A Novel Approach for the Direct Determination of 28 Analytes in a Ce Matrix Without Chemical Separation Using CCD Detector-based ICP-AES

Yougant Airan^a, Arijit Sengupta^{b,*}, S.K. Thulasidas^b, and V. Natarajan^b

^a Chemistry Department, Hindu College, University of Delhi, Delhi, India

^b Radiochemistry Division, Bhabha Atomic Research Centre, Trombay, Mumbai, India

INTRODUCTION

Inductively coupled plasma (ICP) has been employed as a source for atomic emission spectrometry (AES) for over a decade (1-2). Owing to its capability of determining lower concentrations in a wide range of materials (3-4) and the advantages of being a sensitive method with a long dynamic range, it is clearly an excellent method for rapid multi-element analysis (5-6). The high temperature plasma (6000 K - 8000 K) source minimizes matrix effects and prevents the formation of polyatomic species during the excitation process. This in turn produces adequate sensitivity and increases the detection limits for many elements (7). The major disadvantage of ICP-AES is that it is subject to various kinds of interferences of which the spectral interference, arising from the complex nature of the emission spectra, forms the major contribution (8-11).

The rare earth elements (REEs) present line-rich spectra and their analytical wavelengths suffer a large number of interferences when the matrix constituents are other REEs (12-14). Since rare earths are increasingly needed for technological applications, they require rapid and accurate determination (15-17). Cerium (Ce) is the most abundant of the rare earth metals, found on average at the level of 66 parts per million (ppm) in the earth's crust and finds its application in nano medicine (18-19). The unique

ABSTRACT

Cerium is the most abundant rare earth element, consisting of about 0.0046% of the Earth's crust by weight. Thus, there is a great chance for Ce to be present in most minerals and geological samples and hence, the possibility of interfering in the determination of other analytes in the samples. In this work, the spectral interference was studied on 28 analytes (rare earths, Ag, B, Bi, Cd, Cu, Ca, Li, Ni, Sr, Gd, Fe, Mg, Mn, Zn, Dy, Na, Co, Cr, Tl, Lu, Nd, Pr, La, Ba, Ga, In, Al, and Pb) in order to optimize the interference-free spectral line selection for each analyte from a high purity Ce matrix using a highly sensitive capacitive coupled device (CCD) detector-based ICP-AES. The method describes the direct trace level determination of these analytes without chemical separation. The correction factor (mg/L) and analytical performance were evaluated, such as sensitivity (counts/mg/L), detection limit (mg/L), linear dynamic range, precision, and tolerance level in the presence of Ce for each selected line. The results, obtained using synthetic samples prepared from a commercially available standard reference material of the individual analytes, were found in good agreement with the method proposed.

redox properties of cerium and cerium oxide nanoparticles have led to their use in a wide variety of industrial and commercial uses such as oxygen sensors, fertilizers,

as catalyst to remove toxic gases in automobile exhaust, and in nanotechnology fields (20-23). However, rare earths are not easily determined by a standard method owing to their chemical and physical similarity, their typically low concentrations, and their complex emission and absorption spectra. The ICP-AES technique for rare earth determination has superseded the use of earlier techniques, such as neutron activation analysis (24-25) and isotope dilution mass spectrometry (26), with respect to high specificity, high sensitivity, excellent detection capability, high precision and accuracy, and complete element cover.

In this study, ICP-AES with a capacitive coupled device (CCD) detector-based system was used to determine some common analytes and the rare earths Gd, Dy, Pr, Nd, La, and Lu in the presence of a Ce matrix. Several workers reported on their attempts to understand the spectral interference of REEs on other rare earths by ICP-AES with a photomultiplier tube-based detection system (27-31). However, it can be seen that the method proposed using the CCD-based detector is much more precise. Other advantages include the ability to choose alternative analytical lines of the elements. This is of great significance in a situation when the best analytically performed line of an analyte is significantly interfered by the emission-rich matrix element. The results obtained with the proposed method were validated by using synthetic samples.

Corresponding author.
E-mail: arijita@barc.gov.in

EXPERIMENTAL

Instrumental and Operating Conditions

The analysis was carried out using a model Arcos FHS12 inductively coupled plasma atomic emission spectrometer (ICP-AES) which provided a high temperature argon plasma as the source of excitation and a capacitive coupled device (CCD) as the detector system (Spectro Arcos, Germany). The operating conditions and the instrumental specifications are listed in Table I. The detector system, consisting of linear arrays of the CCD detectors (3648 pixels/array), thermally stabilized together with an optical system, provides the ability to choose alternate analytical lines (Figure 1).

Standard Solutions and Reagents

Standard solutions for all of the elements were prepared from CertiPUR® ICP standard reference material solutions of the individual elements (E-Merck, Darmstadt, Germany) by proper dilution. Suprapur® HNO₃ (E-Merck, Darmstadt, Germany) and quartz double distilled Milli-Q® water were used throughout this study. Even though ICP-AES exhibits a high degree of linear dynamic range, in order to obtain more precise calibration curves, multi-point standardization was carried out using 0.5 M HNO₃ as a lower standard and 0.05–1000 mg/L of the corresponding elemental standard as the higher standard for each line after proper peak search, auto-attenuation, etc. For the analysis of each sample, 10 replicate measurements were carried out, while for the determination of the detection limits and sensitivity, 25 replicate measurements were taken into account.

Methods

The method chosen for studying the spectral interference and select-

TABLE I
Specifications and Operating Conditions of ICP-AES

Instrumental Specifications	
Model	Arcos FHS12 ICP-AES (Spectro Arcos)
Optical design	Paschen-Runge mounting, Circular design
Focal length	750 mm
Grating	Holographic
Groove density	1800 grooves/mm (1), 3600 grooves/mm (2)
Wavelength range	130–800 nm
Entrance slit width	15 microns
Resolution (FWHM)	0.01 nm from 130–450 nm 0.02 nm from 450–800 nm
Thermal regulation	Controlled to $30 \pm 1^\circ\text{C}$
Frequency	27.12 MHz
Pump	Dual channel peristaltic pump
Detector	Linear arrays of CCD (3648 pixels/array)
Nebulizer	Concentric nebulizer with cyclonic spray chamber
ICP torch	Demountable, radial viewing
Operating Conditions	
Coolant flow	16 L/min
Auxiliary flow	0.6 L/min
Total time of measurement	28 s
Pump speed	30 rpm
RF power out put	1.2 kW
Input power	230 V AC

Fig. 1. Cross-sectional view of array of CCD detector.

ing the best line(s) in the presence of Ce for each analyte was performed by preparing a series of Ce solutions (commercially available standard reference material elemental solutions from E-Merck, Darmstadt, Germany) of varying concentrations from 0.05 mg/L to 1000 mg/L. The contribution due to Ce in each different channel of each analyte was observed and the correction factor, tolerance level, along with the analytical performance (detection limit, sensitivity, linear dynamic range, and precision for each analyte) were evaluated. Using the idea of the dependence of the correction factor on the concentration of the interfering element, Ce, it becomes easy to directly determine the interferent in the presence of other analytes by ICP-AES. The analytical performance for each identified line of Ce was evaluated.

