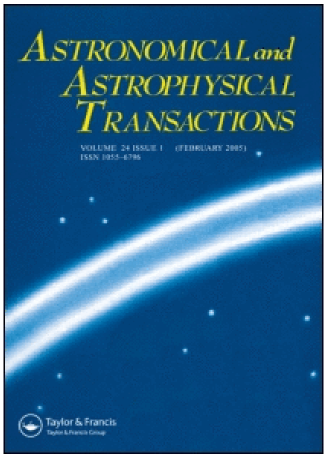

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Experimental study of transitionprobabilities of neutral and singlyionized lanthanide atoms

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EXPERIMENTAL STUDY OF TRANSITION PROBABILITIES OF NEUTRAL AND SINGLY IONIZED LANTHANIDE ATOMS

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A method of extended crossed atomic and electron beams is proposed for determination of the branching ratios for excited states. We measured the branching ratios for Gd I, Er I, Dy I, II and Sm I levels for which the lifetimes had previously been measured by different authors using various methods. Using known lifetimes of the excited levels, we found the absolute transition probabilities for 90 spectral lines of Gd I, 41 lines Er I, 35 lines Dy I, 28 lines Dy II and 156 lines Sm I in the 260–800 nm spectral range. The values of the transition probabilities determined in this paper are in good accordance with the results obtained by the hook method. The error of the reported transition probabilities is estimated not to exceed 25.

KEY WORDS Transition probabilities, lanthanide

1 INTRODUCTION

The interest in radiative constants of rare-earth element (REE) atoms and ions is due primarily to their importance in astrophysical investigations, such as those listed below.

1. Determination of REE in the Sun, where, as is well known, the REE atoms represent one of the maxima on the element distribution curve, and in a class of peculiar stars, where the relative REE abundances exceed those both in the Sun and in meteorites by four to five orders of magnitude.
2. Investigation of the processes that take place in stellar atmospheres and which are of interest for understanding the origin of the Sun and other stars.
3. Theoretical verifications of nucleosynthesis of chemical elements in astrophysical objects.

The data on lifetimes of the levels and oscillator strengths of REE atoms and ions are also important for the development of gas lasers, which have a REE vapor as an active medium. Recently, considerable interest in these atomic constants has arisen in connection with investigations of Rydberg and autoionizing states, which are important also for REE isotope separation.

The investigation of plasmas in thermonuclear devices, where REE are present as impurities, also requires a knowledge of the radiative constants of these elements. However, theoretical models for these complicated atomic systems which can in turn be improved by comparison with experimental data are being developed. Different methods are employed for measuring the spontaneous transition probabilities A_{ki} and the directly related oscillator strengths f_{ik} of the spectral lines (Huber and Sandeman, 1986). Most widely used are the emission, absorption, and dispersion methods; each has its own merits and drawbacks and its own range of applicability. These methods allow one to measure with an adequate accuracy the product $N_k A_{ki}$ or $N_i f_{ik}$ where N_k and N_i are the atomic concentrations in the appropriate initial eigenstates. To obtain the absolute values of A_{ki} or f_{ik} one has to measure the concentration of emitting (N_k) or absorbing (N_i) atoms which is not easy and constitutes the main source of errors in determination of transition probabilities and oscillator strengths.

This problem is commonly solved nowadays by using a method that does not imply measurements of atomic concentrations and uses the independently measured radiative lifetimes τ_k of excited states and the branching ratios h_{ki}.

This radiative lifetime of a level k is known to be expressed via the transition probabilities by

$$\tau_k = \frac{1}{\sum_i A_{ki}},$$

where the summation is made over all transitions from level k to lower lying levels i. When only a single transition from the k level is possible, $\tau_k^{-1} = A_{ki}$. If several transitions to the lower states occur, the concept of branching ratios is introduced, defined by the relationship

$$h_{ki} = \frac{A_{ki}}{\sum_i A_{ki}} = A_{ki}\tau_k,$$

where

$$A_{ki} = \frac{h_{ki}}{\tau_k}.$$

Obviously for any level k, $\sum_i h_{ki} = 1$. Thus, h_{ki} is a dimensionless quantity with the scale being fixed within a group of lines with a common upper level. Therefore, by measuring the relative intensities of spectral lines with a common upper level it is possible to obtain the branching factors, and by using known radiative lifetimes to determine the absolute transition probabilities A_{ki}.

