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Published in:
Physica Scripta

DOI:
10.1238/Physica.Topical.100a00071

2002

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2002 Phys. Scr. 2002 71

(http://iopscience.iop.org/1402-4896/2002/T100/008)

Physica Scripta. Vol. T100, 71–80, 2002

The FERRUM Project: New *f*-value Data for Fe II and Astrophysical Applications

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Received January 18, 2002; accepted February 14, 2002

PACS Ref: 32.70.Cs, 95.30Ky

Abstract

We present the FERRUM Project, an international collaboration aiming at a production and evaluation of oscillator strengths (transition probabilities) of selected spectral lines of singly ionized iron group elements, that are of astrophysical relevance. The results obtained include measurements and calculations of permitted and forbidden lines of Fe II. The data have been applied to both emission and absorption lines in astrophysical spectra. We make comparisons between experimental, theoretical and astrophysical *f*-values. We give a general review of the various measurements, and discuss the UV8 multiplet of Fe II around 1610 Å in detail.

1. Introduction

The chemical composition of a star is obtained from an abundance analysis of its high-resolution spectrum, which consists of a continuous spectrum from blackbody radiation superimposed by absorption lines formed in the outer and cooler layers of the star. The area of the absorption feature depends on the number of particles in the lower state of the corresponding atomic or ionic transition and on the intrinsic line strength of that transition. The line strength or oscillator strength (*f*-value) is thus a crucial atomic parameter in the abundance analysis.

Assuming local thermal equilibrium (LTE) in the stellar atmosphere, the total number of particles for a given ion of a given element can be estimated from the number of particles in a state by means of the Boltzmann distribution law, and the total number of particles of a given element can then be derived by applying the Saha equation. By using an LTE model of the stellar atmosphere we expect to get consistent results for the abundance of a given element independent of the choice of spectral line among the ionization stages present, i.e. independent of the state of excitation and ionization. Inconsistent results may be ascribed to non-valid assumptions about the stellar model atmosphere, line blended spectral features, and/or poor atomic data.

Most atomic *f*-values used in stellar abundance analyses, especially in the satellite ultraviolet region ($\lambda < 3000$ Å), are obtained from theoretical calculations. As these data, in general, have no estimates of the uncertainty, they cannot reveal the source of probable errors occurring in the abundance analysis. It is therefore desirable to have experimental atomic data, with error bars, to judge whether the problem with a deviating line is associated with the atomic data or with the stellar model. The best test is provided by Fe II, since it is rich in lines, which are evenly distributed over the stellar spectrum and over a wide range of excitation energies, due to the high cosmic abundance of iron. The latter fact gives a direct way to test whether the level population follows the Boltzmann law and supports the assumption of local thermal equilibrium (LTE).

Based on the facts given in the previous paragraph we have started an international project, the FERRUM Project, for the production of oscillator strengths (gf-values) of singly ionized iron group elements in general, and of Fe II in particular. In this paper we present the FERRUM project and the results obtained so far, and give at the end an astrophysical application of the data.

2. Presentation of the FERRUM project

The FERRUM project is an international collaboration in atomic astrophysics aiming at the production of *reliable oscillator strengths (f-values) or transition probabilities (A-values) for spectral lines of singly ionized Iron Group Elements which are of astrophysical significance.* For allowed transitions the goal of the project is to provide:

- a set of lines in the satellite ultraviolet ($\lambda < 3000$ Å) region,
- a set of lines in the optical ($\lambda > 3000$ Å) region,
- lines with a large spread in excitation energy,

The project also includes atomic data for *forbidden transitions* based on measurements of radiative lifetimes of metastable states (see paper by Mannervik [1] in these proceedings).

The three requirements listed for the allowed transitions are motivated as follows. Astrophysical spectra may contain absorption and/or emission lines superimposed on a continuous spectrum produced by stellar blackbody radiation (BBR). In general, stellar atmospheres give absorption lines in the continuous spectrum, whereas gas clouds around or between stars give a pure emission line spectrum. Stellar absorption lines are used to determine the chemical abundance in the star's atmosphere, and that procedure requires gf-values. Stellar emission lines are used for temperature and density diagnostics of diluted plasmas, and they might also be the source of information about the concentration of various chemical elements. Stellar spectra are recorded either from the ground ($\lambda > 3000$ Å) or from space (down to about 900 Å), and they often lead to independent analyses. This explains the need for separate data in the optical and satellite UV wavelength regions.

Most abundance analyses assume local thermal equilibrium (LTE) in homogeneous parallel layers of the stellar atmosphere. Thus, by using lines from energy levels of quite different excitation energy in the abundance analysis one can test the validity of the LTE assumption in the stellar model atmosphere by one of the distribution laws in thermal equilibrium, the Boltzmann distribution law. The abundance derived from different spectral lines of a given ion should give a level population that is proportional to the exponential factor in the Boltzmann formula, $\exp(-h\nu/kT)$. As we shall see later, the utilization of lines from high-excitation levels in the abundance analysis may be of great significance, as intrinsically strong lines (large f-values) may result in reasonably faint features in the stellar spectrum and obey the criteria for linear curve of growth analysis.

3. Methods and working scheme

Below we describe a working scheme used in the generation of the line lists with gf-values as well as the experimental and theoretical methods utilized and the astrophysical data used.

3.1. *Allowed lines*

The transition probabilities, A_{ik}, are derived from a combination of measured radiative lifetimes, τ_i, and branching fractions, BF_{ik}, according to the relations

$$BF_{ik} = \frac{A_{ik}}{\Sigma A_{il}} \quad \text{and} \quad \tau_i = \frac{1}{\Sigma A_{il}} \Rightarrow A_{ik} = \frac{BF_{ik}}{\tau_i}. \qquad (1)$$

The A-value is easily converted to an f-value, which is the quantity used in astrophysical formulae for line absorption.

The measurements of radiative lifetimes of non-metastable states are in all subprojects performed at Lund Laser Centre and coordinated by H. Lundberg. The basic method is the Laser Induced Fluorescence (LIF) technique (see paper by Li *et al.* [3] for a general description of the experimental setup), and various ways of excitation have been employed in the different subprojects. The particular experimental arrangements are discussed below for each subproject.

