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Beam-foil spectrum of magnesium

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Abstract : The beam-foil spectrum of magnesium was recorded in the UV visible region using incident ion beam energies in the range of 100–300 keV. Mean lifetimes of several excited levels belonging to MgI to MgIII were determined. Lifetime of the MgIII level ($4p'[3/2]_2$) involved in 3361 Å line is reported for the first time.

Keywords : Beamfoil spectroscopy, Magnesium, lifetimes

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1. Introduction

Magnesium is one of the astrophysically important elements and a correct estimation of abundance is of great interest to astrophysicists. Spectroscopic techniques provide a sensitive method for abundance determination. The spectral line intensity is the product of the abundance of the excited species and the transition probability. From known lifetimes and branching ratios, transition probabilities can be calculated. As beam foil excitation populates highly excited and ionised species including multiply excited configurations and possesses inherent time resolution, it is a powerful technique to determine the mean lifetimes of energy levels with a variety of n and l values. The details and advantages of the technique are dealt with by many authors [1,2]. Mean lifetimes of magnesium were determined earlier by many groups of workers using the beam foil technique [3–9]. It was observed that there was significant scatter between various experimental results. In addition, the theoretical values by different investigators ([10] to [24]) also showed a large

variation. Hence, a reinvestigation of the beam foil spectrum of magnesium and its ions in the UV and visible region was taken up. Further, lifetimes of the excited levels of well resolved J-multiplets of MgI and MgIII were measured to study the J-dependence of lifetimes.

2. Experimental

An isotopically pure, monoenergetic ion beam of $^{24}Mg^+$ in the energy range of 100–300 keV was produced in 400 KV accelerator at the Tata Institute of Fundamental Research. The levels of MgI-MgIII were excited by passing through thin self-supporting carbon foils of 5 $\mu g/cm^2$ thickness. The beam was collimated to 2 mm^2 and the beam current on the foil was restricted to 75 nA to avoid foil breakage. Lifetime and excitation function studies were carried out using a standard beam-foil spectroscopy set-up. Details of the experimental set up are described elsewhere [25]. Wavelength spectra were recorded at 216 and 256 keV Mg^+ beam energies. Excitation function studies were carried out on selected lines in the energy range of 96 to 316 keV. These studies facilitated a detailed examination of spectral line blending and charge state identification. Lifetimes were measured several times and at least at two incident projectile energies. The average measured values are reported here. Estimated energy loss of Mg^+ ions in the carbon foils at 256 and 216 KeV was 43 and 41 KeV respectively. The energy loss was calculated using the computer program code TRIM [26]. Using the corrected energy of Mg^+ ions, post foil velocity was calculated. Intense spectral lines free from blending were chosen for lifetime studies. Effect of beam current fluctuations was compensated for, by normalising the signal with respect to a fixed particle current collected in a Faraday cup. In the present experiments, data involving current fluctuations of more than 20% was rejected. In the present experimental set-up, spectral lines separated by 3 Å could be resolved and yielded a better resolution than some of the earlier reported experiments where 0.25 M and 0.35 M monochromators were used.

3. Results and discussion

3.1. Wavelength spectrum :

Since the beam foil excitation is non-selective, several energy levels belonging to different charge states were populated. The beam-foil spectrum of Magnesium in the 2000–5000 Å region consisted of spectral lines due to MgI–MgIII. It was noticed that only the intense lines of MgI were observed whereas weak transitions of MgII and MgIII were observed with considerable intensity. Figure 1 shows the beam-foil spectrum of Mg in the 3225–3550 Å region. Transitions from the $2p^5$ nl ($n = 3 - 5$, $l = 0 - 4$) levels of MgIII and the $2p^6$ nl ($n = 3 - 5$, $l = 0 - 3$) levels of MgII were observed with very good intensity. The spectral lines were identified and the assignments were made in accordance with the information available from Andersson and Johannesson [27] and Striganov and Sventitskii [28]. For the

lifetime studies, lines which were intense as well as free from blending were chosen on the basis of excitation function studies. The significant contributions from the excitation function studies are discussed in the following section.

