Mon. Not. R. Astron. Soc. **321**, 481–486 (2001)

Radiative lifetime measurements and transition probabilities of astrophysical interest in Er III

E. Biémont,[1,2] H. P. Garnir,[1] T. Bastin,[1] P. Palmeri,[2] P. Quinet,[2★] Z. S. Li,[3] Z. G. Zhang,[3] V. Lokhnygin[3] and S. Svanberg[3]

[1]*Institut de Physique Nucléaire Expérimentale (Bât. B15), Sart Tilman, Université de Liège, B-4000 Liège, Belgium*
[2]*Astrophysique et Spectroscopie, Université de Mons-Hainaut, B-7000 Mons, Belgium*
[3]*Department of Physics, Lund Institute of Technology PO Box 118, S-22100 Lund, Sweden*

Accepted 2000 September 15. Received 2000 August 9; in original form 2000 July 3

ABSTRACT

Radiative lifetimes of seven excited states of Er III have been measured using time-resolved laser-induced fluorescence following two-photon excitation. Relativistic Hartree–Fock calculations taking core-polarization effects into account are found to be in excellent agreement with the experimental results. A large set of new calculated transition probabilities is presented for many transitions of astrophysical interest. These results will be useful for investigating the composition of chemically peculiar stars.

Key words: astrochemistry – atomic data – atomic processes – methods: analytical – techniques: spectroscopic – stars: chemically peculiar.

1 INTRODUCTION

Erbium is a rare-earth element ($Z = 68$) which has six stable isotopes ($A = 162$, 164, 166, 167, 168 and 170). In astrophysics, the erbium ions have been observed in many different types of stars. Erbium isotopes are generated by different processes. ^{162}Er is produced by the p process, ^{167}Er and ^{170}Er by the r process, ^{164}Er by the p or the s process and ^{166}Er and ^{168}Er by the r or the s process (Jaschek & Jaschek 1995).

Er II has been observed in the solar photospheric spectrum but only one resonance line, identified at λ3896.24, has been used for deriving the solar content of this element (Grevesse & Blanquet 1969; Biémont & Youssef 1984; Gorshkov & Komarovskii 1987; Anders & Grevesse 1989). Besides the Sun, Er II has been observed in normal F type stars (Reynolds, Hearnshaw & Cottrell 1988). It is also currently identified in chemically peculiar (CP) stars, i.e. Ap stars (Cowley 1976; Aikman, Cowley & Crosswhite 1979; Cowley & Greenberg 1987), in Bp stars (Cowley & Crosswhite 1978), in Am stars (van t'Veer-Menneret et al. 1988), in Ba stars (Lambert 1985) and in S-type stars (Bidelman 1953).

Doubly ionized erbium has been identified in the spectra of CP stars of the upper main sequence (Adelman 1974; Cowley & Crosswhite 1978; Aikman et al. 1979; Cowley & Greenberg 1987). Er III, and particularly the λ6393.69 line, is suggested by Cowley & Mathys (1998) as possibly present in the spectrum of the extreme peculiar star HD 101065 (Przybylski's star). It should also be emphasized that erbium (Er II and Er III) contributes to more than 300 lines in the spectrum of the CP star HR465 (Bidelman, Cowley & Iler 1995; Wyart et al. 1997).

In most CP stars, large overabundance of lanthanide elements are found when compared with the solar standards. Accurate *f*-values are needed to verify that the very large abundance excesses are not spurious, i.e. caused by departures from local thermodynamic equilibrium or by use of inadequate atmospheric models. In this context, the third spectra of lanthanides are particularly crucial for a better understanding of CP stars because these spectra arise from the dominant, doubly ionized species.

The ground-state configuration of Er III is $4f^{12}\ {}^3H_6$ and the first excited configurations are $4f^{11}6p$, $4f^{11}6s$ and $4f^{11}5d$. The critical compilation of the energy levels of this ion, from Martin, Zalubas & Hagan (1978), is based on a previous analysis by Spector (1973) (137 classified lines involving 45 levels) and on corrections and additions resulting from parametric studies of $4f^{11}(5d + 6s)$ and of $4f^{11}6p$ (Wyart, Blaise & Camus 1974a; Wyart, Koot & Van Kleef 1974b). Later on, a global interpretation of the $4f^n(5d + 6s)$ configurations was undertaken by Wyart & Bauche-Arnoult (1981). More recently, the analysis of the spectrum of Er III was revised by Wyart et al. (1997) on the basis of an unpublished dissertation by Becher (1966): the number of energy levels was increased from 45 to 115, including some levels of the $4f^{11}7s$ configuration.

The lanthanides are characterized by the progressive filling of the 4f subshell. The neutral lanthanides possess a xenon structure of their electronic shell with two or three outer electrons. It is well known that the energy and spatial extension of the 4f eigenfunction drop suddenly at the commencement of the lanthanides (Wybourne 1965) giving rise to the so-called lanthanide contraction. In lanthanum, the 4f eigenfunction is located outside the xenon structure while, in neodymium, the 4f eigenfunction has contracted in such a way that its maximum is located within the $5s^25p^6$ closed shells making accurate calculations of

★ E-mail: quinet@umh.ac.be

wavefunctions and transition probabilities extremely difficult for the first rare-earth ions. In Er III, a somewhat different situation occurs owing to the fact that, apart from the xenon structure, a bigger core containing the $4f^n$ configuration arises with $n = 12$ (ground configuration) or $n = 11$ (excited configurations). Core-polarization effects are consequently expected to play a considerable role but the validity of their inclusion in the semi-empirical or theoretical models needs to be carefully checked. Such a test can be provided by a comparison of the calculated radiative lifetime values obtained with a realistic potential model with laser-induced-fluorescence lifetime measurements independent of cascading problems.

