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Analysis of the Spectra of Pd-Like Praseodymium and Neodymium (Pr XIV and Nd XV)

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Abstract

The spectra of palladium-like Pr^{13+} and Nd^{14+} ions excited in a laser-produced plasma source have been investigated in the 70–700 Å region. Almost all the energy levels of the $4d^95s$, $4d^95p$, $4d^94f$, $4d^95d$ and $4d^95f$ configurations in Pr XIV and Nd XV as well as the energies of the $4d^96s$ levels in Pr XIV have been determined experimentally. One hundred seven spectral lines belonging to the 5s-5p, 5p-5d, 5d-5f, 4f-5d and 5p-6s transitions in Pr XIV and eighty five lines belonging to the 5s-5p, 5p-5d, 5d-5f and 4f-5d transitions in Nd XV have been classified for the first time. The present analysis is based on an accurate extrapolation of energy parameters in the Pd I isoelectronic sequence. The experimental level energies are described by Generalized Least Squares isoelectronic studies of $4d^95l$ configurations.

1. Introduction

The spectra of Pd-like ions attract a high interest as these ions may show laser effect in the extreme ultraviolet and soft X-ray regions. Indeed, significant gain of stimulated emission has been observed in the Pd-like Xe IX spectrum [1] on the $4d^95p^1P_1$ - $4d^95d^1S_0$ ($\lambda \sim 418$ Å) transition between two excited levels above the $4d^{10}$ ground configuration. The laser effect can also occur on the "self-pumped" $4d^95d^1P_1$ - $4d^95f^1P_1$ transition in Pd-like ions, in analogy with the $3d^94d^1P_1$ - $3d^94f^1P_1$ transition in Ni-like ions [2]. However, the analysis of Pd-like ion spectra is complicated by the decrease of the energy of the $4d^94f$ configuration which collapses along the isoelectronic sequence and interacts with the $4d^95p$ configuration in highly charged lanthanide ions. Therefore for a better understanding of processes occurring in lasing plasmas containing these ions, the detailed knowledge of their $4d^95l$ configurations and the nearby $4d^94f$ configuration is necessary. The four first authors have been involved in a systematic study of Pd-like ion spectra including revised and extended analyses of Sb VI, Te VII, I VIII [3] and Xe IX [4, 5] spectra, and subsequent analysis of the Cs X - Ce XIII spectra [5, 6]. In these earlier works, the energy levels belonging to the $4d^95s$, $4d^95p$, $4d^95d$ and $4d^95f$ configurations were determined in all the ions under investigation and also, those of the $4d^94f$ configuration in Ba XI - Ce XIII ions [5]. For heavier Pd-like ions, only some resonance transitions from the $4d^95p$, 4f ($J = 1$) levels were classified until now [7, 8]. The purpose of the present work is the analyses of the spectra of Pr XIV and Nd XV and the determinations of the energy levels of the $4d^95l$ and $4d^94f$ configurations for these ions.

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2. Experimental set-up and theoretical calculations

The praseodymium and neodymium ion spectra were excited in laser-produced plasma (LPP) sources. The output beam of a pulsed neodymium glass laser (1 GW, pulse duration 10 ns) was focused onto a solid target made of the metal of interest, with an power flux of about 10^{13} W/cm^2. The spectra were obtained on a 6.65 m normal incidence spectrograph in the 200–700 Å wavelength region at the Institute of Spectroscopy (ISAN, Troitsk, Russia) and on a 10.7 m grazing incidence spectrograph in the 70–250 Å wavelength region at the National Institute of Standards and Technology (NIST, Gaithersburg, MA, U.S.A.). Also included in the present analysis were some spectra excited in a low-inductance vacuum spark (VS) and recorded in the 70–350 Å region on a 3 m grazing incidence spectrograph at ISAN. Kodak SWR and SC-5 photoplates were used to record the spectra. More detailed descriptions of the sources and spectrographs can be found in ref. [3, 5, 6, 7]. The practical spectral resolution was essentially limited by Doppler broadening, especially in the long-wavelength region of the LPP spectra. It increases from about 5,000 to about 10,000 in the wavelength region from 100 Å to 600 Å.

Since the spectra of highly ionized praseodymium and neodymium did not contain enough lines suitable for wavelength calibration by internal standards, VS spectra of iron or titanium electrodes were superimposed in some cases on the Pr and Nd exposures and wavelengths of Fe lines [9] and Ti lines [10] were used as wavelength standards. The estimated uncertainty of the wavelength measurements in the LPP spectra was ±0.005 Å around 100 Å and increased to ±0.010 Å in the region of 600 Å. The resonance lines of Pr XIV and Nd XV below 110 Å, already classified in [7], have been re-measured against the Ti lines from the VS spectrograms. The uncertainty of our new measurements was estimated to be ±0.003 Å. In all cases, the relative line intensities were measured from the plate densities taking into account the photoemulsion response curve. They were estimated on a scale of 10–1000 with an error margin of 10%, an intensity of $I = 1000$ being attributed to the strongest line in each spectrum.

The Pr XIV and Nd XV spectra were calculated in the Racah-Slater approach followed by the Cowan computer codes [11], with scaled Hartree-Fock (HFR) integrals as radial parameters. We derived energies and transition probabilities for the same sets of electronic configurations which were used in our earlier work [3, 5], i.e. the $4d^{10}$, $4d^9ns$ ($n = 5, 6$), $4d^9nd$ ($n = 5, 6$), $4d^85s^2$, $4d^85s5d$, $4d^85d^2$ and $4p^54d^{10}5p$ even configurations and the $4d^9np$ ($n = 5, 6$), $4d^9nf$ ($n = 4$–6), $4d^85s5p$, $4d^85p5d$, $4p^54d^{10}5s$ and $4p^54d^{10}5d$ odd configurations. The scaling factors

