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SPECTROSCOPIC EFFECTS IN DENSE AND ULTRA-DENSE PLASMAS

by

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ABSTRACT

New plasma sources reach conditions of density and temperature where many accepted spectroscopic techniques become questionable, or fail. A survey is given of possible high-density corrections to ionization equilibria, collision rates, and line shapes via a simple comparison of relevant correlation lengths in the plasma. Relevant experimental work is described.

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1. INTRODUCTION

1.1 General Content

This is the first of two papers concerned with recent developments in the spectroscopy of laboratory plasmas. The present paper concentrates on a discussion of physical effects and problems relevant to spectroscopic studies at high or very high plasma densities, both from the standpoint of the present limits of theoretical understanding, and in so far as the extent to which reliable experimental evidence of various high density effects is yet available. The second paper*, referred to throughout as II, is concerned more with general developments in experimental technique, particularly the application of frequency-tunable lasers to plasma spectroscopic problems and with new results stemming therefrom. The density range of interest in II is therefore wider, and includes discussion of results obtained at relatively modest plasma desnities but with some concentration nevertheless on those medium desnity experiments relating directly to physical behaviour at high or very high plasma densities. In the same spirit, an attempt is made in the present paper to delineate those 'high-density' spectroscopic effects which may become important in work on e.g. laser compressed plasmas but which are nevertheless open to fundamental study using more modest plasma sources by a suitable choice of physical parameters.

1.2 Present Interest in High-Density Effects in Plasma Spectroscopy

To understand the significance of high-density effects in plasma spectroscopy it is necessary to consider for a moment the development of the field as a whole. Two partially-contradictory motives run through the entire history of the spectroscopy of hot, ionized, gases at all densities, whether laboratory or astrophysical, which, we may for convenience, label 'diagnostic' and 'fundamental'. One is the frequent need to use spectroscopy as the only available means of measuring, or 'diagnosing', very basic plasma parameters such as density or temperature. The other is the realisation that, given the basic plasma parameters *a priori* (e.g. from some other diagnostic technique) the detailed structure of the radiation emitted or absorbed by an atom immersed in a plasma can provide us with a wealth of fundamental and often surprising information on the physics of effects as diverse as binary electron-atom collisions, or the many-body behaviour of the plasma as a whole. Each motivation obviously feeds off the knowledge derived from the other. The divide between them is that 'diagnostician' usually wants methods as far as possible dependent only on simple quantities such as density or temperature and hence

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as little as possible related to the actual (many-body) physics of the plasma as per se. On the other hand, the 'fundamentalist' - an academic plasma spectroscopist such as myself - delights in the divergences of spectroscopic properties such as line-shapes, intensities, satellite features etc. from straightforward behaviour, in the hope of furthering the theoretical understanding of the detailed micro-physics of the plasma - primarily for its own sake but with the hope also that new and yet more subtle 'diagnostic' techniques may emerge therefrom.

The point of these otherwise obvious remarks is that at high densities the possibility of any such distinctions may disappear entirely. Interest in high density effects stems largely from a new generation of plasma sources, particularly of course the laser-compressed plasmas of topical interest in fusion research but including also other devices (see below and II). At the date of an earlier review paper I wrote some 6 years ago the upper boundary in density in laboratory plasma spectroscopic work was about 10^{20} cm^{-3} (Burgess, 1972). The new generation of experiments over the past 6 years has raised this limit to 10^{23} - 10^{24} cm^{-3}. This three orders of magnitude increase is notable not so much for its extent - in 1972 laboratory spectroscopic studies of plasma already covered at least 8 orders of magnitude in density - but because the densities now of interest reach simulaneously the boundaries of several basic validity criteria in so far as theoretical treatment of the plasma is concerned. At the same time, hope of using non-spectroscopic methods - laser-based interferometric or Thomson scattering techniques - is lost, primarily becuase the electron plasma frequency, ω_{pe}, at these high densities substantially exceeds the output frequencies of high power lasers likely to be available for some time to come (see below and Figure 1). At least until the advent of high-power X-ray lasers, the 'diagnostician' is stuck with the prospect of having to use spectroscopy and of having to use it in a regime where established diagnostic techniques can no longer be trusted to be free of plasma effects.

The importance of true plasma effects in purely diagnostic work is actually an entirely new situation. At lower densities, even prior to the advent of reliable laser-based diagnostic methods such as Thomson scattering, it was usually possible on simple physical grounds to distinguish between techniques reliable for diagnostic purposes (apart from lack of knowledge about purely atomic data such as f-values or cross sections), and those in which complex plasma effects could interfer, or indeed by paramount. This led to a semi facetious classification made in my earlier review of plasma spectroscopy (Burgess, 1972) into zeroth-order (wavelength) spectroscopy, first-order (binary collisions) and 'multi-order' (true plasma effects). In the early and mid-1960's first-order was the preserve of the clear-headed applied 'diagnostician', whilst 'multi-order spectroscopists' - usually those such as myself then working on line-shapes - pretended to identify where simplifying approximations could be made safely, whilst actually enjoying the underlying complexity for its own sake. With the advent of laser-scattering techniques in the mid-1960's and the temporary release from 100% reliance on spectroscopy as a diagnostic tool, these two areas changed in motivation, the first in the direction of using spectroscopy on plasmas to determine basic atomic data such as excitation cross-sections for complex atoms and ions, and the second into spectroscopic investigations essentially of the statistical mechanics of much simpler atoms such as hydrogen immersed in plasma (see e.g. Seidel 1977, Lee 1978, Griem 1978). This latter, and seemingly academic preoccupation, now recovers significance at very high densities where, as we shall see, the boundaries between binary and non-binary phenomena can become obscured entirely, and effects such as line-broadening again come into their own as diagnostic techniques.

The study of high density effects in the laboratory has three wider implications at present. Firstly, the diagnostic situation for ultra-dense plasmas in fusion research is neither as wide in scope, nor as reliable as at lower densities, and those techniques now in use such as observation of line-shapes from highly ionised emitters, depend crucially on relatively complex statistical mechanical computations, and on understanding not only of atomic physics but of the many-body physics of the dense plasma. Secondly, such plasmas are of interest not only as possible fusion power sources, but because they may also form the basis of X-ray laser systems (see e.g. Waynant and Elton 1976). In this case, high density effects on line shapes and intensities are important not only for diagnostic purposes, but because they may control the ultimate gain available. (For instance, charge neutrality means that there is a fundamental relation between the attainable inversion in an ionic species and the pressure-broadened line-width. This limits the maximum gain available per unit path to an almost universal value, no matter what transition is chosen or how large an inversion may be achieved). Finally, we are now able to study, for the first time in the laboratory, matter at densities approaching those of stellar interiors. The complexities, particularly statistical mechanical ones, in these cases have long been realized by astrophysicists (see e.g. Chiu 1968). It is still a long way before experimental techniques will be accurate enough to impinge directly on such matters, but a necessary first step is to consider where and how existing spectroscopic ideas fail.

The aim of this paper is to outline in very simple terms some of the problems encountered spectroscopically at very high densities. As far as possible, and in view of the nature of the Symposium and Summer School at which the paper was presented, this will be done in an empirical fashion from first principles even when other references exist. Hoever, no attempt will be made to cover the more general background of plasma spectroscopy at lower densities, where copious literature already exists. The reader is referred to general reviews of plasma spectroscopy by Cooper (1966) and by Burgess (1972) which, for obvious reasons connect rather directly in approach with that of the present paper, or to the two books by Griem (1964, 1974). Reviews specifically of high density effects have been given by Vinogradov et al, (1974), and recently by Peacock (1978). The latter review in particular contains much separate but parallel development, again for obvious reasons of personal collaboration relating closely to work in the present paper, and the present author would like to acknowledge from the outset many fruitful discussions and arguments with Dr N J Peacock about high density plasma spectroscopy over a long period of time.

2. PLASMA SOURCES

Figure 1 is a plot of various plasma sources presently under study in various laboratories in terms of the range of electron density, n_e, and electron temperature, T_e, generated. Also plotted is the electron density corresponding to the plasma-frequency transmission cut-off for the ruby laser wavelength, 6943 Å, this being still the only laser normally convenient as a source for Thomson scattering measurements, and the cut-off density for the Xenon excimer laser ($\lambda \simeq 1700$ Å) which appears to be the shortest wavelength laser available at present with which one could envisage making Thomson scattering observations. The cut-off density is given by:-

$$n_e = 1.12 \times 10^{29} \lambda^{-2} \text{ cm}^{-3} \text{ with } \lambda \text{ in Å} \tag{1}$$

In both cases this density is likely to be a very considerable overestimate of the maximum density at which either Thomson scattering or laser interferometry would be possible, because of problems of opacity and refraction by plasma density gradients. For the highest density sources presently under experimental study ($n_e = 3 \times 10^{23}$ cm^{-3}), it would therefore already be necessary to use a laser with wavelength in the 100 Å - 200 Å region in order to make meaningful laser diagnostic measurements. For these very dense sources, therefore, spectroscopy is the only diagnostic technique presently available.

The most significant recent extension in density range available is, of course, represented by the laser-compressed plasmas, plus also that offered by a remarkably simple source, the low inductance vacuum spark (Lie and Elton, 1972, Cilliers et al 1975, Negus and Peacock 1978). The latter source is also significant in terms of the very high mean ion charge generated, which is of considerable importance in terms of several high density effects (see below). Experimental details of these sources will be discussed to some extent in Paper II.

In Figure 1 the condition is plotted for optical depth unity to be reached in the bremsstrahlung continuum of a hydrogenic plasma for a frequency ν, such that $h\nu = 2\ kT_e$ and for path lengths of 1mm and 10 μm. For a mean ion charge of z the appropriate electron density is reduced by $z^{\frac{1}{2}}$, and at any other frequency the density should be scaled as $\nu^{3/2}$. It can be seen that for the very high density sources continuum opacity may easily become a serious problem in any spectroscopic investigation, emission-based or otherwise, the bremsstrahlung opacity being, of course, a lower bound on the total opacity of the plasma.

Figure 1 also includes the locus at which the Debye length, λ_D, becomes equal to the mean inter-electron separation r_{oe}. The significance of this parameter will be discussed below. Finally, the criterion for the electron de Broglie wavelength (at the most probable thermal speed) to equal r_{oe} is plotted and again is discussed below.

3. GENERAL CONSIDERATIONS OF HIGH DENSITY EFFECTS IN PLASMAS

3.1 Basic Plasma Parameters

The fundamental plasma parameters which will enter our discussion of high-density spectroscopy are:-

(a) The Debye length (electrons only)

$$\lambda_D = \left(\frac{kT}{4\pi\ n_e\ e^2}\right)^{\frac{1}{2}} \qquad (2)$$

(b) The mean inter-electron separation

$$r_{oe} = \left(\frac{3}{4\pi\ n_e}\right)^{1/3} \qquad (3)$$

(c) The mean inter-ion separation for ions of charge z

$$r_{oz} = \left(\frac{3}{4\pi\ n_z}\right)^{1/3} \tag{4}$$

(d) The electron de Broglie wavelength evaluated at the mean thermal speed

$$\lambda_B = \frac{h}{m\overline{V}}$$

which with $\overline{V} = (\frac{2kT}{m})^{\frac{1}{2}}$ becomes:-

$$\lambda_B = \left(\frac{h^2}{2mkT}\right)^{\frac{1}{2}} \tag{5}$$

(Note the relationship to the usual electron partition function appearing in Saha's equation).

(e) The ion-ion correlation length for ions of charge z (the separation at which the mean ion-ion interaction becomes equal to kT)

$$\lambda_{zz} = \frac{z^2\ e^2}{kT} \tag{6}$$

(f) The electron-ion correlation length defined similarly:-

$$\lambda_{ez} = \frac{z\ e^2}{kT} \tag{7}$$

(g) The mean free path between 90° deflections for ions of charge z which can be roughly estimated as

$$\lambda_{90} = \frac{1}{\pi\ \lambda^2_{zz} n_z} = \frac{kT}{\pi\ z^4 e^4\ n_z} \tag{8}$$

A more exact analysis (Spitzer 1956) gives a value of:

$$\lambda_{90} = \frac{1.29\ kT}{\pi z^4 e^4\ n_z\ \ell n\Lambda}$$

where $\ell n\Lambda$ is of order 10.

