

# Absolute transition probabilities for the $a^6D \rightarrow y^6P^\circ$ multiplet (#8) of Fe II

K.L. Mullman, M. Sakai, and J.E. Lawler

Department of Physics, University of Wisconsin-Madison, Madison, WI 53706, U.S.A.

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**Abstract.** We report the first laboratory measurement of absorption oscillator strengths ( $f$ -values) for 6 VUV ( $\lambda_{\text{vac}} \sim 162$  nm) transitions of the  $a^6D \rightarrow y^6P^\circ$  multiplet (#8) in Fe II. We have also reconfirmed a recent measurement of the  $f$ -value of the Fe II resonance line at  $\lambda_{\text{vac}} = 160.845$  nm. These measurements are made with the high sensitivity absorption experiment at the University of Wisconsin-Madison. Measurements are also made on UV ( $\lambda_{\text{air}} \geq 200$  nm) lines in Fe II with accurately known  $f$ -values in order to construct a reliable curve of growth for the experiment. Diffusive cooling of  $\text{Fe}^+$  ions in the negative glow of the hollow cathode discharge, which serves as an absorbing sample, results in a non-Maxwellian ion velocity distribution. A satisfactory curve of growth is generated using a full Voigt profile with an artificially low ion temperature in some cases.

**Key words:** atomic data — ISM: abundances — ISM: atoms — ultraviolet: general — Sun: abundances

## 1. Introduction

The need for accurate spectroscopic data in the VUV has become particularly acute with the launch of the Hubble Space Telescope (Leckrone et al. 1990; Leckrone et al. 1993). Elemental abundance studies on stars and on the Interstellar Medium require improved transition probability or oscillator strength ( $f$ -value) data. The absorption method is one of the most accurate methods for relative oscillator strength measurements on neutral atoms, especially when applied to gas phase samples in an oven (Blackwell et al. 1979). Although it will be difficult to match the 1% accuracy of the best experiments on neutral atoms in ovens, experiments using the absorption method on ions in plasmas are quite promising. Recently

Bergeson et al. (1996b) described a VUV absorption experiment which has unique capabilities. This VUV absorption experiment uses the Aladdin storage ring at the Synchrotron Radiation Center as a continuum source, a hollow cathode discharge (HCD) as an absorbing sample, and a large (3 m) echelle spectrograph equipped with a state of the art charge coupled device (CCD) detector array. This experiment is sensitive, i.e. it can be used to measure small equivalent widths. Its sensitivity is due to: the high spectral radiance provided by the storage ring, the high ( $\sim 3 \cdot 10^5$ ) resolving power provided by the echelle spectrograph, and the powerful advantages of a detector array in absorption spectroscopy (Wamsley et al. 1993). The experiment is broadly applicable to many neutral atoms and atomic ions due to the use of a HCD as an absorbing sample.

This work is an extension and improvement of the first results from the high sensitivity absorption experiment at the University of Wisconsin-Madison (Bergeson et al. 1996b). Although the use of a HCD as an absorbing sample provides great flexibility for studying lines from many different metastable lower levels in many atoms and ions, it does have two minor disadvantages. The lower level populations in the HCD are not in local thermodynamic equilibrium (LTE), as are lower level populations in an oven. This minor disadvantage is overcome by using a larger set of reference lines with accurately known  $f$ -values (Bergeson et al. 1996a) to normalize relative  $f$ -value measurements on pairs of lines from a common lower level. The other minor disadvantage is due to the fact that ions in the negative glow region of a HCD often do not have a perfectly Maxwellian velocity distribution. Diffusive cooling tends to deplete the high energy tail of the Maxwellian distribution and thus affect the curve of growth. Extensive measurements in this work of the effects of diffusive cooling of  $\text{Fe}^+$  ions in the negative glow of the HCD allow us to construct a satisfactory curve of growth for use in data analysis. A satisfactory curve of growth is generated by assuming a full Voigt profile with an artificially low ion temperature in some cases. We present

