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EXPERIMENTAL Pd II OSCILLATOR STRENGTHS AND THE PALLADIUM ABUNDANCE IN THE HgMn-TYPE STAR \( \chi \) LUPI

HANS LUNDBERG, SVENERIC G. JOHANSSON, JÖRGEN LARSSON, DAVID S. LECKRÖM, ULF LITZÉN, SUNE SVANBERG, GLENN M. WAHLGREN, AND RAOUl ZERNE

ABSTRACT

Experimental oscillator strengths for 19 ultraviolet lines of Pd II have been derived from measurements of line intensities in calibrated Fourier transform spectra, combined with picosecond-pulse laser measurements of radiative lifetimes. Five of these 19 lines, in addition to other Pd II lines, are present in Hubble Space Telescope/Goddard High-Resolution Spectrograph echelle spectra of the chemically peculiar HgMn star \( \chi \) Lupi, yielding a palladium abundance of \( \log (N_{\text{Pd}}) = +5.0 \), which is 3.3 dex above the solar abundance. Theoretical oscillator strengths have been calculated for all strong ultraviolet transitions associated with the lowest odd-parity configuration of Pd II.

Subject headings: atomic data — line identification — stars: abundances — stars: individual (\( \chi \) Lupi) — ultraviolet: stars

1. INTRODUCTION

In a previous paper Johansson et al. (1994) combined experimental and observational data to determine the abundance of ruthenium in the chemically peculiar (CP) HgMn-type star \( \chi \) Lupi. The laboratory data included measurements of atomic lifetimes and branching fractions for some Ru II lines, from which absolute oscillator strengths were derived. These were applied to seven Ru II lines in the ultraviolet (UV) spectrum of \( \chi \) Lupi, obtained with the Goddard High-Resolution Spectrograph (GGRS) on board the Hubble Space Telescope (HST). The agreement between observed and calculated line profiles using the new Ru II data was good and within the combined uncertainties. The same method has now been applied to five newly identified Pd II lines in the \( \chi \) Lupi spectrum of the GGRS. The identifications are based on coincidences between unidentified features in the stellar spectrum and strong laboratory lines of Pd II, recently remeasured by Lundberg, Litzén, & Johansson (1994). We identified 19 Pd II lines originating from the \( 4d^8 5p \) configuration in our GGRS spectra. The wavelength agreement between the laboratory lines and stellar features was typically 0.005 Å. Palladium is homologous to nickel, and the atomic structure of Pd II mimics that of Ni II. The ground term 4d\(^9\) 2D lies more than 8 eV below the excited 4d\(^8\)5p configuration, placing the resonance lines in the 1300–1400 Å region. The Pd II lines studied in this work appear at wavelengths longward of 2000 Å and result from 4d\(^8\)5s–4d\(^8\)5p transitions. Experimental oscillator strengths have been determined from measurements of branching fractions and radiative lifetimes. The branching fractions were obtained from line intensities in Fourier transform spectra, and the radiative lifetimes were measured in time-resolved laser experiments. The palladium abundance in the primary star of the multiple-star system \( \chi \) Lupi was determined by fitting calculated line profiles to observed HST spectra. Theoretical oscillator strengths have been calculated for all strong transitions between the \( 4d^8 5s \) and \( 4d^8 5p \) configurations in Pd II.

