THE

PHYSICAL REVIEW

A journal of experimental and theoretical physics established by E. L. Nichols in 1893

SECOND SERIES, VOL. 131, No. 5 1 SEPTEMBER 1963

X-Ray Crystal Spectroscopy of a Theta-Pinch Plasma in the Region 15–25 Å*

G. A. SAWYER, A. J. BEARDEN,† I. HENINS, F. C. JAHODA, AND F. L. RIBE
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico
(Received 25 March 1963; revised manuscript received 20 May 1963)

A new synthetic crystal, potassium acid phthalate (KAP), has a spacing between crystal planes, $2d=26.6$ Å. The use of this crystal in a Bragg crystal spectrometer has permitted measurement of the Scylla I x-ray spectrum from 15 to 25 Å, a region inaccessible with the beryl crystal previously used. The principal features of the observed spectrum in this region are the lines of O VII and O VIII arising from oxygen contamination of the discharge by material from the ceramic discharge tube. Six lines of the resonance series of O VII are observed, including both $1s^2\,{}^1S_0-1s2p\,{}^1P_1$ and $1s^2\,{}^1S_0-1s2p\,{}^3P_1$. The first members of the Lyman series of O VIII are also observed. Measurements of Doppler widths of the lines of O VII and O VIII yield an oxygen-ion Doppler temperature of 9.3 ± 2.8 keV. These measurements, when combined with those previously made on other ion species, show that the ions of the plasma are not in collisional equilibrium.

I. INTRODUCTION

SCYLLA I is a theta-pinch device without bias magnetic field or preionization having a single turn coil 7.5 cm in diameter and 10.6 cm long.[1] The magnetic field rises to 52 kG in 1.25 μsec and produces a deuterium plasma with an electron density of $5\times10^{16}/\text{cm}^3$ which emits neutrons and soft x rays for about 0.8 μsec near the maximum of the second half cycle of the magnetic field. Measurements have indicated a deuterium ion "Doppler" temperature of 1.3 keV, and an electron temperature of 350 eV.[2,3] In an earlier determination of the electron temperature by x-ray absorption techniques, it was found that the intensity of the continuum was too large by two orders of magnitude to be accounted for by pure deuterium bremsstrahlung.[4] The explanation was found to be that the x-ray continuum emission occurs predominantly as recombination (free-bound) radiation from the capture of free electrons into bound levels of highly stripped impurity ions. The single-crystal x-ray spectrometer which was built to study the line and continuum radiation from the Scylla I plasma has been described, and the results obtained with a beryl diffracting crystal for $\lambda<15$ Å have already been given.[3,5] These results have now been extended by means of a potassium acid phthalate (KAP) crystal[6] capable of diffracting wavelengths as great as 26 Å. The earlier results are briefly reviewed here because of their direct connection with the present work.

II. INSTRUMENTATION

According to Bragg's law, wavelengths greater than $2d$, where d is the distance between reflecting planes of the crystal, are not diffracted. At the plasma electron temperature produced in Scylla I (~350 eV), many interesting features of the spectrum appear between 5 and 25 Å. The 5 Å lower limit is the practical cutoff of the bremsstrahlung and recombination spectrum, while the hydrogen-like Lyman series of O VIII, an important contaminant ion in the deuterium discharge, falls between 14.2 and 19.0 Å. The helium-like resonance spectrum of O VII falls between 16.8 and 21.6 Å. Beryl was used for diffraction in the lower wavelength portion of this x-ray region up to 15.5 Å. For the longer wave-

* Work performed under the auspices of the U. S. Atomic Energy Commission.
† Permanent address. Department of Physics, Cornell University, Ithaca, New York.
[1] K. Boyer, W. C. Elmore, E. M. Little, W. E. Quinn, and J. L. Tuck, Phys. Rev. **119**, 831 (1960).
[2] D. E. Nagle, W. E. Quinn, F. L. Ribe, and W. B. Riesenfeld, Phys. Rev. **119**, 857 (1960).
[3] A. J. Bearden, F. L. Ribe, G. A. Sawyer, and T. F. Stratton, Phys. Rev. Letters **6**, 257 (1961).
[4] F. C. Jahoda, E. M. Little, W. E. Quinn, G. A. Sawyer, and T. F. Stratton, Phys. Rev. **119**, 843 (1960).
[5] F. C. Jahoda, F. L. Ribe, G. A. Sawyer, and T. F. Stratton, in *Proceedings of the Fifth International Conference on Ionization Phenomena in Gases, Munich* (North-Holland Publishing Company, Amsterdam, 1962), Vol. II, p. 1987; G. A. Sawyer, F. C. Jahoda, F. L. Ribe, and T. F. Stratton, J. Quant. Spectr. Radiative Transfer **2**, 467 (1962).
[6] The KAP crystal was obtained from Isomet Corporation, Palisades Park, New Jersey.