An additional purpose of the present paper is to provide a detailed set of theoretical transition probabilities of astrophysical interest for transitions for which they are missing. Although a limited number of experimental transition probabilities or lifetimes have been published for Er II (Engman, Stoner & Martinson 1976; Bentzen, Nielsen & Poulsen 1982), no experimental data exist so far for Er III. The only theoretical data available have been reported by Wyart et al. (1997) for about 470 transitions. These last results were obtained with the relativistic Hartree–Fock (HFR) method of Cowan (1981) but without inclusion of core-polarization effects and with the consideration of only a limited amount of configuration interaction effects in the separate studies of the arrays $4f^{11}6p$–$4f^{11}7s$, $4f^{12}$–$4f^{11}(5d + 6s)$, $4f^{11}6p$–$4f^{11}(5d + 6s)$. These calculations clearly need further tests in order to assess their reliability.

2 LIFETIME MEASUREMENTS

The ground electronic configuration of the Er III is $4f^{12}$. Through a two-photon excitation from the ground state, radiative lifetimes of seven excited states of the $4f^{11}6p$ configuration have been measured using time-resolved laser-induced fluorescence. The experiment was carried out at the Lund Laser Center (Svanberg et al. 1994) in Sweden.

A pico-second laser system was employed for producing the excitation laser pulses. A Q-switched and mode-locked pico-second Nd:YAG laser provides two frequency doubled 532-nm beams. One green beam was used to pump a distributed feedback dye laser (DFDL), which was continuously tunable in the 720–790 nm region by using different dyes (LDS751, 768). The other green beam, passing through a variable optical delay line, can be used to perform frequency mixing with the tunable laser to produce the required UV radiation. The output pulses from the DFDL were subsequently amplified in linear dye stages by a Ti:Sapphire crystal butterfly amplifier, which was pumped by a second nanosecond Nd:YAG laser. To obtain the required ultraviolet (UV) wavelength in the 240–360 nm region, different non-linear processes were adopted. Frequency doubling of the amplified DFDL output was performed in a KDP crystal, frequency tripling was performed by further mixing with the fundamental frequency in a BBO crystal and frequency mixing of the 532-nm green beam with the DFDL output was also utilized. Information on the wavelength conversion processes and excitation schemes for different levels is provided in Table 1. The resulting UV laser beam, which has a pulse duration of about 60 ps and a pulse energy of a few mJ, was focused on the plume of erbium ions generated by focusing 5 mJ green pulses from a third Nd:YAG laser on a rotating metallic erbium target placed at the centre of a vacuum chamber. The investigated states were selectively populated through different excitation schemes. The decay photons were observed through a monochromator acting as a wavelength selector and detected by a fast MCP photomultiplier. The signal was recorded by a Tektronix TDS684A 5GS/s oscilloscope and analyzed online by a PC. The temporal shapes of the excitation laser pulse were also recorded by the fluorescence detection system. The recorded laser pulse, which is about 1 ns, reflects mainly the time resolution of the detection system, as the real laser pulse is much shorter. The lifetimes were evaluated by fitting the fluorescence signals with a convolution between the detected laser pulse with an exponential decay. The detailed experimental consideration and setup can be found elsewhere (Li et al. 2000).

Table 1. Levels measured and excitation schemes.

Excited level[a] (cm^{-1})	Excitation wavelength $(nm)_{vac}$	Exc. Laser wavelength Conversion scheme	Decay to lower level[a] (cm^{-1})	Observed fluorescence (nm)
55547.30	360.05 × 2	$2\omega_{dye}$	19315.96	276
62598.14	319.50 × 2	532 nm + ω_{dye}	26102.79	274
62607.86	319.45 × 2	532 nm + ω_{dye}	26411.84	276
75221.11	265.88 × 2	$3\omega_{dye}$	38853.02	275
76751.75	260.58 × 2	$3\omega_{dye}$	35294.14	241
80712.97	247.79 × 2	$3\omega_{dye}$	38853.02	239
81837.54	244.39 × 2	$3\omega_{dye}$	40166.45	240

Table 2. Experimental and calculated lifetimes for the $4f^{11}6p$ levels.

