Tungsten spectroscopy in the EUV range observed at a high-temperature superconducting electron-beam ion trap

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We have recorded extreme ultraviolet spectra from W^{11+} to W^{15+} ions using a flat-field spectrometer installed at the Shanghai high-temperature superconducting electron-beam ion trap. The spectra were recorded at beam energies ranging between 200 and 400 eV and showed spectral lines and transition arrays in the 170–260 Å region. The charge states and spectra transitions were identified by comparison with calculations using a detailed relativistic configuration interaction method and collisional-radiative model, both incorporated in the flexible atomic code. Atomic structure calculations showed that the dominant emission arises from $5d \rightarrow 5p$ and $5p \rightarrow 5s$ transitions. The work also identified the ground-state configuration of W^{13+} as $4f^{13}5s^2$ both theoretically and experimentally.

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I. INTRODUCTION

There has been strong interest in tungsten spectroscopy due to the potential use of this element as a plasma-facing material in the International Thermonuclear Experimental Reactor (ITER) tokamak [1,2], especially in the divertor region [3]. Spectra diagnostics of the ITER divertor region will therefore require a large amount of as yet unavailable tungsten atomic data. The ITER divertor soft x-ray spectrometer will operate in the 150–400 Å region [4], where only 108 lines are known [5]. Of these 102 lines originate from W^{4+}, W^{5+}, and W^{6+}. One line is identified as being from W^{51+}, which is too highly ionized to be observed in the divertor region. The plasma temperature in the divertor region of ITER is expected to be in the region of a few to a few hundred eV, which will result in tungsten in charge states of up to around 28+. The remaining five tungsten lines in this wavelength region are reported to be from W^{13+} but might be misidentified [6]. In contrast to this, the diagnostics of the core plasma region has stronger support since considerably more spectroscopic work, both experimental and theoretical, has been reported for the important charge states (see the review by Kramida [7]).

In previous papers we have investigated visible $M1$ transitions in W^{13+} [8], W^{25+} [9], W^{26+} [10], W^{27+} [11] (with an extension to the silver isoelectronic sequence [12,13]), and W^{28+} [14]. In the present work we report on a study of tungsten ions in the wavelength region of interest to ITER divertor diagnostics, i.e., 150–400 Å. Using the Shanghai high-temperature superconducting electron-beam ion trap (SH-HtscEBIT), which was designed for low-energy electron-beam operation, we observed spectra from W^{11+} through W^{15+}. The spectra were recorded using a recently developed high-resolution flat-field spectrometer [15]. From calculations of the relevant atomic structure and also a collisional radiative model, using the flexible atomic code (FAC) [16], we have identified lines and spectral features as originating from $5d \rightarrow 5p$ and $5p \rightarrow 5s$ transitions. We will also discuss the interesting case of W^{13+} in more detail due to the controversy over the classification of the ground state which has existed since the calculations by Curtis and Ellis [17].

II. EXPERIMENTAL METHOD

The experiment was carried out using the SH-HtscEBIT, which is described elsewhere [18]. This EBIT is capable of operating in the range of electron-beam energies between 30 and 4000 eV. The magnetic field, which is created by liquid-nitrogen temperature superconducting coils, compresses the beam radius to 60 μm. The background vacuum pressure in the trap center is estimated to be lower than 10^{-10} Torr, which makes it possible to produce tungsten ions mainly through electron collisional ionization with negligible influence from charge exchange. The spectra were recorded by utilizing a high-resolution grazing-incidence flat-field spectrometer, which covers the range of 10 to 500 Å and reaches a resolving power above 800 [15]. In order to eliminate light from the hot cathode, a 4500-Å-thick aluminum foil was used and mounted on the window of the miniature ultrahigh vacuum gate valve between the SH-HtscEBIT and the spectrometer. Due to the aluminum L absorption edge, only wavelengths longer than 171 Å can pass through this foil. For the present experiment, a Shimazdu varied-line-spacing (VLS) grating (1200 L/mm, part number 001-0659) [19–21] was used, and an Andor CCD camera (model number DO936N-00W-#BN) was placed at different positions to record different wavelength regions. Tungsten ions were obtained by injecting $W(CO)_6$, a volatile compound with a high vapor pressure at room temperature [22]. The experiments were done using electron-beam energies ranging from 200 to 400 eV in steps of about 20 eV and a beam current of 8.1 mA. The spectrometer was calibrated by several background oxygen and nitrogen lines (see Table I).

III. DESCRIPTION OF THE CALCULATION

In order to support the identification of the recorded spectra and to predict the charge-state distributions we performed calculations using FAC version 1.1.1 [16]. This

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A NOVEL METHOD TO DETERMINE MAGNETIC FIELDS IN LOW-DENSITY PLASMA FACILITATED THROUGH ACCIDENTAL DEGENERACY OF QUANTUM STATES IN Fe^{9+}

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ABSTRACT

We propose a new method to determine magnetic fields, by using the magnetic-field-induced electric dipole transition $3p^4\,3d\,^4D_{7/2} \rightarrow 3p^5\,^2P_{3/2}$ in Fe^{9+} ions. This ion has a high abundance in astrophysical plasma and is therefore well suited for direct measurements of even rather weak fields in, e.g., solar flares. This transition is induced by an external magnetic field and its rate is proportional to the square of the magnetic field strength. We present theoretical values for what we will label the reduced rate and propose that the critical energy difference between the upper level in this transition and the close-to-degenerate $3p^4\,3d\,^4D_{5/2}$ should be measured experimentally since it is required to determine the relative intensity of this magnetic line for different magnetic fields.