Table I. *The classified transitions in the Pr XIV spectrum.*

gA[a]	I[b]	λ_{exp} (Å)	$\Delta\lambda$[c] (Å)	σ_{exp} (cm^{-1})	Transition	$E_{low} - E_{upper}$
9532	1000S	84.500	0.000	1183432	4d $^1S_0$–4f $^1P_1$	0–1183432
251	454S	86.274	0.001	1159098	4d $^1S_0$–5p $^3D_1$	0–1159108
1056	638S	88.513	−0.001	1129778	4d $^1S_0$–5p $^1P_1$	0–1129770
97	254S	89.773	−0.001	1113921	4d $^1S_0$–5p $^3P_1$	0–1113908
15	187S	104.225	0.001	959463	4d $^1S_0$–4f $^3D_1$	0– 959475
1.3	56	109.900	0.002	909920	4d $^1S_0$–4f $^3P_1$	0– 909933
91	187	159.487	0.000	627011	5p $^3F_2$–6s $^3D_2$	1108957–1735970
204	285	159.525	0.004	626860	5p $^3P_2$–6s $^3D_3$	1076086–1702962
123	204	159.765	0.000	625920	5p $^3F_2$–6s $^3D_1$	1108957–1734877
193	291	160.163	0.005	624364	5p $^3F_3$–6s $^1D_2$	1080110–1704495
119	200	160.555	0.004	622839	5p $^3F_3$–6s $^3D_3$	1080110–1702962
107	159	160.755	−0.001	622065	5p $^3P_1$–6s $^3D_2$	1113908–1735970
19	98	169.318	−0.005	590604	5p $^3P_1$–6s $^1D_2$	1113908–1704495
324	285	172.191	−0.007	580750	5p $^3F_4$–6s $^3D_3$	1122235–1702962
248	250m	172.920	−0.001	578302	5p $^1F_3$–6s $^3D_2$	1157671–1735970
154	220	173.682	−0.006	575765	5p $^1D_2$–6s $^1D_2$	1159108–1734877
91			0.001		5p $^3D_1$–6s $^3D_1$	1128750–1704495
83	103	173.994	−0.002	574733	5p $^1P_1$–6s $^1D_2$	1129770–1704495
102	149	174.931	0.001	571654	5p $^3D_2$–6s $^3D_2$	1164313–1735970
91	213	175.267	−0.008	570558	5p $^3D_3$–6s $^1D_2$	1133963–1704495
70			0.002		5p $^3D_2$–6s $^3D_1$	1164313–1734877
148	210	175.747	0.000	568999	5p $^3D_3$–6s $^3D_3$	1133963–1702962
13	206	198.173	0.005	504610	4f $^3P_1$–5d $^3P_2$	909933–1414555
15	117?	201.575	0.000	496092	4f $^3P_0$–5d $^3S_1$	904443–1400535
24	108	201.949	0.006	495175	4f $^3H_4$–5d $^3G_3$	948523–1443713
20	125	202.530	0.000	493754	4f $^3P_2$–5d $^3P_2$	920800–1414555
6	134?	202.912	−0.002	492824	4f $^3F_4$–5d $^3G_3$	950893–1443713
31	119	203.831	0.000	490602	4f $^3P_1$–5d $^3S_1$	909933–1400535
220	601	205.742	0.000	486046	4f $^3H_6$–5d $^3G_5$	932518–1418564
13	110	208.071	−0.001	480605	4f $^3D_2$–5d $^1D_2$	946038–1426640
20	200m	208.445	−0.002	479754	4f $^3P_2$–5d $^3S_1$	920800–1400538
31	159	209.308	−0.007	477764	4f $^3F_4$–5d $^3F_4$	950893–1428642
163	442bl	209.852	0.000	476527	4f $^3H_5$–5d $^3G_4$	935439–1411966
27	196	210.207	0.000	475721	4f $^1D_2$–5d $^3D_1$	966919–1442640
99	296	210.639	0.000	474747	4f $^3F_4$–5d $^1F_3$	950893–1425655
164	415	210.688	0.000	474635	4f $^1H_5$–5d $^1G_4$	978769–1453404
41	122	210.877	0.000	474210	4f $^3F_2$–5d $^3P_1$	975847–1450057
19	176	211.192	0.001	473503	4f $^3D_1$–5d $^3P_0$	959475–1432980
109	316	211.245	0.000	473384	4f $^1G_4$–5d $^3G_3$	970329–1443713
34	257	211.590	0.007	472612	4f $^3D_2$–5d $^1P_1$	946038–1418665
45	182	211.885	0.001	471953	4f $^3F_3$–5d $^3D_3$	946308–1418263
82	148	212.802	0.000	469921	4f $^3G_3$–5d $^3D_2$	986790–1456711
77	373m	212.878	−0.006	469753	4f $^3H_4$–5d $^3D_3$	948523–1418263
123	120	213.115	−0.003	469230	4f $^3G_4$–5d $^3F_3$	991285–1460508
143	419	213.302	0.000	468818	4f $^3G_5$–5d $^3F_4$	959824–1428642
24	361	213.434	−0.005	468529	4f $^3D_2$–5d $^3P_2$	946038–1414555
47	208	213.562	−0.001	468248	4f $^3F_3$–5d $^3P_2$	946308–1414555
65	157	215.980	0.000	463006	4f $^3D_3$–5d $^1D_2$	963634–1426640
17	113	216.397	0.003	462113	4f $^3G_4$–5d $^1G_4$	991285–1453404
59	128	221.075	0.000	452335	4f $^1F_3$–5d $^3F_2$	1000523–1452858
15	40	255.630	−0.009	391190	5p $^3P_1$–5d $^1S_0$	1113908–1505085
53	104	266.450	0.007	375305	5p $^1P_1$–5d $^1S_0$	1129770–1505085
102	184	290.782	0.001	343900	5p $^3F_2$–5d $^3F_2$	1108957–1452858
26	368bl	291.906	0.003	342576	5p $^3P_2$–5d $^1P_1$	1076086–1418665
131	220	292.242	−0.005	342182	5p $^3P_2$–5d $^3D_3$	1076086–1418263
84	140	295.027	−0.002	338952	5p $^3P_1$–5d $^3F_2$	1113908–1452858
187	286	295.455	0.007	338461	5p $^3P_2$–5d $^3P_2$	1076086–1414555
162	216	295.731	0.007	338145	5p $^3F_3$–5d $^3D_3$	1080110–1418263
291	322	298.718	−0.007	334764	5p $^3F_2$–5d $^3G_3$	1108957–1443713
423	424	301.336	0.000	331856	5p $^3F_3$–5d $^3G_4$	1080110–1411966
370	120	303.290	0.000	329717	5d $^3D_3$–5f $^3F_4$	1418263–1747981
734	264	303.820	0.000	329142	5d $^3G_4$–5f $^3H_5$	1443713–1772855
598			0.000		5d $^3G_3$–5f $^3H_4$	1411966–1741108
84	114	304.199	0.000	328732	5p $^3P_1$–5d $^3D_1$	1113908–1442640
320	68	305.267	0.000	327582	5d $^3F_2$–5f $^3G_3$	1452858–1780440
196	70	305.495	0.000	327338	5d $^3D_3$–5f $^3F_3$	1418263–1745601
153	224	306.362	0.000	326411	5d $^1P_1$–5f $^1D_2$	1418665–1745076
118	254	308.217	0.005	324447	5p $^3P_2$–5d $^3S_1$	1076086–1400538
453	208	309.588	0.000	323010	5d $^1F_3$–5f $^1G_4$	1425655–1748665