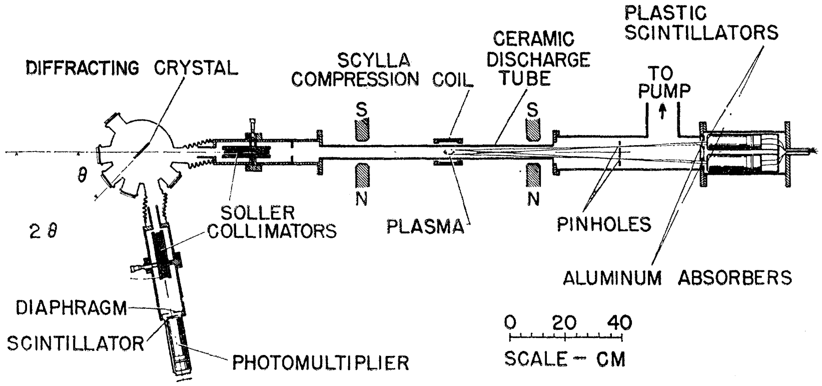

FIG. 1. Diagram of the apparatus.

length portion of the spectrum, KAP has proved to be very suitable. The measurements with our spectrometer of the diffraction angle of O VIII L_α, whose wavelength is accurately known, indicate a $2d$ lattice spacing for KAP of 26.60±0.01 Å. Measurements by A. J. Bearden at Johns Hopkins University with a double-crystal spectrometer, using CuK_α (1.54 Å) and AgL_α (4.14 Å) radiation in high order reflections, gave $2d=26.63$ Å. The difference in the two results is thought to be due to stacking faults in the lattice which affect different orders differently. Quantitative measurements of the KAP crystal reflectivity have not been made.

A single-crystal spectrometer was chosen because of its simple construction, together with the possibility of changing the wavelength resolution by means of interchangeable slit assemblies to meet the separate demands of the continuum and of the line profile studies. Soller slits consisting of stacked vanes and spacers were made as large as necessary to cover the usable source width. The angular definition, and, hence, the wavelength resolution, is determined by the vane spacing and length provided that the slit angular acceptance is greater than the natural diffraction width of the crystal. The slit acceptance was 10 min of arc for studies of the continua and for line identification, with both beryl and KAP crystals, corresponding to a resolution of 0.03 at 10 Å for beryl and 0.05 at 19 Å for KAP. For study of the details of line profiles, Soller slits with an acceptance angle of 2.5 min of arc were used. There is little value in using narrower Soller slits because the diffraction width of the crystal becomes the dominant factor in the resolution at the relatively long wavelengths studied in this work. Although the diffraction width of the beryl crystal is only 20 sec of arc at 1.5 Å, it increases to 5 min of arc at 13 Å. The diffraction width of KAP, to be discussed below, is also several min of arc at the wavelengths studied.

The mechanical design of the spectrometer is based on precision (±6 sec of arc) rotary index tables which allow the crystal and the detector to be set at the proper angles for Bragg reflection, θ and 2θ. Flexible bellows allow a rotation of 8° in θ without breaking the vacuum. The crystal table is positioned by three balls and grooves for easy removal and accurate replacement, and the axes of the Soller slits are adjustable by micrometer screws. Figure 1 shows the spectrograph (at the left) and the Scylla I experiment schematically.

In the previous measurements of the Scylla plasma radiation with the beryl crystal, the x rays were detected by a plastic scintillator. However, for the present work with ultra-soft x rays in the 15–25 Å region, a gas flow proportional counter has also been used. The counter operates at atmospheric pressure with pure methane. Methane was chosen, rather than the conventional argon-methane mixture, because its lower stopping power permits the soft x rays to penetrate more deeply into the counter. The counter window is a thin plastic film of Zapon lacquer produced by spreading a Zapon solution on a water surface and then transferring several layers of the dried film to a fine wire mesh which supports it over the counter window. The Zapon film transmission is 60% for 19-Å x rays. Pulses of single photons are not seen, but rather a "pile-up" pulse of many photon pulses is recorded during the 0.8-μsec burst of Scylla x rays. The proportional counter has been checked with characteristic x rays from a conventional x-ray tube and shows nearly the expected resolution based on the statistics of the number of ion pairs produced in the counter.

