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OBSERVATION OF CHARGE TRANSFER POPULATION OF n=2 EXCITED STATES OF Ar^{16+} IN TOKAMAK PLASMAS

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Results from the first radial measurements of the n=2 to n=1 x-ray transitions of high-Z elements in deuterium tokamak plasmas are presented. The observed line intensity ratios cannot be explained by electron impact and recombination processes only, and the $D + Ar^{17+} \rightarrow D^{+} + Ar^{16+}$ charge transfer reaction is proposed as an additional population mechanism. The lines emitted in the cascade following capture constitute a unique diagnostic probe of the neutral component of plasmas and should provide valuable atomic data on the individual charge transfer rate coefficients.

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High resolution spectroscopy of the He-like n=2 to n=1 x-ray emission of high-Z elements in high temperature plasmas, particularly in tokamaks, has developed into a powerful technique for determining the main plasma parameters such as electron temperature T_e and density N_e as well as the ion temperature and ionic charge state distribution. Detailed rate calculations[1] predict the observed relative intensities of the principal transitions, the resonance (w), the intercombination (x and y) and forbidden (z) lines from respectively the 2^1P_1, $2^3P_{2,1}$ and 2^3S_1 states, and satellite lines [2,3]. The agreement between measured and calculated line ratios confirms that excitation of the Ar^{16+} ground state, by electron impact and dielectronic recombination, is the principal population mechanism. Most measurements, however, have been limited to the plasma core region, where the x-ray emission is brightest and most easily measured, and studies are needed to test this model throughout the plasma.

We report here a systematic study of the He-like spectrum for a high-Z element (argon) in a deuterium plasma as a function of distance from the plasma centre along the minor radius. An earlier study of oxygen has been carried out by Peacock and Summers[4]. The relative intensity of lines of Ar^{16+} originating in triplet and singlet n=2 states is found to increase strongly along the more peripheral lines of sight. The variation cannot be explained by excitation processes and we suggest that the increase arises only in part from radiative recombination and that charge transfer recombination, $D + Ar^{17+} \rightarrow D^+ + Ar^{16+}$, can be a major population mechanism. A fraction of the plasma working gas exists as neutral atoms with the highest concentration found towards the plasma edge owing to recycling from the wall of the vacuum vessel and the plasma limiters. In plasmas heated by neutral beam injection, charge transfer of highly ionized atoms can significantly affect the overall power balance. Excitation by charge transfer in the visible and ultraviolet has been seen in line emission during active H and D beam injection [5-8]. Here we demonstrate the effects of charge transfer recombination on line intensities of the x-ray spectrum of a high-Z element in quiescent, ohmically heated plasma.

The experiment was performed at the MIT Tokamak, Alcator C, using a Bragg crystal spectrometer. The instrument is a new, small spectrometer of von Hamos geometry previously described[9]. It was mounted with a pivot at the spectrometer entrance slit which allowed scanning of the radial dependence of the x-ray line emission with a spatial resolution of about 30 mm. The quartz crystal had a 2d lattice spacing of 6.687 Å using the $10\bar{1}1$ plane. The wavelength band width was about 2.1% so either of the entire H- or He-like spectra of argon could be recorded. For photon detection, we used an active delay-line proportional counter[10] together with commercially available 1-MHz electronics for time-to-digital conversion and storage of the resulting position histograms. The system was operated up to a data rate of about 0.5 MHz and a count rate of up to 200 kHz for the strongest emission line alone; a detailed account of the detection system will be given elsewhere. To achieve the desired count rate, the plasma was seeded with Ar, but the concentration was always small (<0.1%) having no significant effect on Z_{eff} nor did it perturb the plasma. The plasma conditions were kept constant during the radial scan with T_e = 1.45 keV and $N_e = 2.9 \times 10^{14}$ cm^{-3} at the centre for a plasma current of 450 kA and a toroidal field of 8 Tesla. The limiter had a radius of 16.5 cm.