The results of the developed method for the direct trace level determination of 28 analytes in a Ce matrix were also compared with other techniques and using synthetic samples without chemical separation. Ag was determined by flame atomic absorption spectrometry (FAAS) analysis. For REE determination, ion chromatography was used, while other analytes were determined by D.C. arc carrier distillation technique.

RESULTS AND DISCUSSION

Simultaneous Determination of Ce and the Different Analytes by ICP-AES

Since the contribution of Ce on the different analytes is dependent on the concentration of Ce, its correct amount needs to be estimated in the sample. Also, for defining spectral interference quantitatively, the correction factor of each identified line must be known. Even though Ce is a multi-electronic atom, not all of its lines can be used for the analysis and, based on ana-

lytical performance, only five lines were chosen to continue the study. The emission profiles for these five lines of Ce (393.373 nm, 413.380 nm, 413.765 nm, 418.660 nm, and 448.691 nm) are depicted in Figure 2. The calibration curves for these lines were established as shown in Figure 3. The detection limit of Ce using these lines followed the trend: 413.380 nm < 413.765 nm < 418.660 nm < 393.373 nm < 448.691 nm, while that of sensitivity followed the trend: 413.380 nm ~ 413.765 nm > 393.373 nm > 418.660 nm > 448.691 nm. The

slope of the calibration curves was considered as the sensitivity of the analytical lines, whereas the detection limits were calculated as the concentration equivalent to the intensity of the blank ($< x > + 5$ times the relative standard deviation values of the blank (5σ)). Synthetic samples containing Ce in the concentration range of 0.05 mg/L – 1000 mg/L were analyzed using these analytical lines. The results listed in Table II show that the 393.373 nm, 413.380 nm, 413.765 nm, and 418.660 nm lines can be suitably used for the determination

Fig. 2. Emission profiles of different analytical lines of Ce (a) 393.373 nm, (b) 413.380 nm, (c) 413.765 nm, (d) 418.660 nm, and (e) 448.691 nm.

of Ce up to 1000 mg/L. Beyond 1000 mg/L, the experiment was not carried out because of the choking problem of the nebulizer system. The study also revealed that the Ce 448.691 nm line was not suitable for its determination due to poor sensitivity and detection limits.

Spectral Interference of Ce on Other Analytes

Cerium, being the second member after lanthanum of the lanthanide series of 15 elements, has [Xn] 4f², 5d⁰, 6s² ground state electronic configuration and ¹G₄ ground state term. The spectral study of Ce revealed various transition lines in the spectrum due to its multi-electronic nature and therefore it interfered in the determination of other analytes shown in Tables III to VIII. The best lines for each analyte were chosen based on spectral interference and analytical performance (detection limit, sensitivity, linear dynamic range, and precision).

Effect on Ag, B, Bi, Cd, Cu, Ca, Li, Ni, Sr, Gd, Fe, Mg, Mn, Zn, and Dy

The results of spectral interference for Ag, B, Bi, Cd, Cu, Ca, Li, Ni, Sr, Gd, Fe, Mg, Mn, Zn, and Dy are listed in Table III, while the analytical performance is listed in Table IV.

Ag Lines

Of the four lines of Ag (224.641 nm, 243.779 nm, 328.068 nm, 338.289 nm), only the latter two showed no interference from Ce up to 1000 mg/L. The analytical performance of these two lines was similar and better, and thus 328.068 nm and 338.289 nm were chosen as the best lines for the determination of Ag in a Ce matrix.

B Lines

The analytical performance of the four lines of B (249.773 nm,

Fig. 3. Calibration curves for different analytical lines of Ce.

TABLE II
Determination of Ce by ICP-AES

Ce (mg/L)	393.373 nm	413.38 nm	413.765 nm	418.66 nm	448.691 nm
1	0.94 ± 0.02	1.05 ± 0.04	0.98 ± 0.04	0.95 ± 0.07	0.65 ± 0.08
5	5.1 ± 0.4	4.7 ± 0.4	5.2 ± 0.3	4.9 ± 0.3	7.8 ± 0.4
10	10.5 ± 0.7	9.5 ± 0.5	9.7 ± 0.6	10.3 ± 0.5	8.1 ± 0.7
20	18.9 ± 0.9	19.8 ± 0.7	20.5 ± 0.6	21.0 ± 0.9	24.1 ± 0.7
50	48 ± 3	50 ± 3	51 ± 2	48 ± 2	44 ± 3
100	97 ± 5	103 ± 6	98 ± 4	101 ± 3	113 ± 5
500	492 ± 11	508 ± 9	496 ± 11	498 ± 9	508 ± 8
1000	991 ± 12	1008 ± 10	997 ± 11	995 ± 10	1014 ± 8
D.L. (mg/L)	0.21	0.055	0.083	0.094	— ^a
Sensitivity (counts/mg/L)	2216	2314	2312	1899	— ^a
Linear Dynamic Range (mg/L)	0.21–1000	0.055–1000	0.083–1000	0.094–1000	— ^a

^a The Ce 448.691-nm line is not suitable for its determination.

249.677 nm, 182.641 nm, 208.959 nm) were close to each other but only 208.959 nm showed no interference in a Ce matrix up to 1000 mg/L and was chosen for further studies.

Bi Lines

Of the five lines of Bi, only the 306.772 nm line showed no inter-

ference from Ce up to 1000 mg/L. The sensitivity followed the trend: 306.772 nm > 223.061 nm > 206.170 nm > 222.825 nm > 190.241 nm. Thus, the 306.772 nm line was chosen for the determination of Bi in the presence of Ce.

