CLM - P 363

CLM - P 363

E·MINIMIS·MAXIMA

UKAEA RESEARCH GROUP

Preprint

MEASUREMENT OF MEGAGAUSS MAGNETIC FIELDS IN THE PLASMA FOCUS

B A NORTON
N J PEACOCK

CULHAM LABORATORY
Abingdon Berkshire

1973

CLM-P 363
(October 1973)

Corrigenda

p.4 lines 7 and 8: $2s\,^1S_1 - 2p\,^3P_{3,2,1}$

should be $2s\,^3S_1 - 2p\,^3P_{2,1,0}$

p.4 lines 17: 2265Å should be 2266Å

CLM-P 363
(October 1973)

Corrigenda

p.4 lines 7 and 8: $2s\,^1S_1 - 2p\,^3P_{3,2,1}$

should be $2s\,^3S_1 - 2p\,^3P_{2,1,0}$

p.4 lines 17: 2265Å should be 2266Å

CLM-P 363

MEASUREMENT OF MEGAGAUSS MAGNETIC FIELDS IN THE PLASMA FOCUS

B A Norton*, N J Peacock

(To be submitted to Phys.Rev.)

A B S T R A C T

The magnetic field associated with the dense pinch in the Plasma Focus has been measured from the Zeeman splitting of the CV, 2s-2p, emission. Values of the order of one Megagauss are derived in agreement with pressure balance between the self-field due to currents in the pinch and the kinetic pressure of the plasma.

* Royal Holloway College, London University

UKAEA Research Group
Culham Laboratory
Abingdon, Berkshire.

October 1973

INTRODUCTION

The magnitude of the magnetic field has a considerable bearing on the mechanism by which a dense plasma column is transiently formed along the axis of symmetry of the Plasma Focus, coaxial electrode device, described by Mather[1]. There is substantial evidence to show that the Lorentz forces associated with the self-magnetic field in the imploding sheath are responsible for the pinched plasma column. Compression of the plasma particles into the axis of symmetry has been investigated by Morgan and Peacock[2] who have found that only 6 per cent of the particles within the implosion volume are swept up on account of the cusped, conical shape of the imploding plasma boundary. These authors point out that the Bennett relation $\bar{\beta}.I^2 = 2 \sum_{e,i} NkT$, where N is the line density of each particle species, is satisfied for the dense plasma column with a value of $\bar{\beta}$ just less than unity.

The kinetic pressure, $< n_e.kT_e + n_i.kT_i >$, is therefore balanced by the magnetic field pressure, $B_\theta^2/8\pi$ calculated on the assumption that all the circuit current, I, flows in the plasma column. In this case then the self-magnetic fields at the plasma boundary must lie between one and two megagauss. Filippov et al.[3], using a different Focus geometry has indeed deduced field values of this order from the spatial anisotropy of the charged particle production arising from the fusion reactions in the Focus. The results of Morgan and Peacock[2] are in good agreement with the theoretical predictions of a 2-D,2 fluid, numerical code developed by Potter[4]. This code, which describes the structure of the imploding current sheath, correctly predicts the amount of particles collected and derives a value for $\bar{\beta}$ equal to unity for the compressed plasma column.

Alternative explanations have however been proposed to account for plasma compression in some coaxial systems. For example, Bernoulli flow of initially low beta ($\bar{\beta} << 1$) plasma has been suggested by Morozov[5], and in practice it has been verified Newton et al.[6] that this "compressive flow" can be set up with the appropriate operating conditions.

The present paper describes direct measurements of the magnetic field from line profiles of the CV,2s $^3S_1$ - 2p $^3P_{2,1,0,}$ multiplet which is emitted from the dense plasma. These measurements allow us to distinguish between the high beta pinch and such low beta processes as particle focussing or plasma flow.

In order to measure magnetic fields from line profiles it is desirable that the Zeeman splitting be of the same order or greater than frequency shifts due to thermal and mass motion and Stark broadening. The emitting ion must exist for a finite time in the Focus where the dense plasma parameters are $T_e \sim 2$ keV, and $n_e \sim 10^{19}$ cm^{-3}, Peacock et al.[7]. The CV multiplet at 2270.9 Å 2277.9 Å and 2277.3 Å satisfies these requirements and allows polarization measurements to be made with readily available optical components. Stark broadening is described by the electron impact approximation and a suitable scaling of the half-width parameters, Griem[8], leads to a dispersion full half-width of 1.04 angstrom units at an electron density of 3×10^{19} cm^{-3}. The ion energies and spatial density distribution during the dense pinch phase have been measured in the Focus from line profiles in the x-ray region and from laser interferometry respectively; Peacock et al.[7], Morgan and Peacock[2]. Scaling the thermal energies of the ions with their charge/mass ratio gives the relation

