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MEANLIFE MEASUREMENTS IN MANGANESE I AND II AND THULIUM II

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Radiative lifetimes in Mn I, Mn II and Tm II have been measured from beam-foil spectra in the wavelength region 2500–5000 Å, using 249 keV Mn^{+++} and Tm^{+++} ions from the Stockholm electromagnetic isotope separator. Post-foil particle velocities were measured using an electrostatic energy analyzer. Transitions were selected for study on the basis of their previous use in the determination of solar photospheric abundances. The measured lifetimes in Mn I are 2–6 times longer than those inferred by the *gf* values of Corliss and Bozman, and in Mn II the lifetimes show a trend to be similarly longer than those inferred by the emission measurements of Warner. Our results thus suggest and upward revision by 0.5 dex of the solar photospheric Mn abundance. Contrarily, our Tm II lifetimes are shorter than those inferred by the values of Corliss and Bozman, and suggest a reduction by 0.38 dex of the solar photospheric Tm abundance.

1. Introduction

We have investigated atomic mean lives in Mn I, Mn II and Tm II in the wavelength region 2500–5000 Å. Efforts were made to measure those lines which have been used in the determination of the presently accepted Mn and Tm abundances for the solar photosphere.

2. Manganese

The 83 keV isotope separator at the Research Institute for Physics in Stockholm was used to produce a 249 keV beam of Mn^{+++} and the foil emergent energies (typically 190 keV) were measured directly using an electrostatic analyzer. Theoretical estimates of foil scattering of the beam out of the viewing volume were made which indicated a negligible effect for positions less than 45 ns from the foil, increasing slowly to a 20% correction 100 ns from the foil. The length of the beam viewed by the detection array corresponded to 0.6 ns, so the range of reliably measurable meanlives was about 1–40 ns.

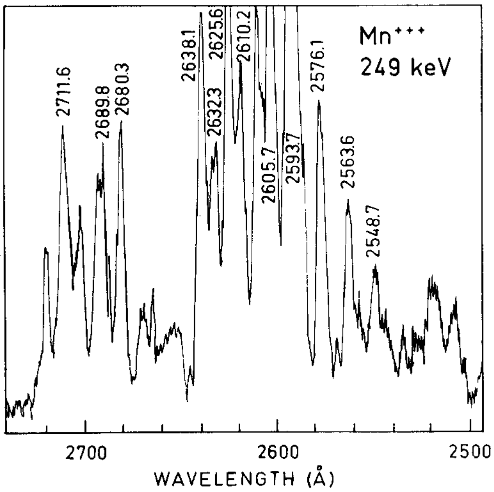

Fig. 1. Beam-foil spectrum of Mn between 2500 and 2740 Å, registered with a Heath 30 cm monochromator, equipped with an EMI 6256S photomultiplier. Most of the observed lines in this region belong to Mn II multiplets. Note the high line density which demands careful studies of the blending problems on beam-foil spectra.

A spectral scan of the region 2500–2700 Å is shown in fig. 1. The resolution in this region was about 5 Å, which agrees with estimates of Doppler broadening and

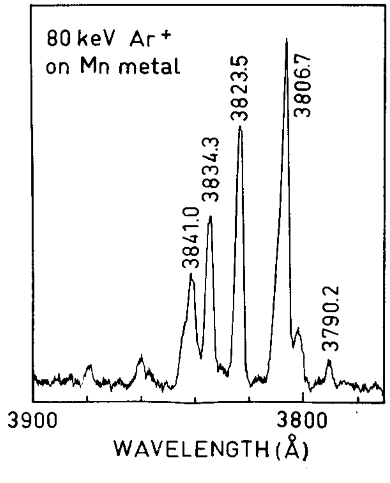

Fig. 2. Partial spectrum of Mn, obtained by bombarding a solid Mn target with 80 keV Ar^+ ions. The strongest lines belong to the Mn I a ^6D–z $^6F^0$ multiplet.