TABLE III
Spectral Interference of Ce on Ag, B, Bi, Cd, Cu, Ca, Li, Dy, Sr, Gd, Fe, Mg, Mn, Ni, and Zn

Elements	Analytical Lines (nm)	Contribution from 1000 mg/L of Ce	Correction Interference	Tolerance Level (mg/L)	Elements	Analytical Lines (nm)	Contribution from 1000 mg/L of Ce	Correction Interference	Tolerance Level (mg/L)
Ag	338.289	– ^a	-	1000	Sr	407.771	– ^a	-	1000
	328.068	– ^a	-	1000		421.552	– ^a	-	1000
	224.641	8.6	8.6×10^{-3}	100		460.733	0.29	2.9×10^{-4}	500
	243.779	1.2	1.2×10^{-3}	200	Gd	342.247	5.7	5.7×10^{-3}	10
B	249.773	0.14	1.4×10^{-4}	500		335.047	0.1	1.0×10^{-4}	500
	249.677	0.16	1.6×10^{-4}	200		336.223	– ^a	-	1000
	182.641	0.29	2.9×10^{-4}	200	Fe	335.862	0.24	2.4×10^{-4}	200
	208.959	– ^a	-	1000		259.941	0.14	1.4×10^{-4}	500
Bi	223.061	1.0	1.0×10^{-3}	200		238.204	0.73	7.3×10^{-4}	100
	190.241	19.0	1.9×10^{-2}	50		239.562	0.17	1.7×10^{-4}	500
	306.772	– ^a	-	1000		244.451	2.9	2.9×10^{-3}	100
	222.825	5.5	5.5×10^{-3}	200		261.187	0.22	2.2×10^{-4}	200
Cd	206.170	2.6	2.6×10^{-3}	100		262.567	4.6	4.6×10^{-3}	100
	214.438	0.072	7.2×10^{-5}	500		262.829	1.0	1.0×10^{-3}	200
	226.502	– ^a	-	1000		275.573	0.43	4.3×10^{-4}	500
	228.802	0.37	3.7×10^{-4}	100		241.331	1.9	1.9×10^{-6}	100
Cu	361.051	5.2	5.2×10^{-3}	50		373.486	– ^a	-	1000
	324.754	– ^a	-	1000	Mg	279.553	– ^a	-	1000–
	327.396	– ^a	-	1000		280.270	– ^a	-	1000
	224.700	0.213	2.1×10^{-4}	200		285.213	0.084	8.4×10^{-5}	500
Ca	219.226	0.68	6.8×10^{-4}	200		279.079	0.41	4.1×10^{-4}	500
	219.958	0.629	6.3×10^{-4}	50		202.647	0.52	5.2×10^{-4}	50
	396.847	0.10	1.0×10^{-3}	100	Mn	257.611	– ^a	-	1000
	393.366	2.1	2.1×10^{-3}	5		259.373	0.16	1.6×10^{-4}	200
	317.933	– ^a	-	1000		260.569	– ^a	-	1000
	315.887	– ^a	-	1000		294.921	0.16	1.6×10^{-4}	500
	183.801	5.8	5.8×10^{-3}	100		403.076	0.50	5.0×10^{-4}	200
	422.673	0.14	1.4×10^{-4}	200	Ni	231.604	0.67	6.7×10^{-4}	100–
Li	670.780	– ^a	-	1000		221.648	0.37	3.7×10^{-4}	200
	460.289	– ^a	-	1000		232.003	0.39	3.9×10^{-4}	100
	323.261	11.7	1.2×10^{-2}	10		227.021	0.51	5.1×10^{-4}	100
	274.118	4.5	4.5×10^{-3}	200		300.249	0.65	6.5×10^{-4}	500
Dy	353.170	– ^a	-	1000		341.476	– ^a	-	1000
	394.468	4.8	4.8×10^{-3}	10	Zn	213.856	– ^a	-	1000
	340.780	– ^a	-	1000		206.200	3.7	3.7×10^{-3}	50
	353.602	– ^a	-	1000		202.613	0.25	2.5×10^{-4}	200
	364.540	9.1	9.1×10^{-3}	10		334.502	4.0	4.0×10^{-3}	50

Note: ^a = No interference.

TABLE IV
Analytical Performance of Ag, B, Bi, Cd, Cu, Ca, Li, Dy, Sr, Gd, Fe, Mg, Mn, Ni, and Zn ,in Presence of Ce

Ele- ments	Analytical Lines (nm)	D.L. (mg/L)	Sensitivity (counts/ mg/L)	Linear Dynamic Range (mg/L)	(%) RSD	Ele- ments	Analytical Lines (nm)	D.L. (mg/L)	Sensitivity (counts/ mg/L)	Linear Dynamic Range (mg/L)	(%) RSD
Ag	224.641	1.5	39	1.5 - 600	4.2	Sr	407.771	0.0002	346709	0.0002 - 1000	0.88
	243.779	0.22	346	0.22 - 700	4.1		421.552	0.0005	262155	0.0005 - 1000	0.96
	328.068	0.011	13737	0.011 - 1000	1.2		460.733	0.032	2307	0.032 - 950	1.5
	338.289	0.018	7156	0.018 - 1000	1.1	Gd	335.047	0.007	6474	0.007 - 1000	1.5
B	182.641	0.024	757	0.024 - 800	2.2		335.862	0.015	3729	0.015 - 990	1.9
	208.959	0.014	4309	0.014 - 1000	1.1		336.223	0.026	4423	0.026 - 1000	1.5
	249.677	0.025	1013	0.025 - 1000	0.95		342.247	0.013	5073	0.013 - 1000	2.2
Bi	249.773	0.013	1587	0.013 - 1000	1.1	Fe	238.204	0.093	800	0.093 - 750	3.5
	190.241	1.29	39	1.29 - 500	3.9		239.562	0.031	2063	0.031 - 1000	1.0
	206.170	0.44	76	44 - 600	2.8		241.331	0.26	229	0.26 - 650	4.1
	222.825	1.45	48	1.45 - 650	1.8		244.451	0.53	157	0.55 - 500	4.8
	223.061	0.30	346	0.30 - 950	1.2		259.941	0.017	1689	0.017 - 1000	1.5
Cd	306.772	0.34	1521	0.34 - 1000	0.87	Mg	261.187	0.025	943	0.025 - 950	2.6
	214.438	0.006	5244	0.006 - 1000	0.66		262.567	0.29	136	0.29 - 850	4.1
	226.502	0.005	11493	0.005 - 1000	0.88		262.829	0.37	194	0.37 - 800	4.2
	228.802	0.025	1884	0.025 - 980	1.1		275.573	0.13	293	0.13 - 900	4.1
	361.051	0.17	318	0.17 - 860	2.3		373.486	0.051	2173	0.051 - 1000	2.2
Cu	219.226	0.12	377	0.12 - 700	4.3	Mn	202.647	0.026	496	0.026 - 800	3.9
	219.958	0.039	762	0.039 - 850	2.7		279.079	0.23	390	0.23 - 750	4.2
	224.700	0.037	1859	0.037 - 1000	1.3		279.553	0.0005	65352	0.0005 - 1000	1.0
	324.754	0.002	52029	0.002 - 1000	0.64		280.270	0.0009	48536	0.0009 - 1000	1.1
	327.396	0.003	34031	0.003 - 1000	0.78		285.213	0.0046	15455	0.0046 - 990	1.6
Ca	183.801	0.53	30	0.53 - 600	4.5	Ni	257.611	0.0016	12854	0.0016 - 1000	1.9
	315.887	0.10	1114	0.10 - 750	3.5		259.373	0.0036	10246	0.0036 - 1000	1.5
	317.933	0.038	3613	0.038 - 900	3.2		260.569	0.010	5858	0.010 - 1000	2.5
	393.366	0.001	521209	0.001 - 1000	1.3		294.921	0.041	1832	0.041 - 800	2.3
	396.847	0.001	400267	0.001 - 1000	1.1		403.076	0.0025	9246	0.0025 - 1000	1.9
Li	422.673	0.004	25333	0.004 - 1000	1.5	Zn	221.648	0.12	848	0.12 - 700	2.9
	274.118	0.80	41	0.81 - 600	3.8		227.021	0.046	154	0.046 - 800	3.2
	323.261	0.047	199	0.047 - 850	2.5		231.604	0.014	853	0.014 - 850	3.9
	460.289	0.18	201	0.18 - 950	2.4		232.003	0.068	703	0.068 - 1000	4.2
	670.780	0.0009	200525	0.0009 - 1000	1.0		300.249	0.11	642	0.11 - 750	2.9
Dy	340.780	0.02	4300	0.02 - 750	2.9		341.476	0.012	4201	0.012 - 1000	2.2
	353.170	0.020	14075	0.02 - 1000	1.5		202.613	0.008	2058	0.008 - 1000	1.3
	353.602	0.053	4040	0.053 - 1000	1.7		206.200	0.21	157	0.21 - 500	4.6
	364.540	0.031	4864	0.031 - 1000	1.9		213.856	0.001	18061	0.001 - 1000	1.1
	394.468	0.042	3884	0.042 - 950	2.1		334.502	0.12	453	0.12 - 600	4.1