The branching fractions have been derived from calibrated emission line intensities in spectra from hollow-cathode and Penning-discharge lamps recorded with Fourier Transform Spectroscopy (FTS). Spectral lines above the quartz cut-off ($\lambda \approx 1800$ Å) have been measured with the FTS instrument at Lund (coordinator U. Litzén), and for shorter wavelengths we have made use of the FTS at Imperial College, London (ICL), which is equipped with a MgF_2 beam splitter. The measurements at ICL are made by J. Pickering.

3.2. *Forbidden lines*

"Forbidden lines" are in astrophysics used as a notation for transitions that disobey the selection rules for electric-dipole (E1) radiation, e.g. transitions between metastable states within the ground configuration or between low configurations of the same parity. Such states can in low-density plasmas decay through magnetic dipole (M1) and electric quadrupole (E2) transitions. Forbidden lines were first identified in astrophysical plasmas more than 70 years ago, when Bowen [2] explained the strong lines observed in nebular spectra as transitions between the ^1D and ^3P in the ground configuration $2p^2$ in O III. Two brackets are used in the astronomical literature to designate E1-forbidden transitions, e.g. [O III], and one bracket, as in N III], to designate LS-forbidden transitions (intercombination lines).

Very little experimental data for forbidden lines of low-ionization species were known prior to the measurements of radiative lifetimes of metastable states in Ca^+ and Sr^+ at the Manne Siegbahn Laboratory (MSL) in Stockholm [1]. We have now exploited the same technique of laser probing at the CRYRING storage ring to measure the radiative lifetimes of metastable states of Fe^+.

As forbidden lines are rarely seen in laboratory plasmas, it is not a straightforward procedure to obtain the branching fractions. Therefore, we make use of intensity calibrated astrophysical spectra and theoretical predictions to convert the measured lifetimes into transition probabilities (gA-values).

3.3. *Working scheme*

The working scheme used to achieve the goal of the FERRUM Project can be listed as follows:

- Measure f-values for some lines in a given transition array (TA) with a spread in excitation energy.
- Calculate all lines in the same TA using the orthogonal operator technique.
- Compare experimental and theoretical values and estimate the uncertainty of the calculated values.
- Make the list of lines in the TA array as complete as possible and add error bars to all f-values.
- Insert the f-values for all the lines in a synthetic spectrum and compare to a stellar spectrum.
- Investigate whether possible deviations in the previous comparison depend on the synthetic spectrum (f-value, model) or the stellar spectrum (blends).
- Adjust the line list by adding the complementary information obtained from the stellar spectrum.

Even if we stress the necessity of measurements it is important to underline the significance of incorporating theoretical data in the line lists. Calculated f-values will always constitute the bulk of the database, and the experimental values will be used to normalize them and to assess their accuracy.

Table I. *Survey of subprojects within the FERRUM Project (see text Section 4).*

	Lifetime			*f*-value			
	Conf.	Lev.	λ_{exc} (nm)	TA	Lines	λ (nm)	Ref.
1	4p,4p′	4	214, 320		0		[3]
2	4p′	6	205–220	4s′-4p′	18	235–280	[6]
3	4s4p	3	162		0		[20]
4	4d	6	260 + 220	4p-4d	29	218–268	[10]
5	5s	4	225 + 285	4p-5s	20	251–308	[11]
6	4p′	0		3d-4p′, 4s-4p′	81	160–350	[7]
7	4f	5		4d-4f	13	488–582	[16]
8	4s,4s^2	2	opt.	4s-4s^2			[17]
9	4s	2	opt	4s-4s′,3d-4s′	8	417–448	[19]
10	4s4p			4s^2-4s4p,3d4s-4s4p	$\simeq$ 30	160–325	[21]

Lev. = No. of levels measured, λ_{exc} = laser excitation pulse(s), TA = transition array,
Lines = No. of lines reported in the wavelength range λ.

4. Results of subprojects

Up to the time of this meeting (August 2001) we have finished seven and started another three subprojects of Fe II, in which we have measured lifetimes of 32 energy levels. This number should be related to the fact that there are more than 1000 energy levels experimentally established in Fe II (S. Johansson, unpublished). The measurements have resulted in experimental *f*-values for nearly 200 lines, and theoretical data have been tested and recommended for five transition arrays. Branching fractions have been measured in the wavelength region 1600–6000 Å and the excitation potential of the lower levels of the transitions ranges from 0 to 10 eV.

In Table I we give a survey of the Fe II measurements, and in Fig. 1 we have indicated the levels involved in a partial term diagram of Fe II. The left part of the table concerns the lifetimes and the right part the *f*-values. The notation for the levels is very rudimentary. The levels are represented by their subconfigurations, **nb**, and unprimed subconfigurations are based on the ground term, a^{5}D, of Fe III (or grandparent ^{6}S in Fe IV for 4s^2 and 4s4p). The primed 4s and 4p subcon-figurations have excited parent terms of Fe III. (We refer to the different publications for exact information.) In the figure the subconfigurations are drawn as boxes. The shaded boxes contain odd parity levels, and the white boxes even parity levels. In the table we have given the number of levels (Lev) measured in each box. Above each box we have inserted a typical lifetime for the levels, and between the boxes we have given a representative wavelength for the most probable radia- tive transitions. The table also includes the wavelength range for laser excitation in the LIF experiments, and the number and wavelength range of the lines with measured *f*-values.

4.1. *The 4p and 4p′ states*

The first subproject [3] concerned only lifetime measurements of four quartet levels, two 4p levels and two 4p′ levels, to test the experimental setup. The 4p levels, which are built on the ground state of Fe III, had been measured before [4,5], whereas the 4p′ levels, built on excited parent terms, were measured for the first time. The 4p′ levels have strong decay channels well below 2000 Å, and the BF:s could not be measured with the Lund FTS.

