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MAGNETO-OPTICAL ABSORPTION SPECTRUM OF CALCIUM IN THE REGION 202 TO 209 nm

MUHAMMAD SHAFQAT MAHMOOD[a] and ISHAQ AHMAD[b]

[a] *Department of Physics, Governement H. A. Ismailia College, Rawalpindi, Pakistan*

[b] *National Research Council of Canada, Ottawa, Canada K1A0R9*

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The measurements of oscillator strengths of the principal series of calcium are presented. The data were taken using the magneto-optical rotation (MOR) spectroscopy technique, utilizing the plane-polarized light emitted by the 2.5 GeV electron accelerator, a 6 T superconducting magnet and a 3 m long high-dispersion spectrograph. The MOR spectra were recorded on photographic plates, which were then digitized using a high-resolution densitometer tracer. More accurate oscillator strengths of transitions, $3p^64s^2\ ^1S_0 \to 3p^64s\ np\ ^1P_1$ (n = 11 to 25) have been determined.

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1. Introduction

Among the atomic constants that can be determined spectroscopically, the oscillator strengths (or equivalently, the transition probabilities or lifetimes) are of much importance in different fields of physics. The main application in astrophysics arises in the determination of stellar abundance of elements. The emission spectrum of solar corona is interpreted better with known transition probabilities. The most urgent need for transition probabilities has arisen in thermonuclear fusion work. In very hot magnetically confined plasma, presence of minute heavy element impurity causes unwanted energy losses in the form of radiation. Its influence can be estimated with the help of known line strengths. To asses the potential of an atomic system as a laser, the transition probabilities and the radiative lifetimes are very important.

In the present work, the oscillator strengths were determined using the well established method of magneto-optical rotation (Faraday effect). In this method, one uses the rotation of the plane of polarization of linearly polarized light in passing a cell in an external longitudinal magnetic field. The rotation is caused by the difference in refractive indices (n_+ and n_-) for the two circularly polarized components (σ_+ and σ_-) of light due to the Zeeman effect. An account of these and other early applications of the magneto-optical rotation (MOR) method is given by Mitchell and Zemansky [1]. Today, through the availability of high-resolution spectrographs and narrow-bandwidth lasers, magneto-optical rotation spectroscopy has developed into a method for very accurate measurements of relative atomic oscillator strengths [2–4].

2. *Experimental set-up*

Our experimental set-up is very similar to the magneto-optical experimental system of Garton et al. [3]. Almost linearly polarized synchrotron radiation from one of the bending magnets of the 2.5 GeV synchrotron at the University of Bonn was passed through a cell inside a superconducting solenoid, capable of generating a magnetic field of up to 6 T. The synchrotron radiation was focused on the entrance slit of a 3 m vacuum spectrograph. The dispersive element in the spectrograph is a 6000 lines/mm holographic diffraction grating. The reflectivity of the grating surface depends strongly on the orientation of the plane of polarization of the synchrotron radiation. Hence, the grating is also a polarization analyzer for the light that had passed through the cell. The spectra were recorded on Kodak SWR photographic plates. The recordings were subsequently digitized using a high-resolution densitometer-tracer.

3. *Determination of oscillator strengths*

The basics of the magneto-optical absorption spectroscopy with linearly-polarized synchrotron radiation were developed by Connerade [5]. Synchrotron radiation is linearly polarized in the orbital plane of electrons in the accelerator. In our experiment, synchrotron radiation from above and below the orbital plane, depending on the arrangement, not necessarily of equal intensity, was accepted in the spectrograph. This lead to an appreciable elliptic polarization which had to be taken into account in the analysis of the spectra. In our experimental arrangement, the diffraction grating served as a polarizing element. The intensity of light reflected from the grating is largest if the electric vector of the incident light is parallel to the grooves of the grating. Therefore, the efficiency P of the grating as a polarizing element must be taken into account for the derivation of the relation for intensity. The intensity of light falling onto the photographic plate (similar relation to that of Ref. 5) is given by