Cd Lines

The detection limit trend for the four lines of Cd was 226.502 nm < 214.438 nm < 228.802 nm < 361.051 nm, while the trend for sensitivity was completely reversed. Also, the 226.502 nm line was the only line not interfering in a Ce matrix up to 1000 mg/L, and thus was chosen for further studies.

Cu Lines

Of the 324.754 nm, 327.396 nm, 219.226 nm, 219.958 nm and 224.700 nm Cu lines, only 324.754 nm and 327.396 nm showed no interference in a Ce matrix up to 1000 mg/L. The analytical performance of these lines was found to be close to each other and superior over the other lines. Thus, 324.754 nm and 327.396 nm were considered the best lines for the determination of Cu in Ce matrix.

Ca Lines

Out of the six lines of Ca (396.847 nm, 393.366 nm, 317.933 nm, 315.887 nm, 183.801 nm, 422.673 nm), only two lines (317.933 nm and 315.887 nm) were found not to be interfered by Ce up to 1000 mg/L. Comparing the analytical performances of these two lines revealed that the 317.933 nm line (detection limit: 0.03874 mg/L and sensitivity: 3613 counts/mg/L) must be chosen over 315.887 nm (detection limit: 0.103 mg/L and sensitivity: 1114 counts/mg/L) for further studies of Ca in a Ce matrix.

Li Lines

Among the four lines of Li (323.261 nm, 274.118 nm, 670.780 nm, and 460.289 nm), two lines (670.780 nm and 460.289 nm) showed no interference from Ce up to 1000 mg/L. However, the analytical performance of the 670.780 nm line was much better and thus found to be best for the determination of Li in a Ce matrix.

Ni Lines

Of the six lines of Ni, only the 341.476 nm line was found not to be interfered by Ce. The detection limit followed the trend: 341.476 nm < 231.604 nm < 227.021 nm < 232.003 nm < 300.249 nm < 221.648 nm. Thus, on the basis of both spectral interference and analytical performance, the 341.476 nm line was chosen for the determination of Ni in a Ce matrix.

Sr Lines

Of the three lines of Sr (407.771 nm, 421.552 nm, and 460.733 nm), the first two lines were found not to be interfered in a Ce matrix. The analytical performance of these two lines was very similar for both and better than the 460.733 nm line. Thus, these two lines were chosen as the best lines for the determination of Sr in the presence of Ce.

Gd Lines

The analytical performance of the four lines of Gd (342.247 nm, 335.047 nm, 336.223 nm, and 335.862 nm) were found close to each other, leaving spectral interference as the criterion for the determination of Gd in a Ce matrix. The only line not to interfere in the presence of Ce was 336.223 nm, and was thus chosen as the best line for further studies of Gd in a Ce matrix.

Fe Lines

Out of 10 lines of Fe, the only line not to be interfered by Ce was 373.486 nm. The sensitivity followed the trend: 373.486 nm > 239.562 nm > 259.941 nm > 261.187 nm > 238.204 nm > 257.573 nm > 241.331 nm > 262.829 nm > 244.451 nm > 262.567 nm. Thus, the 373.486 nm line was chosen for the determination of Fe in the presence of Ce.

Mg Lines

The detection limit of two (279.553 nm and 280.270 nm) of

the five lines (279.553 nm, 280.270 nm, 285.213 nm, 279.079 nm, 202.647 nm) of Mg were found to be very similar and better than the other ones. In addition, these two lines of Mg did not show any significant interference from Ce up to 1000 mg/L and were chosen as the best lines for the determination of Mg in a Ce matrix.

Mn Lines

Of the five lines of Mn (257.611 nm, 259.373 nm, 260.569 nm, 294.921 nm and 403.076 nm), the two lines of 257.611 nm and 260.569 nm did not show to be interfered in a Ce matrix up to 1000 mg/L. The analytical performance for all Mn lines ranged from 5%-10% RSD. So, relying on spectral interference, the 257.611 nm and 260.569 nm lines were considered best for Mn determination in a Ce matrix.

Zn Lines

The four lines of Zn chosen for this study were 213.856 nm, 206.200 nm, 202.613 nm, and 334.502 nm. The only line which showed no interference in a Ce matrix up to 1000 mg/L was 213.856 nm. The detection limit followed the trend: 213.856 nm < 202.613 nm < 334.502 nm < 206.200 nm, while the trend for sensitivity was completely reversed. Thus, the 213.856 nm line of Zn was selected as the best line for further studies in the presence of Ce.

Dy Lines

The detection limit for the five lines of Dy (353.170 nm, 340.78 nm, 353.602 nm, 394.468 nm, and 364.54 nm) was found to range from 5%-10% RSD and therefore was acceptable. Three of the five lines (353.170 nm, 340.780 nm, and 353.602 nm) were found not to be interfered by Ce and were chosen as the best lines for the determination of Dy in a Ce matrix.

