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DOUBLY IONIZED THORIUM: LASER LIFETIME MEASUREMENTS AND TRANSITION PROBABILITY DETERMINATION OF INTEREST IN COSMOCHRONOLOGY

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ABSTRACT

The first lifetime measurements have been performed for six levels of doubly ionized thorium, an important cosmochronometer in astrophysics for estimating the age of the Galaxy. The levels, belonging to the $5f^2$, $5f7p$, $7s7p$, and $6d7p$ configurations of Th III, have been measured by the time-resolved laser-induced fluorescence method and compared with relativistic Hartree-Fock calculations including configuration interaction and core-polarization effects. Taking advantage of the excellent agreement between theory and experiment, a first set of transition probabilities of astrophysical interest has been deduced for this ion from a combination of the experimental lifetimes and of the theoretical branching fractions.

Subject headings: atomic data — line: identification — methods: laboratory — stars: peculiar

1. INTRODUCTION

Doubly ionized thorium (Th III) has a complex electronic structure, and its ground state is $5f6d\,^3H^o_4$. Among the 12 isotopes and isomers of thorium, only ^{232}Th, which is characterized by a half-life of 14.05 Gyr, occurs in the solar system. The other isotopes are short lived, with the exception of ^{230}Th, which has a half-life of 8×10^4 yr.

In astrophysics, the age of a star can be determined by the use of a radioactive isotope of sufficiently long lifetime, and two such isotopes are frequently considered in cosmochronology: ^{232}Th and ^{238}U, which has a half-life of 4.47 Gyr. The abundance patterns in metal-poor halo stars, which are very old, provide some records of the first generations of Galactic nucleosynthesis.

Thorium has frequently been used in the past as a cosmochronometer because its most intense transition (Th II) at 401.9 nm is rather easily accessible (visible range). It has been detected, e.g., in the ultra–metal-poor halo star CS 22892-052 (Sneden et al. 1994, 1996; Cowan et al. 1997) in the framework of the investigation of the third *r*-process peak elements in some halo stars with the *Hubble Space Telescope* (*HST*), the long-lived radioactive nuclei being formed entirely in the *r*-process and being used to determine the age of the stars and of the Galaxy.

Among the long-lived isotopes considered in the literature, let us mention that Butcher (1987) proposed using the ^{232}Th and Nd elements to derive an age for the Galactic disk, the most abundant isotopes of Nd, taken as references, being stable. The consideration of the Th/Eu spectral line ratios for the determination of the age of the Galaxy (see, e.g., François, Spite, & Spite 1993) has also motivated recent efforts in the laboratory to improve our knowledge of the relevant atomic data.

These efforts, however, have been concentrated on singly ionized elements, one obvious reason being that doubly ionized atoms are more difficult to produce in the laboratory; also, knowledge of their spectra is generally more fragmentary (see, e.g., the relevant compilations provided by the NIST[4] and also Blaise & Wyart 1992).

Up to now, no Th III transitions have been considered in cosmochronology, mainly because of the complete lack of atomic data regarding the transition probabilities for this ion. Th III has been marginally identified in some stellar spectra (see below), but the identifications were mostly based on wavelength coincidences. Systematic identification and quantitative abundance analyses have been prevented by the lack of oscillator strengths for this ion.

This justifies the first systematic work that is reported in the present paper. More concretely, the first set of transition probabilities has been deduced from a combination of laser lifetime measurements in a laser-produced plasma and configuration interaction calculations including relativistic and core-polarization (CP) effects.

2. EXPERIMENTAL SETUP

The lifetimes of six levels of Th III were measured in the present work, with the time-resolved laser-induced fluorescence technique. They have been excited according to the schemes summarized in Table 1.

The experimental setup used in our experiment is illustrated in Figure 1. Th^{2+} ions were produced in a laser-induced plasma using 532 nm wavelength laser pulses emitted from a 10 Hz repetition rate and 10 ns duration Nd:YAG laser (continuum Surelite) with variable pulse energy. Pulse energies in the range 2–10 mJ were normally used. The pulses were focused on the surface of a Th foil rotating in a vacuum chamber. In order to obtain the required excitation, 8 ns pulses emitted by another Nd:YAG laser (continuum NY-82) were sent to a stimulated Brillouin scattering (SBS) compressor to shorten the pulses down to 1 ns. The laser was used to pump a dye laser (Continuum Nd-60), and the DCM dye was used in the experiments. According to the excitation requirements, the second- or third-order harmonics of the dye laser were obtained employing a nonlinear optical system, including a KDP crystal, a retarding plate, and a BBO crystal, and they were used to populate three measured levels. Three additional measured levels were excited by the Raman-shifted components of the harmonics, obtained in a cell with

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[4] See http://physics.nist.gov/PhysRefData/contents.html.

