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Systematic Trends in the Mean Lives of the Fine Structure States in the $2p^5\,3p$ Configuration of Na II and Mg III

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The radiative lifetimes of the ten fine-structure levels of the $2p^5\,3p$ configuration of singly charged sodium, and eight of the ten fine-structure levels of the $2p^5\,3p$ configuration of doubly charged magnesium, have been measured by the beam-foil excitation technique. Systematic trends of the $2p^5\,3p$ levels in the Ne I sequence are discussed.

INTRODUCTION

Recently, information on the systematics of transition probabilities and oscillator strengths has been obtained by the beam-foil excitation technique[1] for the $2s\,^2S$-$2p\,^2P^0$ transition in the Li I sequence[2] and for the $2s\,2p\,^1P^0$-$2p^2\,^1D$ transition in the Be I sequence.[3]

It has been the scope of this investigation to extend these studies to isoelectronic sequences with heavier elements, and, as the first case, the Ne I $2p^5 3s$-$2p^5\,3p$ sequence was selected. The $2p^5\,3p$ configuration in Ne I, Na II, and Mg III consists of ten fine structure levels with transitions only to four $2p^5\,3s$ levels. A number of investigations of the same $2p^5\,3p$ levels in Ne I have recently been reported, including mean-life measurements performed either by delayed coincidence technique[4-7] or by gas-cell excitation.[8]

Preliminary studies of the beam-foil spectra of sodium and magnesium beams with energies varying from 100 to 500 keV showed the presence of the $2p^5\,3s$-$2p^5\,3p$ transitions in Na II and Mg III could be studied. Detailed investigations showed that the mean lives of all ten $2p^5\,3p$ levels in Na II could be measured, whereas, with the present experimental technique, only mean lives of eight of the $2p^5\,3p$ levels in Mg III could be determined. Mean-life measurements of the $2p^5\,3p$ levels in Na II and Mg III have not previously been reported in the literature.

EXPERIMENTAL PROCEDURE

The 600-keV heavy-ion accelerator at the Institute of Physics, Aarhus University, which is equipped with a universal ion source and the beam-foil apparatus previously described[9] were used for this investigation. Sodium ion beams $^{23}\mathrm{Na}^+$ were obtained by inserting NaCl in the ion source. Magnesium ion beams $^{24}\mathrm{Mg}^+$ were obtained by the carbon-tetrachloride method, e.g., by a reaction between magnesium oxide and carbon tetrachloride, at ~ 500 °C. This yields the volatile magnesium chloride, which evaporates into the ion source. The beam intensities ranged from 0.05 to 0.2 μA. The ion beams had a diameter of 2.5 mm, and 5 $\mu\mathrm{g/cm}^2$ carbon foils (Yissum Research Development Co., Israel) were used for excitation. The detection system has previously been described.[9]

RESULTS

Sodium. In this investigation, the beam-foil spectra obtained with the $^{23}\mathrm{Na}^+$ beam ranging from 100 to 500 keV were recorded from 2300 to 4100 Å. All the observed lines in this wavelength region could be attributed to Na I, Na II, or Na III. The $2p^5 3s$-$2p^5 3p$ transitions were studied in detail at 300 keV, at which energy the 30 lines, representing all the allowed transitions following the j-l coupling scheme, were detected. The 30 lines were present between 2315 Å, the s_4-p_1 transition (Paschen notation) and 4087 Å, the s_2-p_{10} transition. Figure 1 shows part of the term diagram for Na II, including the twenty-three $2p^5\,3s$-$2p^5\,3p$ transitions, which could be used for mean-life measurements. The remaining seven lines had too low an intensity to allow lifetime measurements with the present experimental technique.