Table I. *Continued.*

$gA^{(a)}$	$I^{(b)}$	λ_{exp} (Å)	$\Delta\lambda^{(c)}$ (Å)	σ_{exp} (cm^{-1})	Transition	$E_{low} - E_{upper}$
857	238	309.810	0.000	322778	5d $^3G_5$–5f $^3H_6$	1418564−1741342
339	252	310.539	0.000	322021	5d $^3D_2$–5f $^3F_3$	1456711−1778732
716	116	311.234	0.000	321302	5d $^1G_4$–5f $^1H_5$	1453404−1774706
594	138	311.587	0.000	320938	5d $^3F_4$–5f $^3G_5$	1428642−1749580
505	156	311.749	0.000	320771	5d $^3F_3$–5f $^3G_4$	1460508−1781279
38	206	313.407	−0.002	319074	5p $^3P_1$–5d $^3P_0$	1113908−1432980
16	180	319.750	−0.013	312745	5p $^3p_1$–5d $^1D_2$	1113908−1426640
66	214	329.519	0.000	303473	5p $^3P_0$–5d $^3P_1$	1146584−1450057
110	174	335.702	0.008	297884	5p $^1D_2$–5d $^1D_2$	1128750−1426640
132	172	336.018	0.000	297603	5p $^3D_1$–5d $^3D_2$	1159108−1456711
140	160bl	336.825	0.017	296890	5p $^1D_2$–5d $^1F_3$	1128750- 1425655
431	254	337.463	0.000	296329	5p $^3F_4$–5d $^3G_5$	1122235−1418564
205	142	337.615	0.000	296195	5p $^3D_2$–5d $^3F_3$	1164313−1460508
348	235	338.143	0.000	295733	5p $^1F_3$–5d $^1G_4$	1157671−1453404
247	150	339.352	0.000	294679	5p $^3D_3$–5d $^3F_4$	1133963−1428642
11	109	341.685	0.011	292667	5p $^3D_3$–5d $^1D_2$	1133963−1426640
90	91	342.820	−0.007	291698	5p $^3D_3$–5d $^1F_3$	1133963−1425655
16	108	344.919	−0.010	289923	5p $^1D_2$–5d $^1P_1$	1128750−1418665
60	116	346.148	0.002	288894	5p $^1P_1$–5d $^1P_1$	1129770−1418665
30	96	356.383	−0.006	280597	5p $^3D_3$–5d $^3P_2$	1133963−1414555
2	50	392.032	0.009	255081	5s $^3D_2$–5p $^1F_3$	902584−1157671
58	271	423.743	−0.006	235992	5s $^3D_3$–5p $^3D_3$	897974−1133963
29	173	426.410	0.004	234516	5s $^3D_1$–5p $^3D_2$	929795−1164313
34	247	432.193	0.002	231378	5s $^3D_2$–5p $^3D_3$	902584−1133963
6	106	433.324	0.004	230774	5s $^3D_3$–5p $^1D_2$	897974−1128750
37	205	433.639	−0.003	230607	5s $^1D_2$–5p $^3D_2$	933708−1164313
33	210	436.095	0.010	229308	5s $^3D_1$–5p $^3D_1$	929795−1159108
28	174	440.173	0.005	227183	5s $^3D_2$–5p $^1P_1$	902584−1129770
52	299	442.149	−0.004	226168	5s $^3D_2$–5p $^1D_2$	902584−1128750
4	78	443.644	−0.011	225406	5s $^1D_2$–5p $^3D_1$	933708−1159108
111	527	445.908	−0.001	224261	5s $^3D_3$–5p $^3F_4$	897974−1122235
84	423	446.495	−0.007	223967	5s $^1D_2$–5p $^1F_3$	933708−1157671
12	269	461.278	0.000	216789	5s $^3D_1$–5p $^3P_0$	929795−1146584
8	250m	473.207	0.000	211324	5s $^3D_2$–5p $^3P_1$	902584−1113908
3	109	500.065	0.002	199974	5s $^3D_1$–5p $^1P_1$	929795−1129770
5	99	510.038	−0.005	196064	5s $^1D_2$–5p $^1P_1$	933708−1129778
2	136	512.717	0.007	195039	5s $^1D_2$–5p $^1D_2$	933708−1128750
1	57	543.133	−0.012	184117	5s $^3D_1$–5p $^3P_1$	929795−1113908
17	334	549.042	0.002	182135	5s $^3D_3$–5p $^3F_3$	897974−1080110
13	182	554.940	0.001	180200	5s $^1D_2$–5p $^3P_1$	933708−1113908
17	216	558.144	−0.010	179165	5s $^3D_1$–5p $^3F_2$	929795−1108957
29	359	561.446	0.001	178112	5s $^3D_3$–5p $^3P_2$	897974−1076086
27	365	563.298	0.000	177526	5s $^3D_2$–5p $^3F_3$	902584−1080110
11	324	570.625	0.008	175246	5s $^1D_2$–5p $^3F_2$	933708−1108957

(a): calculated gA values (given in the $10^9\,s^{-1}$ units), where g stands for statistical weight of the transition upper level and A, for Einstein's coefficient for spontaneous emission.
(b): arbitrary intensity units over a 10–1000 scale (see text); S – line earlier classified by Sugar and Kaufman [7]; bl – blended by a line of lower ionization stage, here, of Pr XII [14]; m – partly masked by the strong neighbouring line; ? – tentatively classified line.
(c): $\Delta\lambda = \lambda_{exp.} - \lambda_{calc.}$ where $\lambda_{calc.}$ is the wavelength calculated by Ritz combination principle from the experimental energies given in the last column.

of energy parameters ($SF = P_{LSF}/P_{HFR}$, ratios of the Least-Squares-Fitted (LSF) values of the parameters to their HF values) were extrapolated from the Sb VI - Ce XIII sequence [3, 5] for the Pr XIV and Nd XV spectra. This extrapolation gave us good initial values of the radial integrals for a more precise calculation of the spectra under investigation in which they were adjusted by least squares fits on the level energies. Finally, the experimentally determined level energies in Pr XIV and Nd XV were confirmed by isoelectronic comparisons when the Generalized Least Squares (GLS) fitting technique was applied (see Section 3).

3. Results and discussion

The preliminary analysis showed that the spectral lines of Pd-like ions were intense in our LPP spectra and were not observed in the VS ones, excluding the strong resonance lines which were clearly seen in both spectra. The lines of Ag-like, Cd-like and In-like ions were strong in the LPP spectra but were also present in the VS spectra with relative intensities depending on the ionic charge. These facts helped us to select the lines which most probably belonged to the spectra of Pd-like ions. The search for energy levels from the line list was carried out using the IDEN computer code [12] for complex spectra identification. This code was based on pattern recognition with visual display and was built to read-in the experimental data together with the output predictions of the Cowan codes.

The lists of spectral lines classified in Pr XIV and Nd XV are presented in Tables I and II. The calculated transition probabilities (gA, where g is the statistical weight of the upper level and A, the Einstein coefficient for spontanous emission)