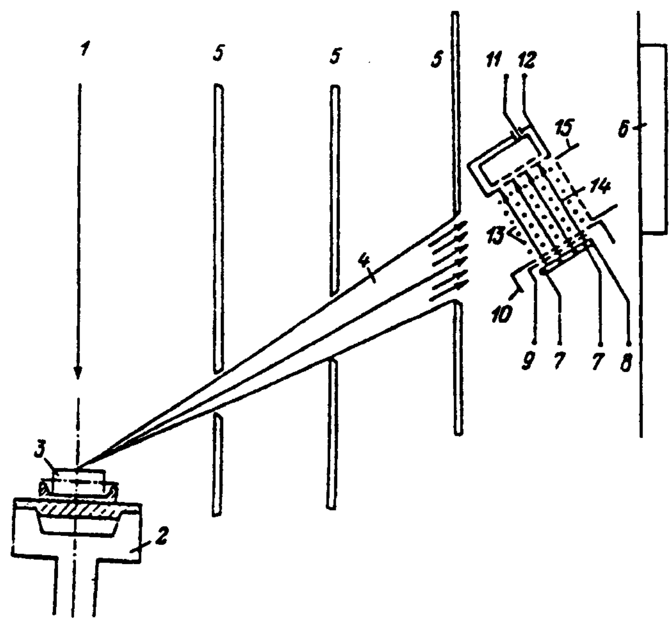

Figure 1 Schematic diagram of the emission source: *1*, electron beam; *2*, water-cooled beam; *3*, substance under study; *4*, atomic beam; *5*, water-cooled diaphragms; *6*, water-cooled panel for condensation of the particles; *7*, cathode heater; *8*, cathode; *9*, control grid; *10*, focusing grid; *11*, internal electron collector; *12*, external electron collector; *13*, tungsten filaments; *14*, electron beam; *15*, removable grid for calibrating plates.

2 EXPERIMENT

The radiation sources commonly used in the measurements of the relative intensities of spectral lines are either electrodeless gas-discharge lamps excited by an rf electromagnetic field or by hollow cathode sources. The use of these sources usually entails certain restrictions arising from the effects of reabsorption on the relative intensities of spectral lines (Bisson *et al.*, 1991). These reabsorption effects can be almost completely eliminated by using crossed atomic and electron beams due to the low density of the emitting medium. The crossed beam in its conventional form does not provide much information since the optical signal generated by this source is quite weak. This problem was solved by the method of extended crossed beams and successfully used until now for systematic measurements of the excitation cross-sections of atoms, molecules, and their ions by electron impact. The method of extended crossed beams, in contrast to conventional methods, a significantly increased (by two or three orders of magnitude) volume of the beam crossing, which results in a corresponding increase of the optical signal without increasing the particle densities in the beams. The experimental technique proposed (Smirnov and Sharonov, 1971) has subsequently been improved.

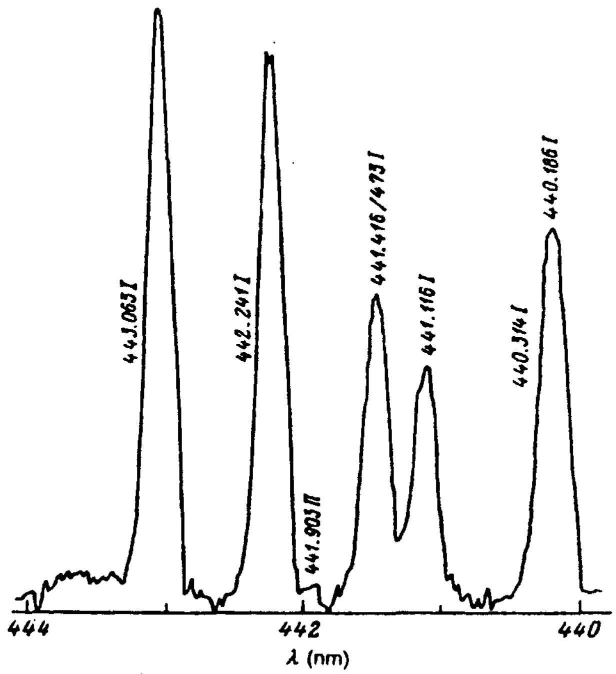

Figure 2 Gadolinium spectrum in the 440–444 nm range. Electron energy is 30 eV.