Spectral lines belonging to the $2p^5\,3p$-$2p^5\,3d$ and $2p^5\,3p$-$2p^5\,4s$ transitions in Na II are also present in the beam-foil spectra; they coincide in wavelength with some of the $2p^5\,3s$-$2p^5\,3p$ transitions, particularly in the 2800–3200-Å region. For a few of the $3p$-$3d$ transitions and for one of the $3p$-$4s$ transitions, the intensity of the spectral lines allowed a determination of the mean life for the upper levels, but usually the intensity of the $3p$-$3d$ and $3p$-$4s$ transitions was considerably smaller than that of the $3s$-$3p$ lines. Since some of the $3s$-$3p$ lines were blended by lines from $3p$-$3d$ and

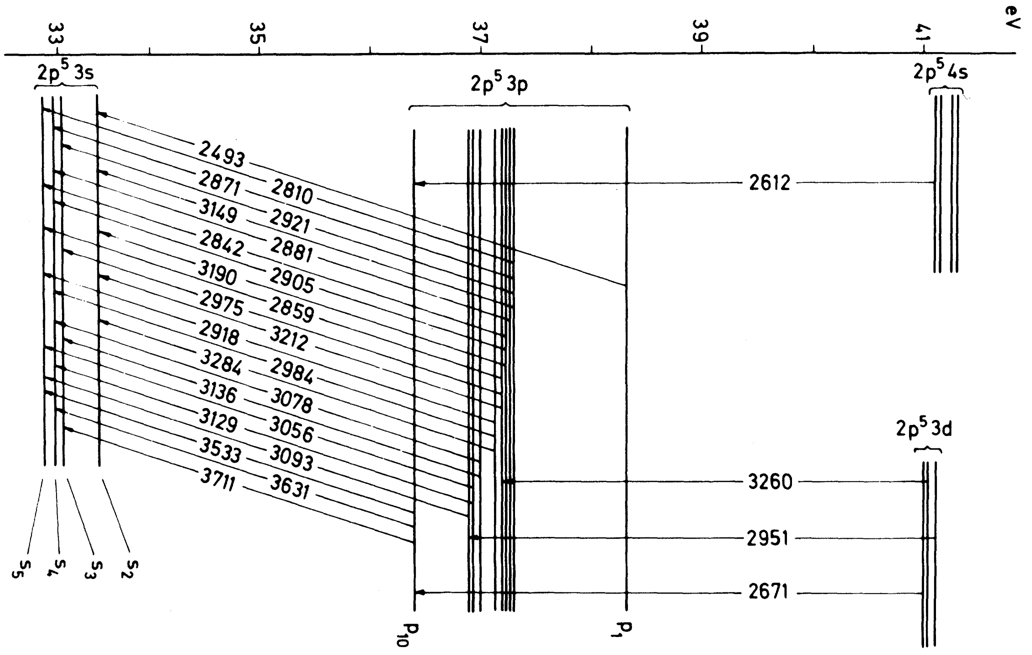

FIG. 1. Partial term diagram for Na II. The transitions used for lifetime measurements are indicated.

$3p$-$4s$ transitions, an intensity determination for all $3s$-$3p$ transitions was impossible; this prevented an evaluation of the transition probabilities for all thirty $3s$-$3p$ transitions.

The lifetime data for the measured 23 $2p^5\,3s$-$2p^5\,3p$ transitions in Na II are given in Table I.

The mean lives of the measured $2p^5 4s$ and $2p^5 3d$ levels are shorter than that of the $2p^5\,3p$ levels they populate. The $4s$ and $3d$ levels, which populate the p_{10} level through the 2612- and 2671-Å transitions, have 2.9 ± 0.3 and 2.3 ± 0.3 nsec mean lives, respectively. For the 2951 and 3260-Å $3p$-$3d$ transitions (Fig. 1), the mean lives were measured to be 4.3 ± 0.4 and 4.2 ± 0.4 nsec, respectively, for the two $3d$ levels. A cascade effect on some of the measured $2p^5\,3p$ levels cannot be excluded, but because of the low intensity of the $3p$-$3d$ and $3p$-$4s$ transition lines compared with the intensity of the $3s$-$3p$ lines, the cascading effect is limited.

For six of the $3s$-$3p$ transitions, a pure exponential decay was observed and no corrections for cascading were performed [Fig. 2(a)]. Since long-lived tails appeared on the other decay curves, cascading corrections were carried out for these

TABLE I. Measured mean lives in Na II (nsec).