$$I = \frac{I_0}{4}\left((1-a)^2 \exp(-\frac{2h\nu}{c}k_-) + (1+a)^2 \exp(-\frac{2h\nu}{c}k_+\right) \tag{1}$$

$$+\frac{I_0}{2}(1-a)^2 \, P \, \exp\left[-\frac{2h\nu}{c}(k_+ + k_-)\right](2\sin^2\phi - 1)\,,$$

where I_0 is the intensity of incident light, a the asymmetry parameter (for $a = 0$ one obtains linearly polarized light), P the efficiency of the grating as a polarizing element, l the length of the heated zone of the furnace and $\phi = (l\omega/2c)(n_+ - n_-)$ represents the Faraday rotation angle. The explicit expressions for $n_\pm$ and $k_\pm$, based on the classical dispersion theory for the singlet – singlet transitions, are given in Ref. 6 as

$$n_\pm(\omega) = 1 - C \frac{\omega_0 \pm \Delta\omega_{\rm Zee} - \omega}{(\omega_0 \pm \Delta\omega_{\rm Zee} - \omega)^2 - (\gamma/2)^2}\,, \tag{2}$$

$$k_\pm(\omega) = C \frac{(\gamma/2)^2}{(\omega_0 \pm \Delta\omega_{\rm Zee} - \omega)^2 - (\gamma/2)^2}\,, \tag{3}$$

$$C = \frac{Nfe^2}{4m_e\epsilon_0\omega_0} \qquad \text{and} \qquad \Delta\omega_{\rm Zee} = \frac{eB}{2m_e c}\,.$$

In the expressions, $\Delta\omega_{\rm Zee}$ is the frequency shift of normal Zeeman effect, γ the natural line width, ω_0 the line center in the absence of the magnetic field, N the particle density, m_e the electron mass and f is the oscillator strength of the transition. Since the transmitted intensity is a function of B, ω_0 and Nfl, it will generate patterns which are observed as magneto-circular dichroism (MCD) and magneto-optical rotation (MOR). These patterns are the magneto-optical or Faraday rotation patterns. Since $n_\pm$ and $k_\pm$ are related to the oscillator strength, the f-value of a transition can be obtained by analyzing its magneto-optical patterns.

4. Results and discussion

The allowed electric-dipole transitions from the 4s^2 ^{1}S$_0$ ground state of calcium are 4s np ^{1}P$_1$ ($n \geq 4$). The resonance level 4s 4p ^{1}P$_1$ lies at 422.67 nm, whereas the inter-combination line 4s 4p ^{3}P$_1$, which arises due to the breakdown of the ΔS selection rule, lies at 657.278 nm. In the present work, we have determined the relative oscillator strengths (f-values) of the principal series of calcium ($11 \leq n \leq 25$). The observed magneto-optical absorption spectrum of calcium, covering the spectral region between 202 and 209 nm is presented in Fig. 1. The strong and broad line lying just above the ionization threshold corresponds to the 3s 4p ^{1}P$_1$ transition of magnesium, which appeared as an impurity in the calcium sample.

The magneto-optical pattern of the 4s 11p ^{1}P$_1$ level of calcium is shown in Fig. 2. The normal Zeeman effect splits the 4s 11p ^{1}P$_1$ line into two Lorentz components labelled σ^+ and σ^-, which appear near the centre of the pattern. The magneto-optical "beats" appear symmetrically about the line centre at the zero magnetic field. The first minimum in the profile appears when the electric-field vector of the incoming light rotates by $\pi/2$ radians (the far wing region). As the frequency of the incident radiation is tuned, the electric-field vector rotates further by π radians, and a maximum occurs in the transmitted intensity. This rotation grows from zero to high angles as a function of the photon energy which results in maxima and minima in the signal as $\sin^2\phi$. For the analysis of the magneto-optical spectra, function given in Eq. (1) was fitted to the experimentally observed line profile, thus determining the product Nfl. The relative f-values could, therefore, be determined for all transitions which were recorded in a single exposure, because N and l remain constant, whereas the f-values vary among the members of the Rydberg series.