E_{exp} (cm^{-1})[a]	J	τ_{exp} (ns)	τ_{calc} (ns)
55547.30	7	2.19 ± 0.15	2.13
56025.40	8		2.14
61032.44	9		1.49
61493.77	6		1.65
61539.18	8		1.49
61699.28	7		1.58
62598.14	6	1.94 ± 0.15	2.02
62607.86	7	1.94 ± 0.15	2.06
65934.64	5		2.11
66077.65	6		2.10
67699.20	8		1.50
67986.38	5		1.59
68084.68	7		1.49
68186.11	6		1.53
68234.37	4		2.14
68332.21	5		2.10
71050.12	5		2.00
71055.16	4		1.92
71459.21	4		1.67
71531.27	7		1.51
71779.39	5		1.57
71785.72	6		1.51
73395.34	3		1.51
73919.99	6		1.51
73920.66	5		1.60
74129.19	4		1.50
74944.47	5		1.99
75221.11	6	2.00 ± 0.15	2.11
76174.34	3		2.01
76480.35	4		2.04
76724.94	6		1.49
76751.75	5	1.46 ± 0.15	1.57
76978.95	4		1.56
77318.02	3		1.64
80712.97	6	1.48 ± 0.15	1.50
81837.54	4	1.46 ± 0.15	1.61

About 20 fluorescence curves were recorded for each level, and the mean values were taken as the final results. The quoted error bars include the random scattering and a conservative estimate of the possible residual systematic errors (see Li et al. 2000). The experimental measurements are reported in Table 2, where they are compared with the theoretical data obtained using the procedure described in Section 3.

3 THEORETICAL CALCULATIONS

The theoretical approach considered in the present paper is the HFR method of Cowan (1981) in which we have incorporated the core-polarization effects. The technique has appeared adequate for accurately predicting radiative lifetimes for complex configurations observed in lanthanide spectra (Biémont et al. 1999; Quinet, Palmeri & Biémont 1999a; Quinet et al 1999b).

The estimate of the core-polarization contributions requires the knowledge of the dipole polarizability of the ionic core, α_d, and of the cut-off radius, r_c. For the first parameter, we have used the value of the static dipole polarizability computed by Fraga, Karwowski & Saxena (1976) for Er IV, i.e. $\alpha_d = 5.80a_0^3$. The cut-off radius, r_c, has been chosen equal to $1.45a_0$, which corrersponds to the HFR average value $\langle r \rangle$ of the outermost core orbitals $5p^6$. Polarization effects were not considered in the atomic orbital calculation of the ground configuration $4f^{12}$. The 4f electrons being inside the Xe-like core, analytical polarization corrections to the dipole operator as introduced in our model (Biémont et al. 1999; Quinet et al 1999a,b) are no longer valid for transitions involving these electrons. In Fig. 1, we have reported the ratio between corrected (d_{pol}) and uncorrected transition matrix elements (d_{nopol}) for transitions not involving a 4f electron as a function of the uncorrected matrix element. A smooth curve was obtained by plotting $|d_{nopol} - \Delta|/|d_{nopol}|$ where Δ is the mean value of $|d_{nopol} - d_{pol}|$ for the transitions not involving a 4f electron. In order to take the polarization effects into account, we have applied scaling factors deduced from this smooth curve to the matrix elements of transitions involving a 4f electron. In fact, this type of curve has appeared very general (see the discussion for Yb IV, Tm III and Ho III in the recent papers by Wyart et al. 2000, Li et al. 2000 and Paquin et al., in preparation). In the present case of Er III, the uncorrected $\langle 4f|r|5d \rangle$ radial matrix element is equal to $1.105a_0$ and the corresponding scaling factor for this matrix element has been chosen to be equal to 0.81 for the $4f^{12}$–$4f^{11}5d$ transitions. This technique was found to give a good agreement between theoretical and experimental lifetimes of $4f^{12}5d$ levels in Tm III (Li et al. 2000) which can only decay to the $4f^{13}$ ground configuration by 4f–5d transitions.

The configuration sets retained for the calculations were $4f^{12}$, $4f^{11}np$ $(n = 6, 7)$ and $4f^{11}nf$ $(n = 5, 6)$ for the even parity and $4f^{11}ns$ $(n = 6, 7)$ and $4f^{11}nd$ $(n = 5$–$7)$ for the odd parity. The weak interactions with the configurations of the type $4f^{10}nln'l'$ are implicitly included in the polarization potential and, consequently, these configurations were not retained in the adopted configuration sets. In addition, the average energies, E_{av}, the Slater parameters, F^k and G^k, and the spin-orbit integrals, ζ_{nl}, were adjusted with a least-squares optimization program minimizing the discrepancies between the calculated and the experimental energy levels of Wyart et al. (1997). This well-established procedure allows us to consider implicitly in the calculations the configurations that are not explicitly introduced in the configuration lists basically because of computer limitations (Cowan 1981).