2. WAVELENGTHS AND BRANCHING FRACTIONS

In an earlier work wavelengths and line intensities for Pd II were measured in the wavelength region 1900–5000 Å using Fourier transform spectroscopy (Lundberg et al. 1994). Many Pd II lines in this region are due to transitions between the low configurations \( 4d^8 5s \) and \( 4d^8 5p \). In that work a hollow cathode discharge was used as a light source, and the accuracy of the wavelength determinations was approximately 1 mÅ. In addition to the measurements of wavelength and peak intensity, Voigt functions were fitted to the observed line profiles, and the area under the fitted curve was adopted as a measure of the intensity. Direct measurements of oscillator strengths require absolute values for the observed intensity. This approach, in turn, requires knowledge of certain light-source parameters and the absolute efficiency of the spectrometer and detector. In most experimental situations it is difficult to obtain this information accurately. A more versatile method, used in this work, is to measure relative intensities or branching fractions and then perform a normalization using an experimental lifetime. When using this method, however, relative intensities for all lines with a common upper level must be known. This can be cumbersome if the lines are spread over long wavelength intervals and different types of recording equipment are used. In the present work Einstein A-values were obtained for lines originating from four levels belonging to the \( 4d^8 5p \) configuration with energies of 70,000 to 80,000 cm\(^{-1}\). These levels decay to states of the \( 4d^8 5s \) configuration through lines, most of which appear in the recorded wavelength region. However, three of the levels...
have branches to the ground state at shorter wavelengths, and calculated $A$-values were used to account for these transitions. To obtain branching fractions from the recorded intensities, the wavelength-dependent efficiency of the spectrometer system must be obtained. It is an advantage if this can be done using reference lines present in the spectra to be calibrated. In the Pd II recordings, either an Ar or an He-Ne mixture was used as the carrier gas, and the efficiency function was obtained from known branching ratios of Ar II lines (Whaling, Carle, & Pitt 1993). However, the branching fractions for Pd II were evaluated utilizing the He-Ne recordings because of a stronger population of the high energy levels in such a discharge. In that procedure we applied the efficiency function obtained using the Ar-Pd hollow cathode. For the theoretical calculations, knowledge of the $4d^75s5p$ configuration is important because of its interaction with the $4d^85p$ levels (see § 4). Pd II wavelengths in the region 1000–1900 Å were derived from photographic plate data obtained with the 10 m spectrograph at the Observatoire de Paris, Meudon. These wavelengths enabled an analysis of the positions of the lowest energy levels of the $4d^75s5p$ configuration, which were included in the calculations. The analysis of this configuration will be published elsewhere.

3. RADIATIVE LIFETIMES

Radiative lifetimes were measured for four levels belonging to the $4d^85p$ configuration. In the experiments free palladium ions were created in a laser-produced plasma. A rotating palladium target was irradiated with a neodymium-doped yttrium aluminum garnet (Nd:YAG) laser, giving pulses with 10 ns duration. The pulses had an energy of about 25 mJ and were focused onto the target by a 30 cm focal length lens. Metastable levels belonging to the $4d^85s$ configuration and with an energy around 25,000 cm$^{-1}$ were then populated in the plasma. Ions were selectively photoexcited from one of these levels to the state under investigation by the light from a dye laser. In order to obtain short duration pulses a distributed feedback dye laser (DFDL) was used. It provided 70 ps duration pulses, which are much shorter than the measured lifetimes. Laser-produced plasmas have been used frequently to produce free atoms or ions of elements with high melting points. It has been found that the plasma environment does not present a problem for accurate determinations of lifetimes of the order of a few nanoseconds (Bergström et al. 1988). For free atoms or ions in the ground state the laser beam can interact with the ions located rather far from the target and for comparatively long periods of time after the plasma has been produced, e.g., in the afterglow of the plasma. In these measurements, however, the optical excitation