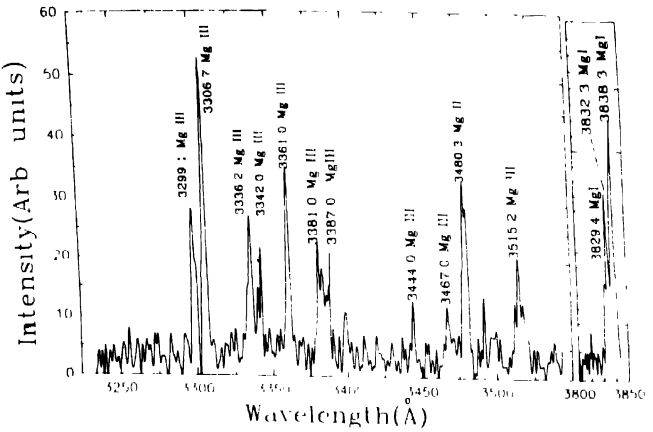

Figure 1. Beamfoil spectrum of magnesium in the wavelength region of 3200 Å - 3850 Å

3.2 *Excitation function studies*.

Beam-foil excitation copiously populates highly excited levels of several charge states. Since the beam-foil source is inherently weak, a monochromator with a high light gathering power and medium resolution was used to record the spectrum. The slit widths used were also large (~200 μm). Therefore, line blending problems were very severe. Blending of lines within the same as well as different charge states was detected. In order to sort out such problems, excitation function studies were carried out. For the excitation function studies, the signal was collected very close to the foil so as to minimise the influence due to cascade repopulation. From the observed variation of intensity of a given spectral line with different beam energies, the population of excited levels was calculated from the following expression [29]:

$$N_t = (4\Pi S_{tl} v) / (\Omega K_{tl} A_{tl} \Delta l Q), \tag{1}$$

where N_t is the population of t^{-th} level, v is the post foil velocity of the emerging ion, S_{tl} is the yield, K_{tl} is the quantum efficiency of the detection system for the wavelength λ_{tl}, Ω is the solid angle subtended by the source at the monochromator, Q is the incident projectile flux, A_{tl} is the transition probability and Δl is the length of the beam in the observation region. Evaluation of level populations requires a knowledge of transition probabilities. Since this information is not available in many cases, relative level populations *viz.* $P_{tl} = (S_{tl} v)/Q$ are calculated and compared with charge state distributions. The strong spectral line at 3480 Å was first observed by Berry *et al* [6]. Subsequently,

Lundin *et al* [7] ascribed the line to a transition involving doubly excited levels of MgII on the basis of excitation function studies. However, they did not assign any transition. This line appears to be a transition from $2p^5\ 3s\ 4s\ ^4P_{1/2} - 2p^5\ 3s\ 3p\ ^2P_{1/2}$ based on energy levels calculated using multiconfiguration Hartree-Fock method with Breit-Pauli relativistic correction (MCHF + BP) by Fischer [16]. However, Brage and Gaarsted [9] using a new MCHF + BP calculation, have assigned the transition to $2p^5\ 3s\ 4f\ ^4G_{11/2} - 2p^5\ 3s\ 3d\ ^4F_{9/2}$