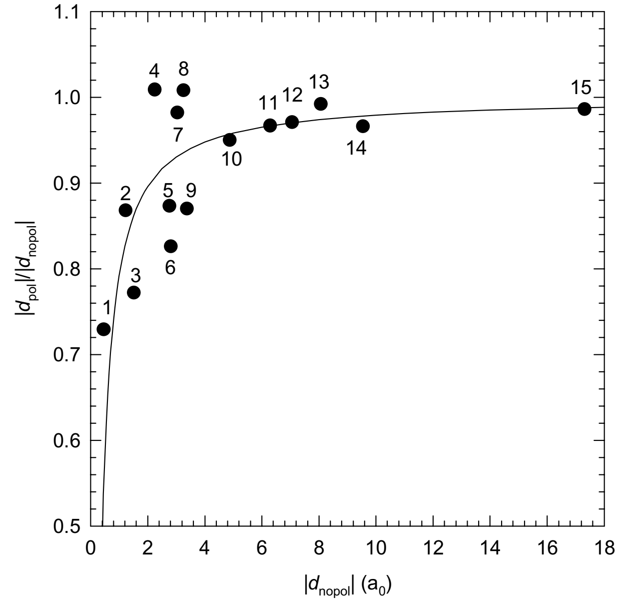

Figure 1. Absolute value of the ratio between transition matrix elements corrected by core-polarization effects (d_{pol}) and uncorrected matrix elements (d_{nopol}) of transitions not involving a 4f electron as a function of the absolute value of the uncorrected data (in Bohr units). A smooth curve has been drawn showing the trend among the following transitions ($4f^{11}$ being the core): (1) 5d–7p, (2) 6p–7d, (3) 5d–6f, (4) 6p–7s, (5) 5d–6p, (6) 5d–5f, (7) 6d–6f, (8) 5f–7d, (9) 6s–6p, (10) 6p–6d, (11) 7s–7p, (12) 6d–7p, (13) 7p–7d, (14) 5f–6d, (15) 6f–7d.

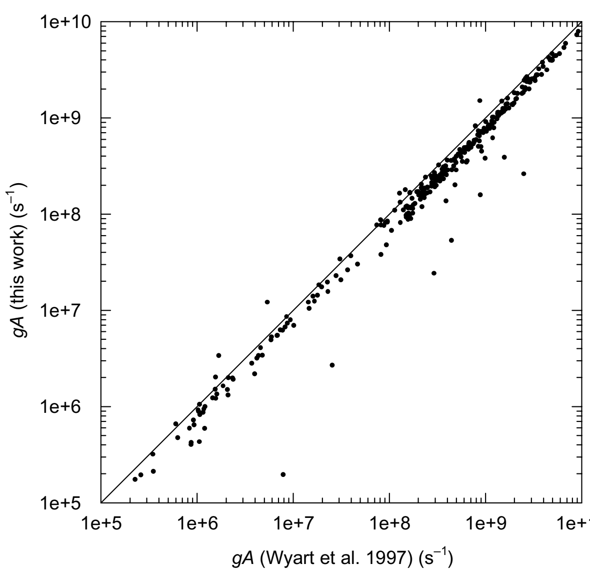

Figure 2. Comparison between our *gA*-values and those reported by Wyart et al. (1997). The straight line on the figure corresponds to the equality of the two sets of data.

A comparison between the calculated and measured lifetime values is presented in Table 2 for the $4f^{11}6p$ levels. The agreement between the two sets of data is particularly good (within 8 per cent). The calculated HFR oscillator strengths and transition probabilities for the most intense transitions depopulating the seven even levels of Table 2 for which the radiative lifetimes were measured are listed in Table 3. Normalized (i.e. multiplied by τ_{calc}/τ_{exp}) *gf*- and *gA*-values are also given in this table. An extensive table of oscillator strengths and transition probabilities

Table 3. Oscillator strengths (log *gf*) and transition probabilities (*gA* in s^{-1}) for the transitions depopulating the seven $4f^{11}6p$ levels of Table 2 for which radiative lifetimes have been measured in the present work. Only lines with *gA*-values greater than $10^7 s^{-1}$ are reported in the table.

