IDENTIFICATIONS OF SOLAR ULTRAVIOLET LINES RESULTING FROM A STUDY OF THE Ar I AND K I ISOELECTRONIC SEQUENCES

U. Feldman, B. S. Fraenkel, and S. Hoory
Laboratory of X-Rays and Far Ultraviolet Spectroscopy, Department of Physics, Hebrew University, Jerusalem*
Received February 18, 1965; revised April 1, 1965

ABSTRACT
The classification of the $3p^5 3d$ level in Ar i isoelectronic spectra and the interaction between configurations $3p^6 3d^{r-1}n^l$ and $3p^6 3d^{r+1}$ are discussed. Solar lines of transitions $3p^6-3p^6 n^l$, $3p^6 3d-3p^6 n^l$ and $3p^5 3d-3p^5 3d^2$ are identified.

I. INTRODUCTION
Far ultraviolet spectra of the Sun have been obtained by rocket spectroscopy during the past few years (Hinteregger 1960, 1961; Hinteregger, Hall, and Schweitzer, 1964; Austin, Purcell, and Tousey 1962a, b, 1964; Behring, Neupert, and Lindsay 1963). Outstanding among these spectra was a spectrum (Austin et al. 1964) showing a resolution of about 0.02 Å in the 170–190-Å range. It has been shown in previous papers (Fawcett, Gabriel, Griffin, Jones, and Wilson 1963; Elton, Kolb, Austin, Tousey, and Widing 1964; House, Deutschman, and Sawyer 1964) that many of these lines are Fe lines. Many of these lines were found by a method of differentiation between ionizations (Fraenkel 1962; Alexander, Feldman, and Fraenkel 1964) to belong to Fe viii and Fe ix (Alexander, Feldman, and Fraenkel 1965a).

In the present paper lines of Fe viii and Fe ix and lines of Ni x and Ni xi are identified in the recently obtained solar spectrum (Hinteregger et al. 1964). The classification of an isoelectronic sequence of a very strong line as $3p^6-3p^6 3d$ transition is discussed. The interaction between the configurations $3p^6 3d^{r-1}n^l$, $n^f$ and the configuration $3p^5 3d^{r+1}$ has also been investigated.

II. CLASSIFICATION OF THE $3p^6-3p^6 3d$ TRANSITION
The isoelectronic sequence of a strong line observed from V vi to Ni xi in the spectra of Ar i is given in Table 1. We propose the classification $3p^6-3p^6 3d$ for these lines. Knowledge of the energy of the $3p^6 3d$ levels is of considerable importance for the determination of the unknown $3p^6 3d^{r+1}$ levels. Because the above transition has not been classified formerly for highly ionized spectra, the way by which we arrived at this classification is described in detail. The lowest term found previously in this range of ionizations, above the ground term $3p^6$, is the $3p^6 4s$ term.

The line discussed is observed to be the strongest line of the spectrum of the pertinent ionization with an energy considerably smaller than the energy of the $3p^6-3p^6 4s$ transition.

Assuming for this line the classification $3p^6-3p^6 3d$, we obtain the term $3p^5 3d$ given in the reduced-term diagram (Fig. 1). We find that the slope of the line connecting these terms behaves as would be expected for a term with $n = 3$. Furthermore, an assumption that the line involved is not due to a ground-state transition cannot be upheld. For instance, in V vi the energy of the line involved is almost equal to the energy difference between ionization energy and the 4s level. It is highly improbable that a single strong line would be seen in a transition originating from a level with a high value of $n$.

* The research reported in this article has been sponsored in part by the Air Force Office of Scientific Research O A.R., through the European Office, Aerospace Research, United States Air Force

© American Astronomical Society • Provided by the NASA Astrophysics Data System
The only possible level between the 4s level and the ground level is the 3d level. In this level a strong transition line could be expected by transitions of a type such as, \(3p^5 3d - 3p^5 4p\). We can assume that the reduced 4p levels are somewhere between 4s and 4d levels on a line parallel to the 4s and 4d lines (dotted line in Fig. 1). The dashed line in the diagram shows \(3p^5 3d\) reduced levels that would result under this assumption. It is clear that the slope of this line does not conform to the slope expected for the isoelectronic sequence of the main quantum number \(n = 3\). This argument would hold even more if the transition were assumed to come from an upper level with \(n > 4\). Therefore, the only remaining classification for the line involved is the transition \(3p^5 3d\).