the first laboratory measurement of 6 absorption  $f$ -values for VUV lines of the  $a^6D \rightarrow y^6P^\circ$  multiplet (#8) of Fe II. These lines have been identified in solar spectra and have been observed in the ISM using the Goddard High Resolution Spectrograph on board the Hubble Space Telescope (Fawcett 1988; Cardelli & Savage 1995). The absolute scale for the measurements is determined by work on branching fractions done previously at Wisconsin & Lund (Bergeson et al. 1994, 1996a), and by work on radiative lifetimes using the laser-fast beam method (Biemont et al. 1991; Guo et al. 1992). The combination of these highly accurate measurements of branching fractions and radiative lifetimes yields 67  $f$ -values of UV transitions in Fe II; 33 of the  $f$ -values are accurate to 5% or better, and 29 more are accurate to within 10% (Bergeson et al. 1996a). The UV transitions with small ( $< 5\%$ ) uncertainty serve as the primary reference lines in this study.

## 2. Absorption

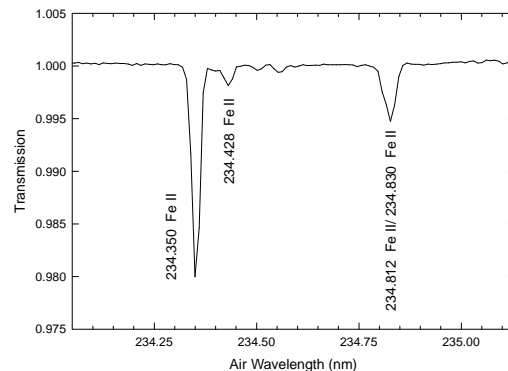
As in any classic absorption experiment, our apparatus consists of three main components: a sample of absorbing atoms or ions, a continuum source, and a detection system.

An iron HCD provides a gas phase sample of  $Fe^+$  distributed through a large number of metastable levels. The cathode is water-cooled, 1 cm in inner diameter and 10 cm long. The discharge uses 2.4 Torr of Ar as a buffer gas; currents ranging from 250 mA to 1.2 A are used in this experiment. Our continuum source is the white light beam line on the Aladdin Storage Ring at the Synchrotron Radiation Center. The ring has a 2.083 m magnetic bending radius and usually operates with an 800 MeV beam and 200 mA of current. The continuum is both spectrally smooth and very stable and covers the entire VUV range.

We have two separate spectrometer/detector systems since we measure relative  $f$ -values. One measures the “reference” line; the other measures the “unknown” line. By measuring both lines simultaneously, we eliminate the need for long term stability in our discharge.

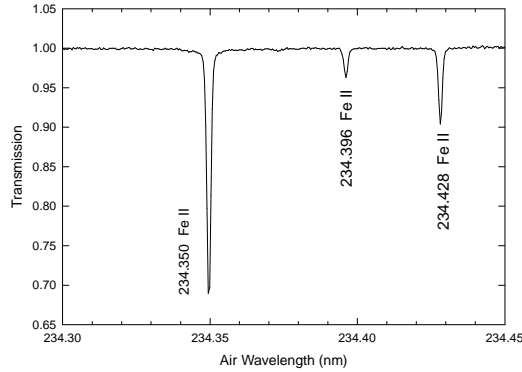
One of the spectrometer/detector systems is an Acton Research Corporation model VM-510, 1 m focal length vacuum compatible spectrometer with a Princeton Instruments 15.5 bit 1024 element photo-diode array (PDA). The spectral resolving power of this system is around  $2 \cdot 10^4$ , limited by the 0.025 mm spacing of the diodes in the array. This system is used to measure a well isolated “reference” line in the UV, so a moderate resolving power is acceptable. The combination of the moderate resolving power and high throughput of this reference spectrometer makes it possible to use a PDA instead of a more sensitive CCD array. The second spectrometer/detector system is a 3 m focal length vacuum compatible echelle spectrometer equipped with a VUV-sensitive CCD detector array. The practical resolving power of this system when used with the 256 mm wide,  $63^\circ$  blaze echelle grating is  $\sim 3 \cdot 10^5$ . The CCD is