In the second project [6] we measured lifetimes for 6 more 4p′ levels, now with the parent terms ^{3}F and ^{3}H. They were excited by laser radiation between 205 and 220 nm from the a^{2}G$_{9/2}$ level. Two of the levels have all their significant decay branches above 200 nm, and we could therefore measure *f*-values for 18 Fe II lines with the Lund FTS. The total BF

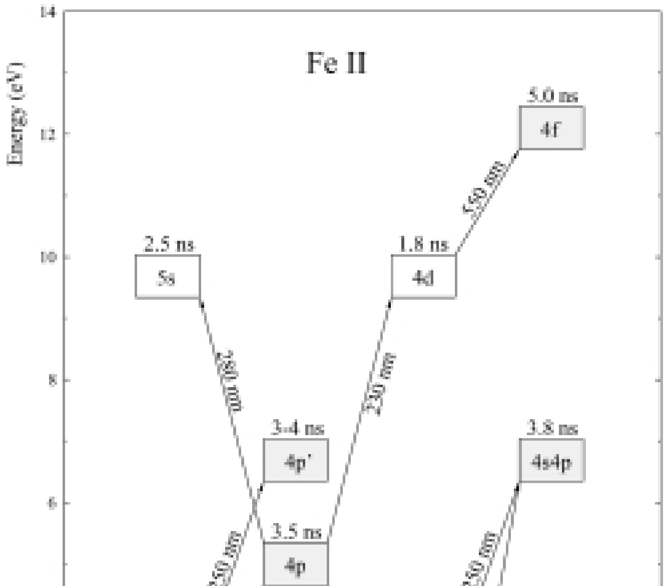

Fig. 1. A simplified term diagram of Fe II, only showing subconfigurations involved so far in the FERRUM Project. The boxes (shaded = odd parity) represent those subconfigurations, for which radiative lifetimes of some levels have been measured. For notations and inserts, see text.

of weak transitions and of transitions outside the measured region was estimated from theoretical calculations to be less than 2%.

In project six (see Table I), J. Pickering used the FTS at Imperial College to reach the branches below 200 nm [7], and *f*-values were obtained for 81 lines from four of the levels discussed in project (2). This was the first time the intensity ratio of the two fundamental branches 3d-4p and 4s-4p was simultaneously measured in a complex spectrum of a singly ionized iron group element.

4.2. *The 4d and 5s states*

The $3d^6(^5D)4d$ and 5s subconfigurations have many common features as regarding the atomic structure, but they seem to be of quite different importance in astrophysics. According to Fig. 1, they are both even parity configurations with an upper excitation energy of about 10 eV, and they decay preferentially by intraparent transitions to 4p. These transitions appear in the satellite ultraviolet region (see Table I and Fig. 1) and are quite prominent in stellar absorption spectra. However, the 4p-5s transitions occur also as a secondary fluorescence channel in H Lyα pumped Fe^+ gas, yielding strong lines around 2850 Å in many astrophysical emission line spectra (discussed at ASOS4 [8]), but there are no signs of the 4p-4d transitions in those spectra.

In Fig. 2 we show the wavelength region with the 4p-5s fluorescence lines in a spectrum of one of the gas clouds (called the Weigelt blobs) close to the central star of η Carinae. The spectrum has been recorded with the Space Telescope Imaging Spectrograph (STIS) aboard *HST* [9]. The excitation and fluorescence scheme is shown in Fig. 3. H Lyα pumps some odd-parity $3d^6(^5D)5p$ levels at about 11 eV, which decay to 5s and subsequently to 4p. This selective photoexcitation thus generates strong Fe II emission lines in the near-infrared (5s-5p) and ultraviolet (4p-5s) wavelength regions.

Since the 4d and 5s configurations have the same parity as the ground state we had to photoexcite them in two steps with two lasers (wavelengths given in Table I) in the lifetime measurements. Lifetimes for 6 and 4 levels of the 4d [10] and 5s [11] subconfigurations, respectively, have been measured. Combining the lifetimes with experimental branching fractions from intensity measurements at the Lund FTS, we have derived absolute *f*-values for 29 4p-4d transitions and 20 4p-5s transitions. The major difference in the BF measurements between this group (5s and 4d) and the 4p′ group is that there is no self-absorption in the laboratory source for the 4p-5s and 4p-4d lines, as they terminate on short-lived levels. All 4p′ levels measured terminate on metastable states.

As an illustration of the good agreement between our experimental data and the theoretical data calculated by

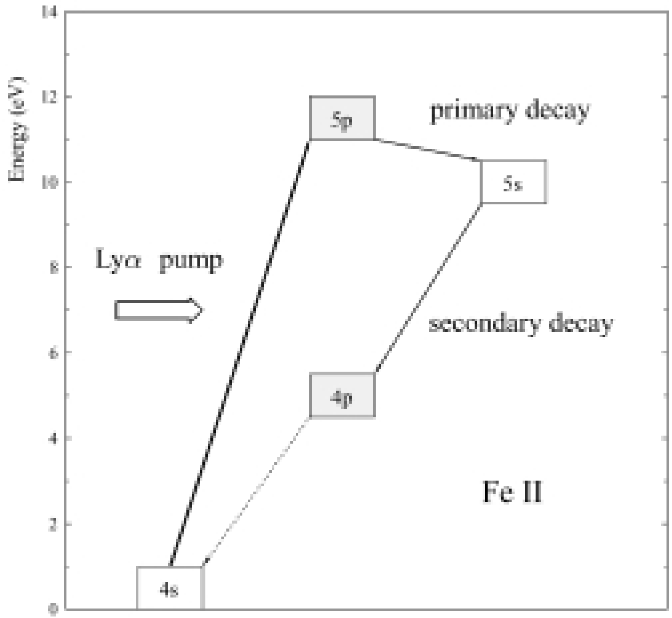

Fig. 3. Simplified energy level diagram of Fe II, showing the pumping and fluorescence channels that produce the spectral lines in Fig. 2. The 4p states are strongly coupled to the 4s states, showing a closed loop.

