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BRANCHING FRACTIONS AND OSCILLATOR STRENGTHS FOR Fe II TRANSITIONS FROM THE $3d^6(^5D)4p$ SUBCONFIGURATION

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ABSTRACT

New experimental branching fractions and transition probabilities are reported for 56 transitions in Fe II. The branching fractions are measured with a Fourier transform spectrometer and also with a high-resolution grating spectrometer on an optically thin hollow cathode discharge. Highly accurate experimental radiative lifetimes from the recent literature provide the normalization required to convert our branching fractions into absolute transition probabilities. Results are compared with experimental and theoretical values in the literature. Our new transition probabilities will establish the absolute scale for relative absorption oscillator strengths of vacuum ultraviolet lines measured using a new high-sensitivity absorption experiment at the University of Wisconsin.

Subject headings: atomic data — ISM: abundances — ultraviolet: general

1. INTRODUCTION

The high abundance of iron and iron-group elements in astrophysical objects has motivated extensive studies of their spectra. Although sufficient transition probability (or *f*-value) data are available at wavelengths longer than 200 nm to let one determine abundances of the iron-group elements, the data are often inadequate to let one perform a reliable spectral synthesis for quantitative study of rarer elements. There is very little accurate transition probability data for Fe II lines at wavelengths shorter than 200 nm.

A new high-sensitivity absorption experiment has been developed at the University of Wisconsin–Madison. The high-sensitivity absorption experiment measures relative oscillator strengths for transitions originating from a common lower level. Currently, that experiment is used to measure the strengths of vacuum ultraviolet transitions in Fe II by comparing to transitions of known *f*-values above 200 nm. This provides further motivation for measuring the most accurate possible (better than $\pm 10\%$) transition probabilities in Fe II that will provide reliable reference lines above 200 nm. These measurements will determine an accurate absolute scale for relative *f*-value measurements below 200 nm.

The critical compilation of atomic transition probabilities by Fuhr, Martin, & Wiese (1988) reviewed experimental transition probability measurements in the iron group spectra before 1988. For Fe II the most accurate transition probability measurements were determined by combining branching fractions, measured on a Fourier transform spectrometer (Kroll & Kock 1987; unpublished work by Whaling reported in Fuhr et al. 1988) with the radiative lifetime measurements of Hannaford & Lowe (1983). A subset of Fe II transition probabilities in this compilation has an uncertainty of $\pm 10\%$. The goal of this study is to check, to expand, and to improve this subset for use as reference lines in the high-sensitivity absorption experiment.

The most widely applicable and reliable method for measuring extensive sets of transition probabilities of lines above 200 nm combines branching fractions, measured using Fourier transform spectroscopy, and radiative lifetimes, measured using laser-induced fluorescence. Studies of Y I and Y II (Hannaford et al. 1982), of Sc I and Sc II (Lawler & Dakin 1989), and of Fe I (O'Brian et al. 1991) in addition to the earlier work on Fe II demonstrate the power of this approach. In this paper we report new experimental branching fractions for most significant branches from the $z\,^6D^o$, $z\,^6F^o$, $z\,^6P^o$, $z\,^4D^o$, and $z\,^4F^o$ terms in Fe II. The energy levels range in energy from 38,000 cm^{-1} to 46,000 cm^{-1}. Highly accurate experimental lifetimes from the recent literature (Biemont et al. 1991; Guo et al. 1992; Hannaford et al. 1992; Schade, Mundt, & Helbig 1988) are used to normalize our branching fractions. Most of the lifetime measurements were performed using the fast beam-laser method and thus are accurate to better than $\pm 5\%$. The combination of these lifetimes and our branching fraction measurements provides new and reliable transition probability determinations for 56 transitions in Fe II.

2. BRANCHING FRACTIONS

In this study, we use two different spectrometers. One is a 0.2 m Fourier transform spectrometer (FTS). The other is a 3 m focal length echelle grating spectrometer. Argon branching ratios are often used to construct a relative radiometric calibration for a FTS in the visible and near-ultraviolet (Whaling, Carle, & Pitt 1993). In this study a limited set of Fe II branching ratios measured using the grating spectrometer is used to construct a relative radiometric calibration for the FTS in the deep UV. Two standard lamps are used for radiometrically calibrating the grating spectrometer.

The emission source is a water-cooled, open-ended hollow cathode discharge. The cathode is 1 cm inner diameter, 10 cm long. Discharge currents from 20 mA to 1.5 A are used in this experiment. The discharge is run with either neon, argon, or a mixture of these as a buffer gas. Emission from Fe II levels is optimized at 1.2 torr argon or 2.3 torr neon. The hollow-cathode discharge system uses essentially all metal seals, allowing stable operation with a static

gas fill.