a Scientific Imaging Technologies uncoated, boron-doped, thinned, back-illuminated, deep UV sensitive device in a camera head from Princeton Instruments. The CCD format is square, 512 pixels on a side. Because the spectrometer operates in 22nd to 36th order for these measurements, a McPherson model 234/303 Seya monochromator is used as an order-sorter. To reduce stray light in the spectrometer, we limit the Seya bandpass to 0.1 nm. This high resolution system is used to measure the “unknown” line. Figures 1 and 2 show sample UV spectra taken on the low resolution and high resolution systems, respectively. The noise in the continuum of each figure is consistent with Poisson statistics. Figure 3 demonstrates the good signal-to-noise ratios of our high resolution spectra in the VUV wavelength range.

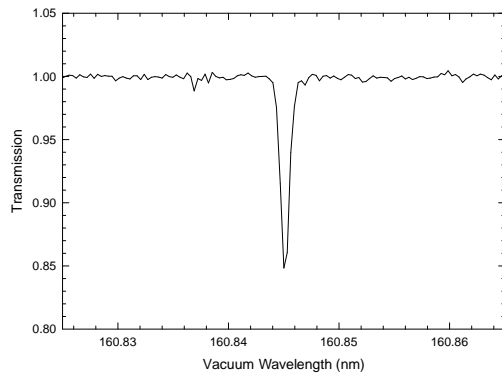


**Fig. 1.** Spectrum at 234 nm taken with the 1 m spectrometer and PDA. The noise in the continuum is consistent with Poisson statistics

Our experiment is now sensitive to fractional absorptions of 0.0003 using the 1 m spectrometer and PDA and is sensitive to fractional absorptions of 0.003 using the 3 m echelle spectrometer and CCD array. It has been possible to achieve sensitivities to fractional absorptions of 0.00001 with modest spectral resolving powers (Menningen et al. 1995). We are optimistic that the experiment described here will ultimately achieve sensitivities to fractional absorptions of 0.0001 with a spectral limit of resolution of  $0.03 \text{ cm}^{-1}$  at wavelengths down to Lyman alpha. This goal corresponds to measuring equivalent widths as small as  $0.00003 \text{ cm}^{-1}$  or ionic column densities of  $N1 = 10^7 \text{ cm}^{-2}/f$ . A sensitivity in this range will extend the dynamic range of the  $f$ -value program, and will make our absorption experiment a more powerful plasma diagnostic than a typical laser induced fluorescence experiment on a glow discharge. This sensitivity goal is likely achievable through a combination of improved optics and



**Fig. 2.** Spectrum at 234 nm taken with the 3 m echelle grating spectrometer and CCD array. The noise in the continuum is consistent with Poisson statistics. The weak Fe II absorption line at 234.396 nm is completely resolved and is observed with a good signal-to-noise ratio in this spectrum; the line is barely visible in Fig. 1



**Fig. 3.** Sample absorption spectrum of the 160.845 nm transition in Fe II. The noise in the continuum is consistent with the Poisson statistics of the photo-electrons in the CCD array

improved detector arrays. The use of a storage ring beam line with an insertion device would also help.

We have carefully reshaped the synchrotron beam using several cylindrical mirrors to match the angular acceptance of each spectrometer; the optical coupling is described in detail elsewhere (Bergeson et al. 1996b). The etendue of the reshaped synchrotron beam is a rather good match to the etendue of the 3 m echelle spectrometer. The synchrotron beam does not have a large enough etendue to fill a typical Fourier Transform Spectrometer (FTS). The lack of a useable etendue advantage, along with a signal-to-noise disadvantage from the spectral redistribution of quantum (Poisson) noise intrinsic to an FTS, means that

an FTS does not have an advantage over a grating spectrometer in this experiment.