In order to compensate for the variability of the Scylla discharge, the total emission spectrum is monitored by means of two scintillators (shown at the right of Fig. 1) which detect radiation through two pinholes and Al absorbers of different thicknesses. The monitor signals are used to normalize the spectrometer signal. The ratio of the two monitor signals also gives a measure of the mean photon energy.[7]

III. LINE SPECTRA

The line spectrum observed with the beryl crystal for a pure deuterium gas filling (90 μHg) is shown in Fig. 2. It consists of lines of the two-electron, wall-impurity ions Na X, Mg XI, Al XII, and Si XIII and also the higher

[7] T. F. Stratton, *Temperature, Its Measurement and Control in Science and Industry* (Reinhold Publishing Corporation, New York, 1955), Vol. 3, p. 663.

members of the Lyman series from one-electron O VIII. Since the series limit of O VII is at 16.8 Å, its resonance spectrum, as well as the first two lines of the O VIII Lyman series, lie outside the range of the beryl crystal. The arrows indicate the positions of the lines, as determined by extrapolation of the He I isoelectronic sequence.[8] The Mg XI and Al XII lines have been observed in spark spectra by Flemberg.[9] All of the identified impurities are constituents of the ceramic discharge tube, which is 96% vitrified Al_2O_3 and contains 4% of other oxides including Na, Mg, and Si. In Fig. 2 there are indicated, in addition to the singlet lines of the principal series, also the triplet-singlet intercombination lines which are expected to be comparably strong in these high Z ions, as discussed by Edlén.[8]

The spectra obtained with the KAP crystal between 15 and 25 Å are shown in Fig. 3. For the particular run shown, 10% O_2 was added to the discharge in order to make the lines brighter, although oxygen lines are observed even with no impurity added to the discharge. The addition of 10% impurity is known to reduce the electron temperature of Scylla to 295 eV.[3] (The fraction of oxygen added was given incorrectly as 6% in Ref. 3.) The first three lines of the Lyman series of O VIII are seen, as well as the complete resonance series of O VII, including the intercombination line $1s^2\,1S_0-1s2p\,^3P_1$. The time histories of the O VII and O VIII lines were measured using a plastic scintillator detector. The O VII lines consistently peak 0.1 μsec before the peak of magnetic field and the more highly ionized O VIII lines peak 0.15 μsec after the peak of magnetic field. Lines of N VI and N VII which would occur in this region of the spectrum are not seen, indicating that there is negligible air contamination of the discharge. Table I gives the wavelengths of the principal lines observed with the KAP crystal.

Measurements of the continuum spectrum, such as were made with the beryl crystal,[3] could not be made at sufficiently many wavelengths in the 15–25 Å region to determine a continuum slope. Because of the relatively high density of spectral lines, the line wings merged, obscuring the continuum level. Figure 4, which is a replot of Fig. 3 on a logarithmic intensity scale, illustrates this effect.

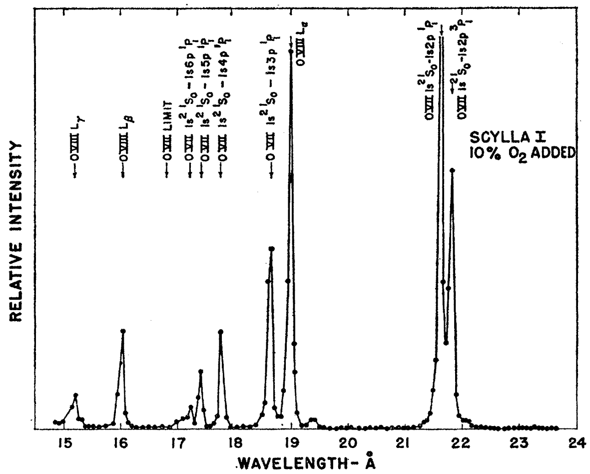

FIG. 3. Line spectrum observed with the KAP crystal. The arrows indicating the identified lines of wall impurities are at the predicted wavelengths of the lines.

TABLE I. Wavelengths of principal lines observed, in Å.