The relative radiometric calibration of the FTS in the deep ultraviolet is based on a limited set of Fe II branching ratios for selected lines from the $z\,^6D^o_{7/2}$, $z\,^6P^o_{7/2}$, and $z\,^4F^o_{5/2}$ levels, and also of the recently published Fe II branching fractions for lines from the $z\,^4D^o_{7/2}$ and $z\,^4F^o_{9/2}$ levels (Bergeson, Mullman, & Lawler 1994). These measurements are made on the 3 m vacuum echelle grating spectrometer at the University of Wisconsin. The observed resolving power exceeds 600,000. Because the instrument is operated in high order, 22–26 for this experiment, a premonochromator is used as an order sorter. The spectrometer uses an uncoated, back-thinned, boron-doped, deep UV sensitive CCD detector array. The CCD chip is from SITe. The camera head, electronics, and software are all from Princeton Instruments.

The relative response of the grating spectrometer–CCD detection system is calibrated as a function of wavelength using a NIST traceable Optronics D_2 lamp and verified using a NIST calibrated argon mini-arc (Bridges & Ott 1977). The Optronics D_2 lamp is a secondary standard of spectral irradiance and should not be imaged onto the spectrometer entrance slit. This means that only parts of the spectrometer grating and mirrors are illuminated in a calibration run. We compensate for this by varying the position of the D_2 lamp in a plane perpendicular to the optical axis of the system and find no variations in the performance of the system. Statistical uncertainty from the apparent branching ratios before the radiometric calibration typically range from $\sim 1\%$ to 5%, indicating the reproducibility and high signal-to-noise ratios in the data. The calibrations of the standard lamps used to set the radiometric scale have uncertainties on the order of 5%. The statistical uncertainty in our calibration runs are typically 1%–3%. Therefore, the accuracy of the branching fractions ranges from 5% to 8%.

Scattered or stray light in the grating spectrometer presents a potential systematic error for the radiometric calibration. The stray light level is determined by measuring the photon flux between orders of the 3 m spectrometer. We checked the validity of this approach by measuring line absorption in Hg I at 254 nm. When the column density of Hg I becomes large, light passing through the Hg absorption cell at line center is completely absorbed. Measuring the light level at line center under conditions of complete absorption gives an independent measurement of stray light inside the spectrometer. The error in our radiometric calibration due to stray light inside the spectrometer is verified to be $\leq 1\%$.

The FTS used in this experiment is the Chelsea Instruments FT500 VUV FTS at the University of Lund. A resolution limit as small as 0.025 cm^{-1}, absolute wavenumber accuracy of 0.001 cm^{-1}, UV response to the quartz cutoff, and an extremely high data handling rate make this instrument ideally suited for measuring branching fractions in Fe II. We measure 27 different spectra under a variety of conditions in the emission source while this instrument is optimized for the UV with an assortment of photomultiplier tubes and filters. Although some of the spectra extend to wavelengths longer than 300 nm, only a few of the weak branches at longer UV and visible wavelengths from the levels of interest are observed in these spectra. This generally occurred for high lamp currents which result in radiation trapping of the dominant branches to the $a\,^6D$ and $a\,^4D$ terms. The weak branches omitted in this study are generally less than 3% of the decay from an upper level. The procedure we use to correct our branching fractions for these omitted branches is described in the following paragraphs. The Fourier transforms of the interferograms and phase corrections are made using the software package GREMLIN, written by J. W. Brault. The Fe II transitions are identified by comparing the emission from the hollow cathode discharge with both previously observed Fe I and Fe II lines (Dobbie 1938; Crosswhite 1975; Johansson 1978; Nave et al. 1994).

The statistical uncertainty in branching ratios from the integrated line intensities approaches 1% for strong lines on the FTS. However, statistical uncertainties for weaker lines are on the order of 5%–10%. In general, the uncertainties in the branching ratios used to set the relative response of the FTS are accurate to this same level.

The emission source is stable over time, but not perfectly. With the FTS, these small variations in intensity do not affect the measured relative intensities of emission lines, because an interferogram is a simultaneous measurement of all spectral elements. However, these intensity fluctuations can contribute to the overall noise level in the transformed spectrum. For measurements on the grating instrument, we alternately measure different lines from the same upper level and average the results. This ensures that any fluctuations or drifts in the emission from the hollow cathode discharge over time are averaged out.

Using the two spectrometers, the apparent branching ratios are measured with resolving powers ranging from 6×10^4 to 10^6, to check for blends with Fe I and Fe II lines or other line structure. Measurements are also made while varying the buffer gas to check for blends with neon or argon, and while varying the current by a factor of 75, to check for radiation trapping. For most of the transitions in this study, we find a low current region where the apparent branching fractions for strong lines are independent of current.

3. LIFETIMES

Recently, new experimental radiative lifetimes were published for the low odd parity levels in Fe II included in this study. The radiative lifetimes for most of the levels in the $z\,^6D^o$, $z\,^6F^o$, and $z\,^6P^o$ terms have been measured by Biemont et al. (1991). The lifetime for most of the levels in the $z\,^4D^o$ and $z\,^4F^o$ terms have been measured by Guo et al. (1992). Both of these studies used the fast beam-laser method, which is one of the more precise and accurate methods for measuring radiative lifetimes. These lifetimes have been confirmed by a number of other workers using the slightly less accurate (but very efficient) time-resolved laser-induced fluorescence method (Hannaford et al. 1992; Salih & Lawler 1983; Schade et al. 1988; Nitz, Bergeson, & Lawler 1995). For the few cases where the measurements of Biemont et al. (1991) and of Guo et al. (1992) are incomplete, we use lifetimes from Hannaford et al. (1992) or from Schade et al. (1988).