Table II. *The classified transitions in the Nd XV spectrum.*

$gA^{(a)}$	$I^{(b)}$	λ_{exp} (Å)	$\Delta\lambda^{(c)}$ (Å)	σ_{exp} (cm^{-1})	Transition	$E_{low} - E_{upper}$
117	247S	77.919	0.000	1283384	4d $^{1}S_{0}$–5p $^{3}D_{1}$	0−1283390
40	396S	79.927	0.000	1251142	4d $^{1}S_{0}$–5p $^{1}P_{1}$	0−1251137
10910	999S	80.508	0.000	1242115	4d $^{1}S_{0}$–4f $^{1}P_{1}$	0−1242112
455	348S	81.203	0.001	1231483	4d $^{1}S_{0}$–5p $^{3}P_{1}$	0−1231500
19	221S	99.141	0.000	1008663	4d $^{1}S_{0}$–4f $^{3}D_{1}$	0−1008663
1.4	57	104.655	−0.001	955518	4d $^{1}S_{0}$–4f $^{3}P_{1}$	0− 955505
25	67	166.570	−0.001	600348	4f $^{3}P_{2}$–5d $^{1}D_{2}$	967382−1567726
24	101	169.398	0.004	590326	4f $^{3}H_{4}$–5d $^{3}G_{3}$	996495−1586835
21	83?	169.500	0.000	589969	4f $^{3}P_{0}$–5d $^{3}S_{1}$	949496−1539465
28	92	170.499	0.001	586514	4f $^{3}P_{2}$–5d $^{3}P_{2}$	967382−1553900
41	69	171.243	−0.001	583965	4f $^{3}P_{1}$–5d $^{3}S_{1}$	955505−1539465
292	427	172.625	0.000	579290	4f $^{3}H_{6}$–5d $^{3}G_{5}$	979670−1558960
13	62	173.402	0.005	576695	4f $^{3}H_{5}$–5d $^{3}G_{5}$	982250−1558960
28	69	175.532	−0.006	569697	4f $^{3}F_{2}$–5d $^{3}F_{2}$	1026887−1596566
217	353	175.787	−0.002	568871	4f $^{3}H_{5}$–5d $^{3}G_{4}$	982250−1551115
35	79	176.080	0.000	567924	4f $^{1}D_{2}$–5d $^{3}D_{1}$	1017570−1585495
226	310	176.168	0.000	567640	4f $^{1}H_{5}$–5d $^{1}G_{4}$	1030580−1598220
141	313	176.292	0.000	567240	4f $^{3}F_{4}$–5d $^{3}D_{3}$	999341−1566581
55	100	176.334	0.006	567105	4f $^{3}F_{2}$–5d $^{3}P_{1}$	1026887−1594010
154	291	176.572	−0.001	566341	4f $^{1}G_{4}$–5d $^{3}G_{3}$	1020498−1586835
25	97	176.762	−0.001	565732	4f $^{3}D_{1}$–5d $^{3}P_{0}$	1008663−1574391
46	121	176.852	0.004	565444	4f $^{3}D_{2}$–5d $^{1}P_{1}$	993218−1558675
108	176	177.745	0.000	562605	4f $^{3}G_{3}$–5d $^{3}D_{2}$	1038920−1601525
111	242	178.099	−0.004	561485	4f $^{3}H_{4}$–5d $^{3}F_{3}$	996495−1557970
196	363	178.218	0.000	561111	4f $^{3}G_{5}$–5d $^{3}F_{4}$	1008720−1569832
166	347	178.239	0.000	561044	4f $^{3}G_{4}$–5d $^{1}F_{3}$	1044412−1605456
32	102	178.350	−0.004	560694	4f $^{3}D_{2}$–5d $^{3}P_{2}$	993218−1553900
62	142	178.514	0.000	560179	4f $^{3}F_{3}$–5d $^{3}P_{2}$	993721−1553900
89	225	180.257	0.000	554762	4f $^{3}D_{3}$–5d $^{1}D_{2}$	1012964−1567726
26	59	180.718	−0.005	553349	4f $^{1}F_{3}$–5d $^{1}F_{3}$	1052123−1605456
77	46	183.679	0.005	544428	4f $^{1}F_{3}$–5d $^{3}F_{2}$	1052123−1596566
12	79	186.058	0.001	537467	4f $^{1}G_{4}$–5d $^{3}F_{3}$	1020498−1557970
25	50m	237.010	−0.005	421923	5p $^{3}P_{1}$–5d $^{1}S_{0}$	1231500−1653432
34	83	243.124	0.004	411313	4f $^{1}P_{1}$–5d $^{1}S_{0}$	1242112−1653432
32	58	248.568	−0.006	402304	5p $^{1}P_{1}$–5d $^{1}S_{0}$	1251137−1653432
118	90	270.016	0.000	370348	5p $^{3}F_{2}$–5d $^{3}F_{2}$	1226218−1596566
208	260	274.323	0.015	364533	5p $^{3}P_{2}$–5d $^{3}P_{2}$	1189347−1553900
185			−0.001		5p $^{3}F_{3}$–5d $^{3}F_{3}$	1193438−1557970
331	238	277.307	0.004	360611	5p $^{3}F_{2}$–5d $^{3}G_{3}$	1226218−1586835
224	148	278.979	−0.004	358450	5d $^{3}D_{2}$–5f $^{3}F_{3}$	1553900−1912345
472	215	279.585	0.003	357673	5p $^{3}F_{3}$–5d $^{3}G_{4}$	1193438−1551115
671	169	280.491	0.000	356517	5d $^{3}G_{3}$–5f $^{3}H_{4}$	1586835−1943352
427	65	280.747	−0.010	356192	5d $^{3}F_{3}$–5f $^{3}F_{4}$	1557970−1914150
824	184	280.959	0.000	355924	5d $^{3}G_{4}$–5f $^{3}H_{5}$	1551115−1907039
363	88	281.737	0.000	354941	5d $^{3}F_{2}$–5f $^{3}G_{3}$	1596566−1951507
219	94	282.192	0.005	354369	5d $^{3}F_{3}$–5f $^{3}F_{3}$	1557970−1912345
95	100	282.490	0.000	353995	5p $^{3}P_{1}$–5d $^{3}D_{1}$	1231500−1585495
135	132	285.619	0.001	350117	5p $^{3}P_{2}$–5d $^{3}S_{1}$	1189347−1539465
508	143	286.614	0.000	348901	5d $^{3}D_{3}$–5f $^{1}G_{4}$	1566581−1915482
958	267	286.857	0.000	348605	5d $^{3}G_{5}$–5f $^{3}H_{6}$	1558960−1907565
333	98	287.189	0.000	348203	5d $^{1}D_{2}$–5f $^{1}F_{3}$	1567726−1915929
375	119	287.380	0.000	347972	5d $^{3}D_{2}$–5f $^{3}D_{3}$	1601525−1949497
800	254	287.652	0.000	347643	5d $^{3}G_{4}$–5f $^{1}H_{5}$	1598220−1945863
564	153	287.978	0.000	347249	5d $^{3}F_{3}$–5f $^{3}G_{4}$	1605456−1952705
664	205	288.749	0.000	346322	5d $^{3}F_{4}$–5f $^{3}G_{5}$	1569832−1916154
142	110	290.439	0.010	344306	5d $^{3}F_{4}$–5f $^{3}F_{4}$	1569832−1914150
39	133	291.641	0.003	342887	5p $^{3}P_{1}$–5d $^{3}P_{0}$	1231500−1574391
36	40	295.721	−0.006	338156	5p $^{1}D_{2}$–5d $^{3}G_{3}$	1248686−1586835
72	174	308.440	−0.007	324212	5p $^{3}P_{0}$–5d $^{3}P_{1}$	1269806−1594010
8	67	309.353	−0.002	323255	5p $^{1}P_{1}$–5d $^{3}P_{0}$	1251137−1574391
120	145	313.440	0.000	319040	5p $^{1}D_{2}$–5d $^{1}D_{2}$	1248686−1567726
142	127	314.332	0.000	318135	5p $^{3}D_{1}$–5d $^{3}D_{2}$	1283390−1601525
155	167	314.570	0.000	317895	5p $^{1}D_{2}$–5d $^{3}D_{3}$	1248686−1566581
470	245	315.116	−0.002	317344	5p $^{3}F_{4}$–5d $^{3}G_{5}$	1241618−1558960
225	166	315.620	0.004	316837	5p $^{3}D_{2}$–5d $^{1}F_{3}$	1288615−1605456
381	113	316.020	0.000	316436	5p $^{1}F_{3}$–5d $^{1}G_{4}$	1281784−1598220
272	117	316.979	0.004	315478	5p $^{3}D_{3}$–5d $^{3}F_{4}$	1254350−1569832
71	129	325.154	−0.009	307546	5p $^{1}P_{1}$–5d $^{1}P_{1}$	1251137−1558675
2	70	358.891	−0.006	278636	5s $^{3}D_{2}$–5p $^{3}D_{1}$	1004758−1283390