Key words: atomic processes – Sun: corona – Sun: magnetic fields – Sun: UV radiation – techniques: spectroscopic

1. INTRODUCTION

One of the underlying causes behind solar events, such as solar flares, is the conversion of magnetic to thermal energy. It is therefore vital to be able to measure the magnetic field of the corona over hot active areas of the Sun that exhibit relatively strong magnetic fields. In order to follow the evolution of a solar flare, continuous observations are required, either from space or by using a network of ground-based instruments. It is therefore unfortunate that there are no space-based coronal magnetic field measurements, but only model estimates based on extrapolations from measurements of the photospheric fields (Schrijver et al. 2008). Ground-based measurements are performed either in the radio range (White 2004) across the solar corona or in the infrared wavelength range (Lin et al. 2004) on the solar limb. Infrared measurements of magnetic fields are limited by the fact that the spectral lines under investigation are optically thin. On the other hand, gyroresonance emission is optically thick, but refers only to a specific portion of the corona, which has a depth of around 100 km. From these measurements an absolute field strength at the base of the corona, above active regions, in the range of 0.02–0.2 T was obtained (White & Kundu 1997).

In this work we present a completely new method to measure magnetic fields of the active corona. This method is based on an exotic category of light generation, fed by the plasma magnetic field, external to the ions, in contrast to the internal fields generated by the bound electrons. The procedure relies on radiation in the soft X-ray region of the spectrum, implying a space-based method. This magnetic-field-induced radiation originates from atomic transitions where the lifetime of the upper energy level is sensitive to the local, external magnetic field (Beiersdorfer et al. 2003; Grumer et al. 2013, 2014; Li et al. 2013, 2014). We will show that there is a unique case where even relatively small external magnetic fields can have a striking effect on the ion, leading to resonant magnetic-field-induced light, due to what is called accidental degeneracy of quantum states.

The impact of the coronal magnetic field on the ion is usually very small due to the relative weakness of these fields in comparison to the strong internal fields of the ions. The effect therefore usually only contributes very weak lines that are impossible to observe. However, sometimes the quantum states end up very close to each other in energy, they are accidentally degenerate, and the perturbation by the external field will be enhanced. If this occurs with a state that without the field has no, or only very weak, electromagnetic transitions to a lower state, a new and distinct feature in the spectrum from the ion will appear—a new strong line. Unfortunately, since the magnetic fields internal to the ion and the external fields generated in the coronal plasma differ by about five to seven orders of magnitude, the probability of a close-enough degeneracy is small. But in this report we will discuss a striking case of accidental degeneracy in an important ion for studies of the Sun and other stars, Fe^{9+}.

The origin of the new lines in the spectra of ions is the breaking of the atomic symmetry by the external field, which will mix atomic states that have the same magnetic quantum number and parity. This will in turn introduce new decay channels from excited states (Andrew et al. 1967; Wood et al. 1968), which we will label magnetic-field-induced transitions (MITs) (Grumer et al. 2014). These transitions have attracted attention recently, when accurate and systematic methods to calculate their rates have been developed (Grumer et al. 2013; Li et al. 2013).

2. STRUCTURE OF CHLORINE-LIKE IONS AND MITS

The structure of the lowest levels of chlorine-like ions is illustrated in Figure 1. The important levels in the present study are the two lowest in the term $3p^4 3d\,^4D^e$, which turn out to have very different decay modes. Without external fields and

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ATOMIC-LEVEL PSEUDO-DEGENERACY OF ATOMIC LEVELS GIVING TRANSITIONS INDUCED BY MAGNETIC FIELDS, OF IMPORTANCE FOR DETERMINING THE FIELD STRENGTHS IN THE SOLAR CORONA

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ABSTRACT

We present a measured value for the degree of pseudo-degeneracy between two fine-structure levels in Fe^{9+} from line intensity ratios involving a transition induced by an external magnetic field. The extracted fine-structure energy difference between the $3p^4 3d\ ^4D_{5/2}$ and $^4D_{7/2}$ levels, where the latter is the upper state for the magnetic-field induced line, is needed in our recently proposed method to measure magnetic-field strengths in the solar corona. The intensity of the $3p^4 3d\ ^4D_{7/2} \rightarrow 3p^5\ ^2P_{3/2}$ line at 257.262 Å is sensitive to the magnetic field external to the ion. This sensitivity is in turn strongly dependent on the energy separation in the pseudo-degeneracy through the mixing induced by the external magnetic field. Our measurement, which uses an Electron Beam Ion Trap with a known magnetic-field strength, indicates that this energy difference is 3.5 cm^{-1}. The high abundance of Fe^{9+} and the sensitivity of the line's transition probability to field strengths below 0.1 T opens up the possibility of diagnosing coronal magnetic fields. We propose a new method to measure the magnetic field in the solar corona, from similar intensity ratios in Fe^{9+}. In addition, the proposed method to use the line ratio of the blended line $3p^4 3d\ ^4D_{7/2,5/2} \rightarrow 3p^5\ ^2P_{3/2}$ with another line from Fe x as the density diagnostic should evaluate the effect of the magnetic-field-induced transition line.

Key words: atomic processes – magnetic fields – Sun: corona – techniques: spectroscopic – UV radiation

1. INTRODUCTION

The determination of the magnetic fields in the solar corona still poses one of the major remaining challenges in solar physics (Judge et al. 2001). In a recent paper (Li et al. 2015) we presented a novel method to determine magnetic-field strengths in low-density plasmas, such as solar flares. The method is unique in that simply by measuring the intensities of EUV lines, both the coronal magnetic-field strength and its rate of change potentially can be measured with modest exposure times short enough even to allow measurements of field evolution over the impulsive phase of solar flares (a few minutes; Watanabe et al. 2010). Knowledge of the changing magnetic field will provide insight into our understanding of the forces driving the dynamics of the solar atmosphere and will ultimately aid space weather forecasting. Our proposed method is based on using a radiative transition that is induced by external magnetic fields. These types of transitions, which we will label magnetic-field-induced transitions (MITs), have recently been investigated for several examples (Grumer et al. 2013; Li et al. 2013, 2014), since computational methods have been developed to predict their rates. In a recent paper, Beiersdorfer et al. (2016) measured the lifetime of a $(1s^2 2s^2 2p^5_{1/2} 3s_{1/2})_{J=0}$ level in Fe xvii with the MIT included at the Livermore electron beam ion trap. The MIT rate is in agreement with our theoretical predictions (Li et al. 2013), which lends a strong support and confidence to our computational methods on predicting MIT rates. Unfortunately so far the available observation of an MIT is for rather strong fields (Beiersdorfer et al. 2003, 2016), and is therefore not feasible for use in the majority of astrophysical plasmas, which either have high density, where these low-rate transitions will not be visible, or low magnetic-field strengths. However, as discussed in (Li et al. 2015), MITs can be enhanced by a close, accidental degeneracy of two quantum states, and we propose a candidate in the Fe^{9+} ion. This makes it possible for even rather weak external fields to compete with the several orders-of-magnitude stronger fields inside the ion, and thereby induce an MIT.

