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Absolute Oscillator Strengths of Si I Lines between 2500 Å and 8000 Å

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Summary. Experimental data for oscillator strengths of Si I lines are quite scarce. Yet silicon is one of the most important elements in astrophysics. For this reason relative oscillator strengths for Si I lines between 2500 Å and 8000 Å were measured in emission in a wall-stabilized arc. The experimental equipment was similar to that used in previous investigations on Cu, Fe and Ni by Kock *et al.* (1968–1970), but since the silicon was brought into the plasma under constant and reproducible conditions the spectra could be observed photoelectrically. The relative values were related to the absolute scale via absolute transition probabilities for principal lines in the UV, which could be determined from lifetimes measured by Marek in our laboratory in 1972. For the absolute oscillator strengths of lines in the visible and near infrared wavelength range, which are of particular astrophysical interest, the uncertainties are about 20–25 %.

Key words: oscillator strengths – Si I – arc measurements

Apparatus

The silicon lines were excited in the three-chamber-arc, which has been described in several previous reports (e.g. Garz *et al.*, 1970). The arc operated in argon at atmospheric pressure with currents between 10 and 60 Amperes. The silicon was brought into the axis of the arc in the form of $SiCl_4$ vapor. In normal conditions $SiCl_4$ is liquid and has a relative high vapor-pressure. During the experiment, a tank containing 100 cm³ $SiCl_4$ was immersed in a constant-temperature-bath, which could be regulated between room temperature and −30° C. This temperature range corresponds to a variation of the vapor-pressure of one order of magnitude. By passing a stream of argon with flow rates between 1 and 20 l/h over the liquid, $SiCl_4$ vapor was carried into the plasma. In this way the amount of silicon in the plasma could be varied by a factor of 100. The intensities of the silicon spectral lines remained constant, as long as the argon flow rates and the temperature of the bath were not changed. Intensity drifts of slow speed were observed only when the silicon formed crystals at the wall of the arc and caused appreciable narrowing of the arc channel.

Because of the good constancy and reproducibility, the silicon spectra could be recorded photoelectrically. The experimental arrangement can be seen from Fig. 1. The axis of the plasma column was projected onto the entrance slit of a grating monochromator (Ebert-type) of 2.5 m focal length and of medium dispersion (3 Å/mm). Behind the exit slit there was a XP 1003 photomultiplier (Valvo) followed by a tuned amplifier

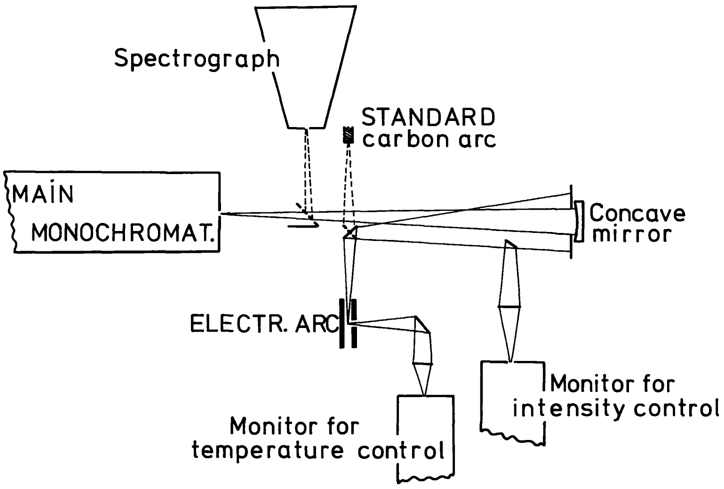

Fig. 1. Optical arrangement (schematically)

and a recorder. In order to reduce the thermal dark currents, the multiplier was cooled. The optical system was calibrated using the anode crater of a carbon arc according to Magdeburg and Schley (1965). During the measurements of the silicon line intensities the constancy of emission was controlled by a monitoring system observing the intensity of one silicon line end-on with the help of a second monochromator and a photomultiplier. With a third monochromator, side-on observations of an Ar I line were possible through a hole drilled in the central plate or through the gaps between the arc discs. The intensity of the Ar I line reflected the temperature in the part of the plasma where the metal was present. In addition the whole spectrum was recorded photographically using a spectrograph with a Wadsworth mounting (Jarrell Ash) to control the photoelectrical measurements, if required.