Table II. *Continued.*

$gA^{(a)}$	$I^{(b)}$	λ_{exp} (Å)	$\Delta\lambda^{(c)}$ (Å)	σ_{exp} (cm^{-1})	Transition	$E_{low} - E_{upper}$
65	259	393.047	−0.002	254422	5s $^3D_3$–5p $^3D_3$	999929−1254350
33	200	395.501	−0.009	252844	5s $^3D_1$–5p $^3D_2$	1035777−1288615
39	184	400.656	0.002	249591	5s $^3D_2$–5p $^3D_3$	1004758−1254350
41	216	401.897	0.012	248820	5s $^1D_2$–5p $^3D_2$	1039788−1288615
37	371	403.867	0.011	247606	5s $^3D_1$–5p $^3D_1$	1035777−1283390
28	121	405.882	0.003	246377	5s $^3D_2$–5p $^1P_1$	1004758−1251137
59	136	409.957	0.000	243928	5s $^3D_2$–5p $^1D_2$	1004758−1248686
5	166	410.495	−0.011	243608	5s $^1D_2$–5p $^3D_1$	1039788−1283390
96	142	413.231	0.001	241995	5s $^1D_2$–5p $^1F_3$	1039788−1281784
125	376	413.755	0.000	241689	5s $^3D_3$–5p $^3F_4$	999929−1241618
6	114	421.314	0.003	237352	5s $^3D_2$–4f $^1P_1$	1004758−1242112
13	191	427.298	0.000	234029	5s $^3D_1$–5p $^3P_0$	1035777−1269806
7	61	441.018	−0.012	226748	5s $^3D_2$–5p $^3P_1$	1004758−1231500
3	76m	451.550	0.001	221459	5s $^3D_2$–5p $^3F_2$	1004758−1226218
3	79	464.343	0.004	215358	5s $^3D_1$–5p $^1P_1$	1035777−1251137
3	308bl	473.141	−0.010	211353	5s $^1D_2$–5p $^1P_1$	1039788−1251137
19	266	516.775	0.003	193508	5s $^3D_3$–5p $^3F_3$	999929−1193438
15	181	521.620	0.004	191710	5s $^1D_2$–5p $^3P_1$	1039788−1231500
19	226	525.093	−0.004	190442	5s $^3D_1$–5p $^3F_2$	1035777−1226218
31	364	527.932	−0.001	189418	5s $^3D_3$–5p $^3P_2$	999929−1189347
28	357	529.994	−0.004	188681	5s $^3D_2$–5p $^3F_3$	1004758−1193438
12	143	536.401	0.007	186428	5s $^1D_2$–5p $^3F_2$	1039788−1226218

See the footnotes to Table I.

Table III. *The measured (E_{obs}) and fitted (E_{fit}) level energies (in cm^{-1}) in the Pd-like Pr XIV ion.*

E_{obs}	E_{fit}	$E_o - E_f$	Conf.	LS term compositions	Leading jj term
Even Configurations:					
$J = 0$					
0	0	0	4d	100% ^1S	100% (3/2, 3/2)
1432980	1433098	−118	5d	98% ^3P + 2% ^1S	55% (5/2, 5/2)
1505085	1505082	3	5d	96% ^1S + 2% ^3P + 1% 6d ^1S	55% (3/2, 3/2)
$J = 1$					
929795	929764	31	5s	100% ^3D	100% (3/2, 1/2)
1400535	1400675	−140	5d	76% ^3S + 22% ^3P + 1% ^3D	74% (5/2, 3/2)
1418665	1418586	79	5d	51% ^1P + 27% ^3D + 17% ^3P	75% (5/2, 5/2)
1442640	1442752	−112	5d	27% ^3D + 49% ^1P + 14% ^3P	80% (3/2, 3/2)
1450057	1449908	149	5d	47% ^3P + 45% ^3D + 8% ^3S	80% (3/2, 5/2)
1734877	1734871	6	6s	100% ^3D	100% (3/2, 1/2)
$J = 2$					
902584	902547	37	5s	53% ^3D + 47% ^1D	98% (5/2, 1/2)
933708	933740	−32	5s	53% ^1D + 47% ^3D	98% (3/2, 1/2)
1414555	1414589	−34	5d	43% ^3P + 48% ^3D + 6% ^3F	93% (5/2, 3/2)
1426640	1426710	−70	5d	46% ^1D + 34% ^3P + 12% ^3F	92% (5/2, 5/2)
1452858	1452837	21	5d	52% ^3F + 40% ^1D + 6% ^3P	96% (3/2, 3/2)
1456711	1456790	−79	5d	43% ^3D + 30% ^3F + 16% ^3P	95% (3/2, 5/2)
1704495	1704490	5	6s	56% ^1D + 44% ^3D	100% (5/2, 1/2)
1735970	1735976	−6	6s	56% ^3D + 44% ^1D	100% (3/2, 1/2)
$J = 3$					
897974	898009	−35	5s	100% ^3D	100% (5/2, 1/2)
1418263	1418311	−48	5d	40% ^3D + 40% ^3F + 10% ^3G	92% (5/2, 3/2)
1425655	1425580	75	5d	38% ^1F + 46% ^3D + 12% ^3G	92% (5/2, 5/2)
1443713	1443626	87	5d	75% ^3G + 21% ^1F + 4% ^3F	94% (3/2, 3/2)
1460508	1460549	−41	5d	53% ^3F + 31% ^1F + 14% ^3D	97% (3/2, 5/2)
1702962	1702967	−5	6s	100% ^3D	100% (5/2, 1/2)
$J = 4$					
1411966	1411784	182	5d	55% ^3G + 41% ^1G + 3% ^3F	98% (5/2, 3/2)
1428642	1428756	−114	5d	79% ^3F + 19% ^1G + 2% ^3G	98% (5/2, 5/2)
1453404	1453369	35	5d	40% ^1G + 42% ^3G + 18% ^3F	99% (3/2, 5/2)
$J = 5$					
1418564	1418436	128	5d	100% ^3G	100% (5/2, 5/2)
Odd Configurations:					
$J = 0$					
904443?	904576	−133	4f	100% ^3P	100% (5/2, 5/2)