The crucial consideration turns out to be the magnitude of all these parameters (except (g)) relative to r_{oe} the mean electron separation. The usual, classical, plasma situation for which virtually all of plasma spectroscopy has been developed corresponds to:-

$$\lambda_D > r_{oz} \gtrsim r_{oe} > (\lambda_{ez}, \lambda_{zz}, \lambda_B)$$

Interchange of the position of any of these parameters with regard to r_{oe} in the inequality results in trouble not only for the physics of the plasma as a whole, but as we shall see for virtually any type of spectroscopic observation. Before considering the various spectroscopic observations themselves, we will consider the physics of a few particular cases where various of the parameters become equal to each other.

1) $r_o = \lambda_D$

The approach of the plasma parameter, r_o/λ_D, to unity (sometimes equivalently called the Debye-shielding parameter, particularly in work on line-broadening theory) is equivalent to saying that the number of particles in a Debye sphere is small. This condition is plotted in Figure 1. Re-arrangement of the expressions for r_o and λ_D shows that an equivalent statement is that the mean inter-electron electrostatic energy has become comparable to kT. (Equality with kT implies a slightly higher density than corresponds to $r_o = \lambda_D$, but the difference is not significant in the present context). Most of the usual expressions in the theory of classical plasmas then fail, and in particular the classical random-phase approximation (RPA) becomes invalid. (For a comment on the rather different situation pertaining to the quantum-mechanical version of the RPA, see below).

The approach of r_o to λ_D at high densities clearly affects many aspects of spectroscopic theory as well, since it implies that the electrons (which control ionization, excitation, and de-excitation mechanisms) are strongly interacting amongst themselves. At lower densities inter-electron correlations are not always very significant in plasma spectroscopy. In many parts of line-broadening theory, e.g. in the broadening of hydrogenic transitions, it is indeed always essential to consider interactions at ranges much larger than r_{oe}, and clearly large changes in the theory can then be expected as r_{oe} tends to λ_D. However, at first sight it might be expected that excitation and de-excitation rates for bound levels would not be much affected, since relevant interaction distances are much shorter than either r_{oe} or λ_D. That this is not necessarily true can be seen by realizing that $r_o = \lambda_D$ implies that λ_{ez}, the electron-ion correlation distance, will be large compared to the mean electron-ion separation. In other words, the electrons within a few mean inter-particle separations of a highly-charged perturbing ion are not 'free' in the usual sense at all (although equally they are not in well-defined bound orbits). Correspondingly, it is unclear what energy distributions to use in the usual calculations of atomic rate processes (this point is returned to in Section 3 below). (In fact, in many plasmas containing highly charged ions this consideration will become important long before r_o approaches λ_D).

2) $\underline{\lambda_B = r_{oe}}$

This condition is also plotted in Figure 1 and corresponds to the onset of electron degeneracy (rearrangement shows that within a small factor the condition is equivalent to equating the Fermi energy with kT).

Curiously, from the point of view of the physics of the plasma itself, degeneracy may be a simplification rather than a complexity. The background to this remark is that e.g. metal physicists regard the RPA as a <u>high</u> density limit, whereas the equivalent approach in a classical plasma is a low density approximation. The reason is that in a very degenerate system the number of interacting electrons is limited to a very few at or near the Fermi surface, hence being equivalent to a low density limit.

However, whilst yet little investigated in detail, it is possible to argue that the onset of even partial degeneracy implies abandonment of most of established spectroscopic theory, including considerations of excitation and ionization rates. The reasons which will be discussed below are that degeneracy corresponds to the breakdown of all binary approximations (crucial to calculations of excitation rates where the electron-atom ion interaction is usually strong) and also because excitation cross sections for ionized species are large at threshold. Consequently, degeneracy of even part of the electron distribution matters, since the energy of the outgoing electron after an excitation event is usually low.

3) $\underline{r_{oz} = \lambda_{zz}}$

Clearly, if the mean interionic repulsion for a pair of ions one ion-sphere radius apart is comparable to kT, the ions in the plasma are not free in the normal sense at all, and the dominant form of ion motion will be collective (wave activity) rather than the random thermal velocities normally encountered. (Electron shielding of the ion-ion interactions does not greatly affect this argument since r_{oe} is not usually all that much smaller than r_{oz}).

One spectroscopic property which would clearly be affected in the case where $r_{oz} \simeq \lambda_{zz}$ would be the pressure-broadened wings of spectral lines, since the usual probability distribution of the ion microfield would be severely modified. Note that for multiply ionized plasmas (e.g. as in many laser generated plasmas) r_{oz} may approach λ_{zz} well before $r_{oe} = \lambda_D$, because of the z^2 dependence of λ_{zz}.

4) $\underline{\lambda_{90} = \lambda_{photon}}$

The spectroscopic significance of this condition, which can easily occur in dense, highly-ionized plasmas, appears not to have been widely recognized, although it relates back to an early paper by Dicke (1953). Dicke pointed out that in general if the mean free path of an emitter (against velocity changing collisions) became short compared to the wavelength, then the nature of the Doppler effect changed drastically. In particular, Doppler broadening is suppressed and Doppler <u>narrowing</u> occurs (see Section 4 below and Rautian and Sobelman 1967).

The condition for this to occur in a plasma is approximately:-

$$\lambda_{photon} = \frac{1.29}{\pi\lambda^2 n_z \ \ell n\Lambda}$$

where $\ell n\Lambda$ (Spitzer 1956) can be taken as 10 for present purposes

$$\text{or} \quad n_z > \left(\frac{kT}{z^2 e^2}\right) \frac{1}{\pi\lambda \ln\Lambda} \qquad (9)$$

This condition is very easily approached in a dense laser-plasma in particular because of the z^4 dependence of $\lambda_{zz}^{\ 2}$. In Figure 2, the critical density is plotted for an emitted wavelength of 100 Å for various emitter charges (assuming the emitter charge is identical to the mean ion charge).

One important consequence of this effect could be an increase in available gain in attempts to produce X-ray lasers because of the line-narrowing produced, but a more likely consequence is an increase in opacity for transitions depopulating the <u>lower</u> level of a lasing transition (and hence a decrease in gain).

3.2 Accessibility of Relevant Regimes with Available Sources

Before turning to discussion of the purely spectroscopic consequences of these various criteria, it is worth considering in which laboratory sources departures from normal low-density behaviour may be expected or observed. From what has already been said, it is clear that laser-compressed plasmas are likely to product conditions approaching or exceeding all the limits discussed, but an important consideration is whether simpler and cheaper sources are also available for fundamental laboratory work studying such effects.

The most important criteria of all is the case where $r_o = \lambda_D$. In this case not only will electron-electron interactions be strong with consequences for the treatment e.g. of Debye shielding effects in line-shape theory, but also mean electron-ion and ion-ion interactions will also automatically become comparable to kT, with potential consequences for ionization equilibria and rate processes in general (see below). Interestingly, this condition is relatively easily approached with very simple laboratory sources by working at moderate density and temperatures, see Figure 1. Baker, and the present author (Baker 1977; Baker and Burgess 1977, 1979) have carried out quantitative spectroscopic work on high-density effects by using a low-inductance Z-pinch in argon, reaching conditions where $n_e = 3 \times 10^{18}$ cm^{-3}, T_e = 25,000 K, corresponding to an r_o/λ_D of 0.68 (3 particles per Debye sphere). Spatially resolved diagnostics have proved possible on this source despite the small plasma size and high density. (See also Section 5 and Paper II). Similar conditions can also be reached in high-energy T-tubes (Elton and Griem 1964) when run in dense gases such as argon (Griem, H R., private communication). Laser-generated (as opposed to laser-compressed plasmas) produced with relatively cheap low power lasers can also approach relevant densities, and finally mechanical compression devices (Lalos and Hammond 1962; Eckart 1975; Burgess and Grindlay 1970) have reached very high densities in neutral gases ($n \simeq 10^{22}$ cm^{-3}) at relatively low temperatures and would offer interesting prospects for work on ionized gases if means for reproducibly seeding with low I P materials such as Cs were available.

On the other hand, effects depending on high emitter charge, such as the Doppler narrowing effect already discussed, only become important at high temperature as well as high density, and therefore require somewhat more extreme plasma sources for observation (although the limit $\lambda_{zz} = r_{oz}$ can be reached in pinch discharges). Finally, degeneracy effects may become important in the core of future laser-compressed plasmas, but are unlikely to be observed with more modest laboratory apparatus.

4. SPECTROSCOPIC CONSEQUENCES OF HIGH DENSITY

We now turn to a consideration of the changes in the established theory of the spectroscopy of plasmas that may occur at high density, in each case seeking to relate the likely consequences to validity criteria based on the parameters defined in 3.1 above. It should be stressed that for most high density effects very little in the way of quantitative treatment yet exists in the lterature, and in those cases where discussion does exist - e.g. the long-standing issue of ionization potential depression in a plasma - the theoretical picture is still confused, and experimental work almost non-existent. Quite a lot of what is said in the present paper is therefore speculative to say the least! However, since there are practical reasons discussed in Section 2 for taking such high density effects seriously at the present time it is hoped that the fairly qualitative arguments given below may at least stir future argument and indeed experiment.

The classical approach to treatment of the radiative properties of an ionized gas can be divided into three parts:-

1) Calculation of the ionization equilibrium in the plasma, allowing for all possible species and ionization stages, together with the plasma equation of state. From a spectroscopic point-of-view, the end product of such considerations is knowledge of the relative and absolute total populations of different ion stages and species.

2) Calculation of the level populations in particular ionization stages of interest, together with radiation rates therefrom. (At low densities, (i.e. when L.T.E. does not apply) this calculation is really the same as that of the ionization equilibrium itself. (For a discussion of related problems at low and medium densities, see e.g. McWhirter 1965).

3) Treatment of the detailed spectral structure of individual transitions, including Doppler and pressure broadening effects etc. If the transition of interest is optically thick, such line-broadening processes must be incorporated into treatment of the radiative transport (and hence emitted intensity) of the radiation of interest, hence potentially interacting back on both (1) and (2)).

In low or medium density plasmas, true plasma effects only enter significantly into (3), (1) and (2) being concerned only with simple thermodynamic considerations (e.g. Saha's equation), or with details of binary rate processes (processes such as 3-body recombination being effectively 'binary' from this standpoint). So long as the plasma is optically thin, therefore, it is possible to go a very long way in interpreting line intensities (and hence in diagnostic applications) without need to worry about the plasma nature of the medium in which the emitters are immersed.

We shall now reconsider this situation at high density.

4.1 Ionization Balance

4.1.1 Classical Plasmas ($r_o < \lambda_D$)

As is well-known from various earlier reviews (Wilson 1962; Cooper 1966; McWhirter 1965), the ionization balance is determined by Saha's equation only if the electron density is sufficiently high that collisional de-excitation processes are faster than radiative ones for all the important transitions in an atom or ion. This criterion is usually hardest to satisfy for the first member of the resonance series.

This condition can be written analytically for hydrogenic-ions (see McWhirter 1965) as :-

$$n_e > 1.7 \times 10^{15} (z + 1)^6 T_e^{\frac{1}{2}} \qquad (10)$$

where T is in ^{o}K, and z is the net ion charge. This is plotted for various ion charges in Figure 3. Often this criterion can be relaxed if the resonance line is optically thick, see Griem 1964, but no account is taken of this in Figure 3 for two reasons. Firstly, in a very dense, inhomogeneous plasma emitters of interest may be exposed to intense radiation fields corresponding to quite separate plasma conditions, so that the full inequality (10) needs to be well satisfied to ensure Local Thermodynamic Equilibrium (L.T.E.). Secondly, in such plasmas transient effects can become very important, making criterion (10) academic (then being very much a lower bound on the density for L.T.E. to apply instantaneously).

If (10) is satisfied, and $\lambda_D > r_{oe} > \lambda_B$ the ionization balance can be obtained from the usual form of Saha's equation:-

$$\frac{n_e \, n_{z+1}}{n_z} = 2\left(\frac{2\pi \, m \, kT}{h^2}\right)^{3/2} \frac{B_{z+1}}{B_z} \, e^{-\left(\frac{V_z - \Delta V_z}{kT}\right)} \qquad (11)$$

where n_z, n_{z+1} are the population densities of two successive ionization stages, B_z, B_{z+1} are the corresponding internal partition functions, V_z is the ionization potential (I.P.) of the ion state z, and ΔV_z is a correction to be discussed below.

Figure 3 shows that for quite modest ionization stages there is almost no regime in which (10) is valid and $r_o < \lambda_D$. For all except the lowest ionization stages (z < 5) therefore Saha's equation is only useful in very extended, optically thick plasmas not usually encountered in the laboratory, at least at densities presently attainable.