TABLE V
Spectral Interference of Ce on Na, Co, Cr, Tl, Lu, Nd, Pr, and La

Elements	Analytical Lines (nm)	Contribution from 1000 mg/L of Ce	Correction Factor	Tolerance Level (mg/L)	Elements	Analytical Lines (nm)	Contribution from 1000 mg/L of Ce	Correction Factor	Tolerance Level (mg/L)
Na	589.592	0.09	9×10^{-5}	500	Lu	261.542	0.10	1.0×10^{-4}	500
	588.995	0.08	8×10^{-5}	500		291.139	0.11	1.1×10^{-4}	500
	330.237	- ^a	-	1000		307.76	3.7	3.7×10^{-3}	10
	330.298	11.2	1.1×10^{-2}	500		219.554	0.30	3.0×10^{-4}	200
Co	228.616	0.59	5.9×10^{-4}	100	Nd	401.225	- ^b	Rejected	0.05
	238.892	0.13	1.3×10^{-4}	500		430.358	0.24	2.4×10^{-4}	200
	230.786	0.57	5.7×10^{-4}	200		406.109	0.80	8.0×10^{-4}	200
	237.862	0.24	2.4×10^{-4}	200		417.731	0.54	5.4×10^{-4}	200
Cr	267.716	0.36	3.6×10^{-4}	200	Pr	411.846	5.5	5.5×10^{-3}	10
	205.618	0.12	1.2×10^{-4}	500		417.939	4.7	4.7×10^{-3}	10
	283.563	0.52	5.2×10^{-4}	100		422.535	0.13	1.3×10^{-4}	500
	284.325	0.17	1.7×10^{-4}	500		414.311	1.8	1.8×10^{-3}	100
Tl	284.984	0.69	6.9×10^{-4}	50	La	408.672	3.0	3.0×10^{-3}	10
	190.864	0.32	3.2×10^{-4}	200		333.749	0.19	1.9×10^{-4}	500
	276.787	6.0	6.0×10^{-3}	200		379.478	5.4	5.4×10^{-3}	5

^a = No Interference.

^b = Significant Interaction,

TABLE VI
Analytical performance of Na, Co, Cr, Tl, Lu, Nd, Pr and La in Presence of Ce

Elements	Analytical Lines (nm)	D.L. (mg/L)	Sensitivity (counts/mg/L)	Linear Dynamic Range (mg/L)	(%) RSD	Elements	Analytical Lines (nm)	D.L. (mg/L)	Sensitivity (counts/mg/L)	Linear Dynamic Range (mg/L)	(%) RSD
Na	330.237	0.81	84	0.81 - 700	4.2	Lu	219.554	0.044	911	0.044 - 800	2.6
	330.298	1.68	52	1.68 - 500	4.6		261.542	0.003	7454	0.003 - 1000	3.9
	588.995	0.015	53419	0.015 - 1000	1.2		291.139	0.021	2427	0.021 - 1000	2.2
	589.592	0.009	32488	0.009 - 1000	1.1		307.76	0.095	2856	0.095 - 1000	2.6
Co	228.616	0.048	826	0.048 - 850	1.9	Nd	401.225	0.003	2961	0.003 - 1000	1.3
	230.786	0.13	658	0.13 - 890	2.2		406.109	0.034	1983	0.034 - 1000	1.5
	237.862	0.043	1457	0.043 - 1000	1.8		417.731	0.059	1745	0.059 - 900	2.2
	238.892	0.032	2001	0.032 - 1000	1.5		430.358	0.057	2954	0.057 - 1000	2.1
Cr	205.618	0.005	4588	0.005 - 1000	1.3	Pr	411.846	0.033	3257	0.033 - 950	1.3
	267.716	0.069	660	0.069 - 800	2.5		417.939	0.038	3605	0.038 - 1000	0.9
	283.563	0.010	3603	0.010 - 790	3.3		422.535	0.033	2983	0.033 - 950	1.1
	284.325	0.078	1559	0.078 - 990	1.8		414.311	0.019	4095	0.019 - 1000	0.8
Tl	284.984	0.017	512	0.017 - 750	3.1	La	333.749	0.017	3927	0.017 - 850	1.5
	190.864	0.02	848	0.02 - 990	4.2		379.478	0.013	5142	0.013 - 1000	1.1
	276.787	0.82	27	0.82 - 950	4.8		408.672	0.012	5525	0.012 - 1000	1.1

Effect of Ce on Na, Co, Cr, Tl, Lu, Nd, Pr and La

The results of spectral interference of these analytes on Ce is shown in Table V, while that of analytical performance is shown in Table VI.

Co Lines

The four lines of Co showed some interference in a Ce matrix. The least interfered line was 238.892 nm. The detection limit followed the trend: 238.892 nm < 237.862 nm < 228.616 nm < 230.786 nm, while the trend for sensitivity was completely reverse. Therefore, the Co 238.892 nm line was considered best for the determination of Co in a Ce matrix.

Cr Lines

The spectral interference of Ce on the five lines of Cr followed the trend: 205.618 nm < 284.325 nm < 267.716 nm < 283.563 nm < 284.984 nm. The analytical performance (detection limit and sensitivity) for the 205.618 nm line was found superior over the other lines and hence, chosen as the best line for the determination of Cr in a Ce matrix.

Tl Lines

The two lines of Tl (190.864 nm and 267.787 nm) were interfered by Ce, but least interference was at 190.864 nm. The analytical performance of the 190.864 nm line of Tl was better than for the 267.787 nm line, and was chosen for further studies in the presence of Ce.

Lu Lines

The spectral interference of Ce on four lines of Lu followed the trend: 261.542 nm < 291.139 nm < 219.554 nm < 307.760 nm. The analytical performance of the 261.542 nm line (detection limit 0.003318 mg/L and sensitivity 7454 counts/mg/L) was found superior over other ones and hence, this line

of Lu was chosen for the determination of Lu in a Ce matrix.

Nd Lines

Out of four lines of Nd (401.225 nm, 430.358 nm, 406.109 nm, and 417.731 nm), the 401.225 nm line was severely interfered by Ce, while the 430.358 nm line was least interfered. The analytical performance of all the lines ranged from 5%–10% RSD. Thus from the spectral interference criterion, the 430.358 nm line, with a tolerance level of 200 mg/L, was chosen for the study of Nd in presence of Ce.