Table III. *Continued.*

E_{obs}	E_{fit}	$E_o - E_f$	Conf.	*LS* term compositions	Leading *jj* term
1146584	1146461	123	5p	100% ^{3}P	100% (3/2, 3/2)
	1733125		5f	100% ^{3}P	100% (5/2, 5/2)
$J = 1$					
909933	909958	−25	4f	96% ^{3}P + 4% ^{3}D	69% (5/2, 5/2)
959475S	959554	−79	4f	96% ^{3}D + 4% ^{3}P	45% (3/2, 5/2)
1113908S	1113679	229	5p	53% ^{3}P + 39% ^{3}D + 8% ^{1}P	81% (3/2, 1/2)
1129770S	1129758	12	5p	78% ^{1}P + 20% ^{3}P + 2% ^{3}D	79% (5/2, 3/2)
1159108S	1159304	−196	5p	59% ^{3}D + 26% ^{3}P + 14% ^{1}P	92% (3/2, 3/2)
1183432S	1183432	0	4f	99% ^{1}P + 1% 5f ^{1}P	51% (5/2, 7/2)
	1735503		5f	87% ^{3}P + 11% ^{3}D + 1% ^{1}P	77% (5/2, 5/2)
	1749640		5f	58% ^{3}D + 37% ^{1}P + 4% ^{3}P	73% (5/2, 7/2)
	1778717		5f	60% ^{1}P + 30% ^{3}D + 9% ^{3}P	94% (3/2, 5/2)
$J = 2$					
920800	920693	107	4f	87% ^{3}P + 10% ^{3}D + 3% ^{1}D	53% (5/2, 7/2)
946038	945869	169	4f	24% ^{3}D + 43% ^{3}F + 32% ^{1}D	74% (5/2, 5/2)
966919	966982	−63	4f	46% ^{1}D + 42% ^{3}D + 12% ^{3}P	61% (3/2, 7/2)
975847	975860	−13	4f	56% ^{3}F + 25% ^{3}D + 19% ^{1}D	84% (3/2, 5/2)
1076086	1076279	−193	5p	67% ^{3}P + 23% ^{3}D + 7% ^{1}D	96% (5/2, 1/2)
1108957	1109007	−50	5p	85% ^{3}F + 6% ^{1}D + 5% ^{3}P	95% (3/2, 1/2)
1128750	1128808	−58	5p	60% ^{1}D + 24% ^{3}P + 16% ^{3}D	92% (5/2, 3/2)
1164313	1164255	58	5p	57% ^{3}D + 26% ^{1}D + 13% ^{3}F	98% (3/2, 3/2)
	1739818		5f	57% ^{3}P + 31% ^{3}D + 12% ^{1}D	65% (5/2, 7/2)
1745076	1745186	−110	5f	43% ^{1}D + 37% ^{3}F + 20% ^{3}D	67% (5/2, 5/2)
	1770986		5f	31% ^{3}D + 42% ^{3}P + 27% ^{1}D	84% (3/2, 7/2)
	1776489		5f	62% ^{3}F + 19% ^{1}D + 18% ^{3}D	87% (3/2, 5/2)
$J = 3$					
946308	946609	−301	4f	58% ^{3}F + 37% ^{3}D + 4% ^{3}G	74% (5/2, 5/2)
963634	963541	93	4f	47% ^{3}D + 19% ^{1}F + 17% ^{3}F	60% (5/2, 7/2)
986790	986520	270	4f	64% ^{3}G + 23% ^{3}F + 9% ^{3}D	59% (3/2, 7/2)
1000523	1000556	−33	4f	78% ^{1}F + 14% ^{3}G + 6% ^{3}D	61% (3/2, 5/2)
1080110	1080058	52	5p	51% ^{3}F + 33% ^{1}F + 16% ^{3}D	99% (5/2, 1/2)
1133963	1133796	167	5p	74% ^{3}D + 26% ^{1}F + 1% ^{3}F	99% (5/2, 3/2)
1157671	1157818	−147	5p	41% ^{1}F + 49% ^{3}F + 10% ^{3}D	99% (3/2, 3/2)
1745601	1745702	−101	5f	48% ^{3}D + 47% ^{3}F + 5% ^{3}G	65% (5/2, 5/2)
	1749235		5f	55% ^{1}F + 18% ^{3}G + 17% ^{3}D	65% (5/2, 7/2)
1778732	1778635	97	5f	40% ^{3}F + 34% ^{3}D + 22% ^{1}F	98% (3/2, 7/2)
1780440	1780499	−59	5f	73% ^{3}G + 22% ^{1}F + 4% ^{3}F	99% (3/2, 5/2)
$J = 4$					
948523	948384	139	4f	52% ^{3}H + 22% ^{3}G + 19% ^{3}F	71% (5/2, 5/2)
950893	950921	−28	4f	69% ^{3}F + 17% ^{3}H + 13% ^{1}G	88% (5/2, 7/2)
970329	970312	17	4f	42% ^{1}G + 31% ^{3}H + 27% ^{3}G	63% (3/2, 5/2)
991285	991496	−211	4f	50% ^{3}G + 38% ^{1}G + 12% ^{3}F	94% (3/2, 7/2)
1122235	1122233	2	5p	100% ^{3}F	100% (5/2, 3/2)
	1747516		5f	51% ^{3}F + 39% ^{3}G + 7% ^{3}H	70% (5/2, 5/2)
1748665	1748527	138	5f	50% ^{1}G + 28% ^{3}F + 14% ^{3}H	70% (5/2, 7/2)
1772855	1772735	120	5f	78% ^{3}H + 13% ^{1}G + 8% ^{3}G	95% (3/2, 5/2)
1781279	1781272	7	5f	45% ^{3}G + 34% ^{1}G + 21% ^{3}F	96% (3/2, 7/2)
$J = 5$					
935439	935373	66	4f	75% ^{3}H + 23% ^{1}H + 2% ^{3}G	94% (5/2, 5/2)
959824	959850	−26	4f	57% ^{3}G + 38% ^{1}H + 5% ^{3}H	91% (5/2, 7/2)
978769	978782	−13	4f	39% ^{1}H + 41% ^{3}G + 20% ^{3}H	86% (3/2, 7/2)
1741108	1741007	101	5f	52% ^{3}H + 47% ^{1}H + 1% ^{3}G	97% (5/2, 5/2)
1749580	1749602	−22	5f	79% ^{3}G + 14% ^{1}H + 7% ^{3}H	96% (5/2, 7/2)
1774706	1774871	−165	5f	39% ^{1}H + 41% ^{3}H + 20% ^{3}G	99% (3/2, 7/2)
$J = 6$					
932518	932458	60	4f	100% ^{3}H	100% (5/2, 7/2)
1741342	1741347	−5	5f	100% ^{3}H	100% (5/2, 7/2)

S – energy has been determined in ref. [7]; ? – tentative value.

in $10^9\,s^{-1}$ units are given in the first columns of the tables. The experimentally measured wavelengths (in vacuum) and the corresponding wavenumbers are respectively given in the third and the fifth columns. The $\Delta\lambda$ values given in the fourth columns represent the differences between the measured wavelengths and those calculated from the experimental level energies (Ritz values) given in the last columns of the tables. It is seen that these differences do not exceed the uncertainties of wavelength measurements as discussed in Section 2. In Tables I and II, level designations are given in the *LS* coupling scheme according to the first components of the level eigenfunctions listed in Tables III and IV. However, strong intermediate coupling effects occur in the

Table IV. *The measured (E_{obs}) and fitted (E_{fit}) level energies (in cm^{-1}) in the Pd-like Nd XV ion.*