<table>
<thead>
<tr>
<th>TABLE 1</th>
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<tbody>
<tr>
<td>Pd II ATOMIC DATA AND DERIVED ABUNDANCES</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Level Data (cm$^{-1}$)</th>
<th>Line (Å)</th>
<th>Einstein $A$ (10$^{6}$ s$^{-1}$)</th>
<th>log $g f$ (Experiment)</th>
<th>log $g f$ (Theory)</th>
<th>log ($N_{Pd}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>69881.712</td>
<td>2658.7201</td>
<td>0.37</td>
<td>−0.40</td>
<td>−0.24</td>
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</tr>
<tr>
<td>$J = 9/2$</td>
<td>2336.5869</td>
<td>0.58</td>
<td>−0.32</td>
<td>−0.09</td>
<td>+6.05</td>
</tr>
<tr>
<td>$\tau_{exp} = 3.2 \pm 0.3$ ns</td>
<td>2331.5907</td>
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<td>+0.21</td>
<td>+0.36</td>
<td>...</td>
</tr>
<tr>
<td>$\tau_{all} = 2.2$ ns</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>73330.716</td>
<td>2698.5351</td>
<td>0.07</td>
<td>−1.24</td>
<td>−1.14</td>
<td>...</td>
</tr>
<tr>
<td>$J = 7/2$</td>
<td>2569.5444</td>
<td>0.43</td>
<td>−0.47</td>
<td>−0.37</td>
<td>...</td>
</tr>
<tr>
<td>$\tau_{exp} = 2.9 \pm 0.3$ ns</td>
<td>2435.3210</td>
<td>1.63</td>
<td>+0.06</td>
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<td>+5.05</td>
</tr>
<tr>
<td>$\tau_{all} = 2.1$ ns</td>
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<td>−0.73</td>
<td>−0.66</td>
<td>...</td>
</tr>
<tr>
<td>...</td>
<td>2162.2617</td>
<td>0.54</td>
<td>−0.52</td>
<td>−0.47</td>
<td>...</td>
</tr>
<tr>
<td>...</td>
<td>2072.0423</td>
<td>0.08</td>
<td>−1.39</td>
<td>−1.23</td>
<td>...</td>
</tr>
<tr>
<td>...</td>
<td>1363.685</td>
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<td>−0.86</td>
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<td>74321.488</td>
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<tr>
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<tr>
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</tr>
<tr>
<td>...</td>
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<td>−0.87</td>
<td>−0.78</td>
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<tr>
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<td>0.05</td>
<td>−1.36</td>
<td>−1.08</td>
<td>...</td>
</tr>
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<td>0.49</td>
<td>−0.40</td>
<td>−0.27</td>
<td>...</td>
</tr>
<tr>
<td>$\tau_{exp} = 1.5 \pm 0.3$ ns</td>
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<td>3.73</td>
<td>+0.37</td>
<td>+0.29</td>
<td>...</td>
</tr>
<tr>
<td>$\tau_{all} = 1.8$ ns</td>
<td>2207.4835</td>
<td>1.30</td>
<td>−0.12</td>
<td>−0.20</td>
<td>+4.80</td>
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<tr>
<td>...</td>
<td>2107.6811</td>
<td>0.04</td>
<td>−1.66</td>
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</tr>
<tr>
<td>...</td>
<td>1254.527</td>
<td>0.97</td>
<td>−0.74</td>
<td>−0.82</td>
<td>...</td>
</tr>
</tbody>
</table>
occurred from comparatively high metastable levels, and in
order to have a substantial population of these levels, it was
necessary to have a short delay between the creation of the
plasma and the dye laser pulse. The plasma expands
rapidly, and the density is much higher at early stages of its
evolution. Collisions can then cause a shortening of record-
ed lifetimes. In the measurements the delay was increased
until no systematic change in the lifetime was observed. A
delay of 0.4 \( \mu \)s was sufficient for the highest metastable level,
whereas the population was too low after 0.6 \( \mu \)s. These
numbers correspond to a laser excitation located 5 mm
from the target. The dye laser was pumped by a mode-
locked and Q-switched Nd:YAG laser. The dye laser output,
tunable in the region 7000–8000 \( \text{Å} \), was amplified to
a pulse energy of about 1 mJ. The laser pulses were mixed
with the fourth harmonic of the Nd:YAG laser in a crystal
giving the desired excitation wavelengths between 2000 and
2200 \( \text{Å} \). The bandwidth of the laser light was about 0.3 \( \text{Å} \).
Fluorescence light was detected in a direction perpendicular
to the flight direction of the ions and the direction of the
exciting radiation. One decay channel, different from the
excitation, was selected using a 0.25 m monochromator,
which also reduced the continuous background radiation
from the plasma. The decay was recorded by a micro-
channel plate photomultiplier tube connected to a digital
oscilloscope. For each lifetime measurement three record-
ings were made: the dye laser pulse without plasma, the
plasma background light without dye laser, and the fluo-
rescence decay. In the evaluation procedure the second curve
was subtracted from the third in order to subtract plasma
background. Figure 1 shows a decay curve obtained in this
way. To avoid possible effects due to the limited time
resolution in the detection system, the lifetime value was
finally obtained by a least-squares fit to a convolution of the
recorded laser pulse and an exponential curve. The lifetime
values are given in Table 1.