Pr Lines

The four Pr lines (411.846 nm, 417.939 nm, 422.535 nm, and 414.311 nm) chosen for this study showed interference from Ce, and the 422.535 nm line with a tolerance level 500 mg/L was found to be least interfered. The analytical performance for all lines was close to each other and thus does not contribute much in the selection for best line. With regard to spectral interference, the 422.535 nm line was considered the best for the determination of Pr in a Ce matrix.

La Lines

The analytical performance for the three lines of La (408.672 nm, 333.749 nm, and 379.478 nm) were almost similar leaving the spectral interference as the only criterion for selecting the best line. The least interfered line was 333.749 nm with a tolerance level of 500 mg/L, and thus was chosen for La determination in the presence of Ce.

Effect of Ba, Ga, In, Al, and Pb

The results of spectral interference of Ba, Ga, In, Al, and Pb in a Ce matrix are listed in Table VII, and the analytical performance is listed in Table VIII.

Ba Lines

The first two of the three lines of Ba (455.404 nm, 230.424 nm,

and 233.527 nm) showed almost similar contribution (1.3 and 1.5, respectively) and the analytical performance (detection limit: 0.028 and 0.012, respectively) and thus both of these lines (455.404 nm and 230.424 nm) were regarded best for the determination of Ba in a Ce matrix.

Ga Lines

Of the three lines of Ga (417.206 nm, 294.364 nm, and 287.424 nm), the least interfered is 287.424 nm, but it showed poor analytical performance. The best analytical performance was acquired by the 417.206 nm line but it showed significant interference in a Ce matrix. The result for the 294.364 nm line was moderate and acceptable and, therefore, this line was chosen as the best line to study Ga in a Ce matrix.

In Lines

Of the four lines of In (230.606 nm, 325.609 nm, 451.131 nm, and 303.936 nm), the 451.131 nm line showed severe interference in a Ce matrix. The contribution of Ce on the 230.606 nm and 325.609 nm lines was very similar and the analytical performance deviated little, while the 303.936 nm line showed significant interaction. Therefore, both the 230.606 nm and 325.609 nm lines were chosen for the determination of In in the presence of Ce.

Al Lines

Of the four lines of Al (308.215 nm, 396.152 nm, 394.401 nm, and 309.271 nm), only the latter line was not interfered by Ce, but it has the worst analytical performance. Line 396.152 nm was least interfered by Ce and due to the detection limit trend: 396.152 nm < 394.401 nm < 308.215 nm < 309.271 nm and was considered the best choice for the analysis of Al in the presence of Ce.

Pb Lines

The contribution of Ce on the four lines of Pb followed the trend: 283.305 nm < 405.778 nm < 220.353 < 261.418 nm. The trend for the detection limit was: 283.305 nm < 220.353 nm ~ 405.778 nm < 261.418 nm. Thus, considering

both parameters, the best line for the determination of Pb in the presence of Ce was 283.305 nm.

Gd, Nd, Ga, Pr, and Dy Lines

The typical spectral interference of Ce on Gd 342.247 nm, Nd 401.22 nm, Ga 417.206 nm, Pr

411.846 nm, and Dy 394.468 nm is shown in Figure 4. It should also be mentioned that the contribution of Ce on the different analytical lines of the elements varied linearly with the Ce concentration. Figure 5 shows the variation of Ce contribution on some specified analytical

TABLE VII
Spectral Interference of Ce on Ba, Ga, In, Al, and Pb

Ele- ments	Analytical Lines (nm)	Contribution from 1000 mg/L of Ce	Correction Factor	Tolerance Level (mg/L)	Ele- ments	Analytical Lines (nm)	Contribution from 1000 mg/L of Ce	Correction Factor	Tolerance Level (mg/L)
Ba	455.404	1.3	1.3×10^{-3}	200	Al	396.152	1.5	1.5×10^{-3}	50
	233.527	1.8	1.8×10^{-3}	50		394.401	^a	Rejected	0.05
	230.424	1.5	1.5×10^{-3}	50		308.215	3.2	3.2×10^{-3}	10
Ga	417.206	9	9.0×10^{-3}	10	Pb	309.271	^{ab}	-	1000
	294.364	3.8	3.8×10^{-3}	10		220.353	1.3	1.3×10^{-3}	100
	287.424	1.9	1.9×10^{-3}	200		405.778	0.82	8.2×10^{-4}	500
In	230.606	0.84	8.4×10^{-4}	100		283.305	0.47	4.7×10^{-4}	100
	325.609	0.69	6.9×10^{-4}	200		261.418	4.3	4.3×10^{-3}	50
	451.131	^a	Rejected						
	303.936	4.9	4.9×10^{-3}	50					

Note :^a = Significant Interference.,
^{ab} = No Interference.

TABLE VIII
Analytical Performance of Ba, Ga, In, Al, and Pb in Presence of Ce

Ele- ments	Analytical Lines (nm)	D.L. (mg/L)	Sensitivity (counts/ mg/L)	Linear Dynamic Range (mg/L)	(%) RSD	Ele- ments	Analytical Lines (nm)	D.L. (mg/L)	Sensitivity counts/ mg/L)	Linear Dynamic Range (mg/L)	(%) RSD
Ba	230.424	0.011	793	0.011 - 1000	2.5	Al	308.215	0.036	1821	0.036 - 950	2.2
	233.527	0.091	388	0.091 - 800	2.9		309.271	1.88	3130	1.88 - 800	2.9
	455.404	0.027	2479	0.021 - 1000	1.1		394.401	0.016	3109	0.016 - 1000	2.2
Ga	287.424	0.26	182	0.26 - 850	4.6	Pb	396.152	0.013	10037	0.013 - 1000	1.1
	294.364	0.031	864	0.031 - 1000	3.9		220.353	0.12	275	0.12 - 900	4.3
	417.206	0.033	7693	0.033 - 1000	0.9		261.418	0.28	99	0.28 - 800	4.1
In	230.606	0.069	577	0.069 - 1000	4.2		283.305	0.068	719	0.068 - 950	2.2
	303.936	0.1	535	0.10 - 800	4.8		405.778	0.12	777	0.12 - 950	2.9
	325.609	0.074	1489	0.074 - 1000	2.5						
	451.131	8.4	31	8.4 - 500	4.9						

lines of all the elements (due to the spectral interference) as a function of Ce concentration. Though the linear relationship was found to be valid for all of the analytical lines, for the clarity of presentation, only a single analytical line of each element is represented in Figure 5.