λ (Å)[a]	E_{lower}[b]		J_{lower}	E_{upper}[b]		J_{upper}	log gf_{HFR}[c]	gA_{HFR}[c]	log gf_{norm}[d]	gA_{norm}[d]
1585.664	17648	(o)	7.0	80713	(e)	6.0	−1.93	3.12E+07	−1.92	3.15E+07
1671.661	22017	(o)	5.0	81838	(e)	4.0	−2.22	1.43E+07	−2.18	1.58E+07
1672.927	16976	(o)	6.0	76752	(e)	5.0	−2.33	1.10E+07	−2.30	1.18E+07
1736.919	17648	(o)	7.0	75221	(e)	6.0	−2.12	1.69E+07	−2.06	1.79E+07
1741.854	23303	(o)	7.0	80713	(e)	6.0	−1.99	2.26E+07	−1.98	2.28E+07
1818.351	20226	(o)	7.0	75221	(e)	6.0	−1.91	2.50E+07	−1.85	2.65E+07
1971.712	29996	(o)	5.0	80713	(e)	6.0	−2.21	1.05E+07	−2.20	1.06E+07
2013.830	32197	(o)	4.0	81838	(e)	4.0	−2.17	1.11E+07	−2.07	1.22E+07
2045.132	27871	(o)	5.0	76752	(e)	5.0	−2.05	1.42E+07	−1.97	1.53E+07
2060.356	32193	(o)	5.0	80713	(e)	6.0	−1.45	5.55E+07	−1.44	5.61E+07
2078.400	32614	(o)	5.0	80713	(e)	6.0	−2.15	1.11E+07	−2.14	1.12E+07
2111.251	27871	(o)	5.0	75221	(e)	6.0	−2.04	1.38E+07	−1.98	1.46E+07
2151.311	30283	(o)	6.0	76752	(e)	5.0	−2.15	1.02E+07	−2.07	1.10E+07
2173.159	30750	(o)	4.0	76752	(e)	5.0	−1.75	2.53E+07	−1.67	2.73E+07
2176.375	35904	(o)	4.0	81838	(e)	4.0	−1.70	2.78E+07	−1.60	3.06E+07
2183.312	34925	(o)	5.0	80713	(e)	6.0	−1.29	7.14E+07	−1.28	7.21E+07
2188.925	36167	(o)	3.0	81838	(e)	4.0	−2.13	1.04E+07	−2.03	1.14E+07
2189.611	31096	(o)	6.0	76752	(e)	5.0	−1.80	2.19E+07	−1.72	2.37E+07
2190.780	16976	(o)	6.0	62608	(e)	7.0	−1.55	3.94E+07	−1.52	4.18E+07
2195.319	31215	(o)	5.0	76752	(e)	5.0	−1.69	2.84E+07	−1.61	3.07E+07
2196.791	36331	(o)	5.0	81838	(e)	4.0	−1.99	1.41E+07	−1.89	1.55E+07
2201.246	29806	(o)	5.0	75221	(e)	6.0	−2.00	1.38E+07	−1.94	1.46E+07
2210.453	29996	(o)	5.0	75221	(e)	6.0	−2.02	1.31E+07	−1.96	1.39E+07
2223.990	17648	(o)	7.0	62598	(e)	6.0	−1.80	2.15E+07	−1.76	2.24E+07
2243.542	32193	(o)	5.0	76752	(e)	5.0	−1.90	1.65E+07	−1.82	1.78E+07
2252.460	36331	(o)	5.0	80713	(e)	6.0	−1.05	1.17E+08	−1.04	1.18E+08
2264.953	32614	(o)	5.0	76752	(e)	5.0	−1.35	5.89E+07	−1.27	6.36E+07
2268.102	36637	(o)	7.0	80713	(e)	6.0	−1.88	1.72E+07	−1.87	1.74E+07
2269.066	36656	(o)	5.0	80713	(e)	6.0	−1.84	1.87E+07	−1.83	1.89E+07
2286.648	33033	(o)	4.0	76752	(e)	5.0	−1.43	4.73E+07	−1.35	5.11E+07
2294.965	33192	(o)	6.0	76752	(e)	5.0	−1.93	1.48E+07	−1.85	1.60E+07
2309.191	19316	(o)	8.0	62608	(e)	7.0	−0.86	1.72E+08	−0.80	1.82E+08
2323.359	32193	(o)	5.0	75221	(e)	6.0	−1.09	1.00E+08	−1.03	1.06E+08
2329.568	38924	(o)	3.0	81838	(e)	4.0	−1.90	1.53E+07	−1.80	1.68E+07
2348.258	39266	(o)	5.0	81838	(e)	4.0	−0.88	1.60E+08	−0.78	1.76E+08
2358.791	20226	(o)	7.0	62608	(e)	7.0	−0.39	4.86E+08	−0.33	5.15E+08
2359.332	20226	(o)	7.0	62598	(e)	6.0	−0.03	1.13E+09	0.01	1.18E+09
2370.620	39667	(o)	4.0	81838	(e)	4.0	−1.15	8.38E+07	−1.05	9.22E+07
2384.117	38782	(o)	6.0	80713	(e)	6.0	−0.58	3.12E+08	−0.57	3.15E+08
2388.190	38853	(o)	6.0	80713	(e)	6.0	0.47	3.42E+09	0.48	3.45E+09
2390.105	34925	(o)	5.0	76752	(e)	5.0	0.25	2.08E+09	0.33	2.25E+09
2399.015	40166	(o)	4.0	81838	(e)	4.0	−0.06	1.00E+09	0.04	1.10E+09
2411.369	35294	(o)	4.0	76752	(e)	5.0	0.19	1.79E+09	0.27	1.93E+09
2411.977	39266	(o)	5.0	80713	(e)	6.0	−1.15	8.24E+07	−1.14	8.32E+07
2412.987	40408	(o)	3.0	81838	(e)	4.0	−0.74	2.09E+08	−0.64	2.30E+08
2417.884	33875	(o)	6.0	75221	(e)	6.0	−1.66	2.49E+07	−1.60	2.64E+07
2423.087	40580	(o)	4.0	81838	(e)	4.0	−1.49	3.71E+07	−1.39	4.08E+07
2439.449	40857	(o)	5.0	81838	(e)	4.0	−0.66	2.48E+08	−0.56	2.73E+08
2444.538	35857	(o)	6.0	76752	(e)	5.0	−0.74	2.05E+08	−0.66	2.21E+08
2447.371	35904	(o)	4.0	76752	(e)	5.0	−1.32	5.29E+07	−1.24	5.71E+07
2463.442	22017	(o)	5.0	62598	(e)	6.0	−1.52	3.35E+07	−1.48	3.48E+07
2473.218	36331	(o)	5.0	76752	(e)	5.0	−0.49	3.50E+08	−0.41	3.78E+08
2480.900	34925	(o)	5.0	75221	(e)	6.0	−1.14	7.77E+07	−1.08	8.24E+07
2487.947	36570	(o)	6.0	76752	(e)	5.0	−0.14	7.85E+08	−0.06	8.48E+08
2493.253	36656	(o)	5.0	76752	(e)	5.0	−1.74	1.94E+07	−1.66	2.10E+07
2499.753	22606	(o)	6.0	62598	(e)	6.0	−1.95	1.20E+07	−1.91	1.25E+07
2539.598	35857	(o)	6.0	75221	(e)	6.0	−0.88	1.37E+08	−0.82	1.45E+08
2553.928	37608	(o)	4.0	76752	(e)	5.0	−1.48	3.40E+07	−1.40	3.67E+07
2570.565	36331	(o)	5.0	75221	(e)	6.0	−1.77	1.71E+07	−1.71	1.81E+07
2590.957	36637	(o)	7.0	75221	(e)	6.0	−0.70	1.98E+08	−0.64	2.10E+08
2591.845	16976	(o)	6.0	55547	(e)	7.0	0.16	1.42E+09	0.15	1.38E+09
2592.215	36656	(o)	5.0	75221	(e)	6.0	−1.62	2.41E+07	−1.56	2.55E+07
2632.857	38782	(o)	6.0	76752	(e)	5.0	−0.68	2.00E+08	−0.60	2.16E+08
2637.778	17648	(o)	7.0	55547	(e)	7.0	−0.03	8.92E+08	−0.06	8.68E+08
2637.825	38853	(o)	6.0	76752	(e)	5.0	−0.65	2.15E+08	−0.57	2.32E+08
2666.874	39266	(o)	5.0	76752	(e)	5.0	−0.78	1.56E+08	−0.70	1.68E+08
2692.758	25482	(o)	8.0	62608	(e)	7.0	0.24	1.58E+09	0.30	1.67E+09
2738.535	26103	(o)	7.0	62608	(e)	7.0	0.15	1.25E+09	0.21	1.33E+09
2739.265	26103	(o)	7.0	62598	(e)	6.0	0.44	2.44E+09	0.48	2.54E+09

