one pair is incorrect. This illustrates a further point, that unless a very well controlled statistical experiment is performed exact statistical analysis will be of no use. In the present case the lack of precisely stated predictions and the non-random nature of the radio surveys would make exact analysis extremely difficult.

Because of these difficulties we think that it is more useful to compare tests made for substantiating a prediction with other tests reflecting the statistical properties of the real test as closely as possible. Such tests were made by Solheim[1], but the apparently obvious conclusion—that comparison tests showed deviations as large as those claimed for the real test—was not drawn.

Table 1. TEST ON EXCESS OF SOURCES IN OPPOSITE DIRECTIONS FOR THE RADIO SOURCES IN THE PARKES CATALOGUE

Distance from opposite direction θ (min of arc)	Number of sources found within θ	Average number within θ for comparison tests	Excess	Transverse velocity v_{tr} (km/s)
3	0	0·6	-1 ± 1	400
6	1	3·6	-3 ± 2	800
12	5	9·0	-4 ± 3	1,600
18	13	18·9	-6 ± 4	2,400
24	30	33·1	-3 ± 6	3,200
30	46	48	-2 ± 7	4,000
36	59	72	-13 ± 8	4,800
42	89	94	-5 ± 10	5,600
48	124	116	$+8\pm11$	6,400
54	153	143	$+10\pm12$	7,200
60	185	174	$+11\pm13$	8,000

In Table 1 we present the results of an analysis of the 1,237 sources in the $+20°$ to $-20°$ zones of the Parkes Catalogue of radio sources[6]. Column 1 gives the radius of the area searched in the opposite direction of each radio source. Column 2 gives the number of pairs found. For direct testing of this number, a series of five comparisons was made in areas displaced by constant amounts (in right ascension) from the opposite directions. The average from these tests is shown in column 3. Column 4 gives the excess which could be caused by near and ghost images and the r.m.s. error in this number assuming Poisson statistics to be applicable. In column 5 we give the value of the transverse velocity needed for the excess sources to lie in the angular separation of the corresponding row. The average radio source position errors are $<1·0$ min of arc so they do not significantly increase the angular separation. For velocities up to 8,000 km/s no statistically significant excess of pairs in opposite directions has been found. Furthermore, because we expect only 1 per cent of the sources to have pairs of images, any $v_{tr}>$ 4,000 km/s will make it impossible to detect this excess.

From these data, and the data from the 4*C* catalogue presented by Solheim, we can draw the following obvious conclusions. (*a*) If the universe is Lemaître type then either the inhomogeneities, such as galaxies, were formed at an early epoch, or sources near the antipode have random velocities in excess of 6,000 km/s. (*b*) The universe is not Lemaître type.

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1 Petrosian, V., Salpeter, E. E., and Szekeres, P., *Astrophys. J.*, **147**, 1222 (1967).
2 Shlovskii, J., *Astrophys. J. Lett.*, **150**, L1 (1967).
3 Khardaslev, N., *Astrophys. J. Lett.*, **150**, L135 (1967).
4 Solheim, J.-E., *Nature*, **217**, 41 (1968).
5 Solheim, J.-E., *Nature*, **219**, 45 (1968).
6 Day, G. A., Shimmins, A. J., Ekers, R. D., and Cole, D. J., *Austral. J. Phys.*, **19**, 35 (1966).
7 Shimmins, A. J., Day, G. A., Ekers, R. D., and Cole, D. J., *Austral. J. Phys.*, **19**, 837 (1966).
8 Petrosian, V., *Astrophys. J.*, **155**, 1029 (1969).
9 Rees, M. J., and Setti, G., *Nature*, **219**, 127 (1968).
10 Schmidt, M., *Astrophys. J.*, **146**, 7 (1966).
11 Petrosian, V., and Salpeter, E. E., *Astrophys. J.*, **151**, 411 (1968).
12 Gower, J. F. R., *Mon. Not. Roy. Astron. Soc.*, **133**, 151 (1966).
13 Ceccarelli, M., and Grueff, G., *Nuovo Cimento*, **48**, 425 (1967).
14 Piper, D. E., *Nature*, **219**, 846 (1968).

Measurement of the Electron Temperature by Thomson Scattering in Tokamak T3

by

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Electron temperatures of 100 eV up to 1 keV and densities in the range 1–3×10^{13} cm^{-3} have been measured by Thomson scattering on Tokamak T3. These results agree with those obtained by other techniques where direct comparison has been possible.