In order to explain the classification a specific coupling has been chosen. It has been shown (Shadmi 1961) that the \(3p^5 3d\) configuration has a predominantly \(LS\) coupling.

### Table 1

<table>
<thead>
<tr>
<th>Ion</th>
<th>(\lambda(\text{Å}))</th>
<th>(1/\lambda (\text{cm}^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cr VII</td>
<td>224 504</td>
<td>445430</td>
</tr>
<tr>
<td>Mn VIII</td>
<td>202 826</td>
<td>493030</td>
</tr>
<tr>
<td>Fe IX</td>
<td>185 459</td>
<td>539200</td>
</tr>
<tr>
<td>Co X</td>
<td>171 075</td>
<td>584540</td>
</tr>
<tr>
<td>Ni XI</td>
<td>158 780</td>
<td>629800</td>
</tr>
<tr>
<td></td>
<td>148 610</td>
<td>672900</td>
</tr>
</tbody>
</table>

Fig. 1.—Reduced-term diagram for Ar I isoelectronic sequences
Fig. 2.—Reduced-term diagram for K i isoelectronic sequences, including the Ar i $3p^6 3d$ isoelectronic sequence. The shaded area indicates the range of interaction of $3p^6nl$ configurations with the $3p^6 3d^2$ configuration. Note: in the notation for the ordinate read $(\xi + 1)^{-1}$ instead of $(\xi + 1)$. 
in Ca III. We assume this coupling to be predominant at this stage of experimental evidence and also at higher ionizations, although the coupling of the configuration may change for such high energies in a manner similar to the situation observed in the 3p\(^{6}\) 4d configuration.

### III. Interaction Between the Configurations 3p\(^{6}\) 3d\(^{r-1}\)np, nf and the Configuration 3p\(^{6}\) 3d\(^{r+1}\)

The 3p\(^{6}\) 3d\(^{r-1}\) 4p terms for r = 1, 2, 3, 4 are known from the isoelectronic sequences of K I, Ca I, Sc I, and Ti I. The identification in all these sequences breaks down at the eighth spectrum. It has been suggested (Bowen 1935) that this happens because of the interaction of this configuration with the corresponding 3p\(^{6}\) 3d\(^{r+1}\) configuration.

For the 3p\(^{6}\) 3d\(^{r-1}\) 4f terms, isoelectronic extrapolation breaks down at the sixth spectrum and behaves normally in higher and lower spectra: the 3p\(^{6}\) 4f levels are known up to the eleventh spectrum except for Cr vi (Moore 1952; Alexander et al. 1965b). The 3p\(^{6}\) 3d 4f levels are known only in the seventh (Edlén as cited by Moore 1952), eighth (Edlén 1964; Alexander, Feldman, Fraenkel, Hoory, and Shadmi 1965), ninth and tenth (ibid.) spectra. The 3d\(^{2}\) 4f and the 3d\(^{8}\) 4f spectra have not yet been classified but can be seen on our plates. These spectra also seem to behave abnormally in the sixth spectrum.

We may assume that the energies of the 3p\(^{6}\) 3d levels are, in the same element, nearly equal to the energies of the 3p\(^{6}\) 3d\(^{r+1}\) levels where the levels are measured from the ground level of each ion. For instance, in our plates a group of lines is observed in each element of the K I isoelectronic sequence with energies near the 3p\(^{6}\)-3p\(^{6}\) 3d transition energies of the Ar I isoelectronic spectrum of each of the elements as given in Table 1. These groups of lines of the K I isoelectronic sequence do not have the characteristics of a one-electron spectrum. Furthermore, in many of these groups pairs of lines were observed with a splitting equal to the corresponding 3p\(^{6}\) 3d \(\Delta E_{4\frac{1}{2},4\frac{3}{2}}\) difference showing that the lines are transitions to the ground term. Transitions from the 3p\(^{6}\) 3d\(^{2}\) configurations seem to be the only ones that fit the above findings.