TABLE 1

Th III LEVELS MEASURED AND THE CORRESPONDING EXCITATION SCHEMES

MEASURED LEVEL					
State[a]	Energy (cm^{-1})	LOWER LEVEL (cm^{-1})	λ_{exc} (AIR) (nm)	EXCITATION SCHEME[b]	λ_{obs} (AIR) (nm)
$5f^2\ {}^3P_2$	32867.274	510.758	308.967	2ν	508.5
$5f7p$ (7/2, 1/2)$_4$	38580.600	3188.301	282.464	2ν + AS	309.8
$7s7p\ {}^3P^o_0$	42259.714	5523.881	272.133	2ν + AS	272.1
$7s7p\ {}^3P^o_1$	45063.970	4676.432	247.526	2ν + 2AS	246.4
$6d7p$ (5/2, 3/2)$^o_4$	53052.47	6537.815	214.918	3ν	232.5
$6d7p$ (5/2, 3/2)$^o_2$	53151.57	4056.020	203.619	3ν	234.1

NOTE.—AS means anti-Stokes component, and 2AS is written for second anti-Stokes component.
[a] From Blaise & Wyart 1992.
[b] 2ν means frequency doubling and 3ν frequency tripling.

hydrogen at 10 bars when the harmonics were focused into the cell. In the experiments, the excitation light was isolated with a CaF_2 Pellin-Broca prism and focused by two CaF_2 lenses at a distance of about 1 cm above the foil. The two Nd:YAG lasers were triggered by a digital delay generator (Stanford Research System, model 535) and the delay between the ablation and excitation pulses was adjusted by the generator. The ions produced by the ablation pulse were excited selectively by the excitation laser beam crossing the plasma horizontally. The fluorescence, decaying from the excited levels, was imaged by two CaF_2 lenses and concentrated on the entrance slit of a vacuum monochromator. A Hamamatsu R3809U-58 photomultiplier was used for the detection.

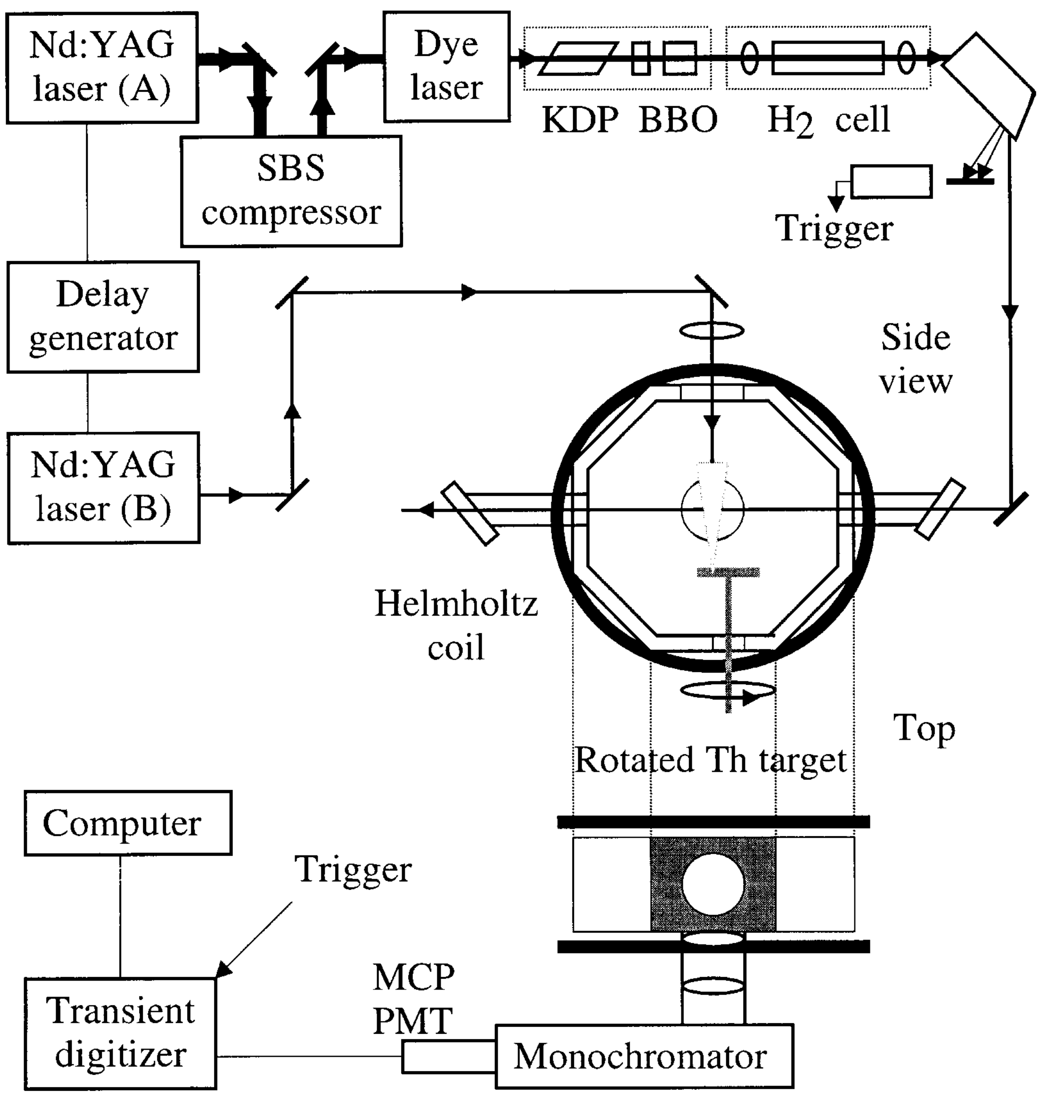

FIG. 1.—Experimental setup used in the Th III lifetime measurements

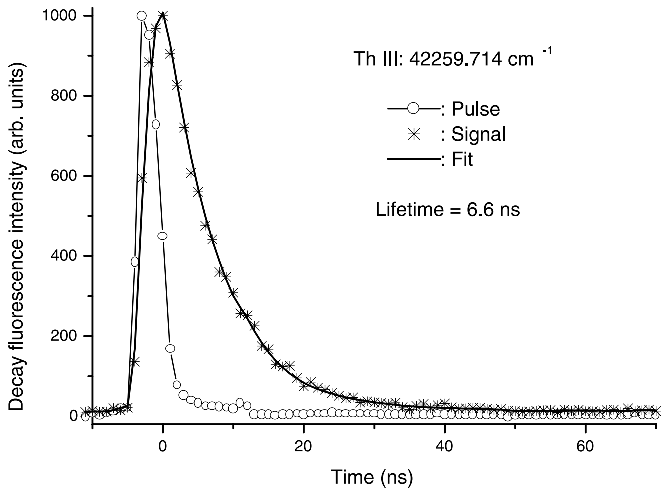

FIG. 2.—Typical experimental time-resolved fluorescence signal from the level at 42259.714 cm^{-1} in Th III. The lifetime deduced from the fit was 6.6 ns.