MEASUREMENTS have been made of the electron temperature and density of the plasma in the toroidal discharge apparatus Tokamak T3 (ref. 1) at the Kurchatov Institute, using Thomson scattering by the plasma electrons of 6943 Å light from a Q-spoiled ruby laser. Important features of recent measurements on Tokamak T3 have been the high total energy of the plasma[2], the long confinement time[2] and the evidence for thermonuclear reactions in the confined plasma column[3]. In the T3 torus (which has a major diameter of 2 m and a minor diameter of 0·4 m) the electron energy has previously been obtained only for a short (20 ms) current pulse using the diamagnetic technique[4]. In the Thomson scattering experiment on T3 the discharge period is 70 ms, with a flat topped current pulse; measurements are reported for different values of the longitudinal stabilizing field H_z up to 25 kOe and for peak discharge currents $\hat{I}_z$ up to 85 kA. In a smaller, related apparatus, TM3, the electron temperature has been obtained from the electromagnetic emission spectrum in the energy range 2 to 10 keV (ref. 5). The experiment described here gives the velocity distribution of the electrons as a function of time and position throughout the discharge. Temperatures of up to about 1 keV have been measured.

Experimental Technique

The technique for determining the electron temperature in a plasma from the Thomson scattering of the beam from a Q-spoiled ruby laser is now well established, although our experiment represents an extension of this method to densities lower than those used previously[6] on hot plasmas.

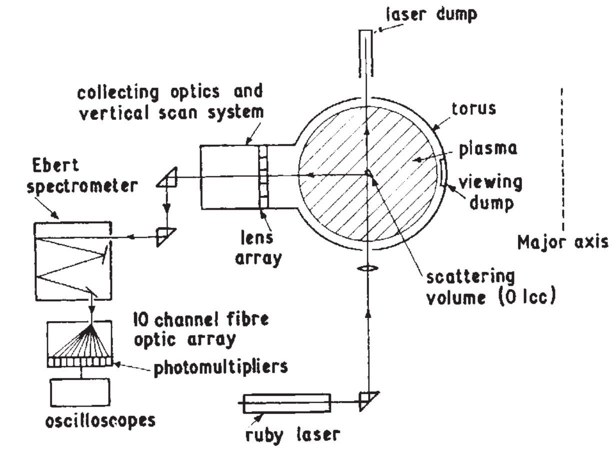

Fig. 1. Schematic diagram of experimental arrangement for Thomson scattering experiment on Tokamak T3.

The experimental arrangement is shown schematically in Fig. 1. The laser beam, with a divergence of 2·5 mrad, is passed vertically upwards through the minor cross-section of the torus and the photons scattered at 90° in the horizontal plane are detected by a ten-channel spectrometer with an F/6 equivalent aperture. Each recording channel covers 78 Å on the short wavelength side of the laser wavelength which enables temperatures between 0·05 and 1·5 keV to be measured. Because in the Tokamak plasma the Debye length is much longer than the ruby laser wavelength the scattering parameter $\alpha \ll 1$ (ref. 7), and the Doppler shifted scattered spectrum reflects the velocity distribution of the plasma electrons. For a Maxwellian velocity distribution the scattered spectrum is Gaussian with half width proportional to the square root of the temperature.

The scattered light is transmitted by a fibre optics system to photomultipliers with S20 photocathodes coupled to $\times 15$ current gain amplifiers. A lens system incorporating a periscope and viewing lenses coupled to small angle prisms allows a radial scan of the plasma through five windows in the vertical plane.

Before and after each experiment the transmission of the collection optics and spectrometer, together with the sensitivities of the channels, were calibrated absolutely. For this purpose an optical arrangement was used equivalent to that used for the Thomson scattering, with an absolutely calibrated tungsten ribbon lamp as the light source. The laser power (typically 4 J in 25 ns at the input window) was measured by means of a calorimeter and thus the plasma density can be obtained from the total scattered radiation.

While the volume of the irradiated plasma viewed by the spectrometer is only 0·1 cm³, background light—the principal source of noise—is collected from a plasma volume of 10 cm³. Parasitic light scattered from the primary laser beam by the input and dump optics is usually observed on channel 1, which is centred on the ruby laser wavelength of 6943 Å. The other channels are usually free of parasitic light. An additional check to confirm that the signal on these channels is due to Thomson scattering by the plasma electrons was made by moving the focus of the collection lens to a part of the plasma adjacent to the irradiated volume; negligible signal was found. On channels 5 and 6 the signal-to-noise ratio was relatively poor due to Balmer α radiation believed to come from the outer regions of the plasma.