4.1.2 High Density Corrections to Saha's Equation

The term ΔV_z in the exponent of Saha's equation represents a much-discussed (but little experimentally studied) phenomenon, the depression of the ionization potential.

The first point to make is the obvious one that the I.P. depression is a quite separate phenomenon from that of the merging of spectral lines, as given by the Inglis-Teller limit (the latter almost always occurs at considerably lower quantum numbers than that corresponding to the I.P. depression). In fact, since every atom in a plasma is in a different environment, the only meaning to I.P. depression is a statistical one, i.e. the I.P. depression is defined by whatever happens to be the appropriate correction to insert in the exponent of Saha's equation. Discussion of the value of this correction has provoked very considerable controversey (see e.g. Proceedings of thw Workshop Conference on I.P. depression, JILA, University of Colorado, 1965, JILA Report No. 79). A related issue is the cut-off required in the partition functions B_z, B_{z+1} in the Saha equation (11). As is well known these always diverge unless some cut-off is applied - although usually (at low density and so long as $kT \lesssim V_z$) the value of this latter cut-off is quite uncritical. (Note, however, that in spectroscopic applications the value of the partition functions often does not matter, since one usually observes relative populations of specific states of successive ionization stages, so that the partition functions are replaced simply by individual statistical weights).

That there is a mean lowering of the I.P. in a plasma is easily seen by realizing that the electron and ion produced in an ionization event each polarize the plasma. A simple estimate of the associated free energy associated with each, assuming a Debye potential, then shows the I.P. depression, ΔV_z, to be given by:-

$$\Delta V_z = \frac{Ce^2}{\lambda_D} \quad \text{with } C \simeq 1 \qquad (12)$$

The exact value of the constant to be used even within the Debye model has caused much discussion, see e.g. Ecker and Kroll (1963). However, regardless of this, the whole approach clearly fails if $r_{oe} > \lambda_D$, since it is fundamentally based on the Debye approximation in the first place.

An alternative approach, of rather obvious physical significance, was first put forward by Unsold. This is based on a nearest-neighbour approach, and considers the situation when the perturbation due to one neighbouring particle approaches the binding energy of the optical electron. This gives an estimate for ΔV_z rather larger than the Debye model, namely:-

$$\Delta V_z \simeq \frac{e^2}{r_{oe}} \quad \text{(for singly charged particles).}$$

However, this neglects the fact that the bound electron is not affected by particles of one charge only, and that the effects of nearby ions and electrons tend to cancel. Certainly, at low densities something approaching the Debye value is still the most widely accepted value to use despite much detailed theoretical work (see e.g. Ecker and Kroll 1966; Stewart and Pyatt 1966; Dekeyzer 1965; Rouse 1967), but a moment's thought in the spirit of the Unsold model shows that trouble with the Debye value may well be expected before $r_{oe} = \lambda_D$. In a multiply-ionized plasma, large corrections may be expected whenever $\lambda_{ez} \simeq r_{oe}$ or $\lambda_{zz'} \simeq r_{oz'}$, since then the whole basis of the Debye approach (that kT is large compared to average interaction energies) is invalid. Note that ΔV_z always becomes important precisely when the Debye approach fails!

Obviously, if the density is such that r_{oz} becomes comparable to $a_o^H z^{-1}$ where a_o^H is the Bohr radius for hydrogen, there is no longer any meaning to the idea of a localized bound state. This condition may well be approached in laser compression plasmas in the near future and is sometimes referred to as 'pressure ionization' (see Peacock 1977).

4.1.3 Non-L.T.E. Plasmas

If L.T.E. does not apply, the ionization balance has to be computed from a detailed calculation of all competing collisional and radiative processes (see e.g. McWhirter 1965). The question of high density corrections then becomes that of corrections to specific collisional and radiative rates, which is the subject of the next section.

4.2 Radiative and Collisional Rate Coefficients

4.2.1 Collision Rates

Most 'diagnostic' applications of spectroscopy are based on the search for effects that depend on the interaction of an emitter with only a single electron at a time - i.e. binary collisions phenomena - since then the observed quantity depends only on the electron number density and on some function of the velocity distribution (i.e. of the temperature). A large part of the historical success of spectroscopy as a diagnostic tool, both in the laboratory and astrophysically, depends upon the fact that under normal circumstances excitation and de-excitation rates are indeed purely linear in the electron density and very insensitive to high density (non-binary) corrections. We will begin by looking at the usual justification for this and then consider a number of possible objections to the argument which pertain at high densities.

The usual justification for the binary collision treatment is that effective collision cross sections for most excitation and de-excitation processes in atoms are really quite small - within say an order of magnitude or so of the 'classical' atomic radius squared $(n^2 a_0^H/z)^2$, where n^2 is the relevant principal quantum number, a_0^H the Bohr radius for hydrogen, and z the emitter charge. (Exceptions to this are events in which the energy transfer is very small compared to kT, as in line-broadening collisions, where the effective cross-section can be very much larger). Clearly, if $n^2 a_0^H/z$ becomes comparable to r_{oe}, then collisional excitation and de-excitation will no longer be binary - however, one notes that this is precisely the condition for 'pressure ionization' to occur (see the previous section, 4.1.2), so that localized bound states are no longer relevant.

A more formal way of stating the same thing is to say that if the mean collision rate exceeds the inverse of the duration of a typical collision, then the collisions will no longer be binary, i.e. if:-

$$<n_e \sigma(v)V> > \frac{\overline{V}}{\sigma^{\frac{1}{2}}}$$

where σ is the relevant cross-section, < > implies an average over the velocity distribution, and $\overline{V}$ on the right hand side has to be chosen to correspond to a typical velocity for electrons causing the process of interest, *not* necessarily to the mean thermal velocity (i.e. for collisional excitation of resonance lines the appropriate value may be several times the thermal velocity). In this form, the condition is essentially that for the *impact* approximation to hold in line broadening theory, see Griem 1964.

Estimates based on this approach then suggest one is on rather safe ground even at very high densities (but see below). For example, for excitation of the resonance line of Ne X, the critical density on this argument for the binary approximation to fail comes out to be in excess of 10^{25} cm^{-3}.

However, there are two exceptions that may be taken to this simple - but nearly universally applied - argument. Firstly, a number of collisional processes actually depend quite sensitively on the long range interaction between the emitter and the incoming particle, essentially in classical terms because this controls the perturber velocity at the point when it has come close enough to interact strongly and cause excitation. Examples are excitation rates for ionized emitters, where the cross-sections are finite at threshold, due to the long-range Coulomb interaction. A similar effect occurs for H-e collisions where again the interaction is attractive at long range. That these effects significantly alter overall rates can be seen by comparing line-broadening predictions made with and without allowance for the emitter-perturber Coulomb interaction, where e.g. for Ar^+ line widths differ by factors of 2 and more (see e.g. Jalufka and Oertel 1965; Roberts 1966; Cooper, J and Oertel, G S. 1967). The question then arises whether e.g. Debye shielding and other particle correlation effects could affect the long range interaction in such a way as to perturb the effective collision cross-section significantly. A rough estimate of when this might become important is when the electron-emitter correlation length becomes comparable to the screening length, i.e.

$$\lambda_{ez} \simeq \lambda_D.$$

For Ne X in a 100 eV plasma, not untypical of present laser compression experiments, this corresponds to a density of 2.3×10^{23}, i.e. considerably lower than the 10^{25} cm^{-3} resulting from considering only the close-range part of the interaction. No attention yet seems to have been paid to whether such effects are indeed important, which can only be solved by direct computation. (However, results obtained in tunable laser experiments measuring collision rates in atomic hydrogen have shown apparent density dependent discrepancies for near-threshold collisions, see Burgess, Kolbe and Ward, 1978 and Paper II. The origin of these discrepancies is not yet understood).

A second and related consideration, which again needs further consideration in so far as to its numerical effects at high densities, is the question of the initial perturber velocity distribution in the first instance. Clearly, in the 'ion-sphere' limit - i.e. when $\lambda_{ez} > r_{oe}$ - the effective electron velocity distribution will be severely modified by the electron-ion correlations (i.e. by the consequent changes in the chemical potential). Note that this condition may well be reached before λ_{ez} approaches λ_D - for the same example of Ne X, assuming all ions in the plasma to be in the same ionization stage, the critical density becomes only 7×10^{22} cm^{-3}.

Finally, once the plasma becomes degenerate, i.e. $r_{oe} = \lambda_B$, the binary collision approximation cannot strictly be valid (since the wavefunctions of 2 or more electrons always then overlap the interaction region), although in some cases the effects of individual perturbers might still be scalarly additive (i.e. if 2nd order perturbation theory is valid for the emitter-perturber interaction). Also, clearly, near-threshold excitation rates will be severely modified since the density of final states available to the (perturbing) electron after the excitation event will decrease as the Fermi sea becomes filled up. For excitations or ionization events very close to threshold this may become important at densities considerably lower than those for a Fermi distribution to apply to the electron distribution as a whole. Again, such effects seem to have been largely ignored e.g. in MHD codes modelling laser compression and incorporating excitation, ionization and radiative processes.

General Comment on High-Density Corrections to Collisional Rates

The above discussions suggests that the validity criteria for the adoption of the trusted and tried low-density expressions for electron excitation and ionization rates may be more fragile at high densities than usually assumed! Obviously, the arguments given above in no way prove that high density corrections are indeed important, but they do suggest that much more attention is needed to some of these problems. To say the least, it seems very dubious whether it is worth inserting atomic physics packages into large scale MHD compression codes for near degenerate, highly ionized, plasmas whilst merely adopting low density values for the relevant collision rates - however, this seems to be a fashionable industry, nevertheless!

4.2.2 Radiative Transition Probabilities

In contrast to the above, high density corrections to radiative transition probabilities are not very important, provided one is careful to redefine one's definition of a spectral line slightly. The electric microfield, of course, 'mixes' states of opposite parity, so that one effect of such a perturbation is to redistribute oscillator strength from allowed lines into nearby parity-forbidden transitions. Correspondingly, a very well known feature in high density plasmas is the appearance of dipole-forbidden transitions whose relative intensity increases rapidly with rising density (and hence mean electric field). An example of such a transition is shown in Figure 4, which is a computation by R W Lee of the $1^1S - 2^1P$ and $1^1S - 2^1S$ transitions in Si XIII (He-like) at an assumed density of 3×10^{23} cm^{-3}. However, the important point as far as spectral intensities are concerned is that the forbidden line never becomes strong until the line width is comparable to the allowed-forbidden line separation (again see Fig.4). (This can easily be proved from the elementary theory of the static Stark effect). Since the total oscillator strength in the allowed-forbidden line pair is conserved, no correction arises so long as the total line structure is treated as a single entity. Exactly similar considerations apply to discrete satellite structures induced by oscillating field components, e.g. electron plasma waves (see 4.3 below).

Mostly therefore, total line intensities are not sensitive to high density corrections, other than to any of those already discussed potentially affecting collision rates and hence level populations. (Of course, in many cases line intensities are nevertheless density dependent due to details of the particular competing excitation and decay rates - e.g. the various applications of resonance/intercombination line ratios, or those of parent lines relative to dielectronic satellites - see e.g. Gabriel 1972 and Peacock 1978).

However, a very interesting exception to the above rule is due to Davis and Jacobs, 1975, who considered electric field effects on doubly excited states otherwise metastable to autoionization. Parity mixing then causes induced autoionization via coupling with nearby autoionizing levels. One effect is an increase in line-width for radiative transitions out of the metastable level. A second, and probably more significant effect, is a possible rapid decrease in population for the metastable level once a density is reached sufficient for the induced autoionization rate to approach or exceed the normal radiative decay rates. Consequently, line intensities out of such metastable states may be very density dependent under some conditions. This is not, of course, a density-dependent change of the radiative transition probability itself, but neither is it a purely binary collision effect on the level population, so that in this sense it can be considered a true high density effect.