$$E(Z/M) = 1.5 \frac{Z^{2.1}}{M}$$

which yields 3.67 keV for the ion temperature of the CV ions and a full half-width due to thermal motion of 3 angstrom units. Mass motion shifts[7] of the plasma boundary, $\lesssim 3 \times 10^7$ cm sec^{-1}, give wavelength shifts of the same order. Temporal variations in the values of T_i or n_e of the order of 100% will result in uncertainties in the overall width of the Stark-thermal profile of about 50%. But the total broadening is still of the same order or less than the expected Zeeman shifts of several angstrom units. This is illustrated in figure 1 where the spectral intensity of the CV (2s - 2p) multiplet viewed orthogonal to the magnetic field is calculated for field values between 10^5 and 2×10^6 gauss. The effect of mass motion shifts [7] on the line profile is well illustrated by the splitting of the π components at the lowest field values in figure 5. Over this range of field values, figures 1 and 5, the intensities and frequency shifts of the σ and π components are calculated in the weak field approximation which is strictly only valid for values less than 1×10^6 gauss. However the weak field approximation holds good for much higher field values if attention is restricted, as in this work, to the high frequency side of the $^3P_2 - {}^3S_1$ component.

The profiles were scanned on a shot to shot basis through a quartz-stack polarizer, using a photomultiplier and normal-incidence monochromator arrangement with a time resolution of 8 nanoseconds and a wavelength resolution of 0.85 angstrom units. The emission from the 2s - 2p multiplet was enhanced by adding 2.5% ethylene by volume to deuterium at a total pressure of 2.1 torr.

The emission was accepted from a plasma cross-section 4 mm long in the axial direction and only 0.01 mm in radial extent at the axis of symmetry. The line of sight is orthogonal to this axis and to the local direction of the B_θ magnetic field. Assuming azimuthal symmetry, i.e. only poloidal field, the Zeeman components of the emission should therefore be plane-polarized, as in Figure 1, in directions transverse (π) and parallel (σ) to the axis of symmetry.

The 2s - 2p multiplet could be measured above the continuum and neutron noise background for about 60 nanoseconds before the steep rise in the neutron intensity, which is estimated to be +20 nanoseconds later than when the plasma boundary first implodes onto the axis. The neutron emission is shown in Figure 2 delayed by a further 35 nanoseconds due to time of flight. A wavelength scan of the $2s\,^1S_1$ - - $2p\,^3P_{3,2,1}$ multiplet extended to about 10 angstroms to the high frequency side of the 2270.9 Å line centre. Polarization of the line emission, figure 3, is in contrast to that of the unpolarised continuum at 2256 Å, and indicates that frequency shifts of the line are due to Zeeman splitting. Isolated wavelength regions show predominantly σ components in the far wings and π components at the centre of the line, as illustrated in figure 4. Comparison of these results with reconstructions of the line profile under a variety of different plasma conditions allows an evaluation of the field. The appearance of mainly σ radiation at 2265 Å and π radiation at 2272 Å, figures 3 and 5, sets a lower limit to the field of 0.8×10^6 gauss. An upper limit to B_θ is set at 2×10^6 gauss when mass motion is included, figure 5, and 3×10^6 gauss when there is zero mass motion, figure 1, due to the fact that no π emission is observed at wavelengths shorter than 2265 Å. Rapid temporal variations in the mass-motion shifts just before peak compression of the pinch make it difficult to predict the actual line profile and therefore to give a precise value for the field. A best estimate for B_θ is between 0.8×10^6 and 2×10^6 gauss. It should be noted that for the parameters of the dense pinch, Peacock et al[7], the "burn through" time for CV ions is $\sim$ 1 nanosecond. The CV line profiles are therefore likely to be emitted from the outer boundary of the dense pinch which is not necessarily coincident with maximum fields in the plasma column. The results however confirm the results of Morgan and Peacock[2] that all, or nearly all, of the circuit current flows in the dense plasma column on the axis of symmetry, and that a high beta pinch is the correct model, Potter[4], to account for the formation of this plasma.