4. OSCILLATOR STRENGTHS

Theoretical oscillator strengths were obtained using the
Cowan computer code package (Cowan 1981; Raclenko &
Kramida 1995). The final calculations were performed using
wave functions obtained after a least-squares fit of calcul-
ated levels to observed energy levels. The configurations
4\( d^9 \), 4\( d^85s \), 4\( d^95d \), 4\( d^85s^2 \), 4\( d^95p \), and 4\( d^85s^25p \) were
included in the calculations. The log \( gf \) values were calcu-
lated for all transitions between the 4\( d^95p \) and 4\( d^85s \) con-
fignurations that were observed by Lundberg et al. (1994),
and a complete list is available upon request. In Table 1 we
only include values for those transitions that were investi-
gated experimentally. The four levels, for which lifetimes
were measured, were chosen because lines that were
observed in \( HST \) spectra originate from these levels. The
level \( J = 9/2 \) does not combine with the ground state, and
all lines from this level were covered by the Fourier trans-
form spectra. For the other levels the branching fractions to
the ground state were taken from the Cowan calculations.
The highest level has transitions to the 4\( d^85s \) configuration
at wavelengths below 1900 \( \text{Å} \) as well as possible unknown
infrared transitions to the 4\( d^95s^2 \) configuration. According
to the calculations, the former contribute 5\% to the total
decay, whereas the latter are negligible. Other transitions to
the 4\( d^85s \) configuration were calculated to be at least 1
order of magnitude weaker than any of those listed, and
they were not detected in the Fourier transform spectra.

The experimental lifetimes given in the first column of Table
1 have error bars set by the statistical spread amongst the
different recordings. For the lifetimes it can be seen that
the calculated values have a rather small spread around 2 ns,
while the experimental value differs by more than a factor of
2. For other levels in the configuration, however, the Cowan
calculations show a larger variation. In the fifth column the
calculated log \( gf \)-values are given for comparison. The table
also includes three transitions to the ground state although
these lines appear at shorter wavelengths and thus were not
observed in the intensity-calibrated spectra. The values
reported as experimental are in these cases equal to the
theoretical values rescaled by means of the experimental
lifetime. As already mentioned, in the evaluation of experi-
mental log \( gf \)-values the relative intensities were taken from
the recordings using He-Ne as a carrier gas. An estimate of
the errors in the branching fractions due to noise in the
recorded profiles can be obtained by comparing with results
from the argon recordings or using peak intensities instead
of areas under fitted curves. This procedure shows a varia-
tion of typically 20\%. The relative error in the lifetimes is
10\%–20\%. To this, one should add an uncertainty in the
efficiency calibration. Three of the four levels have branches
in unobserved lines. These were taken from the calculations
and correspond to 15\%–20\% of the total decay. The intensi-
ities of the \( Pd \) lines are much higher in the He-Ne than in
the \( Ar \) recordings, indicating a considerably lower \( Pd^+ \)
density in the latter case. Comparisons between line ratios
from the two recordings indicate that the influence from
self-absorption on the branching fractions is negligible com-
pared to the other sources of error. In total, an estimated
uncertainty of 40\% corresponds to \( \pm 0.15 \) dex in the
log \( gf \)-value.