The Measurements

Typical scattered signals are shown on Fig. 2 for channels 3 and 8, which are centred at 156 Å and 546 Å from the laser wavelength; these illustrate the ratio of signal to background noise. Calculated and observed scattered light intensity profiles for a range of electron temperatures are shown in Fig. 3. The experimental points (which are a mean over several discharges) are plotted for three plasma conditions. Within the statistical errors (typical errors are shown on Fig. 3) the channel intensities have a Gaussian distribution and a temperature can therefore be ascribed in each case with an accuracy of approximately 15 per cent.

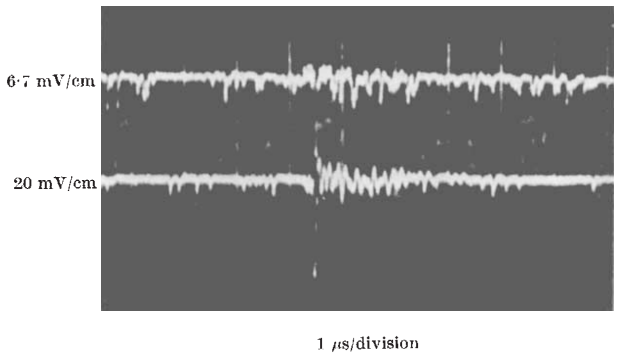

Fig. 2. Oscillograms of scattered light signals on channel 8 (above, $\Delta\lambda = 546$ Å) and channel 3 (below, $\Delta\lambda = 156$ Å). Discharge conditions, $\hat{I}_z = 60$ kA, $H_z = 17$ kOe, $t = 25$ ms. The temperature in this discharge was 530 eV.

Values of the electron temperature and density at different times are given in Table 1 for two discharge conditions. The temperature increased during the first 15 ms and remained approximately constant thereafter until the current decreased appreciably.

The density obtained from Thomson scattering has been compared with simultaneous measurements made by Gorbunov from the phase shifts in a multichannel 2 mm microwave interferometer[8]; a good agreement was found for the variation of density from one discharge to another. Absolute densities evaluated by the two methods have been compared for the second discharge condition shown in Table 1, and were found to agree within about ± 5 per cent. Although the possibility of systematic errors of up to ± 30 per cent on the Thomson scattering calibration cannot be excluded, it is evident that most of the electrons in the plasma must contribute to the scattered signal.

Table 1. VALUES OF TEMPERATURE AND DENSITY ON THE AXIS OBTAINED FROM THOMSON SCATTERING AT VARIOUS TIMES AFTER THE INITIATION OF THE DISCHARGE

$H_z = 25$ kOe	$\hat{I}_z = 85$ kA		$p_0 = 2\cdot6 \times 10^{-4}$ torr		
t (ms)	5	10	15	25	45
T_e (eV)	180	470	1,050	900	950
n_e (10^{13} cm^{-3})	0·65	1·55	2·25	2·8	1·8
$H_z = 17$ kOe	$\hat{I}_z = 60$ kA		$p_0 = 2\cdot4 \times 10^{-4}$ torr		
t (ms)	10	25	35	50	
T_e (eV)	240	560	540	410	
n_e (10^{13} cm^{-3})	1·2	1·5	1·5	1·2	

Typical standard deviations of individual measurements from the mean over five to ten discharges are, for the temperature, 15 per cent, and for the density, 10 per cent.

Some preliminary observations of the radial distributions of temperature and density, made at current maximum, are shown in Fig. 4. The temperature and density profiles are flat over the central core of the plasma column. At a radius of 12 cm the values of density and temperature are still more than half those on the axis. At radii larger than about 15 cm no scattering measurements have been made, but the microwave measurements[8] indicate that the density decreases rapidly. The total electron energy is in approximate agreement with the value determined from diamagnetic measurements[2] for the shorter current pulse, but with the same stabilizing field and longitudinal current as in Fig. 4.