4. RESULTS

Branching fractions from this work are listed in Table 1. The number in parentheses after an entry is the uncertainty in the last digit(s). We have included for completeness our earlier results on lines from the $z\,^4D^o_{7/2}$ and $z\,^4F^o_{9/2}$ levels in Table 1 (Bergeson et al. 1994). We do not detect some of the

TABLE 1

BRANCHING FRACTIONS IN Fe II

UPPER LEVEL			LOWER LEVEL			λ_{air}	BRANCHING FRACTIONS				
Term	g_k	E_k (cm^{-1})	Term	g_i	E_i (cm^{-1})	(nm)	This Work	FMW[a]	N&NP[b]	Fawcett[c]	Kurucz[d]
$z\,^6D^o$	10	38458.981	$a\,^6D$	10	0.000	259.940	0.872(5)	0.86	0.818	0.867	0.878
			$a\,^6D$	8	384.790	262.567	0.126(5)	0.13	0.180	0.131	0.121
$z\,^6D^o$	8	38660.043	$a\,^6D$	10	0.000	258.588	0.317(10)	0.32	0.238	0.312	0.327
			$a\,^6D$	8	384.790	261.187	0.453(7)	0.44	0.447	0.451	0.451
			$a\,^6D$	6	667.683	263.132	0.229(8)	0.24	0.314	0.236	0.220
$z\,^6D^o$	6	38858.958	$a\,^6D$	8	384.790	259.837	0.516(9)	0.52	0.436	0.515	0.530
			$a\,^6D$	6	667.683	261.762	0.178(8)	0.18	0.171	0.172	0.173
			$a\,^6D$	4	862.613	263.105	0.305(11)	0.31	0.392	0.312	0.296
$z\,^6D^o$	4	39013.206	$a\,^6D$	6	667.683	260.709	0.665(11)	0.65	0.605	0.662	0.673
			$a\,^6D$	4	862.613	262.041	0.0146(20)	0.014	0.0109	0.0124	0.0132
			$a\,^6D$	2	977.053	262.829	0.319(11)	0.33	0.384	0.324	0.313
$z\,^6D^o$	2	39109.307	$a\,^6D$	4	862.613	261.382	0.793(8)	0.80	0.777	0.797	0.802
			$a\,^6D$	2	977.053	262.167	0.205(8)	0.20	0.220	0.200	0.197
$z\,^6F^o$	12	41968.046	$a\,^6D$	10	0.000	238.204	1.00	1.0	1.000	1.000	1.00
$z\,^6F^o$	10	42114.818	$a\,^6D$	10	0.000	237.374	0.120(5)	0.11	0.186	0.132	0.116
			$a\,^6D$	8	384.790	239.563	0.864(5)	0.87	0.798	0.860	0.869
$z\,^6F^o$	8	42237.033	$a\,^6D$	8	384.790	238.863	0.314(11)	0.36	0.337	0.319	0.315
			$a\,^6D$	6	667.683	240.489	0.668(11)	0.62	0.627	0.672	0.668
$z\,^6F^o$	6	42334.822	$a\,^6D$	6	667.683	239.924	0.458(11)	0.48	0.461	0.448	0.442
			$a\,^6D$	4	862.613	241.052	0.532(11)	0.51	0.471	0.513	0.519
$z\,^6F^o$	4	42401.302	$a\,^6D$	6	667.683	239.542	0.089(5)	0.11	0.121	0.0943	0.0869
			$a\,^6D$	4	862.613	240.666	0.568(10)	0.52	0.567	0.567	0.565
			$a\,^6D$	2	977.053	241.331	0.335(12)	0.36	0.306	0.332	0.337
$z\,^6F^o$	2	42439.822	$a\,^6D$	4	862.613	240.443	0.199(8)	0.23	0.221	...	0.196
			$a\,^6D$	2	977.053	241.107	0.794(8)	0.77	0.771	...	0.794
$z\,^6P^o$	8	42658.224	$a\,^6D$	10	0.000	234.350	0.644(9)	0.63	0.738	0.676	0.644
			$a\,^6D$	8	384.790	236.483	0.220(9)	0.23	0.206	0.224	0.221
			$a\,^6D$	6	667.683	238.076	0.111(7)	0.12	0.0336	0.0881	0.114
$z\,^6P^o$	4	43620.957	$a\,^6D$	6	667.683	232.740	0.236(6)	0.23	0.279	0.243	0.234