A schematic diagram of an up-to-date emission source is shown in Figure 1. The electron beam (1) from a melting electron gun heats the substance under study (3), placed in the crucible (2). The material and design of the crucible depend on the physical and technological properties of the substance studied. A water-cooled set of diaphragms (5) select from atoms or molecules evaporated from the crucible the beam (4) of 26 x 200 mm^2 cross-section square it intersects with the electron beam (14). The distance between the intersection region and the crucible is 280 mm, the beam fan angle is $\approx 40°$, and the beam tilt relative to the horizontal plane is 25°. After passing the intersection region, the particles are condensed on a water-cooled panel.

The beam of slow electrons with controlled energy is produced by a low-voltage electron gun with an indirectly heated flat oxide cathode (8). The transverse beam dimensions are 13 $\times$ 200 mm^2, the total flight span being 30 mm. The internal electron collector (11) is kept at +15 V relative to the external collector (12), which entails collecting the scattered and secondary emitted electrons. The spread of the electron energy distribution measured by the stopping-potential method is 0.9 eV at an electron energy of 100 eV and, respectively, 1.0 eV at 20 eV and 200 eV (for 90 percent of electrons).

As our experimental setup was primarily designed for measuring cross-sections of low-energy inelastic collisions with heavy particles in the range, special measures were taken to reduce the effect of the electron-beam space charge. For this purpose, in collision region along the axis of the optical system (i.e., perpendicular to the plane of Figure 1 26-μm diameter tungsten filaments (13) spaced by 4×4 mm^2 were placed, serving as equipotential lines with the potential equal to that of the setup frame. These filaments permitted us to improve the equipotentiality in the collision region by more than an order of magnitude, which is of particular importance for electron energies below 10–15 eV. When measuring the branching ratios, it is expedient to employ higher electron energies (30–50–100 eV). Besides, the spectrum is scanned at a fixed electron energy so that the problem of equipotentiality in the collision region proves to be of secondary importance.

Emission of the excited atoms and molecules in the collision region normal to the atomic and electron beams was focused by a two-mirror condenser on to the entrance slit of an MDR-23 monochromator equipped with a 1200 or 600-grooves mm^{-1} difraction grating. Using only reflecting optical elements in the optical system allowed us to study in the 190–850-nm spectral range without additional adjustment of the system.

The spectral resolution employed in most experiments was 0.10–0.15 nm, reaching in certain cases 0.05 nm. As an illustration, in Figure 2 we show the spectrum of gadolinium in the 440–444-nm range recorded at 30 eV energy of exciting electrons.

The optical detector used was a PMT (FEU-39A or FEU-79), the spectral sensitivities being independently calibrated at three laboratories. Since the difference between the results of three sets of measurements did not exceed 5–12 percent over the whole spectral range, average values of the spectral sensitivity were used.

The spectral transmission of the optical channel (condenser, monochromator, and optical windows) was measured with two identical successively placed monochromators for two mutually orthogonal linear polarizations. The final error for the relative excitation cross-sections varied from 5 percent (for lines of moderate intensity in the 300–700 nm spectral range) to 15 percent (for weak lines located beyond the indicated spectral region). Metal was evaporated by the electron beam at a surface temperature of 1850 K. The atomic concentration at the beam intersection was 10^{10} cm^{-3}. When detecting intense resonance lines, the atomic concentration was reduced to 10^9 cm^{-3}. We have measured the excitation cross-sections of numerous gadolinium, erbium, dysprosium, samarium atoms and singly ionized dysprosium spectral lines excited by 30 eV electrons. These results will be presented in a separate publication.

The excitation cross-sections of the spectral lines are known (Peterkop, 1982) to be proportional to spontaneous transition probabilities, which allows us to measure the branching ratios for the excited levels. We used this circumstance to obtain the absolute A_{ki} values for the spectral lines of Gd I, Er I, Dy I, II and Sm I, from the lifetimes of excited levels τ_k measured earlier by different authors using various methods. For this purpose, the data of the tables (Wysocka–Lisek, 1970; Meggers *et al.*, 1975; Martin *et al.*, 1978) and original papers were analyzed to elucidate all possible transitions of Gd I, Er I, Dy I, II, Sm I for which the lifetimes of the excited levels had been collected by Blagoev and Komarovskii (1994). It appeared that these levels decayed principally via transitions terminating at the ground-state