The close degeneracy is between the $3p^4 3d\ ^4D_{7/2}$ level, which in a field-free space only decays with a slow M2 decay to the $3p^5\ ^2P_{3/2}$ level, and the $3p^4 3d\ ^4D_{5/2}$ level, which decays with a faster electric-dipole-allowed transition to the same state. (See Figure 1, where we label the small energy difference ΔE, i.e., the fine-structure energy separation between the two involved excited states.) It is especially fortunate that this close degeneracy occurs for Fe^{9+}, since this ion has a high abundance in astrophysical plasmas including the solar corona (Jordan 1969). The influence of the external magnetic field opens an allowed E1 transition from the $^4D_{7/2}$ to the ground state through mixing with the $^4D_{5/2}$. We presented theoretical values in Li et al. (2015), from large-scale Grasp2K-calculations (Jönsson et al. 2013) for most properties needed to determine the dependence of the rate of this new transition on the strength of the external/solar magnetic field. However, the close pseudo-degeneracy between $^4D_{7/2}$ and $^4D_{5/2}$ is not possible to be determined theoretically, since it would require a prediction of the excitation energies of the two states to within one part in 10–100 thousands. The two lines will appear as a blend in warm plasmas, being at 257.259, 257.263 Å (see Table 1). It is worth noting that current solar observations with spectral resolutions near 10^4 will not resolve such lines; in Doppler units the difference in wavelength is 3 km s^{-1}. Indeed line widths from coronal plasma generally have an FWHM

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Investigation of M1 transitions of the ground-state configuration of In-like tungsten

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Abstract

Three visible lines of M1 transitions from In-like tungsten were recorded using the Shanghai Permanent Magnet Electron Beam Ion Trap. The experimental wavelengths were measured as 493.84 ± 0.15, 226.97 ± 0.13 and 587.63 ± 0.23 nm (vacuum wavelengths). These results are in good agreement with theoretical predictions obtained using the large-scale relativistic many-body perturbation theory, in the form of the flexible atomic code.

Keywords: visible spectroscopy, forbidden lines, EBIT, Tungsten, fusion plasma diagnostics

(Some figures may appear in colour only in the online journal)

1. Introduction

There is a large demand for atomic data for the different charge states of tungsten (W), since it is considered as a strong candidate for the coating material in the International Tokomak Experimental Reactor (ITER), especially in the divertor region. This is due to its excellent thermomechanical properties and its very low erosion under various physical and chemical conditions [1, 2]. Unfortunately, there is very little spectroscopic data available for tungsten in the charge states between W^{6+} and W^{28+} [3], which are important in the divertor region, where the electron temperature will be considerably lower than in the core plasma.

The need for visible spectral lines from tungsten ions in all charge states for ITER diagnostics was pointed out by Skinner in 2006 [4]. Recently we have focused on the charge states of interest in the divertor region of ITER (W^{6+} to W^{28+}) [5–10]. For W^{25+}, W^{26+} and W^{27+}, which are systems with few 4f-electrons (between one and three), most visible lines will originate from magnetic dipole (M1) transitions between fine structure levels of the ground-state configurations. W^{27+} has a very simple ground-state configuration consisting of only two levels, namely 4f $^2F_{5/2}$ and $^2F_{7/2}$ and just one M1 transition, which we recently identified and analyzed [5]. W^{26+} is more complex having a $4f^2$ ground-state configuration. We reported in [6] on our identification of seven transitions between its levels, which made it possible to determine the excitation energy of seven of the 13 levels in this configuration. The good agreement between theoretical and experimental values for W^{27+} and W^{26+} lends strong support and confidence to our method for dealing with the few 4f-electron systems. In the work presented here we continue along the lines laid down in the earlier works [5, 6] and study M1 forbidden lines from W^{25+}, which is more complex having a ground configuration of $4f^3$ with 41 fine structure levels.

2. Experiment

The spectra were recorded using the Shanghai Permanent Magnet Electron Beam Ion Trap (SH-PermEBIT) [11, 12].

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Magnetic-field- and hyperfine-induced $^3P_0$-$^1S_0$ transitions in Be- and Ne-like ions

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In this work, we investigate the magnetic-field- and hyperfine-induced $^3P_0 \rightarrow {}^1S_0$ transitions in Be- and Ne-like ions along the respective isoelectronic sequence by using the multiconfiguration Dirac-Hartree-Fock method. The transition probabilities are in this case dependent on the magnetic hyperfine quantum number M_F of the upper state. We show that it is important to include perturbers with $\Delta F = \pm 1$. The calculated transition rates are compared to experimental results, when available. The discrepancies between the resulting magnetic-field- and hyperfine-induced transition rates and the experimental values in Be-like ions are discussed as well as the observability of the hyperfine-induced transitions in Ne-like ions.