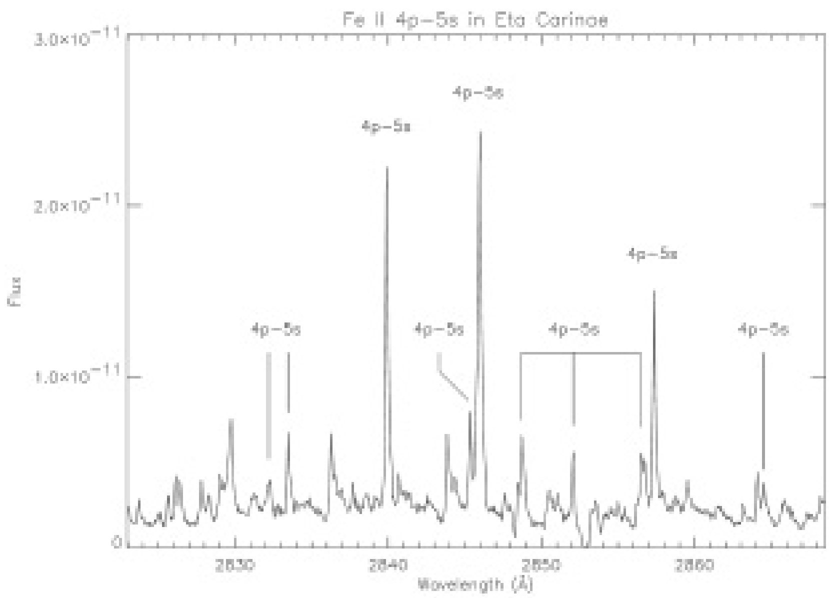

Fig. 2. Extract from a HST/STIS spectrum of a gas cloud close to η Carinae with strong emission lines of Fe II, produced by selective excitation of 11 eV levels by HLyα pumping. The 4p-5s lines are secondary cascades in the decay scheme of the 11 eV levels, see Fig. 3.

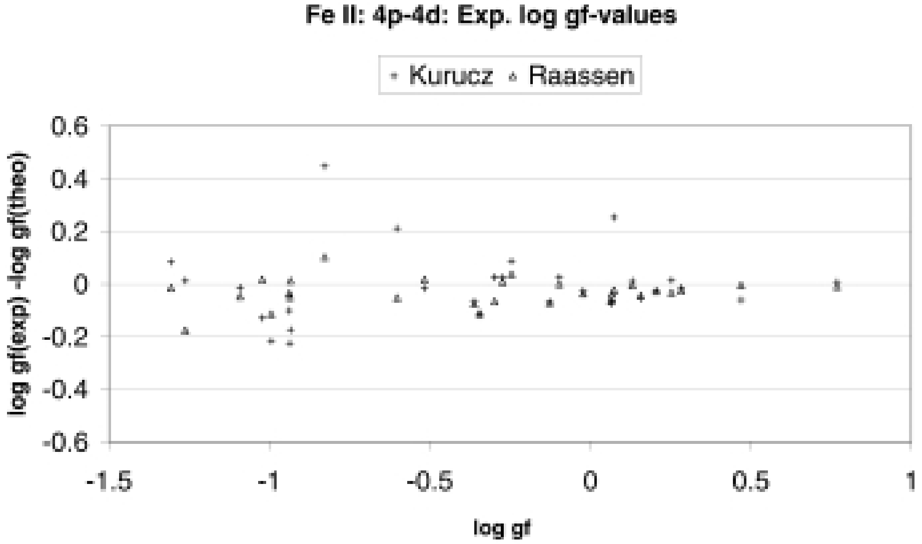

Fig. 4. Comparison between experimental and theoretical log *gf*-values of 4p-4d transitions in [10] and theoretical log *gf*-values from Kurucz [14].

Raassen and Uylings [12,13], we show in Fig. 4 the difference between experimental and theoretical *f*-values for 4p-4d transitions as a function of the *f*-value. The scatter is very small even for small *f*-values. We have also included the *f*-values calculated by Kurucz [14], which in general show a larger scatter.

4.3. *The 4f states*

As is shown in Fig. 1 the 4d-4f transitions appear in the optical region and they may provide a critical test of the LTE conditions in stellar atmospheres, as the corresponding absorption lines have an excitation energy of 10 eV. In the same spectral region there are also low excitation Fe II lines with known *f*-values. The presence of 4d-4f transitions in stellar spectra was shown nearly 20 years ago [15].

We have measured the lifetime of five 4f levels at Lund Laser Centre using three-step excitation. The 4d levels are pumped as in subproject (4) and the 4d-4f step by a separate laser operating at optical wavelengths. We have measured the branching fractions for those levels having a sufficiently high J-value ($J > 11/2$), as these levels can only decay to 4d. However, most 4f levels have also a decay branch down to 3d (not indicated in Fig. 1) at very short wavelengths ($\lambda \approx 1000$ Å). It will be very difficult to measure the branching ratios between lines located at 500 nm and 100 nm. Our strategy will be to consult the theoretical calculations, as there is probably very little configuration interaction, and also check for consistency in stellar spectra. This subproject is in progress [16].

4.4. *The metastable 4s′ and 4s^2 states*

Some of the energy radiated from a central star onto various types of gas ejecta around the star is stored as excitation energy in metastable states. Due to the low particle density in such ejecta the probability for collisional deexcitation is low, and the metastable states decay in "forbidden" transitions by electric quadrupole (E2) or magnetic dipole (M1) radiation. A low optical thickness and a large column length may build up a substantial intensity in these forbidden lines and make them very prominent in spectra of low density plasmas. To get information about temperature, density, chemistry of stellar ejecta one therefore needs to analyse the forbidden lines. Due to the large number of metastable states in Fe II, the high cosmic abundance of iron, and the ionization balance, the spectra of low-density gas clouds contain a large number of forbidden Fe II lines, denoted [Fe II]. Since the intensity ratio of the [Fe II] lines is the observed quantity used for getting the astrophysical plasma parameters, the transition probability (A_{ik}) is the critical atomic parameter. For example, for two close forbidden lines from two different metastable levels close in energy, the intensity ratio approaches the ratio between the statistical weights (g_i) in the low-density limit, whereas it equals the ratio between the g_iA_{ik} values at high density. Intermediate values of the ratio imply intermediate densities.

We have measured radiative lifetimes for four different metastable Fe II levels using the laser probing technique at the storage ring (CRYRING) in Stockholm (projects 8 and 9 in Table I). The technique is described in detail by Mannervik [1] in these proceedings. The measurements were done at two different campaigns, and the results of the first experiment (8) have been published [17]. The lifetimes of the four levels range between 0.2 and 4.1 s. Two of them agree quite well with recent theoretical calculations [18], whereas one level, $b^2H_{9/2}$, in subproject (9) deviates by about 25% due to level mixing.