These field measurements also allow us to consider the conditions necessary for 'compressive flow' in the Plasma Focus. For the compressed plasma column we now know that $B_\theta \gtrsim 8 \times 10^5$ gauss; $\bar{n}_e = 8 \times 10^{18}$ cm^{-3} and $\bar{r} = 0.9$ mm, Morgan and Peacock[2]. Thus at a starting pressure of 2.5 torr and with an inner electrode radius of 25 mm we have for the product of the density and radius,

$$\langle \rho_o r_o \rangle \sim \langle \rho_p r_p \rangle \quad ,$$

where the subscripts 'o' and 'p' refer to the plasma in the interelectrode space and in the pinch respectively. The isomagnetic condition for 'compressive flow' however requires, Morozov[5], that

$$\frac{B}{\rho . r} = \text{constant} \quad ,$$

which is clearly inadmissible in the present experiment. The accumulation of plasma onto the axis of symmetry in the Plasma Focus cannot therefore be due to a continuous flow of low beta plasma from the interelectrode space. If such a flow system could be set up however, it would be useful in sustaining the transient dense plasma produced in these experiments by the implosion of the cusped conical plasma boundary.

ACKNOWLEDGEMENTS

The authors would like to thank R. Peacock for his help in the alignment and calibration of the spectroscopic apparatus for these experiments. This research is partly supported by the United Sates Air Force (European office) under grant AFOSR-73-2428.

REFERENCES

1. MATHER, J.E. (1970). Methods of Experimental Physics, vol.9-15, pp.187-249. Editor, H.R. Griem, published New York, Academic Press.
2. MORGAN, P.D. and PEACOCK, N.J. (1972) Proc. 2nd APS Topical Conference on Pulsed High Beta Plasmas, Garching, Paper E9. Published Max-Planck-Institut fur Plasmaphysik, IPP 1/127.
3. FILIPPOV, N.V. et al. (1971) Plasma Physics and Controlled Nuclear Fusion Research, vol.1, pp.573 - IAEA Vienna.
4. POTTER, D.E. (1971) Physics Fluids 14, pp.1911.
5. MOROZOV, A.I. (1969) Plasma Physics and Controlled Nuclear Fusion Research, vol.2, p.3, IAEA Vienna.
6. NEWTON, A.A., MARSHALL, J., MORSE, R.L. (1969) Proc. 3rd European Conference on Controlled Fusion and Plasma Physics, pp.119. Published, Wolters - Noordhoff, Utrecht, Netherlands.
7. PEACOCK, N.J. et al. (1971) Plasma Physics and Controlled Nuclear Fusion Research, vol.1, pp.537-551. Published IAEA Vienna.
8. GRIEM, H.R. (1964) U.S.N.R.L. Report 6084 - Washington D.C.