Table 3 – *continued*

λ (Å)[a]	E_{lower}[b]		J_{lower}	E_{upper}[b]		J_{upper}	log gf_{HFR}[c]	gA_{HFR}[c]	log gf_{norm}[d]	gA_{norm}[d]
2743.456	38782	(o)	6.0	75221	(e)	6.0	−0.36	3.89E+08	−0.30	4.12E+08
2746.030	26193	(o)	5.0	62598	(e)	6.0	−0.02	8.44E+08	0.02	8.78E+08
2748.850	38853	(o)	6.0	75221	(e)	6.0	0.23	1.50E+09	0.29	1.59E+09
2759.226	19316	(o)	8.0	55547	(e)	7.0	0.56	3.21E+09	0.53	3.12E+09
2761.919	26412	(o)	6.0	62608	(e)	7.0	0.43	2.36E+09	0.49	2.50E+09
2762.661	26412	(o)	6.0	62598	(e)	6.0	−0.12	6.62E+08	−0.08	6.88E+08
2774.808	26580	(o)	7.0	62608	(e)	7.0	0.03	9.23E+08	0.09	9.78E+08
2775.557	26580	(o)	7.0	62598	(e)	6.0	−0.48	2.86E+08	−0.44	2.97E+08
2780.411	39266	(o)	5.0	75221	(e)	6.0	−0.15	6.12E+08	−0.09	6.49E+08
2805.872	19918	(o)	8.0	55547	(e)	7.0	−0.14	6.20E+08	−0.17	6.03E+08
2830.338	20226	(o)	7.0	55547	(e)	7.0	−0.03	7.79E+08	−0.06	7.58E+08
2845.296	27472	(o)	6.0	62608	(e)	7.0	−0.57	2.19E+08	−0.51	2.32E+08
2846.083	27472	(o)	6.0	62598	(e)	6.0	−0.15	5.81E+08	−0.11	6.04E+08
2864.463	46937	(o)	4.0	81838	(e)	4.0	−0.93	9.69E+07	−0.83	1.07E+08
2878.733	27871	(o)	5.0	62598	(e)	6.0	−0.64	1.87E+08	−0.60	1.94E+08
2909.169	40857	(o)	5.0	75221	(e)	6.0	−0.86	1.09E+08	−0.80	1.16E+08
2955.082	28778	(o)	6.0	62608	(e)	7.0	−1.34	3.50E+07	−1.28	3.71E+07
2955.932	28778	(o)	6.0	62598	(e)	6.0	−0.94	8.83E+07	−0.90	9.18E+07
2958.642	28818	(o)	7.0	62608	(e)	7.0	−1.00	7.65E+07	−0.94	8.11E+07
2959.493	28818	(o)	7.0	62598	(e)	6.0	−1.53	2.25E+07	−1.49	2.34E+07
3021.145	48747	(o)	5.0	81838	(e)	4.0	−1.86	1.01E+07	−1.76	1.11E+07
3067.188	30014	(o)	6.0	62608	(e)	7.0	−1.44	2.56E+07	−1.38	2.71E+07
3092.705	30283	(o)	6.0	62608	(e)	7.0	−1.54	2.02E+07	−1.48	2.14E+07
3093.635	30283	(o)	6.0	62598	(e)	6.0	−1.55	1.98E+07	−1.51	2.06E+07
3100.413	23303	(o)	7.0	55547	(e)	7.0	−0.93	8.22E+07	−0.96	8.00E+07
3234.642	31701	(o)	8.0	62608	(e)	7.0	−1.64	1.47E+07	−1.58	1.56E+07
3327.017	32560	(o)	7.0	62608	(e)	7.0	−1.62	1.46E+07	−1.56	1.55E+07
3479.363	33875	(o)	6.0	62608	(e)	7.0	−1.58	1.46E+07	−1.52	1.55E+07
3480.540	33875	(o)	6.0	62598	(e)	6.0	−1.24	3.20E+07	−1.20	3.33E+07
3853.580	36656	(o)	5.0	62598	(e)	6.0	−1.56	1.24E+07	−1.52	1.29E+07

