Mon. Not. R. Astron. Soc. **363,** 905–910 (2005) doi:10.1111/j.1365-2966.2005.09493.x

Radiative parameters for some transitions in the spectrum of Ag II

J. Campos,[1⋆] M. Ortiz,[1] R. Mayo,[1] E. Biémont,[2,3]† P. Quinet,[2,3] K. Blagoev[4] and G. Malcheva[4]

[1]*Department of Atomic Physics, Faculty of Physics, Universidad Complutense de Madrid, E-28040 Madrid, Spain*
[2]*IPNAS (Bât. B15), University of Liège, Sart Tilman, B-4000 Liège, Belgium*
[3]*Astrophysics and Spectroscopy, University of Mons-Hainaut, B-7000 Mons, Belgium*
[4]*Institute of Solid State Physics, 72 Tzarigradsko Chaussee, BG-1784 Sofia, Bulgaria*

Accepted 2005 August 3. Received 2005 June 13; in original form 2005 March 17

ABSTRACT

Radiative parameters for transitions depopulating the levels belonging to the $4d^85s^2$, $4d^96s$ and $4d^95d$ configurations of Ag II have been obtained from a combination of theoretical lifetimes and experimental branching fractions. On the experimental side, a laser-produced plasma was used as a source of Ag^+ ions. The light emitted by the plasma was analysed by a grating monochromator coupled with a time-resolved optical multichannel analyser system. Spectral response calibration of the experimental system was performed using a deuterium lamp in the wavelength range from 200 to 400 nm, and a standard tungsten lamp in the range from 350 to 600 nm. The transition probabilities were obtained from measured branching ratios and theoretical radiative lifetimes of the corresponding states calculated with a relativistic Hartree–Fock approach including core-polarization effects and configuration interaction in an extensive way. Theoretical and experimental data have been compared and the new data have also been compared with the few previous results available in the literature.

Key words: atomic data – line: identification – methods: analytical – techniques: spectroscopic – stars: general.

1 INTRODUCTION

Accurate atomic data, such as radiative lifetimes and transition probabilities, are of common interest in many fields of physics. In astrophysics, the analysis of the high-resolution stellar spectra now available, in order to deduce information concerning the chemical composition of the stars, relies heavily upon the availability of reliable atomic data, particularly of transition probabilities (Biémont & Quinet 2003; Jorissen 2004). Silver has been identified in the solar spectrum (see e.g. Biémont & Grevesse 1977) and has been detected in other stars by Merril (1947) (S type) and by Jaschek & Brandi (1972) (Ap star of the Cr-Eu-Sr subgroup). More recent identifications of Ag in some Ap stars (like Przybylski's star) have been published (see e.g. Cowley et al. 2000). The Goddard High Resolution Spectrograph (GHRS) on board the *Hubble Space Telescope* (*HST*) has opened the way to a detailed investigation of the composition of chemically peculiar stars, particularly for the heavy elements ($32 \leqslant Z \leqslant 82$) provided the relevant atomic data are available (Leckrone et al. 1993). Morton (2000) has also recently emphasized the need for accurate atomic data for heavy elements, including silver, with wavelength range longward of the Lyman limit.

In laser physics, lifetimes and transition probabilities are decisive for predictions of potential laser action in some specific media (see e.g. Svanberg 2001). There exist a number of experimental studies of neutral silver lifetimes and transition probabilities [for references, see e.g. the compilation in NIST (2005a)], but very little experimental work on Ag^+ has been published (see below). From a theoretical point of view, the oscillator strengths of heavy ions are frequently very sensitive to electronic coupling schemes and to configuration-interaction effects and, consequently, they are important for testing the validity of theoretical models and also their predictive power. In a heavy ion such as Ag II, the correlation and relativistic effects are both expected to be important, and they must be taken into account properly in atomic structure calculations if accurate results are needed.

Ag II belongs to the Pd I isoelectronic sequence. The ground state is $[Kr]4d^{10}\ ^1S_0$ and the lowest excited configurations are $4d^9ns$ (n = 5–6), $4d^9np$ (n = 5–6), $4d^95d$ and $4d^85s^2$ (Moore 1958; Benschop, Joshi & van Kleef 1975). Silver has two stable isotopes, ^{107}Ag and ^{109}Ag, which are present in the Solar system with abundances of 51.82 and 48.18 per cent, respectively, and the two isotopes are produced in stellar nucleosynthesis by both the r and s processes.