			$a\,^6D$	4	862.613	233.801	0.406(9)	0.43	0.412	0.412	0.409
			$a\,^6D$	2	977.053	234.428	0.344(5)	0.32	0.292	0.337	0.350
$z\,^4F^o$	10	44232.512	$a\,^6D$	10	0.000	226.008	0.0124(8)	0.020	...	0.00981	0.0122
			$a\,^6D$	8	384.790	227.992	0.0174(4)	0.016	...	0.0139	0.0184
			$a\,^4F$	10	1872.567	236.000	0.127(7)	0.098	0.159	0.130	0.172
			$a\,^4F$	8	2430.097	239.148	0.0142(9)	0.011	0.0138	0.0126	0.0157
			$a\,^4D$	8	7955.299	275.574	0.824(8)	0.85	0.790	0.832	0.780
$z\,^4D^o$	8	44446.878	$a\,^6D$	10	0.000	224.918	0.0091(6)	0.015	...	0.00651	0.0121
			$a\,^6D$	8	384.790	226.882	0.00120(12)	...	...	...	0.00209
			$a\,^4F$	10	1872.567	234.812	0.195(10)	0.19	0.317	0.232	0.291
			$a\,^4F$	8	2430.097	237.928	0.0733(15)	0.056	0.0347	0.0674	0.0734
			$a\,^4F$	6	2837.950	240.260	0.0065(6)	0.0071	0.00172	...	0.00583
			$a\,^4D$	8	7955.299	273.955	0.682(11)	0.71	0.522	0.658	0.577
$z\,^4F^o$	8	44753.799	$a\,^6D$	6	667.683	226.759	0.0128(12)	0.012	...	0.0103	0.0130
			$a\,^4F$	10	1872.567	233.131	0.115(6)	0.11	0.0183	0.101	0.102
			$a\,^4F$	8	2430.097	236.202	0.048(4)	0.049	0.130	0.0561	0.0875
			$a\,^4F$	6	2837.950	238.501	0.0121(12)	0.013	0.0221	0.0136	0.0186
			$a\,^4D$	6	8391.938	274.932	0.783(7)	0.79	0.673	0.800	0.748
$z\,^4D^o$	4	45044.168	$a\,^4F$	6	2837.950	236.860	0.181(8)	0.20	0.282	0.210	0.264
			$a\,^4F$	4	3117.461	238.439	0.097(5)	0.077	0.0688	0.0936	0.103
			$a\,^4D$	6	8391.938	272.754	0.284(8)	0.29	0.219	0.274	0.244
			$a\,^4D$	4	8680.454	274.918	0.364(6)	0.37	0.244	0.331	0.281
			$a\,^4D$	2	8846.768	276.181	0.0412(15)	0.037	0.151	0.0530	0.0672
$z\,^4F^o$	6	45079.879	$a\,^6D$	6	667.683	225.094	0.0109(11)	0.0092	...	...	0.0103
			$a\,^6D$	4	862.613	226.086	0.0074(8)	0.0062	...	...	0.00689
			$a\,^4F$	8	2430.097	234.396	0.117(6)	0.086	0.0316	...	0.110
			$a\,^4F$	6	2837.950	236.659	0.0376(22)	0.029	0.118	0.0460	0.0742
			$a\,^4F$	4	3117.461	238.236	0.0120(12)	0.012	0.0225	...	0.0182
			$a\,^4D$	8	7955.299	269.283	0.0061(8)	0.0035	0.0082	...	0.000288
			$a\,^4D$	6	8391.938	272.488	0.0361(22)	0.29	0.199	0.0560	0.0773
			$a\,^4D$	4	8680.454	274.648	0.767(6)	0.56	0.600	0.776	0.698
$z\,^4D^o$	2	45206.450	$a\,^4F$	4	3117.461	237.519	0.285(11)	...	0.351	...	0.370
			$a\,^4D$	4	8680.454	273.697	0.353(12)	...	0.313	...	0.307
			$a\,^4D$	2	8846.768	274.949	0.336(7)	...	0.309	...	0.280
$z\,^4F^o$	4	45289.801	$a\,^4F$	6	2837.950	235.489	0.099(5)	0.098	0.0354	0.0859	0.0894
			$a\,^4F$	4	3117.461	237.050	0.058(4)	0.057	0.139	0.0664	0.104
			$a\,^4D$	4	8680.454	273.073	0.103(5)	0.10	0.231	0.123	0.143
			$a\,^4D$	2	8846.768	274.320	0.728(6)	0.73	0.568	0.713	0.651