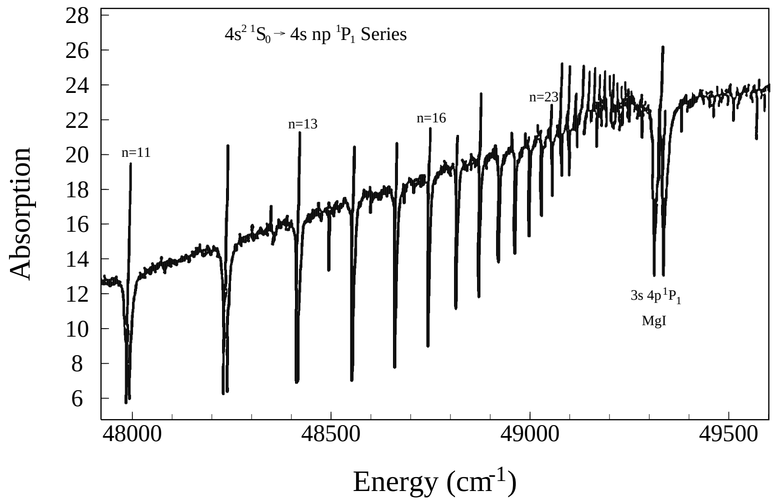

Fig. 1. Magneto-optical absorption spectrum of the principal series $3p^6 4s^2\ ^1S_0 \rightarrow 3p^6 4s\ np\ ^1P_1$ *($n \geq 11$) of calcium in the spectral region between 202 and 209* nm. *Above the ionization threshold, the magneto-optical rotation pattern is due to the* $3s\ 4p\ ^1P_1$ *transition of magnesium, which was present as an impurity.*

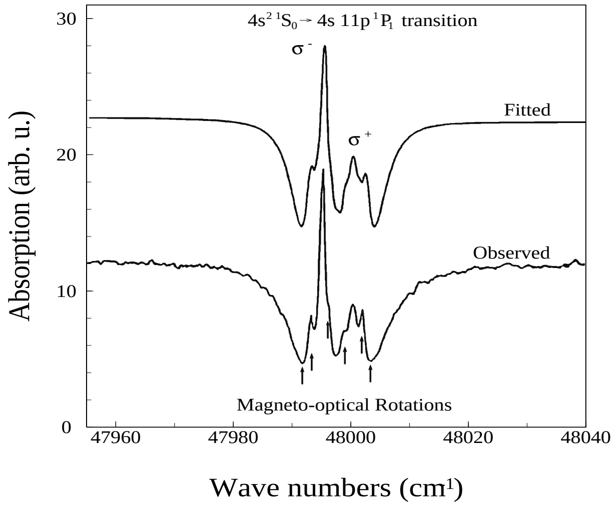

Fig. 2. The experimental and fitted magneto-optical rotation pattern for the 4s 11p $^1P_1$ *line of calcium in a magnetic field of 5.7* T.

The experimentally observed magneto-optical rotaton pattern for the 4s 11p $^1P_1$ transition and the fitted pattern are shown in Fig. 2. With a similar fitting procedure, we have determined the products (Nfl) for all observed line profiles with $11 \leq n \leq 25$. The results are placed on an absolute scale in which the oscillator strengths of the 4s 11p $^1P_1$ line is fixed at $\log(gf) = -2.69 \pm 0.05$ [7], where (gf) is the product of the oscillator strength f and the statistical weight of the ground state $^1S_0$. A comparison of the previously determined f-values and the present results is given in Table 1. The first, second and third columns give the principal quantum

