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The FERRUM Project: Oscillator Strengths of the Iron Group Elements: Fe II

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Abstract. We report on an international collaboration, the FERRUM Project, which aims at extending the database of experimental oscillator strengths for iron group elements and possibly evaluating theoretical and astrophysical data. The selection of individual projects is made with respect to their relevance for abundance work and plasma diagnostics in astrophysics. In this paper we present recent measurements of gf-values in Fe II. We also report on the first measurements of forbidden lines of the same spectrum, [Fe II].

1. Introduction

Recent advances in spectral analysis of astrophysical sources are due to computer models of stellar atmospheres, the synthetic spectrum technique and a wealth of theoretical atomic and molecular data. The accuracy of the stellar parameters obtained from such an analysis, e.g. chemical abundances, is determined by the accuracy of the atomic data for a given model. In general, the unknown uncertainties for individual lines in the theoretical database scatter, and inconsistencies in abundance values can thus be "explained" as a result of "poor atomic data".

The present paper on the FERRUM project suggests a way of improving the situation described above, but it does not provide a solution. The idea with the project is to produce experimental gf-values for about 25-100 lines in one particular spectrum distributed over a number of different transition arrays and a spread in excitation energy and wavelength. We compare the experimental data with existing theoretical data and get an idea about the quality of the calculated data for different kinds of transitions in different theoretical databases. Due to the problems with configuration interactions in complex spectra, the theoretical data for one transition array might be more reliable than for another.

It is important to state that we will never be able to replace the data available in the theoretical databases with experimental values, and the treatment of individual features in line-rich stellar spectra will always depend on calculated values for additional lines that contribute to the "stellar feature" and to the apparent continuum. By providing error bars on the atomic data we may provide a test whether "inconsistencies" in an analysis of a stellar spectrum might be due to questionable assumptions in the stellar model atmosphere.

2. Method

The gf-values are derived from experimental Einstein A-values, which are obtained by combining radiative lifetimes (τ_i) and measured branching fractions (BF_{ik}) according to the relations

$$\tau_i = \frac{1}{\sum_k A_{ik}}, \quad BF_{ik} = \frac{A_{ik}}{\sum_k A_{ik}} \propto \frac{I_{ik}}{\sum_k I_{ik}} \implies A_{ik} = \frac{BF_{ik}}{\tau_i}, \tag{1}$$

where τ_i is measured using the laser-induced fluorescence technique at Lund Laser Centre and the BF:s are measured at the Fourier Transform Spectrometer at the Division of Atomic Spectroscopy, Lund. For weak branches, that do not show up in our spectra because of low intensity or location outside the recorded spectral region, the BF:s have been estimated from theoretical data.

The experimental gf-values are compared with theoretical data from various databases, and if the agreement is good for a transition array, we recommend the calculated values of that particular database for the remaining lines of that transition array. If available, we also apply the data to stellar spectra of high quality to test the agreement between observed and synthetic spectra for the lines measured.

3. Fe II

Given the aim of the FERRUM Project it was natural to start with Fe II, as the span in excitation energy of the lower level of the Fe II lines observed in the absorption spectrum of a 10,000 K star is often more than 10 eV. This is due to the high cosmic abundance of iron and the high ratio of Fe^+ ions in stellar atmospheres, which allow a relatively high population of highly excited Fe II states. Based on this fact, we have worked on a number of subprojects of Fe II, where we have measured radiative lifetimes and branching fractions.

1) Lifetimes of low and medium-excited 4p states (Li et al. 1999)
2) Absolute gf-values for 18 lines from medium-excited 4p states at 7.5-8 eV (Sikström et al. 1999)
3) Absolute gf-values for 29 lines from 4d states at 10.5 eV (Nilsson et al. 2000)
4) Absolute gf-values for 20 lines from 5s states at 9.7 eV (Karlsson et al. 2001)
5) Absolute gf-values for lines from the 4f configuration
6) Lifetimes of the y^6P term (Li et al. 2000)
7) Lifetimes of two metastable states (Rostohar et al. 2000)

Below we discuss briefly the different subprojects.

3.1. Medium 4p-states (1,2)

Lifetimes for 10 4p levels and gf-values for 18 4s-4p lines around 2500 Å have been published by Li et al. (1999) and Sikström et al. (1999). Some of the levels also have strong branches to 3d levels at about 1600 Å and branching fractions for these lines are being measured at Imperial College, London. There is a very good agreement with the calculations by Raassen and Uylings (2000) as shown in Figure 1, which we recommend for the 4s-4p transition array. The agreement with the Kurucz data is good for strong lines. The Iron Project includes only pure LS transitions, which limits the comparison.