LS			$3s\,^3P_2^0$	$3s\,^3P_1^0$	$3s\,^3P_0^0$	$3s\,^1P_1^0$	
	Racah		$3s[\frac{3}{2}]_2^0$	$3s[\frac{3}{2}]_1^0$	$3s'\,[\frac{1}{2}]_0^0$	$3s'\,[\frac{1}{2}]_1^0$	
		Paschen	$1s_5$	$1s_4$	$1s_3$	$1s_2$	Result
$3p\,^1S_0$	$3p'\,[\frac{1}{2}]_0$	$2p_1$	...[a]	...[b]	...[a]	2.9	2.9 ± 0.3
$3p\,^3P_1$	$3p'\,[\frac{1}{2}]_1$	$2p_2$	6.6[c]	6.7	5.8[c,d]	6.2[c]	6.5 ± 0.3
$3p\,^3P_0$	$3p\,[\frac{1}{2}]_0$	$2p_3$	...[a]	5.4	...[a]	...[b]	5.4 ± 0.3
$3p\,^3P_2$	$3p'\,[\frac{3}{2}]_2$	$2p_4$	6.5[c,d]	5.5[c,d]	...[a]	6.5[c]	6.5 ± 0.3
$3p\,^1P_1$	$3p'\,[\frac{3}{2}]_1$	$2p_5$	6.6	...[b]	6.4[c,d]	6.3[c]	6.5 ± 0.3
$3p\,^1D_2$	$3p\,[\frac{3}{2}]_2$	$2p_6$	7.2[c,d]	5.5[c,d]	...[a]	7.1[c]	7.1 ± 0.3
$3p\,^3D_1$	$3p\,[\frac{3}{2}]_1$	$2p_7$	...[b]	7.4[c]	7.8[d]	...[b]	7.4 ± 0.4
$3p\,^3D_2$	$3p\,[\frac{5}{2}]_2$	$2p_8$	5.5[c,d]	7.8	...[a]	...[b]	7.8 ± 0.4
$3p\,^3D_3$	$3p\,[\frac{5}{2}]_3$	$2p_9$	8.0	...[a]	...[a]	...[a]	8.0 ± 0.4
$3p\,^3S_1$	$3p\,[\frac{1}{2}]_1$	$2p_{10}$	9.3[c]	10.4[c]	9.5[c]	...[b]	9.7 ± 0.4

[a] Forbidden transition in j-1 coupling.

[b] Weak intensity.

[c] Cascading correction.

[d] Line mixture.

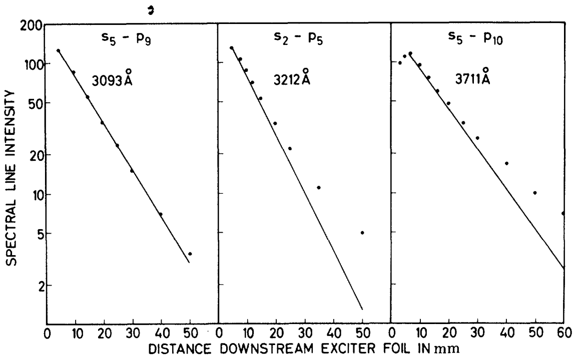

FIG. 2. The decay of the p_9 level (s_5-p_9 transition, 3093 Å), p_5 level (s_2-p_5 transition, 3212 Å), and the p_{10} level (s_3-p_{10} transition, 3711 Å) of Na II. The beam energy was 300 keV, carbon foil thickness 5 μg/cm^2.

17 lines. The corrections were usually a constant term [Fig. 2(b)]. The origin of this cascading has not been studied. Only for the 3s-3p transitions originating from the p_{10} level was cascading due to the 3p-4s and 3p-3d transitions observed [Fig. 2(c)]. The short-lived cascade population in Fig. 2(c) is in agreement with the measured mean lives for the levels populating the p_{10} level.

Magnesium. The beam-foil spectra of magnesium were studied from 2020 to 4500 Å with singly charged magnesium beams with energies of 100, 300, and 400 keV. The 13 spectral lines present between 2040 and 2530 Å could all be assigned to $2p^5 3s$-$2p^5 3p$ transitions in Mg III. Of the remaining spectral lines, eight were due to transitions in Mg II (2790, 2795, 2797, 2802, 2928, 2936, 3104, and 4481 Å), and eight to transitions in Mg I (2782, 2848, 2852, 2938, 3094, 3334, 3832, and 3838 Å).