Table 1. Electronic transition probabilities of the Gd I spectral lines

$\lambda(nm)$	$E_L(cm^{-1})$	$E_U(cm^{-1})$	J_L	J_U	$A_{ki}(10^{-8}\ s^{-1})$	
					KS(1992)	*K*
769.445	10222	23215	1	2	0.020	
765.032	10576	23644	3	4	0.027	
633.634	6786	22564	4	3	0.0094	
614.439	6550	22821	3	4	0.011	
611.407	1719	18070	6	6	0.050	
610.907	1719	18084	6	5	0.0093	
604.401	7103	23644	5	4	0.017	
602.113	6786	23390	4	3	0.017	
599.908	6550	23215	3	2	0.019	
593.771	6378	23715	2	2	0.033	
593.684	6550	23390	3	3	0.029	
593.029	6786	23644	4	4	0.037	
590.456	999	17931	5	4	0.018	
585.622	999	18070	5	6	0.042	
585.163	999	18084	5	5	0.038	
582.397	215	17381	3	2	0.0075	
579.138	533	17795	4	3	0.032	
575.417	7480	24854	6	6	0.011	
575.188	0	17381	2	2	0.0091	
574.636	533	17931	4	4	0.015	
573.598	7947	25376	7	7	0.011	
573.216	533	17974	4	4	0.0060	
570.942	999	18509	5	5	0.018	
570.135	215	17750	3	2	0.027	
569.622	533	18084	4	5	0.052	
564.324	215	17931	3	4	0.043	
563.225	0	17750	2	2	0.046	
562.955	215	17974	3	4	0.016	
561.791	0	17795	2	3	0.044	
557.613	6786	24715	4	3	0.011	
557.253	7103	25044	5	5	0.010	
553.337	6976	25044	5	5	0.010	
549.875	7480	25661	6	6	0.0033	
547.572	6786	25044	4	5	0.0098	
546.972	7103	25381	5	5	0.0059	
538.415	10884	29451	4	5	0.071	
491.012	6976	27337	5	6	0.012	
464.764	1719	23229	6	6	0.037	0.034
458.129	999	22821	5	4	0.14	0.11
453.781	533	22564	4	3	0.25	0.27
451.966	215	22335	3	2	0.38	0.38
450.379	999	23196	5	5	0.019	0.010
449.713	999	23229	5	6	0.14	0.13
448.548	533	22821	4	4	0.018	0.013
447.612	0	22335	2	2	0.38	0.37
447.328	215	22564	3	3	0.024	0.013
443.063	0	22564	2	3	0.30	0.29
442.241	215	22821	3	4	0.31	0.26
441.473	999	23644	5	4	0.18	0.20
441.116	533	23196	4	5	0.14	0.12

Table 1. Continued

$\lambda(nm)$	$E_L(cm^{-1})$	$E_U(cm^{-1})$	J_L	J_U	$A_{ki}(10^{-8}\ s^{-1})$	
					KS(1992)	K
440.186	1719	24430	6	6	0.36	0.41
437.383	533	23390	4	3	0.27	0.29
434.662	215	23215	3	2	0.37	
432.569	533	23644	4	4	0.50	0.50
432.120	1719	24854	6	6	0.13	0.14
431.384	215	23390	3	3	0.41	0.43
430.634	0	23215	2	2	0.35	0.34
428.612	1719	25044	6	5	0.036	
427.417	0	23390	2	3	0.060	0.078
426.700	215	23644	3	4	0.059	0.062
426.660	999	24430	5	6	0.13	0.12
422.585	1719	25376	6	7	0.89	
422.503	1719	25381	6	5	0.050	
419.163	999	24850	5	4	0.12	0.14
419.078	999	24854	5	6	0.42	0.30
417.554	1719	25661	6	6	0.44	0.42
415.778	999	25044	5	5	0.033	0.036
413.416	533	24715	4	3	0.26	0.27
410.026	999	25381	5	5	0.16	0.17
408.053	215	24715	3	3	0.055	0.060
407.870	533	25044	4	5	0.70	0.59
405.822	215	24850	3	4	0.66	0.57
405.364	999	25661	5	6	0.63	0.62
404.501	0	24715	2	3	0.40	
402.335	533	25381	4	5	0.17	
390.565	1719	27316	6	5	0.14	0.14
379.575	999	27337	5	6	0.079	0.059
378.305	999	27425	5	4	0.75	0.94
377.126	533	27042	4	3	0.056	0.072
375.794	533	27136	4	3	0.45	0.57
373.267	533	27316	4	5	0.083	
372.657	215	27042	3	3	0.057	0.044
371.748	533	27425	4	4	0.51	0.67
371.592	215	27119	3	2	0.13	0.074
371.357	215	27136	3	3	0.68	0.92
369.693	0	27042	2	3	0.055	0.042
368.413	0	27136	2	3	0.71	0.91
367.405	215	27425	3	4	0.24	0.34
360.487	1719	29451	6	5	0.41	0.59
351.365	999	29451	5	5	0.25	0.25