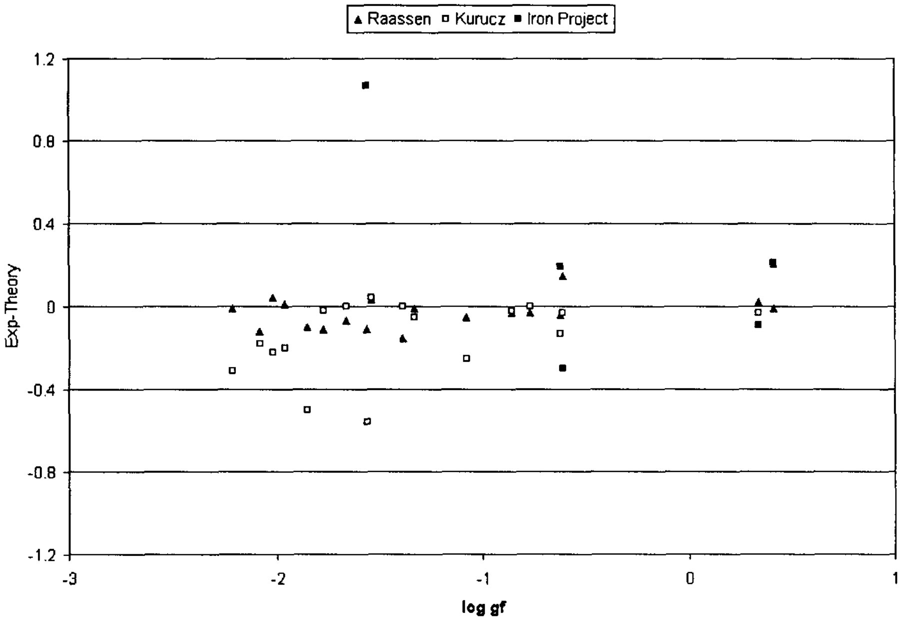

Figure 1. Comparison between experimental and theoretical log gf-values for 18 4s-4p UV transitions of Fe II. Comments on the different theoretical data sets are given in the text.

3.2. High 4d and 5s states (3, 4)

In these projects the 4d and 5s levels were excited by two-step excitation via a low 4p state in the lifetime measurements. Combined with branching fractions we could determine absolute oscillator strengths for 29 4p-4d lines (Nilsson et al. 2000). The lines appear around 2300 Å in satellite spectra of stars in a region which is a bit outside the crowded resonance region. High f-values compensate for the reduced population of the lower levels (4p), and many lines are on the linear part of the curve of growth.

The 4p-5s transitions we are interested in are located around 2800 Å and they are very often enhanced in emission line spectra of various objects, cool star chromospheres, symbiotic stars, η Carinae etc. The reason is that the lines appear in a fluorescence cascade chain as a result of resonant pumping of 5p states in Fe II by HLyα (see e.g. Johansson & Hamann 1993). In order to model this fluorescence it is important to have atomic parameters. This subproject is now finished and will soon be submitted for publication (Karlsson et al. 2001).

3.3. 4f states at 13 eV (5)

There are numerous 4d-4f transitions in the range 4800-6500 Å that show up in stellar spectra (Johansson & Cowley 1984), and they have never been used in quantitative analyses. The lower levels have an E.P. of 10 eV, and most lines appear on the linear part of the curve of growth. In the same region of the stellar spectrum there are numerous 4s-4p lines, with E.P.:s around 3 eV.

We have obtained experimental lifetimes for some levels, by combining two-photon excitation to a 4d state with a third excitation to 4f. The experimental problem is the branching fractions as some levels ($J \leq 11/2$) have branches around 1000 Å down to 3d states. To start with we concentrate on the 4f levels having $J > 11/2$. Parallel to the laboratory project we perform a stellar analysis using these lines.

3.4. The UV8 multiplet: Interstellar lines (6)

Lifetimes of the three y^6P levels around 7.5 eV have been measured (Li et al. 2000), that will be combined with branching fractions to get absolute gf-values. The latter measurements require an FTS instrument in the VUV region, and they are performed at Imperial College, London. The y^6P term involves the UV 8 multiplet around 1610 Å which contains the strongest interstellar line of Fe II below 2000Å.

3.5. Metastable states - forbidden lines (7)

Finally, we have measured the lifetime for metastable states of Fe II for the first time in collaboration with scientists at Stockholm University using the storage ring CRYRING at MSI, Stockholm. The lifetimes of the $a^6S_{5/2}$ and $b^4D_{7/2}$ levels were measured to be 230 ms and 530 ms, respectively (Rostohar et al. 2000), in fairly good agreement with calculations. The data will be used to derive A-values by estimating branching fractions from astrophysical spectra. Forbidden lines are used in astrophysics to determine certain parameters (temperature, density, abundance) in nebular plasmas.

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References

Johansson, S. & Cowley, C.R. 1984, A&A, 139, 243

Johansson, S. & Hamann, F. 1993, Phys, Scr. T47, 157

Karlsson, H., Sikström, C.M., Johansson, S., Li, Z.S. & Lundberg, H. 2001, A&A, 371, 360

Li, Z.S., Lundberg, H., Sikström, C.M., Johansson, S. 1999, Eur.Phys.J.D, 6, 9

Li, Z.S, Lundberg, H., Berzinsh, U., et al. 2000, J.Phys.B (in press)

Nilsson, H., Sikström, C.M., Li, Z.S., et al. 2000, A&A, 362, 410

Raassen, A.J.J. & Uylings, P.H.M. 2000, (atomic data from http://www.science.uva.nl/pub/orth/iron)

Rostohar, D., Derkatch, A., Hartman, H. et al. 2000, Phys.Rev.Lett, subm.

Sikström, C.M., Schultz-Johanning, M., Li, Z.S. et al. 1999, J. Phys. B: At. Mol. Opt. Phys., 32, 5687