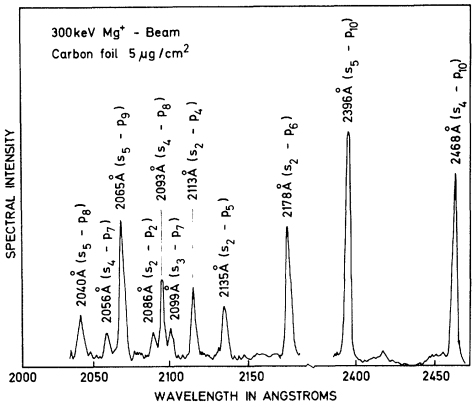

FIG. 3. Spectral scans (2030–2180 and 2390–2470 Å) obtained from a 300-keV Mg⁺ ion beam. All the lines present belong to 3s-3p transitions in Mg III.

Three lines in the spectral region 3300–3375 Å. have not been assigned. Figure 3 shows the spectral regions with the Mg III lines, which have been used for the mean life measurements.

Of the thirteen $2p^5 3s$-$2p^5 3p$ transitions in Mg III it was possible to use 11 for the determination of the mean lives of the p_2, p_4, p_5, p_6, p_7, p_8, p_9, and p_{10} levels. Transitions originating from the p_1 and p_3 levels were not present within the investigated spectral region.

All the decay curves could be resolved either in a pure exponential decay (e.g., the s_4-p_{10} and the s_2-p_2 transitions), or they could be resolved into two components, a major component due to the 3s-3p transition, and a minor cascading component with a long mean life, similar to the example shown in Fig. 2(b). Cascading effects as those seen in Fig. 2(c) have not been observed. Since the 3p-3d transitions all occur below 2000 Å, it has not been possible to determine the mean life of the $2p^5 3d$ levels. Through cascading, the 3p-3d transitions may populate the studied 3p levels. The results for the 3p levels are listed in Table II.

DISCUSSION OF ERRORS

The mean lives reported in Tables I and II are the average values of two to six determinations. The velocity of the beam after passing the carbon foil was known within 3%, and the accuracy of determining downstream positions was 0.05 mm, equivalent to 0.5–2% uncertainty in the present data. The intensity of the light emitted from a given foil at a given position was checked carefully before and after recording a decay curve. Only measurements giving repeatable intensity data were accepted for mean life determinations. The uncertainty in the exponential fit to the recorded decay curves and the uncertainty due to cascade corrections account for 2–5% in the present data. The experimental error for a single

TABLE II. Measured mean lives in Mg III.

Level	Transition	Wavelength (Å)	τ (nsec)
$2p_2$	s_2-p_2	2086	3.10 ± 0.10
$2p_4$	s_2-p_4	2113	3.00 ± 0.10
$2p_5$	s_2-p_5	2135	3.00 ± 0.10
$2p_6$	s_2-p_6	2178	3.35 ± 0.10
$2p_7$	s_3-p_7	2099	3.10 ± 0.15
$2p_7$	s_4-p_7	2056	3.30 ± 0.15
$2p_8$	s_4-p_8	2093	3.35 ± 0.15
$2p_8$	s_5-p_8	2040	3.35 ± 0.15
$2p_9$	s_5-p_9	2065	3.60 ± 0.15
$2p_{10}$	s_4-p_{10}	2468	4.95 ± 0.10
$2p_{10}$	s_5-p_{10}	2396	5.10 ± 0.15

TABLE III. Mean lives for the $2p^5\,3p$ levels in Ne I, Na II, and Mg III (nsec).

	Ref. 4 Ne I	Ref. 5 ±1−3% Ne I	Ref. 6 ±5% Ne I	Ref. 7 ±1−5% Ne I	Ref. 8 ±3% Ne I	Beam-foil ±2−5% Na II	Mg III
$2p_1$	14.7	14.4	14	15.2	14.45	2.9	···
$2p_2$	16.3	18.8	20	19.6	19.75	6.5	3.10
$2p_3$	23	17.6	18	17.0	25.4	5.4	
$2p_4$	22	19.1	24	20.9	26.3	6.5	3.00
$2p_5$	18.9	19.9	23	22.4	18.7	6.5	3.00
$2p_6$	22.0	19.7	21	23.1	28.9	7.1	3.35
$2p_7$	20.3	19.9	22	19.3	20.2	7.4	3.20
$2p_8$	24.3	19.8	25	23.4	27.8	7.8	3.35
$2p_9$	22.5	19.4	24	···	30.5	8.0	3.60
$2p_{10}$	···	24.8	26	27.8	43	9.7	4.95

measurement may be 5–10% relatively, whereas the average values have an uncertainty on 3–5%.

