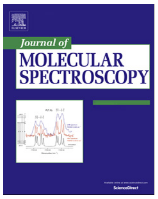
Journal of Molecular Spectroscopy 303 (2014) 46–53

Contents lists available at ScienceDirect

Journal of Molecular Spectroscopy

journal homepage: www.elsevier.com/locate/jms



Determination of Landé factors in the $F\,^4\Delta_{5/2,7/2}$ state of ^{56}FeH by laser excitation spectroscopy

Patrick Crozet [a,*], Georgi Dobrev [a,b], Cyril Richard [a], Amanda J. Ross [a]

[a] Institut Lumière Matière, UMR5306 Université Lyon 1-CNRS, Université de Lyon, 69622 Villeurbanne cedex, France
[b] Department of Physics, Sofia University, 5 James Bouchier Blvd, 1164 Sofia, Bulgaria

ARTICLE INFO

Article history:
Received 19 June 2014
In revised form 24 July 2014
Available online 7 August 2014

Keywords:
Molecular Landé factor
Zeeman effect
Wing Ford band
Electronic spectrum of FeH
Sunspots
Cool stars

ABSTRACT

This paper provides a set of effective Landé factors g_J for the first rotational levels of vibrational levels 0 and 1 of the $F\,^4\Delta$ state of FeH, obtained from analysis of partially-resolved Zeeman patterns recorded in laser excitation, working at magnetic fields between 2000 and 5000 Gauss.

1. Introduction

The near-infrared electronic spectrum of FeH continues to interest astrophysicists studying cool stellar systems and molecular physicists trying to unravel the complexity of the electronic structure of this small radical, whose properties result from extensive configuration mixing effects. The species remains an interesting challenge both for theoretical chemistry and for laboratory spectroscopy.

The electronic $F\,^4\Delta$–$X\,^4\Delta$ system of FeH in stars was first recognized in the late 1960s, with the work of Wing and co-workers on M- and S-type dwarfs [1]. Historical developments have been reviewed by Jorgensen [2] and more recently by DeYonker and Allen [3]. Simple molecules survive in cool solar or stellar environments; those with the strongest electronic transition dipole moments and greatest abundances are observed as band spectra. Species with significant magnetic response can be used to assess magnetic fields (strength and direction) in such objects, provided that the magnetic response has been established either through reliable models – not available for FeH – or by laboratory work. Two molecular bands of FeH give rise to now well-established signatures in the spectra of cool stellar surfaces, such as sunspots [4,5] or brown dwarf stars [6]: the 1-0 band at 869.2 nm, and the so-called Wing Ford band, 0-0 at 989.6 nm. Thus considerable effort has been made in the laboratory to address astronomers' expressed needs for line positions, line strength factors [7], and magnetic response [8,9].

The presence of FeH in cool stars is explained by reaction of H (the most abundant element) and Fe (the most abundant metal produced by stellar nucleosynthesis).The dissociation energy of FeH is estimated to be $D_0^0 = 1.86$ eV [3] so once formed, the radicals can survive at (cool stellar surface) equilibrium temperatures of several thousand Kelvin. The sunspot umbral absorption atlas of Wallace and co-workers [10] identifies numerous lines of the F–X system of FeH in the near infrared. Many of these profiles can be seen to be Zeeman-broadened when compared with a laboratory absorption spectrum taken at zero field, as shown in Fig. 1.

It is perhaps surprising, given the interest of these particular bands (located in a relatively uncluttered region of the solar spectrum, where Zeeman splittings start to be significant relative to Doppler broadening) that laboratory data are lacking. But it has proved difficult to provide extensive benchmark measurements in well-controlled conditions. The King furnace source is not readily compatible with a large and homogeneous magnetic field, and other methods of production used in laser spectroscopic work (laser ablation [12], discharge in iron pentacarbonyl [13–16] or sputter sources [17]), while offering higher spectral resolution, have fallen seriously short in terms of thermal distribution. The Wing-Ford band in particular happens to lie in an optically awkward region (1 μm), at the very edge of currently available tuneable Ti:sapphire lasers, and well away from the peak sensitivity

---

[*] Corresponding author.
E-mail address: patrick.crozet@univ-lyon1.fr (P. Crozet).

http://dx.doi.org/10.1016/j.jms.2014.07.005
0022-2852/© 2014 Elsevier Inc. All rights reserved.