The time-resolved signal was recorded and averaged with a digital transient recorder (Tektronix model DSA 602), and the fluorescence decay curve was sent to a personal computer for lifetime determination. The lifetime evaluation was performed by fitting the recorded time-resolved curve from the measured level with a convolution of the time-resolved laser pulse curve and an exponential curve with adjustable parameters. The evaluation procedure has been described and tested in a previous work carried out in our laboratory (Li et al. 2000).

In order to be sure that the Th^{2+} transitions of interest were indeed studied, the modification of the fluorescence signal as a function of the delay time was investigated, the occurrence of a maximum fluorescence signal appearing at shorter delay times for Th III than for Th I and Th II ions. Possible flight-out-of-view effects were eliminated by enlarging the slit of the monochromator.

In order to avoid the recombination of the ions and electrons during the ablation process, a magnetic field was added in the plasma zone by a pair of Helmholtz coils. It was observed that the laser-induced fluorescence signal disappeared when the field was switched off and that the recombination light was strongly reduced when a field at about 100 G was applied.

In order to obtain a sufficiently high signal-to-noise ratio, a decay curve was obtained by averaging fluorescence photons from more than 2000 pulses. A typical decay curve is shown in Figure 2.

For each level measured, 6–9 fluorescence decay curves were recorded under different experimental conditions, where the delay time and intensities of the ablation and excitation laser pulses were varied. Thus, the measurements were performed for different concentrations and temperatures of the plasma. The evaluated lifetimes from the curves were found to be well coincident. This showed that there were neither saturation effects nor reabsorption or collisional effects occurring, and the final result was formed by averaging these lifetimes. The six lifetimes measured are reported in the last column of Table 2. The error bars reflect not only the statistical scattering, but also a conservative estimate of the possible remaining systematic errors. Thus, 0.2 ns was considered as an minimum error bar for any lifetimes of less than 2 ns, and any error bar must be larger than 5% for measured lifetimes of more than 2 ns, even if the statistical scattering is much less than 5% of the measured lifetimes.

3. HARTREE-FOCK CALCULATIONS IN TH III

The Th III spectrum was first analyzed by de Bruin & Klinkenberg (1940). Their analysis led to the subsequent publication by Klinkenberg (1950) of a comprehensive description of the spectrum of this ion. Based on infrared observations, Litzén (1974) was able to determine the position of $6d^2\ ^3F_2$ relative to the ground state $5f6d\ ^3H^o_4$. Additional level values and the ionization limit were derived by Wyart & Kaufman (1981) from sliding-spark spectra in the ultraviolet region. The first parametric study was performed by Racah (1950) and reconsidered by Blaise & Wyart (1992) for inclusion in their compilation on the energy levels of the actinides. This compilation (Blaise & Wyart 1992) contains 82 odd and 93 even levels belonging to the $5f6d$, $5f7s$, $6d7p$, $7s7p$, $5f8s$, $5f7d$, $6d6f$; and $6d^2$, 6d7s, $7s^2$, $5f^2$, $5f7p$, $6d7d$, $5f8p$, $5f6f$, and $5f8p$ configurations, respectively. The NIST database[5] lists only 34 transitions in the range 188.812 and 810.514 nm. The energy levels of Blaise & Wyart's compilation were retained for the fitting procedure of the present calculation (see below). The energies and the designations of the levels involved in the present work are summarized in Table 3 for both parities ($E < 85{,}000$ cm^{-1}).

[5] Available at: http://physics.nist.gov/PhysRefData/contents.html.

TABLE 2

CALCULATED AND EXPERIMENTAL LIFETIMES IN Th III AS OBTAINED IN THIS WORK

MEASURED LEVEL		LIFETIME (ns)				
State[a] (1)	Energy (cm^{-1}) (2)	A (3)	B (4)	C (5)	D (6)	EXPERIMENT (7)
$5f^2\ ^3P_2$	32867.274	11.2	38.3	23.9	23.7	25.8 ± 1.5
$5f7p\ (7/2, 1/2)_4$	38580.600	2.0	2.6	2.6	2.6	2.7 ± 0.2
$7s7p\ ^3P^o_0$	42259.714	5.1	6.9	5.6	7.3	6.6 ± 0.4
$7s7p\ ^3P^o_1$	45063.970	2.5	3.4	2.2	2.9	2.4 ± 0.2
$6d7p\ (5/2, 3/2)^o_4$	53052.47	1.0	1.5	1.0	1.4	1.3 ± 0.2
$6d7p\ (5/2, 3/2)^o_2$	53151.57	2.4	3.2	2.4	3.2	3.1 ± 0.2

NOTE.—Columns (3)–(6) give HFR calculations A, B, C, and D, respectively (see text).
[a] From Blaise & Wyart 1992.