Radiative parameters available for Ag II transitions are very sparse. In fact, the first measurements in this ion were the arc measurements of Corliss & Bozman (1962) for four ultraviolet (UV) transitions. Later, theoretical lifetimes values were calculated by

⋆Deceased.
†E-mail: E.Biemont@ulg.ac.be

Theodosiou (1986) for the $4d^9 6s$ and $4d^9 5d$ levels using a Hartree–Slater type potential to represent the ionic core. The transition probabilities of the two-electron $nd^8(n+1)s^2$–$nd^9(n+1)p$ transitions and the radiative lifetimes of the $nd^8(n+1)s^2$ states have been investigated theoretically (Hartree–Fock method) by Blagoev et al. (1990). In the case of the $4d^9 6s$ configuration, experimental data for the radiative lifetimes have been reported by Plekhotkina (1981) using a delayed-coincidence technique and by Molhave & Sorensen (1971) using beam–foil spectroscopy.

The lifetimes reported by Irving et al. (1995) (beam–foil spectroscopy) and by Biémont et al. (1997) (beam–laser measurements) concern the $4d^9 5p$ configuration. The transition probabilities published by Ferrero et al. (1995, 1996) from measurements of emission-line intensities in an optically thin laser-produced plasma or by Bogdanovich & Martinson (1999) (superposition-of-configuration approach) are related to transitions originating from the $4d^9 5p$ levels in Ag II.

The main purpose of the present work is to provide radiative data, i.e. transition probabilities, for the transitions emitted from the levels of the $4d^8 5s^2$, $4d^9 5d$ and $4d^9 6s$ configurations of Ag II. The recent development of laser spectroscopy techniques, in both the time and wavelength domains, has made laser measurements of transition probabilities in high-energy atomic or ionic levels feasible. In the current study, transition probabilities of excited states up to 128 000 cm^{-1} have been measured by laser-produced plasma and time-resolved spectroscopy. Theoretical calculations have also been performed by a relativistic Hartree–Fock approach (HFR method), in which core-polarization (CP) effects and extensive configuration interaction have been included. The final set of data results from a combination of the theoretical lifetimes and the experimental branching fraction (BF) measurements.

Preliminary results were presented at the VUV14 meeting in Cairns, Australia (2004 July) (Biémont et al. 2005).

2 EXPERIMENTAL MEASUREMENTS

The transitions and levels studied in Ag II are shown in Fig. 1. The energy levels quoted in the compilation of Moore (1958), later on revised by Benschop et al. (1975) on the basis of observations in the wavelength range 40.0–230.0 nm, were adopted in the present study.

The experimental setup used for the transition probability measurements is illustrated schematically in Fig. 2. A description has been given recently (Xu et al. 2004). A plasma produced by laser ablation was employed as a source of Ag^+ ions, but the plasma contains at the same time neutrals and doubly ionized atoms. A focused Nd:YAG laser beam was used to generate this plasma on the surface of a silver target in a controlled argon atmosphere (∼8 Torr). A 1064 nm Nd:YAG laser generated 240 mJ pulses of 7 ns duration at a frequency of 20 Hz. The light emitted by the laser-produced plasma was incident on the input slit of 1-m grating Czerny–Turner monochromator (resolution 0.03 nm). The spectra were recorded by a time-resolved optical multichannel analyser (OMA III, EG&G), which allowed recording of spectral regions at different delays after the laser pulse and during a selected time interval (Fig. 3).

The calibration of the spectral response of the experimental system was carried out, before the experiment, using a standard deuterium lamp in the wavelength range 200–400 nm, and a standard tungsten lamp in the range 350–600 nm. The final calibration was achieved from overlapping of several joint regions covered by the deuterium and tungsten lamps using a least-squares fitting procedure. The calibration of the array was also checked by measurements of the BFs of well-known Ar I and Ar II spectral lines. The two types of calibration were in agreement within an error limit of 5 per cent. In order to check the time evolution of the response of the OMA photodiode array, the calibration of the array was repeated regularly and was compared with the response of the photodiode