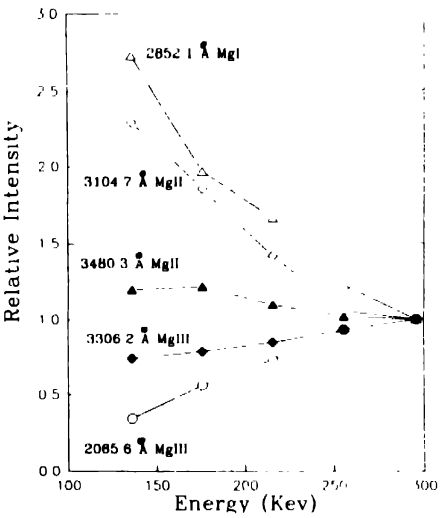

Figure 2. Comparative study of 3480.3 Å MgII line with MgI, MgII and MgIII lines

In the present work, the line at 3480 Å was reinvestigated and the excitation function studies confirmed that the transition involves high lying excited states of MgII. Figure 2 shows the comparative study of the relative level population variations of the spectral lines 2852.1 Å (MgI), 3104.7 Å (MgII), 3480.3 Å and 3336.2 Å (MgIII). The relative intensities of the lines were normalised with respect to 2795 Å line and all ratios were normalised to unity at 296 keV. We could not observe any other strong line involving core excited states of MgII to compare with the population of the 3480 Å line. A spectral line at 3337 Å was reported as belonging to MgI with a life time of 6.1 ± 1.0 ns by Liljeby *et al* [8] using an ion-beam energy of 100 keV. Lundin *et al* [7] using an ion-beam energy of 300 keV reported a line at 3336 Å as belonging to MgIII with a life time to 7.9 ± 0.8 ns. The present excitation function studies of the line at 3336 Å (Figure 3) when compared with charge state fraction, clearly indicate that the transition is due to MgIII.

3.3 Mean lifetime measurements:

3.3.1. MgI:

In general, spectral lines due to MgI were weak compared to those of MgII and MgIII. However, the multiplet at 3835 Å could be observed with measurable intensity at an

excitation energy of 196 KeV. This multiplet consists of 3829.35 Å ($3p\ ^3P_0 - 3d\ ^3D_1$) 3832.30 Å ($3p\ ^3P_1 - 3d\ ^3D_1$) 3832.30 Å ($3p\ ^3P_1 - 3d\ ^3D_2$) 3838.29 Å ($3p\ ^3P_2 - 3d\ ^3D_3$) and

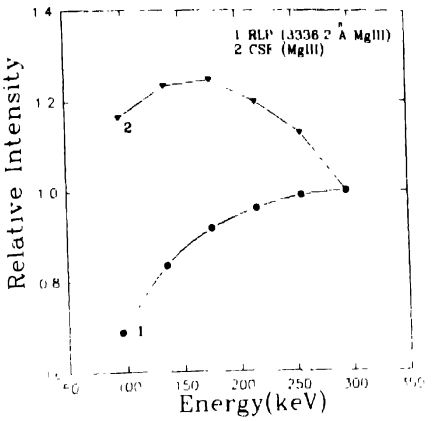

Figure 3. Comparison of relative level population of 3336.2 Å line with charge state fraction of MgIII with variation of excitation energy

3838.29 Å ($3p\ ^3P_2 - 3d\ ^3D_3$). Earlier, experimental determinations of lifetimes on the unresolved multiplet at an average value of 3829 Å and 3838 Å were carried out [4,6,8,16,31] and theoretical calculations were performed Victor *et al* [17], Weiss [11], Zare [12], Fischer [15], Wiese *et al* [18] and Warner [13]. The components of the multiplet could be resolved into three lines at 3829.4 Å, 3832.3 Å and 3838.3 Å in the present investigations, thereby facilitating lifetime determination of the resolved components. Out of these, the 3829.4 Å line is free from blending. The decay curves were fitted to two exponentials and the primary lifetimes are reported in Table 1. A cascading lifetime of 12 ns corresponding to the value reported by Schaefer [31] as primary lifetime was also obtained. As can be seen from Table 1, our values agree well with those reported by Berry *et al* [6]. A comparison of lifetimes of different components of the multiplet does not show any dependence on total angular momentum.

3.3.2. *MgII*:

The mean lifetimes of four of the excited states $3p\ ^2P$, $3d\ ^2D$, $4f\ ^2F$ and $5f\ ^2F$ were determined from the intensity decay measurements of spectral lines at 2795.5 Å, 2790.8 Å, 4481.3 Å and 3104.7 Å respectively. The lifetimes were extracted from the decay curves using a multi-exponential fit program. There has been extensive discussion by Berry *et al* [6] and Lundin *et al* [7] on the lifetimes of the $3p\ ^2P$ and $3d\ ^2D$ levels. The values derived in the present investigations agree well with those of Berry *et al* [6]. It was found that the decay curve for 2790.8 Å *i.e.* the $3d\ ^2D$ term has a long lived decay component having a mean lifetime of 12.6 ns. It appears that the cascading is from the $6f\ ^2F$ level since the lifetime measured for 2660 Å [5,8] is comparable to this value. The lifetimes of $4f\ ^2F$ and $5f\ ^2F$ terms evaluated in the present studies agree well with those of Anderson *et al* [5]. The lifetime measurement of the core excited 3480.3 Å line yielded a value of 5.9 ± 0.1 ns

Table 1. Lifetimes of magnesium.