Since forbidden lines are extremely difficult to produce in a laboratory light source, we have to use other sources to get the branching fractions for the metastable states. We will make use of theoretical calculations and astrophysical spectra, which both have their weaknesses. It is difficult to estimate the uncertainties of the theoretical A-values, and even if the astrophysical spectra are intensity calibrated, there is an uncertainty in the observed intensity due to interstellar extinction. In fact, reliable intensity ratios are needed for determining the interstellar extinction curve. However, we will iteratively work with astrophysical spectra and theoretical data by starting in a small wavelength region, compare intensity ratios with calculated values, and work towards larger wavelength intervals. Such work is in progress by H. Hartman [19] making use of the calculations by Quinet *et al.* [18] and the STIS spectra of η Carinae.

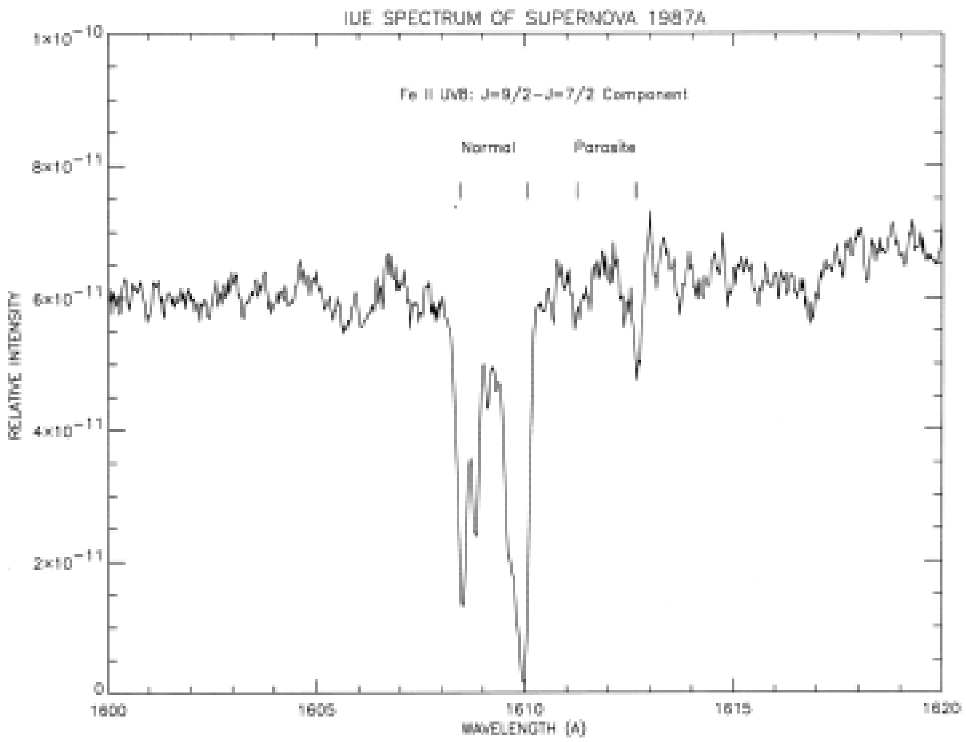

Fig. 5. One of the very first IUE spectra of SN1987A showing the λ1608 feature absorbed in the Large Magellanic Clouds (red component) and the Galaxy (blue components). The parasite feature at 1611 Å shows the same structure (see text).

5. Astrophysical application: interstellar UV 8 line from the 4s4p state

In Fig. 5 we show a picture of the interstellar Fe II line at 1608 Å in multiplet UV8, which connects the ground term a^6D with the 4s4p term y^6P° (indicated as 4s4p in Fig. 1). The feature shown in Fig. 5 appears in one of the very first *International Ultraviolet Explorer (IUE)* spectra of supernova SN1987A, which explains the number of velocity components. The strong, most red-shifted component at 1610 Å is associated with the Large Magellanic Cloud (LMC), the site of the supernova, and the blue components are due to interstellar absorption in the disk and the halo of our galaxy. A couple of Ångström towards the red there is a feature that mimics the Fe II line, and that is a parasite line to the λ1608 line, resulting from a mixing of the upper levels of the two transitions, $y^6P^{\circ}_{7/2}$ and $y^4F^{\circ}_{7/2}$. This mixing generates parasite lines from both levels, and we show below some examples from stellar spectra.

In Fig. 6 we see the interstellar UV8 line and its parasite companion in spectra of two other objects, β^1 Sco and HD141637. The λ1608 line is regarded as the most important ground state transition in Fe II for abundance analyses of interstellar spectra, and its *f*-value is therefore of vital interest. There are astrophysical, theoretical and experimental *f*-values of the line available in the literature, and we discuss these in Section 5.2 below.

5.1. *New experimental f-value*

The laboratory measurement of the *f*-value of the UV8 λ1608 line of Fe II is a good example of problem-oriented atomic astrophysics within the FERRUM Project, where joint efforts manage to solve a seemingly simple atomic physics problem. Compared to previous work we had to set up the instrumentation for both lifetime and branching fraction measurements for the vacuum ultraviolet (VUV) region. In subproject (3), Z.S. Li measured the radiative lifetimes of the three y^6P° levels at Lund Laser Centre by using the LIF method. The excitation wavelength in this case was 161 nm, which means that the pathway for the laser excitation pulse had to be evacuated. The complicated generation of the excitation laser pulse, compressed both in time and wavelength, is described in detail by Li *et al.* [20].

Based on the success in bringing the UV and VUV regions together in the branching fraction measurements (subproject 6 [21]) J. Pickering has measured the ratios between 3d-3p and 4s-4p branches in the $3d^54s^2$-$3d^54s4p$ transition array for the first time (subproject 8). The measurements were peformed at Imperial College, London, using the VUV Fourier Transform Spectrometer, which is equipped with a MgF_2 beam splitter. The instrument was intensity calibrated with a deuterium lamp, and experimental details are given in [7,21]. For the UV8 λ1608 Fe II line the absorption *f*-value obtained in [21] is 0.058(5), and *f*-values for the other UV 8 components will also be given in the paper.

5.2. *Comparison with previous work*

Previous data regarding the *f*-value of the UV8 λ1608 Fe II line come from theoretical, experimental and observational work. In Fig. 7 we show the different *f*-values obtained for λ1608 as a function of time, and distinguish between laboratory (Lab.), theoretical (Theory) and astrophysical (Astro.) values. The Lab. and Astro. values are accompanied by error estimates. We will make some comments on the various data points.