The spatial scan measurement, spanning three decades in count rate, was made possible only by the combination of high plasma density, high through-put in the spectrometer and the argon seeding. Typical examples of spectra taken for three lines of sight, at d = -0.7, 8.3 and 11.3 cm off the plasma axis, are shown in Figs. 1a, 1b and 1c respectively; d is the shortest distance along the plasma minor radius from the plasma axis to the chord of observation. Spectra were recorded for each 20 ms of the discharge but those shown were integrated over 200 ms to increase the statistics; the plasma conditions were constant during this time period, with no obvious change in the He-like spectrum. In all, He-like spectra were recorded for ten lines of sight in the range d = -7.8 to 12.8 cm and H-like spectra in the range d = -4.5 to 7.1 cm. Line fits were made to eight readily distinguishable transitions for the He-like spectrum (shown in Fig. 1) from which we determined the following line intensity ratios: G = (x+y+z)/w, K = k/w and Q = q/w. The dependence of these ratios on T_e and the abundance ratio $N(Ar^{15+})/N(Ar^{16+})$ are the standard diagnostic probes. To this list we added S = (x+y)/w which is the triplet to singlet ratio for the 2P state. To obtain the intensity of the z line, we included a correction of -1.3 times the intensity of the line k to account for the estimated admixture of the unresolved line j^2. The measured line ratios are given in Fig.2 as functions of d.

The most conspicuous feature of the data in Fig.2 is the behaviour in the region d $\gtrsim$ 8 cm. Thus, S and G increase rapidly with d, followed by a tendency to level off at large d, and K and Q increase towards large d, followed by decrease at ≈ 8 cm. From the population by excitation processes, we expect a monotonic increase in the line ratios G, K and Q with decreasing T_e. In the range T_e = 1.4 to 0.2 keV, corresponding to the temperatures[11] at d=0 and 12.8 cm, G is indeed predicted[12] to increase, but only by 25%. The ratio K shows initially the expected increase with decreasing $T_e(d)$, but the trend is interrupted at $d \approx 10$ cm. Such effects suggest underlying changes in population mechanisms.

At the diminished temperatures, the excitation processes proceed more slowly, while the recombination rates increase. For instance, at $T_e = 350$ eV, which is reached at d=11.3 cm, the rate coefficient for excitation of Ar^{16+} is 5×10^{-15} cm^3s^{-1}, whereas that for recombination of Ar^{17+} is 3×10^{-12} cm^3s^{-1}. Accordingly, the latter process is the more effective one when the Ar^{17+} to Ar^{16+} abundance ratio exceeds 2×10^{-3}, which indeed seems to be the case, as discussed later. Some of the variations in line intensity ratios are thus qualitatively consistent with radiative recombination but also with charge transfer which must be considered. Charge transfer recombination has a rate coefficient of about 10^{-7} cm^3s^{-1}, depending weakly on T_e, so that at 350 eV it is comparable to radiative recombination, when the fractional neutral content N_o/N_e is 3×10^{-5}. Models of the neutral deuterium distribution[13] in the Alcator machine indicate $N_o/N_e \approx 10^{-4}$ at a minor radius of 12 cm, toroidally close to the limiters. In contrast to the principal lines (w,x,y and z), the satellites are not affected by radiative or charge transfer recombination. The observed decrease in the line ratios K and Q is thus consistent with the suggested change in population mechanism at $d \approx 8$ cm.

We suggest that the measured intensity variations can be explained by a combination of contributions from excitation processes and from radiative and charge transfer recombination. There is a narrow spatial region, between 8 and 12 cm from the plasma axis, in which the dominant contribution switches from excitation to recombination. The charge transfer process varies slowly with T_e and its effectiveness grows rapidly at large radii because of the increase in neutral particle density towards the plasma edge, and should become the major population mechanism beyond some critical distance from the plasma axis. Indeed there may occur three regions dominated in turn by the three processes.

The recombination of Ar^{17+} relative to excitation of Ar^{16+} depends on the abundance ratio $N(Ar^{17+})/N(Ar^{16+})$. If this ratio were given by the ionization and recombination of ions in coronal equilibrium, it should decrease rapidly with T_e and hence with radius to become less than 10^{-4} for d> 8 cm. Our measurements of the H- and He-like Ar spectra in the range d=0 to 8 cm suggest a rather moderate decrease with radius so that $N(Ar^{17+})/N(Ar^{16+})$ remains above 10^{-2} at 8 cm. We take this to mean that in regions of large radial N_e and T_e gradients, ion transport becomes a factor in the charge state balance which would, in effect, reduce the rate at which the $N(Ar^{17+})/N(Ar^{16+})$ ratio would otherwise decrease with radius. The finding that radiative or charge transfer recombination is needed to explain the data for d > 8 cm is thus consistent with the large $N(Ar^{17+})/N(Ar^{16+})$ ratios deduced from the relative intensities of H- and He-like spectra measured separately in this experiment. It can be noted that more direct information on the charge state balance will be provided by planned experiments with spectrometers of extended bandwidth ($\Delta\lambda/\lambda$ = 10%) for simultaneous measurements of the H- and He-like spectra.