E_{obs}	E_{fit}	$E_o - E_f$	Conf.	*LS* percentage composition	*jj* leading term
Odd configurations:					
$J = 0$					
0	0	0	4d	100% ^{1}S	100% 4d(3/2, 3/2)
1574391	1574507	−116	5d	97% ^{3}P+ 2% ^{1}S	56% 5d(5/2, 5/2)
1653432	1653429	3	5d	96% ^{1}S+ 3% ^{3}P	55% 5d(3/2, 3/2)
$J = 1$					
1035777	1035744	33	5s	100% ^{3}D	100% 5s(3/2, 1/2)
1539465	1539628	−163	5d	73% ^{3}S+ 25% ^{3}P+ 2% ^{3}D	77% 5d(5/2, 3/2)
1558675	1558653	22	5d	52% ^{1}P+ 26% ^{3}D+ 15% ^{3}P	78% 5d(5/2, 5/2)
1585495	1585660	−165	5d	28% ^{3}D+ 48% ^{1}P+ 13% ^{3}P	81% 5d(3/2, 3/2)
1594010	1593968	42	5d	46% ^{3}P+ 45% ^{3}D+ 9% ^{3}S	81% 5d(3/2, 5/2)
	1921411		6s	100% ^{3}D	100% 6s(3/2, 1/2)
$J = 2$					
1004758	1004721	37	5s	52% ^{3}D+ 48% ^{1}D	98% 5s(5/2, 1/2)
1039788	1039822	−34	5s	52% ^{1}D+ 48% ^{3}D	98% 5s(3/2, 1/2)
1553900	1553835	65	5d	44% ^{3}P+ 47% ^{3}D+ 6% ^{3}F	93% 5d(5/2, 3/2)
1567726	1567785	−59	5d	47% ^{1}D+ 34% ^{3}P+ 12% ^{3}F	91% 5d(5/2, 5/2)
1596566	1596669	−103	5d	54% ^{3}F+ 39% ^{1}D+ 6% ^{3}P	97% 5d(3/2, 3/2)
1601525	1601584	−59	5d	44% ^{3}D+ 28% ^{3}F+ 17% ^{3}P	96% 5d(3/2, 5/2)
	1887162		6s	55% ^{1}D+ 45% ^{3}D	100% 6s(5/2, 1/2)
	1922573		6s	55% ^{3}D+ 45% ^{1}D	100% 6s(3/2, 1/2)
$J = 3$					
999929	999965	−36	5s	100% ^{3}D	100% 5s(5/2, 1/2)
1557970	1557968	2	5d	41% ^{3}F+ 37% ^{3}D+ 12% ^{1}F	94% 5d(5/2, 3/2)
1566581	1566569	12	5d	49% ^{3}D+ 37% ^{1}F+ 11% ^{3}G	93% 5d(5/2, 5/2)
1586835	1586626	209	5d	76% ^{3}G+ 20% ^{1}F+ 3% ^{3}F	95% 5d(3/2, 3/2)
1605456	1605571	−115	5d	31% ^{1}F+ 53% ^{3}F+ 14% ^{3}D	97% 5d(3/2, 5/2)
	1885551		6s	100% ^{3}D	100% 6s(5/2, 1/2)
$J = 4$					
1551115	1550967	148	5d	55% ^{3}G+ 42% ^{1}G+ 4% ^{3}F	98% 5d(5/2, 3/2)
1569832	1569879	−47	5d	79% ^{3}F+ 19% ^{1}G+ 2% ^{3}G	98% 5d(5/2, 5/2)
1598220	1597968	252	5d	40% ^{1}G+ 43% ^{3}G+ 17% ^{3}F	99% 5d(3/2, 5/2)
$J = 5$					
1558960	1558885	75	5d	100% ^{3}G	100% 5d(5/2, 5/2)
Even configurations:					
$J = 0$					
949496?	949369	127	4f	100% ^{3}P	100% 4f(5/2, 5/2)
1269806	1269660	146	5p	100% ^{3}P	100% 5p(3/2, 3/2)
	1898755		5f	100% ^{3}P	100% 5f(5/2, 5/2)
$J = 1$					
955505	955438	67	4f	96% ^{3}P+ 4% ^{3}D	70% 4f(5/2, 5/2)
1008663S	1008670	−7	4f	96% ^{3}D+ 4% ^{3}P	45% 4f(3/2, 5/2)
1231500S	1231480	20	5p	49% ^{3}P+ 40% ^{3}D+ 10% ^{1}P	84% 5p(3/2, 1/2)
1242112S	1242112	0	4f	86% ^{1}P+ 8% 5p ^{1}P	45% 4f(5/2, 7/2)
1251137S	1251146	−9	5p	68% ^{1}P+ 12% 4f ^{1}P	70% 5p(5/2, 3/2)
1283390S	1283360	30	5p	58% ^{3}D+ 28% ^{3}P+ 14% ^{1}P	93% 5p(3/2, 3/2)
	1901293		5f	87% ^{3}P+ 12% ^{3}D+ 2% ^{1}P	77% 5f(5/2, 5/2)
	1915441		5f	54% ^{3}D+ 42% ^{1}P+ 3% ^{3}P	75% 5f(5/2, 7/2)
	1948017		5f	56% ^{1}P+ 34% ^{3}D+ 10% ^{3}P	96% 5f(3/2, 5/2)
$J = 2$					
967382	967551	−169	4f	85% ^{3}P+ 11% ^{3}D+ 3% ^{1}D	53% 4f(5/2, 7/2)
993218	993278	−60	4f	24% ^{3}D+ 42% ^{3}F+ 33% ^{1}D	73% 4f(5/2, 5/2)
1017570	1017683	−113	4f	46% ^{1}D+ 40% ^{3}D+ 13% ^{3}P	62% 4f(3/2, 7/2)
1026887	1027132	−245	4f	57% ^{3}F+ 25% ^{3}D+ 17% ^{1}D	83% 4f(3/2, 5/2)
1189347	1189369	−22	5p	66% ^{3}P+ 24% ^{3}D+ 8% ^{1}D	97% 5p(5/2, 1/2)
1226218	1226260	−42	5p	84% ^{3}F+ 7% ^{1}D+ 5% ^{3}P	96% 5p(3/2, 1/2)
1248686	1248675	11	5p	60% ^{1}D+ 25% ^{3}P+ 15% ^{3}D	93% 5p(5/2, 3/2)
1288615	1288650	−35	5p	56% ^{3}D+ 26% ^{1}D+ 13% ^{3}F	99% 5p(3/2, 3/2)
	1906078		5f	55% ^{3}P+ 33% ^{3}D+ 11% ^{1}D	63% 5f(5/2, 7/2)
	1911689		5f	43% ^{1}D+ 37% ^{3}F+ 18% ^{3}D	65% 5f(5/2, 5/2)
	1941531		5f	29% ^{3}D+ 43% ^{3}P+ 27% ^{1}D	83% 5f(3/2, 7/2)
	1947308		5f	61% ^{3}F+ 19% ^{3}D+ 19% ^{1}D	86% 5f(3/2, 5/2)
$J = 3$					
993721	994086	−365	4f	58% ^{3}F+ 37% ^{3}D+ 5% ^{3}G	75% 4f(5/2, 5/2)
1012964	1012592	372	4f	45% ^{3}D+ 21% ^{1}F+ 18% ^{3}G	62% 4f(5/2, 7/2)
1038920	1038647	273	4f	62% ^{3}G+ 25% ^{3}F+ 10% ^{3}D	61% 4f(3/2, 7/2)