Validation of Method for the Direct Determination of Analytes in a Ce Matrix

The method proposed and developed for the direct determination of analytes in the presence of a high purity cerium matrix and selecting the best line for each ana-

lyte was validated by using six sets of synthetic samples, prepared from commercially available standard reference materials of the individual elemental solutions. The samples were then fed to the hotter argon plasma and the results obtained were analyzed without

Fig. 4 (a-e): Spectral interference of Ce on :
(a) Gd 342.247 nm,
(b) Nd 401.220 nm,
(c) Ga 417.206 nm,
(d) Dy 394.468 nm
(e) Pr 411.846

Fig. 5. Contributions on Ce on analytical lines of the elements as a function of Ce concentration.

chemical separation. The content of the six synthetic samples prepared was as follows:

1. Synthetic sample 1 (S 1): 0.1 mg/L of Ag, B, Bi, Cd, Cu, Ca, Li, Ni, Sr, Gd, Fe, Mg, Mn, Zn, and Dy in 1000 mg/L of Ce.
2. Synthetic sample 2 (S 2): 1 mg/L of Ag, B, Bi, Cd, Cu, Ca, Li, Ni, Sr, Gd, Fe, Mg, Mn, Zn, and Dy in 1000 mg/L of Ce.
3. Synthetic sample 3 (S 3): 0.2 mg/L of Na, Co, Cr, Tl, Lu, Nd, Pr, and La in 1000 mg/L of Ce.
4. Synthetic sample 4 (S 4): 2 mg/L of Na, Co, Cr, Tl, Lu, Nd, Pr, and La in 1000 mg/L of Ce.
5. Synthetic sample 5 (S 5): 1 mg/L of Ba, Ga, In, Al, and Pb in 1000 mg/L of Ce.
6. Synthetic sample 6 (S 6): 10 mg/L of Ba, Ga, In, Al, and Pb in 1000 mg/L of Ce.

From the results it became evident that Ag, B, Bi, Cd, Cu, Ca, Li, Ni, Sr, Gd, Fe, Mg, Mn, Zn, and Dy can be estimated in the presence of a cerium matrix even at 0.1 mg/L.

The analytes Na, Co, Cr, Tl, Lu, Nd, Pr, and La (which were slightly interfered by Ce) can be estimated at 0.2 mg/L, and Ba, Ga, In, Al, and Pb (which were significantly interfered by Ce) can be estimated as low as 1 mg/L in the presence of 1000 mg/L of Ce. The analyses results of the synthetic samples are listed in Tables IX - XI.

Comparison of Present Method With Other Existing Analytical Methods

A comparison of the present methodology with existing analytical techniques was carried out and the results are listed in Table XII. The synthetic samples contained 0.5 mg/L of Ag, B, Bi, Cd, Cu, Ca, Li, Ni, Sr, Gd, Fe, Mg, Mn, Zn, and Dy; 1.0 mg/L concentration of Co, Cr, La, Lu, Tl, Nd, and Pr; 2.0 mg/mL of Al, Ba, Ga, In, and Pb in 1000 mg/L of Ce. The synthetic sample was directly fed to the plasma for analysis without chemical separation. The results were corrected for spectral interference of Ce using correction factors as evaluated. The analytical results thus obtained were compared with

the existing analytical techniques. For Ag, flame atomic absorption spectrometry was used (32); for common metallic analytes, the D.C. arc carrier distillation technique (33) was used; and for rare earth elements, ion chromatography was employed (34). The results obtained by the present method were found to compare well with the existing methods.

CONCLUSION

The systematic studies on the spectral interference of Ce on different analytes and the analytical performance of the different analytical lines of these analytes revealed that the analytical lines of Ag 328.608 nm and 338.289 nm; B 208.959 nm and Bi 306.772 nm; Cd 226.502 nm, Cu 327.396 nm and Cu 324.754 nm; Ca 317.923 nm; Li 670.780 nm; Ni 341.476 nm; Sr 21.552 nm and Sr 407.771 nm; Gd 336.223 nm; Fe 373.486 nm; Mg 280.270 nm; Mn 257.611 nm and Mn 260.569 nm; Zn 213.856 nm; and Dy 353.602 nm, Dy 353.170 nm, and Dy 340.780 nm were not interfered by Ce. These lines also showed the best analyti-

TABLE IX
Validation of the Method Using Synthetic Samples Containing
Ag, B, Bi, Cd, Cu, Ca, Li, Ni, Sr, Gd, Fe, Mg, Mn, Zn, and Dy

Ele- ments	Analytical Lines (nm)	S1		S2	
		Actual Conc. (mg/L)	Amount Estimated After Incorporating Correction Factor (mg/L)	Actual Conc. (mg/L)	Amount Estimated After Incorporating Correction Factor (mg/L)
Ag	328.068	0.1	0.092 ± 0.003	1	1.16 ± 0.05
	338.289	0.1	0.098 ± 0.006	1	1.08 ± 0.09
B	208.959	0.1	0.106 ± 0.005	1	0.97 ± 0.04
Bi	306.772	0.1	0.108 ± 0.006	1	0.98 ± 0.06
Cd	226.502	0.1	0.096 ± 0.005	1	1.02 ± 0.07
Cu	327.396	0.1	0.097 ± 0.004	1	1.11 ± 0.09
	324.754	0.1	0.099 ± 0.005	1	1.06 ± 0.05
Ca	317.923	0.1	0.102 ± 0.007	1	0.93 ± 0.07
Li	670.78	0.1	0.093 ± 0.008	1	0.96 ± 0.05
Ni	341.476	0.1	0.098 ± 0.003	1	1.03 ± 0.08
Sr	421.552	0.1	0.106 ± 0.007	1	0.99 ± 0.03
	407.771	0.1	0.101 ± 0.003	1	1.09 ± 0.09
Gd	336.223	0.1	0.092 ± 0.004	1	1.10 ± 0.06
Fe	373.486	0.1	0.095 ± 0.006	1	0.98 ± 0.06
Mg	280.27	0.1	0.092 ± 0.003	1	0.97 ± 0.06
Mn	257.611	0.1	0.097 ± 0.003	1	1.01 ± 0.05
	260.569	0.1	0.104 ± 0.006	1	1.04 ± 0.04
Zn	213.856	0.1	0.108 ± 0.003	1	0.93 ± 0.06
Dy	353.602	0.1	0.095 ± 0.004	1	1.08 ± 0.06
	353.17	0.1	0.109 ± 0.008	1	1.07 ± 0.08
	340.78	0.1	0.092 ± 0.007	1	0.95 ± 0.05

cal performance and hence can be chosen for the determination of these analytes in the presence of a Ce matrix without chemical separation and without incorporation of the correction factors. The best analytical lines for the following analytes were: Co 238.892 nm; Cr 205.618 nm; La 333.749 nm; Na 589.592 nm and Na 588.995 nm; Lu 261.542 nm; Tl 190.864 nm; Nd 430.388 nm; Pr 422.535 nm; Al 396.152 nm; Ba 455.404 nm; Ga 294.364 nm; Pb 283.305 nm; and In 230.606 nm and In 325.609 nm. A simple, rapid ICP-AES-based method was developed for the determination these 28 analytes in a Ce matrix without chemical separation. The method was validated using synthetic samples prepared from commercially available standard reference materials of the individual solutions. The method was also compared with other existing analytical techniques such as flame atomic absorption, ion chromatography, and D.C. arc distillation. The present approach appeared to be exciting, and the analytical data were found to be in good agreement.