Note. References: K, Komorovskii (1991); KS, Komarovskii and Smirnov (1992).

levels as well as at the nearby levels, yielding spectral lines in the visible range. In all possible cases, we measured branching coefficients for levels with known lifetimes τ and calculated probabilities of corresponding transitions. We did not take into account possible weak transitions to levels of higher lying terms with respect to the

Table 2. Electronic transition probabilities of the Er I spectral lines

$\lambda(nm)$	$E_L(cm^{-1})$	$E_U(cm^{-1})$	J_L	J_U	$A_{ki}(10^{-8}\ s^{-1})$	
					KS(1993)	*K*
692.593	6958	21393	5	5	0.26	
639.813	6958	22583	5	6	0.14	
591.646	6958	23856	5	5	0.35	
590.606	6958	23855	5	5	0.51	
585.531	0	17074	6	6	0.24	
582.679	0	17157	6	7	1.2	1.0
576.280	0	17348	6	5	0.84	1.1
549.172	6958	25162	5	5	0.57	
533.937	6958	25682	5	5	0.20	
531.189	5035	23856	4	5	0.21	
520.652	0	19201	6	5	20	
496.697	5035	25162	4	5	1.5	
484.203	5035	25682	4	5	1.9	
473.901	6958	28054	5	6	1.5	
472.269	0	21168	6	7	1.2	
467.316	0	21393	6	5	1.1	
460.661	0	21702	6	6	7.7	7.5
442.677	0	22583	6	6	2.6	2.7
440.934	0	22673	6	5	5.8	5.7
439.742	10751	33485	4	5	12	
419.070	0	23856	6	5	6.2	6.7
418.548	0	23885	6	5	1.1	
415.111	0	24083	6	5	99	96
409.810	6958	31353	5	4	59	
408.763	0	24457	6	6	27	30
402.051	6958	31824	5	6	125	
400.796	0	24943	6	7	180	170
398.233	6958	32062	5	5	100	
397.358	0	25159	6	7	37	37
397.304	0	25162	6	5	35	48
395.642	0	25268	6	6	3.9	3.8
394.442	5035	30380	4	5	140	
393.701	0	25393	6	6	29	29
390.540	0	25598	6	7	16	15
389.268	0	25682	6	5	58	
386.285	0	25880	6	6	115	116
381.033	0	26237	6	6	28	27
379.863	5035	31353	4	4	12	
356.354	0	28054	6	6	3.8	5.2
333.156	0	30007	6	6	7.7	7.8
298.552	0	33458	6	5	12	23

Note. References: KS (1993), Komarovskii and Smirnov (1993); K, Komarovskii (1991).

ground-state level that can result in a small overestimation of the transition probabilities obtained. Moreover, blending of closely spaced spectral lines precluded the measurement of branching coefficients for a number of levels.

Table 3. Electronic transition probabilities of the Dy I spectral lines

$\lambda(nm)$	$E_L(cm^{-1})$	$E_U(cm^{-1})$	J_L	J_U	$A_{ki}(10^{-8}\ s^{-1})$	
					KS(1994)	*K*
793.498	4134	16733	7	8	0.0081	
737.604	4134	17688	7	7	0.14	
719.865	4134	18022	7	8	0.0067	
679.030	4134	18857	7	7	0.060	
625.909	0	15972	8	9	0.82	0.82
598.856	0	16694	8	7	0.53	0.46
597.449	0	16733	8	8	0.39	0.37
569.933	4134	21675	7	7	0.21	
566.643	20194	37836	8	9	12	
566.441	4134	21783	7	7	0.086	
565.201	0	17687	8	7	0.37	0.45
563.950	0	17727	8	9	0.41	0.60
562.749	4134	21899	7	8	0.16	
554.727	0	18022	8	8	0.26	0.39
537.610	19241	37836	9	9	10	
530.158	0	18857	8	7	0.91	1.1
485.897	4134	24709	7	7	0.18	
474.491	7050	28120	6	6	1.7	
461.226	0	21675	8	7	8.3	8.9
458.936	0	21783	8	7	13	14
457.778	0	21838	8	9	2.1	2.4
456.509	0	21899	8	8	0.67	0.86
422.111	4134	27817	7	8	150	150
421.809	4134	27835	7	7	180	140
421.172	0	23737	8	9	210	180
419.484	0	23832	8	8	85	76
418.682	0	23878	8	8	120	110
416.797	4134	28120	7	6	150	210
413.035	0	24204	8	8	1.7	1.8
404.597	0	24709	8	7	180	170
401.382	0	24907	8	7	3.3	3.2
296.460	0	33721	8	8	10	7.1
286.270	0	34922	8	7	10	7.0
264.215	0	37836	8	9	14	
262.369	0	38103	8	9	43	