In Figure 2 a reduced-term diagram of the K I isoelectronic sequences is given. Known terms are indicated by a plus. "Missing terms," i.e., investigated spectra where the corresponding term could not be found, are indicated by a zero. In order to appraise the possible range of interaction of these terms with the 3p\(^{6}\) 3d\(^{2}\) terms, the Ar I 3p\(^{6}\) 3d isoelectronic sequence is also given in the figure. In a corridor along this line the 3p\(^{6}\) 3d\(^{2}\) terms should be found, as discussed above.

All the missing terms are found close to the 3p\(^{6}\) 3d reduced-term line. Thus the 4f is seen at both sides of the region of interaction while it is definitely missing in the region itself. This diagram explains the classification difficulties in the 3p\(^{6}\) 4p levels of Fe viii and Co ix, and in the 3p\(^{6}\) 4f levels of Cr vi. This diagram also explains the missing 3p\(^{6}\) nf, n > 4 levels of V v.

It follows that in this region the 3p\(^{6}\) 3d\(^{2}\) configuration and the 3p\(^{6}\) np or 3p\(^{6}\) nf configurations are mixed and an estimate of their interaction will be necessary for line classification in this region. The same considerations apply generally for corresponding interactions between 3p\(^{6}\) 3d\(^{r-1}\) nf, np and 3p\(^{6}\) 3d\(^{r+1}\) terms. These interactions should appear in about the same degrees of ionization as in the case of 3p\(^{6}\) nf, np configurations.

The above 3p\(^{6}\) 3d\(^{r-1}\) nf, np levels may also interact with the 3p\(^{6}\) 3d\(^{r}\) 4s levels; this interaction is not treated here.

We are now trying to classify the 3p\(^{6}\) 3d lines by using the irregularities caused by the interaction described above in the following way. In the region of high degrees of ionizations no interaction exists. In a reduced-term diagram pairs of lines may appear in this region showing the splitting of the ground term \(\Delta \gamma = 3p^6 3d (\pm D_{\Delta_{T\Delta z}=D_{\Delta z}})\). These lines will result from transitions from levels with \(j = \frac{5}{2}\) or \(j = \frac{3}{2}\), but assignment
of the correct \( j' \)s to them seems very difficult. However, near the intersection with the \( 3p^6 \) \( 4f \) isoelectronic levels, the levels with \( j = \frac{5}{2} \) should be disturbed at the \( 4f \) crossing and the levels with \( j = \frac{3}{2} \) at the \( 4p \) crossing. The decision on assignment of the \( j' \)s may be based on the appearance of these irregularities. Similar considerations may help to classify the \( 3p^6 \) \( 3d^2 \) levels with \( j = 2 \) and \( j = 4 \).

IV. \textbf{Fe and Ni Lines at Wavelengths Below 190 Å in the Solar Spectrum}

Table 2 gives \( \text{Fe VIII} \) and \( \text{Fe IX} \) lines and \( \text{Ni X} \) and \( \text{Ni XI} \) lines that have not been identified previously in the solar spectrum obtained by Hinteregger \textit{et al.} in May, 1963 (Hinteregger \textit{et al.} 1964). These include the \( 3p^6 \) \( 3d^2 \rightarrow 3p^6 \) \( 4f \) transitions of \( \text{Fe VIII} \) and the \( 3p^6 \) \( 3p^8 \) \( 3d \) transition of \( \text{Fe IX} \). The \( 3p^6 \) \( 3p^8 \) \( 4s \) transitions of \( \text{Fe IX} \) seen by Zirin (1964) are also listed. The transitions \( 3p^6 \) \( 3d^2 \rightarrow 3p^6 \) \( 4f \) of \( \text{Ni X} \) and \( 3p^6 \) \( 3p^8 \) \( 3d \) of \( \text{Ni XI} \) also appear clearly in this solar spectrum. Other transitions of these ions such as \( 3p^6 \) \( 3d^2 \rightarrow 3p^6 \) \( n\ell \) or