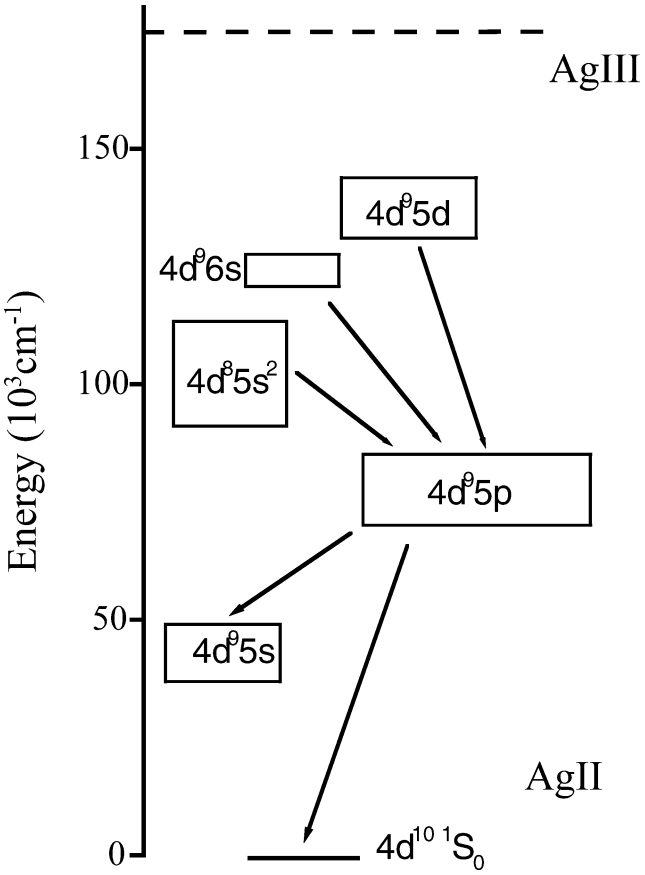

Figure 1. Partial Grotrian diagram showing the transitions investigated in the present work.

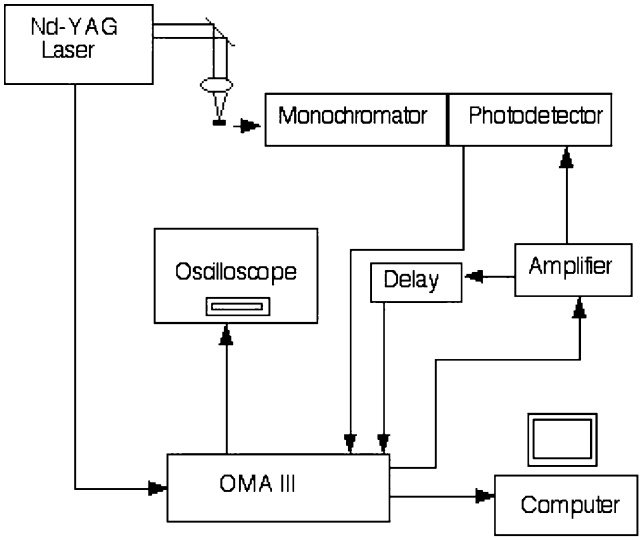

Figure 2. Experimental setup used for branching fraction measurements. See the text for more details.

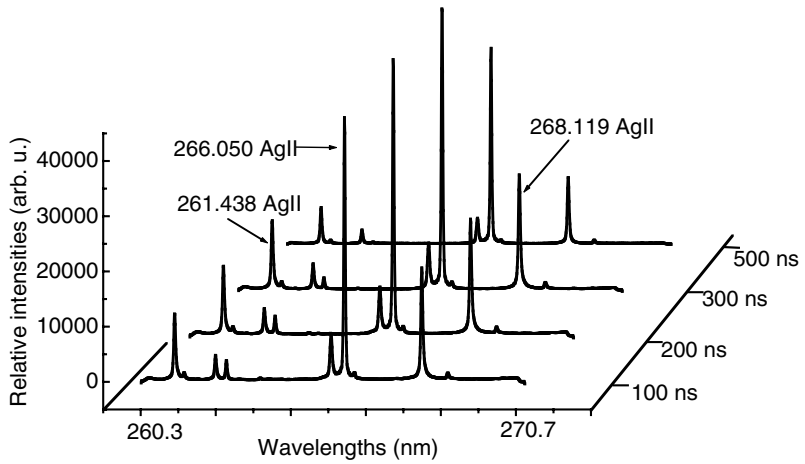

Figure 3. Time evolution of the Ag plasma.

Table 1. Experimental and theoretical lifetimes in Ag II.