4.3 Line Shapes

4.3.1 General Comments

One of the most characteristic effects of increasing density in any plasma is the occurrence of pressure as opposed to Doppler broadened line-profiles. Since the limits on observable transitions (in terms of maximum observable principal quantum number) are often set by pressure-broadening, it follows that in most plasmas it is possible to find high enough transitions that pressure-broadening dominates the Doppler effect. Consequently, the potential usefulness of pressure-broadened line shapes as a diagnostic has long been recognised and exploited (see e.g. Wiese 1965). Long-established and copious literature therefore exists on this topic (see particularly references in Griem 1974). A major difference exists between the fields of line-broadening in neutral vapours - where the fundamental problem is usually the atomic physics of the emitter-perturber interaction itself - and plasma broadening, where even for transitions from very simple atomic systems, such as hydrogen and helium, quite fundamental statistical mechanical problems exist in treating the broadening of spectral lines because of the long-range interactions in the surrounding plasma. However, it is the very complexity of the many-body interaction of an emitting atom or ion with the surrounding plasma which opens up the possibility of using line shapes for obtaining much subtler information than simply densities or temperatures - as one example on the intensity and spectral distribution of plasma wave activity (see e.g. Griem 1974). In consequence, over the last 15 years, and as purely binary collision phenomena have become better understood, more and more attention has been paid to the statistical mechanical aspects of line-broadening, particularly to effects that are fundamentally due to many-particles interactiong simulataneously (see e.g. Burgess 1972, and Griem 1974). (One notes also that in addition to diagnostic possibilities, the consequences of the strong coupling of atoms or ions to relatively discrete plasma modes may perhaps yet hold surprises also in laser physics as interest moves from predominantly neutral media to dense ionized plasmas, as in current work on X-ray lasers). These many-particle effects are very closely related to the other spectroscopic problems at very high densities discussed in the present paper - although in the case of line shapes it is sometimes possible to encounter or study such effects at much lower density by a suitable choice of transition.

Within the context of this paper, it is clearly impossible to discuss the derivations of the very large number of new theoretical approaches to the line shape problem. What, however, can be done is to attempt an 'overview' of the content of the various approaches in terms of the type of phenomena discussed earlier, and to try to delineate the boundaries of their validity in terms of the range of plasma conditions encountered. In considering such a review, it should be clearly realized that there is no single 'best' theoretical approach. Indeed, on the day that there is a single definitive plasma line-broadening theory, all of physics other than elementary particle physics will have been solved. The validity limits of all the theories to be discussed are not set by atomic physics, but by quite fundamental statistical mechanical problems - common to the physics of condensed matter, as much as to various branches of plasma kinetic theory. (In this context, the plasma spectroscopist at least has the advantage, experimentally, over his solid-state colleague of being able to vary the basic parameters of his system over large ranges at will, see Sections 2 and 3 above). All of the theories mentioned below are limited to treatments of differing specific phenomena over various ranges of conditions rather than being comprehensive and complete line shape theories. The simpler and longer-established theories may appear to treat fewer plasma effects (e.g. see Fig. 6), but very often are more amenable to estimation of new effects as these are encountered. Much of the fundamental understanding in the field has developed not from systematic algebraic derivation, but from initially-empirical incorporation of specific effects. (Unfortunately, this often makes understanding hard for the new initiate!).

A brief discussion will first be given of Doppler broadening at high densities, where complications may arise in the usual complete separation from pressure-effects on line-profiles (see e.g. Rautian and Sobelman 1967). These complications are particularly significant for high-z emitters in dense laser plasmas. An 'overview' will then be given of the basic problems of treating line-shapes in dense plasmas, and of the physical content and validity limits of current theoretical approaches. Finally, some recent experimental results relevant to basic theoretical problems will be described.

4.3.2 Doppler Broadening at Very High Densities, and in the Presence of Pressure Effects

In most plasma line-broadening problems, Doppler broadening can be treated as statistically independent of pressure effects and hence dealt with merely by convolving the two separate resultant profiles at the end of the calculation. Largely this separation is due to two simple facts:-

a) The small electron/emitter mass ratio, and the consequent high electron thermal speeds, imply that electron collisional effects are very insensitive to the emitter's own velocity.

b) In many cases, perturbing ions can be treated as static (relative to the emitter) because of their relatively low thermal velocities (see Section 4.3.3.2 and Figure 5).

(a) is almost always valid, so that under almost no conditions is the electron broadening correlated with the Doppler broadening. One circumstance in which in principle an exception applies to (b) is now quite widely studied, namely the possibility of so-called 'ion dynamic effects'. These were first encountered in experiments on induced forbidden lines (Burgess and Cairns 1970, 1971; Burgess 1970), which have been further verified both by experiment (Barnard and Stevenson 1975) and by the success of theories incorporating such 'ion dynamic' contributions (Lee 1973; Barnard, Cooper and Smith 1974). An important point, in relation to the independence of pressure and Doppler effects, is implied by the closely related work of Kelleher and Wiese 1973; and Wiese, Kelleher and Helbig 1975, on Hβ line-profiles. The latter authors realized that in many circumstances the important consideration is not just the velocity of the perturbing ions, but that of the emitter itself. For example, 'ion dynamic' effects are larger for a hydrogen atom perturbed by argon ions than for a deuterium atom perturbed by deuterons at the same temperature, although the ion velocity is larger in the latter case. "Ion dynamics' is therefore a misnomer. In reality, the ion broadening of the profile is correlated with the emitter velocity, and hence the Doppler and pressure broadening are no longer truly statistically independent. This subject is not yet fully explored, theoretically or experimentally.

A more fundamental exception has already been mentioned (Section 3) which applies at very high densities and for high-z emitters, and has not been yet sufficiently considered in actual experiments. This stems from a very early realisation by Dicke (1953) of an effect subsquently considered in some detail by Rautian and Sobelman (1967). If the emitter velocity changes many times due to collisions during a single cycle of the emitted radiation the effect of the individual Doppler shifts at each particular velocity during the cycle may cancel out. Consequently, no Doppler broadening occurs. This phenomenon is known as'pressure-narrowing' and has been observed in the far I.R. spectroscopy of ordinary neutral gases.

The implications in a plasma at very high densities and high ion charges can be seen as follows. Let the ion mean free path (against 90^o collisions) be λ_{90} and the wavelength of interest be λ. The number of velocity-changing collisions per second is therefore V/λ_{90}. The condition for the effects of the individual emitter velocities during the observation time to average out is simply that the relative phase shift due to the Doppler shift between any two collisions is less than 2π (otherwise the emission at times when the emitter has different velocities is essentially incoherent).

Hence we require $\Delta\phi = 2\pi\Delta\nu_{\text{Doppler}} \ \Delta t_{90} < 2\pi$

where $\Delta t_{90} = \frac{\lambda_{90}}{V}$

and $\lambda_D = \frac{V}{C}\nu$

Hence, the condition for pressure narrowing to occur becomes:-

$$2\pi \frac{V}{C} \nu \frac{\lambda_{90}}{V} < 2\pi$$

or $\lambda_{90} < \lambda$

Consequently, if the 90^o deflection distance becomes less than the wavelength of interest, the usual Gaussian Doppler profile will not appear (see Dicke 1953). The significance in a plasma is the strong dependence of λ_{90} on the emitter charge, z, and the mean ion charge $\bar{z}$ ($\lambda_{90} \propto \frac{1}{z^2\ \bar{z}^2}$).

The condition for pressure narrowing to occur is shown in Figure 2 - it can be seen that in, say, a laser plasma with $z = \bar{z} = 10$, pressure-narrowing may occur at quite low densities. To date, the author is unaware of any observation of this effect in such plasmas, or indeed of its actual consideration in analysing line-profiles from such plasmas for diagnostic purposes.

4.3.3 Pressure Broadening

Figures 5, 6 and 7 attempt to provide an overview of the current status of line-broadening theory in application to dense plasmas.

In considering specific high density effects on line-shapes, the most important single consideration is the effect of particle correlations (both perturber-perturber and emitter-perturber), particularly in so far as they modify the character and strength of the emitters interaction with its environment. However, to understand the degree to which such particle correlations can be incorporated into contemporary line-shape theories, it is first necessary to review briefly the other major topic in all line-shape theories, namely the alternative uses of the well-known impact and static approximations since there is a considerable difference in the extent to which correlations can be treated in these two limits, and to consider alternative means of dealing with effects not falling completely in either limit.

Limiting Approximations for a Typical Spectral Line

Figure 5 illustrates some very simple but general features of most line-broadening theories. The usual assertion (on the basis of the Fourier Theorem) is that there are two universal limiting approximations, the impact and static limits, applying close enough to line-centre or far enough into the line wings respectively. These limits are of considerable importance (assuming their existence in a particular case, see below), because in either instance a very great simplification results in the underlying theoretical treatment. The usual approach to the validity of these two limits is via an argument in the time-domain (see e.g. Baranger 1962; Griem 1964, 1974) - as indeed implied by the very names 'impact' or 'static' - in which a particular species of perturber is considered as contributing either in one limit or the other. A consequence of this type of time-domain approach, which has received much recent theoretical attention (e.g. Smith, Cooper and Vidal 1969; Vidal, Cooper and Smith, 1971, 1973, Voslamber 1969; is the search for a unified treatment in which a given perturber species is treated by a single theoretical approach yielding the impact and static approximations as asymptotic limits. The usual time-domain derivations of the impact and static approximations are very widely discussed in the literature, so will only be surveyed quickly here. What appears more useful to the present author is to use this discussion to express a certain amount of heresy, of particular consequence when particle correlation effects are considered. The points at issue will be returned to below, but can be summarized as follows. Firstly, there exist quite simple situations where the quasi-static approximation never applies, however far from line-centre. Second, (and closely related), the usual time-domain treatment obscures the fact that high and low frequency Fourier components of the overall microfield (e.g. corresponding to the impact and static limits) cause physically (and experimentally) distinguishable effects, so that one may enquire how useful (except as a mathematical truism) is the established idea that the two approximations are really limits of a common theory. Thirdly, individual particles may contribute to more than a single Fourier component of the overall microfield - so that the fact that a particle's full contribution to the zero-frequency (static) component has been treated does not rule out the possibility that its effects should also be counted 'again' in higher-frequency components (a not unusual situation in many other physical problems). This is of particular importance in the consideration of ion dynamics, where unfortunately considerable confusion has arisen because of the time-domain based belief that a full static treatment of the ion broadening rules out additional effects in which same ions also take part, and that attempts at their inclusion in some way corresponds to 'overcounting'.

4.3.3.1 Impact Approximations

The validity conditions for the impact approximation to hold are one of the most discussed subjects in line-broadening theory, see in particular Griem (1974). Essentially, the impact approximation holds when the fluctuation properties of the perturbations affecting the emitting atom or ion are more important in determining the line-shape than are the frequency shifts produced by the instantaneous value of the perturbation. The physical process underlying the impact approximation can be considered as an energy transfer process between the emitter and the surrounding plasma, see e.g. Burgess (1972). The emitter is of course exposed to a perturbing microfield which in reality is due to both electrons and ions. In most (but not all) line-broadening theories these two species of perturbers are treated separately, an approximation which is often very good but which may fail at the highest densities. The impact approximation holds if the relevant fluctuation timescale in the perturbations is shorter than the inverse of the frequency separation from line centre, see Fig. 5. Clearly the fluctuation time is very different for that part of the microfield due to the electrons and that due to the ions, lower bounds in each case being set by the electron and ion plasma frequencies respectively. Hence, if as is frequently valid it is possible to consider the electron broadening independently of that due to the ions from the Fourier theorem, the impact approximation will certainly hold for frequency separations from line centre at least out to the electron plasma frequency, ω_{pe}. However, it is important to note that the fluctuations causing the broadening may not be on the same timescale as the fluctuation time of the total microfield. For instance, many non-hydrogenic atoms have tightly bound optical electrons, which only interact significantly with the surrounding plasma when a perturbing particle comes very close. The corresponding timescale of the interaction will then be very short and the impact approximation will give an accurate representation of the line profile over a much wider frequency range from line centre than just the electron plasma frequency.

In view of the usual separation in line-broadening theories, it is important to note that the fluctuation properties of the electron microfield will certainly be affected by electron-ion correlations. These will become crucially important when the electron-ion interaction energy approaches kT, that is to say in terms of Section 3 essentially when λ_{ez} is comparable to r_{oe}. Because of the dependence of the electron-ion correlation length on the ion charge, this may occur considerably before the mean inter-electron separation r_{oe} approaches the Debye length λ_D, see Figure 1. In such cases orthodox formulation of the electron impact approximation will become very doubtful. Very little work has yet been done in considering this point quantitatively (but see, however, Griem 1978). Theories do exist, see Lee (1973 and below), which include electron-ion correlations in the dynamical (impact) part of the broadening, and these produce significant modifications to spectral line-shapes under some conditions (i.e. in comparison with the predictions of orthodox theories) (see Lee 1978). However these theories are fundamentally based on the validity of the random phase approximation, R.P.A., and this fails precisely at the point at which the mean interparticle interaction becomes comparable to the thermal energy. (In so far as the plasma physics part of the problem is concerned it may be possible in some cases to calculate the so-called structure factor beyond RPA. However, in almost all such cases the limit is then that one cannot simultaneously go beyond 2nd order in the emitter-plasma interaction). Emitter-electron correlations may also become very important, for high emitter charges, but in most instances these can be taken into account by a suitable calculation of the incoming perturber trajectory (in classical path theories) or in quantum terms by the use of Coulomb wave functions for the perturber. However these approaches will again fail if electron-electron or electron-other ion correlations become important, and in very dense plasmas there will also be a problem in determining the incoming perturber velocity distribution, since the local environment of the emitter may come very different from that of the plasma as a whole. In other words, it becomes impossible to factor the density matrix into separate parts referring to the emitter on the one hand and the plasma on the other. This latter problem, the initial correlation problem, is one of the most intractable in the whole of line-broadening theory. (See Hussey, T., Dufty, J., Hooper, C H., 1975).