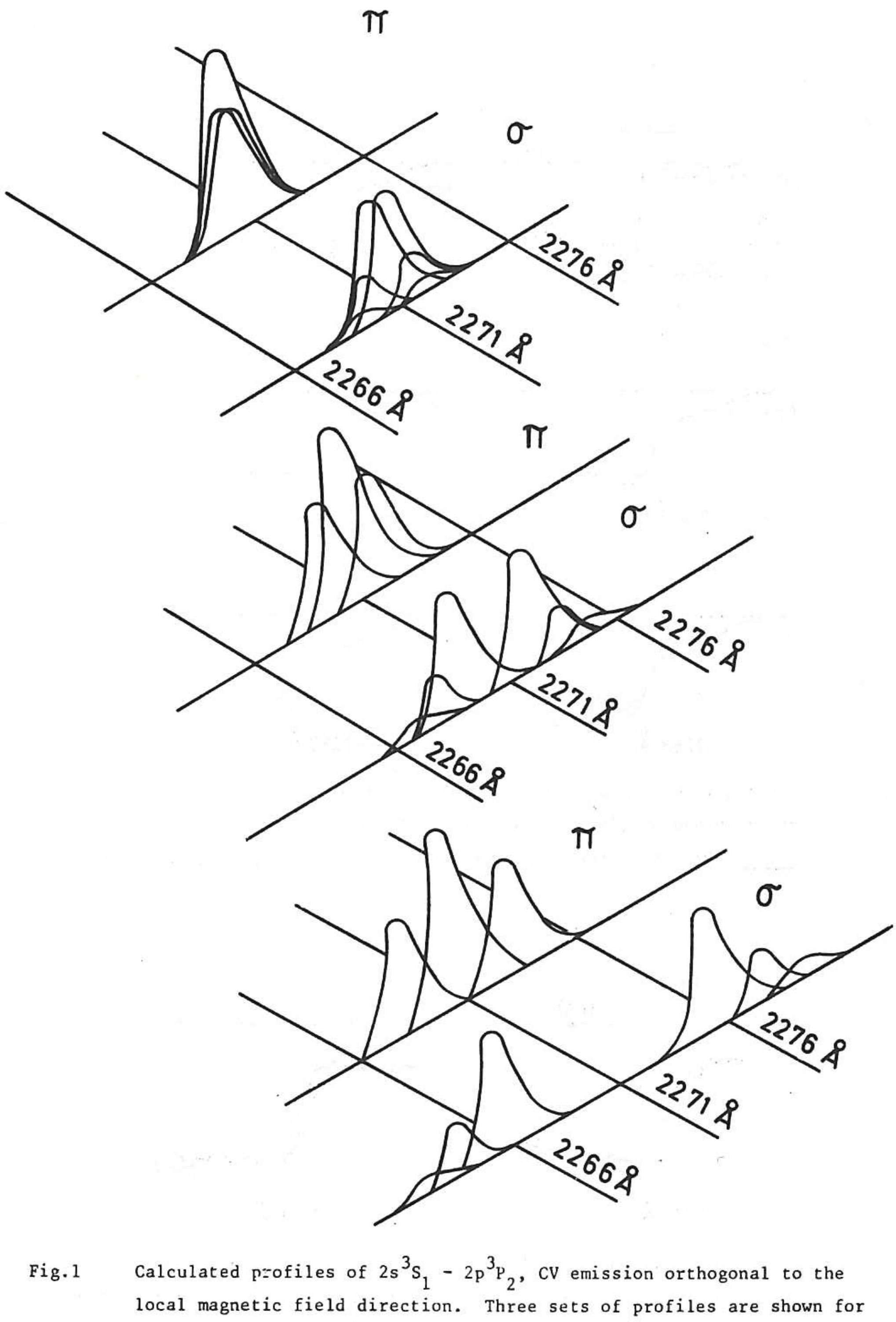

Fig.1 Calculated profiles of $2s^3S_1 - 2p^3P_2$, CV emission orthogonal to the local magnetic field direction. Three sets of profiles are shown for magnetic field values, from top to bottom of 0.1, 0.8 and 2 Megagauss. The profiles of the individual Zeeman components are broadened due to thermal-Stark effects. The ion temperature is assumed to be 1 keV and the electron density, 2×10^{19} cm^{-3}. Mass-motion of the plasma is neglected.

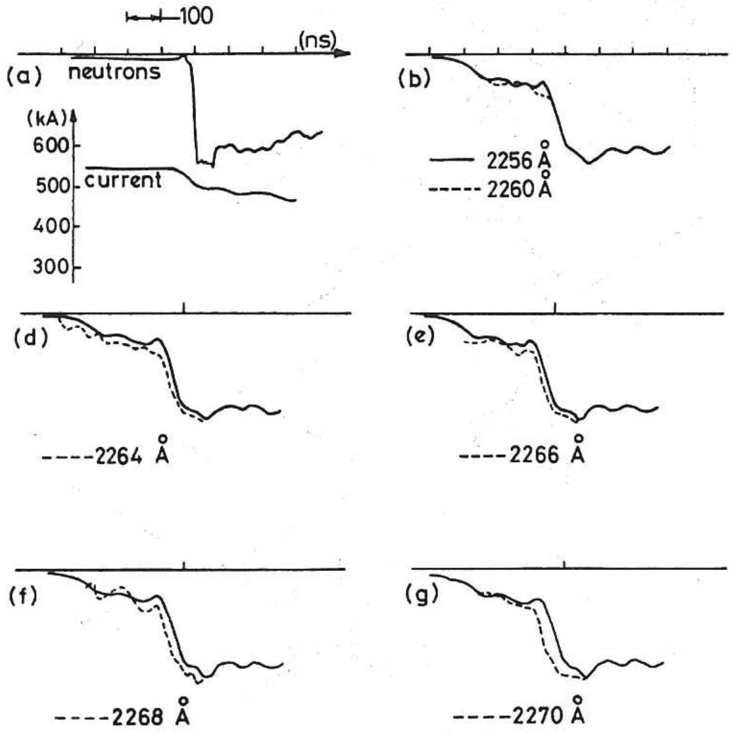

Fig.2 Intensity, during the Plasma Focus discharge, of
------ broadened, $2s^3S_1 - 2p^3P_2$ CV emission
______ the sum of the continuum and the neutron emission. CLM-P 363