[a] Fuhr, Martin, & Wiese 1988. [b] Nahar 1995, also Nahar & Pradhan 1994. [c] Fawcett 1988. [d] Kurucz 1988.

TABLE 2

gf-VALUES IN Fe II

λ_{air} (nm)	LEVEL Upper	LEVEL Lower	Multiplet	λ_{vac} (nm)	*gf*-VALUES This Work	FMW[a]	Unc.[b]	N&NP[c]	Fawcett[d]	Kurucz[e]
224.918.....	$z\,^4D^o_{7/2}$	$a\,^6D_{9/2}$	uv 5	224.988	0.0182(14)	0.025	C	...	0.017	0.0303
225.094.....	$z\,^4F^o_{5/2}$	$a\,^6D_{5/2}$	uv 4	225.163	0.0132(15)	0.014	C	...	...	0.0145
226.008.....	$z\,^4F^o_{9/2}$	$a\,^6D_{9/2}$	uv 4	226.078	0.0244(19)	0.037	D	...	0.025	0.0279
226.086.....	$z\,^4F^o_{5/2}$	$a\,^6D_{3/2}$	uv 4	226.156	0.009(1)	0.0096	C	...	...	0.00973
226.759.....	$z\,^4F^o_{7/2}$	$a\,^6D_{5/2}$	uv 4	226.829	0.0217(21)	0.019	D	...	0.022	0.0249
226.882.....	$z\,^4D^o_{7/2}$	$a\,^6D_{7/2}$	uv 5	226.952	0.00245(25)	...	...	...	...	0.000532
227.992.....	$z\,^4F^o_{9/2}$	$a\,^6D_{7/2}$	uv 4	228.062	0.0350(18)	0.030	C	...	0.036	0.0429
232.740.....	$z\,^6P^o_{3/2}$	$a\,^6D_{5/2}$	uv 3	232.811	0.213(13)	0.19	B	0.237	0.299	0.234
233.131.....	$z\,^4F^o_{7/2}$	$a\,^4F_{9/2}$	uv 35	233.202	0.207(12)	0.19	C	0.0362	0.227	0.207
233.801.....	$z\,^6F^o_{3/2}$	$a\,^6D_{3/2}$	uv 3	233.872	0.370(22)	0.35	B	0.355	0.511	0.412
234.350.....	$z\,^6P^o_{7/2}$	$a\,^6D_{9/2}$	uv 3	234.421	1.14(2)	1.1	C+	1.26	1.662	1.29
234.396.....	$z\,^4F^o_{5/2}$	$a\,^4F_{7/2}$	uv 35	234.468	0.155(10)	0.14	B	0.0466	...	0.166
234.428.....	$z\,^6P^o_{3/2}$	$a\,^6D_{1/2}$	uv 3	234.500	0.315(18)	0.26	B	0.253	0.421	0.355
234.812.....	$z\,^4D^o_{7/2}$	$a\,^4F_{9/2}$	uv 36	234.883	0.43(3)	0.34	C+	0.860	0.661	0.794
235.489.....	$z\,^4F^o_{3/2}$	$a\,^4F_{5/2}$	uv 35	235.561	0.089(7)	0.078	B	0.0346	0.097	0.0902
236.000.....	$z\,^4F^o_{9/2}$	$a\,^4F_{9/2}$	uv 35	236.072	0.275(20)	0.20	C	0.396	0.362	0.430
236.202.....	$z\,^4F^o_{7/2}$	$a\,^4F_{7/2}$	uv 35	236.274	0.088(8)	0.088	C	0.263	0.130	0.182
236.483.....	$z\,^6P^o_{7/2}$	$a\,^6D_{7/2}$	uv 3	236.555	0.396(17)	0.41	C+	0.359	0.562	0.453
236.659.....	$z\,^4F^o_{5/2}$	$a\,^4F_{5/2}$	uv 35	236.732	0.051(4)	0.050	B	0.178	0.078	0.115
236.860.....	$z\,^4D^o_{3/2}$	$a\,^4F_{5/2}$	uv 36	236.932	0.204(16)	0.20	B	0.383	0.306	0.366
237.050.....	$z\,^4F^o_{3/2}$	$a\,^4F_{3/2}$	uv 35	237.122	0.053(5)	0.048	C+	0.138	0.076	0.106
237.374.....	$z\,^6F^o_{9/2}$	$a\,^6D_{9/2}$	uv 2	237.446	0.313(14)	0.28	B	0.527	0.466	0.340
237.519.....	$z\,^4D^o_{1/2}$	$a\,^4F_{3/2}$	uv 36	237.592	0.166(13)	0.16	D	0.238	0.230	0.259
237.928.....	$z\,^4D^o_{7/2}$	$a\,^4F_{7/2}$	uv 36	238.000	0.165(8)	0.10	C+	0.0967	0.197	0.206
238.076.....	$z\,^6P^o_{7/2}$	$a\,^6D_{5/2}$	uv 3	238.149	0.203(13)	0.22	C	0.0593	0.224	0.236
238.204.....	$z\,^6F^o_{11/2}$	$a\,^6D_{9/2}$	uv 2	238.277	3.20(4)	3.9	D	3.43	4.344	3.61
238.236.....	$z\,^4F^o_{5/2}$	$a\,^4F_{3/2}$	uv 35	238.308	0.0163(17)	0.020	C+	0.0342	...	0.0286
238.439.....	$z\,^4D^o_{3/2}$	$a\,^4F_{3/2}$	uv 36	238.511	0.110(9)	0.080	C+	0.0948	0.138	0.145
238.501.....	$z\,^4F^o_{7/2}$	$a\,^4F_{5/2}$	uv 35	238.573	0.0227(24)	0.023	D	0.0458	0.032	0.0394
238.863.....	$z\,^6F^o_{7/2}$	$a\,^6D_{7/2}$	uv 2	238.936	0.66(3)	0.71	C+	0.774	0.904	0.740
239.148.....	$z\,^4F^o_{9/2}$	$a\,^4F_{7/2}$	uv 35	239.221	0.0314(26)	0.023	D	0.0353	0.036	0.0404
239.542.....	$z\,^6F^o_{3/2}$	$a\,^6D_{5/2}$	uv 2	239.615	0.092(6)	0.11	C	0.136	0.134	0.102