Received April 10, 2015.

TABLE X
Validation of the Method using Synthetic Samples Containing Na, Co, Cr, La, Lu, Tl, Nd, and Pr

Ele- ments	Analytical Lines (nm)	S3			S4		
		Actual Conc. (mg/L)	Amount Estimated Before Incorporating Correction Factor (mg/L)	Amount Estimated After Incorporating Correction Factor (mg/L)	Actual Conc. (mg/L)	Amount Estimated Before Incorporating Correction Factor (mg/L)	Amount Estimated After Incorporating Correction Factor (mg/L)
Na	589.592	0.2	0.30 ± 0.02	0.22	2	2.05 ± 0.05	1.97
	588.995	0.2	0.27 ± 0.01	0.18	2	2.1 ± 0.06	2.01
Co	238.892	0.2	0.32 ± 0.01	0.19	2	2.20 ± 0.05	2.07
Cr	205.618	0.2	0.33 ± 0.01	0.21	2	2.08 ± 0.03	1.96
La	333.749	0.2	0.39 ± 0.02	0.2	2	2.22 ± 0.07	2.03
Lu	261.542	0.2	0.29 ± 0.02	0.19	2	2.15 ± 0.07	2.05
Tl	190.864	0.2	0.53 ± 0.03	0.21	2	2.35 ± 0.08	2.03
Nd	430.388	0.2	0.46 ± 0.02	0.22	2	2.29 ± 0.05	2.05
Pr	422.535	0.2	0.35 ± 0.01	0.22	2	2.11 ± 0.07	1.98

TABLE XI
Validation of the Method using Synthetic Samples Containing Al, Ba, Ga, In, and Pb

Ele- ments	Analytical Lines (nm)	S5			S6		
		Actual Conc. (mg/L)	Amount Estimated Before Incorporating Correction Factor (mg/L)	Amount Estimated After Incorporating Correction Factor (mg/L)	Actual Conc. (mg/L)	Amount Estimated Before Incorporating Correction Factor (mg/L)	Amount Estimated After Incorporating Correction Factor (mg/L)
Al	396.152	1	2.70 ± 0.05	1.2	5	6.46 ± 0.06	4.96
Ba	455.404	1	2.19 ± 0.08	0.89	5	6.35 ± 0.08	5.05
Ga	294.364	1	4.70 ± 0.06	0.9	5	9.00 ± 0.08	5.2
In	230.606	1	1.90 ± 0.07	1.06	5	5.94 ± 0.09	5.1
	325.609	1	1.71 ± 0.06	1.02	5	5.75 ± 0.09	5.06
Pb	283.305	1	1.44 ± 0.05	0.97	5	5.52 ± 0.07	5.05

TABLE XII
Comparison of the Present Methodology with Existing Analytical Techniques

Ele- ments	Analytical Lines (nm)	Estimated by Present Method (mg/L)	Comparison With Other Method (mg/L)	Ele- ments	Analytical Lines (nm)	Estimated by Present Method (mg/L)	Comparison With Other Method (mg/L)
Ag	328.068	0.51 ± 0.03	0.49 ± 0.02 ^a	Dy	353.602	0.49 ± 0.03	0.51 ± 0.04 ^c
	338.289	0.47 ± 0.02	0.46 ± 0.04 ^a		353.17	0.51 ± 0.05	0.48 ± 0.04 ^c
B	208.959	0.50 ± 0.03	0.48 ± 0.04 ^b		340.78	0.50 ± 0.04	0.48 ± 0.04 ^c
Bi	306.772	0.49 ± 0.01	0.51 ± 0.03 ^b	Na	589.592	1.15 ± 0.08	0.98 ± 0.07 ^b
Cd	226.502	0.51 ± 0.04	0.50 ± 0.04 ^b		588.995	1.05 ± 0.07	1.13 ± 0.07 ^b
Cu	327.396	0.48 ± 0.02	0.51 ± 0.05 ^b	Co	238.892	0.98 ± 0.08	1.05 ± 0.08 ^b
	324.754	0.49 ± 0.04	0.47 ± 0.03 ^b	Cr	205.618	1.10 ± 0.06	1.08 ± 0.07 ^b
Ca	317.923	0.51 ± 0.04	0.49 ± 0.03 ^b	La	333.749	0.97 ± 0.06	0.96 ± 0.07 ^c
Li	670.78	0.50 ± 0.02	0.51 ± 0.04 ^b	Lu	261.542	0.99 ± 0.05	0.97 ± 0.08 ^c
Ni	341.476	0.47 ± 0.04	0.51 ± 0.03 ^b	Tl	190.864	1.08 ± 0.07	0.98 ± 0.08 ^b
Sr	421.552	0.47 ± 0.02	0.50 ± 0.03 ^b	Nd	430.388	1.11 ± 0.09	1.01 ± 0.07 ^c
	407.771	0.49 ± 0.05	0.46 ± 0.05 ^b	Pr	422.535	0.97 ± 0.08	1.06 ± 0.08 ^c
Gd	336.223	0.51 ± 0.02	0.47 ± 0.04 ^c	Al	396.152	2.10 ± 0.09	2.05 ± 0.08 ^b
Fe	373.486	0.50 ± 0.05	0.48 ± 0.04 ^b	Ba	455.404	1.97 ± 0.08	2.11 ± 0.07 ^b
Mg	280.27	0.50 ± 0.02	0.48 ± 0.04 ^b	Ga	294.364	2.05 ± 0.07	1.95 ± 0.07 ^b
Mn	257.611	0.49 ± 0.02	0.51 ± 0.04 ^b	In	230.606	1.98 ± 0.06	1.94 ± 0.07 ^b
	260.569	0.47 ± 0.03	0.50 ± 0.03 ^b		325.609	1.99 ± 0.08	1.92 ± 0.08 ^b
Zn	213.856	0.48 ± 0.04	0.46 ± 0.04 ^b	Pb	283.305	2.01 ± 0.08	2.11 ± 0.07 ^b

Note: The Ce concentration in the synthetic sample is 1000 mg/L.
^a = refers to the analysis by atomic absorption spectroscopy.
^b = refers to the analysis by D.C. arc carrier distillation technique.
^c = refers to the analysis by chromatographic technique.

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