We use a digital subtraction technique to discriminate against line emission in the HCD (Wamsley et al. 1993). With the synchrotron continuum passing through our sample, the spectrum is a combination of the synchrotron continuum, absorption from atoms and ions in the line of sight, emission from the HCD and dark signal from the array. By blocking the synchrotron, we get a spectrum of only the HCD emission plus the dark signal. The subtraction of these two spectra results in the continuum plus absorption spectrum. Pixel to pixel variations in the quantum efficiency of the detector can be accounted for by dividing the difference spectrum described above by a dark signal corrected, high signal-to-noise continuum spectrum taken with the HCD off.

When using this digital subtraction technique, the linearity of the detector arrays is especially important (Menningen et al. 1995). We measure the fractional non-linearity of our CCD array and find it to be less than 0.001 from 4% full well to 85% full well. We have designed our optical coupling so that the HCD line emission is much less than the synchrotron continuum. In this situation, the small non-linearities of the detector have no effect on our absorption signal.

Precise temporal gating of the detector arrays is also essential for reliable digital subtraction of the HCD line emission spectrum. The standard readout procedure of a CCD array involves shifting the photoelectron pattern across the array. This procedure may not provide the required precision gating. Wamsley et al. (1993) used a gated image intensifier to achieve the required precision. Image intensifiers have many disadvantages in a high sensitivity absorption experiment. They are expensive and easily damaged. They also reduce the saturation fluence of the array, decrease the spectral resolving power of the experiment, and add noise to the spectra. A frame transfer technique, in which the photoelectron pattern from the exposed part of the CCD array is rapidly transferred to a masked part of the array, provides precise gating of the CCD array. The normal readout mechanism of the PDA provides precise temporal gating.

Scattered light can cause an error in absorption measurements; we have taken special care to accurately account for any scattered light in our system. Earlier tests have verified that the scattered light level in this experiment is less than 1% of the continuum (Bergeson et al. 1996b). A small correction eliminates any error due to scattered or “leakage” light.

We see evidence of a non-Maxwellian velocity distribution in our discharge. A model of our discharge suggests that this is due to competition between the ambipolar diffusion (ion loss) rate and the collisional thermalization that fills out the high energy tail of the Maxwellian profile. With our discharge parameters and operating conditions, the diffusive loss rate and collisional thermalization

**Table 1.** Well-known absorption  $f$ -value ratios for pairs of lines sharing a common lower level in Fe II and our measurements at each hollow cathode discharge current used in the experiment. The last row gives the effective ion temperature used for the Voigt profile in the curve of growth analysis. The number in parentheses following a table entry is an uncertainty in the last digit(s) of the table entry

$(\lambda_1/\lambda_2)_{\text{air}}$ (nm)	$(f_1/f_2)^{\text{p}}$	Hollow cathode discharge current (A)													
		0.20	0.25	0.30	0.40	0.50	0.55	0.60	0.80	0.85	0.90	0.95	1.00	1.20	
259.940/234.350	2.10(5)	2.12(9)	2.13(9)	2.22(10)	2.21(12)	2.20(13)	2.23(15)	2.17(15)	2.23(22)	2.02(20)	2.32(23)	2.25(19)	2.31(20)	2.19(23)	
239.563/236.483	5.81(27)	5.39(19)	5.52(18)	5.52(17)	5.16(17)	5.27(20)	5.09(18)	5.45(24)	5.58(34)	5.66(39)	5.40(36)	5.54(42)	5.29(40)	5.28(37)	
259.940/237.374	7.64(36)	8.28(44)	7.77(41)	7.49(35)	7.99(41)	8.58(51)	7.70(52)	7.74(53)	7.21(49)	7.39(62)	7.11(56)	7.31(57)	7.77(63)	8.06(72)	
238.204/237.374	10.2(5)	10.4(4)	10.5(6)	10.1(5)	10.6(6)	9.8(6)	--	--	--	--	--	--	--	--	
T(K)		193(5)	263(6)	310(6)	412(6)	478(6)	589(9)	625(10)	651(10)	731(9)	761(9)	761(9)	784(10)	849(9)	