COMPARISON WITH NE I

Since 1966, five independent studies[4-8] of the mean lives of the $2p^5\,3p$ levels in Ne I have been reported. Table III lists the published data and the quoted errors. The beam-foil data indicate that the mean lives should be

$$p_{10} > p_9 \sim p_8 \sim p_7 \sim p_6 \geq p_5 \sim p_4 \sim p_2 > p_3 > p_1 .$$

The data of Bennett,[5] Oshirovich,[6] and Nodwell,[7] excluding p_7 in Nodwell's results, are all in excellent agreement with this prediction. Figure 4 shows a comparison between the experimentally observed mean lives of hyperfine levels in Na II and Mg III (this investigation) and the results for Ne I (Bennett[5] and Nodwell[7]). The data obtained by the gas-cell excitation technique[8] seem to differ significantly from the sequence above, particularly in the determination of the p_3, p_4, p_5, p_6, and p_7 levels. The tendency of the gas-cell technique to lead to excessively long mean lives has been observed before.[10]

The decrease in the mean lives of the $2p^5\,3p$ levels in the Ne I sequence may be compared with the $2p^5\,4s$ and $2p^5\,3d$ levels in the same sequence. The mean lives of the $3p$ levels are reduced from ~ 20 nsec for Ne I to ~ 7 nsec for Na II and ~ 3 nsec for Mg III. For the $4s$ and $3d$ levels, the decrease is one order of magnitude higher. The mean lives for the $4s$ and $3d$ levels in Ne I are 100–200 nsec,[7,11] but only 3–4 nsec for Na II. Our preliminary investigations of the $3p^5\,4p$ and $3p^5\,4d$ levels in the Ar I sequence have shown the same trend for Ar I, K II, and Ca III.

The observed Z dependence for the mean life values of the $3p$ and $4s$ levels in the Ne I sequence is in agreement with the Z dependence of the spontaneous transition probability per unit time for the $3s$-$3p$ and $3p$-$4s$ transitions. The spontaneous transition probability is proportional to the third power of the transition energy and to the multiplet strength of the transition. These two quantities can be expanded as functions of the atomic number Z, using, for example, the screening theory of atomic spectra suggested by Layzer[12] and applied by Linderberg.[13,14]

The transition energy is proportional to the second power in Z for the $3p$-$4s$ transition and to Z

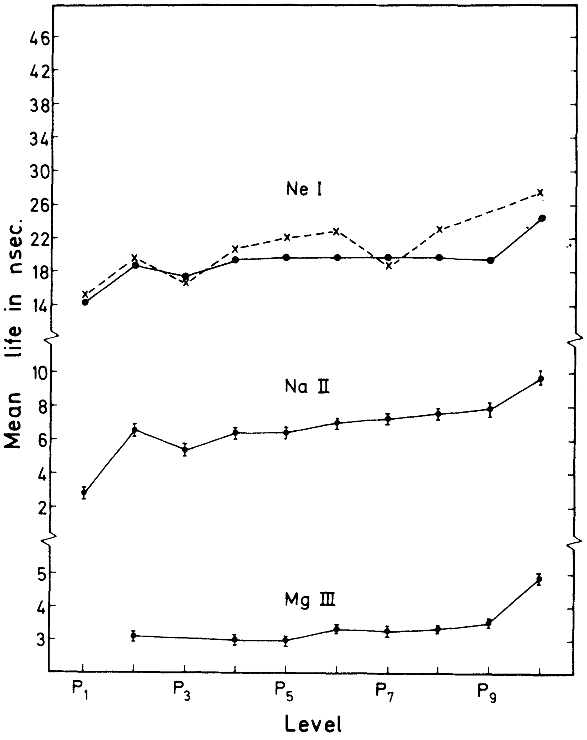

FIG. 4. Comparison between experimentally reported mean lives for Ne I^5(·), Ne I^7(×), Na II, and Mg III.

for the 3s-3p transition. Since the multiplet strength for both transitions will be proportional to Z^{-2}, the transition probability will be proportional to Z^4 for the 3p-4s transition and to Z for the 3s-3p transition. Taking the screening into account a calculation based upon the Z dependence for the mean life of the 3p levels in Ne I, Na II, and Mg III shows that the ratio between the mean lives for the 4s levels in Ne I and Na II should be 30–40, in reasonable agreement with the observed values.