In the region where either radiative or charge transfer recombination is dominant, the triplet to singlet ratio S should statistically be about three, as is observed at large radii. Differences, however, can occur in the 2^3S_1 and $2^3P_{1,2}$ level populations resulting from differences in the capture distributions of the two processes. In $Ar^{17+} + D \rightarrow Ar^{16+} + D^+$, captures occur preferentially into states of principal quantum numbers lying in the range n=7 to 11, and at the low ion velocities involved, into states of low angular mementum ℓ[14]. The high-lying states cascade down with the emission of dipole radiation, sometimes directly to the ground $1s^2\ ^1S_0$ state, but most decays pass through the excited n = 2 states. Unlike charge transfer, radiative recombination is not a resonance process, so that captures will be distributed over a range of states and orbitals starting from ℓ=0 and n=1. In order to investigate the effect of such capture differences, we have performed cascade calculations based on the assumption of capture into the s and p states of the orbital n=9 for charge transfer and statistically weighted captures into the s,p,d and f states of the orbitals $n < 4$ for radiative recombination. In this way, we obtain ratios of x/y = 0.65 and 0.75, and z/(x+y) = 2.5 and 1.2, for radiative recombination and charge transfer, respectively. These calculations suggest that the two population mechanisms would be distinguishable and the observed ratios of x/y = 0.72±.1 and z/(x+y) = 0.9±.2, in the region of d = 8 to 12 cm, would favor the charge transfer mechanism. It is worth noting that the n=2 to n=1 transitions studied are part of the Lyman series of transitions. The most direct manifestation of charge transfer would therefore be the spectrum of transitions spanning the range Δn=1 to 10, corresponding to a wavelength range λ=4.0 to 3.0 Å. The signature of charge transfer population would be found in the Δn intensity distribution, which would also reflect the capture rates to certain atomic states and the neutral density in the plasma. Such an experiment, therefore, might be done by developing a spectrometer with extra large Bragg angle span, i.e. $\Delta\Theta$ of about 11° in our case.

In conclusion, we have presented new measurements of the x-ray line emission of He-like Ar from both central and peripheral regions of a tokamak plasma. We find that the principal lines of the spectrum for peripheral plasma regions ($r/a > 0.5$) are dominated by population through radiative and charge transfer recombination because of two factors: the temperature in this region is low, so as to disfavour population by core excitation of n=2 Ar^{16+} states; the abundance ratio $N(Ar^{17+})/N(Ar^{16+})$ is found to be enhanced which is believed to come from radial ion transport. We argue that charge transfer will become the supreme population mode for the principal lines of the He-like spectrum beyond some critical radius because of the rapid increase of the neutral concentration N_o/N_e towards the plasma edge. Our spectra for $d > 10$ cm are consistent with dominant charge transfer population. The results illustrate that the technique is sufficiently efficient to record fractional neutral concentrations of 10^{-4} to 10^{-5} at T_e = 200 - 500 eV and we suggest that dedicated studies of higher Δn transitions should offer even greater sensitivity. The spectroscopy of He-like ions can thus be used for the diagnosis of neutrals in tokamak plasmas (from both passive and active sources) and it can also be of interest for atomic rate studies.

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Figure Captions

Fig.1 The He-like spectrum of argon recorded during 200 ms of single plasma discharges for three different lines of sight through the plasma centre (a), and through points of d = 8.3 (b) and 11.3 cm (c) off from the centre. The low data points in (a) are shown as a thick line. The abscissas give the actual counts recorded without correction for variations in the Ar concentration. Predicted wavelengths (Ref.2) are indicated relative to the resonance line (w). Key to the letter symbols (Ref.3):

w, $1s^2\ {}^1S_o-1s2p\,{}^1P_1$; x, $1s^2\ {}^1S_o-1s2p\,{}^3P_2$; y, $1s^2\ {}^1S_o-1s2p^3{}_1$;
q, $1s^22s\ {}^2S_{1/2}-1s(2s2p\,{}^1P)\,{}^2P_{3/2}$; r, $1s^22s\ {}^2S_{1/2}-1s(2s2p\,{}^1P)\,{}^2P_{1/2}$;
a, $1s^22p\ {}^2P_{3/2}-1s2p^2\ {}^2P_{3/2}$; k, $1s^22p\ {}^2P_{1/2}-1s2p^2\ {}^2D_{3/2}$;
z, $1s^2\ {}^1S_o-1s2s\ {}^3S_1$; j, $1s^22p\ {}^2P_{3/2}-1s2p^2\ {}^2D_{5/2}$.