<sup>p</sup>Oscillator strengths from emission branching fraction and laser induced fluorescence lifetime measurements (Bergeson et al. 1996a).

rates are nearly the same. Thus the more energetic ions diffuse out of the negative glow to the cathode of the discharge and are thus lost at a higher rate than low energy ions. Collisional thermalization is unable to completely “fill out” the high energy tail of the Maxwellian distribution. This is referred to as “diffusive cooling” and results in a truncated Voigt profile. While operating with a resolving power of  $\sim 3 \cdot 10^5$ , we are unable to resolve the lineshape of an absorption feature. We have experimented with a variety of approximations for generating a curve of growth. The simplest and most satisfactory approximation is to use a full Voigt profile in our curve of growth analysis with the Lorentzian component being primarily radiative (natural) broadening. To determine an “effective” ion temperature of our discharge, we measure several strong UV line pairs with well-known  $f$ -values at a given discharge current and find the temperature which gives the best overall consistency for all of the  $f$ -value ratios. Since we continue to assume a full Voigt profile in our curve of growth, the result of our temperature determination is artificially low or unphysical (below 293 K, the temperature of the HCD cooling water) for discharge operating currents below 300 mA. We recognize that this effective ion temperature is not a true heavy particle temperature of the discharge, but we use it in analyzing Fe<sup>+</sup> absorption data with the discharge operating under a well defined set of conditions. This effective ion temperature is used to determine the curve of growth for all other data taken under the same discharge conditions. Table 1 shows the effective ion temperatures and the resulting absorption  $f$ -value ratios for several pairs of lines sharing a common lower level at each HCD current setting used in the experiment. A few entries are missing in the bottom row of Table 1. The largest  $f$ -value ratio was not measured at the highest currents because the highest currents were used only for measuring the weaker lines. The solid agreement between the absorption data from this experiment and the accepted  $f$ -value ratios from emission branching fraction and laser induced fluorescence lifetime measurements re-

ported in the literature demonstrates the reliability of this method over a wide range of discharge conditions.

### 3. Results

We measure 7 of the VUV lines of the  $a^6D \rightarrow y^6P^\circ$  multiplet (#8) of Fe II; each of the 7 VUV lines is measured relative to two different UV transitions. This provides us with an internal consistency check for our data since we know accurate absorption  $f$ -values for all of the UV transitions of Fe II used as reference lines in this experiment. For example, we measure the transition at  $\lambda_{\text{vac}} = 162.916$  nm relative to both  $\lambda_{\text{air}} = 263.132$  nm and  $\lambda_{\text{air}} = 232.740$  nm. The results are:  $f(\lambda_{\text{air}} = 263.132 \text{ nm}) / f(\lambda_{\text{vac}} = 162.916 \text{ nm}) = 3.05(32)$  and  $f(\lambda_{\text{air}} = 232.740 \text{ nm}) / f(\lambda_{\text{vac}} = 162.916 \text{ nm}) = 1.30(7)$ . From previous work (Bergeson et al. 1996a), we know  $f(\lambda_{\text{air}} = 263.132 \text{ nm}) / f(\lambda_{\text{air}} = 232.740 \text{ nm}) = 2.42(18)$ . We can verify that our VUV work agrees with this as well:  $\{f(\lambda_{\text{air}} = 263.132 \text{ nm}) / f(\lambda_{\text{vac}} = 162.916 \text{ nm})\} / \{f(\lambda_{\text{air}} = 232.740 \text{ nm}) / f(\lambda_{\text{vac}} = 162.916 \text{ nm})\} = 2.35(28)$ . This cross-check allows us to identify inconsistencies in our data set.