239.563.....	$z\,^6F^o_{9/2}$	$a\,^6D_{7/2}$	uv 2	239.636	2.30(4)	2.2	B	2.31	3.091	2.59
239.924.....	$z\,^6F^o_{5/2}$	$a\,^6D_{5/2}$	uv 2	239.997	0.712(26)	0.72	C+	0.788	0.957	0.782
240.260.....	$z\,^4D^o_{7/2}$	$a\,^4F_{5/2}$	uv 36	240.333	0.0150(15)	0.013	D	0.00487	...	0.0166
240.443.....	$z\,^6F^o_{1/2}$	$a\,^6D_{3/2}$	uv 2	240.516	0.104(10)	0.12	C	0.126	...	0.116
240.489.....	$z\,^6F^o_{7/2}$	$a\,^6D_{5/2}$	uv 2	240.562	1.42(5)	1.2	C+	1.46	1.929	1.59
240.666.....	$z\,^6F^o_{3/2}$	$a\,^6D_{3/2}$	uv 2	240.739	0.591(21)	0.56	C+	0.644	0.812	0.668
241.052.....	$z\,^6F^o_{5/2}$	$a\,^6D_{3/2}$	uv 2	241.125	0.84(3)	0.76	C+	0.812	1.107	0.927
241.107.....	$z\,^6F^o_{1/2}$	$a\,^6D_{1/2}$	uv 2	241.180	0.420(4)	0.42	C+	0.440	0.568	0.471
241.331.....	$z\,^6F^o_{3/2}$	$a\,^6D_{1/2}$	uv 2	241.405	0.351(16)	0.38	C+	0.349	0.478	0.401
258.588.....	$z\,^6D^o_{7/2}$	$a\,^6D_{9/2}$	uv 1	258.665	0.691(25)	0.65	B	0.548	0.841	0.766
259.837.....	$z\,^6D^o_{5/2}$	$a\,^6D_{7/2}$	uv 1	259.915	0.864(24)	0.79	B	0.758	1.047	0.935
259.940.....	$z\,^6D^o_{9/2}$	$a\,^6D_{9/2}$	uv 1	260.017	2.39(4)	2.2	B	2.40	2.969	2.61
260.709.....	$z\,^6D^o_{3/2}$	$a\,^6D_{5/2}$	uv 1	260.787	0.708(22)	0.66	B	0.706	0.902	0.796
261.187.....	$z\,^6D^o_{7/2}$	$a\,^6D_{7/2}$	uv 1	261.265	1.01(2)	0.88	B	1.05	1.238	1.08
261.382.....	$z\,^6D^o_{1/2}$	$a\,^6D_{3/2}$	uv 1	261.461	0.432(12)	0.40	B	0.458	0.546	0.476
261.762.....	$z\,^6D^o_{5/2}$	$a\,^6D_{5/2}$	uv 1	261.840	0.303(15)	0.27	B	0.301	0.355	0.310
262.041.....	$z\,^6D^o_{3/2}$	$a\,^6D_{3/2}$	uv 1	262.119	0.0157(22)	0.015	B	0.0129	0.017	0.0158
262.167.....	$z\,^6D^o_{1/2}$	$a\,^6D_{1/2}$	uv 1	262.245	0.112(5)	0.10	B	0.130	0.138	0.117
262.567.....	$z\,^6D^o_{9/2}$	$a\,^6D_{7/2}$	uv 1	262.645	0.353(15)	0.34	B	0.540	0.459	0.367
262.829.....	$z\,^6D^o_{3/2}$	$a\,^6D_{1/2}$	uv 1	262.908	0.346(15)	0.36	B	0.455	0.449	0.376
263.105.....	$z\,^6D^o_{5/2}$	$a\,^6D_{3/2}$	uv 1	263.183	0.523(22)	0.48	B	0.699	0.650	0.536
263.132.....	$z\,^6D^o_{7/2}$	$a\,^6D_{5/2}$	uv 1	263.211	0.516(21)	0.50	B	0.749	0.658	0.532
269.283.....	$z\,^4F^o_{5/2}$	$a\,^4D_{7/2}$	uv 62	269.363	0.0107(15)	0.0080	D	0.0159	...	0.000577
272.488.....	$z\,^4F^o_{5/2}$	$a\,^4D_{5/2}$	uv 62	272.569	0.064(5)	0.066	B	0.397	0.126	0.158
272.754.....	$z\,^4D^o_{3/2}$	$a\,^4D_{5/2}$	uv 63	272.835	0.42(3)	0.38	B	0.395	0.528	0.448
273.073.....	$z\,^4F^o_{3/2}$	$a\,^4D_{3/2}$	uv 62	273.154	0.125(9)	0.11	B	0.304	0.187	0.194
273.697.....	$z\,^4D^o_{1/2}$	$a\,^4D_{3/2}$	uv 63	273.778	0.274(21)	...	...	0.281	0.334	0.285
273.955.....	$z\,^4D^o_{7/2}$	$a\,^4D_{7/2}$	uv 63	274.036	2.04(10)	1.8	B	1.93	2.548	2.14
274.320.....	$z\,^4F^o_{3/2}$	$a\,^4D_{1/2}$	uv 62	274.401	0.89(5)	0.82	B	0.756	1.091	0.891
274.648.....	$z\,^4F^o_{5/2}$	$a\,^4D_{3/2}$	uv 62	274.730	1.39(5)	1.3	B	1.21	1.772	1.46
274.918.....	$z\,^4D^o_{3/2}$	$a\,^4D_{3/2}$	uv 63	274.999	0.55(4)	0.48	B	0.448	0.650	0.524
274.932.....	$z\,^4F^o_{7/2}$	$a\,^4D_{5/2}$	uv 62	275.013	1.96(6)	1.9	B	1.85	2.512	2.10
274.949.....	$z\,^4D^o_{1/2}$	$a\,^4D_{1/2}$	uv 63	275.030	0.263(19)	0.24	D	0.280	...	0.262
275.574.....	$z\,^4F^o_{9/2}$	$a\,^4D_{7/2}$	uv 62	275.655	2.43(11)	2.4	B	2.69	3.151	2.66
276.181.....	$z\,^4D^o_{3/2}$	$a\,^4D_{1/2}$	uv 63	276.263	0.063(5)	0.052	B	0.278	0.105	0.126