Level	Energy[a] (cm^{-1})	Lifetime (ns) B90[b]	MS71[c]	T86[d]	P81[e]	HFR(A)[f]	HFR(B)[f]
$5s^2\ ^1D_2$	110 769.41	480/590				260	290
$5s^2\ ^1G_4$	113 598.12	370/340				150	170
$6s\ ^3D_3$	120 529.45			2.548	3.2 ± 0.5	2.20	2.18
$6s\ ^3D_2$	120 907.13		2.8 ± 0.7	2.566		2.24	2.23
$6s\ ^3D_1$	125 122.38			2.534		2.19	2.17
$6s\ ^1D_2$	125 400.89			2.607	3.2 ± 0.4	2.23	2.23
$5d\ ^3P_1$	126 763.70			1.391	3.2 ± 0.5	1.51	1.44
$5d\ ^3D_3$	127 205.00			1.454	3.7 ± 0.2	1.48	1.39
$5d\ ^3F_3$	127 484.50			1.463	4.7 ± 0.5	1.48	1.40
$5d\ ^3D_2$	127 517.00			1.462		1.57	1.49
$5d\ ^3F_4$	127 601.80			1.518		1.61	1.51
$5d\ ^3P_0$	128 528.80			1.634		1.46	1.38

[a]From Moore (1958) and Benschop et al. (1975). [b]Blagoev et al. (1990): Hartree–Fock length/velocity results. [c]Molhave & Sorensen (1971): beam–foil spectroscopy. [d]Theodosiou (1986): Hartree–Slater type potential. [e]Plekhotkina (1981): delayed-coincidence technique. [f]This work (see text).

array using the 431.6 nm Kr I spectral line, which was measured by different channels of the detector (50 channel steps in a 1024 array). The difference due to time evolution of the calibration is around 2 per cent. The error due to the calibration is estimated at around 6 per cent. Detection was made in synchronization with the electronic trigger of the Q-switched laser. During data acquisition, background subtraction was performed.

The method used here is based on the fact that, after laser ablation, there is an optimized delay time for recording the spectrum of the selected ion. For that purpose, the measurements were made at several delay times after the laser pulse, more precisely after 0.1, 0.2, 0.3 and 0.5 ms. The measurements of BFs for the determination of transition probabilities have been made on the spectra of Ag II obtained at a delay of 0.2 ms because the lines were better resolved and narrower than those obtained with shorter delays, on the one hand, and were more intense than those corresponding to longer delays, on the other. It was verified, however, that the measured BFs did not depend upon the delay time.

The spectra were stored in a computer and processed to separate close or overlapping lines and to determine their relative intensities. The relative intensities were obtained by a fitting procedure based on the use of Voigt profiles, after background subtraction. In the present experiment, the possible overlapping of the investigated spectral lines with other spectral lines of silver ions or of Ar I and Ar II were investigated with care. The final intensity of each line was the average of five different measurements.

3 HFR CALCULATIONS

The atomic structure calculations were performed in the framework of the pseudo-relativistic Hartree–Fock (HFR) method with the help of Cowan's suite of computer codes (Cowan 1981) modified for consideration of core-polarization (CP) effects (see e.g. Quinet et al. 1999). This approach, although based on the Schrödinger equation, does include the most important relativistic effects like the mass–velocity corrections and Darwin contribution. This procedure is described in detail by, for example, Biémont et al. (2000), and has been able to provide a large number of new results in heavy elements including the lanthanides (see e.g. the database DREAM[1] and references therein).

The HFR lifetime values of the levels studied are presented in Table 1. The theoretical transition probabilities (calculations A and B, see below) of the lines depopulating the levels of interest are

[1] http://www.umh.ac.be/astro/∼dream.shtml

Table 2. Transition probabilities for the $4d^85s^2 \longrightarrow 4d^95p$ transitions of Ag II. L: Length form; V: velocity form.