Table 2 lists the absorption  $f$ -values for 7 of the VUV transitions from the ground term to the  $y^6P^\circ$  multiplet of Fe II. The 2 weakest lines in the multiplet at  $\lambda_{\text{vac}} = 162.591$  nm and  $\lambda_{\text{vac}} = 163.435$  nm are not included in Table 2 because the data quality was unsatisfactory. Energy levels in Table 2 are from Johansson (1978). The absorption  $f$ -values are accurate to typically 10%. This accuracy is limited in part by the uncertainty on the primary UV reference lines as discussed in the Introduction. The somewhat larger uncertainty on the  $f$ -value of the line at  $\lambda_{\text{vac}} = 163.633$  nm is due to larger photon statistical noise. This particular line is far from the blaze angle of the echelle grating. The  $f$ -values are compared to the theoretical results of Kurucz (1988), Fawcett (1988), and Nussbaumer et al. (1981) as well as to the observational results of Cardelli & Savage (1995) and Shull et al. (1983).

**Table 2.** Absolute VUV absorption oscillator strengths compared to values in the literature

$\lambda_{vac}(\text{nm})$	LOWER LEVEL		UPPER LEVEL		absorption $f$ -values	
	Level	$E_l(\text{cm}^{-1})$	Level	$E_u(\text{cm}^{-1})$	This work	Other values
160.845	$a^6D_{9/2}$	0.000	$y^6P^\circ_{7/2}$	62171.615	0.058(5)	0.0963 <sup>a</sup> , 0.062(18) <sup>b</sup> , 0.0716 <sup>c</sup> , 0.0431 <sup>d</sup> , 0.0619(62) <sup>e</sup> , 0.058(5) <sup>f</sup>
161.847	$a^6D_{7/2}$	384.790	$y^6P^\circ_{7/2}$	62171.615	0.022(2)	0.0349 <sup>a</sup> , 0.0256 <sup>c</sup> , 0.0154 <sup>d</sup>
162.169	$a^6D_{7/2}$	384.790	$y^6P^\circ_{5/2}$	62049.025	0.041(4)	0.0607 <sup>a</sup> , 0.0406 <sup>c</sup> , 0.0268 <sup>d</sup>
162.916	$a^6D_{5/2}$	667.683	$y^6P^\circ_{5/2}$	62049.025	0.028(3)	0.0583 <sup>a</sup> , 0.0384 <sup>c</sup> , 0.0253 <sup>d</sup>
163.113	$a^6D_{3/2}$	667.683	$y^6P^\circ_{3/2}$	61974.933	0.018(2)	0.0290 <sup>a</sup> , 0.0208 <sup>c</sup>
163.633	$a^6D_{3/2}$	862.613	$y^6P^\circ_{3/2}$	61974.933	0.032(5)	0.0659 <sup>a</sup> , 0.0469 <sup>c</sup> , 0.0278 <sup>d</sup>
163.940	$a^6D_{1/2}$	977.053	$y^6P^\circ_{3/2}$	61974.933	0.049(5)	0.0947 <sup>a</sup> , 0.0668 <sup>c</sup> , 0.0395 <sup>d</sup>

<sup>a</sup>Nussbaumer et al. 1981 <sup>b</sup>Shull et al. 1983 <sup>c</sup>Kurucz 1988 <sup>d</sup>Fawcett 1988 <sup>e</sup>Cardelli & Savage 1995  
<sup>f</sup>Bergeson et al. 1996b

#### 4. Summary

We present VUV oscillator strength measurements for the  $a^6D \rightarrow y^6P^\circ$  multiplet (#8) of Fe II from the high sensitivity absorption experiment at University of Wisconsin-Madison. The absorption  $f$ -values are accurate to  $\sim 10\%$ . While this work focuses on Fe II, the method is applicable to many elements in the periodic table, both neutral and singly ionized species, over a wide range of wavelength and line strength.

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