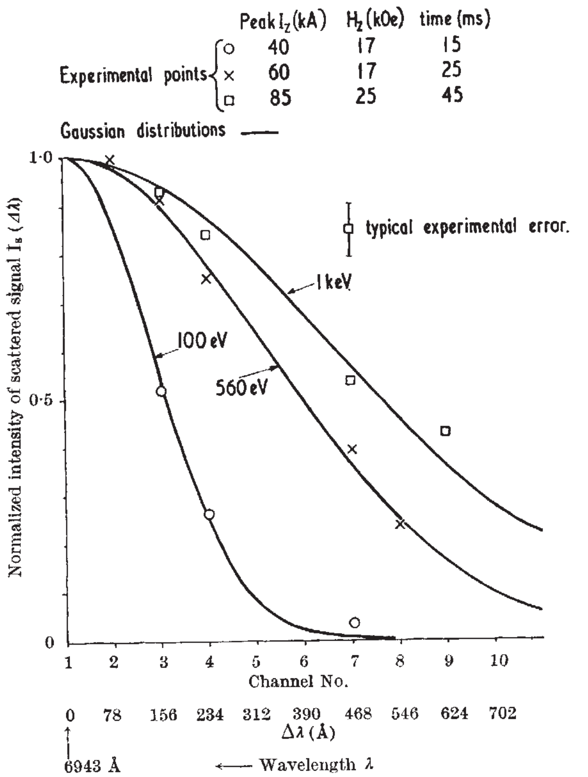

Fig. 3. Spectrum of scattered light for three discharge conditions. Experimental points and theoretical curves for assumed Maxwellian distributions at various temperatures are shown. $\Delta\lambda$ is measured from the laser line at 6943 Å to shorter wavelengths.

For the limited range of discharge parameters studied, additional data indicate that the peak temperature (at about 25 ms) is insensitive to the longitudinal magnetic field and increases approximately as the square of the peak current. Further experiments to determine the radial distribution of electron energy in different discharge conditions and to make a direct comparison between the diamagnetic signal and the Thomson scattering measurements are in progress.

In conclusion, electron temperatures from 100 eV up to 1 keV have been measured by Thomson scattering in Tokamak T3 in the discharge conditions studied. The electron densities measured by this technique are in the range $1-3 \times 10^{13}$ cm^{-3}. Within the experimental error the Maxwellian electron distributions involve all the plasma electrons in the cases studied. The temperature increases approximately as the square of the discharge current and (in conditions where the temperature was 600 eV) its radial distribution is flat over about half the plasma radius. Our measurements of electron temperature and density agree with those obtained by other techniques[2,7] where direct comparison has been possible.

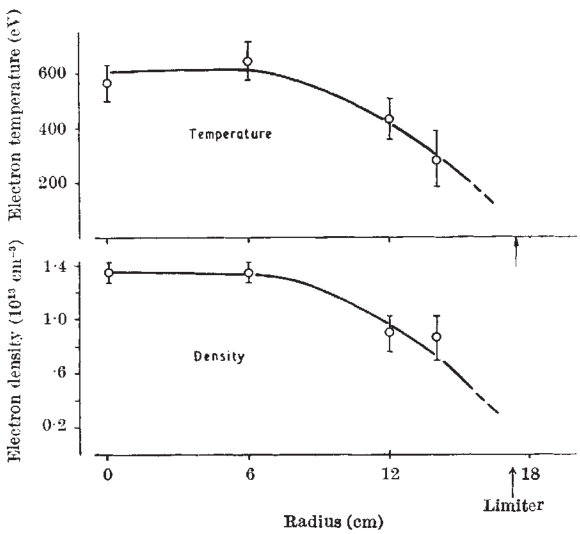

Fig. 4. Radial variation of electron temperature and density. The lines shown are drawn through the experimental points. ($\hat{I}_z = 60$ kA, $H_z = 17$ kOe, $t = 25$ ms).

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1 Artsimovich, L. A., Brobrovskii, G. A., Gorbunov, E. P., Ivanov, D. P., Kirillov, V. D., Kuznetsov, E. I., Mirnov, S. V., Petrov, M. P., Rasumova, K. A., Strelkov, V. S., and Shcheglov, D. A., *Proc. Third Intern. Conf. on Plasma Physics and Nuclear Fusion*, Novosibirsk, 1968, **1**, 157 (Paper CN24/B1) (International Atomic Energy Agency, Vienna, 1969).

2 Gorbunov, E. P., Mirnov, S. V., and Strelkov, V. S., *I. V. Kurchatov Institute of Atomic Energy, Report IAE 1681*, 1 (1968).

3 Artsimovich, L. A., Anashin, A. M., Gorbunov, E. P., Ivanov, D. P., Petrov, M. P., and Strelkov, V. S., *Zh.E.T.F. Lett.*, **10**, 130 (1969).

4 Mirnov, S. V., *Nuclear Fusion*, **9**, 57 (1969).

5 Shcheglov, D. A., *Zh.E.T.F. Lett.*, **6**, 949 (1967).

6 Robinson, D. C., and King, R. E., *Proc. Third Intern. Conf. on Plasma Physics and Nuclear Fusion*, Novosibirsk, 1968, **1**, 263 (Paper CN24/B8) (International Atomic Energy Agency, Vienna, 1969).

7 Salpeter, E. E., *Phys. Rev.*, **120**, 1528 (1960).

8 Gorbunov, E. P., Dnestrovskii, V. N., Kostomarov, D. P., and Mul'chenko, B. F., in *Plasma Diagnostics*, Issue 2, 188 (Atomizdat, Moscow, 1968).