5. ASTROPHYSICAL APPLICATIONS

Use of the GHRS echelle mode together with the experi-
mental results discussed in the previous sections have
allowed us to identify and analyze \( Pd \) lines found in the
UV spectrum of the CP HgMn-type primary star of the \( \chi \)
Lupi (B9.5p HgMn + A2Vm) binary star system. CP stars
are known to exhibit strong spectral lines from a variety of
heavy elements. Among the stars of the CP magnetic
sequence (Ap stars), spectral lines of \( Pd \) have been identi-
fied in optical region spectrograms of \( \chi \) Equ (Adelman,
Bidelman, & Pyper 1979) and HR 465 (Bidelman 1966;
Bidelman, Cowley, & Ille 1995; Cowley et al. 1973; Hartoog,
determined the abundance log \( N_{Pd} = +6.4 \) from three \( Pd \) lines (on a scale where log \( H = 12.00 \)). A
\( Pd \) abundance has also been estimated for the Sun, +1.69
(Biemont et al. 1982), and Procyon, +1.60 (Orlov & Shav-
rina 1991). We refer the interested reader to the recent work
of Jaschek & Jaschek (1995) for discussions pertaining to
elemental identifications in stellar spectra. \( \chi \) Lupi has been
the subject of both optical and UV studies as a result of its
extremely sharp spectral lines that originate from its low
rotational velocity and small atmospheric turbulent mixing.
Its UV spectrum is an excellent resource for researching
problems in atomic physics under physical conditions that
are not normally found in the laboratory (Johansson et al.
1995) or that originate from elements/ions that exist at trace
abundance levels in stars of more solar-like chemical com-
position. The GHRS spectra used in this study were
obtained during 1993 February as part of \( HST \) GTO.
The data reduction and synthetic spectrum analysis techniques employed have been discussed by Leckrone et al. (1993) and Wahlgren et al. (1995). The data typically have signal-to-noise ratios between 60 and 80 at the continuum level. The GHTS isochronal mode provides spectral resolving powers between \( R = \delta \lambda / \lambda = 80,000 \) and 95,000. Each of the four observations that were employed in this analysis was independently normalized by a technique that utilizes synthetic spectra to identify the actual continuum level, which often occurs at higher flux values than are found the spectrum peaks. The palladium abundance in the primary star \( \chi \) Lupi A was determined by fitting the flux normalized observations with spectra generated by the program SYNTHETE (Kurucz & Avrett 1981), using ATLAS9 model atmospheres created from the stellar parameters determined by Wahlgren, Adelman, & Robinson (1994). The co-addition of spectra generated for each of the binary star components was based upon the ephemeris of Dworetsky (1972). Five of the lines presented in Table I are located within the bounds of the spectral data obtained to date for \( \chi \) Lupi. Additional lines of \( \text{Pd} \) II have also been identified in the data; however, without accurate \( gf \)-values these lines take on a supportive role in the abundance determination. Lines of \( \text{Pd} \) II were not identified in the secondary star spectrum. Although terrestrial palladium is composed of six isotopes, we do not see any structure or asymmetry in the laboratory line profiles. Thus, there is no measurable effect upon the positions and shapes of line profiles either in our laboratory spectra or in the stellar spectra, and we have modeled the stellar \( \text{Pd} \) II lines as single-component structures. The bulk of the atomic line data in the synthetic spectrum calculations are taken from the compilations of Kurucz (1991). Figures 2 through 6 illustrate the results of the synthetic spectrum analysis. Each of the figure captions...
files is minimal. We suspect that the Pd II abundance derived from the $\lambda2336.587$ line is unrealistically high as a result of the presence of an unidentified spectral line(s), and we therefore exclude it from the final Pd II abundance value quoted. The other lines provide reasonably consistent results and no evidence for the exclusion of additional lines from the Pd II abundance determination. A straight averaging of the derived abundances from the remaining four lines, as presented in Table 1, yields log $(N_{\text{Pd}})$ = +5.0. Figure 4 also includes the line Pd II $\lambda2336.432$, for which we have obtained $gf$ = +1.156 from a Cowan code calculation. Its depth is matched well by the average Pd abundance determined, but its greater observed width indicates that other blending lines, for which we have no knowledge at the present time, are likely to be present. Thus, the abundance of palladium in $\chi$ Lupi is determined to be 3.3 dex greater than the solar value. However, we caution the reader that comparisons of elemental abundances made between HgMn stars and the Sun may be affected by the choice of ion and our understanding of the physical mechanisms that are responsible for the great line strengths in HgMn stars. The enhancement of palladium is approximately 1.5 orders of magnitude greater than the Ru II enhancement in $\chi$ Lupi (Johansson et al. 1994) and nearly 3 orders of magnitude greater than the Cd II enhancement (Wahlgren et al. 1995). Lines from the adjacent odd atomic number elements Rh and Ag have yet to be detected. In $\chi$ Lupi, the palladium abundance enhancement is only surpassed by those for the very heavy ions platinum, gold, and mercury (Wahlgren et al. 1995) and thallium (Leckrone et al. 1996).

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