		Observed	Predicted[a]
Hydrogen isoelectronic sequence			
O VIII L_α	$1s\,^2S_{1/2}-2p\,^2P_{3/2,1/2}$	18.97	18.971
L_β	$1s\,^2S_{1/2}-3p\,^2P_{3/2,1/2}$	16.01	16.007
L_γ	$1s\,^2S_{2/1}-4p\,^2P_{3/2,1/2}$	15.18	15.177
Helium isoelectronic sequence			
O VII	$1s^2\,^1S_0-1s2p\,^1P_1$	21.61	21.60
	$1s^2\,^1S_0-1s2p\,^3P_1$	21.81	21.80
	$1s^2\,^1S_0-1s3p\,^1P_1$	18.64	18.63
	$1s^2\,^1S_0-1s4p\,^1P_1$	17.77	17.77
	$1s^2\,^1S_0-1s5p\,^1P_1$	17.42	17.40
	$1s^2\,^1S_0-1s6p\,^1P_1$	17.21	17.20

[a] See in *Atomic Energy Levels*, edited by Charlotte E. Moore, National Bureau of Standards Circular 467 (U. S. Government Printing Office, 1949), Vol. I, p. 59.

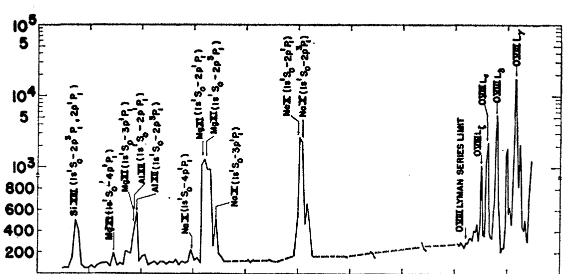

FIG. 2. Line spectrum observed with the beryl crystal. The arrows indicating the identified lines of wall impurities are at the predicted wavelengths of the lines. Intensity scale is relative.

IV. LINE BROADENING

As a preliminary to line broadening measurements, the instrumental resolution was measured by a detector arm scan of the pattern produced by the 2.5-min entrance Soller slit and stationary KAP crystal combined. Scans were made with a conventional 0.010-in. single slit at the proportional counter. Figure 5 shows typical scans taken with the Scylla O VIII L_α and O VII $1s^2\,^1S_0-1s3p\,^1P_1$ radiation as sources. This curve shows an instrumental width of 6 min of arc. A correction is necessary, however, because the detector and scanning slit rotate around the crystal axis, while that part of the angular spread of the instrument due to the entrance Soller slit is centered at the Soller slit. When the proper correction is made for this effect, the instru-

[8] B. Edlén, Arkiv Fysik 4, 441 (1951).
[9] H. Flemberg, Ark. Nat. Astr. O. Fys. 28A, No. 18 (1942).

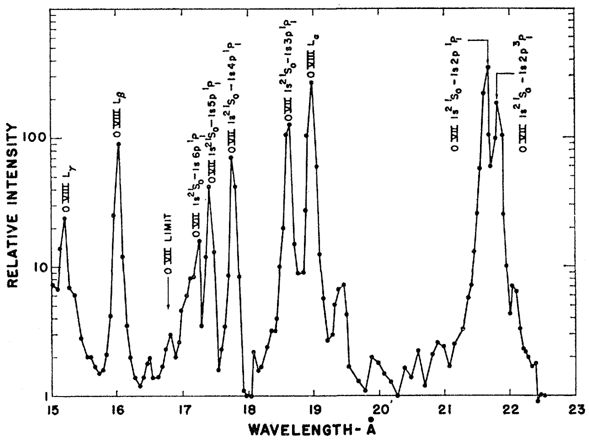

FIG. 4. The line spectrum of Fig. 3 replotted with a logarithmic intensity scale. The merging of spectral lines which obscures the continuum is illustrated.

mental width is reduced to 5 min. In using this method of determining instrumental resolution, it is only necessary that the entrance slits be filled with radiation and that the Bragg condition be fulfilled. Although O VII and O VIII line radiation was used for the measurement in order to get sufficient intensity, the lines were relatively broad compared to the instrumental resolution, and, thus, approximated a continuum source sufficiently