5.2.1. *Astrophysical values.* Shull *et al.* [22] determined astrophysical *f*-values for 21 ground state transitions of Fe II in the satellite ultraviolet region between 1055 and 2600 Å

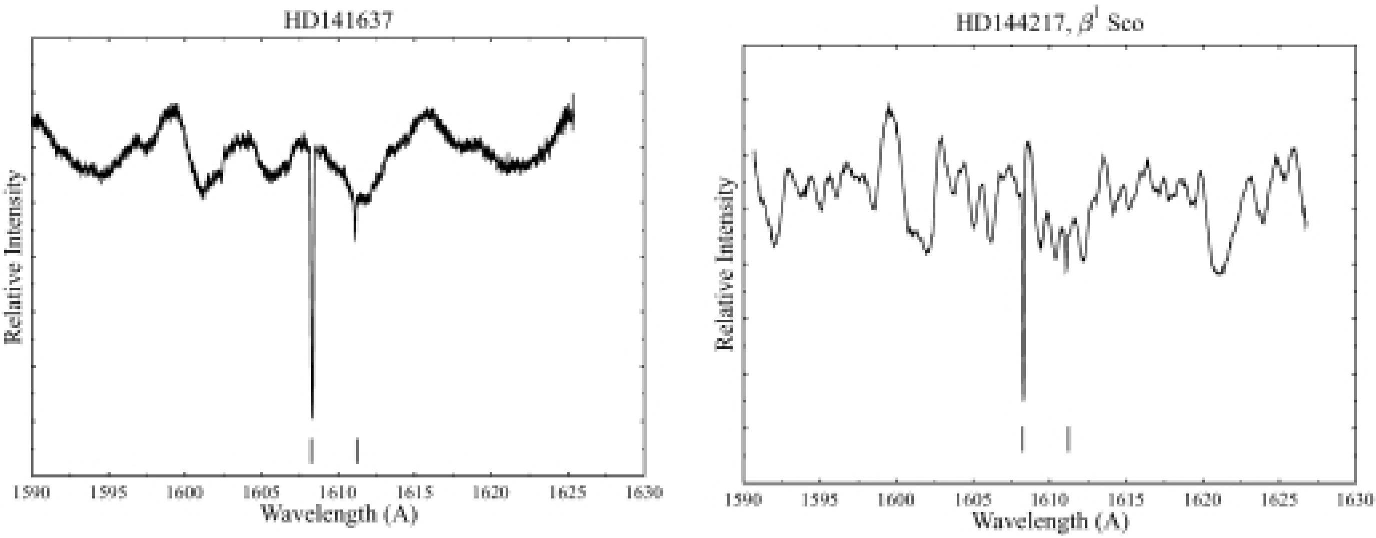

Fig. 6. *HST*/GHRS spectra showing (tick marks) the interstellar λ1608 line and its parasite line at 1611 Å against two different targets, β^1 Sco and HD141637. The broad stellar lines reflect high thermal and rotational Doppler broadening in contrast to the narrow interstellar lines.

by applying the curve of growth method on data from the *Copernicus* and *IUE* satellites. They derived a value of $f = 0.062$ with an uncertainty of 30%. This was a factor of three lower than the previously used value by Morton [23]. By using interstellar data from the Goddard High Resolution Spectrograph aboard the *Hubble Space Telescope* Cardelli & Savage [24] could reduce the error bars considerably when deriving an improved astrophysical *f*-value for the UV8 λ1608 Fe II line. However, Cardelli & Savage [24] reported a value of 0.0619, which is equal to the previous one by Shull *et al.* [22]. The difference is the 1σ error of 10%.

5.2.2. *Theoretical values.* There are a number of theoretical calculations of oscillator strengths in Fe II available in the literature at different level of complexity. Nussbaumer *et al.* [25] made a calculation of the sextet system assuming pure *LS* coupling and no mixing between terms of another multiplicity. This works for many sextets, but as we have seen in Fig. 6, for example, the y^6P° levels are mixed with quartet levels, which will affect the *f*-values. Thus, the high *f*-value of the λ1608 line obtained in [25] is probably a result of the assumption of pure *LS* coupling. The same is true for the value calculated in the IRON project [26], where also pure *LS* coupling is applied to Fe II. Both these theoretical values, 0.096 [25] and 0.089 [26], respectively, are about 50% greater than the experimental and astrophysical *f*-values.

Even though Fawcett [27] and Kurucz [14] are using the same computer code (the Cowan code) the theoretical values they obtain for the 1608 Å line are quite different, 0.043 and 0.072, respectively. Thus, there is a total span of a factor of 2.2 for the different theoretical values discussed so far.

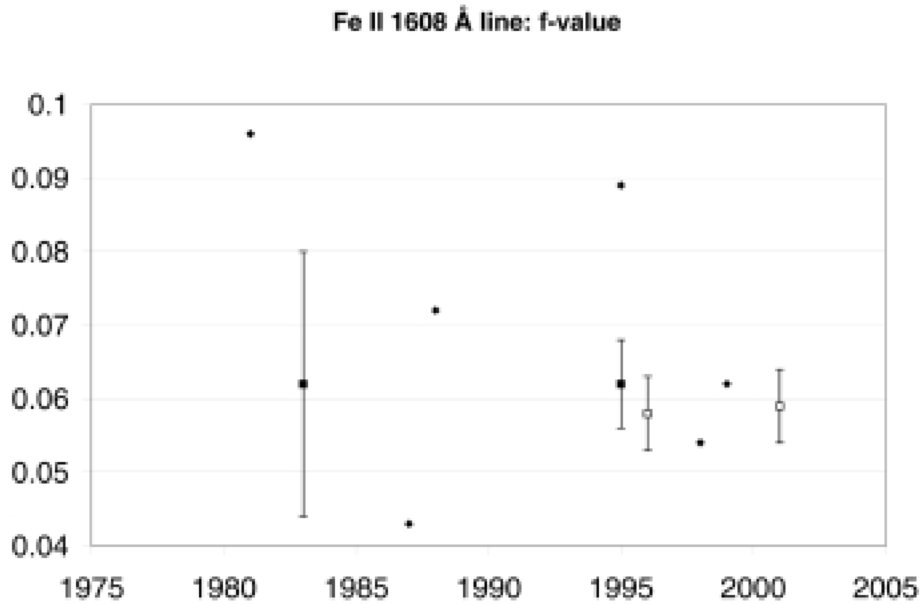

Fig. 7. Experimental, theoretical and astrophysical *f*-values of the interstellar Fe II 1608 Å line reported 1981–2002. Astrophysical (■): Shull *et al.* (1983) [22], Cardelli and Savage (1995) [24] Experimental (□): Bergeson *et al.* (1996) [29], Pickering *et al.* (2002) [21] Theoretical (◆): Nussbaumer *et al.* (1983) [25], Fawcett (1987) [27], Kurucz (1988) [14], IRON project (1995) [26], Raassen & Uylings (1998) [12], Donnelly & Hibbert (1999) [28].