Notes to the table: [a] Deduced from the experimental energy levels (Wyart et al. 1997). These wavelengths are given in air above 2000 Å and in vacuum below that limit.
[b] Experimental levels (in cm^{-1}) compiled by Wyart et al. (1997).
[c] HFR approach including core-polarization corrections (see text).
[d] Values normalized using the experimental radiative lifetimes given in Table 2.
(o) Odd parity.
(e) Even parity.

for about 1300 transitions in Er III between 1000 and 10 000 Å is available in the DREAM data base on the web at http://www.umh.ac.be/~astro/dream.shtml.

Some transitions of astrophysical interest identified in the spectrum of the star HR465 are reported in Table 4.

In Fig. 2, we show a comparison between our *gA*-values and those reported by Wyart et al. (1997). The straight line on the figure corresponds to the equality of the two sets of data. Our *gA*-values appear in good agreement, although systematically smaller, with those of Wyart et al. (1997). This is expected because Wyart et al. did not consider core-polarization effects in their calculations. Large scatter is observed for seven points appearing below the straight line. For the four points for which *gA*(Wyart et al. 1997) $<10^9\,s^{-1}$, this can be explained by severe cancellation effects. For the other three points, no explanation has been found for the discrepancies.

In view of the overall good agreement observed between theory and experiment in Table 2, the theoretical transition probabilities for the most intense transitions considered in the present work are expected to be accurate within a few (<10) per cent. For the weaker lines, not reported in the present paper but listed in the DREAM data base, this uncertainty could be larger particularly for the transitions affected by severe cancellation effects. For such transitions, the cancellation factor (CF) as defined by Cowan (1981) is very small (typically CF ⩽ 0.01) indicating that the corresponding computed oscillator strengths and transition probabilities must be considered with some care. The CF-values obtained in our calculations are given for all the transitions reported in the DREAM data base.

ACKNOWLEDGMENTS

Financial support from the Belgian National Fund for Scientific Research (FNRS) is acknowleged by EB, PP and PQ. The experimental work was performed in Lund in the framework of the EU-TMR Access-to-Large-Scale-Facility programme (contract ERBFMGECT 950020). The members of the Belgian team would like to thank the warm hospitality enjoyed during their stay at Lund University.

Table 4. Calculated oscillator strengths and transition probabilities for transitions of Er III identified in the spectrum of the star HR465 by Wyart et al. (1997).

λ (Å)[a]	E_{lower}[b]		J_{lower}	E_{upper}[b]		J_{upper}	log *gf*	*gA* (s^{-1})	*CF*[c]
3262.946	6970	(e)	5.0	37608	(o)	4.0	−2.30	3.17E+06	0.109
3376.155	0	(e)	6.0	29611	(o)	7.0	−2.55	1.63E+06	−0.335
3377.374	6970	(e)	5.0	36570	(o)	6.0	−2.46	2.02E+06	0.255
3404.900	6970	(e)	5.0	36331	(o)	5.0	−2.23	3.36E+06	−0.053
3455.125	32560	(o)	7.0	61494	(e)	6.0	−2.33	2.63E+06	0.018
3460.795	6970	(e)	5.0	35857	(o)	6.0	−2.07	4.74E+06	−0.131
3473.913	0	(e)	6.0	28778	(o)	6.0	−1.21	3.40E+07	0.297
3492.753	5082	(e)	4.0	33704	(o)	5.0	−3.07	4.63E+05	−0.022
3501.160	27472	(o)	9.0	56025	(e)	8.0	−2.08	4.55E+06	0.006
3638.972	0	(e)	6.0	27472	(o)	6.0	−1.29	2.61E+07	0.243
3687.433	5082	(e)	4.0	32193	(o)	5.0	−2.97	5.29E+05	−0.142
3698.902	10786	(e)	4.0	37813	(o)	3.0	−2.81	7.45E+05	0.041
3739.423	6970	(e)	5.0	33704	(o)	5.0	−1.75	8.56E+06	−0.183
3812.549	6970	(e)	5.0	33192	(o)	6.0	−3.00	4.53E+05	0.066
3825.530	5082	(e)	4.0	31215	(o)	5.0	−3.06	4.00E+05	−0.020
3898.356	6970	(e)	5.0	32614	(o)	5.0	−2.34	1.97E+06	0.134
3913.506	10786	(e)	4.0	36331	(o)	5.0	−1.90	5.47E+06	0.198
3945.163	12473	(e)	3.0	37813	(o)	3.0	−2.55	1.21E+06	−0.119
3963.453	6970	(e)	5.0	32193	(o)	5.0	−2.61	1.05E+06	−0.146
3977.301	12473	(e)	3.0	37608	(o)	4.0	−3.06	3.72E+05	−0.075
4065.038	13220	(e)	2.0	37813	(o)	3.0	−2.48	1.34E+06	−0.086
4123.446	6970	(e)	5.0	31215	(o)	5.0	−2.30	1.98E+06	0.065
4203.956	6970	(e)	5.0	30750	(o)	4.0	−3.97	4.09E+04	0.006
4356.549	13220	(e)	2.0	36167	(o)	3.0	−1.46	1.21E+07	−0.286
4362.200	38782	(o)	6.0	61699	(e)	7.0	−2.42	1.33E+06	0.079
4443.276	6970	(e)	5.0	29469	(o)	4.0	−2.85	4.74E+05	0.025
4463.007	10786	(e)	4.0	33186	(o)	3.0	−3.01	3.28E+05	0.049
4493.608	10786	(e)	4.0	33033	(o)	4.0	−2.35	1.49E+06	0.057
4579.808	10786	(e)	4.0	32614	(o)	5.0	−2.72	5.93E+05	−0.191
4669.091	10786	(e)	4.0	32197	(o)	4.0	−2.52	9.24E+05	−0.084