4.3.3.2 Quasi-static Approximation

The quasi-static approximation, which for practical purposes may simply be called the static approximation, is the inverse of the impact approximation in that it holds in the extreme line-wings. In the static limit the emitter is regarded as being perturbed by an interaction whose time rate-of-change is small compared to the reciprocal of the frequency shifts produced by the instantaneous interaction. In many line-broadening situations this applies over the whole of the line-profile for the ion contribution to the total microfield, but is only usually satisfied in the very far line-wings for the electrons (again see e.g. Griem 1974). It is important to note that the validity of this approximation, as for the impact limit, is rooted in the Fourier theorem as apllied to the dipole-dipole autocorrelation function for the plasma as a whole. One consequence - which long escaped notice - was that the usual validity limit only applies to a monotonically decreasing profile, such as a Lorentzian or a Gaussian, but will not apply if any discrete satellite structure exists in the line-wing. In the case of plasma broadening, the failure of the usual static ion approximation if measured from the centre of the main transition of interest was first noticed experimentally by the present author and C J Cairns (Burgess and Cairns 1970, 1971) for induced forbidden transitions alongside allowed helium lines (see also Barnard, Cooper and Smith 1974; Barnard and Stevenson 1975). However, the exact nature of such satellite transitions is irrelevant to the argument, the fact remaining that if any discrete spectral structure exists in the profile, for whatever reason, the validity of the static approximation has to be carefully considered when computing the profiles, see Fig. 5. The static approximation may also fail for other reasons, see below.

The attraction of the static approximation is that within it, it is possible to incorporate the effects of perturber-perturber and emitter-perturber correlations to a very high order. In the normal plasma regime where r_{oe} is less than λ_D, computations of the static (instantaneous) distribution of electric microfield at both neutral and charged points are very highly advanced, the initial development being due to Baranger and Mozer (1959, 1960), and the theory having been greatly extended and refined by Hooper (1966,1968), whose microfield distributions are almost universally used. In fact, comparison e.g. with Monte Carlo calculations suggests that the computed distributions using this analytic theory are indeed valid very close to, or even exceeding the limit in which r_o become comparable to λ_D. Three types of correlation have to be considered in computing e.g. the static ion microfield distribution, namely the ion-ion correlation, the shielding of the latter by the electrons, and the ion-emitter correlation (if the emitter happens to be charged). For many cases involving high-z emitters in dense plasmas, and particularly for far line wings, the emitter-ion correlation is the most important effect. The crucial limitation in terms of the underlying theory is the situation when r_{oz} becomes small compared to λ_{zz}, in the terminology of Section 3 above. However, given the great simplification resulting in the actual line-shape computation in the static approximation, even if these validity limits are exceeded it is possible to compute the microfield distribution directly, e.g. by Monte Carlo methods, and hence extend line broadening theories in the static limit to very high densities indeed.

The difficulty with the definition of the static approximation really lies in the question of at what point in the line profile it becomes valid. For both impact and static approximations what really matters is the fluctuation timescale of those perturber configurations leading to significant line broadening, not the fluctuation timescale of an average distribution of perturbers. We have already seen that for the impact approximation this means that we can set a lower bound on the limit of its validity, without needing to refer to any of the atomic physics of the underlying interaction. Unfortunately, the opposite is true of the static approximation. Since closer and closer perturber separations are involved in the far line-wings, with the consequent fluctuation timescale of the perturbation becoming shorter, one has to consider the particular atomic physics of the situation of interest before being able to set any secure bound on where the static approximation will become valid. Further, there exist transitions (both hypothetically and to some extent in practice) for which the static approximation never becomes valid, precisely because there is no frequency shift of the transition in a static electric field, however large. Two examples of where this consideration matters are the intensity between an allowed-forbidden line pair (see e.g. Fig. 4 for an example of such a transition), which is always due to dynamical effects alone since in a static field the two components shift outwards from their unperturbed positions, or alternatively the central unshifted components of a hydrogenic line such as Hα, where again no static field, however large, causes any broadening. (Vinogradov et al. 1974 point out the consequent advantage in laser-plasma diagnostics of using only lines without unshifted components, such as Balmer-beta). Finally, particularly in considering the transition to electron static broadening one has to take into account the fact that the emitter-perturber interaction may become large enough that the change in interaction during the spectral transition is enough to transfer significant energy to the perturber. This corresponds to the breakdown of the so-called no 'back-reaction' condition in classical path line broadening theories, and may also limit the range validity of any static approximation. An interesting example of such a problem is the work of Tranh-Minh and van Regemorter (1975) who carried out what is usually known as a 'unified' calculation of the electron broadening of the Lyman-alpha transition of atomic hydrogen in a fully quantum-mechanical approximation. Their treatment showed that the asymptotic nearest-neighbour static wing expected was never approached for electron broadening regardless of the separation from line-centre.

4.3.4 Survey of Existing Theoretical Treatments

Figures 6 and 7 are an attempt to provide a survey of existing line-broadening theories with particular reference to the extent to which they incorporate any realistic treatment of particle correlations and to what extent they may be expected to be valid at very high densities. The various electron impact type theories, which come in classical-path, fully quantum-mechanical and semi-empirical versions are the most widely used treatments, and have had a great deal of success at low densities. Within these theories the ions are treated in a static approximation, and, as already described, within this limit a good account can be taken of particle correlations. Attempts to include e.g. Debye shielding within the electron broadening are at best very approximate in these theories, although when the classical-path impact theories are used the electron broadening may need only be treated to second-order in perturbation theory, in which case a reasonable approximation to the effects of electron-electron correlations can be included.

The various types of 'unified' theories are attempts to treat electron broadening continuously within a single theory valid from the line centre to the line wing. Such a treatment is only possible if binary interactions dominate the entire line profile, and correlations cannot be included in any consistent manner, essentially becuase the random phase approximation always fails in those situation in which a unified theory is needed. The 'relaxation' theories were the first consistent attempts to go beyond the classical-path electron impact approximation in terms of treating correlations in the dynamical part of the broadening, and through second order in perturbation theory are capable of a consistent account of electron-electron correlations within the random phase approximation. They therefore naturally incorporate such effects as satellite features due to electron plasma waves, at least in so far as these can be treated to 2nd order only in the atom-plasma interaction (again if higher order treatments are necessary the RPA fails). Very comparable in many respects are the various theoretical treatments derived from standard many-body perturbation theories, whether diagramatic or otherwise, referenced in Fig. 7.

The difficulty with all these treatments is that there is no consistent way to incorporate the effects of electron-ion correlations or of the dynamical contributions to the broadening already discussed due to both ion and emitter motion, i.e. those under the general heading of "ion dynamic" effects. The difficulty is that a very large static contribution from the ions remains, and conditioned perhaps by the classical-path derivation of most line-broadening theories, one is inclined to worry about treating any particular perturbing species more than once. An analytic solution to this difficulty, valid through second order in perturbation theory, has been outlined by Dufty (1969) and in line-broadening applications by Lee (1973, 1978). These theories allow the full contribution of the ions to the dynamical broadening to be included through second order in the atom-plasma interaction, with the plasma treated in the random phase approximation, via the incorporation of a small subtractive term. The origin of this term is not particularly mysterious, when one realises that it simply cancels the divergent low frequency behaviour otherwise included in the standard second order form of the impact broadening operator (even in purely electron impact broadening theories!). Nor is it really surprising that in these theories particular ions are, in a sense, summed over twice, once in the static microfield and once in the dynamical broadening operator, if one gives up the orthodox idea of 2 limits of a common process, and thinks instead of the impact broadening (which in laser physics terms yields a homogeneous line-profile) as being in some way a separate physical process from the static (inhomogeneous) broadening, in that the impact limit corresponds to a real dynamical energy transfer between the atom and the surrounding plasma. Another way of looking at this is to realise that the atom is exposed to a microfield due to the ions which consists of two parts, an essentially static dc level and a superimposed fluctuating component. This is precisely analogous to the classical theory of the Stark effect, in which an atom emits or absorbs radiation in the presence of a constant applied dc field. In the latter case the atom is really exposed to a single electric field, but it is possible to treat the physical consequences accurately by computing the full frequency shifts due to the static part, and then using perturbation theory to treat the small fluctuating residue. In Fourier space it is no surprise to find that individual particles contribute to more than one Fourier component of the electric field, and that the effects of these separate Fourier components may often be computed individually.

Finally, the model microfield theories are an attempt to find a suitable form for a microfield which approximates the actual situation in the plasma sufficiently closely in all limits, but in terms of its fluctuation properties is amenable to unified calculation. It is probably fair to say that these theories have not yet been subjected to sufficient experimental test for a full appreciation of their content to be achieved (see in particular a recent paper by Seidel 1977).

4.3.5 High Density Corrections

Two separate types of high density correction can be distinguished. As already pointed out, in situations e.g. where the number of particles per Debye sphere become small ($r_{oe} \simeq \lambda_D$) or the mean interaction between an electron and an emitting ion becomes large compared to kT at typical inter-particle separations, the basic statistical properties of the plasma will be considerably changed. Particularly significant is the case of a multiply ionized emitter immersed in a dense plasma, where the local plasma environment will become inhomogeneous, invalidating usual theoretical procedures in many-body theory, (such as the assumption that propagators are functions only of co-ordinate differences), and where it will not necessarily be valid to assume e.g. a Maxwellian distribution of initial perturber velocities. Very little progress has yet been made in treating such initial correlation problems. The second type of high density correction involves changes in the emitter-perturber interaction from the usually assumed dipole-electric field case. Considerably more progress has been made in this respect, although not in any very unified sense, the situation consisting of a number of seprately-treated but actually closely related effects. These will now be considered in turn.

1) DEBYE SHIELDING

So long as r_{oe} is less than the Debye length and the impact approximation holds, a reasonably consistent treatment of the shielding of the emitter-perturber interaction is possible, including both electron-electron and (in the Lee-Dufty theory) electron-ion correlations. Although at times considerable controversy has surrounded the treatment of such shielding effects, particularly within the classical-path impact theories (see e.g. Chappell, Cooper and Smith 1969; Burgess 1970 and Griem 1974), the situation now appears reasonably resolved in those theories derived via a full quantum many-body treatment of the broadening operator. These later theories are also capable of treating consistently the non-thermal effects due to a specified non-Maxwellian velocity distribution via an *a priori* calculation of the quantum mechanical dielectric function for the plasma, and thus can treat through second-order the appearance of satellite features due to the discrete frequencies of plasma wave activity. However, as first pointed out by Griem and co-workers (e.g. Davis 1972), it is important to notice that for interactions due to a relatively discrete frequency such as that of electron plasma waves, second order perturbation theory may not be valid in any case, the interaction of the atom and the periodic electric field almost always becoming strong. The difficulties here are identical with those in treating the interaction of isolated atoms with strong multi-mode electromagnetic fields, and these considerations become serious at high plasma densities where modification to spectral structures due to plasma wave may be important even in relatively thermal plasmas (see Vinogradov et al 1974).

In contrast to a great deal of theoretical activity, really quantitative experimental evidence of dynamical shielding effects on line shapes is still relatively very hard to find. However, many reports exist of the observation of satellite spectral structures at the plasma frequency and its harmonics, usually in highly turbulent low density plasmas (see e.g. Kunze and Griem 1969; Zelenin et al 1970; Gallagher and Levine 1973; Matt and Scott 1972; Nee and Griem 1976), but also in dense laser-compressed (Boiko et al 1974) and vacuum-spark (Beier and Kunze 1978) plasmas. However, in nearly all these cases very little is known about the underlying plasma turbulence conditions other than via observation of the satellite structures themselves, and prospects for the observation of such features in quiescent, thermal plasmas remain important (see the paper by Burgess, Kolbe and Playford in the present conference).

