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MULTIPOLE LINES IN THE SPECTRUM OF Te I

By T. Kornalewski and H. Niewodniczański[†]

Institute of Physics, Jagellonian University, Cracow*

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The wavelengths of multipole lines of Te I have been determined: *E2*: 4309.42±0.01 Å and *M1*: 5419.23±0.02 Å. The terms $^1S_0$ and $^3P_1$ of the ground state configuration of Te I obtained from these values are 23198±0.1 cm^{-1} and 4750.8±0.2 cm^{-1}, respectively. The intensity ratio of the multipole lines of Te I has been measured and amounts to $I_{5419}/I_{4309} = 14.6 \pm 3$. This result has been compared with the theoretical predictions. Experimental results published so far, concerning the determination of relative multipole transition probabilities, are compared with the results of corresponding theoretical papers. The Zeeman pattern of the 5419.23 Å line has also been analyzed.

Introduction

In the present paper multipole radiation means electric quadrupole (*E*2) and magnetic dipole (*M1*) radiation.

The frequent occurence of multipole lines in the spectra of many astrophysical objects has stimulated many theoretical papers devoted to the calculation of multipole transition probabilities. The greatest difficulty encountered when calculating the probability of such transitions is the calculation of the radial integral by means of which the *E*2 transition probability is expressed. Since this integral does not appear in the expression for the *M1* transition probability, the experimental determination of the ratio of the *M1* to *E2* transition permits the value of the radial integral to be determined semi-empirically. The measurement of the ratio of the *M1* to *E2* transition probabilities can be made either by measuring the intensity ratio of *M1* and *E2* lines which have the same upper energy level or by measuring the intensities of the components of Zeeman splitting of the multipole line of mixed character.

In spite of the importance of such measurements there are only very few experimental papers on the determination of the relative intensity of multipole lines owing to the difficulty of this problem. The intensities of multipole lines observed in laboratory conditions are usually very small, and, in addition the intensities of the lines compared often differ even by two orders of magnitude, and the lines lie in different spectral regions.

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* Address: Instytut Fizyki UJ, Kraków, ul. Reymonta 4, Polska.

[†] Deceased.

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The purpose of the present work was the determination of the relative intensities of the multipole lines of the Te I spectrum as well as a precise measurement of their wavelengths. The multipole transitions between the levels of the ground state configuration of Te I are shown in Fig. 1. The wavelengths of the lines observed in laboratory conditions are also given in this figure. The multipole lines in the Te I spectrum were first observed by Niewodniczański and Lipiński in 1938. These authors have observed three lines: *M1* 5420 Å, and *E2* 4309 Å and 7909 Å. Heldt (1967), has investigated the Zeeman effect of the lines and has thus confirmed their multipole character. He also found for the first time a mixed 9468 Å line.

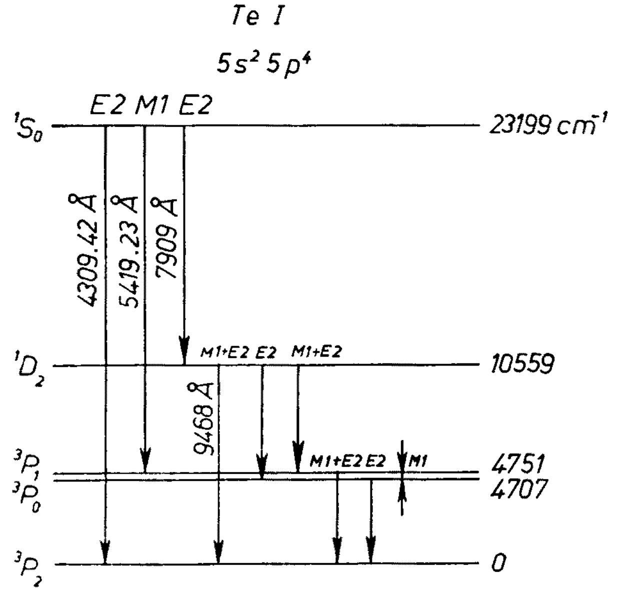

Fig. 1. The multipole transitions between the levels of the ground state configuration of Te I