Upper level	Lower level	λ (nm)	A_{ik} (10^5 s^{-1}) Exp.[a]	$A^{\rm L}_{ik}$ (10^5 s^{-1}) B90[b]	$A^{\rm V}_{ik}$ (10^5 s^{-1}) B90[b]	A_{ik} (10^5 s^{-1}) HFR(A)[a]	A_{ik} (10^5 s^{-1}) HFR(B)[a]
$5s^2\ ^1G_4$	$5p\ ^3D^o_3$	368.333	9.9 ± 0.7	6	5	11.0	9.9
	$5p\ ^1F^o_3$	408.590	11.2 ± 0.5	9	10	18.2	16.1
	$5p\ ^3F^o_3$	318.070	43.0 ± 2.0	14	14	36.3	33.4
	$5p\ ^3F^o_4$	333.987	2.1 ± 0.1	–	–	0.3	0.2
$5s^2\ ^1D_2$	$5p\ ^1P^o_1$	478.839	9.5 ± 1.7	1	6	6.9	5.4
	$5p\ ^3P^o_1$	368.246	0.90 ± 0.09[c]	2	0.7	1.3	1.1
	$5p\ ^3P^o_2$	326.733	8.7 ± 0.9	10	7	13.1	11.5
	$5p\ ^3D^o_2$	390.930	–	2	0.2	–	–
	$5p\ ^3F^o_2$	418.547	3.7 ± 0.7	–	–	4.7	4.4
	$5p\ ^1D^o_2$	502.733	3.4 ± 0.4[c]	4	0.7	5.1	4.6
	$5p\ ^3D^o_3$	411.189	1.2 ± 0.1	1	0.2	0.2	0.2
	$5p\ ^1F^o_3$	462.004	2.1 ± 0.4	0.6	2	3.2	2.7
	$5p\ ^3F^o_3$	349.528	7.4 ± 1.3	–	–	3.3	2.8
	$5p\ ^3D^o_1$	489.132	1.0 ± 0.1[c]	–	–	1.5	1.8

[a]This work (see text). [b]Blagoev et al. (1990). [c]Spectral lines for which theoretical BFs were taken into account, because of the spectral line blending problems.

reported in Tables 2–4, where they are compared with the experimental results of the present work and with previous data when available.

In the first calculation (calculation A), the following configurations were considered: $4d^{10} + 4d^95s + 4d^96s + 4d^95d + 4d^96d + 4d^95g + 4d^85s^2 + 4d^85p^2 + 4d^85d^2 + 4d^85s5d$ (even parity); and $4d^95p + 4d^96p + 4d^94f + 4d^95f + 4d^96f + 4d^85s5p + 4d^85s4f + 4d^85s5f + 4d^85p5d$ (odd parity).

CP effects, which are expected to be important in this heavy singly ionized element, were introduced in the calculations in the following way. For the static dipole polarizability, we used the value corresponding to the ionic core of Ag XII as published by Johnson, Kolb & Huang (1983), i.e. $\alpha_{\rm d} = 0.70$ atomic units. This value is in good agreement with the one previously computed by Fraga, Karwowski & Saxena (1976), i.e. $\alpha_{\rm d} = 0.61$ atomic units. The cut-off radius $r_{\rm c}$ was chosen equal to 1.00 au and corresponds to the HFR mean value $\langle r \rangle$ of the outermost orbital 4p in the configuration $4p^6$.

The calculated eigenvalues of the Hamiltonian were optimized to the observed energy levels via a least-squares fitting procedure using the available experimental energy levels. In fact, all the levels taken from the NBS compilation (NIST 2005b), including refined values due to Benschop et al. (1975) and to Kalus et al. (2002), were included in the fitting procedure. The scaling factors of the F^k, G^k and R^k integrals (not optimized in the least-squares fitting procedure) were chosen equal to 0.80, while the spin–orbit integrals were left at their ab initio values. This choice results from the considerable experience of the authors concerning calculations of atomic structures in heavy ions (see the above-mentioned database DREAM) and is justified on theoretical grounds in Cowan (1981).

In a second calculation (calculation B), the following configurations were considered: $4d^{10} + 4d^95s + 4d^96s + 4d^97s + 4d^98s + 4d^95d + 4d^96d + 4d^97d + 4d^98d + 4d^85s^2 + 4d^85p^2 + 4d^85d^2 + 4d^85s5d + 4d^84f5p + 4d^85p5f + 4p^54d^{10}5p + 4p^54d^{10}4f + 4p^54d^{10}5f$ (even parity); and $4d^95p + 4d^96p + 4d^97p + 4d^98p + 4d^94f + 4d^95f + 4d^96f + 4d^97f + 4d^85s5p + 4d^85p5d + 4d^84f5s + 4d^84f5d + 4p^54d^{10}5s + 4p^54d^{10}5d$ (odd parity).

This set of configurations extends considerably the one considered in calculation A. In particular, configurations involving five electrons in the 4p subshell were added in order to include explicitly some core–valence correlation. Thus, no additional core-polarization corrections were incorporated in this second model. The scaling factor adopted for the Slater and configuration-interaction integrals was also 0.80.

The results obtained during the calculations A and B are reported in Table 1 (lifetimes) and in Tables 2–4 (transition probabilities). It is seen that the two sets of results are in close agreement [within a few (<10) per cent] indicating that probably the largest part of the configuration-interaction effects have been captured in the CP model adopted in calculation A.

