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Oscillator Strengths for Some Mn II Lines and the Solar Mn Abundance

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Abstract

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Oscillator strengths are given for transitions belonging to the $a\,{}^5S{-}z\,{}^5P^0$ and $a\,{}^5D{-}z\,{}^5P^0$ multiplets in Mn II. The data originate from beam-foil measurements of the $z\,{}^5P^0_{1,2,3}$ level lifetimes and branching-ratio determinations. Theoretical *f*-values are also given for these transitions, the agreement between experiment and theory being satisfactory. Using the experimental *gf*-values obtained in this work and empirical solar models, the solar abundance of Mn has been determined to be $\log N_{\mathrm{Mn}} = 5.4 \pm 0.2$ (on the $\log N_{\mathrm{H}} = 12.00$ scale).

1. Introduction

In connection with astrophysical studies of element abundances it is of great importance to have access to reliable absolute oscillator strengths (*f*-values) for the second spectra of the iron-group elements. Many such *f*-values have been determined by Warner [1] by an emission technique. It is difficult to avoid systematic uncertainties in such measurements, but recently Smith [2] has found corrections which should be applied to Warner's data. It is also important to determine *f*-values by other techniques, and the beam-foil method is an obvious alternative. However, most excited levels in singly-ionized iron-group elements decay to several lower terms and thus the lifetime data from beam-foil experiments cannot be converted directly into *f*-values. The additional information needed concerns relative transition probabilities or branching ratios. Several authors have therefore combined lifetime and branching-ratio measurements for the iron group elements, see e.g. ref. [3]. In the present paper we report such work for some transitions in Mn II.

A few years ago Martinson et al. [4] made a beam-foil study of Mn I and Mn II lifetimes using an 80 kV isotope separator at the Research Institute of Physics, Stockholm. The Mn I data agreed very well with the results of Woodgate [5] who used an emission method. In the case of Mn II the beam-foil lifetimes exceeded those computed from Warner's *gf*-values by typically 30–40%. Results very similar to those of ref. [4] were independently obtained by Pinnington and coworkers [6, 7] who also used the beamfoil method.

The previous beam-foil measurements of Mn had interesting astrophysical consequences. The lifetimes gave strong support to Woodgates's Mn I *f*-values which typically are four times lower than those employed by Müller and Mutschlecner [8] in their study of the Mn abundance in the solar photosphere. The beam-foil data thus justify a revision of the estimated solar abundance from $\log N_{\mathrm{Mn}} = 4.80$ (on the $\log N_{\mathrm{H}} = 12.00$ scale)—given in ref. [8]—to $\log N_{\mathrm{Mn}} = 5.4$, in excellent agreement with the values $\log N_{\mathrm{Mn}} = 5.42$ and 5.41, given by Blackwell et al. [9] and Margrave [10], respectively. These values are significantly higher than Warner's [11] value $\log N_{\mathrm{Mn}} = 4.88$, which is largely based on his *f*-values for the $a\,{}^5D{-}z\,{}^5P^0$ multiplet of Mn II. It was suggested in ref. [4] that Warner's $a\,{}^5D{-}z\,{}^5P^0$ *gf*-values could be in error by a much larger amount than the average difference between the lifetimes obtained from beam-foil experiments and those computed from the data in ref. [1]. This suggestion was supported by the fact that Woodgate [5] also gave *f*-values for five lines belonging to the $a\,{}^5D{-}z\,{}^5P^0$ multiplet, the differences between refs. [1] and [5] ranging from factors 2 to 9. A remeasurement of the $a\,{}^5S{-}z\,{}^5P^0$ and $a\,{}^5D{-}z\,{}^5P^0$ *f*-values was therefore worthwhile.

2. Experiment

Our task was to obtain reliable absolute *f*-values for allowed transitions depopulating the Mn II $z\,{}^5P^0_{1,2,3}$ levels at 43 370–43 557 cm^{-1}. The decay is illustrated in Fig. 1.