Measurements of the Si I Line Intensities

The investigations were carried out in two sections. In the UV wavelength region the strong resonance lines belonging to the multiplet UV 1 (Moore, 1967) and a few other lines were recorded using only low Si-concentrations in the arc plasma, so as to guarantee that the emission arose in optically thin layers. In particular the branching-ratios for the upper term $4s\,^3P^0$ had to be measured. The relative scale also contained the line $\lambda = 3906$ Å. This line later on served in an intermediate step required to connect the weak lines in the visible and near infrared region to the resonance lines. The photoelectrical measurements of the silicon spectra emitted by the arc plasma in the UV presented no problems, while the measurements of the carbon arc spectral distributions caused some difficulties. The intensity of the carbon arc decreases by two orders of magnitude going from the visible part of the spectrum to the UV. In addition the spectral sensitivity of the optical arrangement decreases too. Therefore, the measurements were sensitive to scattered light. By analysis of the carbon arc spectrum with the help of WG filters (Schott), which absorbed all of the light below steep edges at 3000 Å and 4000 Å and which are fully transparent to longer wavelengths, a scattered light contribution of the order of 50% could be accounted for. To be sure that the absolute calibration of the visible and UV parts of the spectrum did not suffer from a misinterpretation of the scattered light, this important step was controlled with the aid of the photographed spectra.

The measurements of the spectral lines between 5000 Å and 8000 Å demanded a silicon density about 100 times higher than for the measurements in the UV. Most of these Si I lines were broadened by the Stark effect and were sometimes blended with strong Ar I and Cl I lines. So the measurements of the relative line intensities in this wavelength range were effected by greater uncertainties than the measurements in the UV. The measurements included the lines $\lambda = 3906$ Å and $\lambda = 4102$ Å for the purposes of intensity calibrations.

The electrical current of the arc could be varied between 10 and 60 Amperes. During most of the investigations the arc was operated at 30 Amperes. For the intensity measurements of lines having closely adjacent upper levels, the current was reduced to 10 Amperes in order to minimize disturbances by blends. Furthermore, the relative intensities were observed at widely different silicon densities.

For the line measurements and for the calibration in the wavelength range between 4000 Å and 8000 Å, filters were used to eliminate higher order spectra.

Results and Discussions

The relative oscillator strengths were calculated according to the well known relation

$$\log \frac{gf_1}{gf_2} = \log \frac{I\lambda_1^3}{I\lambda_2^3} + 0.4343\,\frac{E_1 - E_2}{kT}. \qquad (1)$$

The indices 1 and 2 denote the different spectral lines; g is the statistical weight, f the oscillator strength, λ the wavelength, k Boltzmann's constant and E the excitation potential of the upper state. I is the measured line intensity. The temperature T was determined from intensity measurements of the Ar I line $\lambda = 4300$ Å for which the transition probability is known.

If one knows the oscillator strength of one Si I line absolutely, then the relative oscillator strengths can be put on an absolute scale. Savage and Lawrence (1966) determined the radiative lifetime of the unresolved multiplet $3p^2\,^3P - 4s\,^3P^0$ by a phase-shift method. They obtained $\tau = 6.1$ ns $\pm$ 13%. However, our measurements of relative line intensities showed that LS-coupling is not obeyed, and so it was impossible to evaluate absolute transition probabilities from this lifetime measurement. Marek (1972, 1973) also measured the lifetime of this multiplet, but he was able to calculate the different lifetimes of the three levels of the term $4s\,^3P^0$ with the aid of the intensity ratios of the fluorescence light, which he measured, and with the relative lifetimes from our experiment. Marek's values are:

$$\tau_{J=0} = 5.53 \text{ ns}, \quad \tau_{J=1} = 5.39 \text{ ns}, \quad \tau_{J=2} = 5.95 \text{ ns} \pm 8\%,$$

corresponding to the following absolute transition probabilities:

J	λ (Å)	A (s^{-1})
0	2524.1	$1.81 \cdot 10^8$
1	2514.3	$6.08 \cdot 10^7$
	2519.2	$4.56 \cdot 10^7$
	2528.5	$7.68 \cdot 10^7$
	2987.7	$2.40 \cdot 10^6$
	4102.9	$9.58 \cdot 10^4$
2	2506.9	$4.66 \cdot 10^7$
	2516.1	$1.21 \cdot 10^8$
	2970.4	$5.50 \cdot 10^4$

Since the deviations from LS-coupling are not very strong, the lifetime measurements of Savage and Lawrence can be regarded as a confirmation of Marek's values.