2) HIGHER MULTIPOLE CONTRIBUTIONS TO THE INTERACTION

For far line wings, where very close perturber separations are important, or in very dense plasmas such that the interparticle separations approach orbital radii for bound electrons, the usual dipole-electric field approximation in the Stark effect fails, and it becomes necessary to consider higher-multipoles in the interaction. These are really a special case of a more general situation, see (3) below, but specific treatments of the effects of quadrupole interactions have been given by Sholin (1969) and Bacon (1977), and asymmetries of hydrogen transitions due to quadrupole interactions have been observed by Fussman (1975), Preston (1977) and by Baker and the present author

(Baker, 1977, Ph.D Thesis, Univ. of London; Baker and Burgess 1979).

3) QUASI-MOLECULAR SATELLITE STRUCTURES

Under conditions in which the quadrupole interaction becomes important, one has to consider whether any multipole expansion of the emitter-perturber interaction will be adequate. One aspect of this is the possibility of appearance of discrete satellite spectral structures, essentially due to the details of interatomic potentials for free states of molecular ions corresponding to the emitter-perturber pair. In cases where the potential difference between the two states of interest goes through an extremum, static shifts in the relevant region of the profile remain constant over a wide range of emitter-perturber separations, and consequently give rise to the appearance of a discrete peak in the profile. The appearance of such satellites in plasma broadening problems was first predicted by Stewart, Peak and Cooper (1973) but only recently have such features been observed (see Section 5 below). (Note however a close resemblance to long studied effects in neutral-neutral broadening). In a plasma such satellite features are characteristic of high-density, because they become important when the emitter-perturber separation is small, and at low density relevant frequency separations in the line-profile are usually irrelevant.

4) POLARISATION EFFECTS

Finally one must consider one effect, much discussed, which involves both initial correlation problems and high density corrections to the interaction, namely some consequences of the polarisation of the surrounding plasma by the net emitter charge. This is usually discussed in the line-broadening literature under the name 'plasma polarisation shift' - see e.g. Burgess (1972); Griem (1974); Volonte (1975, 1978) and Baker (1977).

Near an ionized emitter the local plasma will not be typical of the plasma as a whole. Some consequences of this - e.g. the Coulomb acceleration of individual electrons - are routinely taken into account at low density e.g. in calculations of binary collisional excitation rates for ions. However, other effects become significant at high density. For instance, if λ_{ez} approaches r_{oz}, the local environment of every ion will be quite different from the average condition of the plasma. One effect of this is that the local increase in electron density will tend to screen the bound electron from its parent nucleus, giving rise to a (predicted) shift in spectral line wavelength. This is not an appropriate place to review differing estimates of this effect, but see e.g. Griem (1964, 1966); Grieg et al. (1970); Burgess and Peacock

(1971); Volonte (1974), and, for reviews of the situation, Burgess (1972) and Griem (1974). Estimates vary widely, but regardless of this, the effect is likely to become significant even on the smallest predictions (e.g. Burgess and Peacock 1971) if $\lambda_{ez} = r_{oz}$, - which, as we have seen occurs for multiply ionized species some way before $r_{oe} = \lambda_D$.

As noted above, the effects of the local polarisation on the bound electron-parent nucleus interaction have been estimated - even if estimates sometimes differ by several orders of magnitude. However, one should also note that the local polarisation will alter also the shielding of interactions of charged particles with the emitter e.g. in line-broadening collisions. To the present author's knowledge this second polarisation effect has not been considered numerically at all, although certainly once λ_{ez} approaches r_{oe} it should become significant. The major difficulty is that then the local plasma can not longer be treated as homogeneous when treating the shielding of emitter-perturber interactions, whereas normal treatments e.g. in the RPA, rely on all quantities of interest being a function only of co-ordinate difference.

5) CURRENT THEORETICAL AND EXPERIMENTAL WORK ON HIGH DENSITY EFFECTS

In discussing current work, one has to be careful to distinguish between theoretical work, where steady effort has been underway for a long time (although until recently without much hope of accurate test in the laboratory), recent experimental work at very high densities but using extensions of diagnostics techniques basically developed at lower densities, and experimental work specifically designed to study high density problems.

The elementary discussion of possible problems at high density given in this paper is in no way intended to obscure the fact that systematic theoretical work has been carried out for many years on related topics, particularly on ionization equilibria, and on line-shape theories. (Rather less seems to have been done in considering whether collision rates are as immune from high density corrections as usually assumed, see Section 4.2). Work on ionization equilibria, however, has largely been centred on the related question of the equation of state, rather than on direct spectroscopic observables. A very obvious reason for this is that high density corrections are immediately relevant to the shock-compression of a target at near solid densities, even before substantial heating has taken place. A common means of going beyond the limitations of a Debye model is to use some sort of Thomas-Fermi approach. Stewart and Pyatt

(1966), for instance, performed such calculations in a manner going asymptotically from the Debye to the ion-sphere limits, and more recently the Thomas-Fermi method has been used to calculate correlations to equations of state by the group at Rochester (see e.g. Laboratory for Laser Energetics, University of Rochester, N.Y. Annual Report 1978, Vol 1, pg 122).

Theoretical work on line shapes has also long had some emphasis on conditions where correlations become important. Again, the emphasis in the present article has merely been to point out that many of the important validity limits are reached simultaneously in nearly all existing theories. The possibility of treatment of correlations within the static model has already been described in sufficient detail, as have various fundamental theoretical attempts at treating dynamic correlations. However, one should note that such matters are a very live issue, experimentally as well as theoretically. One interesting recent development is a treatment by Griem (1978) of the effects of low-frequency fluctuations, due to electrons in the local polarisation clouds of ions, on line shapes for Lyman-alpha of hydrogen and hydrogenic-ions. This effect is predicted to cause a change of a factor of 2 in line-width for H Lyman-alpha, i.e. explaining the experimental results of Grutzmacher and Wende (1977). Obviously, the effect discussed by Griem is very akin to some of the other correlation effects mentioned in this paper, in so far as it will become of particular importance when λ_{ez} approaches r_{oe}. How far the treatment of Griem (1978) is in reality similar to the somewhat differently formulated theory of Lee (1978a) which also very adequately explains Grutzmacher and Wende's profile, remains to be seen. Lee's theory includes electron-ion correlations to second order in the RPA, and hence at least to some extent the 'ion cloud' effects discussed by Griem. An interesting feature of this in Lee's work (Lee, 1978(b), submitted to J.Phys.B), is the occurrence of enhanced resonance effects in high z plasmas at the ion plasma frequency, again due to coupling of the electrons with ion motion. (A similar effect in Thomson scattering from multiply ionized plasmas was first pointed out by Evans, 1970).

A considerable amount of theoretical work is in progress specifically aimed at predicting line-shapes for high z emitters in dense plasmas (see e.g. Tighe and Hooper (1976); Kepple and Griem (1976) and Lee (1978b)). The particular approach used by Lee incorporates a treatment of 'ion dynamic' effects already discussed above, and is capable also of handling the onset of electron degeneracy, since the calculation is inherently quantum statistical. One interesting feature is that the particular division used of the emitter-plasma interaction includes some contributions normally excluded if a simple d.E interaction is used, and which to some extent correspond to the polarisation effects described above. These do indeed cause shifts (and asymmetries) of hydrogenic transitions, but rather smaller than those predicted on other theoretical estimates. An example is the Lyman-alpha profile of Si XIV predicted for plasma conditions of 3 x 10^{23} cm^{-3} and 450 eV shown in Fig. 8. There is also some evidence that the static ion approach may not be as secure under these conditions as claimed by Vinogradov et al. (1974).

Experimental work at high densities has largely centred on laser-generated and laser-compressed plasmas. Many authors have used the intensity ratios of dielectronic satellites near to resonance lines of highly ionized species, whose importance in diagnostic applications was pointed out by Gabriel (1972). Similarly, ratios of allowed to to intercombination line intensities in He-like ions can be density and temperature sensitive. Specific examples of the use of line ratios of various kinds are the papers by Boiko, Faenov et al. (1977) on intercombination lines from the n=3 state in He-like ions, a paper by the same group on resonance line satellites of H-like ions (Boiko, Pikuz et al 1977), work by Dotschek et al (1975) on density sensitive transitions in high stages of ion, and a paper by Vinogradov et al (1978) on the ratio of the fine-structure components of Lyman-alpha for H-like ions. (The latter case is particularly interesting since ion-ion collisions may be important). All of these treatments, of course, rely on collision rates being unaffected by high density corrections.

Similarly, several groups have used orthodox (electron impact, static ion) line-shape theories in studying densities via line-shapes in laser-generated plasmas. Examples are the work of the Rochester group (Ya'akobi et al 1977) on Ne X at a density estimated at about 7 x 10^{22} cm^{-3}, using the profiles calculated by Tighe and Hooper (1976), already mentioned above, work by Richards and Peacock at Culham on C VI at a density of 10^{21} using a code written by Richards when at Imperial College (Richards, unpublished, but see Peacock (1978)), and work by the Rutherford group (Key et al. 1978) using the same code on Ne X and Si XIII (He-like) allowed and forbidden line pairs. (however, the line profiles used in the latter paper are currently being recomputed, since in the profiles originally used by Key et al, the forbidden component intensity does not appear to vary appropriately with density). Datla and Griem (1978) have observed pressure broadening in the Lyman series of Al XIII at 10^{22} cm^{-3} in a vacuum spark rather than a laser compressed plasma (see Paper II).

One experimental problem in all these papers is the question of line-centre optical depth, and the age-old difficulty that optically thick pressure-broadened profiles can often be fitted to a very wide range of densities simply by varying the assumed emitter density and optical path. Ya'akobi et al (1977) used one important route to circumvent this problem, which of course is particularly acute for resonance lines, namely systematic observation of several members of the resonance series simultaneously. An alternative approach is to study much higher transitions, and a particular example of this is the work of Irons (1973) on very high (visible region) transitions in C VI. However, this type of approach becomes impossible because of the high line widths and large visible region opacity in laser-compressed plasmas. One simple, but powerful, way round the line centre optical depth problem is due to Smith and Peacock (1978) who use the line-wing to continuum ratio at a specified wavelength point rather than the apparent profile as a means of determining density. From a diagnostic standpoint this also has the attraction that the result is much less sensitive to questions of ion dynamic effects and particle correlations than fits to an estimated line-centre opacity, since these latter effects tend to predominate in the central regions of the profile (emitter-perturber correlations however remain important in the line wings).

It will probably still be a considerable time before diagnostic information on laser-compressed plasmas is good enough to allow these plasmas to be used for systematic fundamental study of high density effects even though these may interact back on diagnostic results. In the meantime, therefore, fundamental aspects of the subject have to be studied on simpler sources, see Fig. 1. Systematic attempts to product conditions violating any of the validity conditions already described are actually still quite rare, although see e.g. the work of Zwicker (1968). Nevertheless, many related effects can be studied at lower densities, particularly via observations of line-shapes. In this respect, in addition to papers already referenced one notes that the question of 'ion dynamic' effects on the central regions of H-beta (see e.g. Wiese et al 1975) is still not fully resolved by theory (e.g. R W Lee 1978c), and indeed that some discrepancies still exist between different experiments (e.g. Burgess and Mahon 1972; Wiese et al 1975; Bengston et al 1976). Similarly, whilst discrepancies for the He II 304 transition (profile as opposed to shift) appear to have been resolved (Neiger and Griem 1976; Smith and Burgess 1978), the situation is not so clear for other He II lines (e.g. the Balmer series). There is in fact, a pressing need for more work on hydrogenic-transitions of ionized emitters of low z, particularly at high densities.

As far as the various high density interaction effects listed in 4, 3, 5 are concerned, sufficient examples have already been given of work on plasma satellite lines. Higher multipole contributions to the interaction have also been observed experimentally, e.g. in studies of the asymmetry of Lyman-alpha by Fussman (1975) and by Preston (1977). These two authors have also observed quasi-molecular satellites due to details of the $H-Ar^+$ interaction, Preston (1977) in particular proving the nature of these features beyond any reasonable doubt by careful control of the plasma conditions (hence varying n_H and n_{Ar^+} separately). The relation of the quadrupole asymmetry to the mechanism underlying satellite formation has already been noted in Section 4.3.5 and it is no surprise that the two effects are seen together. As far as the polarisation shift is concerned, one can only say that what one believes in the way of theoretical treatment is strongly correlated with what specific transition is observed. Results range from definite blue shifts for He II 304 (Neiger and Griem 1978) through red shifts for He II Balmer series lines (van Zandt et al 1976), and small shifts for other He II lines (Kelleher, D, private communication) to no shift at all for Ar II and Ar III resonance lines (Baker and Burgess 1979).