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[*] Presented the paper.

instrumental acceptance. In this region, seven decay curves arising from five multiplets were measured. For example all three components of the Mn II a ^{7}S–z ^{7}P^0 resonance septet were measured; they are clearly seen at λλ 2576.1, 2593.7 and 2605.6 Å. Although Mn II was much stronger than Mn I in our spectra, blending was not severe since most Mn II transitions lie below 3500 Å and most Mn I transitions lie above 3800 Å. To aid in our identification, we were able to obtain an intense in-beam comparison spectrum of Mn I by bombarding a solid Mn target by a 20 μA argon beam and observing the light from the backsputtered Mn. A spectrum obtained in this manner is shown in fig. 2. Very favorable signal-to-noise ratios were obtained with a resolution of 3 Å. With the exception of two small Fe peaks to the left (due to a steel screw in the sample holder) all prominent peaks in this scan arise from the Mn I a ^{6}D–z ^{6}F^0 multiplet, and have approximately the same intensity ratios as reported in emission studies. There was good general agreement between the Mn I lines which appeared in our sputtering spectra and those which appeared in our beam-foil spectra. A notable exception occurred for the Mn I resonance multiplet transitions at λλ 4031, 3, 4 Å which were the strongest lines in our sputtering spectra, but were barely discernable in our beam-foil spectra.

Sample decay curves are shown in fig. 3, for the three components of the multiplet a ^{7}S–z ^{7}P^0. The three decay curves are consistent with a common mean life of 4.5 ± 0.4 ns. Although cascade corrections were necessary in a few cases, our decay curves were generally describable by a single exponential, indicating either that cascading was weak and hidden in the noise, or else completely dominated the process. In an attempt to resolve this question, searches were made for radiation corresponding to the cascade transitions. For example, for the Mn II z ^{7}P^0 level we would expect the principal cascades to come from e ^{7}D at λλ 2428, 38, 52 Å and from e ^{7}S at λλ 2762, 96 Å. Our spectra showed no appreciable intensities at these wavelengths. Similar cascade searches for other transitions generally indicated that cascading did not have a strong effect in our decay curves.

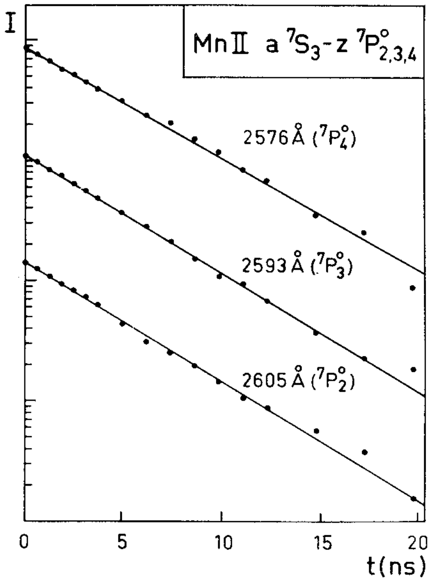

Fig. 3. Examples of experimental decay curves. The mean lifetime of the Mn II z ^{6}P^0 term was measured from all three J-states of the upper term, $J = 4$ (2576 Å), $J = 3$ (2593 Å) and $J = 2$ (2605 Å). These decay curves are consistent with a z ^{6}P^0 lifetime of 4.5 ± 0.4 ns.

The results of our meanlife measurements in Mn I are shown in table 1. Our results can be compared with the lifetimes inferred from four sets of reported values: those of Woodgate[1]), Allen and Asaad[2]), Allen[3]), and Corliss and Bozman[4]). Our results are clearly in close agreement with those of Woodgate, Allen and Asaad, and Allen, but are from 2–6 times longer (with an average of approximately 3) than the values of Corliss and Bozman. There are some additional consistencies within these results since Woodgate based his f-value normalization on the Penkin scale[5]), which is a factor of 3 lower than the Corliss and Bozman scale for the λλ 3216, 24 Å Mn I doublet which was measured by both. Further, Allen and Asaad normalized to the absolute f-values of the Mn I resonance multiplet determined by Huldt and Lagerqvist[6]) and Bell et al.[7]), with which the Penkin scale agrees well. Thus our measurements seem to support a reduction of the Corliss and Bozman scale by a factor of approximately 3 (0.5 dex) for these transitions, which include the z ^{6}D^0 and z ^{4}P^0, used in the solar photospheric Mn I abundance determination.[8])