4 DISCUSSION OF THE RESULTS

For the 6s and 5d levels, our HFR lifetime values (A and B) agree quite well with the results of Theodosiou (1986) obtained in an independent way, indicating a good coherence between the two sets of data. For 6s, they are systematically smaller, but within reasonable limits (differences <15 per cent). The comparison of our theoretical lifetimes (and those of Theodosiou 1986) with experiment (Molhave & Sorensen 1971; Plekhotkina 1981) is not conclusive, a large scatter being observed, but it is hard to estimate the accuracy of the measurements. Both experiments were performed by non-selective excitation experimental methods and the values obtained are systematically larger than those of theory. The reason could be associated with a cascading problem in the experiments. Further experimental investigations, using a completely independent method, are clearly needed to confirm the published experimental results.

A first argument in favour of the HFR(A) model results from the fact that previous HFR calculations (Biémont et al. 1997), obtained with a similar atomic model, are in close agreement (the mean deviation being 6.1 per cent for 10 levels) with accurate beam–laser measurements for $4d^95p$ levels.

A second argument in favour of our theoretical models results from the fact that, in Cu II, the homologous ion of Ag II, but in the fourth row of the periodic table, the HFR lifetimes obtained with a model similar to that adopted in the present paper (Pinnington et al. 1997; Biémont et al. 2000) were in reasonable agreement with, but systematically smaller than, the accurate experimental

Table 3. Transition probabilities for the $4d^9 6s \longrightarrow 4d^9 5p$ transitions of Ag II (this work, see text).

Upper level	Lower level	λ (nm)	A_{ik} (10^7 s^{-1}) Exp.	A_{ik} (10^7 s^{-1}) HFR(A)	A_{ik} (10^7 s^{-1}) HFR(B)
$6s\ ^3D_3$	$5p\ ^3P^o_2$	247.712	13.9 ± 3.1	12.7	12.8
	$5p\ ^3F^o_3$	260.597	3.0 ± 0.4	4.3	4.4
	$5p\ ^3F^o_4$	271.187	20.0 ± 3.6	18.9	19.1
	$5p\ ^3D^o_3$	293.402	7.2 ± 0.7	8.9	9.1
	$5p\ ^1F^o_3$	318.391	0.4 ± 0.04	0.4	0.4
	$5p\ ^1D^o_2$	337.220	0.1 ± 0.01	0.2	0.2
	$5p\ ^3D^o_2$	282.940	–	–	–
	$5p\ ^3F^o_2$	297.130	–	–	–
$6s\ ^3D_1$	$5p\ ^3P^o_0$	256.423	6.2 ± 0.7	5.4	5.4
	$5p\ ^3F^o_2$	261.439	13.6 ± 1.6	13.8	14.7
	$5p\ ^3D^o_1$	287.341	10.6 ± 1.3	8.3	7.5
	$5p\ ^3P^o_2$	222.399	–	0.4	0.2
	$5p\ ^3P^o_1$	240.885	–	1.7	1.6
	$5p\ ^3D^o_2$	250.389	9.2 ± 0.8	7.2	6.4
	$5p\ ^1P^o_1$	283.758	0.4 ± 0.03	3.6	4.6
	$5p\ ^1D^o_2$	291.982	6.0 ± 0.7	5.3	5.5
$6s\ ^1D_2$	$5p\ ^1F^o_3$	275.627	19.8 ± 3.4	18.6	19.0
	$5p\ ^1P^o_1$	281.532	7.1 ± 0.5	6.6	5.9
	$5p\ ^1D^o_2$	289.625	8.4 ± 0.8	8.7	8.8
	$5p\ ^3P^o_2$	221.030	0.3 ± 0.02	1.1	0.9
	$5p\ ^3F^o_3$	231.232	–	0.1	0.1
	$5p\ ^3P^o_1$	239.279	2.5 ± 0.2	2.8	2.9
	$5p\ ^3D^o_2$	248.655	1.6 ± 0.2	1.4	1.3
	$5p\ ^3D^o_3$	256.699	2.5 ± 0.3	1.4	1.2
	$5p\ ^3F^o_2$	259.548	2.8 ± 0.3	3.3	3.5
	$5p\ ^3D^o_1$	285.059	–	0.9	1.3

Table 4. Transition probabilities for the $4d^9 5d \longrightarrow 4d^9 5p$ transitions of Ag II (this work, see text).