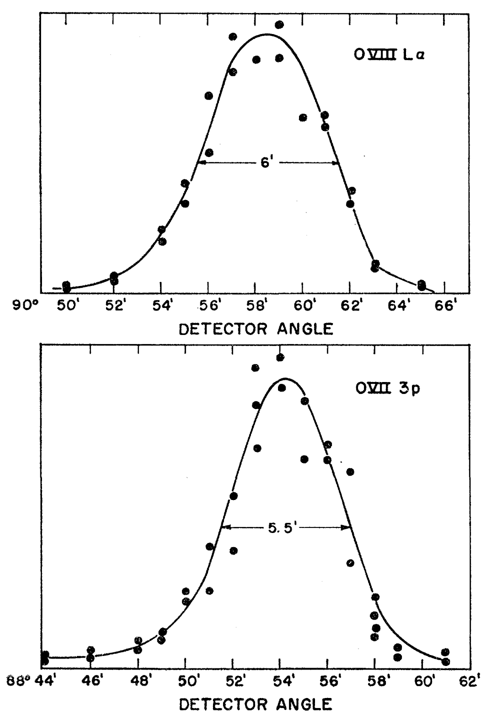

FIG. 5. Scan with a single detector slit to determine the spectrometer resolution. The measured intensity profile includes width due to both the entrance Soller slit and the KAP crystal diffraction pattern.

well for this purpose. Since the Soller slits used have only 2.5 min angular acceptance, the crystal must have a diffraction width of several min of arc.

After measuring the instrumental resolution, the widths of the O VIII L_α (18.97 Å) and O VII $1s^2\,{}^1S_0-1s3p\;{}^1P_1$ (18.63 Å) lines were measured with results shown in Fig. 6. For these measurements the slit on the detector arm was removed and the lines scanned step-by-step with crystal and detector in the θ-2θ Bragg relation. The particular O VII and O VIII lines chosen are close together in wavelength, and thus the instrumental resolution is the same for both. The two line scans are both about 10 min wide. If it is assumed that the instrument function is a dispersion shape of 5 min width and that the line shape is Gaussian, the actual line-

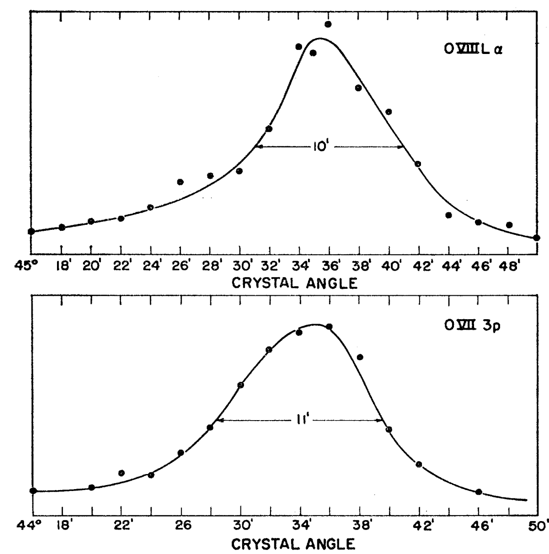

FIG. 6. Observed line profiles of O VIII L_α and O VII $1s^2\,{}^1S_0-1s3p\;{}^1P_1$. The reduction of the observed width to a Doppler temperature is explained in the text.

widths then reduce to 7 min. The widths of several other members of the O VII and O VIII series were examined and found to be of equivalent width.

The observed shape and width of the characteristic x-ray lines, Ni L_α, Zn L_α, and Cu L_α made with the beryl crystal were fitted best by a dispersion function. Detailed measurements of the instrumental function have not been made with the KAP crystal and it is not certain that the instrument has a dispersion shape. However, the dispersion shape leads to smaller values of true linewidth and temperature than any other reasonable instrumental function, e.g., a Gaussian shape. The analysis which follows shows that even this lower limit of apparent temperature is remarkably large.

Since the spectral lines observed are all resonance lines, depression of the line peaks by self-absorption

TABLE II. Doppler temperature of deuterons and impurity ions.

Spectrum	Ion	Spectral line	Z	M	Z^2/M	Doppler T (keV)	Doppler T scaled to B_{max}	Instrumental width correction in $\Delta\lambda$
Nuclear	D II	($d-d$ Protons)	1	2	0.50	1.3±0.2	1.3±0.2	nil
uv	C V	$1s2s\,^3S_1-1s2p\,^3P_2$	4	12	1.33	4.3±0.9	6.7±1.3	nil
X-ray	O VII	$1s^2\,^1S_0-1s3p\,^1P_1$	6	16	2.25	9.3±2.8	9.3±2.8	30%
X-ray	O VIII	Lyman α	7	16	3.06	9.3±2.8	9.3±2.8	30%
X-ray	Ne IX	$1s^2\,^1S_0-1s2p\,^1P_1$	8	20	3.20	9.9±3.0	9.9±3.0	30%

must be considered as a plausible but physically uninteresting cause for the large line breadths.