Note. References: KS(1994), Komarovskii and Smirnov (1994); K, Komarovskii (1991).

3 RESULTS

The values of A_{ki} found for 90 spectral lines of Gd I (Komarovskii and Smirnov, 1992), 41 lines of Er I (Komarovskii and Smirnov, 1993), 35 lines of Dy I and 28 lines of Dy II (Komarovskii and Smirnov, 1994) and 156 lines of Sm I (in press) in the 260–800 nm range are presented in Tables 1–5. The first five columns of the tables contain transition wavelengths λ(nm), energies of lower $E_L(\mathrm{cm}^{-1})$ and upper $E_U(\mathrm{cm}^{-1})$ levels, and their total angular momenta J_L and J_U. In tne sixth

Table 4. Electronic transition probabilities of the Dy II spectral lines

$\lambda(nm)$	$E_L(cm^{-1})$	$E_U(cm^{-1})$	J_L	J_U	$A_{ki}(10^{-8}\ s^{-1})$
					KS(1994)
727.357	15691	29437	13/2	15/2	5.1
476.005	4341	25343	15/2	17/2	1.3
465.477	4341	25818	15/2	17/2	0.80
425.634	828	24316	15/2	17/2	16
414.309	4756	28885	13/2	15/2	13
411.134	0	24316	17/2	17/2	82
410.330	828	25192	15/2	15/2	17
407.796	828	25343	15/2	17/2	34
407.312	4341	28885	15/2	15/2	9.2
405.057	4756	29437	13/2	15/2	20
404.632	4341	29109	15/2	15/2	3.9
400.045	828	25818	15/2	17/2	38
398.367	4341	29437	15/2	15/2	20
396.839	0	25192	17/2	15/2	42
394.468	0	25343	17/2	17/2	18
387.211	0	25818	17/2	17/2	11
378.618	828	27233	15/2	17/2	100
364.541	828	28252	15/2	17/2	48
356.315	828	28885	15/2	15/2	14
353.852	0	28252	17/2	17/2	32
353.496	828	29109	15/2	15/2	27
353.170	0	28307	17/2	19/2	140
350.681	828	29336	15/2	17/2	7.6
349.449	828	29437	15/2	15/2	24
346.097	0	28885	17/2	15/2	28
343.437	0	29109	17/2	15/2	19
340.780	0	29336	17/2	17/2	48
339.616	0	29437	17/2	15/2	9.6

column, the probabilities of spontaneous transitions are given. The last column shows for comparison the A_{ki} values recalculated from the oscillator strength values for the Gd I, Er I, Dy I, Sm I spectral lines measured earlier by the hook method and published in Komarovskii (1991). The comparison shows that in most cases the results obtained by different methods are in good agreement. Data on oscillator strengths and transition probabilities of neutral and singly ionized atoms of the REE are available in a number of experimental and theoretical works reviewed in Komarovskii (1991). Transition probabilities for 70 elements are given in the monograph by Korliss and Bozman (1968) which contains experimental data obtained by the radiation method. Semi-empirical calculations of gf-values are given in the tables by Kurucz and Peytermann (1975). From numerous investigations by different authors, it follows that the results presented in (Korliss *et al.*, 1968; Kurucz *et al.*, 1975) are often inconsistent with the most reliable experimental data and differ from them by several times or, sometimes, by orders of magnitude. Therefore, we did not compare our experimental results with the transition probabilities given in Korliss *et al.* (1968) and Kurucz and Peytermann (1975). The errors in the transi-