In view of several experimental improvements undertaken at the Research Institute of Physics after the conclusion of ref. [4] a new lifetime measurement was motivated. The beam of Mn$^+$ ions was obtained from the 400 kV Nucletec heavy-ion accelerator and sent through carbon foils of accurately known thickness. The higher terminal voltage of the new machine allowed lifetime work at several beam energies. It was also possible to obtain more favourable signal-to-noise ratios than in ref. [4] and thus work at higher spectral resolution. In ref. [4] comparatively high energy losses in the foils were reported for 250 keV Mn ions, values which have not been confirmed by other investigators. A possible explanation is that foil-thickening effects were underestimated in the earlier work. In the present study we have chosen to use the semi-empirical energy loss values according to the

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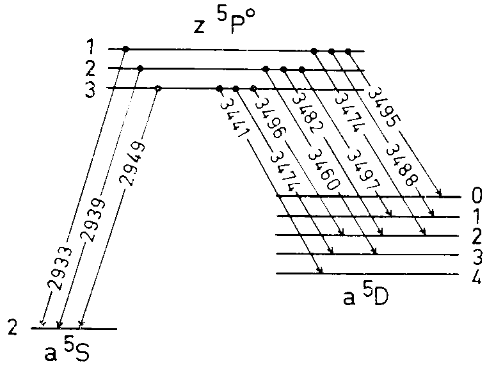

Fig. 1. Schematic illustration of the decay of the $z\,^5P^c$ term to $a\,^5S$ and $a\,^5D$.

Table I. *Lifetimes of the* $z\,^5P^0_{1,2,3}$ *levels in Mn II (beam-foil data)*

Level	Lifetime (ns) ([a])	([b])	([c])	([d])
$z\,^5P^0_1$	4.4±0.6			
$z\,^5P^0_2$	4.3±0.5	5.3±0.5	4.1±0.2	5.2±0.5
$z\,^5P^0_3$	4.6±0.5	5.4±0.5	3.6±0.3	5.0±0.5

[a] This work.
[b] Martinson et al. [4].
[c] Pinnington et al. [6].
[d] Pinnington and Lutz [7].

procedure recommended by Roberts et al. [3]. Unfortunately there was no suitable electrostatic analyzer at the Research Institute for Physics when the lifetime measurements reported here were performed.

Fig. 2 shows a section of a beam-foil spectrum above 2 900 Å with the Mn II lines at 2 933, 2 939 and 2 949 Å ($a\,^5S_2$–$z\,^5P^0_{1,2,3}$). The observed intensity ratio differs from the expected one (3 : 5 : 7 in *LS*-coupling) but this is largely due to a blend at 2 940 Å from Mn I lines. The relative intensities of the 2 939 and 2 940 Å lines varied much less with the beam energy than we would have expected for lines belonging to different spectra. This fact may indicate additional blends at 2 940 Å. No strong Mn II and Mn III lines have been listed close to 2 940 Å, however [11].

Two examples of the decay curves for the 2 949 Å line are shown in Fig. 2. The curves were satisfactorily fitted to two well separated exponentials plus a small background. In ref. [4] we concluded that most decays were single exponentials. However, with the more favourable signal-to-noise ratio in the new experiment it was possible to follow the decays over longer time intervals and thereby obtain information about weak cascading processes. The decay curves for the 2 933 and 2 939 Å lines were similar to those shown in Fig. 2. The decay of the 2 939 Å line was studied on the short-wavelength side to minimize the effect of blends. The results obtained for the 2 933, 2 939 and 2 949 Å lines were confirmed by measurements on $a\,^5D$–$z\,^5P^0$ transitions (3 441–3 495 Å) but since these lines were weaker the statistics are poorer. The lifetime results are given in Table I where we also make comparisons with previously determined data.

The branching ratios for the $a\,^5S$–$z\,^5P^0$ and $a\,^5D$–$z\,^5P^0$ transitions were measured at the California Institute of Technology, using a 5 m Paschen–Runge spectrometer, described by Lennard et al. [3]. The spectrometer was calibrated against a tungsten-strip radiance standard. The cathode was made of Spec Mn powder, 0.999 purity, sintered to a solid and machined. The

