-linearity of the Stark shift?

D.D. Burgess: This, I think, is an important question that nesed answering by detailed calculations. In simple systems (e.g. helium) such interactions will of course always cause increased red-shift contributions, i.e. they will increase the shifts of already red-shifted lines and decrease those of blue-shifted lines. The lines for which I showed the comparison between experiment and theory made by Jenkins (Ph. D. thesis, Univ. of London) are already red-shifted. Also, since these lines are subject to quadratic Stark effect in any case, I do not see why higher quantum number effects should alter the *density-dependence* of the shifts, although they might affect magnitudes. The transition from quadratic to linear Stark effect is more likely to affect the density dependence. However if this effect is responsible it seems surprisingly strong at low densities, and also surprisingly similar for all the three lines mentioned.