Perhaps one may be allowed to end with the indulgence of a few remarks about one particular experiment, since this does illustrate the fact that the important condition $r_{oe} = \lambda_D$ can easily be approached in simple laboratory sources, and that when one does so, some surprising things happen - and some expected things doe not! I have already mentioned work by Dr Elizabeth Baker and myself in which we used a z-pinch to produce an argon plasma with only about 3 particles per Debye sphere. Laser-based techniques allowed accurate spatially resolved diagnostics in this plasma (see Baker 1977, Ph.D. Thesis University of London) despite the small plasma radius. One feature we have already reported (Baker and Burgess 1977) is the observation of interference asymmetries modifying line wing shapes, an effect I first predicted in 1968 (Burgess, 1968), for which the underlying physics is quantum mechanical rather than specifically high density, but which nevertheless only becomes evident at high densities when line widths are large. Other effects, however, which are specifically high-density ones, were also very evident in this plasma and will be discussed in a forthcoming paper (Baker and Burgess 1978). As expected from the discussion given in 4.3.5. we were able to observe the same effects as described under the references to Fussman (1975) and Preston (1977), but very considerably more pronounced due to the much higher density. Strong asymmetry was observed in the wing of the hydrogen Lyman-alpha line, but not in very good agreement with existing predictions of the quadrupole contribution. Satellite features to Lyman-alpha were seen, due to $H-Ar^+$ interactions and in one case due to $H-Ar^{++}$. But one of the main features which we intended to study with this device was not observed at all, namely the polarization shift which was looked for on the resonance lines of Ar II and Ar III, and on transitions of N IV. Despite the fact that theories used to explain observed shifts of He II 304 predicted shifts for the Ar II and III resonance lines which in some cases exceeded 10^6 Angstroms (not a misprint!) - essentially because the critical parameter λ_{ze}/r_{oe} was becoming very large - no density dependent shift whatever was observed for any transition! Much work obviously remains to be done on these and related problems before adequate understanding is obtained of problems at even higher densities. However, it is interesting to note that in this rather simple and easily studied laboratory device, one could not only approach the condition $r_{oe} = \lambda_D$ (in our case $r_{oe} = 0.68\ \lambda_D$), but e.g. for the Ar^{++} and N^{+++} ions one could also achieve the condition $\lambda_{zz'} = r_{o\bar{z}}$, defining the beginning of the transition to the ion-sphere limit.

In conclusion, a great deal of fundamental high density plasma physics, identical to that relevant in the core of laser compression plasmas, can probably be studied in very much simpler plasmas. A very interesting prospect would be to run a high-density pinch discharge in a more easily ionized species than argon, so that the mean ion charge could be increased without a large increase in temperature. Such conditions were indeed achieved by Zwicker (1968) in xenon, and it would be interesting to repeat such measurements with a species better adapted to quantitative spectroscopic predictions (i.e. in so far as the atomic physics is concerned). Of the conditions discussed in the present paper, almost the only one that cannot be approached except in laser compression experiments is the onset of electron degeneracy.

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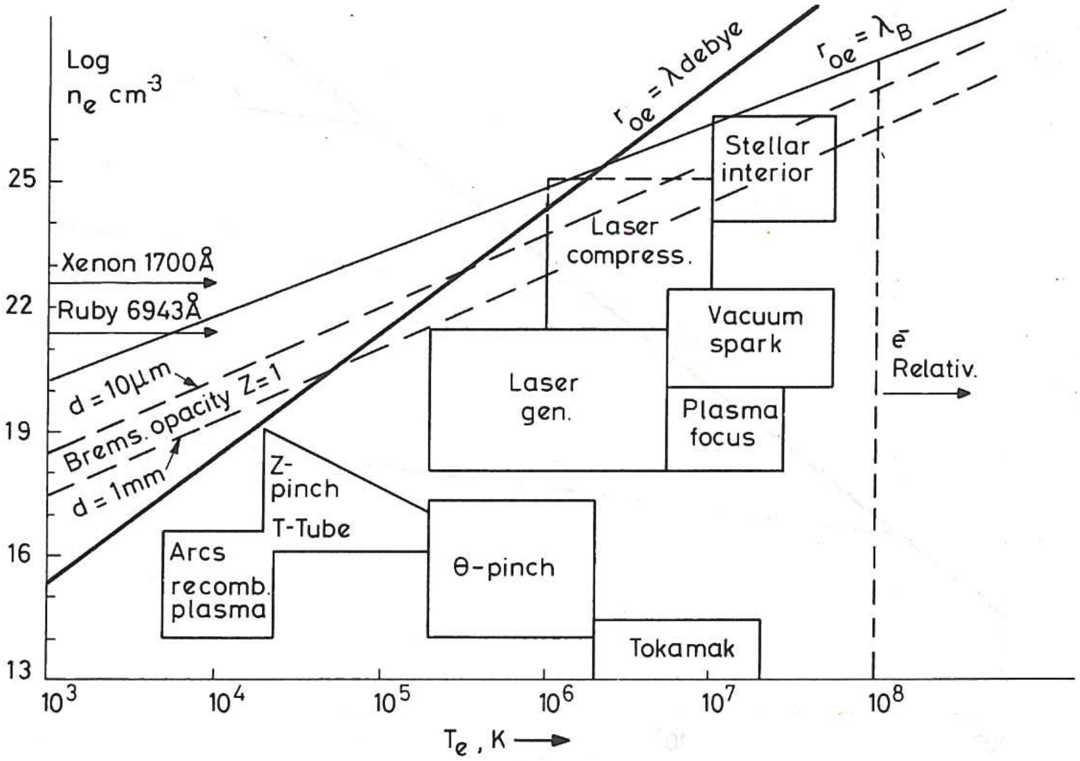

Fig.1 Laboratory plasma sources.

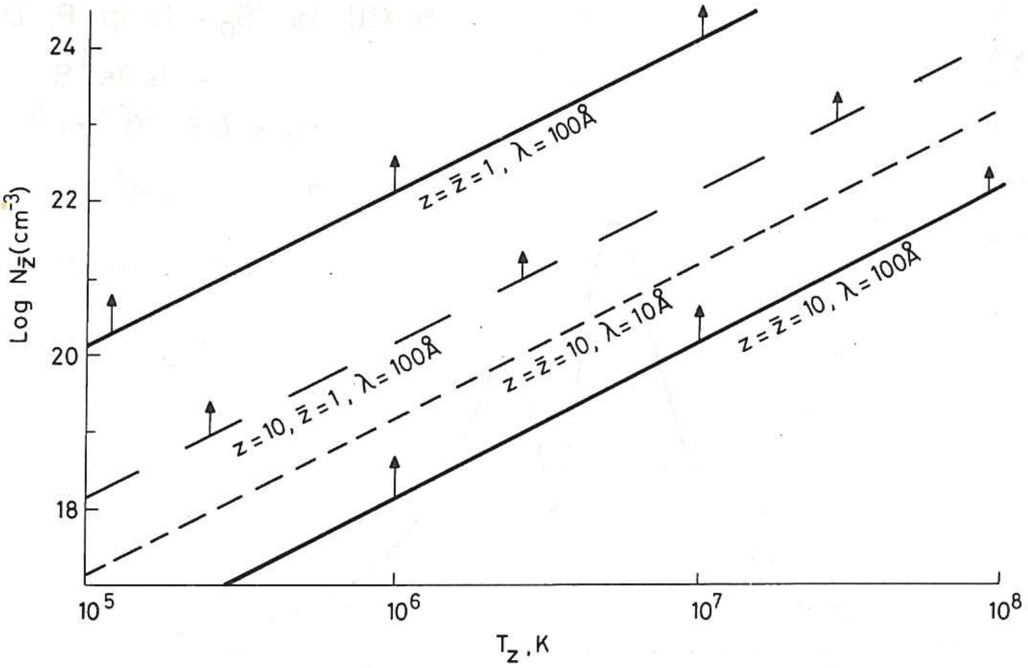

Fig.2 Critical ion densities for doppler narrowing ($\lambda_{90} = \lambda$) ($n_e = \bar{z}\, n_z$).

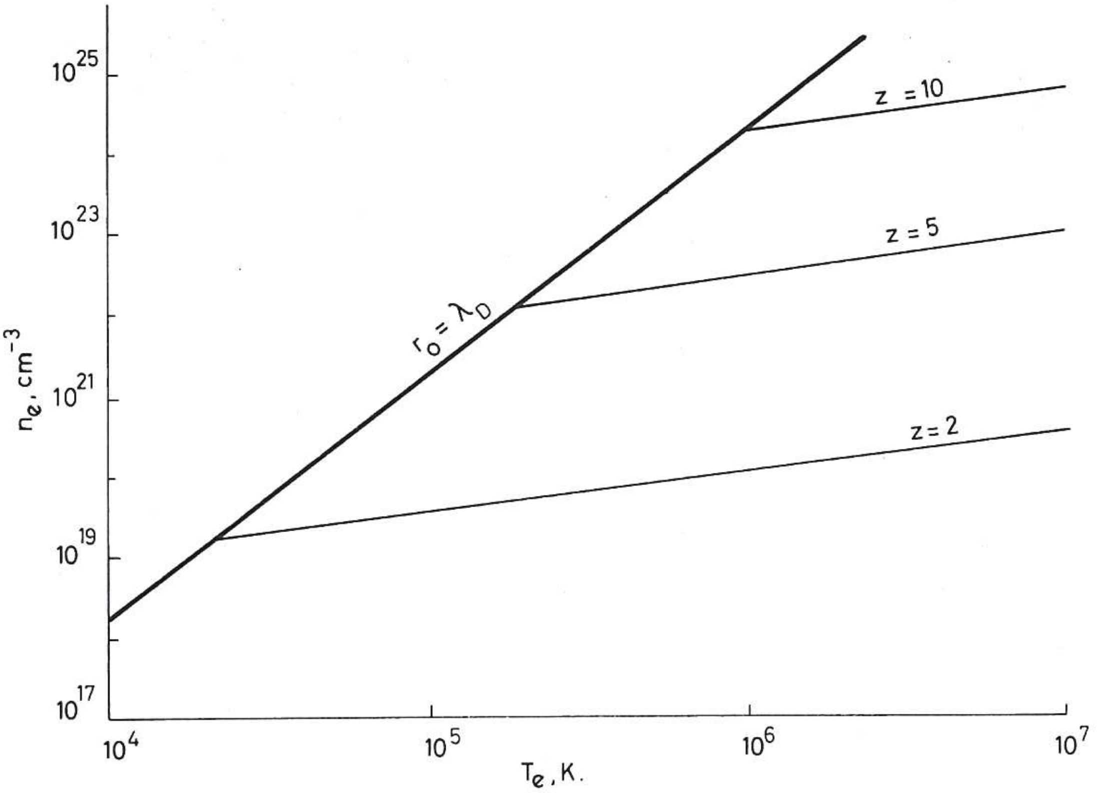

Fig.3 Density for LTE (Saha) to apply as a function of ion charge.

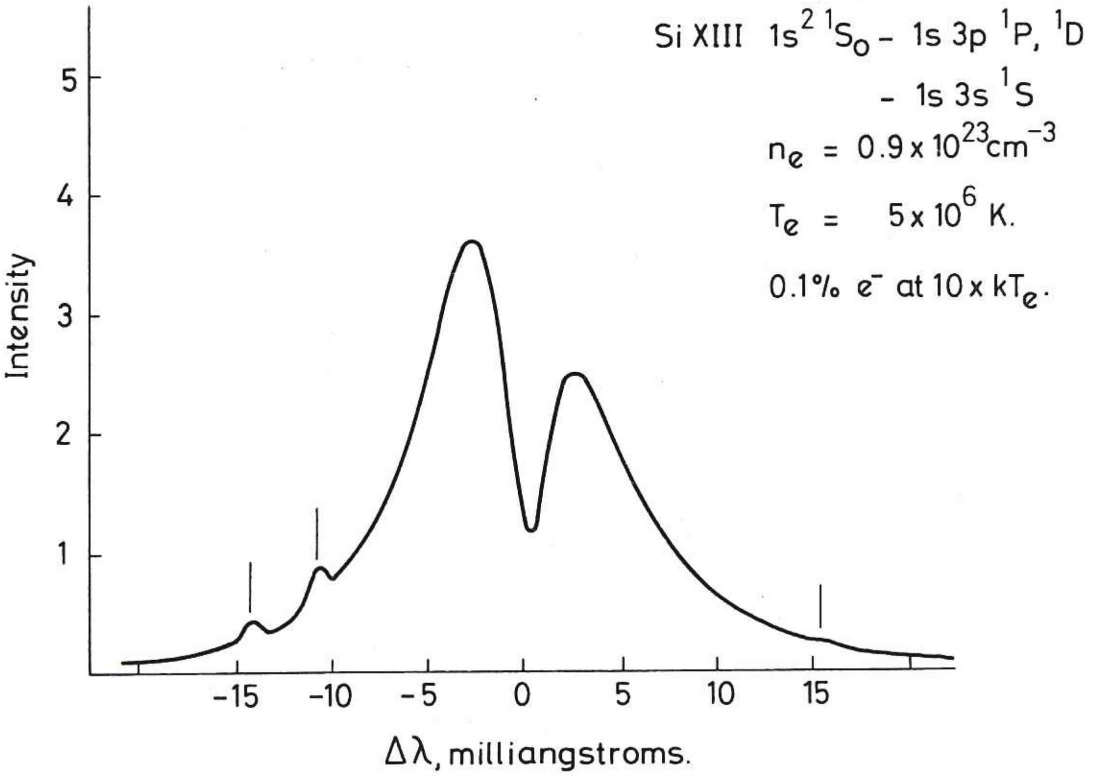

Fig.4 He-like allowed/forbidden line pair (Si XIII, R.W. Lee 1978).