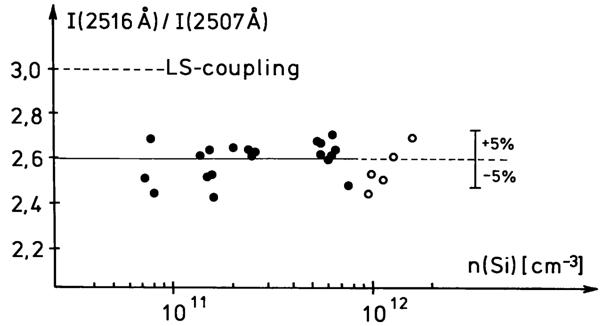

Fig. 2. The intensity ratio of two resonance lines as the silicon density in the plasma was varied. For the measurements represented by the open circles the emission was not sure to arise from optically thin layers

A discrepancy which is most important for the determination of the absolute scale concerns the intensity ratio of $\lambda = 2516$ Å to $\lambda = 2507$ Å. In contrast to many authors who have published values for these lines, our value is about 13% smaller than the theoretical one, as can be seen from Fig. 2. Since $\lambda = 2516$ Å is the strongest line of the multiplet UV 1, one may suspect, that the intensity measurements suffer from absorption. However, the fact that the measured intensity ratios are independent of the silicon density, which is demonstrated in Fig. 2, and results from controls, which are discussed in the Appendix, are in contradiction with this statement.

For the lines of the multiplet UV 1 there are several values available for comparison: Corliss and Bozman (1962), Khokhlov (1963), Slavenas (1964), Lawrence (1967), Hofman (1969), Lvov (1970), Zyrnicki *et al.* (1970). In most of these publications, the oscillator strengths are on relative scales. Hofman calibrated his results by the lifetime measurements of Savage and Lawrence. Lawrence calculated the relative f-values (in intermediate coupling) and used his experimental data to provide an absolute scale. Our own absolute scale is about 5% higher. Excepting the results of Corliss and Bozman and of Zyrnicki *et al.*, the relative oscillator strengths agree to such an extent that the mean absolute deviations for the individual values of two authors are below 5%. The oscillator strengths of Corliss and Bozman are known to be afflicted with some uncertainties. In the case of Zyrnicki *et al.* the spectral lines were obviously self-absorbed, since their results could be reproduced by feeding the arc plasma with extreme silicon concentrations.

In addition to the UV-lines of the 1st multiplet, records of $\lambda = 2881$ Å (UV 43), $\lambda = 2631$ Å (UV 83) and $\lambda = 2532$ Å (UV 86) were analysed. The last two lines mentioned belong to upper levels which lie 6.62 and 6.80 eV above the ground state, respectively, and thus much higher than the upper levels of the other UV-lines. Therefore these lines were suitable for investigations of departures from thermodynamic equilibrium, which are described in the Appendix.

The spectral lines of the visible region were normalized to the resonance lines via $\lambda = 3906$ Å and $\lambda = 4102$ Å. The infrared lines were then related to the visible lines. In the first instance, the relative $\log gf$ values were calculated from the intensity ratios and the end-on measured Ar temperature according to Eq. (1). In so doing, one has to pay attention to the fact that the measurements were made using comparatively high silicon densities. As a result of this, the temperature in the central part of the arc decreases relative to the pure argon plasma in the outer parts. In the Appendix these investigations are described in detail. If the depression of the temperature as a function of the density distribution of the silicon is taken into consideration (as was done by Heise, 1973), the relative f-values of two lines of which the upper levels are separated by 2 eV has to be corrected by +7%. This is the case when the visible lines are related to the UV-lines.

Previous investigations of Cu, Fe and Ni showed that, below certain densities of the metals and of the electrons in the plasma, departures from local thermodynamic equilibrium may occur in such a manner that the distribution temperature of the energy levels of the metallic admixture is not equal to the electron temperature of the argon plasma. As can be seen from the Appendix, controlling measures justified the assumption of LTE for the silicon/argon mixture.