Upper level	Lower level	λ (nm)	A_{ik} (10^7 s^{-1}) Exp.	A_{ik} (10^7 s^{-1}) HFR(A)	A_{ik} (10^7 s^{-1}) HFR(B)
$5d\ ^3F_4$	$5p\ ^3F^o_3$	220.030	–	0.3[a]	0.3[a]
	$5p\ ^3F^o_4$	227.531	21.6 ± 1.5	20.4	21.9
	$5p\ ^3D^o_3$	242.968	39.5 ± 2.8	41.2	43.7
	$5p\ ^1F^o_3$	259.857	0.8 ± 0.1	0.3[a]	0.3[a]
$5d\ ^3D_2$	$5p\ ^3D^o_2$	236.220	26.3 ± 1.8	26.4	29.0
	$5p\ ^3P^o_1$	227.743	15.0 ± 1.0	14.7	15.7
	$5p\ ^3F^o_3$	220.441	5.6 ± 0.7	5.4	5.7
	$5p\ ^3P^o_2$	211.149	1.0 ± 0.1	1.3	1.2
	$5p\ ^3D^o_1$	268.837	1.4 ± 0.1	2.4	3.0
	$5p\ ^3F^o_2$	246.031	11.8 ± 0.8	11.2	10.4
	$5p\ ^1F^o_3$	260.431	–	–	-
	$5p\ ^1P^o_1$	265.697	2.9 ± 0.2	2.2	2.0
	$5p\ ^1D^o_2$	272.895	–	0.1[a]	0.1[a]
	$5p\ ^3D^o_3$	243.469	–	0.1[a]	0.1[a]
$5d\ ^3D_3$	$5p\ ^3P^o_2$	212.550	14.7 ± 0.9	21.7	23.4
	$5p\ ^3F^o_4$	229.605	6.0 ± 0.4	5.8	6.1
	$5p\ ^3D^o_2$	237.975	–	0.09[a]	0.1[a]
	$5p\ ^3D^o_3$	245.334	36.9 ± 2.6	29.7	31.4
	$5p\ ^3F^o_3$	221.968	7.3 ± 0.5	8.3	8.7
	$5p\ ^3F^o_2$	247.935	–	0.3	0.3
	$5p\ ^1F^o_3$	262.566	3.0 ± 0.2	1.7	1.7
	$5p\ ^1D^o_2$	275.240	–	0.1[a]	0.1[a]
$5d\ ^3P_0$	$5p\ ^3P^o_1$	222.611	61.1 ± 6.1	63.5	67.0
	$5p\ ^1P^o_1$	258.739	–	0.2[a]	0.4
	$5p\ ^3D^o_1$	261.715	6.9 ± 0.5	5.1	4.8

[a]Cancellation effects present (CF < 0.01).

results obtained in the framework of a beam–laser experiment. As core-polarization effects were not considered by Pinnington et al. (1997) in their calculation, while they are included in the present one (their overall effect being to increase the lifetimes by about 10–30 per cent), it is reasonable and justified to consider that the present HFR calculations are accurate. Consequently, the HFR(A) results, which incorporate more configuration interaction within the CP scheme than the HFR(B) data, were adopted for the normalization of the relative experimental transition probabilities.

In a first step, relative transition probabilities were indeed obtained experimentally and then, in a second step, they were put on an absolute scale using the measured BFs and the HFR(A) radiative lifetimes of the $4d^8 5s^2$, $4d^9 6s$ and $4d^9 5d$ upper states. These data are presented in Tables 2, 3 and 4. The total errors were determined from the radiative lifetime errors, from the uncertainties affecting the calibration (6 per cent) and from statistical errors, which, for the different lines, ranged from 5.0 to 12 per cent.

The temperature of the laser-produced plasma was determined from the slope of a Boltzmann plot of the line intensities of transitions with known transition probabilities and, under the present experimental conditions, it was determined to be $15\,200 \pm 2500$ K.

For most of the transitions, there is generally a good agreement (within 15 per cent) between the BFs (and consequently the transition probabilities) measured in the present work and the calculated HFR(A) and HFR(B) values. Only for a few transitions, some of them being very weak, are larger discrepancies observed, but they have no systematic character. The present set of results is therefore expected to provide astrophysicists with reliable oscillator strengths for a number of Ag II transitions of potential astrophysical interest. The present absolute results clearly depend upon the lifetimes values adopted for the 'normalization' process of the relative results. If accurate experimental lifetimes (obtained, for example, with selective laser excitation) became available, the present transition probability scale could be easily adjusted.