TABLE 3

Energy Level Values (in cm^{-1}) of Th III from Blaise & Wyart (1992)

Odd Parity				Even Parity			
Configuration	Designation	J	Energy	Configuration	Designation	J	Energy
$5f6d$	$^3H^o$	4	0.000	$6d^2$	^3F	2	63.267
$5f6d$	$^3F^o$	2	510.758	$6d^2$	^3F	3	4056.020
$5f7s$		3	2527.095	$6d^2$		2	4676.432
$5f7s$	$^3F^o$	2	3181.502	$6d^2$	^3P	0	5090.057
$5f6d$		4	3188.301	$6d7s$	^3D	1	5523.881
$5f6d$	$^3H^o$	5	4489.641	$6d^2$	^3F	4	6537.815
$5f6d$		3	4826.826	$6d7s$	^3D	2	7176.107
$5f6d$	$^3G^o$	3	5060.544	$6d^2$	^3P	1	7875.827
$5f6d$		2	6288.221	$6d7s$	^3D	3	9953.580
$5f7s$	$^3F^o$	4	6310.807	$6d^2$	^3P	2	10440.240
$5f7s$		3	7500.605	$6d^2$	^1G	4	10542.898
$5f6d$	$^3D^o$	1	7921.088	$7s^2$	^1S	0	11961.133
$5f6d$	$^3G^o$	4	8141.749	$5f^2$	^3H	4	15148.519
$5f6d$	$^3H^o$	6	8436.824	$6d7s$	^1D	2	16037.641
$5f6d$		4	8980.557	$5f^2$	^3H	5	17887.409
$5f6d$	$^3D^o$	2	10180.766	$5f^2$	^3F	2	18863.869
$5f6d$	$^3D^o$	3	10741.150	$6d^2$		0	18993.313
$5f6d$	$^3P^o$	1	11123.179	$5f^2$	^3H	6	20770.895
$5f6d$	$^3P^o$	0	11232.615	$5f^2$	^3F	3	20840.488
$5f6d$	$^3G^o$	5	11276.807	$5f^2$	^3F	4	21783.869
$5f6d$	$^3P^o$	2	13208.214	$5f^2$	^1G	4	25972.172
$5f6d$	$^1F^o$	3	15453.411	$5f^2$	^1D	2	28232.502
$5f6d$	$^1H^o$	5	19009.908	$5f^2$	^1I	6	28349.961
$5f6d$	$^1P^o$	1	20710.949	$5f^2$	^3P	0	29299.515
$6d7p$	$(3/2, 1/2)^o$	2	37280.229	$5f^2$	^3P	1	30402.855
$6d7p$	$(3/2, 1/2)^o$	1	39280.863	$5f^2$	^3P	2	32867.274
$7s7p$	$^3P^o$	0	42259.714	$5f7p$	(5/2, 1/2)	3	33562.349
$6d7p$	$(5/2, 1/2)^o$	2	44088.281	$5f7p$	(5/2, 1/2)	2	34996.087
$6d7p$	$(5/2, 1/2)^o$	3	44464.958	$5f7p$	(7/2, 1/2)	3	38431.640
$7s7p$	$^3P^o$	1	45063.97	$5f7p$	(7/2, 1/2)	4	38580.600
$6d7p$	$(3/2, 3/2)^o$	2	47679.97	$5f7p$	(5/2, 3/2)	3	42313.055
$6d7p$	$(3/2, 3/2)^o$	3	49980.67	$5f7p$	(5/2, 3/2)	4	43701.665
$6d7p$	$(3/2, 3/2)^o$	1	50992.57	$5f7p$	(5/2, 3/2)	2	43759.222
$6d7p$	$(3/2, 3/2)^o$	0	51745.37	$5f7p$	(5/2, 3/2)	1	44603.100
$6d7p$	$(5/2, 3/2)^o$	4	53052.47	$5f7p$	(7/2, 3/2)	4	47261.099
$6d7p$		2	53151.57	$5f7p$	(7/2, 3/2)	5	47421.939
$6d7p$	$(5/2, 3/2)^o$	1	53939.27	$5f7p$	(7/2, 3/2)	3	47471.48
$7s7p$	$^3P^o$	2	55399.07	$5f7p$	(7/2, 3/2)	2	49805.94
$6d7p$	$(5/2, 3/2)^o$	3	55552.37	$5f^2$	^1S	0	51161.63
$7s7p$	$^1P^o$	1	69001.00	$6d8s$	^3D	1	81706.37
$5f8s$	$(5/2, 1/2)^o$	2	74644.27	$6d7d$	(3/2, 3/2)	1	83358.66
$5f8s$	$(5/2, 1/2)^o$	3	74784.31	$6d7d$	(3/2, 3/2)	3	83702.11
$5f7d$	$(5/2, 3/2)^o$	3	78327.71				
$5f7d$	$(5/2, 3/2)^o$	2	78332.73				
$5f7d$	$(5/2, 3/2)^o$	4	78417.26				
$5f8s$	$(7/2, 1/2)^o$	4	78929.56				
$5f8s$	$(7/2, 1/2)^o$	3	79082.84				
$5f7d$	$(5/2, 5/2)^o$	4	79329.56				
$5f7d$	$(5/2, 3/2)^o$	1	79484.15				
$5f7d$	$(5/2, 5/2)^o$	3	79646.36				
$5f7d$	$(5/2, 5/2)^o$	2	79915.98				
$5f7d$	$(5/2, 5/2)^o$	5	80137.22				
$5f7d$	$(5/2, 5/2)^o$	1	80784.25				
$5f7d$	$(5/2, 5/2)^o$	0	80906.30				
$5f7d$	$(7/2, 3/2)^o$	4	82348.62				
$5f7d$	$(7/2, 3/2)^o$	3	82827.05				
$5f7d$	$(7/2, 3/2)^o$	5	83023.21				
$5f7d$	$(7/2, 3/2)^o$	2	83237.74				
$5f7d$	$(7/2, 5/2)^o$	4	83552.91				
$5f7d$	$(7/2, 5/2)^o$	6	83962.90				
$5f7d$	$(7/2, 5/2)^o$	5	84239.02				
$5f7d$	$(7/2, 5/2)^o$	3	84374.16				
$5f7d$	$(7/2, 5/2)^o$	2	84532.54				

Note.—Energies less than 85,000 cm^{-1} only are quoted.