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I. INTRODUCTION

Unexpected transitions [1,2], e.g., spin-, hyperfine- (HIT), and magnetic-field-induced (MIT) transitions, are important in the diagnostics of different plasmas since they are sensitive and unique tools for the determination of, e.g., electron densities, isotope compositions, and magnetic fields [3–5]. These transitions pose a challenge to computations since their predictions often require a careful and thorough treatment of the atomic structure. However, when accurate and systematic methods to calculate their rates are used, theoretical predictions are in agreement with available experimental values for most ions, but some differences still remain.

The MITs have so far been investigated mainly for isotopes without nuclear spin, when the HIT is absent, but in the presence of an external magnetic field, where the interaction with the field breaks the symmetry of the atomic system and opens up magnetic-field-induced transitions. To distinguish these cases from when hyperfine interaction is present, we label them MIT-fs. The theory for these has been discussed in recent publications for Be-, Ne-, and Cl-like ions [6–8].

An MIT was first observed in Ne-like Ar, as the $2p^5 3s\ {}^3P_0 \rightarrow 2p^6\ {}^1S_0$ transition, by Beiersdorfer *et al.* [9], who also discussed the use of this transition as a diagnostic tool for magnetic fields in plasmas. More recently, the same transition was observed for the Ne-like Fe by the same group [10]. The experimental results for the MIT-fs rates of Ne-like ions are in good agreement with previous theoretical predictions [6]. Recently, it was also proposed that MIT-fs in Cl-like Fe could be used to probe the solar coronal magnetic field [8,11].

Hyperfine-induced transitions (HITs) have low rates and are only present for isotopes with nuclear spin and can therefore be important for diagnostics of isotopic compositions for extremely low density plasmas [3]. A number of recent papers present rates of HITs [3,12–20] in the absence of magnetic fields. For HIT, experimental and theoretical studies for He-like ions [21–29] and Ni-like Xe [15,30–32] are in good agreement. The resulting rate for Be-like N by Brage *et al.* [33], obtained by modeling of a planetary nebulae, are also in agreement with theory, albeit with fairly large experimental uncertainty.

The measured rate for Be-like S by Schippers *et al.* [34] also appears to agree with theoretical work within the experimental uncertainties. At the same time, there are significant discrepancies for Be-like Ti by Schippers *et al.* [35] and Mg-like Al by Rosenband *et al.* [36] between the computed and the experimental HIT rates and the reason for these discrepancies remains unclear. It is clear that in these measurements, performed at storage rings, there are magnetic fields present, the effect of which has to be included in the calculations. The simultaneous inclusion of MIT and HIT, in what we will label MIT-hfs transitions, is the object of this paper.

II. COMPETITION BETWEEN HIT AND MIT

When atoms with nuclear spin are in a magnetic field, the magnetic and hyperfine interactions will contribute to the atomic system simultaneously. To compare the size of different interactions, and predict when these can become important, we present theoretical rates for the different transition channels from the $^3P_0$ to lower states (see the schematic energy-level diagram and denotation of transition channels in Fig. 1) for Be-like ($7 \leqslant Z \leqslant 73$) and Ne-like ($11 \leqslant Z \leqslant 35$) ions in Fig. 2, where the MIT-fs rates are plotted for a range of field strengths. As can be seen from this figure, for Be-likes ions, HIT rates dominate over the MIT-fs channel for ions with larger nuclear charge, even at the strong magnetic field of 12 T. For the ions at the neutral end of the isoelectronic sequence, the rates of the two transition channels are, in general, of comparable size in the given magnetic-field strength region. However, we do have to remember that the HIT rate is given for the most abundant isotope with nuclear spin. In the case of even nuclei, this is usually not the most abundant isotope overall. As an example, consider Be-like C or O, where the nonspin isotopes completely dominate. In these cases, MIT

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Solar Spectral Lines with Special Polarization Properties for the Calibration of Instrument Polarization

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Abstract

We investigate atomic transitions that have previously been identified as having zero polarization from the Zeeman effect. Our goal is to identify spectral lines that can be used for the calibration of instrumental polarization of large astronomical and solar telescopes, such as the Daniel K. Inouye Solar Telescope, which is currently under construction on Haleakala. We use a numerical model that takes into account the generation of scattering polarization and its modification by the presence of a magnetic field of arbitrary strength. We adopt values for the Landé factors from spectroscopic measurements or semi-empirical results, thus relaxing the common assumption of LS-coupling previously used in the literature. The mechanisms dominating the polarization of particular transitions are identified, and we summarize groups of various spectral lines useful for the calibration of spectropolarimetric instruments, classified according to their polarization properties.

Key words: atomic data – line: profiles – polarization – scattering – Sun: atmosphere – Sun: magnetic fields

1. Introduction

The measurement of solar magnetic fields is critical to our understanding of most of the unsolved problems of solar physics. Measurement of the polarization of light as a function of wavelength, known as spectropolarimetry, is the most powerful tool for the accurate determination of solar magnetic fields. In the case of solar magnetism, the polarization signals that need to be interpreted are often very weak, ranging from several percents for the stronger fields of sunspots, to only a small fraction of a percent in quiet regions of the solar atmosphere. For this reason, one of the most critical and difficult observational challenges in the diagnosis of solar magnetism is the precise polarization calibration of the instruments employed. This is especially important for the operations with the 4 m, Daniel K. Inouye Solar Telescope (DKIST, formerly ATST; Keil et al. 2009) after its first light scheduled for the end of 2019, because of the off-axis design of the telescope, which is expected to produce several percents of instrumental polarization (Harrington & Sueoka 2017).