The results of our Mn II meanlife measurements for which comparisons are available are shown in table 2 [a complete list of our Mn lifetime measurements will be published elsewhere[9])]. We have listed as sources for comparison the emission measurements of Corliss and Bozman[4]), and three sets of values obtained by Warner[10]) based upon emission measurements, theoretical calculations using the Coulomb approximation, and the results of a renormalization of the values of Corliss and Bozman. Our meanlives are from 3.5 to 10 times longer than those inferred by Corliss and Bozman, and are about 4 times longer than Warner's emission measurement for e ^{5}S. For the z ^{5}P^0 level, Warner measured only the 3442 Å branch, so the value quoted represents

TABLE 1

Radiative lifetimes in Mn I.

Upper term	Wavelength (Å)	Lifetime (ns) This work	Woodgate[a]	Allen and Asaad[b]	Allen[c]	Corliss and Bozman[d]
z $^{6}\mathrm{D}^{0}$	4049, 4083	10.9 ± 1.5	12	8.9	11	2.7
z $^{6}\mathrm{F}^{0}$	3806, 3823	20 ± 3	18	8.7	9.3	3.3
z $^{4}\mathrm{F}^{0}$	4764	15 ± 3	20	17	14	6.0
e $^{6}\mathrm{D}$	4456	11 ± 2	20			5.2
z $^{2}\mathrm{I}$	4626	16 ± 3	28			10

[a] B. Woodgate, Monthly Notices Roy. Astron. Soc. **134** (1966) 287. Emission measurement.

[b] C. W. Allen and A. S. Asaad, Monthly Notices Roy. Astron. Soc. **117** (1957) 36. Emission measurement.

[c] C. W. Allen, Monthly Notices Roy. Astron. Soc. **121** (1960) 299. Theory (Coulomb approximation).

[d] C. H. Corliss and W. R. Bozman, Nat. Bur. Std. Monograph no. 53 (1962). Emission measurement.

TABLE 2

Radiative lifetimes in Mn II.

Upper term	Wavelength (Å)	Lifetime (ns) This work	Warner[a*]	Warner[a†]	Warner[a+]	Corliss and Bozman[b]
z $^{7}\mathrm{P}^{0}$	2576, 2593, 2605	4.5 ± 0.4		7.3	3.3	1.3
z $^{5}\mathrm{P}^{0}$	2933, 2939, 2949, 3442	5.4 ± 0.5	3.0[c]	3.1	4.2	0.56
z $^{5}\mathrm{G}^{0}$	2708	5.3 ± 0.5		3.0	3.3	1.0
e $^{5}\mathrm{S}$	3029	7.0 ± 0.7	1.6		3.3	

[a] B. Warner, Mem. Roy. Astron. Soc. **70** (1967) 165. * Emission measurement; † renormalization of the Corliss and Bozman scale; + theory (Coulomb approximation).

[b] C. H. Corliss and W. R. Bozman, Nat. Bur. Std. Monograph no. 53 (1962). Emission measurement.

[c] Upper limit, with one branch neglected.

only an upper limit to the lifetime inferred from his scale. Woodgate also measured this branch of the Mn II z $^{5}\mathrm{P}^{0}$ level, in an attempt to use his Mn I results to base an Mn II scale on the Penkin scale. He found his *f*-values were 0.60 dex lower than those of Warner if he used the Penkin scale, but agreed with Warner if he used the Corliss and Bozman scale. Thus our results support Woodgate's suggestion of a 0.6 dex reduction of Warner's scale for Mn II, from which Warner estimated the solar photospheric Mn II abundance.

Since the present Mn I and Mn II photospheric abundances are in general agreement, the upward revision by 0.5 dex suggested by our results would yield $\log N(\mathrm{Mn}) = 5.4$ [on a scale where $\log N(\mathrm{H}) = 12.00$], which brings us closer to the coronal abundance of 5.9[11]) and in reasonable agreement with the meteoritic abundance of 5.2[12]).