For the relative oscillator strengths of the lines of the visible region, some comparison data are available: Schulz-Gulde (1969) also used an electrical cascade arc as a light source; Miller and Bengtson (1969) and Damm (1971) used gas-driven shock tubes. The values of Wiese *et al.* (1969) were calculated with the aid of the Coulomb approximation. If one looks at the mean absolute deviations of the individual values of two authors, the theoretical oscillator strengths clearly show greater differences than the experimental ones.

The results of our experiment are given in Table 1. The tabulated values are absolute oscillator strengths. The given uncertainties are probable errors (square roots of the sum of the squares of the individual errors).

In the literature, only a few absolute values can be found for comparison. The oscillator strengths which are recommended by Wiese *et al.* (1969) are mainly based upon theoretical investigations. The values for lines below 4100 Å were normalized to the lifetime measurements of Savage and Lawrence (1966). In the visible and infrared part of the spectrum, the absolute values were determined by the Coulomb approximation. In the visible region, the absolute scale proposed by Wiese *et al.* is a factor of 2 higher than our scale, but both scales approach each other in the infrared region, where the calculations should be more reliable. In the experimental work of Hey (1959), a cascade arc burning $SiCl_4$ vapor was used as a light source, but Hey did not take into account demixing effects in the

Table 1. Absolute transition probabilities and log(gf)-values for Si I lines

λ (Å)	Mult.	E_{up} (eV)	This investigation A (s^{-1})	log(gf)$_{abs.}$	Wiese *et al.*	Hey	Schulz-G.	Damm
2506.9	UV 1	4.95	$4.66 \cdot 10^7$	-0.66 ± 0.04	−0.71			
2514.3	UV 1	4.93	$6.08 \cdot 10^7$	-0.76 ± 0.04	−0.80			
2516.1	UV 1	4.95	$1.21 \cdot 10^8$	-0.24 ± 0.04	−0.24			
2519.2	UV 1	4.93	$4.56 \cdot 10^7$	-0.89 ± 0.04	−0.92			
2524.1	UV 1	4.92	$1.81 \cdot 10^8$	-0.76 ± 0.04	−0.80			
2528.5	UV 1	4.93	$7.68 \cdot 10^7$	-0.66 ± 0.04	−0.71			
2532.4	UV 86	6.80	$2.63 \cdot 10^7$	-1.12 ± 0.08				
2631.3	UV 83	6.62	$9.69 \cdot 10^7$	-0.52 ± 0.08				
2881.6	UV 43	5.08	$1.89 \cdot 10^8$	-0.15 ± 0.06	−0.18			
2970.4	1	4.95	$5.50 \cdot 10^4$	-3.44 ± 0.08	−3.81			
2987.7	1	4.93	$2.40 \cdot 10^6$	-2.02 ± 0.06	−2.05			
3905.5	3	5.08	$1.18 \cdot 10^7$	-1.09 ± 0.06	−1.00		−1.56	
4102.9	2	4.93	$9.58 \cdot 10^4$	-3.14 ± 0.08	−2.91	−2.89	−3.12	−3.50
5645.6	10	7.12	$3.03 \cdot 10^5$	-2.14 ± 0.08	−1.64[a]		−2.24	
5665.6	10	7.11	$6.31 \cdot 10^5$	-2.04 ± 0.08	−1.74[a]		−2.19	
5684.5	11	7.13	$1.54 \cdot 10^6$	-1.65 ± 0.08	−1.41[a]		−1.77	
5690.4	10	7.11	$1.17 \cdot 10^6$	-1.87 ± 0.08	−1.86[a]		−2.02	
5701.1	10	7.10	$1.83 \cdot 10^6$	-2.05 ± 0.08	−1.74[a]		−2.20	