In a recent proof-of-concept paper, Judge (2017) reviewed how certain atomic transitions could help provide the calibration data, and how lines with no linear and/or very small circular polarization might help measure instrumental polarization reliably. This is accomplished by first making some realistic assumptions about the symmetry of the Mueller matrix describing the polarization properties of the telescope, which allows us to fully define that matrix in terms of a small number of unknown parameters. Then, the Stokes vectors corresponding to the polarization input states characteristic of the various test lines are used to produce a set of independent output signals that can be expressed as linear expressions of the unknown parameters. Depending on the number of test lines adopted, the inference of these parameters can finally be accomplished either by straightforward linear inversion or by nonlinear optimization of a minimum problem. The LS-coupling scheme was adopted in that review, but Judge emphasized that the effects of mixing the eigenstates of the atomic Hamiltonian on the Landé factors needed further study. For example, several lines with zero Landé factors, which are also strictly forbidden according to LS-coupling selection rules (typically by parity violation, such as for intercombination lines; see Table 9.4 of Landi Degl'Innocenti & Landolfi 2004), can be permitted as electric-dipole (E1) transitions due to level-mixing. But this also means that the Landé factors of the mixed levels will be non-zero.

Operational plans for the polarimetric calibration of solar instrumentation typically rely on observations of weakly magnetized regions of the quiet Sun. For this reason, we rely on the so-called "weak-field" approximation for our characterization of the Zeeman signatures of the spectral lines considered in this work. It is important to remark that the weak-field approximation in practice remains valid for field strengths of up to several hundred Gauss (Landi Degl'Innocenti & Landolfi 2004), and it thus provides a completely justified characterization scheme for magnetic-sensitive spectral diagnostics in a large variety of solar studies.

For an E1 transition between an atomic level of angular momentum J_1 and Landé factor g_1, and a second level of angular momentum J_2 and Landé factor g_2, in the weak-field approximation, the following two parameters completely characterize the possible Zeeman patterns of spectral lines (see Landi Degl'Innocenti & Landolfi 2004, Section 9.6):

$$\bar{g} = \frac{1}{2}(g_1 + g_2) + \frac{1}{4}(g_1 - g_2)d, \tag{1}$$

$$\bar{G} = \bar{g}^2 - \delta, \tag{2}$$

where

$$\delta = \frac{1}{80}(g_1 - g_2)^2(16s - 7d^2 - 4), \tag{3}$$

$$d = J_1(J_1 + 1) - J_2(J_2 + 1), \tag{4}$$

$$s = J_1(J_1 + 1) + J_2(J_2 + 1). \tag{5}$$

$\bar{g}$ is the well-known effective Landé factor entering the expression for the circular polarization of a spectral line

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Experimental Testing of Scattering Polarization Models

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Abstract

We realized a laboratory experiment to study the scattering polarization of the Na I D-doublet at 589.0 and 589.6 nm in the presence of a magnetic field. This work was stimulated by solar observations of that doublet, which have proven particularly challenging to explain through available models of polarized line formation, even to the point of casting doubts on our very understanding of the underlying physics. The purpose of the experiment was to test a quantum theory for the polarized scattering of spectrally flat incident radiation, on which much of the current magnetic diagnostics of stellar atmospheres is based. The experiment has confirmed the predictions of that theory, and its adequacy for the modeling of scattering polarization under flat-spectrum illumination.

Key words: magnetic fields – polarization – scattering

1. Introduction

Over the past few decades, scattering polarization and its modification in the presence of a magnetic field have become fundamental diagnostics of many physical properties of astrophysical plasmas (Trujillo Bueno 2001b; Casini & Landi Degl'Innocenti 2008). In particular, spectrally resolved observations of the polarized radiation from the solar disk near the limb, using high-sensitivity ($S/N \gtrsim 10^3$) instrumentation, have produced an extremely rich amount of data (the so-called "Second Solar Spectrum;" Stenflo & Keller 1997; Gandorfer 2000) of great diagnostic value (Landi Degl'Innocenti 1997; Stenflo et al. 1998; Manso Sainz & Trujillo Bueno 2003; Trujillo Bueno et al. 2004). However, the interpretation of these observations has often proven to be difficult, and continues to challenge our understanding of how polarized radiation is produced and transported in the solar atmosphere.

One notable example is the linear polarization of the D_1 resonance line of neutral sodium at 589.6 nm, which has been the target of many observations (Stenflo & Keller 1996; Stenflo et al. 2000; Trujillo Bueno 2001a; Bommier & Molodij 2002). In the optically thin limit, this $J = 1/2 \leftrightarrow J' = 1/2$ transition cannot produce broadband linear polarization, despite the polarizability of its hyperfine-structure (HFS) levels (Mitchell & Zemansky 2009; Casini et al. 2002; Trujillo Bueno et al. 2002). This is because the spectral shape of its emissivity turns out to be anti-symmetric, and so it averages out to zero when the transition is spectrally unresolved. However, observations by Stenflo & Keller (1996) and Stenflo et al. (2000) surprisingly had shown the presence of a strong linear polarization signal in the line core, raising many questions about its origin, and even about the reliability of those observations (Trujillo Bueno 2001a; Bommier & Molodij 2002). While the complexity of the line-formation problem in the optically thick and magnetized atmosphere of the Sun is expected to play a role in determining the spectral shape of this line, the "enigma" posed by those observations has even brought some authors (Thalmann et al. 2006; Stenflo 2015) to question the adequacy of the quantum-electrodynamic formalism on which many of our interpretation tools for solar polarimetric observations are based (Landi Degl'Innocenti & Landolfi 2004). This impasse convinced us of the need to put this theoretical framework to the test with a specifically designed laboratory experiment.

2. Experiment

2.1. Experimental Setup

We built a scattering experiment where a vapor of neutral sodium under controlled conditions of temperature and magnetic field is illuminated by a light beam. The scattered radiation is analyzed polarimetrically, separately for the $D_1(3p^2P_{1/2} \rightarrow 3s^2S_{1/2}$, 589.6 nm) and $D_2(3p^2P_{3/2} \rightarrow 3s^2S_{1/2}$, 589.0 nm) transitions.

A top-view schematics of the experiment is shown in Figure 1. This consists of a Na I vapor cell surrounded by two air-cooled Helmholtz-coil pairs, and flanked by four "legs" with different functions. Light enters the apparatus from the bottom leg, is focalized at the center of the vapor cell, and the light scattered from the vapor at 90° is analyzed in the left leg. The top leg uses a photodiode to monitor the light level of the source, and the right leg is used to input specific polarization states for the purpose of polarimetric calibration.