Self-absorption can be characterized in terms of a parameter p such that the intensity distribution $I(\nu)$ over frequency of light originating in a uniformly excited source is given by[10]

$$I(\nu)=I_0(P(\nu_0)/2p)[1-\exp(-2pP(\nu-\nu_0)/P(\nu_0))], \quad (3)$$

where

$$p=(h\nu_0/c)BP(\nu_0)\frac{1}{2}\int_{-\infty}^{\infty}n_a(x)\,dx \quad (4)$$

and

$$B=(g_u/g_l)(c^3/8\pi h\nu_0^3)A\,. \quad (5)$$

Here B and A are the Einstein absorption and emission coefficients, respectively, ν_0 is the line-center frequency, and g_u and g_l are the statistical weights of the upper and lower levels.

For a Doppler distribution of ions of mass M,

$$P(\nu)=(\pi\delta^2)^{-1/2}\exp[-(\nu-\nu_0)^2/\delta^2]\,, \quad (6)$$

$$\delta^2=2kT\nu_0^2/Mc^2\,. \quad (7)$$

For the O VIII Lyman α line,

$$A=Z^4A_H\approx 1.9\times 10^{12}\text{ sec}^{-1},$$
$$\nu_0\approx 1.5\times 10^{17}\text{ sec}^{-1},$$
$$g_u/g_l=4\,.$$

The region of hot compressed plasma in Scylla I is 2 cm long according to neutron collimation measurements.[1] However, measurements of plasma diameter by both x-ray and neutron measurements agree and it seems likely that the effective length of the plasma for x rays is about 2 cm. The 10% oxygen impurity amounts to an oxygen ion density of 6×10^{15} cm^{-3}. However, not all of the oxygen is in the O VIII ground state, some being in other states of ionization. With the upper limit $\frac{1}{2}\int n_a dx=6\times 10^{15}$ cm^{-2}, and assuming $(kT_0)=10$ keV, one obtains $p=0.2$.

Inserting this value of p in Eq. (3) one can calculate that taking the observed linewidth without correction for self-absorption gives a temperature value 15% too high. Conversely, if the true temperature of the oxygen ion were $kT_0=1$ keV (equal to the deuterium temperature), then $p\approx 0.6$ and the additional broadening due to self-absorption would yield a temperature of only 2.6 keV, rather than the observed value of 10 keV. The data, thus, do not allow equality of oxygen and deuterium temperatures.

O VIII L_α has the largest expected self-absorption among the lines measured. It is shown above that the parameter p is directly proportional to the A value and the statistical weight of the upper level and inversely proportional to the third power of frequency. Thus, for the Lyman γ line, for instance, p is a factor 18 less than for Lyman α. The experimentally observed temperature, however, is the same for the Lyman α and γ lines within the uncertainty of 30%. A 15% temperature error for Lyman α ($p=0.2$) is, therefore, not detectable, whereas an appreciably larger value of p for Lyman α would give different temperatures for the α and γ lines. An additional experimental proof is that the ratio of peak intensities of L_α to L_γ was observed with 10% air impurity instead of the usual 10% O_2. The intensity ratio was the same in the two cases although the O_2 concentration differed by a factor five. Thus, from the approximate equality of the widths of Lyman α and γ, and the constancy of their intensity ratio versus O_2 concentration, it can again be concluded that self-absorption can be neglected in the analysis that follows.

Since line broadening is expected to be due entirely to the Doppler effect,[5] the line width can be converted to an apparent ion temperature, in this case 9.3±2.8 keV for both O VII and O VIII ions.

The width of Ne IX $1s^2\,^1S_0-1s2p\,^1P_1$ (13.44 Å) has been rechecked with the beryl crystal and found to be the same as measured previously.[5] A small correction was made to the instrumental width however, resulting in a best value for the neon ion temperature of 9.9±3 keV.

V. DEPENDENCE OF DOPPLER TEMPERATURES ON IONIC SPECIES

The present x-ray data on the Doppler broadening of O VII, O VIII, and Ne IX can be combined with earlier broadening results to make an analysis of the Scylla I plasma at maximum magnetic compression. The results are summarized in Table II. In the first row is given the Doppler temperature of the deuterons, obtained by measuring the broadening of the 3-MeV $d-d$ proton spectrum as described in detail in Ref. 2. The second

[10] R. D. Cowan and G. H. Dieke, Rev. Mod. Phys. **20**, 418 (1948).