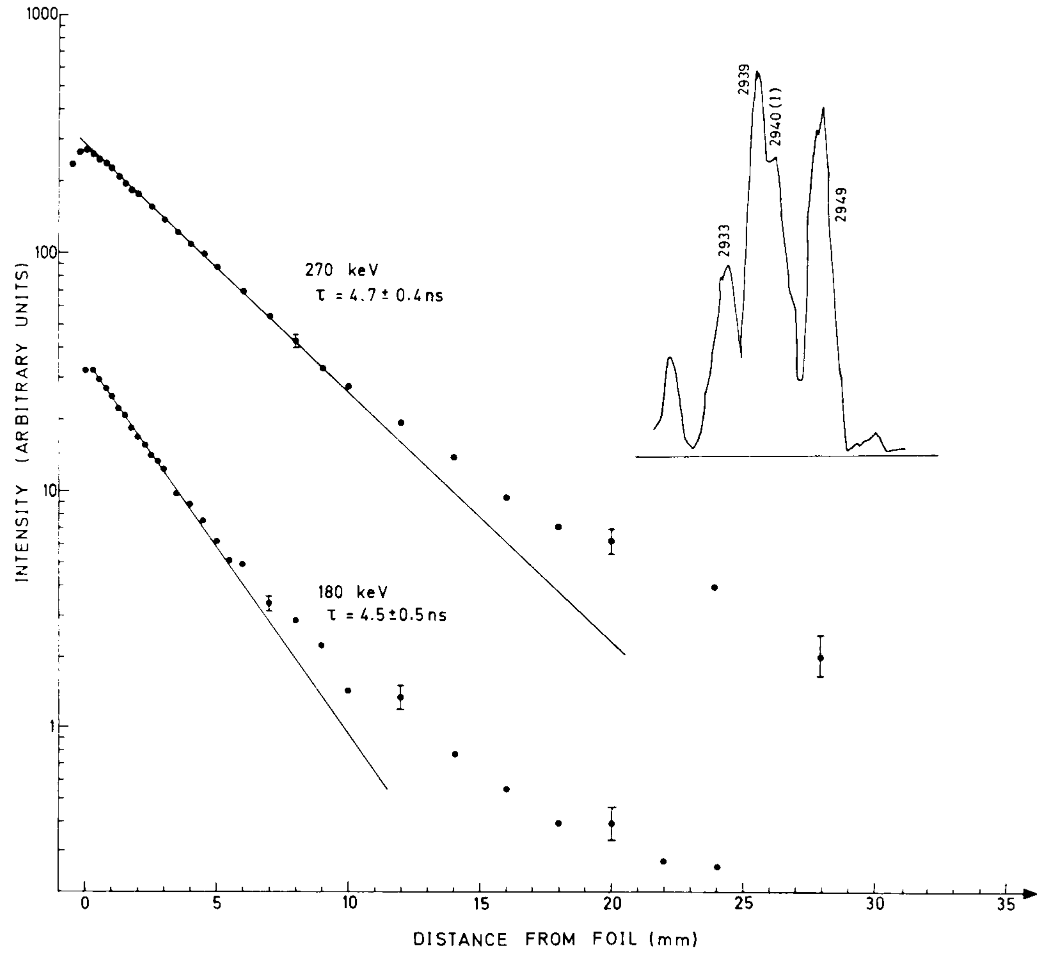

Fig. 2. Two examples of decay curves for the 2 949 Å line ($a\,^5S_2$–$z\,^5P^0_3$) measured at different ion energies. The $a\,^5S$–$z\,^5P^0$ multiplet, as it appears in beam-foil spectra, is also shown.

Table II. *Branching ratios in Mn II*

Wavelength/Å	Transition	Branching ratio
2 933.06	$a\,^5S_2\text{–}z\,^5P^0_1$	0.770
3 474.124	$a\,^5D_2\text{–}z\,^5P^0_1$	0.0673
3 488.67	$a\,^5D_1\text{–}z\,^5P^0_1$	0.112
3 495.381	$a\,^5D_0\text{–}z\,^5P^0_1$	0.0501
2 939.3	$a\,^5S_2\text{–}z\,^5P^0_2$	0.753
3 460.312	$a\,^5D_3\text{–}z\,^5P^0_2$	0.139
3 482.9	$a\,^5D_2\text{–}z\,^5P^0_2$	0.0861
3 497.536	$a\,^5D_1\text{–}z\,^5P^0_2$	0.0219
2 949.2	$a\,^5S_2\text{–}z\,^5P^0_3$	0.756
3 441.98	$a\,^5D_4\text{–}z\,^5P^0_3$	0.201
3 474.032	$a\,^5D_3\text{–}z\,^5P^0_3$	0.0364
3 496.814	$a\,^5D_2\text{–}z\,^5P^0_3$	0.0074

branching ratios are given in Table II. The values listed are the average of several runs and the repeated measurements agreed within 10%. However, the system was calibrated between 3 000 and 7 500 Å and some uncertainty is introduced by the fact that the $a\,^5S\text{–}z\,^5P^0$ multiplet is around 2 940 Å. It was estimated that the efficiency drops by 4% between 3 000 and 2 940 Å. The branching-ratios in Table II should therefore be accurate to within 10–15%.