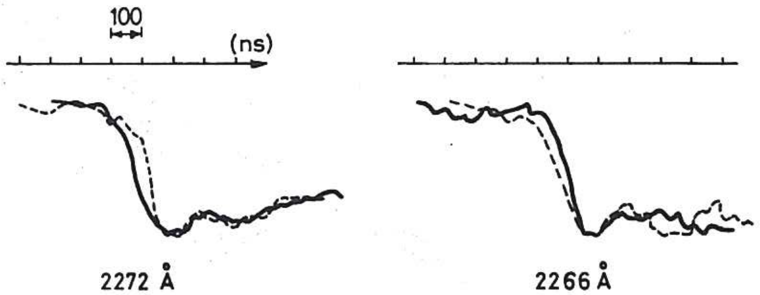

Fig.3 Effect of polariser on $2s^3S_1 - 2p^3P_2$, CV emission from Plasma Focus
------ analyser plane of polarisation parallel to axis of symmetry
______ analyser plane of polarisation perpendicular to axis of symmetry
CLM-P 363

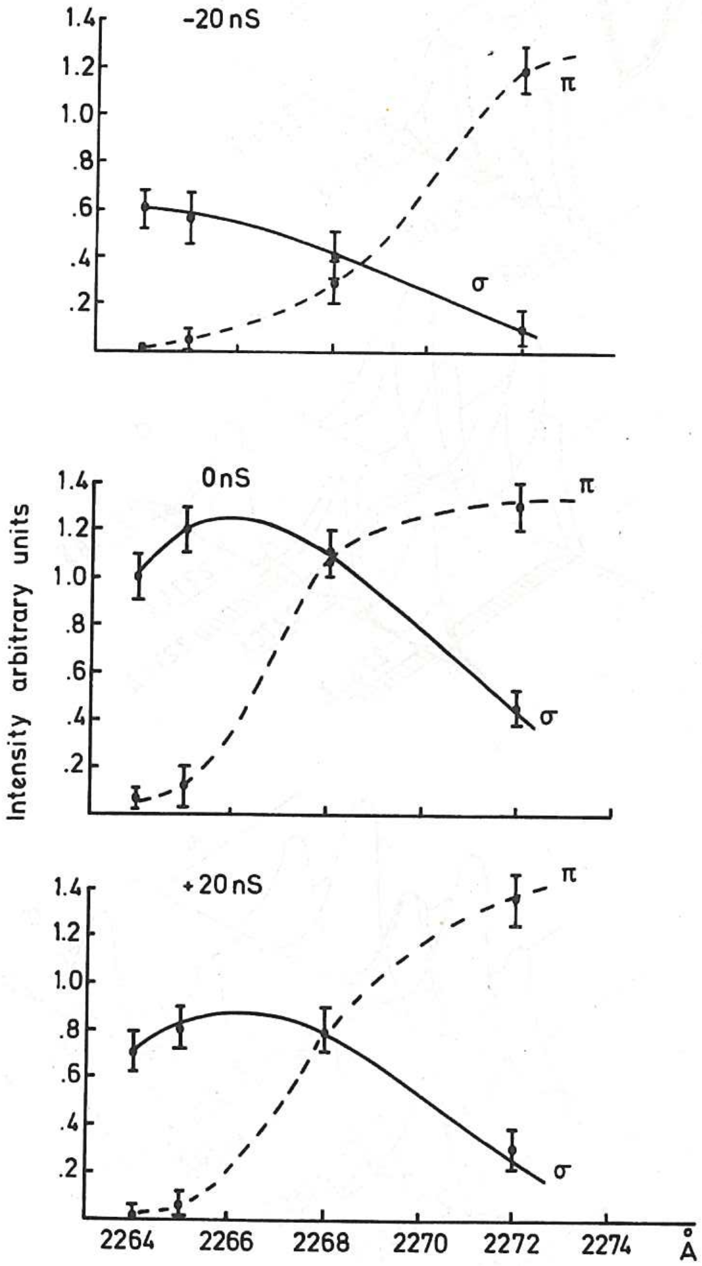

Fig.4 Intensity of π, σ components on short wavelength side of $2s^3S_1 - 2p^3P_2$ CV line during the Plasma Focus discharge. 0 nsec refers to the time when the current sheath meets the axis of symmetry.