[a] Fuhr, Martin, & Wiese 1988.

[b] The letters in the column "Unc." represent the uncertainty in the FMW compilation: A ≤ 5%; B ≤ 10%; C ≤ 25%; D ≤ 50%.

[c] Nahar 1995, also Nahar & Pradhan 1994.

[d] Fawcett 1988.

[e] Kurucz 1988.

TABLE 3

DISCUSSION OF POSSIBLE BLENDS

UPPER LEVEL	λ IN AIR (nm)	POSSIBLE BLEND		COMMENT
		Lower Level	Upper Level	
$z\,^6F^o_{7/2}$	238.863	Fe II $(a\,^3F)4p\,x\,^4D^o_{3/2}$	$(^3P)4d\,^2P_{3/2}$	a
$z\,^6D^o_{5/2}$	261.762	Fe II $(a\,^3G)4p\,x\,^4G^o_{11/2}$	$(^3H)4d\,^4G_{9/2}$	a
$z\,^6P^o_{3/2}$	233.801	Fe II $(a\,^3F)4p\,y\,^4F^o_{9/2}$	$(^3H)4d\,^4F_{9/2}$	a
$z\,^6P^o_{5/2}$	235.911	?	?	b
$z\,^4D^o_{1/2}$	273.697	Fe I $(^4F)4s\,a\,^5F_2$	$(^4P)4p\,y\,^5S^o_2$	c
$z\,^4D^o_{5/2}$	274.698	Fe I $(^4F)4s\,a\,^5F_5$	$(^3H)sp^3\,z\,^5H^o_6$	d

[a] The upper levels of the possible blending transitions are not efficiently populated in a low current discharge with Ar buffer gas. The upper levels can be efficiently populated in a discharge with Ne buffer gas by charge exchange in the discharge. We observe only a real effect from blending for the transition at 233.801 nm. We measure the branching ratios for all three of these transitions in a low-current discharge with Ar as the buffer gas.

[b] In our data we saw an unexplainable trend in current. We have searched wavelength tables trying to find a candidate for a blend, but have found nothing in Ar I, Ar II, Ne I, Ne II, Fe I, Fe II, or any of the possible contaminants in either the cathode material or the buffer gas. We have omitted this line from the table. Since this line is apparently a significant branch, we are unable to publish any transition probability data for any transition out of this upper level. Table 4 lists only the branching ratios for the other observed transitions.

[c] The Fe I blend here is real. We measured the intensity of the Fe I transition at 226.72 nm from the $y^5S^o_2$ upper level, the blended feature at 273.70 nm and the Fe II transition at 274.95 nm from the $z\,^4D^o_{1/2}$ upper level on several different spectra. A linear least-square analysis is used to determine the contribution of the Fe I and Fe II lines to the feature at 273.70 nm. For the particular excitation conditions in our hollow cathode discharge for the spectra studied, the Fe II contribution to the feature at 273.70 nm is more than 90%.