5708.4	10	7.12	$1.39 \cdot 10^6$	-1.47 ± 0.08	−1.15[a]		−1.58	−2.08
5772.2	17	7.23	$3.56 \cdot 10^6$	-1.75 ± 0.08	−1.38[a]		−1.92	−2.34
5780.4	9	7.06	$2.97 \cdot 10^5$	-2.35 ± 0.08	−1.82[a]		−2.51	
5793.1	9	7.07	$3.46 \cdot 10^5$	-2.06 ± 0.08	−1.48[a]		−2.21	
5797.9	9	7.09	$2.52 \cdot 10^5$	-2.05 ± 0.08	−1.19[a]		−2.02	−2.49
5948.6	16	7.17	$2.22 \cdot 10^6$	-1.23 ± 0.08	−1.24	−1.24	−1.29	−1.82
6741.6	60.02	7.82	$5.22 \cdot 10^5$	-1.75 ± 0.13				
6976.5	60	7.73	$1.85 \cdot 10^6$	-1.17 ± 0.13	−1.08[a]			
7003.6	60	7.73		} -0.48 ± 0.08 (7003.6 + 7005.9)	} −0.60[a] (7003.6 + 7005.9)			
7005.9	60	7.75						
7034.9	42.10	7.63	$2.54 \cdot 10^6$	-0.88 ± 0.13				
7164.5	42.09	7.60	} $3.45 \cdot 10^6$ (7164.5 + 7165.5)	} -0.72 ± 0.08 (7164.5 + 7165.5)				
7165.5	42.08	7.60						
7184.6	21.06	7.34		} -1.73 ± 0.08 (7184.6 + 7184.9)			} −1.69 (7184.6 + 7184.9)	
7184.9	21.06	7.34						
7193.6	21.06	7.34		} -1.72 ± 0.08 (7193.6 + 7193.9)			} −1.69 (7193.6 + 7193.9)	
7193.9	21.06	7.34						
7226.2	21.05	7.33	$7.89 \cdot 10^5$	-1.51 ± 0.08			−1.41	
7235.3	21.05	7.33		} -1.32 ± 0.08 (7235.3 + 7235.8)			} −1.16 (7235.3 + 7235.8)	
7235.8	21.05	7.33						
7250.1	21.05	7.33		} -1.20 ± 0.08 (7250.1 + 7250.6)			} −1.04 (7250.1 + 7250.6)	
7250.6	21.05	7.33						
7289.2	21.04	7.32		} -0.67 ± 0.08 (7289.2 + 7290.3)			} −0.20 (7289.2 + 7290.3)	
7290.3	21.04	7.32						
7405.8	21.02	7.29	$3.68 \cdot 10^6$	-0.82 ± 0.10			} −0.32 (7405.8 + 7409.1)	
7409.1	21.03	7.29	$2.29 \cdot 10^6$	-0.88 ± 0.10				
7415.4	21.02	7.29		} -0.71 ± 0.08 (7415.4 + 7415.9)			} −0.44 (7415.4 + 7415.9)	
7415.9	21.02	7.29						
7680.3	36	7.48	$4.62 \cdot 10^6$	-0.69 ± 0.08	−0.56[a]			
7918.4	57	7.52	$5.22 \cdot 10^6$	-0.61 ± 0.10	−0.59[a]			
7932.3	57	7.53	$5.13 \cdot 10^6$	-0.47 ± 0.10	−0.45[a]			
7944.0	57	7.54	$5.75 \cdot 10^6$	-0.31 ± 0.13	−0.38[a]			
7970.3	57	7.52	$7.11 \cdot 10^5$	-1.47 ± 0.13	−1.32[a]			

[a]) These values were calculated with the Coulomb approximation.

arc. Nevertheless, Hey's values almost coincide with ours. Schulz-Gulde (1969) obtained his absolute scale by comparing the line Si I $\lambda = 5949$ Å with the line Si II $\lambda = 5979$ Å and its theoretical f-value. Recently, Schulz-Gulde (1972) checked this result by photoelectrical measurements and obtained the same value. The absolute oscillator strengths of Schulz-Gulde are compared with our own values in Fig. 3. On the average, the absolute scales agree well. However, for the visible lines the values of Schulz-Gulde are lower and for the infrared lines higher than ours. Since Schulz-Gulde (1969) worked photographically and the records of the different wavelength regions required different technologies, the results are likely to have systematic errors. For the line $\lambda = 3906$ Å, the f-value of which shows a rather large deviation from our value, one can reason-