	Wavelength (Å)	Upper state	Lifetime (ns)		
			Present Work	Others	
				Experiment	Theory
Mg I					
	2852.1	$2p^6\,3s\,3p\,{}^1P^0_1$	2.30 ± 0.1	2.0 ± 0.1	2.18[a]
				1.5 ± 0.2[b]	2.13[c]
				2.09 ± 0.1[d]	2.08[e]
				2.2 ± 0.2[f]	2.36[g]
				1.99 ± 0.15[h]	2.13[i]
				3.29 ± 0.16[j]	2.02[k]
				1.9 ± 0.3[l]	2.27[m]
				2.03 ± 0.06[n]	2.12[o]
				2.9 ± 0.7[p]	
				2.03 ± 0.06[q]	
	3829.4	$2p^6\,3s\,3d\,{}^3D_1$	4.25 ± 0.3	4.9 ± 0.5[a]	9.25[a]
				3.7 ± 1.0[b]	4.5[i]
	3832.3	$2p^6\,3s\,3d\,{}^3D_1$	3.20 ± 0.2	—	—
		$2p^6\,3s\,3d\,{}^3D_2$			
	3838.3	$2p^6\,3s\,3d\,{}^3D_3$	3.70 ± 0.1	5.1 ± 0.5[a]	9.25[a]
				6.6 ± 0.5[b]	6.42[c]
		$2p^6\,3s\,3d\,{}^9D_2$		6.5 ± 0.5[d]	5.79[e]
				11.3 ± 0.8[q]	5.83[r]
				6.4 ± 0.5[p]	5.95[k]
					6.09[m]
Mg II					
	2790.7	$2p^6\,3d\,{}^2D_{3/2}$	2.12 ± 0.1	2.2 ± 0.2[a]	2.12[a]
				2.3 ± 0.4[b]	2.01[k]
				1.9 ± 0.2[f]	
				2.2 ± 0.2[d]	
	2795.5	$2p^6\,3p\,{}^2P^0_{3/2}$	4.52 ± 0.1	4.0 ± 0.3[d]	3.74[k]
				3.67 ± 0.18[n]	3.92[s]
				4.5 ± 0.8[b]	
				3.7 ± 0.5[l]	
	3104.7	$2p^6\,5f\,{}^2F^0_{7/2}$	7.22 ± 0.15	8.3 ± 0.4[a]	8.27[a]
				5.8 ± 0.5[b]	8.22[k]
	3104.8	$2p^6\,5f\,{}^2F^0_{5/2}$	5.91 ± 0.1	9.1 ± 0.6[f]	
	3480.3	$2p^6\,5f\,{}^2F^0_{5/2}$		5.0 ± 0.6[d]	5.33[t]
				5.5 ± 0.3[t]	
	4481.1	$2p^6\,4f\,{}^2F_{7/2}$	5.23 ± 0.11	4.9 ± 0.3[a]	4.38[a]
	3	$2p^6\,4f\,{}^2F_{5/2}$		3.7 ± 0.4[b]	4.28[k]
				5.0 ± 0.4[f]	4.48[s]
				4.6 ± 0.3[d]	

Table 1. *(Cont'd)*

	Wavelength (Å)	Upper state	Lifetime (ns)		
			Present Work	Others	
				Experiment	Theory
Mg III	2040.2	$2p^5\,3p\ ^3D_2$	3.60 ± 0.1	3.35 ± 0.15[r]	
	2065.5	$2p^5\,3p\ ^3D_3$	3.46 ± 0.1	3.60 ± 0.15[r]	
	2113.5	$2p^5\,3p\ 3p_2$	3.42 ± 0.1	3.00 ± 0.1[r]	
	2134.7	$2p^5\,3p\ 1p_1$	3.25 ± 0.1	3.00 ± 0.1[r]	
	2178.4	$2p^5\,3p\ ^1D_2$	3.47 ± 0.1	3.35 ± 0.1[r]	
	2468.5	$2p^5\,3p\ ^3S_1$	4.72 ± 0.1	4.95 ± 0.1[r]	
	3299.1	$2p^5\,4p\ [5/2]_2$	6.56 ± 0.2	6.60 ± 0.5[d]	
	3306.7	$2p^5\,4p\ [5/2]_3$	6.55 ± 0.2	7.60 ± 0.7[d]	
	3336.2	$2p^5\,4p\ [3/2]_2$	7.78 ± 0.15	7.90 ± 0.8[d]	
		$2p^5\,4p\ [5/2]_3$			
	3361.0	$2p^5\,4p'\ [5/2]_2$	6.06 ± 0.20		