The center of the sodium cell is located at the intersection of the four legs of the apparatus. The sodium is evaporated into the cell from a reservoir that is temperature controlled at a typical value of 205 °C. Along with the sodium vapor, the cell also contains 17 mmHg of Ar buffer gas. The two Helmholtz-coil pairs allow the generation of a magnetic field between 0 and 150 G with any desired direction in the scattering plane (plane of Figure 1).

To ensure the condition of *complete frequency redistribution* (CRD; see Modeling section) of the scattered radiation, we employed a 50 W halogen bulb with stabilized output, which provides a largely flat and structureless spectrum over the frequency range of the D lines. An input polarization selector, consisting of a linear polarizer mounted in a precision rotation

[4] Egidio Landi Degl'Innocenti was one of the promoters of the experiment, and a principal contributor to its interpretation and to the drafting of this Letter. Sadly, he passed away, prematurely and unexpectedly, before he could see its completion.
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Effect of an external magnetic field on the determination of E1M1 two-photon decay rates in Be-like ions

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In this work we report on *ab initio* theoretical results for the magnetic-field-induced $2s\,2p\,^3P_0 \to 2s^2\,^1S_0$ E1 transition for ions in the beryllium isoelectronic sequence between $Z = 5$ and 92. It has been proposed that the rate of the E1M1 two-photon transition $2s\,2p\,^3P_0 \to 2s^2\,^1S_0$ can be extracted from the lifetime of the $^3P_0$ state in Be-like ions with zero nuclear spin by employing resonant recombination in a storage ring. This experimental approach involves a perturbing external magnetic field. The effect of this field needs to be evaluated in order to properly extract the two-photon rate from the measured decay curves. The magnetic-field-induced transition rates are carefully evaluated, and it is shown that, with a typical storage-ring field strength, it is dominant or of the same order as the E1M1 rate for low- and mid-Z ions. Results for several field strengths and ions are presented, and we also give a simple Z-dependent formula for the rate. We estimate the uncertainties of our model to be within 5% for low- and mid-Z ions and slightly larger for more highly charged ions. Furthermore we evaluate the importance of including both perturber states, $^3P_1$ and $^1P_1$, and it is shown that excluding the influence of the $^1P_1$ perturber overestimates the rate by up to 26% for the mid-Z ions.

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I. INTRODUCTION

Two-photon transitions are exotic decay modes in atoms and ions. Nevertheless, they are of practical interest, e.g., in astrophysics where the $2s \to 1s$ (2E1) transition in hydrogen contributes to the observed continuum radiation from planetary nebulae [1], Herbig-Haro objects [2], and H II regions [3]. Theoretical work on two-photon transitions started at the dawn of quantum mechanics [4]. Since then, theoretical and experimental work has mainly focused on H-like and He-like systems ([5], and references therein). Various aspects of two-photon transitions, such as resonance effects [6], negative continuum effects [7], relativistic and QED effects [8], and higher-order multipole effects [9] on two-photon transitions in H-like ions, in these isoelectronic sequences of ions have been addressed in very recent (mostly theoretical) studies. Additionally, the sensitivity of the spectral shape of the emitted photon continuum to relativistic effects [10] and angular correlations [11] and quantum correlations [12] between the two-photons have been investigated.

In He-like ions there exist three long-lived metastable states which decay (partly) via the two-photon transitions $1s\,2s\,^1S_0 \to 1s^2\,^1S_0$ (2E1), $1s\,2s\,^3S_1 \to 1s^2\,^1S_0$ (2E1), and $1s\,2p\,^3P_0 \to 1s^2\,^1S_0$ (E1M1). The latter competes with the dominating $1s\,2p\,^3P_0 \to 1s\,2s\,^3S_1$ one-photon E1 transition. The relative importance of the E1M1 transition increases with nuclear charge Z. For $Z = 92$ the E1M1 branching ratio has been calculated to amount to about 32% [13,14].

With Be-like ions the situation is much more clear-cut. The $2s\,2p\,^3P_0$ state is the lowest excited state, and for isotopes with a nonzero nuclear spin, the $J = 0 \to 0$ transition channel opens up due to mixing of the hyperfine levels, leading to a so-called hyperfine-induced transition (HIT). Such a shortening of lifetimes of metastable states owing to hyperfine interaction is referred to as hyperfine quenching and has been investigated for Be-like ions both theoretically [15–20] and experimentally [21,22]. For isotopes with zero nuclear spin, on the other hand, a one-photon transition to the ground state $2s^2\,^1S_0$ is strictly forbidden in a field-free region, and the lowest-order decay channel is a very slow E1M1 two-photon process. The most important third-order process is a 3E1 three-photon decay, which has a transition rate smaller than the two-photon process by a factor of α, the fine-structure constant, according to Laughlin [23].

The calculation of E1M1 rates involves potentially significant negative-energy contributions to the transition amplitudes [13]. Thus, an accurate measurement of the experimental decay rate would constitute an ultimate benchmark of relativistic many-body theoretical methods and computational schemes. So far no experimental observations of E1M1 transitions in He-like or Be-like systems exist [5].

Recently, future storage-ring experiments have been proposed [24–26] to measure $2s\,2p\,^3P_0 \to 2s^2\,^1S_0$ E1M1 two-photon transition rates for heavy Be-like ions with nuclear charges $Z \gtrsim 50$. However, the magnetic field of the storage-ring dipole magnets will give rise to a magnetic-field-induced E1 transition (from here on referred to as a MIT), possibly with a rate of the same order of magnitude as the rate of the two-photon transition. Hence, to correctly deduce the two-photon rate from such an experiment, there is a need for accurate MIT rates as discussed in Ref. [26].