TABLE 4

Th III TRANSITIONS DEPOPULATING THE LEVELS FOR WHICH THE RADIATIVE LIFETIMES HAVE BEEN MEASURED IN THE PRESENT WORK

	Lower Level			Upper Level				
λ (nm)	Energy (cm^{-1})	Parity	*J* Value	Energy (cm^{-1})	Parity	*J* Value	*gA*[a]	CF[b]
188.3654......	63	e	2.0	53152	o	2.0	7.97E+06	−0.008
203.6190......	4056	e	3.0	53152	o	2.0	1.33E+08	0.464
204.0309......	4056	e	3.0	53052	o	4.0	1.49E+08	−0.740
206.2254......	4676	e	2.0	53152	o	2.0	1.39E+08	−0.056
209.8953......	5524	e	1.0	53152	o	2.0	2.35E+05	−0.001
214.9184......	6538	e	4.0	53052	o	4.0	1.45E+09	−0.743
217.4392......	7176	e	2.0	53152	o	2.0	4.75E+07	0.016
220.8000......	7876	e	1.0	53152	o	2.0	8.03E+07	−0.191
222.1496......	63	e	2.0	45064	o	1.0	1.44E+08	0.202
231.4211......	9954	e	3.0	53152	o	2.0	1.05E+08	−0.027
231.9533......	9954	e	3.0	53052	o	4.0	5.20E+09	0.839
235.1692......	10543	e	4.0	53052	o	4.0	2.70E+08	−0.776
247.5263......	4676	e	2.0	45064	o	1.0	5.07E+08	−0.553
250.0878......	5090	e	0.0	45064	o	1.0	8.69E+06	−0.046
252.8319......	5524	e	1.0	45064	o	1.0	3.59E+07	0.031
259.1201......	0	o	4.0	38581	e	4.0	1.09E+07	−0.016
263.7461......	15149	e	4.0	53052	o	4.0	1.52E+06	0.528
263.8581......	7176	e	2.0	45064	o	1.0	4.00E+08	−0.267
268.8231......	7876	e	1.0	45064	o	1.0	4.20E+07	−0.530
269.3607......	16038	e	2.0	53152	o	2.0	5.71E+07	0.080
272.1332......	5524	e	1.0	42260	o	0.0	1.32E+08	−0.296
277.2837......	2527	o	3.0	38581	e	4.0	8.45E+06	−0.002
282.4642......	3188	o	4.0	38581	e	4.0	3.77E+08	−0.330
290.7487......	7876	e	1.0	42260	o	0.0	1.96E+07	0.752
291.5644......	18864	e	2.0	53152	o	2.0	1.61E+07	−0.111
293.2471......	4490	o	5.0	38581	e	4.0	6.64E+08	−0.497
296.1766......	4827	o	3.0	38581	e	4.0	7.36E+07	−0.033
298.2418......	5061	o	3.0	38581	e	4.0	4.75E+07	0.057
302.0009......	11961	e	0.0	45064	o	1.0	5.30E+07	−0.323
308.9670......	511	o	2.0	32867	e	2.0	1.73E+07	−0.052
309.4015......	20840	e	3.0	53152	o	2.0	4.12E+06	−0.433
309.7974......	6311	o	4.0	38581	e	4.0	9.31E+08	−0.315
310.3534......	20840	e	3.0	53052	o	4.0	4.09E+06	0.577
319.7172......	21784	e	4.0	53052	o	4.0	4.00E+07	0.644
321.6575......	7501	o	3.0	38581	e	4.0	5.94E+08	−0.212
328.4329......	8142	o	4.0	38581	e	4.0	2.44E+06	−0.001
329.5010......	2527	o	3.0	32867	e	2.0	4.11E+06	0.042
336.7650......	3182	o	2.0	32867	e	2.0	1.92E+05	−0.001
337.7403......	8981	o	4.0	38581	e	4.0	2.82E+08	−0.144
344.4161......	16038	e	2.0	45064	o	1.0	8.24E+06	−0.048
356.5259......	4827	o	3.0	32867	e	2.0	3.17E+06	0.057
359.1000......	10741	o	3.0	38581	e	4.0	1.55E+08	0.311
359.5226......	5061	o	3.0	32867	e	2.0	2.51E+06	−0.020
366.1452......	11277	o	5.0	38581	e	4.0	1.69E+08	0.274
369.1671......	25972	e	4.0	53052	o	4.0	1.44E+07	0.645
376.1292......	6288	o	2.0	32867	e	2.0	7.20E+06	−0.016
381.5696......	18864	e	2.0	45064	o	1.0	3.73E+06	−0.078
383.4642......	18993	e	0.0	45064	o	1.0	9.97E+06	0.203
394.1065......	7501	o	3.0	32867	e	2.0	8.25E+04	−0.001
400.7496......	7921	o	1.0	32867	e	2.0	2.16E+06	−0.019
401.1857......	28233	e	2.0	53152	o	2.0	5.52E+06	−0.048
432.2699......	15453	o	3.0	38581	e	4.0	7.94E+06	−0.036
439.4618......	30403	e	1.0	53152	o	2.0	3.14E+06	0.179
440.6668......	10181	o	2.0	32867	e	2.0	3.25E+06	−0.014
451.8277......	10741	o	3.0	32867	e	2.0	2.65E+07	0.080
459.7662......	11123	o	1.0	32867	e	2.0	1.75E+07	0.122
492.8546......	32867	e	2.0	53152	o	2.0	1.28E+07	0.243
508.5296......	13208	o	2.0	32867	e	2.0	7.78E+07	−0.248
510.8258......	19010	o	5.0	38581	e	4.0	6.89E+07	−0.289
512.9375......	33562	e	3.0	53052	o	4.0	1.05E+05	−0.020
550.6448......	34996	e	2.0	53152	o	2.0	1.11E+05	0.003
574.0959......	15453	o	3.0	32867	e	2.0	2.94E+07	0.225