3. Thulium

In connection with these comments on solar abundances, I would like also to mention some interesting results which we have recently obtained in a meanlife study of the rare earths which we have undertaken. The photospheric abundance of thulium was determined by Gevesse and Blanquet[13]) on the basis of equivalent width measurements of 4 lines in Tm II, using the *gf* values of Corliss and Bozman. We have measured the meanlives of these lines, using Tm^{+++} ions and the same experimental array as was used for Mn, and our results are shown in table 3. Here, our measured lifetimes are *shorter* than those inferred by Corliss and Bozman by an average factor of 1/2.4 (−0.38 dex). If we adjust Grevesse and Blanquet's abundance downward by this amount, we obtain $\log N(\mathrm{Tm\ II}) = 0.05 \pm 0.20$. Since the meteoretic abundance is $\log N(\mathrm{Tm}) = 0.90$ [14]) this revision removes the disagreement between the thulium abundance in the solar photosphere and meteoritic determinations.

Thus, while there is much evidence favoring a *downward* revision of the *gf* values of Corliss and

TABLE 3

Radiative lifetimes in Tm II.

Upper term	Wavelength (Å)	Lifetime (ns) This work	Lifetime (ns) Corliss and Bozman
29967	3362	11	33
28875	3462	26	44
27254, 27009	3700, 3701	34	89

Bozman for certain elements of the iron group, there is also evidence favoring an *upward* revision of the *gf* values of Corliss and Bozman for at least one member of the rare earth group.

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[10]) B. Warner, Mem. Roy. Astron. Soc. **70** (1967) 165.

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[12]) H. E. Seuss and H. C. Urey, Rev. Mod. Phys. **28** (1956) 53.

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Discussion

P. SMITH: This comment is not just on Dr Curtis' work but on the several papers that we have heard on the second spectra of the iron group. We heard Pinnington, Lutz and Carriveau, who discussed chromium, cobalt, and manganese; Roberts, Andersen and Sørensen, who discussed titanium; and Curtis, Martinson and Buchta, who discussed manganese. In all these papers, I believe that there has been comparison with the work of Brian Warner, who made quite an extensive measurement of the second spectra of the iron group lines in about 1967. I would like to suggest that, because of errors involved in Warner's analysis, his results are meaningless, but that there is a correction that could be made to them.

His analysis, which gave the oscillator strengths from the line intensities seen on the photographic plates, required use of the "known" oscillator strength for the neutral atoms of the elements studied. In the case of Fe I, these were the Corliss and Bozman results or, actually, the Corliss and Warner results. This work has been shown to contain an excitation-potential-dependent error, a fact that was pointed out by Wiese at the Lysekil conference. The use of the incorrect oscillator strengths meant that Warner made an error in the estimation of his source temperature – in fact, a crude estimate indicates that the temperature may have been close to 10 000°, whereas Warner thought it was only 6100°.

Warner normalized his results by comparing with some calculated f values. However, he found that his normalization function was not constant, but that it was a function of the excitation potential of the upper levels studied. This, of course, was a consequence of temperature error.

Ward Whaling and I have found that if the temperature error in Warner's work is corrected, and if the excitation-potential-dependent normalization function is removed from Warner's results, the ratio of Warner's f-values to those of several other researchers is essentially constant. This other work is our beam-foil work, the shock-tube work of Grasdalen et al. at Harvard, and Wolnik et al. at the Air Force Cambridge Research Laboratory, and the wall-stabilized arc work of Baschek et al. at Kiel. There are four experiments with three different methods. As I said, the ratio of Warner's f-values to this work is essentially constant, as a function of excitation potential, and wavelength and f-value. A paper describing this work will be submitted to the Astrophysical Journal very shortly and preprints will be available.

We believe that the temperature error probably affects all of Warner's work on the second spectra of the iron group elements and thus a correction should be applied before comparison with Warner's f-values. This could, of course, be confirmed by the beam-foil research and I would be interested to see if this other work actually agrees with our correction to Warner's work. As was pointed out in my paper, Warner's work was used for many abundance calculations in this group of elements, and it is urgent to determine the accuracy of his f-values.