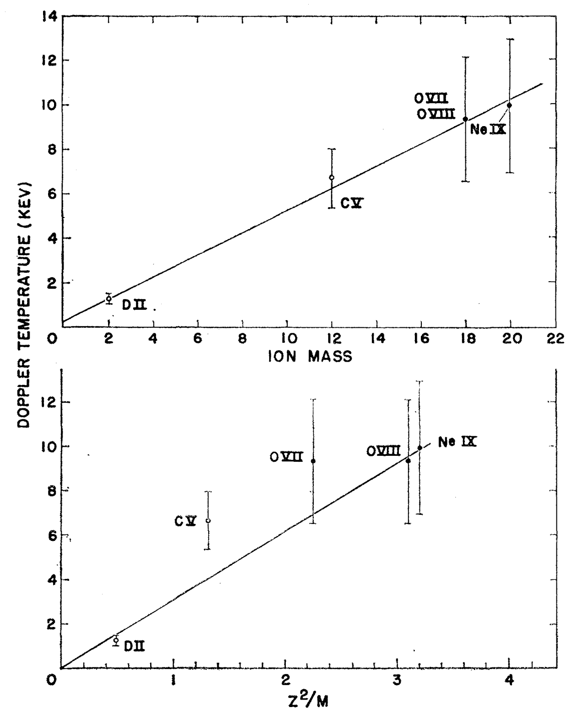

FIG. 7. Variation of measured Doppler temperatures of various ionic constituents of the Scylla I plasma with M and Z^2/M. Here M is the ion mass and Z is the charge.

row summarizes the data obtained from measurements of the 2271-Å C v line which were made in connection with Zeeman measurements of the Scylla I magnetic field.[11] In this case the C v light has it maximum before peak magnetic compression and T_D has been scaled linearly to $B_{\max}$. The last three rows of Table II give the results of the present Doppler measurements.

In experiments on a Stellarator[12] it has been shown that T_D for various trace impurity ions exhibits an approximately linear dependence on Z^2/M, where Z is the ionic charge and M is the mass. Such a variation of T_D arises if the plasma ions are being energized by fluctuating electric fields in the plasma. Another possibility is a linear variation with M which would imply a common velocity component for all ionic species.[13]

Figure 7 shows T_D plotted as functions both of ion mass and Z^2/M. The function T_D appears to be more nearly linear in M than in Z^2/M. Assuming the M dependence, the best linear fit to the data indicates a slope corresponding to a common ion velocity of about 3×10^7 cm/sec. The intercept on the T_D axis is interpreted as a true temperature common to all ion species. The uncertainty is large and the intercept could have any value between 0 and 500 eV. Whether the common velocity is truly random and thus represents a different kinetic temperature for each ion, or is a flow along the axial direction (both toward and away from the spectrometer) is not determined by these data.

VI. DISCUSSION

In considering various interpretations of the broadening data, it is useful to state the results of previous experiments on Scylla I. For the case of no added impurity ($\sim2\%$ oxygen impurity is present from the wall)[4] the following parameters are independently measured[1–4]: $n_e=5\times10^{16}$ cm^{-3} (charge neutrality then implies $n_d=4.3\times10^{16}$ cm^{-3}; $n_0=8.6\times10^{14}$ cm^{-3}), $T_d=1.3$ keV, $T_e=0.350$ keV, plasma volume ≈3 cm^3, neutron yield $Y_n=5\times10^6$. Here T is temperature, n is density, and the subscripts d, e, and 0 refer to deuterons, electrons, and oxygen ions, respectively. Probe[14] and Zeeman[11] measurements show that

$$\beta=\text{total particle pressure}/\text{external magnetic pressure}>0.79. \quad (1)$$

These data are self-consistent, giving pressure balance:

$$(B^2/8\pi)=12\,\text{J/cm}^3\approx n_ekT_e+n_dkT_d+n_0kT_0 \quad (2)$$

at the measured value of compression magnetic field $=52$ kG. The neutron yield Y_n is also consistent with deuteron Doppler temperature, density, and plasma volume.

When the present line broadening results are included it is more difficult to make a self-consistent explanation of the data.