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[1] *Beam-Foil Spectroscopy*, Vols. I and II, edited by S. Bashkin (Gordon and Breach, New York, 1968).

[2] K. Berkner, W. S. Cooper III, S. N. Kaplan, and R. V. Pyle, Phys. Letters 16, 35 (1965); I. Bergström, J. Bromander, R. Buchta, L. Lundin, and I. Martinson, *ibid.* 28A, 721 (1969); T. Andersen, K. A. Jessen, and G. Sørensen, *ibid.* 29A, 384 (1969); W. S. Bickel, I. Martinson, L. Lundin, R. Buchta, J. Bromander, and I. Bergström, J. Opt. Soc. Am. 59, 830 (1969).

[3] W. S. Bickel and S. Bashkin, Phys. Letters 20, 488 (1966); B. Cornutte, W. S. Bickel, R. Girardeau, and S. Bashkin, *ibid.* 27A, 680 (1968); W. S. Bickel, R. Girardeau, and S. Bashkin, *ibid.* 28A, 154 (1968); T. Andersen, K. A. Jessen, and G. Sørensen, *ibid.* 28A, 459 (1968); Phys. Rev. 188, 76 (1969); I. Bergström, J. Bromander, R. Buchta, L. Lundin, and I. Martinson, Phys. Letters 28A, 721 (1969).

[4] J. Z. Klose, Phys. Rev. 141, 181 (1966).

[5] W. R. Bennett and P. J. Kindlmann, Phys. Rev. 149, 38 (1966).

[6] A. L. Oshirovich and Y. V. Verolainen, Opt. i Spektroskopiya 22, 181 (1967) [Opt. Spectry. (USSR) 22, 329 (1967)].

[7] R. A. Nodwell, H. W. H. van Andel, and A. Robinson, J. Quant. Spectr. Radiative Transfer 8, 859 (1968).

[8] A. Denis, J. Desesquelles, and M. Dufay, Compt. Rend. 266B, 1016 (1968).

[9] T. Andersen, K. A. Jessen, and G. Sørensen, J. Opt. Soc. Am. 59, 1197 (1969).

[10] See T. Andersen *et al.*, Ref. 2.

[11] W. R. Bennett, P. J. Kindlmann, and G. N. Mercer, Appl. Opt. Suppl. 2, 34 (1965).

[12] D. Layzer, Ann. Phys. (N.Y.) 8, 271 (1959).

[13] J. Linderberg, J. Mol. Spectr. 9, 95 (1962).

[14] J. Linderberg, Phys. Letters 29A, 467 (1969).

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Analytically Solvable Problems in Radiative Transfer. II

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In the previous paper, the Biberman-Holstein integral equation was solved for a slab and for all line shapes of interest in the limit of high optical depth. The eigenfunctions and eigenvalues obtained are used for the general calculation of the stationary number density in the excited state, when collisional excitation and deexcitation takes place, when excitation takes place by absorption of external radiation, or by both combined. General expressions are given for the line shape of a spectral line emitted by an optically dense slab, showing typical broadening and self-reversal.

I. INTRODUCTION

In many plasmas, the assumption of (local) thermodynamic equilibrium for the number densities of atoms in low-lying levels is invalid. It is therefore necessary to solve the rate equations directly. For most levels, it can be assumed that the plasma is optically thin so that the radiation escapes without being absorbed. Resonance lines are severely absorbed, however, and allowance for this effect must be included. Up to now this has been done by fairly rough approximations[1] or by numerical calculations.[2] In a preceding paper[3] (hereafter referred to as I), we solved the transfer equation, when the optical depth was large, for a number of line shapes, Doppler profiles