Experimental

To obtain multipole lines of Te I the classical method of electrodeless discharge of high frequency in tellurium vapour in inert gas atmosphere has been used. The tellurium vapour was excited in a 20 cm long quartz tube with the diameter of 18 mm located in a furnace with the temperature of about 800°C. The discharge tube was connected with a second quartz tube whose other end was placed in a furnace with the temperature close to 420°C. This second tube contained spectrally pure tellurium. The inert gas was argon. The measurements were made under argon pressures between 1 and 10 mm of mercury. The temperature, which defines the tellurium vapour pressure, was changed during the measurements from 390°C to 440°C. The spectrum was excited by a 20 MHz oscillator. The wavelengths of the multipole lines of the Te I were determined by means of a triprismatic spectrograph manufactured by Carl Zeiss, Jena, with an autocollimating camera $f = 130$ cm.

The intensity ratio of the investigated lines was measured using the camera with the focal length of 27 cm being a part of this spectrograph. The Te I radiation was detected by means of photographic plates: ORWO Spektral-Platte WU1, WO1 and WO3. Ar I lines were used as reference lines for the determination of the investigated wavelengths. The wavelengths of the Ar I lines were taken from the paper of Burns and Adams (1953). The intensity ratio of the 5419 Å and 4309 Å lines was determined by means of the photographic method of heterochromatic spectrophotometry. A tungsten with the colour temperature of 2353°K was used as a standard. The colour temperature of the tube was determined in the National Bureau of Quality Control and Measurement in Warsaw. Two spectrophotometric methods were used, one, in which the total light flux falling on the photographic plate was taken as the measure if the line intensity, and another method, in which the illumination of the plate in the middle of the line was used as this measure. In the second method the factors taken into account were the difference in the dispersion of thesspectrograph for the two wavelengths compared and the difference in linear magnification for both wavelengths in the dispersion plane.

It was found that the excitation conditions are different for the Te I and Ar I lines. The multipole lines of Te I are of maximum intensity when the furnace temperature, which determines the tellurium vapour pressure is close to 420°C and the pressure of argon is 7÷10 mm of mercury. In such conditions the intensities of the argon lines in the blue part of the spectrum are similar to that of the *E2* 4309 Å line, while the Ar I lines in the vicinity of the *M1* 5419 Å are invisible. The wavelength of the 4300 Å line was measured in these conditions and also the intensity ratio of the *M1* 5419 Å and *E2* 4309 Å lines. The wavelength of the 5419 Å line was determined with the temperature defining the Te-vapour pressure amounting to 390°C and the argon pressure about 1 mm of mercury. In these conditions several Ar I lines appear in the green part of the spectrum thus providing convenient reference for wavelength measurement. It should be noted that the intensity of 5421.35 Å Ar I line is similar to that of the *M1* 5419.23 Å line of tellurium. In optimum conditions for excitation of multipole lines of Te I, the 5421.35 Å line is not visible. The ORWO Infrarot-Platte I 750 plates permitted registration of the 7909 Å line, its intensity, however, was too small for measurement.

Discussion of results

The wavelengths of the multipole lines of Te I measured are:

$$E2\colon\ 4309.42 \pm 0.01\ \text{Å},$$

$$M1\colon\ 5419.23 \pm 0.02\ \text{Å}.$$

The r.m.s. errors of these results amount 0.003 Å and 0.005 Å, respectively. There are however some systematic errors connected with interpolation and the accuracy of the reference wavelengths, which had to be taken into account. The results obtained permit the values of $^1S_0$ and $^3P_1$ terms of the ground state configuration of Te I to be given with a better precision than in the book of C. Moore (1958). Table I gives the values of these

TABLE I

Term	Value given in literature	Value determined in the present experiment
$5p^4\ {}^3P_2$	0 cm^{-1}	0 cm^{-1}
${}^3P_1$	4751	4750.8 ± 0.2
${}^1S_0$	23199	23198.5 ± 0.1

terms according to the tables given by Moore and the values obtained in the present work.

The ratio of the intensities of the Te I multipole lines determined in the present paper is

$$\frac{I_{5419}}{I_{4309}} = 14.6 \pm 3.$$

The error of the measurement was accepted as the maximum spread of the results taking into consideration the systematic errors resulting from the accepted method. From the determined intensity ratio of the multipole lines follows the ratio of the transition probabilities $A_{5419}/A_{4309} = 18.4$.