However, recent calculations by Raassen & Uylings [12,13] and by Donnelly & Hibbert [28] show a satisfactory agreement and give values of 0.055 and 0.062, respectively. Full calculations of the UV8 multiplet by Donnelly & Hibbert will be included in [21].

5.2.3. *Experimental values.* In a first direct measurement of VUV oscillator strengths of Fe II using synchrotron radiation as the background source, Bergeson *et al.* [29] measured the *f*-value of the λ1608 line by doing a high sensitivity absorption experiment at the Aladdin storage ring at the University of Wisconsin-Madison. The ion source irradiated by the "white light" is a hollow-cathode lamp. By measuring the oscillator strength relative to other well-known Fe II absorption lines above 2000 Å an f-value $= 0.058(5)$ was derived. This value agreed within the uncertainties with the published astrophysical f-values, discussed above. The *f*-value obtained by Bergeson *et al.* [29] was later confirmed by the same group [30] in complementary measurements of the UV 8 multiplet.

The experimental value ($f = 0.058(5)$, see above) obtained within the FERRUM Project reproduces the value measured by the Madison group, and together with the recent calculated data [13,28] there are now two completely different experiments and two different theoretical approaches, giving an *f*-value of 0.058 ± 0.005.

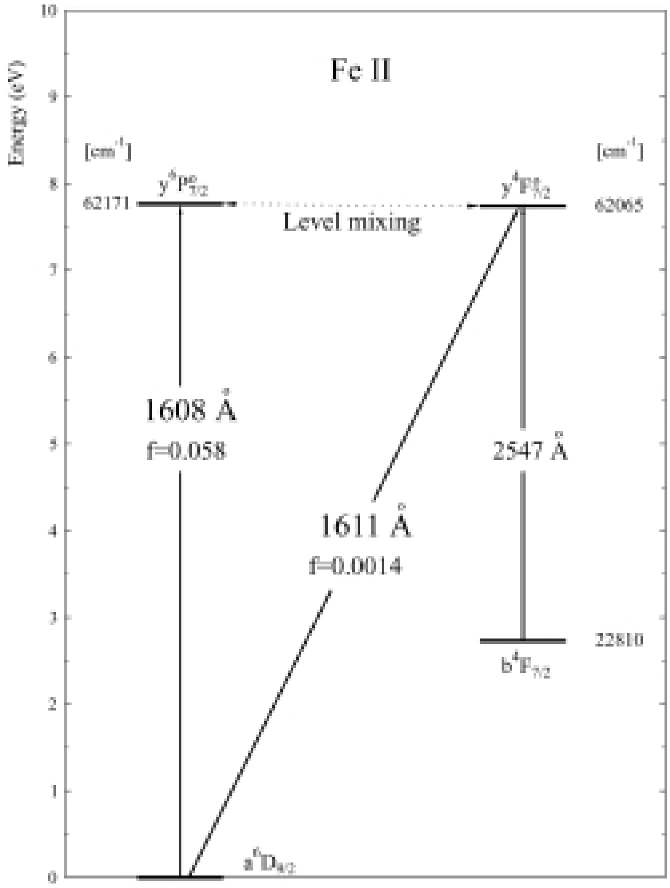

Fig. 8. Schematic term diagram of Fe II showing the mixing between $y^6P^\circ_{7/2}$ and $y^4F^\circ_{7/2}$, generating the interstellar λ1608 line and its parasite λ1611 line shown in Figs. 5 and 6. New experimental *f*-values are indicated. The strongest intraparent transition from $y^4F^\circ_{7/2}$ at 2547 Å is also indicated.

6. Level mixing

A complex spectrum like Fe II with a high density of energy levels offers numerous examples of level mixing which are very difficult to predict. The traditional way of separating terms (levels) according to multiplicity and treat them as independent systems does not work in Fe II. Transitions between the systems of different multiplicity (intercombination lines) have often the same high probability as intrasystem transitions. On the other hand, some apparently clear cases of *LS*-allowed transitions have transition probabilities of the same order as parity-forbidden lines.

Level mixing has been found in the octet system of Fe II [31], even though there are only four octet terms known in Fe II. In the sextet system of odd-parity configurations only the very low sextets (≈5 eV) seem to be pure *LS*-terms. A very strange case of doublet-sextet mixing was solved theoretically by Brage in [32] for the x^6P° term, the upper term of the strange UV191 multiplet of Fe II and a companion to the y^6P° term discussed in the present paper. As was mentioned already in the introduction of Section 5 and illustrated in Fig. 5, the upper level of the λ1608 line, $y^6P^\circ_{7/2}$, is mixed with $y^4F^\circ_{7/2}$. The two levels belong to different configurations, $3d^54s4p$ and $3d^64p$, respectively, but are close in energy. The $y^4F^\circ_{7/2}$ level is also mixed with other 4p levels, so the situation is even more complex than is discussed here. In Fig. 8 we show a schematic picture of the energy levels involved in the level mixing and the transitions generated.