TABLE 1. Results for oscillator strengths of the principal series of calcium, transitions $4s^2\ ^1S_0 \rightarrow 3p^64s\ np\ ^1P_1$. *Effective quantum numbers and resonance energies have been taken from Ref. 8. Results of the present measurements are given in the fifth column. The oscillator strengths measured by the hook method of Ref. 7 (^{a}) and of Ref. 9 (^{b}) are given in the sixth and seventh columns, respectively, while the results of semiempirical calculation of Ref. 10 are given in the eighth column (^{c}) .*

n	Energy	n^*	Nfl	$\log(gf)$	$\log(gf)^a$	$\log(gf)^b$	$\log(gf)^c$
7	45425.39	5.318			-1.49±.06	-1.48±.04	-1.71
8	46479.96	6.231			-1.91±.06	-1.90±.04	-2.20
9	47184.43	7.192			-2.26±.05	-2.25±.04	-2.58
10	47662.10	8.170			-2.49±.05	-2.52±.04	-2.91
11	47997.49	9.158	2.009	-2.69±.05	-2.69±.05	-2.75±.04	-3.12
12	48240.53	10.149	1.201	-2.91±.05	-2.86±.05	-2.94±.04	-3.31
13	48422.09	11.142	0.797	-3.09±.05	-3.06±.06	-3.11±.04	-3.29
14	48561.10	12.138	0.578	-3.23±.05	-3.16±.08	-3.25±.04	-3.61
15	48669.83	13.134	0.427	-3.36±.06	-3.26±.08	-3.34±.04	-3.74
16	48756.45	14.131	0.326	-3.48±.06	-3.36±.08	-3.43±.04	-3.85
17	48826.54	15.129	0.243	-3.61±.07		-3.55±.04	-3.96
18	48884.06	16.127	0.185	-3.73±.08			-4.05
19	48931.82	17.126	0.137	-3.86±.09			-4.06
20	48971.93	18.124	0.102	-3.98±.10			-4.18
21	49005.92	19.124	0.085	-4.06±.12			
22	49034.98	20.123	0.067	-4.17±.12			
23	49060.02	21.122	0.065	-4.18±.13			
24	49081.75	22.122	0.055	-4.25±.14			
25	49100.72	23.121	0.036	-4.44±.15			

numbers, enegies and effective quantum numbers for each transition, respectively. We have estimated the errors by varying the final value of (Nfl) in the numerical fit until a significant difference of experimental and theoretical spectrum was noticed. The error of the absolute values of the oscillator strengths is maily due to the results of the measurements of Parkinson [7], which were used to normalize our relative oscillator strengths. An inspection of Table 1 shows that the experimental error in the absolute f-values increases as the principal quantum number increases. This fact may be attributed to the limited rotations observed in the far wings of the absorption profiles. In addition, the oscillator strengths of an unperturbed Rydberg series decrease with the principal quantum number as $1/(n^*)^3$, which further reduces the possibility of the observation of rotations for high Rydberg members. The relatively larger error in the f-values is also due to the limited resolution and dispersion of our spectrograph.

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MAGNETSKO-OPTIČKI APSORPCIJSKI SPEKTAR KALCIJA U PODRUČJU 202 DO 209 nm

Prikazuju se mjerenja oscilatornih jakosti glavnog niza kalcija. Primijenili smo metodu magnetsko-optičko-rotacijske (MOR) spektroskopije, s linearno polariziranim svjetlom iz elektronskog sinkrotrona 2.5 GeV, uz upotrebu supravodljivog magneta 6 T i spektrografa visokog razlučivanja dugog 3 m. MOR spektri su se bilježili na fotografskim pločama a snimke smo digitalizirali pomoću densitometra visokog razlučivanja. Postigli smo točnije vrijednosti oscilatornih jakosti prijelaza $3p^6 4s^2\ ^1S_0 \rightarrow 3p^6 4s\ np\ ^1P_1$ ($n = 11$ do 25).