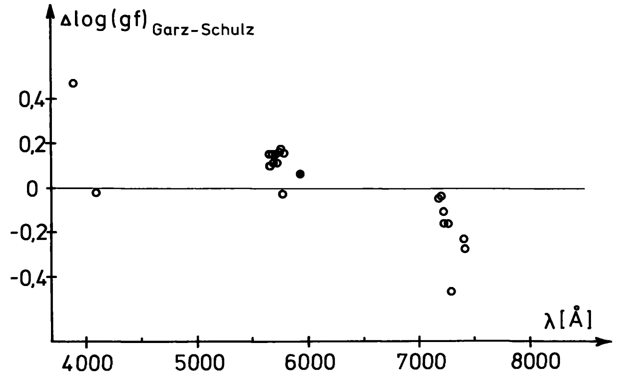

Fig. 3. A comparison of the absolute $\log gf$ values of Schulz-Gulde (1969) and of the present author as a function of wavelength. The full circle represents the Si I line $\lambda = 5949$ Å, which Schulz-Gulde used as a reference line and which he remeasured in 1972

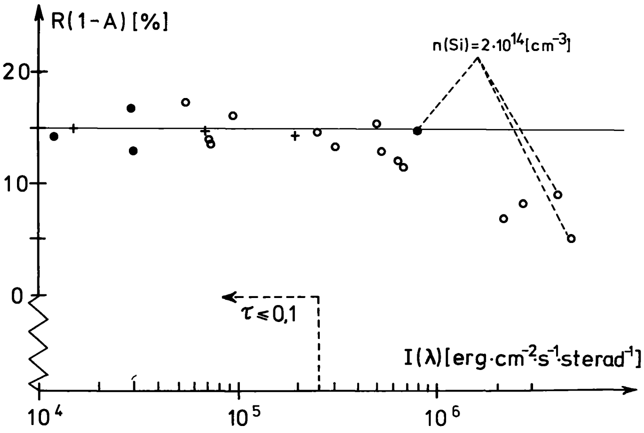

Fig. 4. For analysis of the absorption rate A of the plasma. R is the reflection coefficient of the concave mirror. $I(\lambda)$ is the absolute intensity of the relevant spectral line. The open circles mark $\lambda = 2524$ Å and $\lambda = 2529$ Å (UV 1), the full circles mark $\lambda = 2532$ Å (UV 86). For the measurements marked by crosses, the carbon anode was exchanged for a Cu anode

ably suppose that there was self-absorption in the experiments of Schulz-Gulde. The most recent results are those published by Damm (1971), who obtained the oscillator strengths by absolute shock tube measurements. On the average, his values are a factor of 3 lower than ours.

Hey, Schulz-Gulde and Damm set their absolute oscillator strength scales in different ways, but only Hey and Damm made their measurements absolutely in the true sense of the word. If one compares the various absolute oscillator strengths for the line $\lambda = 5949$ Å, then the very good agreement between our value and those of Hey and Schulz-Gulde is quite striking. Only Damm's value is different. As additional evidence for the satisfactory establishment of the absolute scale, there is also the good agreement between experiment and theory for the infrared spectral lines.

Appendix

As stated in the previous chapters, the results of measurements of the relative intensities of some spectral lines suggest that the measurements may suffer from reabsorption. The possible effects had to be investigated. Furthermore, we had to decide whether the interpretation of the measured temperature was correct.

Reabsorption

Reabsorption, particularly of the resonance lines, was possible in the cold boundary layers when using carbon electrodes (which in our case had a Si content of 0.2 ppm) and in the middle part of the plasma column, when the spectral lines were emitted from not optically thin layers. In order to investigate these effects, the arc was projected end-on into itself with the aid of a concave mirror. For the UV wavelength range, the intensities of the three lines $\lambda = 2524$ Å, $\lambda = 2529$ Å and $\lambda = 2532$ Å were measured with the mirror, I_H, and without the mirror, I_O. The lines $\lambda = 2524$ Å and $\lambda = 2529$ Å are principal lines of the multiplet UV 1, whereas $\lambda = 2532$ Å has an upper level at 6.80 eV and a lower level at 1.90 eV above the ground state. In the course of this procedure, the arc was operated at 30 Amperes and the silicon density was varied as much as possible. Also the carbon anode was exchanged for a Cu electrode.