[a] Ref [8], [b] Ref [6], [c] Ref [10], [d] Ref [7], [e] Ref [14], [f] Ref [4], [g] Ref [11], [h] Ref [9], [i] Ref [16], [j] Ref [19], [k] Ref [17] Ref [20] [m] Ref [12] [n] Ref [21], [o] Ref [22], [p] Ref [18], [q] Ref [30]; [r] Ref [3], [s] Ref [23], [t] Ref [9]

3.3 *MgIII*

In the case of doubly ionised Magnesium, lifetime data were obtained for six levels. The lifetime for $4p'[3/2]_2$ level involved in the transition at 3361.0 Å is reported for the first time. The lines at 3299.1 Å, 3306.4 Å and 3336.2 Å arise from different J-multiplets of the term $4p[5/2]$. A study of the lifetimes of these lines shows no dependence on the total

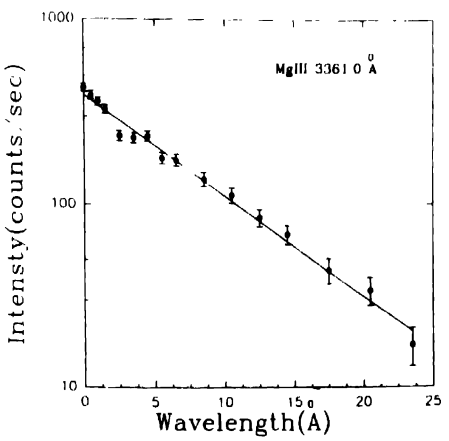

Figure 4. Decay curve of 3361 Å line (MgIII)

angular momentum. A similar conclusion can be made from the evaluation of lifetimes of the 2040.2 Å and 2065.5 Å lines arising from $3p\ ^3D_2$ and $3p\ ^3D_3$ respectively. Figure 4 shows the decay curve for the 3361.0 Å line. The decay curves for the spectral lines at

2065.5 Å and 2178.4 Å were fitted to two exponentials and two lifetimes have been extracted. The secondary lifetimes correspond to the cascading transitions from upper levels like $3d\ ^3F_4$, $3d\ ^3P_4$, $3d'\ ^3F$ and $3d'\ ^3P$. Most of the transitions lie in the VUV region, and were not accessible to the present experimental set-up. The lifetime of the 3336.2 Å was reinvestigated in the present studies, and a value of 7.8 ns is obtained which agrees with the value reported by Lundin *et al* [7] for $4P[3/2]_2$ level of MgIII. Excitation function study on this line has confirmed that the observed transition belongs to MgIII. This fact is further

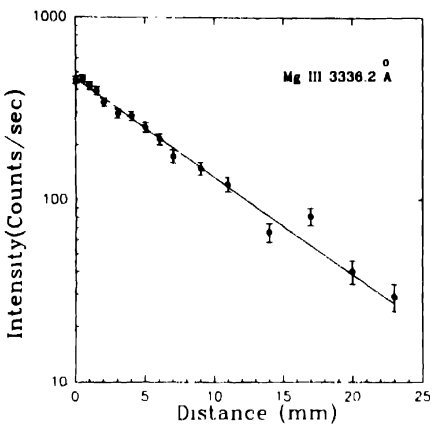

Figure 5. Decay curve of 3336.2 Å line (MgIII)

confirmed from lifetime studies. Figure 5 shows the decay curve of 3336.2 Å. Results of the lifetime studies are included in Table 1.

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