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|}
\hline
\textbf{Ion} & \textbf{Transition} & \textbf{\( \lambda(\text{Å}) \)} & \textbf{\( \lambda(\text{Å}) \) in Solar Spectrum} & \textbf{Counts per Second in Solar Spectrum} \\
\hline
\text{Fe VIII} & \( 3p^6 \) \( 3d^2 \) \( D_{3/2} \rightarrow 3p^6 \) \( 4f \) \( F_{7/2} \) \( P_{3/2}^{3/2} \) & 131 1 & 131 1 & \( 3 \times 10^5 \) \\
& \( 3p^6 \) \( 3d^2 \) \( D_{3/2} \rightarrow 3p^6 \) \( 4f \) \( F_{7/2}^{3/2} \) & & & \\
\text{Fe IX} & \( 3p^6 \) \( 1S_{0} \rightarrow 3p^6 \) \( 3d \) \( 1P_{1/2}^{1/2} \) & 171 075 & 171 1 & \( 5 \times 10^5 \) \\
& \( 3p^6 \) \( 1S_{0} \rightarrow 3p^6 \) \( 3d \) \( 4f \) \( F_{7/2}^{3/2} \) \( 4s(3/2)^{0} \) & 105 230 & 105 2 & \( 2 \times 10^5 \) \\
& \( 3p^6 \) \( 1S_{0} \rightarrow 3p^6 \) \( 3d \) \( 4f \) \( F_{7/2}^{3/2} \) \( 4s(1/2)^{0} \) & 103 580 & 103 7 & \( 3 \times 10^5 \) \\
\text{Ni X} & \( 3p^6 \) \( 3d^2 \) \( D_{3/2} \rightarrow 3p^6 \) \( 3d \) \( 1P_{1/2}^{1/2} \) & 91 787 & 91 8 & \( 2 \times 10^5 \) \\
& \( 3p^6 \) \( 3d^2 \) \( D_{3/2} \rightarrow 3p^6 \) \( 3d \) \( 1P_{3/2}^{3/2} \) & 91 527 & 91 6 & \( 1 \times 10^5 \) \\
\text{Ni XI} & \( 3p^6 \) \( 3d^2 \) \( D_{3/2} \rightarrow 3p^6 \) \( 3d \) \( 1P_{1/2}^{1/2} \) & 148 610 & 148 5 & \( 9 \times 10^5 \) \\
\hline
\end{tabular}
\end{table}

\( 3p^6 \) \( 3p^8 \) \( nd \) with higher values of \( n \) are considerably weaker than the listed lines. They may be present in the solar spectrum, but it seems necessary to have a better resolution for a positive identification.

Near the strong \( 3p^6 \) \( 3p^8 \) \( 3d \) transition of \( \text{Fe IX} \), an aggregation which belongs to other strong lines of \( \text{Fe VIII} \) and \( \text{Fe IX} \) is found in the solar spectrum as discussed in § III. Unclassified \( \text{Fe VIII} \) lines in this region, which were listed previously (Alexander \textit{et al.} 1965a), seem to belong to \( 3p^6 \) \( 3d \rightarrow 3p^6 \) \( 3d \) transitions. A similar aggregation is seen near the corresponding \( \text{Ni XI} \) line and may be explained in the same way.

The authors gratefully acknowledge the help given to them by Professor E. Alexander and the many fruitful discussions they have had with him.

REFERENCES


Austin, W. E., Purcell, J. D., and Tousey, R. 1962a, \textit{A J.}, 67, 110


———. 1964, \textit{A J.}, 69, 133.

© American Astronomical Society • Provided by the NASA Astrophysics Data System


Edlén, B. 1964, "Atomic Spectra," *Hdb. d. Phys.*, Vol. 27 (Berlin: Springer-Verlag), Fig. 46.