Arguably, a MIT was observed for the first time in 2003 by Beiersdorfer *et al.* in Ne-like Ar, using the EBIT-II Electron Beam Ion Trap at the Lawrence Livermore National

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Forbidden-line spectroscopy of the ground-state configuration of Cd-like W

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By only using electric-dipole forbidden emission lines, in what we label *forbidden-line spectroscopy*, we identified several energy levels in cadmium-like tungsten, W^{26+}. The spectrum was recorded at the Shanghai permanent-magnet electron beam ion trap in the visible region. The identifications were supported by large-scale multiconfiguration Dirac–Hartree–Fock calculations which involved careful investigations of core-valence and core-core correlation effects, and by relativistic many-body perturbation theory calculations. With this novel method we identified in all seven lines and measured their wavelengths. From this we can determine the relative position of seven energy levels. Due to the close degeneracy of two levels, we give alternative energies for three of the levels.

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I. INTRODUCTION

There is considerable interest in the determination of atomic data for ions of tungsten [1,2]. This is driven by the potential use of tungsten as a plasma-facing material in the International Tokamak Experimental Reactor (ITER), especially in the divertor region [3]. There is very little spectroscopic data for tungsten in the charge states between W^{6+} and W^{28+} [4], which is unfortunate since these ions should be abundant in the divertor region, where the electron temperatures will be considerably lower than in the core plasma region. In two recent papers [5,6], we discussed the visible $M1$ transition between the $j = 5/2$ and $7/2$ fine structure levels of the $4d^{10}4f\,^2F$ ground term in Ag-like W, W^{27+}. Even for this seemingly simple case, earlier theoretical predictions of energy separation were inconclusive and yielded diverse results. This confusion was resolved in Refs. [5,6], where we reported on good agreement between experimental and critically evaluated theoretical values for this energy separation. In this paper we apply a similar method of *forbidden-line spectroscopy* to establish seven of the thirteen possible energy levels of the $4f^2$ ground configuration of Cd-like W, W^{26+}, through the observation of seven forbidden lines.

The identification of the lines was aided by calculations using both the GRASP2K [7] and FAC [8] codes. The GRASP2K calculations were done along similar lines to those presented in Refs. [5,6]. The FAC calculations will be presented in some detail. Cd-like W was previously studied both experimentally and theoretically by Komatsu *et al.* in Ref. [9] and in more detail by Ding *et al.* in Ref. [10]. Ding *et al.* give a good overview of why tungsten data is needed for fusion diagnostics and an extensive list of references.

II. THEORETICAL METHODS

For the computations in this work we use two different but complementary computational techniques. One is the multiconfiguration Dirac–Hartree–Fock (MCDHF) method (see, for example, the book by Grant [11] for a comprehensive theoretical description) in the form of the GRASP2K program suite, recently published in a new version [7]. The other is based on multireference relativistic many-body perturbation theory (MR-RMBPT) calculations performed with the FAC code [8].

A. Multireference relativistic many-body perturbation theory calculations

The theoretical tools implemented in FAC allows for a combination of configuration interaction and second-order many-body perturbation theory. This method is based on the work of Lindgren on Rayleigh–Schrödinger perturbation theory extended to a multiconfigurational zero-order wave function [12].

The Hamiltonian of the many-electron system is taken as the Dirac–Coulomb–Breit (DCB) Hamiltonian H_{DCB} [13]

$$\mathcal{H}_{\mathrm{DCB}} = \sum_i [h_d(i) - Z/r_i] + \sum_{i<j} (1/r_{ij} + B_{ij}), \quad (1)$$

where $h_d(i)$ is the Dirac Hamiltonian for a single free electron and B_{ij} is the frequency-independent Breit interaction

$$B_{ij} = -[1/(2r_{ij})]\big[\boldsymbol{\alpha}_i \cdot \boldsymbol{\alpha}_j + (\boldsymbol{\alpha}_i \cdot \boldsymbol{r}_{ij})(\boldsymbol{\alpha}_j \cdot \boldsymbol{r}_{ij})/r_{ij}^2\big], \quad (2)$$

where the matrix vector $\boldsymbol{\alpha}_i$ can be expressed in Pauli spin matrices $\boldsymbol{\sigma}_i$ as

$$\boldsymbol{\alpha}_i = \begin{pmatrix} 0 & \boldsymbol{\sigma}_i \\ \boldsymbol{\sigma}_i & 0 \end{pmatrix}. \quad (3)$$

For all other entries in Eq. (1) we use standard notations. H_{DCB} is separated into a zero-order, H_0, and a perturbation Hamiltonian, H', which are defined as

$$H_0 = \sum_i [h_d(i) + V(r_i)], \quad (4)$$

$$H' = -\sum_i [Z/r_i + V(r_i)] + \sum_{i<j} (1/r_{ij} + B_{ij}), \quad (5)$$

where the model potential $V(r_i)$ includes screening effects of all electrons and is chosen to minimize the perturbation H'.

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Review of highly charged tungsten spectroscopy research using low energy EBITs at the Shanghai EBIT laboratory

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Abstract

We present an overview of recent work on the spectroscopy of tungsten ions, related to tokamak edge plasma. The spectra were recorded from the newly-built low energy electron beam ion traps (EBITs) in the Shanghai EBIT laboratory. By analyzing the spectra with the help of accurate theoretical calculations, using state-of-the-art techniques, we were able to identify term and fine structure splittings in the ground and the first excited configuration for a number of charge states. The theoretical models included a careful study of correlation and showed an excellent agreement with our experimental results for transition energies and rates. Some metastable levels which have extremely long lifetime and high population were found, and the influences of these levels on the charge state distribution of tungsten ions in tokamaks are discussed.