3. Results and discussion

Our new lifetime data are in satisfactory agreement with previous values (Table I). It can be noted, however, that the results of the present investigation are 15–20% lower than those in ref. [4] and the errors barely overlap. A few per cent of this discrepancy is due to different approaches to the energy-loss problem (discussed above) while the main part can be explained by the increase in sensitivity which reduced the influence of possible blends and made it possible to obtain better decay curves.

Table III. *Oscillator strengths for Mn II lines belonging to the* $a\,^5S\text{–}z\,^5P^0$ *and* $a\,^5D\text{–}z\,^5P^0$ *multiplets*

Wavelength (Å)	Transition	log *gf* ([a])	([b])	([c])	([d])	([e])	([f])
2 933.06	$a\,^5S_2\text{–}z\,^5P^0_1$	−0.17	−0.01	0.03 α −0.03 β		−0.06	−0.65 −0.71
2 939.30	$a\,^5S_2\text{–}z\,^5P^0_2$	0.06	0.21	0.09 β		0.16	−0.59
2 949.20	$a\,^5S_2\text{–}z\,^5P^0_3$	0.18	0.35	0.19 β		0.31	−0.49
3 474.12	$a\,^5D_2\text{–}z\,^5P^0_1$	−1.08	−0.87	−0.51 γ	−1.20	−1.19	−1.19
3 488.67	$a\,^5D_1\text{–}z\,^5P^0_1$	−0.86	−0.77	−0.51 β	−0.75	−1.09	−1.19
3 495.83	$a\,^5D_0\text{–}z\,^5P^0_1$	−1.20	−1.12	−0.65 α −0.68 β	−1.20	−1.44	−1.33 −1.36
3 460.31	$a\,^5D_3\text{–}z\,^5P^0_2$	−0.54	−0.45	−0.23 β		−0.76	−0.91
3 482.9	$a\,^5D_2\text{–}z\,^5P^0_2$	−0.74	−0.66	−0.32 β		−0.97	−1.00
3 497.53	$a\,^5D_1\text{–}z\,^5P^0_2$	−1.33	−1.25	−0.73 α −0.75 β	−1.34	−1.56	−1.41 −1.43
3 441.98	$a\,^5D_4\text{–}z\,^5P^0_3$	−0.27	−0.16	0.05 β		−0.47	−0.63
3 474.03	$a\,^5D_3\text{–}z\,^5P^0_3$	−1.00	−0.75	−0.44 γ		−1.06	−1.12
3 496.81	$a\,^5D_2\text{–}z\,^5P^0_3$	−1.69	−1.60	−1.04 α −1.07 β	−1.76	−1.91	−1.72 −1.75

[a] This work, experiment.
[b] This work, theory.
[c] Warner [1] emission measurements (α), revision of CB scale (β), Warner [11] corrected value (γ).
[d] Woodgate [5] emission measurement.
[e] Kurucz and Peytremann [13] theory.
[f] Correction of Warner *f*-values by the Smith method [2]. The correction is $\log gf = \log (gf)_W - 0.68$ (see text).

Table IV. *Solar abundance of manganese deduced from Mn II lines*

W_λ (mÅ) = Measured equivalent widths, in mÅ. The following models have been adopted: (1) Harvard Smithsonian Reference Atmosphere [18], (2) model of Vernazza et al. [20], (3) revised Holweger model [19]

	Abundance				
λ (Å)	W_λ (mÅ)	(1)	(2)	(3)	Weight
3 474.12	140.	5.38	5.50	5.49	2
3 488.67	135.	5.12	5.24	5.24	2
3 495.83	128.	5.40	5.52	5.51	2
3 460.31	158.	4.98	5.10	5.11	2
3 482.90	153.	5.16	5.29	5.28	2
3 497.53	114.	5.38	5.49	5.46	3
3 441.98	235.	5.07	5.19	5.20	1
3 474.03	181.	5.56	5.68	5.68	1
3 496.81	111.	5.63	5.74	5.73	3

More detailed information can be obtained from the *f*-values. In Table III such information is summarized in the form of log *gf* where *g* is the statistical weight of the lower level.