Fig.2 Results on the line intensity ratios, S=(x+y)/w, G=(x+y+z)/w, K=k/w and Q=q/w for different lines of sight given by the distance from the plasma centre. The errors shown are statistical and the arrows show the position of the plasma limiters.

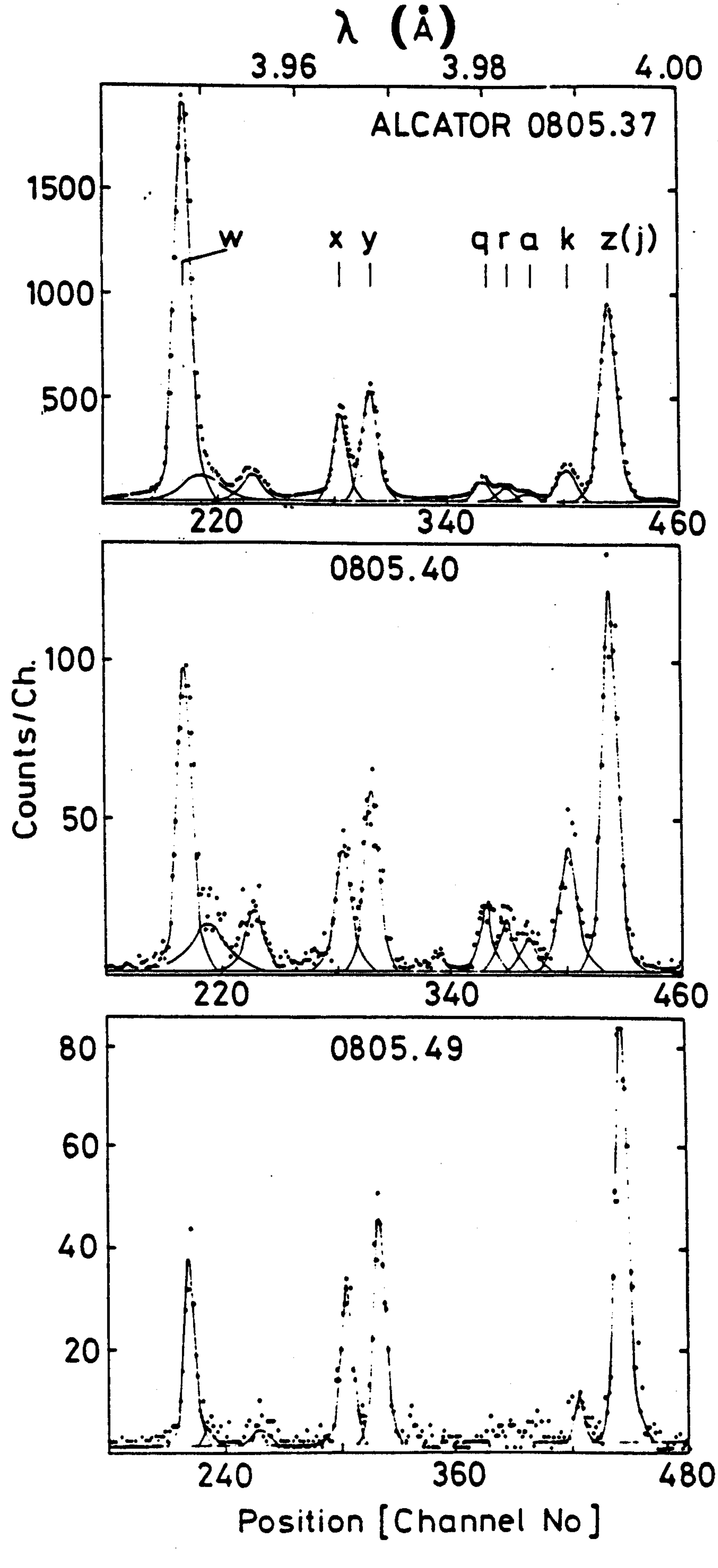
λ (Å)
3.96
3.98
4.00
ALCATOR 0805.37
1500
1000
500
w
x y
q r a k z(j)
220
340
460
0805.40
100
50
Counts/Ch.
220
340
460
0805.49
80
60
40
20
240
360
480
Position [Channel No]