Table 5. Electronic transition probabilities of the Sm I spectral lines

$\lambda(nm)$	$E_L(cm^{-1})$	$E_U(cm^{-1})$	J_L	J_U	$A_{ki}(10^{-8}\ s^{-1})$	
					KS(in press)	K
653.396	812	16112	2	1	0.64	0.50
658.053	1490	16682	3	2	0.28	0.26
642.590	2273	17831	4	3	0.26	0.35
636.741	1490	17190	3	2	0.39	0.41
631.949	293	16112	1	1	0.03	
629.597	812	16691	2	1	0.13	0.16
625.894	1490	17462	3	2	0.04	0.02
620.472	0	16112	0	1		0.01
611.779	1490	17831	3	3	0.21	0.23
610.395	812	17191	2	2	0.03	0.02
609.990	293	16682	1	2	0.30	0.26
609.655	293	16691	1	1	0.19	0.11
608.412	812	17244	2	3	0.45	0.54
602.752	1490	18076	3	2	0.21	0.18
600.418	812	17462	2	2	0.42	0.50
599.509	2273	18949	4	3	0.49	0.52
598.968	0	16691	0	1	0.28	0.26
591.636	293	17190	1	2	0.48	0.46
589.535	812	17770	2	1	0.40	0.32
587.421	812	17831	2	3	0.45	0.37
586.779	3125	20163	5	4	1.5	2.2
580.284	2273	19501	4	3	2.5	2.5
579.091	812	18076	2	2	0.29	0.20
577.924	1490	18788	3	2	1.5	1.6
574.119	812	18225	0	1	0.2	0.1
573.295	4021	21459	6	5	2.7	3.8
572.606	1490	18949	3	3		0.02
572.019	293	17770	1	1	1.2	1.4
571.145	2273	19777	4	3	0.45	0.79
568.698	4021	21600	6	5	1.3	1.1
565.986	812	18475	2	1	8.2	8.0
564.747	1490	19198	3	4		0.11
564.267	2273	19990	4	4	2.9	1.9
562.601	0	17770	0	1	3.9	2.2
562.179	293	18076	1	2	1.7	1.1
558.820	2273	20163	4	4	1.0	1.1
558.183	2273	20183	4	5		0.1
557.489	293	18225	1	1	2.2	1.7
556.137	812	18788	2	2	0.65	0.54
555.040	1490	19501	3	3	4.3	6.5
551.210	812	18949	2	3	2.6	3.6
550.090	812	18986	2	1	0.32	0.37
549.821	293	18475	1	1	6.0	4.9
549.372	812	19009	2	2	11	10
548.542	0	18225	0	1	4.4	4.5
546.672	1490	19777	3	3	6.0	7.1
545.300	3125	21459	5	5	10	16
542.157	2273	20713	4	4	2.4	1.8
541.139	3125	21600	5	5	2.1	
540.523	293	18788	1	2	5.7	4.9

Table 5. Continued

$\lambda(nm)$	$E_L(cm^{-1})$	$E_U(cm^{-1})$	J_L	J_U	$A_{ki}(10^{-8}\ s^{-1})$	
					KS(in press)	*K*
540.370	1490	19990	3	4	2.7	4.7
536.835	4021	22643	6	6	9.7	13
535.062	3125	21810	5	5	3.9	3.3
534.912	812	19501	2	3	2.2	1.0
534.807	293	18986	1	1	1.3	1.4
534.126	293	19009	1	2	4.9	4.2
532.058	2273	21063	4	5	4.5	6.2
529.922	812	19677	2	2	0.25	0.28
528.291	4021	22944	6	6	16	26
527.139	812	19777	2	3	18	17
526.565	0	18986	0	1	1.5	1.1
525.191	3125	22161	5	6	12	17
521.075	2273	21459	4	5	1.0	0.7
520.059	1490	20713	3	4	27	27
518.709	1490	20763	3	2	1.8	1.2
518.552	812	20091	2	1	0.72	0.44
517.275	2273	21600	4	5	8.1	9.6
515.723	293	19677	1	2	2.5	2.0
514.582	2273	21701	4	3	1.1	1.3
512.216	3125	22643	5	6	15	25
511.716	2273	21810	4	5	24	31
508.832	812	20459	2	3	2.6	2.2
504.950	293	20091	1	1	2.6	2.4
504.427	3125	22944	5	6	18	28
501.088	812	20763	2	2	0.7	0.4
497.595	0	20091	0	1	18	16
494.630	1490	21701	3	3	5.8	7.9
491.899	1490	21813	3	2	32	39
491.040	2273	22632	4	3	44	53
490.496	812	21194	2	1	23	24
484.831	2273	22893	4	4	24	24
484.170	4021	24669	6	5	87	140
478.588	812	21701	2	3	19	20
478.312	293	21194	1	1	64	53
477.020	2273	23231	4	3	4.7	
475.072	2273	23317	4	3	13	15
472.843	1490	22632	3	3	49	57
471.707	0	21194	0	1	38	31
468.873	2273	23595	4	4	33	33
468.155	1490	22844	3	2	24	26
467.083	1490	22893	3	4	14	
467.075	1490	22893	3	2	25	
466.356	2273	23710	4	3	25	30
464.949	812	22314	2	1	61	66
464.540	293	21813	1	2	30	20
461.125	812	22492	2	2	4.4	6.3
459.674	293	22041	1	0	83	67
456.958	2273	24151	4	3	3.8	6.9
456.677	1490	23381	3	2	8.9	9.0
455.663	3125	25065	5	4	3.5	6.6