Keywords: spectroscopy, highly charged ion, EBIT

(Some figures may appear in colour only in the online journal)

1. Introduction

Tungsten is often considered as a main candidate for plasma facing material for the International Thermonuclear Experimental Reactor (ITER) fusion device [1, 2], since it exhibits a number of favorable physical and chemical properties, e.g. high energy threshold of sputtering, low sputtering yield, high re-deposition efficiency, low tritium retention, and excellent thermal properties. However, even though the sputtering properties are favorable, some tungsten atoms and ions will still make their way into the fusion plasma. Tungsten, being a high *Z* element and therefore having a complex electronic structure, will contribute to a large fraction of the energy radiated out from the plasma, leading to plasma cooling. This is a similar situation to the plasma in a fluorescent tube, where only one mercury atom in an environment of about 1000 noble gas atoms dominates the light output. It is well known that high *Z* elements have a high radiative power. One of the first uses of tungsten in a fusion device was as a limiter in the Princeton Large Torus in the late 1970s. However it was soon abandoned due to the large radiation losses caused by impurity tungsten atoms/ions leading to significantly degradation of the plasma performance [3]. Similar problems will exist at ITER if the influx of tungsten atoms/ions is not controlled.

It is important to monitor the influx and transport of tungsten to be able to control it. This requires high quality atomic structure data for many charge states of tungsten ions. The charge state distribution of tungsten ions in the plasma is a good indication of the amount of power that will be radiated out. There are models predicting this distribution in a fusion plasma like the one in ITER [4], but we will argue that these models may lack some important contributions to ionization from metastable levels and will therefore be inaccurate.

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Removal of Spectro-polarimetric Fringes by Two-dimensional Principal Component Analysis

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Abstract

We investigate the application of two-dimensional Principal Component Analysis (2D PCA) to the problem of removal of polarization fringes from spectro-polarimetric data sets. We show how the transformation of the PCA basis through a series of carefully chosen rotations allows us to confine polarization fringes (and other stationary instrumental effects) to a reduced set of basis "vectors," which at the same time are largely devoid of the spectral signal from the observed target. It is possible to devise algorithms for the determination of the optimal series of rotations of the PCA basis, thus opening the possibility of automating the procedure of defringing of spectro-polarimetric data sets. We compare the performance of the proposed method with the more traditional Fourier filtering of Stokes spectra.

Key words: instrumentation: polarimeters – instrumentation: spectrographs – methods: data analysis – methods: statistical – techniques: image processing

1. Introduction

The advent of new instrumentation for the investigation of solar phenomena—in particular, with regard to the short- and long-term variability of the Sun's magnetic activity, and its impact on the near-Earth environment—has put unprecedented demands on the conception of data management plans and infrastructures, which aim to deliver reliable, science-ready data products to the community in a timely fashion.

The U.S. community is getting ready for the completion and first light of the 4 m Daniel K. Inouye Solar Telescope (DKIST; Tritschler et al. 2016) in early 2020, with its suite of complex post-focus instruments, most of which will have polarimetric capabilities, in order to detect the subtle signatures of the Sun's magnetic field in its light spectrum. The 1.5 m GREGOR telescope (Schmidt et al. 2012) and the 1.6 m Goode Solar Telescope (Cao et al. 2010) have already started to reveal the complexity of the solar spectrum when unprecedented higher spatial and temporal resolutions are attained in solar observations. Other countries are pursuing similar endeavors, such as India's 2 m National Large Solar Telescope (Hasan et al. 2010), the 4 m European Solar Telescope (Collados et al. 2013), and the 8 m annular-mirror Chinese Giant Solar Telescope (Liu et al. 2014).

Beyond the intrinsic complexity of the theoretical problem of how polarized radiation is formed and transported through the solar atmosphere (e.g., Stenflo 1994; Landi Degl'Innocenti & Landolfi 2004; Casini & Landi Degl'Innocenti 2008; Trujillo Bueno 2010, for a description of the various mechanisms at play), the need to detect and confidently measure very small levels of polarization (down to 0.01% of the intensity, for the most demanding scientific applications) puts very hard requirements on the identification and removal of instrumental artifacts from the detected signals.

One recurrent issue in spectro-polarimetric instruments is the appearance of polarization "fringes" that overlap with the actual spectral signal from the observed target. These fringes are interference patterns that are produced by the presence of optical elements in the system of the telescope and the instrument having varying phase retardance properties (e.g., around their optical axis). Such components include polarization modulators, polarizing beam-splitters, and any optical element where parallel optical interfaces may occur (e.g., interference filters, detector windows). These fringes have the appearance of more or less regular two-dimensional (2D) patterns, preferentially arranged along the spectral dimension of the data (see Figure 1). We refer to review studies of polarized fringes (Lites 1991; Semel 2003; Clarke 2004) for a thorough description of this phenomenon, and to recent work by Harrington et al. (2017) on the use of Berreman calculus for the modeling of fringes in polarimetric instrumentation.

The most common fringe correction methods used in spectro-polarimetric data reduction are Fourier filtering and derivations from it, such as wavelet analysis (Rojo & Harrington 2006). However, Fourier filtering only works satisfactorily when the frequency domains of the fringes and of the target spectral signal (in the spectral and/or spatial domains) are clearly separated, and it is severely limited when the fringe pattern's period or amplitude vary over the image. Wavelet analysis is a powerful method for removing smoothly varying fringes in flat-field images. However, it becomes difficult to control in the presence of strong spectral signals from the observed target.

In this paper, we extend previous work on the identification and isolation of polarization fringes by Principal Component Analysis (PCA; Pearson 1901; Jolliffe 2002). Casini et al. (2012) considered the implementation and performance of a two-dimensional Principal Component Analysis (2D PCA) algorithm based on the method described by Yang et al. (2004; hereafter, Y-PCA). In that approach, the spectral data gets "contracted" over the spatial dimension before performing PCA decomposition. As a result, the PCA basis of *eigenfeatures* consists of spectro-polarimetric profiles (rather than 2D images similar to Figure 1), which are akin to spatial averages of the principal components (PCs) of the data. One advantage of the Y-PCA approach is the fast convergence of the singular-

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