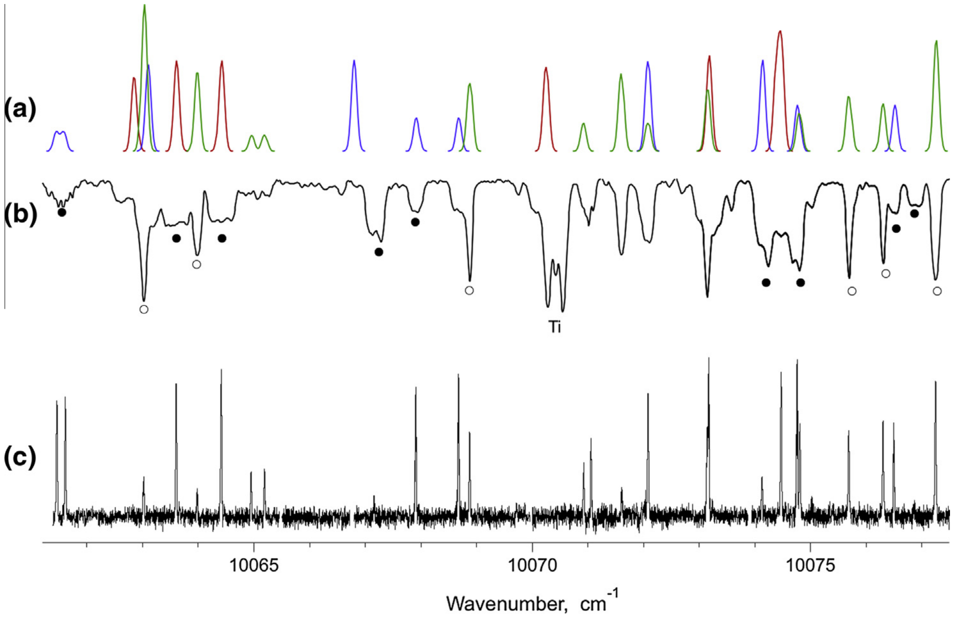


Fig. 1. Comparison between zero field and sunspot spectra in the Wing-Ford band of FeH. FeH spectrum recorded in this work (trace c) at zero field, and corresponding solar umbral absorption (trace b) taken from the solar atlas of Wallace et al. [10]. The upper trace gives relative intensities predicted from the FeH Atlas [18] at 3300 K, assuming fwhm = 0.12 cm^{-1} for all contributions (no Zeeman broadening). F_1 components are drawn with thick (red) solid lines, F_2 with thinner (blue) ones, and F_3 transitions as broken (green) lines. Magnetically active or inactive lines are indicated by filled or empty circles respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of Si and InGaAs detectors used in the near infrared. The fact that laser-induced fluorescence from the Wing-Ford band happens to be quasi-resonant complicates the detection issue a little further, as laser scatter cannot be attenuated with optical filters. Thus for many of the lines, the best estimates of Landé factors available in the literature are still those extracted from the profiles of sunspot data, for example by Harrison and Brown [4], or Afram and co-workers [6].

The Doppler-limited zero-field thermal emission spectrum recorded using a King furnace near 2000 K recorded and analysed by Phillips and co-workers [11], has provided an extensive collection of rotational data of the *F*–*X* system, involving all four spin–orbit components of both electronic states, and covering seven vibrational bands. Dulick et al. [18] took the analysis of these data some steps further, and produced an Atlas designed to assess molecular opacities; their model predicted parity splittings that were unresolved in the original spectrum, as well as positions of many unobserved lines.

Laboratory measurements of Landé factors have emerged gradually in the literature. Accurate g_J Landé factors for several rotational levels of the ground $X\,^4\Delta_\Omega$ state were determined by laser magnetic resonance spectroscopy (LMR), first with a variable magnetic field tuning pure rotational transitions into resonance with methanol lines pumped by a CO_2 laser in work performed at NIST, Boulder [13], in 1988. The range of rotational levels was gradually extended, and when shorter-wavelength laser lines became available, fine-structure transitions were also measured [14]. The paper from Brown et al. [14] became a reference for ground state energies for the lowest rotational levels, giving proton hyperfine parameters and effective Landé factors for ^{56}FeH that have provided the basis for deducing $F\,^4\Delta$ state Landé factors in subsequent laboratory work on optical spectra. The first high-resolution investigation of the Zeeman effect in the *F*–*X* system of FeH was reported by Harrison et al., who formed the radical in a laser ablation source, and used a supersonic expansion to work at rotational temperatures <20 K [12]. Only transitions in the 1-0 band, from the lowest rotational level of the ground state, were recorded, but Zeeman broadening was obvious at fields <600 Gauss. Two Landé factors were extracted for the $F\,^4\Delta_{7/2}$ state, for $v = 1$, $J = 7/2$ and 9/2. Given this key information as a starting point, Harrison and Brown went on to model the profiles of some of the FeH lines identified in the sunspot atlas [10], with upper state Landé factors being the parameters to be determined [4]. A lower spectral resolution and some uncertainty in the effective magnetic field in the umbral regions complicated the task, but this approach remains the only option to study transitions originating from thermally excited lower levels. In a similar vein, Afram and co-workers [6] fitted the profiles of selected magnetically sensitive lines of FeH in data from the sunspot atlas, plus polarimetric data taken by Rüedi et al. [19] to determine effective Landé factors for more levels. They then parameterised the trend of the Landé factors in order to extrapolate to high *J*, motivated by the need for this information if FeH features were to be used as a probe for magnetic fields in L-type stars. Even if the extrapolation parameterisation is not entirely convincing, the match in line profiles was close enough to conclude that this system of FeH was indeed a good choice for magnetic field diagnostics. At about the same time, Shulyak and co-workers were faced with a similar need for reliable Landé factors, as they tried to understand the molecular Zeeman spectra observed in M-dwarf stars [20], where FeH lines (notably in the Wing-Ford band) are particularly pronounced. They calculated effective g_J factors from considerations of molecular angular momentum, testing different empirical descriptions to describe the appropriate 'intermediate' between the limiting Hund's case (a) and (b) coupling regimes. They likewise relied on comparison with solar umbral spectra to adjust their parameters, and mentioned the inadequacies of such a model to accurately represent the electronic structure of this species. It seems useful then to extend the range of laboratory benchmark measurements. The work presented here is a compromise between the two extremes. FeH is formed in a sputter source, at rotational temperatures around 500 K, and probed with a laser between permanent magnets, generating well-defined magnetic fields of the order of 3000 Gauss (comparable with sunspot field strengths). This is sufficient to partially resolve the Zeeman pat-