Table 5. Continued

$\lambda(nm)$	$E_L(cm^{-1})$	$E_U(cm^{-1})$	J_L	J_U	$A_{ki}(10^{-8}\ s^{-1})$	
					KS(in press)	*K*
455.003	2273	24245	4	3	4.0	6.2
453.757	812	22844	2	2	2.1	1.9
453.244	1490	23546	3	2	7.3	8.2
452.742	812	22893	2	2	3.6	4.5
452.318	812	22914	2	1	21	16
452.255	1490	23595	3	4	6.1	6.3
450.338	293	22492	1	2	15	15
449.911	1490	23710	3	3	33	36
449.002	3125	25391	5	5	2.2	3.9
448.032	0	22314	0	1	27	24
447.750	3125	25453	5	5	5.7	7.6
445.929	812	23231	2	3	19	17
444.228	812	23317	2	3	24	
443.334	3125	25676	5	5	4.5	
443.308	293	22844	1	2	7.8	
442.966	812	23381	2	2	36	41
442.338	293	22893	1	2	4.6	3.9
441.933	293	22914	1	1	61	55
441.158	1490	24151	3	3	18	22
440.312	2273	24978	4	5	36	42
439.734	812	23546	2	2	16	16
439.335	1490	24245	3	3	14	15
438.622	2273	25065	4	4	7.6	11
436.595	812	23710	2	3	2.2	2.0
436.291	0	22914	0	1	49	43
435.082	1490	24467	3	3	2.6	3.8
433.002	293	23381	1	2	38	24
432.446	2273	25391	4	5	13	20
431.285	2273	25453	4	5	19	17
429.914	293	23546	1	2	5.8	4.8
429.674	4021	27288	6	7	100	170
428.350	812	24151	2	3	24	
424.045	1490	25065	3	4	2.6	2.9
422.618	812	24467	2	3	13	13
418.333	1490	25387	3	4	14	13
399.002	3125	28181	3	4	43	66
397.466	2273	27425	4	3	51	60
395.189	1490	26787	3	3	51	32
392.522	812	26281	2	1	49	56
384.878	812	26787	2	2		8.5
384.676	293	26281	1	1	6.8	6.3
383.281	2273	28356	4	3	10	16
382.297	812	26962	2	1	4.6	8.4
380.394	0	26281	0	1	24	23
378.268	293	26721	1	2	5.1	3.1
377.333	293	26787	1	2	26	12
375.641	812	27425	2	3	26	21
374.852	293	26962	1	1	21	15
374.546	1490	28181	3	4	27	30
372.816	812	27627	2	2	7.5	6.1

Table 5. Continued

$\lambda(nm)$	$E_L(cm^{-1})$	$E_U(cm^{-1})$	J_L	J_U	$A_{ki}(10^{-8}\ s^{-1})$	
					KS(in press)	*K*
372.103	1490	28356	3	3	13	18
370.785	0	26962	0	1	12	10
369.008	2273	29365	4	4	5.8	17
365.731	293	27627	1	2	6.1	4.5
362.948	812	28356	2	3	7.8	7.2
358.636	1490	29356	3	4	11	4.8

Note. References: KS, Komarovskii and Smirnov (in press); K, Komarovskii (1991).

tion probabilities obtained in the present paper are mainly determined by the errors in the measured excitation cross-section of the spectral lines and the lifetimes of the excited levels and also by disregarding the weak IR transitions when calculating the branching ratios. The maximum error is estimated to lie within 25 percent.

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