Notes to the tabe: [a] Deduced from the experimental energy levels (Wyart et al. 1997). These wavelengths are given in air above 2000 Å and in vacuum below that limit.
[b] Experimental levels (in cm^{-1}) compiled by Wyart et al. (1997).
[c] Cancellation factor, *CF*, as defined by Cowan (1981). Small values of this factor (typically $CF < 0.01$) indicate transitions affected by severe cancellation effects.
(o) Odd parity.
(e) Even parity.

REFERENCES

Adelman S. J., 1974, ApJ, 254, 51
Aikman G. C. L., Cowley C. R., Crosswhite H. M., 1979, ApJ, 232, 812
Anders E., Grevesse N., 1989, Geochim. Cosmochim. Acta, 53, 197
Becher J., 1966, PhD thesisJohns Hopkins Univ., Baltimore, USA,
Bentzen S. M., Nielsen U., Poulsen O., 1982, J. Opt. Soc. Am., 72, 1210
Bidelman W. P., 1953, ApJ, 117, 377
Bidelman W. P., Cowley C. R., Iler A. L., 1995, Wavelength identifications in the Magnetic CP Star HR465, Vol. XII. Publ. Obs. Univ. Michigan
Biémont E., Youssef N. H., 1984, A&A, 140, 177
Biémont E., Li Z. S., Palmeri P., Quinet P., 1999, J. Phys. B: At. Mol. Opt. Phys., 32, 3409
Cowan R. D., 1981, The Theory of Atomic Structure and Spectra. Univ. of California Press, Berkeley
Cowley C. R., 1976, ApJS, 32, 631
Cowley C. R., Greenberg M., 1987, PASP, 99, 1201
Cowley C. R., Crosswhite H. M., 1978, PASP, 90, 108
Cowley C. R., Mathys G., 1998, A&A, 339, 165
Engman B., Stoner J. O.,Jr Martinson I., 1976, Phys. Scr., 13, 363
Fraga S., Karwowski J., Saxena K. M. S., 1976, Handbook of Atomic Data. Elsevier, Amsterdam
Gorshkov V. N., Komarovskii V. A., 1987, SvA, 30, 333
Grevesse N., Blanquet G., 1969, Solar Phys., 8, 5
Jaschek C., Jaschek M., 1995, The Behavior of Chemical Elements in Stars. Cambridge Univ. Press, Cambridge
Lambert D. L., 1985, in Jaschek M., Keenan P. C., eds, Cool Stars with Excesses of Heavy Elements. Reidel, Dordrecht
Li Z. S. et al., 2000, J. Phys. B: At. Mol. Opt. Phys., submitted
Martin W. C., Zalubas R., Hagan L., 1978, Atomic Energy Levels – The Rare-Earth Elements, NSRDS-NBS, Washington
Quinet P., Palmeri P., Biémont E., 1999a, J. Quant. Spectrosc. Radiat. Transfer, 62, 625
Quinet P., Palmeri P., Biémont E., McCurdy M. M., Rieger G., Pinnington E. H., Wickliffe M. E., Lawler J. E., 1999b, MNRAS, 307, 934
Reynolds S. E., Hearnshaw J. B., Cottrell P. L., 1988, MNRAS, 235, 1423
Spector N., 1973, J. Opt. Soc. Am., 63, 358
Svanberg S., Larsson J., Persson A., Wahlstrom C.-G., 1994, Phys. Scr., 49, 187
van t'Veer-Menneret C., Burkhart C., Coupry M. F., 1988, A&A, 203, 123
Wyart J.-F., Blaise J., Camus P., 1974a, Phys. Scr., 9, 325
Wyart J.-F., Koot J. J. A., Van Kleef Th. A. M., 1974b, Physica C, 77, 159
Wyart J.-F., Bauche-Arnoult C., 1981, Phys. Scr., 22, 583
Wyart J.-F., Blaise J., Bidelman W. P., Cowley C. R., 1997, Phys. Scr., 56, 446
Wyart J.-F., Tchang-Brillet Wan-U L., Spector N., Palmeri P., Quinet P., Biémont E., 2000, Phys. Scr., in press
Wybourne B. G., 1965, Spectroscopic Properties of Rare-Earths. John Wiley & Sons Inc., New York, USA

This paper has been typeset from a TEX/LATEX file prepared by the author.