CLM-P 363

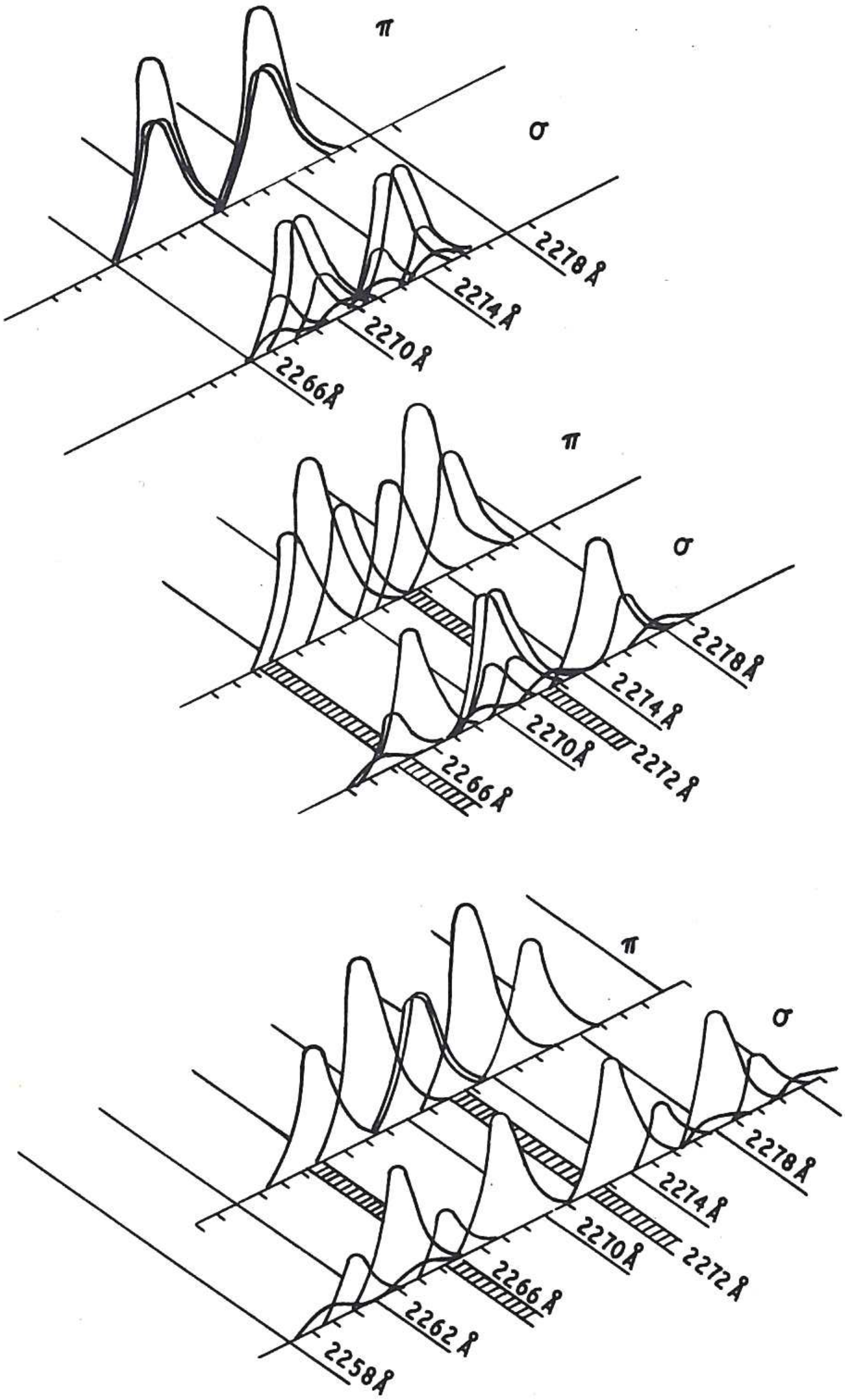

Fig.5 Calculated profiles of $2s^3S_1 - 2p^3P_2$, CV emission orthogonal to the local magnetic field direction. Three sets of profiles are shown for magnetic field values, from top to bottom, of 0.1, 0.8 and 2 Megagauss. Mass motion shifts correspond to a velocity of $\pm$ 2.5 × 10^7 cm sec^{-1} orthogonal to the axis of symmetry in Plasma Focus. The profiles of the individual Zeeman components are broadened due to thermal-Stark effects. The ion temperature is assumed to be 1 keV and the electron density, 2 × 10^{19} cm^{-3}.