Combining the lifetime and branching-ratio uncertainties we obtain estimated uncertainties of ±20% for our *gf*-values. There are several other lower terms which combine with $z\,^5P^0$, e.g. $a\,^7S$ (2 300 Å), $a\,^5P$ (7 400 Å) and $b\,^5D$ (9 400 Å). According to ref. [12] all these transitions are quite weak compared to the lines of the $a\,^5S\text{–}z\,^5P^0$ and $a\,^5D\text{–}z\,^5P^0$ multiplets. This is in agreement with the semi-empirical calculations of Kurucz and Peytremann [13] according to which the probability of the $a\,^7S\text{–}z\,^5P^0$ intercombination multiplet is of the order of 10^6 s^{-1} while the decays to $a\,^5P$ and $b\,^5D$ terms have probabilities smaller than 10^5 s^{-1}. A neglect of these branches therefore introduces an error in our *f*-values well below 1%.

In Table III we compare our *f*-values for the $a\,^5S\text{–}z\,^5P^0$ and $a\,^5D\text{–}z\,^5P^0$ lines to the theoretical values given in ref. [13]. The overall agreement is satisfactory. We also include new theoretical *gf*-values, calculated by one of us (E. B.) by means of the scaled Thomas–Fermi method as described in ref. [14]. These recent theoretical *f*-values are, with a few exceptions, in very good agreement with our experimental data. Theory and experiment seem to be in particularly good accord for the $a\,^5D\text{–}z\,^5P^0$ lines whereas the theoretical *f*-values are slightly but significantly higher than the experimental ones for the $a\,^5S\text{–}z\,^5P^0$ branch. Table III further shows that our theoretical and—in particular—experimental values confirm the *f*-values for five Mn II lines, given by Woodgate [5]. The *gf*-values of Warner [1] quoted in Table III were determined by him in several ways. Some of the values came from emission measurements while the majority are corrected Corliss and Bozman [15] data, the correction factor being −0.74 dex. For two lines, 3 474.03 Å and 3 474.12 Å revised values are given in ref. [11].

Table III makes clear that Warner's *f*-values for the $a\,^5D\text{–}z\,^5P^0$ lines are far too high. We have therefore confirmed the suggestion in ref. [4] that the data for the $a\,^5D\text{–}z\,^5P^0$ branch, used in the solar abundance determination from Mn II transitions [11], contain much larger systematic errors than a comparison of lifetimes would indicate. The $z\,^5P^0$ lifetime is namely strongly dominated by the $a\,^5S\text{–}z\,^5P^0$ transition probability and here our data are in good agreement with Warner's values, as can be seen from Table III.

In a critical analysis of the data in ref. [1], Smith [2] has derived a correction formula to be applied to Warner's *f*-values in the iron group. For levels with excitation energy E_2 below 50 kK the formula can be written as follows

$$\log gf = \log gf_W + 0.45 - 0.026E_2$$

where gf_W are the data from ref. [1]. In the present case those data should be reduced by 0.68. Such corrected data are also given in Table III. The correction does not work well for the $a\,^5S$–$z\,^5P^0$ lines whereas satisfactory agreement with our experimental f-values can be noted for the $a\,^5D$–$z\,^5P^0$ transitions.

The solar abundance of Manganese has been investigated on the basis of the *experimental gf*-values obtained in this work. The nine lines of the multiplet $a\,^5D$–$z\,^5P^0$ are present in the solar photospheric spectrum, some of them being blended [11, 16]. The equivalent widths have been carefully remeasured on high resolution solar spectra obtained by Delbouille et al. [17]. It must be emphasized that for most of the lines the continuum is poorly determined. Individual abundances have been computed by an iterative method previously described [14] and by using three empirical currently available solar models [18, 19, 20]. The results are presented (in the usual scale) in Table IV. They have been obtained with an isotropic, optical-depth independent microturbulence ($\xi = 1.0$ km s^{-1}), when this parameter was not given with the solar model [18, 20]. Dividing the microturbulence by a factor 2 (using thus $\xi = 0.5$ km s^{-1}) increases the mean abundances by ~0.06 dex. From Table IV we obtain $A_{\mathrm{Mn}} = 5.4 \pm 0.2$. This result agrees with the meteoritic abundance obtained from carbonaceous chondrites (see for example ref. [21]) and with recently compiled photospheric values: 5.39 [22], 5.42 [23], 5.4 [24]. Moreover, we have shown by using Mn II lines, that one can obtain the same photospheric abundance as recently found from Mn I transitions.

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