ACKNOWLEDGMENTS

E. Biémont and P. Quinet are Research Director and Research Associate of the Belgian FNRS. Financial support from this organization is acknowledged. The experimental part of this work was supported by the Academic Exchange Program between the Consejo Superior de Investigaciones Cientificas – Universidad Complutense de Madrid and the Bulgarian Academy of Sciences. K. Blagoev and G. Malcheva are grateful to colleagues from the Universidad Complutense de Madrid for their kind hospitality and support.

REFERENCES

Benschop H., Joshi Y. N., van Kleef T. A. M., 1975, Can. J. Phys., 53, 700
Biémont E., Grevesse N., 1977, Phys. Scr. 16, 39
Biémont E., Quinet P., 2003, Phys. Scr., T105, 38
Biémont E., Pinnington E. H., Kernahan J. A., Rieger G., 1997, J. Phys. B, 30, 2067

Biémont E., Pinnington E. H., Quinet P., Zeippen C. J., 2000, Phys. Scr., 61, 567
Biémont E., Blagoev K., Campos J., Mayo R., Malcheva G., Ortiz M., Quinet P., 2005, J. Electron. Spectrosc. Relat. Phenom, 27, 144
Blagoev K., Dimitrov N., Benhalla A., Bogdanovich P., Momkauskaite A., Rudzikas Z. B., 1990, Phys. Scr., 41, 213
Bogdanovich P., Martinson I., 1999, Phys. Scr., 60, 217
Corliss C. H., Bozman W. R., 1962, NBS Monograph 53, Experimental Transition Probabilities for Spectral Lines of Seventy Elements. US Department of Commerce, Washington, DC
Cowan R. D., 1981, The Theory of Atomic Structure and Spectra. Univ. California Press, Berkeley
Cowley C. R., Ryabchikova T., Kupka F., Bord D. J., Mathys G., Bidelman W. P., 2000, MNRAS, 317, 299
Ferrero F. S., Cerezo C., Cigona M. J. F., Campos J., 1995, J. Quant. Spectrosc. Radiat. Transfer, 54, 971
Ferrero F. S., Cerezo C., Cigona M. J. F., Campos J., 1996, J. Quant. Spectrosc. Radiat. Transfer, 55, 533
Fraga S., Karwowski J., Saxena K. M. S., 1976, Handbook of Atomic Data. Elsevier, Amsterdam
Irving R. E., Maniak S. T., Beideck D. J., Bengtsson P., Curtis L. J., Hellborg R., Kalus G., Martinson I., 1995, Phys. Scr., 51, 351
Jaschek M., Brandi E., 1972, A&A, 20, 233
Johnson W. R., Kolb D., Huang K.-N., 1983, At. Data Nucl. Data Tables, 28, 333
Jorissen A., 2004, Phys. Scr., T112, 73
Kalus G., Litzén U., Launay F., Tchang-Brillet W. U. L., 2002, Phys. Scr., 65, 46
Leckrone D. S., Johansson S. G., Wahlgren G. M., Adelman S. J., 1993, Phys. Scr., 47, 149
Merril P. W., 1947, ApJ, 105, 360
Molhave L., Sorensen G., 1971, in 2nd Eur. Conf. on Beam–Foil Spectroscopy, Lyon, France
Moore C. E., 1958, Atomic Energy Levels, Vol. III, Nat. Bur. Stand. Circ. 467. US Government Printing Office, Washington, DC
Morton D. C., 2000, ApJS, 130, 403
NIST, 2005a, http://physics.nist.gov/PhysRefData/Fvalbib/html/reffrm0.html
NIST, 2005b, http://physics.nist.gov/cgi-bin/AtData/main_asd
Pinnington E. H., Rieger G., Kernahan J. A., Biémont E., 1997, Can. J. Phys., 75, 1
Plekhotkina G. L., 1981, Opt. Spectrosc. (USSR), 51, 106
Quinet P., Palmeri P., Biémont E., McCurdy M. M., Rieger G., Pinnington E. H., Wickliffe M. E., Lawler J. E., 1999, MNRAS, 307, 934
Svanberg S., 2001, Atomic and Molecular Spectroscopy, 3rd edn. Springer, Berlin
Theodosiou C., 1986, J. Opt. Soc. Am. B, 3, 1107
Xu H. et al., 2004, Phys. Rev. A, 70, 042508

This paper has been typeset from a Microsoft Word file prepared by the author.