FIGURE 1

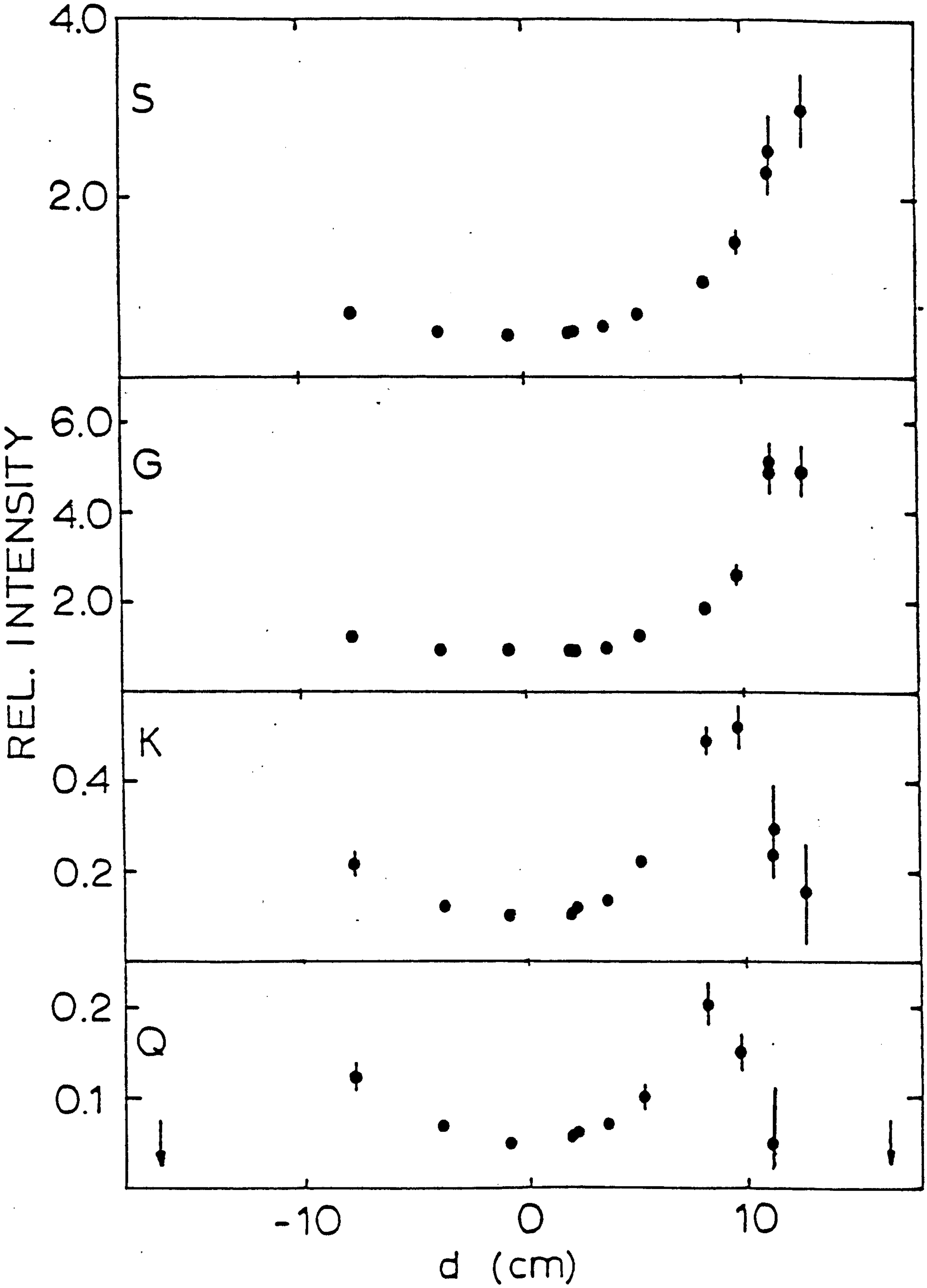

FIGURE 2