It has been suggested[15] that mass motion out of the ends of the plasma in the axial direction can produce all of the observed variation of Doppler broadening with ion mass. In this case the impurity ions may have the same temperature as the deuterons plus an axial velocity which is the same for all ions. Such a common axial velocity would explain the mass dependence of effective ion temperature observed by Doppler broadening. However, the common temperature derived from the intercept of the curve of Fig. 7 with the T_D axis is too low to account for the pressure balance of Eq. (2) and the neutron yield. For self-consistency it is necessary to assume more than 1 keV of ion temperature. There is, therefore, a discrepancy unless it is assumed that transverse ion energy is greater than axial ion energy. But the energy equilibration times t_E with the deuterons of the plasma for the ions Ne IX, O VIII, O VII, and C V, which are calculated on the basis of Coulomb collisions,[16] are, respectively, 0.3, 0.3, 0.4, and 0.5 μsec. The time t_i

[11] F. C. Jahoda, F. L. Ribe, and G. A. Sawyer, Phys. Rev. **131**, 24 (1963). A profile of the C v $1s2s\,^3S_1-1s2p\,^3P_2$ line is given there.
[12] J. G. Hirschberg and R. W. Palladino, Phys. Fluids, **5**, 48 (1962).
[13] R. Wilson, J. Quant. Spectr. Radiative Transfer **2**, 477 (1962).
[14] F. C. Jahoda and G. A. Sawyer, Phys. Fluids (to be published).
[15] R. S. Pease (private communication).
[16] L. Spitzer, *Physics of Ionized Gases* (Interscience Publishers, Inc., New York, 1956).

during which the ionic species exist is 0.8 μsec. Hence, the ratio $t_E/t_i \approx 0.4$ would indicate that collisional equilibrium should occur. It may be, however, that the calculated values of t_E are not sufficiently reliable to require that collisional equilibrium must occur. If the restriction imposed by the calculated t_E is dropped, another possibility can be equally well considered. This is the assumption that the plasma ions actually have the indicated different temperatures, but the different ion species are not in collisional equilibrium with each other. In this case, the observed variation of ion temperatures at peak magnetic compression could merely be an end result, after adiabatic compression, of an earlier nonequilibrium state produced during the initial dynamic or shock state of the discharge. The temperatures can then be understood simply in terms of Maxwellian distributions of ions and electrons.

However, if the added oxygen impurity has either a true temperature or a transverse temperature of $\sim$10 keV, the pressure balance of Eq. (2) can no longer be maintained unless the product n_dT_d is lowered. When 10% oxygen is added, nkT of oxygen is nearly equal to that of deuterium,[17] requiring that n_dT_d be lowered a factor of two. It must then be assumed that n_d decreases and that T_d remains relatively constant because a decrease in T_d by a factor of two would decrease the neutron yield a factor of 50,[18] whereas the observed decrease in neutron yield is only a factor of four. Such a decrease of n could come about either by leakage of plasma or an increase of the plasma volume at peak compression. The latter possibility is ruled out because if the temperature remains constant the final plasma volume must also remain constant, since the final temperature arises largely from adiabatic compression. Thus, when impurity is added the data suggest a loss of plasma from the compressed region in order to maintain the pressure balance.

[17] We are indebted to A. C. Kolb for pointing out this difficulty.
[18] J. L. Tuck, Nucl. Fusion, 1, 201 (1961).

In the discussion above, two alternatives have been presented. In the first it is assumed that the ions stream out the ends of the discharge with a velocity of 3×10^7 cm/sec but that their random energy in the axial direction is only a few hundred eV. Their transverse energy, however, must be about 1 keV. For the other alternative, the different ion species are assumed to have different true temperatures, i.e., axial and transverse energy are the same within each ion species. Both of these alternatives require that the time t_E for the ions to reach collisional equilibrium be longer than that calculated. Since only axial ion energies are measured in Scylla, the choice between these alternatives cannot be made. Technical difficulties involved in making the necessary transverse measurements in Scylla have not yet been solved.

An altogether different possibility is that equilibrium would be reached in the time available but that an instability provides a mechanism for keeping the ions out of equilibrium. A gross hydromagnetic instability is ruled out by the stable appearance of the plasma as seen in streak photographs.[19] A smaller scale instability such as turbulence or plasma waves is more likely.

VII. CONCLUSION

Doppler broadening measurements on Scylla I of the impurity spectral lines of one and two-electron ions in the soft x-ray region, when combined with previous results, indicate an approximate mass dependence of the effective ion temperature. The origin of this dependence is not understood, and the observed Scylla parameters cannot be fitted into a single self-consistent picture. The measurements of impurity ion energies, as well as the measurement of deuteron energy, were made in the axial direction. A measurement of the transverse ion energies, not yet possible, is necessary to choose between the alternative interpretations given.

[19] E. M. Little, W. E. Quinn, F. L. Ribe, and G. A. Sawyer, Suppl. Nucl. Fusion, 1962 Part 2, 497 (1962).