The absorption rate A of the plasma can be determined from the relation

$$R(1-A) = (I_H/I_O) - 1\,, \tag{2}$$

where R is the reflection coefficient of the concave mirror. The quantity $R(1-A)$ as a function of the intensity of the relevant spectral line is shown in Fig. 4. From the constancy of $R(1-A)$ for small intensities it can be concluded that there is no absorption and the reflection coefficient of the mirror amounts to 15%. As can be seen clearly from the figure, the absorption rate depends only on the spectral radiation density. The distance of the line's energy levels from the ground state are obviously not important for the amount of absorption. The same applies to the nature of the electrodes. One result of these investigations is that reabsorption in the boundary layers near the electrodes is not important. We also see from Fig. 4 that the absorption coefficient increases for intensities higher than $3 \cdot 10^5\ \mathrm{erg \cdot cm^{-2} \cdot s^{-1} \cdot sterad^{-1}}$, as was suspected from an estimate for the optical depth τ of the Si-plasma, which yields $\tau(\lambda)_{\max} \geqq 0.1$ for $I \geqq 2.6 \cdot 10^5\ \mathrm{erg \cdot cm^{-2} \cdot s^{-1} \cdot sterad^{-1}}$ ($T = 10250$ K). The formula, which was confirmed by the more detailed study, is

$$\tau(\lambda)_{\max} = \frac{I}{\pi \cdot \Delta\lambda_D \cdot B}\,, \tag{3}$$

where I is the total intensity of the line, $\Delta\lambda_D$ is the Doppler width and B is the Kirchhoff-Planck function. Since the lines are assumed to be broadened exclusively by the Doppler effect, this formula gives an upper limit for τ. In determining the oscillator strengths, only lines with $\tau(\lambda)_{\max} \leqq 0.1$ were taken into account.

The Temperature in the Centre of the Arc

In cases where ionizable metals were brought into the plasma, a decrease of the temperature especially in the centre of the arc, where the metal was introduced, was to be expected. This effect was investigated with the aid of the side-on monitor. From the intensity of the line Ar I $\lambda = 4159$ Å, which depended on the Si density ratios in the plasma, the temperature drop could be estimated. Figure 5 shows the temperature decrease in the centre of the arc as a function of the Si density (arc current: 30 Amperes). For the density range which was suitable for the measurements of the UV lines, the temperature diminished by less than 100 K. But for the measurements of the other lines the particle numbers of Si were much higher and the temperature decreased by about 300 K to 800 K, and this had to be taken into account when determining oscillator strengths.

In addition the temperature profile in the direction of the arc axis was measured through the gaps between the arc discs at different points on the central chamber of the arc, which was 4 cm in extent: The temperature curve could be approximated by a gaussian distribution with a half width of about 2.4 cm. Therefore, when the Si number densities were calculated from the absolute line intensities the effective length of the metal plasma layer was also assumed to be 2.4 cm.

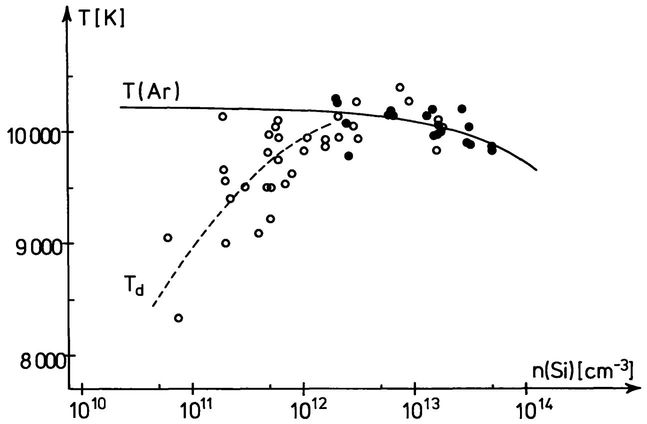

Fig. 5. The distribution temperature T_d for some Si I levels compared with the temperature of the argon plasma T(Ar) as a function of the Si particle density. The open circles were obtained from relative measurements $\lambda = 2631$ Å/$\lambda = 2507$ Å, the full circles from $\lambda = 2532$ Å/$\lambda = 2988$ Å. The arc current was 30 Amperes