TABLE 4—*Continued*

	Lower Level			Upper Level				
λ (nm)	Energy (cm^{-1})	Parity	J Value	Energy (cm^{-1})	Parity	J Value	gA[a]	CF[b]
593.9607......	28233	e	2.0	45064	o	1.0	1.22E+06	0.137
679.1636......	38432	e	3.0	53152	o	2.0	1.75E+05	0.003
681.8882......	30403	e	1.0	45064	o	1.0	6.92E+05	0.406
683.7670......	38432	e	3.0	53052	o	4.0	5.35E+06	−0.228
690.8051......	38581	e	4.0	53052	o	4.0	9.37E+05	0.026
819.6688......	32867	e	2.0	45064	o	1.0	1.67E+04	−0.008
822.3909......	20711	o	1.0	32867	e	2.0	2.29E+06	0.114
843.1620......	30403	e	1.0	42260	o	0.0	2.94E+05	−0.647
922.3825......	42313	e	3.0	53152	o	2.0	1.02E+04	−0.001
930.8940......	42313	e	3.0	53052	o	4.0	2.29E+05	0.097

Note.—For each transition, we give the wavelength (λ), the lower and upper levels (energy, parity, J value), the weighted transition probability (gA), and the cancellation factor (CF).

[a] This work, calculation D (see the text). Calculation normalized with the experimental lifetimes (see Table 2).

[b] Small values of the cancellation factor, CF, indicate large cancellation effects.

The computational procedure used for calculating the oscillator strengths and radiative lifetimes in Th III is the pseudo-relativistic Hartree-Fock (HFR) method (Cowan 1981). Four sets of calculations (A, B, C, and D) were performed in the present work, each of them being combined with a well-established semiempirical adjustment of the radial parameters minimizing the differences between computed and experimental energy levels (Cowan 1981). In calculations A and B, the same sets of interacting configurations were retained, i.e., $5f6d$, $5f7d$, $5f8d$, $5f7s$, $5f8s$, $6d7p$, $6d8p$, $6d6f$, $6d7f$, $6d8f$, $7s7p$, and $7s8p$ for the odd parity, and $5f7p$, $5f8p$, $5f6f$, $5f7f$, $5f8f$, $5f^2$, $6d^2$, $7s^2$, $7p^2$, $6d7s$, $6d8s$, $6d7d$, and $6d8d$ for the even parity. While core-polarization (CP) effects were not considered in calculation A, such contributions were included in calculation B using a core-polarization potential and a correction to the dipole matrix elements according to the procedure originally introduced by Migdalek & Baylis (1978) and recently used with success for different complex atomic systems belonging to lanthanide ions (as, e.g., La III–Lu III: Biémont et al. 1999; Er III: Biémont et al. 2001a; Pr III: Palmeri et al. 2000, Biémont et al. 2001c; Tm III: Li et al. 2001; and Yb III: Biémont et al. 2001b). In the latter approach, the CP parameters were chosen equal to $\alpha_d = 10.26a_0^3$ and $r_c = 1.89a_0$. These values correspond to the dipole polarizability of the ionic core Th V as computed by Fraga, Karwowski, & Saxena (1976) and to the expectation value of r for the outermost core orbitals ($6p^6$) as calculated by the HFR technique, respectively. All the levels of the $5f6d$, $7s7p$, $6d7p$, $5f7d$, $5f7s$, and $5f8s$ odd configurations have been considered in the fitting procedure, and the average energies, Slater integrals, and spin-orbit integrals of these configurations were varied as well as the R^k integrals for the interactions $5f6d$–$5f7s$ and $6d7p$–$7s7p$. The levels of the $6d6f$ configurations, strongly overlapping those of the configurations $5f8d$, $6d8p$, and $7s8p$ unknown experimentally, were not considered in the adjustment procedure. For 64 levels (fitted using 35 parameters), the mean deviation in calculations A and B was 175 cm^{-1}. For the even parity, the 39 levels below 80,000 cm^{-1}, belonging to the $5f7p$, $5f^2$, $6d^2$, $7s^2$, and $6d7s$ configurations, were included in the least-squares fit. Twenty-five parameters (E_{av}, F^k, G^k, ζ, effective interaction parameters) were left free to vary. In the $5f8p$, $5f6f$, $6d8s$, and $6d7d$ configurations, only the average energies were adjusted because many high-lying levels have not yet been determined experimentally or their designation is unknown. The mean deviation in the fit was 87 cm^{-1} (calculations A and B).