The multipole transition probabilities in the Te I spectrum have been calculated from theory by Garstang (1964). The value of the radial integral for the $5p^4$ configuration was determined by Garstang by extrapolation of the results of theoretical calculations performed for the configurations $2p^4$, $3p^4$ and $4p^4$. The assumption made by Garstang was the linear dependence of the parameter $s_q^{+1/2}$ on the atomic number Z, where $s_q = \frac{2}{5} e \int\limits_0^\infty r^2R^2(np)dr$. The very crude character of this approximation is pointed out even in the avbove-mentioned paper. By assuming for the lowest configuration of Te I the value $s_q = 3.1$ Garstang obtained for the transition probabilities the values: $A_{5419} = 37$ sec^{-1} and $A_{4309} = 0.79$ sec^{-1} and thus the ratio $A_{5419}/A_{4309} = 47$.

One can obtain agreement of the theoretical results with the experimental value obtained in the present work by putting $s_q = 5$.

Because of the approximate character of Garstang 's calculations the agreement of this value with that predicted by the theory seems reasonable.

In connection with the difference between the result obtained in this paper and that predicted theoretically, it seems interesting to compare the experimental results on the relative multipole transition probabilities obtained so far with those given in corresponding theoretical papers. This comparison is made in Table II.

The striking feature of the results listed in Table II is the very good agreement between the experimental values obtained by McConkey *et. al.* for O I and S I with the theoretical values calculated by Garstang and Czyzak. The results of other experimental papers considerably differ from the theoretical predictions, the experimental values of the ratio of *E2* — to *M1* transition probabilities being several times greater than those obtained from theoretical calculations. The discrepancies for Te I and Pb I can be expalained in terms of inaccurate knowledge of the radial integral for the configurations $5p^4$ and $6p^2$.

TABLE II

Element and configuration	Transition probability ratio	Experimental value and reference		Theoretical value and reference	
O I $2p^4$	$M1\ {}^1S_0-{}^3P_1/E2\ {}^1S_0-{}^3P_2$	45	*a*	210	*b*
		200	*c*		
	$E2\ {}^1S_0-{}^1D_2/M1\ {}^1S_0-{}^3P_1$	18.6		16.4	
	mixed ${}^1D_2-{}^3P_1$/mixed ${}^1D_2-{}^3P_2$	0.33		0.32	
S I $3p^4$	$E2\ {}^1S_0-{}^1D_2/M1\ {}^1S_0-{}^3P_1$	5.1	*d*	5.09	*e*
				12	*f*
Te I $5p^4$	$M1\ {}^1S_0-{}^3P_1/E2\ {}^1S_0-{}^3P_2$	18.4	*g*	47	*h*
Si I $3p^2$	$M1\ {}^1S_0-{}^3P_1/E2\ {}^1S_0-{}^3P_2$	1	*i*	30	*k*
Pb I $6p^2$	$M1\ {}^1S_0-{}^3P_1/E2\ {}^1S_0-{}^3P_2$	3.6	*m*	7.8	*h*

a) Liszka, Niewodniczański (1958)
b) Garstang (1951)
c) McConkey *et al.* (1966)
d) McConkey *et al.* (1968)
e) Czyzak, Kruger (1963)
f) Osterbock (1951)
g) present paper
h) Garstang (1964)
i) Niewodniczański, Pietruszka (1965)
k) Warner (1968)
m) The value of the intensity ration of the multipole lines corresponding to these transitions was determined by Mrozowski (1940) as equal to 5. Using this value Gerjuoy (1941) determined the value of the parameter $s_q^2 = 171$. In a later paper Mrozowski (1944) corrected this value to $s_q^2 = 240$. The value of the transition probability ratio corresponding to this corrected value equals 3.6.

The experimental results for heavy elements should be more accurate than those for light elements since in general the intensity of multipole lines increases with increasing atomic number Z while the difference between the intensities of the *M1* and *E2* lines decreases. The discrepancies in the results obtained for light elements should be rather ascribed to inaccurate measurements. One should point out that in the papers of McConkey *et al.* the spectrum was registered by means of the photoelectric method while in the remaining experimental papers the spectrum was registered on photographic plates. The photographic method permits the registration of very small intensities by cumulation during the exposure time, however in spectrophotometric measurements it provides more possibilities of systematic errors than the photoelectric registration method. A possible source of considerable and hardly predictable errors in heterochromatic spectrophotometry by means of the photographic method may be the so called Eberhard effect (1912).