Thermodynamic Equilibrium

It was observed that the intensity of the line $\lambda = 2631$ Å (UV 83) relative to $\lambda = 2507$ Å (UV 1) increased with increasing Si density. For an arc current of 30 Amperes, the relative intensity values became constant (after the intensity of $\lambda = 2507$ Å was adjusted to that appropriate to an optically thin layer) when the Si density exceeded $3 \cdot 10^{12}$ cm^{-3}. For a pair of lines having lower intensities than the two lines mentioned above but nearly the same energy difference for their upper levels, $\lambda = 2532$ Å (UV 86) and $\lambda = 2988$ Å (1), the behavior of the intensity ratio was followed up to higher densities. The relative intensities now came out constant (the influence of the temperature decrease on the intensity ratio was less than 4%). If the relative oscillator strengths are determined from these values, which were independent of the Si density, the measurements are consistent with the following interpretation: for a nearly constant electron density of about $2 \cdot 10^{16}$ cm^{-3} (30 Amperes) and for Si densities below $3 \cdot 10^{12}$ cm^{-3} the energy levels of Si I were not populated according to a Boltzmann distribution at the electron temperature (Ar temperature). Previous investigations of arcs operating with Cu, Fe and Ni have shown similar departures from LTE (e.g. Kock and Richter, 1968). From the supposed f-values and the measured intensity ratios, distribution temperatures could be calculated. Figure 5 shows the strong decrease of the distribution temperature compared with the Ar temperature at low densities.
The Si I lines above 4000 Å, which could only be measured at Si particle densities higher than 10^{13} cm^{-3}, have upper energy levels which should be populated in the same way as the levels of the UV lines mentioned above. Thus, we could be rather sure that LTE conditions applied to the measurements of the visible and infrared lines.
In general, the measuring range for an electrical current of 30 Amperes may be divided into two sections. Below a silicon density of about $3 \cdot 10^{12}$ cm^{-3}, the argon plasma temperature was scarcely influenced by the admixture of the metal component. The principal lines were emitted from an optically thin layer, but the silicon was not in equilibrium with the argon plasma. Beyond this critical particle density of Si, the Ar temperature decreased when the particle density was increased. The radiation of the resonance lines was more and more absorbed, which obviously favoured the establishment of LTE conditions between the silicon and the argon.

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References

Corliss, C.H., Bozman, W.R. 1962, NBS Monograph No. 53, Washington
Damm, F.L. 1971, *J. Quant. Spectrosc. Radial Transfer.* **11**, 323
Garz, T., Heise, H., Richter, J. 1970, *Astron. & Astrophys.* **9**, 296

Heise, H. 1973, *Astron. & Astrophys.* to be published
Hey, P. 1959, *Z. Phys.* **157**, 79
Hofman, W. 1969, *Z. Naturforsch.* **24** a, 990
Khokhlov, M. Z. 1963, *Izv. Krymskoi Astrofiz. Obs.* **24**, 131
Kock, M., Richter, J. 1968, *Z. Astrophys.* **69**, 180
Lawrence, G. M. 1967, *Astrophys. J.* **148**, 261
Lvov, B. V. 1970, *Opt. Spectrosc.* **28**, 8
Magdeburg, H., Schley, U. 1965, *Z. Angew. Phys.* **20**, 465
Marek, J. 1972, *Astron. & Astrophys.* **17**, 83
Marek, J., Richter, J. 1973, *Astron. & Astrophys.* to be published
Miller, M. H., Bengtson, R. D. 1969, *Astrophys. J.* **156**, 393
Moore, Ch. E. 1967, Selected Tables of Atomic Spectra, Si I, NSRDS-NBS 3, Sect. 2, Washington
Savage, B. D., Lawrence, G. M. 1966, *Astrophys. J.* **146**, 940
Schulz-Gulde, E. 1969, *J. Quant. Spectrosc. Radial Transfer.* **9**, 13
Schulz-Gulde, E. 1972, *Astron. & Astrophys.* **21**, 313
Slavenas, I.-Yu. Yu. 1964, *Opt. Spectrosc.* **16**, 214
Wiese, W. L., Smith, M. W., Miles, B. M. 1969, Atomic Transition Probabilities Vol. II, NBS, Washington
Zyrnicki, W., Czernichowski, A., Mleczko, W. 1970, *Acta Phys. Polon.* A **38**, 177

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