Radiative lifetimes deduced from calculations A and B are compared to the experimental results in columns (3) and (4) of Table 2. As expected, because of the neglect of CP corrections, the HFR(A) results are not in good agreement with the measurements. When including such effects (calculation B), one can observe that the agreement between theory and experiment is improved for some levels, while it is deteriorated for some others. In the particular case of the $5f^2$ level situated at 32867.274 cm^{-1}, quite sensitive to CP effects, the HFR(B) lifetime value is now 33% longer than the experimental result. As already mentioned in previous papers concerning lanthanides (see, e.g., Biémont et al. 2001a, 2001b, 2001c; Palmeri et al. 2000), this is probably due to the fact that the CP corrections, as introduced in our model, are no longer valid for configurations including at least a $5f$ electron, as this orbital considerably overlaps the $6s^2 6p^6$ core subshells.

In order to estimate the importance of core-core interactions, additional configurations with $6p$ to $5f$ core excitations have been included in the model (calculations C and D). These configurations, added to the ones retained in calculation A, were $6p^5 5f^2 6d$, $6p^5 5f^2 7d$, $6p^5 5f^2 7s$, $6p^5 5f^2 8s$, $6p^5 5f7s7p$, and $6p^5 5f6d7p$ for the odd parity, and $6p^5 5f^3$, $6p^5 5f^2 7p$, $6p^5 5f6d^2$, $6p^5 5f7s^2$, and $6p^5 5f6d7s$ for the even parity. Thus in calculation C, 18 even and 18 odd configurations were considered but no core polarization was introduced in the model. In calculation D, CP contributions for the configurations not involving a $5f$ electron (using the same CP parameters as the ones adopted in calculation B) were considered. The mean deviations in calculations C and D reached 186 cm^{-1} (odd parity) for 64 levels and 93 cm^{-1} (even parity) for 39 levels. Radiative lifetimes obtained in the approximations C and D are reported in columns (5) and (6) of Table 2. The results of calculation D are expected to be the most accurate reported in the present paper, and consequently have been adopted as the final theoretical results.

Using the procedure D, transition probabilities and oscil-

TABLE 5

RADIATIVE PARAMETERS FOR THE MOST INTENSE Th III LINES AS OBSERVED IN THE LABORATORY

	Lower Level			Upper Level						
λ (nm)	Energy (cm^{-1})	Parity	J Value	Energy (cm^{-1})	Parity	J Value	log gf[a]	gA[a] (s^{-1})	CF[b]	Intensity[c]
130.7439......	6538	e	4.0	83023	o	5.0	−0.33	1.82E+09	−0.558	3000
132.8488......	4056	e	3.0	79330	o	4.0	−1.84	5.51E+07	−0.216	1500
135.6924......	10543	e	4.0	84239	o	5.0	−0.14	2.62E+09	−0.495	3500
135.8707......	6538	e	4.0	80137	o	5.0	−0.84	5.22E+08	−0.433}	1500
135.8708......	9954	e	3.0	83553	o	4.0	−2.19	2.33E+07	−0.026	
146.3346......	16038	e	2.0	84374	o	3.0	−1.22	1.86E+08	−0.186	2500
188.8098......	16038	e	2.0	69001	o	1.0	0.00	1.90E+09	0.376	100
214.9184......	6538	e	4.0	53052	o	4.0	−0.03	1.35E+09	−0.743	50
216.2817......	5524	e	1.0	51745	o	0.0	−0.26	7.82E+08	0.683	50
219.9752......	9954	e	3.0	55399	o	2.0	0.35	3.15E+09	−0.578	50
220.6611......	4676	e	2.0	49981	o	3.0	−0.51	4.28E+08	0.190	50
229.1612......	4056	e	3.0	47680	o	2.0	−0.04	1.16E+09	0.697	50
230.1166......	6538	e	4.0	49981	o	3.0	0.24	2.19E+09	0.648	100
231.9533......	9954	e	3.0	53052	o	4.0	0.59	4.83E+09	0.839	100
232.4676......	4676	e	2.0	47680	o	2.0	−0.08	1.03E+09	0.332	80
236.3046......	7501	o	3.0	49806	e	2.0	0.24	2.06E+09	−0.304	100
236.8913......	5061	o	3.0	47261	e	4.0	−0.69	2.43E+08	0.209	50
237.1412......	5524	e	1.0	47680	o	2.0	0.04	1.28E+09	0.829	100
238.1466......	11961	e	0.0	53939	o	1.0	−0.20	7.34E+08	0.754	80
239.1484......	511	o	2.0	42313	e	3.0	−0.39	4.78E+08	0.231	100
241.3466......	3182	o	2.0	44603	e	1.0	0.13	1.53E+09	−0.452	200
242.4557......	2527	o	3.0	43759	e	2.0	−0.55	3.20E+08	−0.054	50
242.7946......	2527	o	3.0	43702	e	4.0	0.30	2.27E+09	−0.311	200
243.1693......	6311	o	4.0	47422	e	5.0	0.30	2.24E+09	−0.292	200
244.1245......	6311	o	4.0	47261	e	4.0	0.42	2.95E+09	0.420	200
246.3661......	3182	o	2.0	43759	e	2.0	0.14	1.53E+09	0.376	100
247.3952......	4056	e	3.0	44465	o	3.0	−0.10	8.58E+08	−0.721	50
250.1068......	7501	o	3.0	47471	e	3.0	0.24	1.87E+09	0.384	100
251.2693......	2527	o	3.0	42313	e	3.0	0.26	1.90E+09	0.274	60
251.4302......	7501	o	3.0	47261	e	4.0	0.14	1.45E+09	−0.353	50
289.8934......	511	o	2.0	34996	e	2.0	−0.04	7.17E+08	−0.312	27
297.8660......	0	o	4.0	33562	e	3.0	0.09	9.40E+08	−0.497	50
307.8967......	2527	o	3.0	34996	e	2.0	−0.32	3.35E+08	0.153	11
309.7974......	6311	o	4.0	38581	e	4.0	0.15	9.67E+08	−0.315	11
314.8065......	5524	e	1.0	37280	o	2.0	−0.11	5.35E+08	0.560	16
322.1212......	2527	o	3.0	33562	e	3.0	0.11	8.28E+08	−0.466	43
329.0600......	3182	o	2.0	33562	e	3.0	0.07	7.22E+08	−0.315	37
331.3678......	4827	o	3.0	34996	e	2.0	−0.16	4.21E+08	0.287	17
350.7546......	5061	o	3.0	33562	e	3.0	−0.43	2.04E+08	−0.192	13
384.9183......	0	o	4.0	25972	e	4.0	−1.36	1.95E+07	−0.057	10
455.5719......	6288	o	2.0	28233	e	2.0	−0.52	9.56E+07	−0.235	16
458.9267......	0	o	4.0	21784	e	4.0	−1.25	1.77E+07	0.133	14
508.4699......	6311	o	4.0	25972	e	4.0	−0.96	2.83E+07	0.188	12
537.6130......	3188	o	4.0	21784	e	4.0	−0.69	4.74E+07	0.243	42
544.7153......	511	o	2.0	18864	e	2.0	−0.79	3.67E+07	−0.240	65
545.8967......	2527	o	3.0	20840	e	3.0	−1.24	1.29E+07	0.158	17
588.3625......	8981	o	4.0	25972	e	4.0	−0.85	2.72E+07	−0.237	12
624.2941......	4827	o	3.0	20840	e	3.0	−0.98	1.76E+07	−0.158	15
633.5406......	5061	o	3.0	20840	e	3.0	−1.18	1.10E+07	−0.243	16
659.9482......	0	o	4.0	15149	e	4.0	−1.03	1.44E+07	−0.191	59
746.1875......	4490	o	5.0	17887	e	5.0	−1.01	1.19E+07	−0.179	32
810.5394......	8437	o	6.0	20771	e	6.0	−0.97	1.10E+07	−0.185	16
991.0075......	5061	o	3.0	15149	e	4.0	−0.74	1.26E+07	0.250	45