As we see in Figs. 5 and 6 the level mixing generates extra spectral lines, and in the present case an extra interstellar Fe II line. This is the effect of the mixing of the $y^6P^\circ_{7/2}$ level, but the $y^4F^\circ_{7/2}$ level has its main decay channels in the resonance region around 2500 Å. Thus, the mixing of the $y^4F^\circ_{7/2}$ level also generates extra lines originating from $y^6P^\circ_{7/2}$ and now in the 2500 Å region. We illustrate that by showing an extract from a stellar spectrum in Fig. 9, where the curve (full line) is the *HST*/GHRS spectrum of χ Lupi. The dashed line (upper

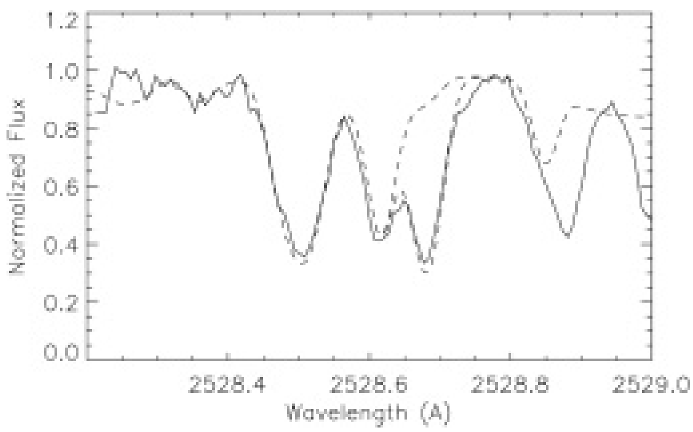

Fig. 9. Extract of a *HST*/GHRS spectrum of χ Lupi containing the "parasite" line at 2528.6 Å, i.e., the $b^4F_{9/2}$-$y^6P^\circ_{7/2}$ transition (see Fig. 10). The full curve is the stellar spectrum, and the dashed curves show synthetic spectra, where the upper one is based on the Kurucz database. In the lower dashed curve the Kurucz *f*-value for the λ2528 line has been replaced by the new experimental value from the FERRUM project.

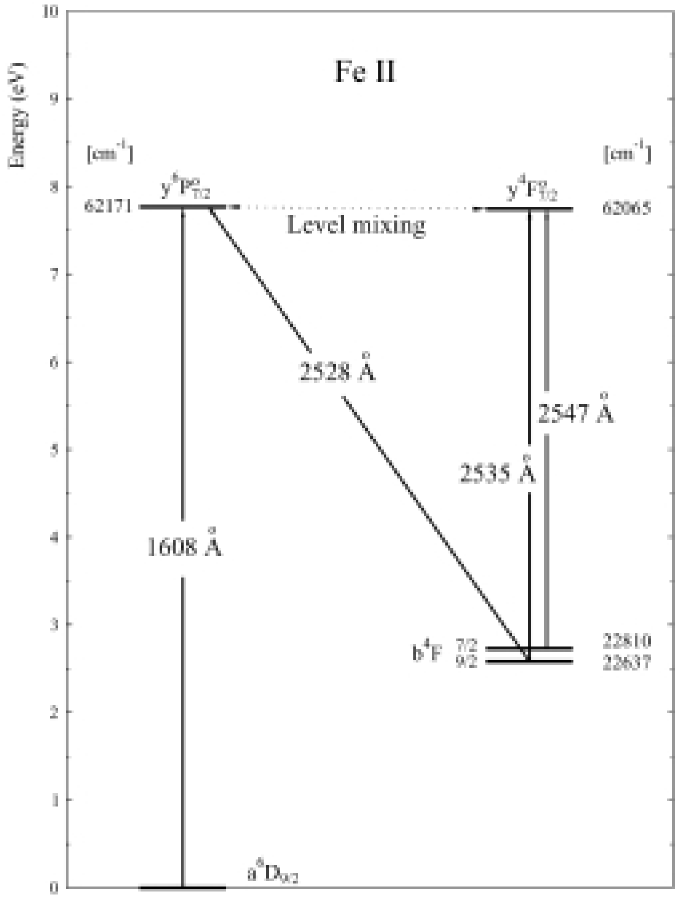

Fig. 10. The level mixing illustrated in Fig. 8 introduces also "parasite" lines from $y^6P^\circ_{7/2}$. We show here the transition and level scheme involved in the λ2528 line in Fig. 9.

curve) represents the calculated spectrum with $\log gf$-values from Kurucz [14], and in the lower dashed curve appearing around the 2528.7 Å feature the Kurucz $\log gf$-value has been replaced by our new experimental $\log gf$-value.

The stellar line at 2528.7 Å in Fig. 10 is also a parasite transition, $b^4F_{9/2}$-$y^6P^\circ_{7/2}$, to the $b^4F_{9/2}$-$y^4F^\circ_{7/2}$ transition at 2535.5 Å. The theoretical f-values from [14] are $1.1{\cdot}10^{-6}$ and 0.042, respectively. The experimental f-values are 0.0017 and 0.058, respectively. Thus, there is a marginal difference in the main λ2535 line, but there is a difference of nearly three orders of magnitude for the parasite line. The new experimental value of the 2528.6 Å line is nicely confirmed by the stellar spectrum and explains fully the origin of that seemingly unidentified feature in the spectrum of χ Lupi.

7. Conclusions

We have briefly reviewed the present (August 2001) status of the FERRUM Project, by discussing ten completed or ongoing subprojects on experimental transition probabilities (oscillator strengths) for Fe II. The experiments include lifetime measurements in the nanosecond-microsecond regime of "normal" excited states, performed at Lund Laser Centre, as well as measurements in the millisecond-second regime of metastable states, performed at the Manne Siegbahn Laboratory, Stockholm. Branching fractions have been obtained by Fourier Transform Spectrometry at the Atomic Spectroscopy Division, Lund, and at Imperial College, London. All measurements aim at improving the database for users of atomic data in astrophysics, and the subprojects are chosen by certain criteria.

As an illustration of the astrophysical application we have chosen to discuss the interstellar λ1608 line of Fe II, which is accompanied by a parasite line because of level mixing. Recent experimental, theoretical and observational data of the oscillator strength (f-value) of the λ1608 line have been obtained independently by completely different methods, and they agree well within the experimental uncertainties.

The future plans of the FERRUM Project include similar measurements of other iron group elements, but to a lesser extent. The reason is simply the dominance of iron lines in astrophysical spectra compared to the contribution from its neighbours in the periodic table, and this reflects both the higher cosmic abundance of iron and the complex atomic structure of Fe II.

Acknowledgements

The Lund part of the FERRUM Project is supported by grants (SJ) from the Swedish Research Council and the Swedish National Space Board. PLS was supported in part by NASA Grant NAG5-4348. MPD and AH were supported by Rolling Grant PPA/G/O/2000/00024 from PPARC,UK. JCP thanks PPARC, UK and The Royal Society for their support.

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