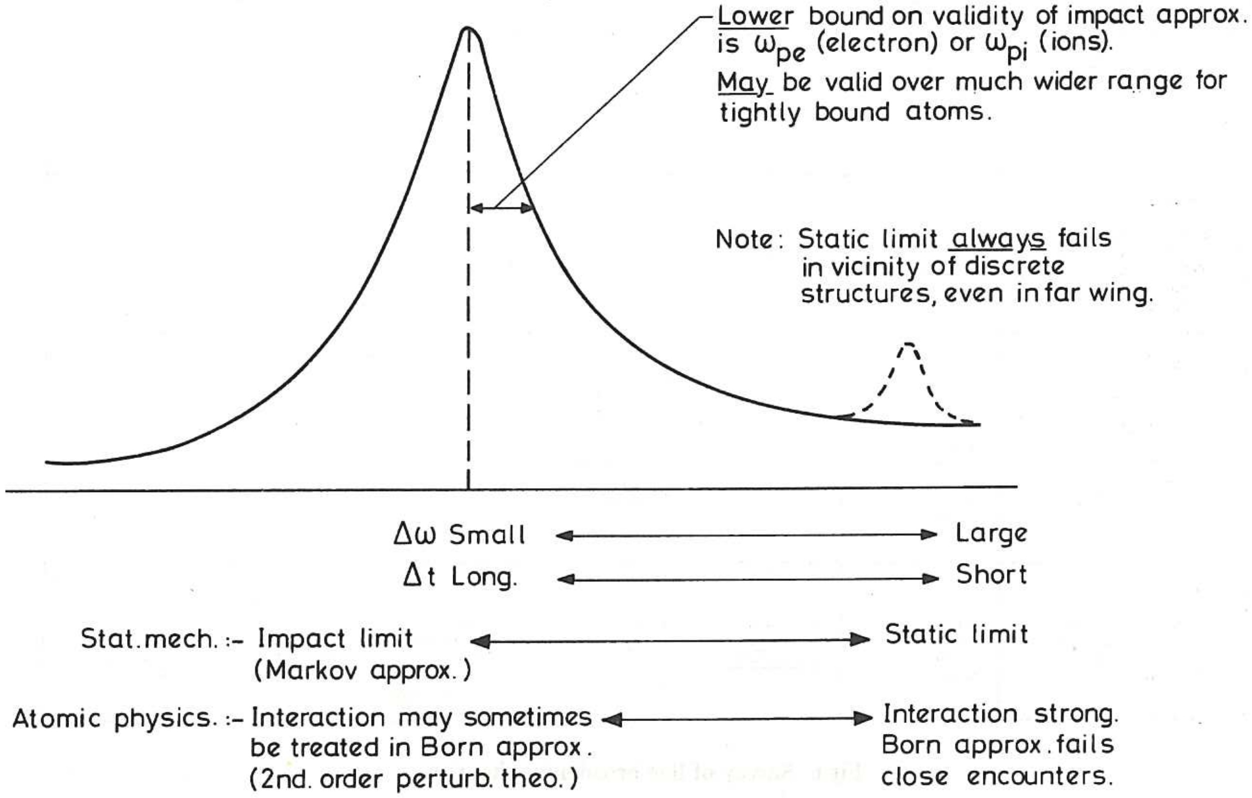

Fig.5 Typical pressure broadened line.

THEORY	ELECTRONS	IONS	e^--e^- CORRELN	PLASMA SATELLITES	e^--i CORRELNS	i-i CORRELNS
'Baranger-Griem' (1958), 1962 on - see Griem 1974). (Many variants, classical and quantal)	IMPACT (bare e^-)	STATIC (Cluster integral)	Very approx only Thermal plasmas only	Separate	STATIC only	STATIC only
'Unified' Smith, Cooper, Vidal 1968 on. Voslamber 1968 on. Other semi-classical and quantal variants	Binary e^- only, but valid throughout profile	STATIC (as above)	NONE (despite claims!) (Violates basic postulate of unified theo)	NO	STATIC only	STATIC only
'Relaxation' Smith and Hooper 1966 'Many-body' Ross (1964) Bezzerides (1967) Lee (1970), Burgess (1970), Zaidi (1970) etc.	IMPACT (dressed e^- - also generalised to include frequency-dependence)	STATIC (as above)	Good thru' 2nd order in atom-plasma interact. Can treat non-Maxwellian plasma	YES In profile to 2nd order in interactn	STATIC only	STATIC only
Dufty-Lee Dufty (1969) (basic theo.) Line-shape applicns. Lee-1973 on.	IMPACT (as relaxation theo.)	Full static ion plus ion dynamics	As relaxn. theo.	YES As relaxn. theo. plus structure due to ions	YES Dynamic in RPA plus full static	YES Dynamic in RPA plus full static

Fig.6 Survey of line-broadening theories.

THEORY	BASIC CONTENT	COMMENTS
'Baranger-Griem' (1958, 1962 on) plus Hooper Microfield	1) Electrons treated in impact (collisional) approx. Fundamentally binary (despite assertions in classical path variants) - individual collisions add scalarly. No dependence of e^- broadening on ion field other than in atomic Hamiltonian (no e^--ion correlations in impact part). 2) Ions treated in static approximation. Cluster integral treatment of microfield, including e^- shielding, valid if $r_{oe} < \lambda_D$. Well verified.	Majority of calculations. Very useful for rapid computation. Various classical or full quantal derivations. Can include RPA shielding effects for electron boradening but only in an approximate manner (usually simply a cut-off). Derivations via classical path approx. cumbersome and misleading. Best to approach via a proper quantum theory (e.g. diagrammatic many-body) and take classical limit.
'Unified' theories. Semi-classical and quantal. Smith, Cooper, Vidal 1968. Voslamber 1968 etc.	As above, except attempt to treat binary electron collisions to all orders in perturbation theory, including frequency-dependence (i.e. t-matrix approx,) so that static limit is approached in wing. Valid only if close collisions dominate broadening.	No correlations in dynamic part. (RPA treatment of e^- shielding invalid if 'unified' theory needed - i.e. if theory differs from purely impact prediction).
'Relaxation' theories (Smith 1966) 'Many-body' theories (various)	As Baranger-Griem, but including frequency-dependence of broadening operator (i.e. self-energy part for emitter). Full RPA (classical or quantal) treatment of e^--e^- correlations. 2nd order in atom-plasma interaction. Can include non thermal effects via dielectric function, $\varepsilon(k,w)$.	No consistent treatment involving perturber correlations to higher order than second in atom-perturber interaction. Not adequate for ions. Dubious whether 2nd order in atom-plasma interaction adequate for plasma satellites.
'Dufty-Lee' (1972 on)	Includes ion dynamics, e^--i correlations etc. to 2nd order in atom-plasma interaction (via dielectric function) whilst retaining full ion static contributions as well. Subtractive (analytic) term avoids "overcounting".	Significant changes from other theories near forbidden lines, satellite features, line-centre etc. Restrictions for plasma satellite features as per relaxation theory, but includes ion frequency satellite effects in addition.
Model Microfield. (Frisch-Brissaud, etc. See Seidel 1977)	Attempt to find a model total microfield allowing soluble atomic physics whilst retaining all relevant correlation properties of real microfield in both short and long time limits.	Results not (yet) adequately verified by experiment. See Seidel (1977) for comparison with other theories and experiments.

Fig.7 Comments on various line-shape theories.

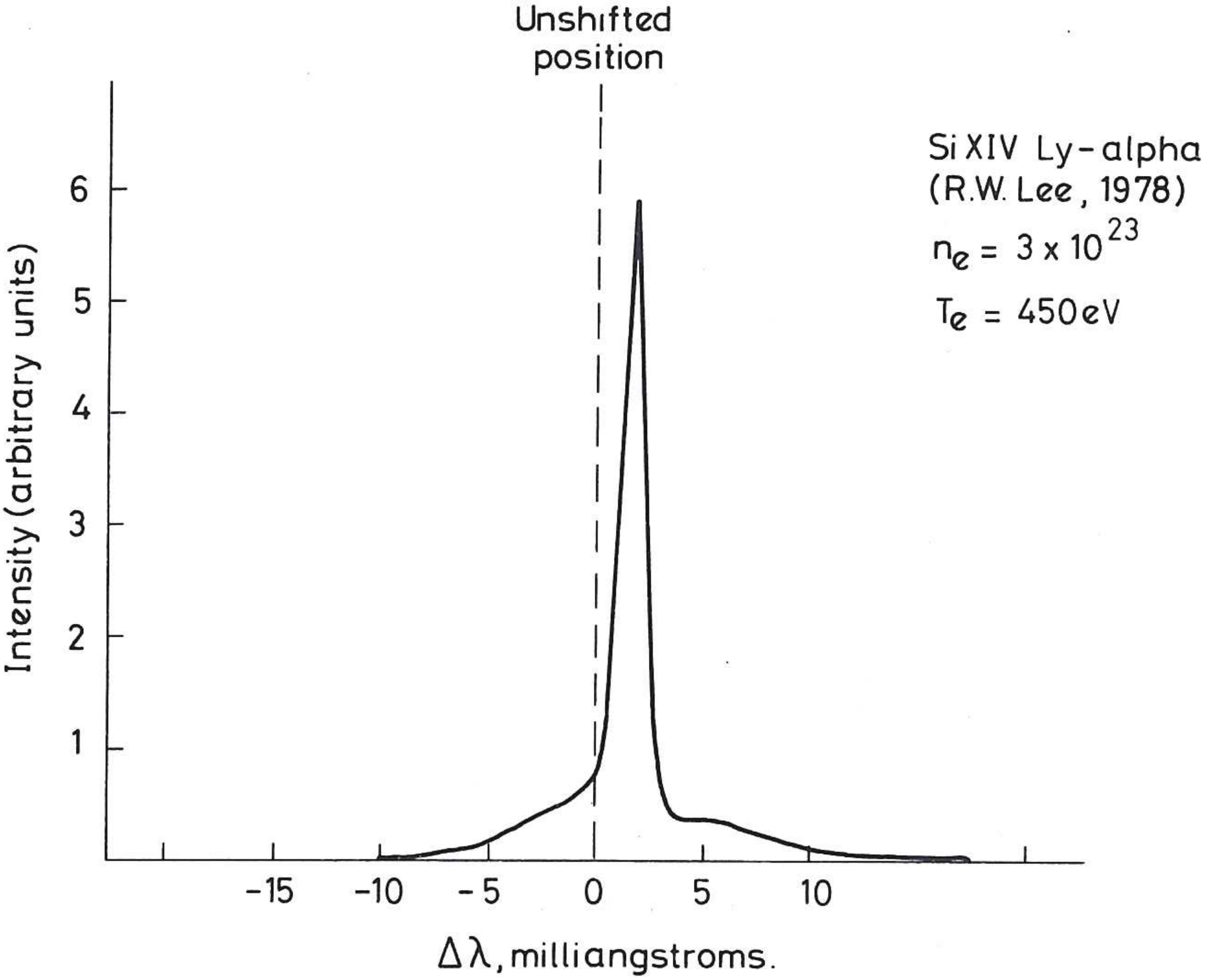

Fig.8 Pressure-broadened SI XIV.