NOTE.—For each transition, we give the wavelength, the lower and upper levels (energy, parity, J value), the weighted oscillator strength (log gf) and transition probability (gA), the cancellation factor (CF), and the laboratory intensity.

[a] HFR + CP values as obtained in this work (calculation D; see text).

[b] Small values of CF indicate strong cancellation effects.

[c] According to Blaise & Wyart 1992.

lator strengths have been calculated for about 900 transitions of Th III. Because of space limitations, all these results cannot be reported here, but they can be found in a database of astrophysical interest, DREAM.[6]

In Table 4, however, we give the transitions depopulating the levels for which the lifetimes have been measured in the present work. For each of these transitions, we quote both the weighted HFR transition probabilities (calculation D) and also, in the last column, the A-values normalized according to the lifetime measurements reported here. These last numbers are expected to be the most accurate data. Table 5 contains the oscillator strengths and the Einstein coefficients for the most intense transitions observed in the laboratory (Blaise & Wyart 1992).

The uncertainties affecting the oscillator strengths, which rely upon the accuracy of the theoretical branching ratios, are difficult to assess because no experimental data are available for comparison. However, from comparisons between theory and experiment carried out in a recent past for a variety of heavy ions, the accuracy of the *f*-values of the intense transitions is expected to scatter around 5%–10%. For the weak transitions (also difficult to measure with precision), the uncertainties could be larger, particularly when cancellation effects are affecting the line strength calculations. It should be emphasized, however, that all the transitions of Table 5 are not affected by such effects.

4. THORIUM IN THE STARS

Thorium has been relatively little considered in stellar spectra. This is related to the fact that the Th II transitions are relatively weak and that the resolution reached until recently on many stellar spectra did not allow detailed quantitative study of weak line profiles in relation to blending problems. The high resolution and signal-to-noise ratio that are now reachable on the most recent spectra (e.g., the *HST* spectra) allow a more accurate quantitative analysis of the chemical composition of the stars.

It is worth noting here that the 401.9129 nm transition of the radionuclide ^{232}Th II has been investigated by Butcher (1987, 1988) in 20 G-type dwarfs and giants of various ages in order to connect the timescale of nucleosynthesis to that of stellar and Galactic evolution. Thirteen lines of Th II have been also suggested as present or possibly present in the Przybylski star (HD 101065) in the spectral range 395.9–500.0 nm (see the paper by Cowley et al. 2000; see also the wavelength list on Cowley's Web site[7]). In the same wavelength range, four transitions observed at 455.560, 458.917, 467.626, and 486.313 nm, respectively, have been identified as being due to doubly ionized thorium (Th III).

As doubly ionized lanthanides are currently observed in many CP stars, frequently with large overabundances, it is expected that some doubly ionized actinides, and particularly Th III, should also appear in the UV or visible spectra of some hot stars. A detailed investigation of high-resolution spectra (e.g., those obtained with the *HST*) is needed to firmly establish such identifications. It is anticipated that the *f* values obtained in the present work will allow a quantitative investigation of thorium abundance in these stars.

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[6] DREAM is available at: http://www.umh.ac.be/~astro/dream.shtml; it is also available through anonymous ftp at: ftp://umhsp02.umh.ac.be/pub/ftp_astro/dream.

[7] Available at: http://www.astro.Isa.umich.edu/users/cowley/prznew2.html.

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