[d] The level $z\,^5H^o_6$ has only one branch. It is at 274.698 nm, coincident with this line from the $z\,^4D^o_{5/2}$ level. Radiative lifetime measurements (O'Brian et al.1991) and intensity measurements on other levels in the $z\,^5H^o$ indicate that this blend is a major component to the apparent strength of the line. We publish only branching ratio information for the other lines out of this upper level in Table 4.

weaker Fe II transitions, but these unobserved branches contribute typically 3% or less of the total decay from the upper level. Using the data from the critical compilation (Fuhr et al. 1988), we correct our branching fractions for these unmeasured branches. For example, in level $z\,^6D^o_{9/2}$, we do not observe the branches at 273.245 nm and 327.735 nm. The critical compilation indicates that these transitions comprise 0.12% of the total decay from the upper level. Accordingly, instead of normalizing our branching fractions to 1.0, we correct for the unmeasured branches by normalizing to 0.9988. For this reason, the branching fractions for most levels in Table 1 sum to a few percent less that 1.0. These corrections are generally within the uncertainty in the branching fractions and reflect a small adjustment to our values.

Our data are compared to the previously published experimental values from the critical compilation (Fuhr et al. 1988), and also the theoretical values of Fawcett (1988), of Nahar (1995) and Nahar & Pradhan (1994), and of Kurucz (1988). In Table 1, we correct the branching fractions of Nahar (1995) and Nahar & Pradhan (1994), and of Fawcett (1988) for the uncalculated branches as described in the previous paragraph. The agreement between the branching fractions from the critical compilation and our results is very good. Omitting the $z\,^4F^o_{5/2}$ and the $z\,^4D^o_{1/2}$ level from the comparison, the average and rms difference between our work and the critical compilation is −1.6% and 14.8%, respectively. Further limiting the comparison to branching fractions stronger than 0.2, the average and rms difference between our work and the critical compilation is −0.6% and 4.7%, respectively. The agreement between the branching fractions of Fawcett (1988) and the current work is also good. For the entire data set, the average and rms difference between Fawcett's branching fractions and our results is −0.8% and 13.2%, respectively. For the limited subset of levels in the $z\,^6D^o$ and $z\,^6F^o$ terms, the agreement is even better. The average and rms agreement is 0.07% and 4.4%, respectively. Our new branching fraction measurements are also in rather good agreement with work by Kurucz (1988).

Table 2 presents *gf*-values from this work along with results from the literature. This table includes both vacuum and air wavelengths and is organized by wavelength for the reader's convenience. It was not practical to include in Table 2 all of the experimental work on Fe II *gf*-values. Some very recent work on lines connected to the ground fine structure level is based on observations of the interstellar medium using the Goddard High Resolution Spectrograph aboard the *Hubble Space Telescope* (Cardelli & Savage 1995). In particular a *gf*-value of 0.326(23) for the resonance line at 237.374 nm was determined by Cardelli & Savage. The good agreement with our new value of 0.313(14) is indicative of the much improved internal consistency and absolute accuracy of these Fe II *gf*-values.

Even with resolving powers of 10^6, there are several blends in Fe II that we cannot resolve. Some of these blends are with Fe II transitions originating in very high lying levels, which are inefficiently populated in a low current

TABLE 4

BRANCHING RATIOS FOR TRANSITIONS OUT OF THE $z\,^6P^o_{5/2}$ AND $z\,^4D^o_{5/2}$ LEVELS[a]

UPPER LEVEL			LOWER LEVEL			λ_{air} (nm)	BRANCHING RATIOS				
Term	g_k	E_k (cm^{-1})	Term	g_i	E_i (cm^{-1})		This Work	FMW[b]	NP[c]	Fawcett[d]	Kurucz[e]
$z\,^6P^o$	6	43238.586	$a\,^6D$	8	384.790	233.280	1.00	1.00	1.000	...	1.000
			$a\,^6D$	6	667.683	234.830	0.86(3)	0.80	0.700	...	0.865
$z\,^4D^o$	6	44784.761	$a\,^4F$	8	2430.097	236.029	1.00	1.00	1.000	1.000	1.000
			$a\,^4F$	6	2837.950	238.324	0.538(15)	0.58	0.207	...	0.389
			$a\,^4D$	8	7955.299	271.441	0.98(5)	0.93	0.417	0.810	0.571

[a] Significant branches out of these upper levels have intractible blends, which prevent a complete branching fraction measurement for the upper levels.

[b] Fuhr, Martin, & Wiese 1988.

[c] Nahar 1995, also Nahar & Pradhan 1994.

[d] Fawcett 1988.

[e] Kurucz 1988.

discharge with argon buffer gas. Others are blends with Fe I or possibly another element in our discharge. Table 3 lists the potentially blended lines, the possible blending candidates, and states briefly how we treated the problem. For levels where the dominant branches are blended, and where we cannot determine transition probabilities, we list branching ratios for other transitions out of the upper level in Table 4.

5. CONCLUSION

We report new experimental branching ratios and absolute transition probabilities for 56 transitions in Fe II. The transitions are from the lowest 25 odd parity energy levels in Fe II, which range in energy from 38,000 cm^{-1} to 46,000 cm^{-1}. Our results are compared to previously published results in the literature. In the future, these lines with accurately known oscillator strengths will be used as reference lines in a high sensitivity absorption experiment on Fe II, to determine oscillator strengths of vacuum ultraviolet lines.

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