In the discussion of the results of relative intensity measurements of multipole lines for transitions having the same upper energy level it is assumed that these results give directly the relative probabilities of the corresponding multipole transitions. This is true when there is no self-absorption and when the transitions under consideration are spontaneous.

Both the experimental data and theoretical considerations indicate that there is no influence of self-absorption on the results of measurements of relative multipole line intensities. The present paper shows that the results do not depend on the tellurium vapour pressure in the radiation source. The lack of self-absorption influence on the results of intensity ratio measurements of O I multipole lines was also found experimentally by McConkey *et al.* (1966). The amount of self-absorption can be estimated theoretically from the knowledge of the number fo atoms per unit volume in the radiation source. For instance in the case of our experiment the tellurium vapour pressure at 420°C amounted to about 10^{-1} mm of mercury. For this pressure the concentration of molecules at the temperature of 1100°K is about 10^{15} molecules/cm^3. Assuming for the tellurium multipole line the following values: population of the lower energy level equal to 10^{15} atoms/cm^3, the Doppler width of 2000 MHz and the transition probability equal to 10^2 sec^{-1}, we obtain the absorption coefficient for the middle part of the line $k_0 = 10^{-2}$ cm^{-1}. In fact the value of k_0 is still smaller. The decisive factor for the influence of self-absorption on the spectral line intensity is the value of the Ladenburg–Levy function $S(k_0 1)$ (1930). When there is no self-absorption $S(k_0 l) = 1$. In the case considered for tube lenght of 10 cm, the optical thickness of the source $k_0 l = 10^{-1}$, which corresponds to the value of the Ladenburg–Levy function $S(k_0 l) = 0.96$. For each of the tellurium lines observed the optical thickness of the source is smaller than 10^{-1}, and thus $S(k_0 l) \approx 1$.

In the multipole lines sources used in laboratory conditions the current densities are, in general, quite small and thus, the probability of forced transitions brought about by external fields seems to be small. The *E1* transitions forced by a uniform electric field satisfy the selection rules such as the *E2* radiation. The probability of such transitions between the levels of the ground state configuration is, however, very small owing to the great distance from these levels to the nearest levels of opposite parity. It seems, however, that there were so far no theoretical considerations on the possibility of an admixture of *M1* transitions forced by internal fields occuring in the low-temperature plasma to *E2* transitions. It is thus difficult to decide whether this possibility could influence the multipole line intensities observed.

Zeeman effect of the 5419.23 Å line[1]

In order to confirm the magnetic-dipole character of the 5419.23 Å line the transverse Zeeman effect of this line was recently investigated.

The light source applied in this investigation was essential the same as that described in the experimental part of this paper. The radiation was observed in the direction perpendicular to the discharge tube. A glass-prism spectrograph together with a Fabry-Perot interferometer was employed in observations of the Zeeman splitting components. The interferometer plates were silver-coated and set 5.69 mm apart. A Du Bois electromagnet was used for generating a magnetic field of 3300 Gs. The gap between the electromagnet pole pieces was 60 mm.

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[1] The investigation the Zeeman effect of the 5419.23 Å line was performed by M. Wusatowska

Fig. 2 present the microphotometric record of the Zeeman pattern of the line in mention. Analysis of the polarization of the Zeeman spliting components showed that the Te I line of wavelength of 5419.23 Å is a magnetic-dipole line inquestionably.

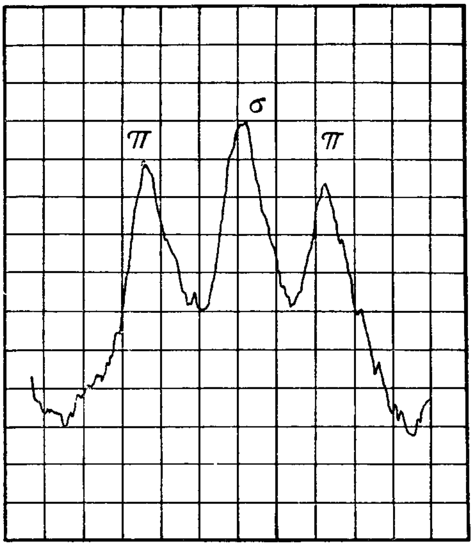

Fig. 2. Microfotometric record of the transverse Zeeman pattern of the 5419.23 Å line

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