Table IV. *Continued.*

E_{obs}	E_{fit}	$E_o - E_f$	Conf.	*LS* percentage composition	*jj* leading term
1052123	1052239	−116	4f	75% ^{1}F+ 16% ^{3}G+ 7% ^{3}D	63% 4f(3/2, 5/2)
1193438	1193392	46	5p	50% ^{3}F+ 33% ^{1}F+ 16% ^{3}D	99% 5p(5/2, 1/2)
1254350	1254224	126	5p	73% ^{3}D+ 26% ^{1}F+ 1% ^{3}F	99% 5p(5/2, 3/2)
1281784	1281899	−115	5p	41% ^{1}F+ 49% ^{3}F+ 10% ^{3}D	100% 5p(3/2, 3/2)
1912345	1912235	110	5f	49% ^{3}F+ 45% ^{3}D+ 6% ^{3}G	70% 5f(5/2, 5/2)
1915929	1915865	64	5f	56% ^{1}F+ 19% ^{3}D+ 17% ^{3}G	70% 5f(5/2, 7/2)
1949497	1949685	−188	5f	35% ^{3}D+ 39% ^{3}F+ 23% ^{1}F	98% 5f(3/2, 7/2)
1951507	1951493	14	5f	74% ^{3}G+ 21% ^{1}F+ 4% ^{3}F	99% 5f(3/2, 5/2)
$J = 4$					
996495	996305	190	4f	47% ^{3}H+ 25% ^{3}G+ 21% ^{3}F	75% 4f(5/2, 5/2)
999341	999443	−102	4f	66% ^{3}F+ 18% ^{3}H+ 15% ^{1}G	88% 4f(5/2, 7/2)
1020498	1020493	4	4f	40% ^{1}G+ 35% ^{3}H+ 25% ^{3}G	67% 4f(3/2, 5/2)
1044412	1044312	100	4f	50% ^{3}G+ 37% ^{1}G+ 13% ^{3}F	94% 4f(3/2, 7/2)
1241618	1241774	−156	5p	100% ^{3}F	100% 5p(5/2, 3/2)
1914150	1914163	−13	5f	47% ^{3}F+ 41% ^{3}G+ 8% ^{3}H	75% 5f(5/2, 5/2)
1915482	1915349	133	5f	50% ^{1}G+ 32% ^{3}F+ 12% ^{3}H	75% 5f(5/2, 7/2)
1943352	1943240	112	5f	80% ^{3}H+ 13% ^{1}G+ 7% ^{3}G	95% 5f(3/2, 5/2)
1952705	1952582	123	5f	45% ^{3}G+ 34% ^{1}G+ 21% ^{3}F	97% 5f(3/2, 7/2)
$J = 5$					
982250	982115	135	4f	74% ^{3}H+ 24% ^{1}H+ 2% ^{3}G	94% 4f(5/2, 5/2)
1008720	1008831	−111	4f	60% ^{3}G+ 35% ^{1}H+ 5% ^{3}H	93% 4f(5/2, 7/2)
1030580	1030564	16	4f	41% ^{1}H+ 38% ^{3}G+ 21% ^{3}H	88% 4f(3/2, 7/2)
1907039	1907065	−26	5f	52% ^{3}H+ 47% ^{1}H+ 1% ^{3}G	97% 5f(5/2, 5/2)
1916154	1916526	−372	5f	80% ^{3}G+ 13% ^{1}H+ 6% ^{3}H	97% 5f(5/2, 7/2)
1945863	1945659	204	5f	39% ^{1}H+ 42% ^{3}H+ 19% ^{3}G	99% 5f(3/2, 7/2)
$J = 6$					
979670	979667	3	4f	100% ^{3}H	100% 4f(5/2, 7/2)
1907565	1907712	−147	5f	100% ^{3}H	100% 5f(5/2, 7/2)

S – energy has been determined in ref. [7]; ? – tentative value.

investigated ions (see below) and the *jj* coupling scheme happens to be more adequate in some cases. To avoid possible ambiguities, the experimental energies of the upper and lower levels of each transition are given in the last columns of Tables I and II.

The $4d^95s$ - $4d^95p$, $4d^95p$ - $4d^95d$, $4d^95d$ - $4d^95f$ transitions as well as the $4d^94f$ - $4d^95d$ transitions were classified in both Pr XIV and Nd XV spectra. It should be pointed out that in Nd XV, the $4d^95p\ ^1P_1$ and $4d^94f\ ^1P_1$ levels lie relatively close to each other and are mixed. As a consequence, two lines having approximately equal intensities were observed at 405.882 Å and 421.314 Å and could be assigned as transitions from these levels to the $4d^95s\ ^3D_2$ level (see Table II). We also identified the $4d^95p$ - $4d^96s$ transitions in Pr XIV which were not classified in the Pd-like ions from Xe IX through Ce XIII [5, 6]. These transitions appeared as a distinct array in the grazing incidence praseodymium spectrum excited in the LPP source. Further analysis showed that the calculated $4d^96s$ level energies could very accurately fit the experimental energies and that the fitted $4d^96s$ energy parameters followed the isoelectronic regularities obtained in the Sb VI - I VIII sequence [3]. A similar array was also observed in the 140–160 Å region of the neodymium spectrum. Unfortunately it was too weak for an unambiguous classification as the $4d^95p$ - $4d^96s$ transitions in Nd XV.

The energies of the excited configurations relative to the ground $4d^{10}\ ^1S_0$ state, i.e., their absolute positions, were derived from the wavelengths of the $4d^{10}\ ^1S_0$ - $4d^95p$, 4f ($J = 1$) resonance transitions. The corresponding uncertainties were respectively 30 cm^{-1} and 40 cm^{-1} for Pr XIV and Nd XV. Previous measurements of the transition wavelengths [7] are in agreement with our measurements within the stated uncertainties. The very weak $4d^{10}\ ^1S_0$ - $4d^94f\ ^3P_1$ transitions, previously unknown, have been classified in Pr XIV and Nd XV, and have been confirmed by the classification of transitions from levels of the $4d^95d$ configuration to the $4d^94f\ ^3P_1$ level. It should be pointed out that uncertainties on the relative positions of the excited levels were estimated to be less than 10 cm^{-1}, smaller than the uncertainties on their absolute positions, since the relative positions of levels were obtained from transitions of longer wavelengths compared with the resonance transitions.

The experimental level energies (E_{obs}) in the Pd-like Pr XIV and Nd XV spectra are presented in Tables III and IV respectively, with comparison to their fitted values from the least squares fits (E_{fit}), the level percentage compositions in *LS* coupling scheme and the leading compositions in *jj*-coupling scheme. It is seen that in general the *jj*-coupling scheme describes the levels more adequately. However we decided to give the *LS* designations in Tables I and II, thus allowing easy comparison with the earlier papers devoted to the Pd-like ion analyses [3–7]. In some cases, these first *LS* terms are not the leading terms because of the mixing effects mentioned above. The parameters adjusted by the least squares fit (LSF) of the observed level energies (Tables III and IV) are given in Table V.

In the Generalized-Least-Squares method, the energy parameters are constrained as functions of the net charge $Z_c = Z - N_e + 1$ of the ionic core along the isoelectronic sequence with N_e electrons. The Slater integrals are expanded as: $R^k = A + BZ_c + C/(Z_c + D)$ and the spin-orbit integrals are expanded as a fourth order polynomial in Z_c. The coefficients of expansions are fitted using all the known level energies of the isoelectronic sequence. This method was already applied to lower-Z ions from

Table V. *Least-Squares-Fitted (LSF) and Hartree-Fock (HF) energy parameters (in cm^{-1}) and their ratios in the Pd-like Pr XIV and Nd XV ions.*

Energy Parameter[a]	Pr XIV			Nd XV		
	LSF[b]	HF	LSF/HF	LSF[b]	HF	LSF/HF
Eav (4d^{10})	1403 (115)	1907		1429 (143)	1946	
Eav (5s)	913050 (59)	921465		1016704 (73)	1025718	
ζ (4d)	12706 (47)	12375	1.027	14316 (58)	13916	1.029
G^2 (4d,5s)	20760 (575)	22425	0.925	21535 (714)	23140	0.931
Eav (5d)	1433152 (29)	1439196		1575000 (36)	1581815	
ζ (4d)	12732 (25)	12428	1.024	14302 (30)	13972	1.024
ζ (5d)	3549 (29)	3139	1.131	4150 (35)	3677	1.129
F^2 (4d,5d)	46088 (293)	49448	0.932	49361 (364)	52627	0.938
F^4 (4d,5d)	28448 (414)	24563	1.158	28307 (531)	26310	1.076
G^0 (4d,5d)	9728 (19)	11685	0.833	10472 (24)	12444	0.841
G^2 (4d,5d)	13581 (350)	15002	0.905	15239 (444)	15990	0.953
G^4 (4d,5d) r	11634 (300)	12852	0.905	13085 (381)	13730	0.953
Eav (6s)	1716425 (59)	1720004		1900632 (fix)	1904955	
ζ (4d)	12765 (47)	12450	1.025	14347 (fix)	13997	1.025
G^2 (4d,6s)	6453 (574)	6835	0.944	6805 (fix)	7163	0.950
R^2 (4d,4d;4d,5s)	− 2323 (fix)	− 2733	0.850	− 1528 (fix)	− 1798	0.850
R^2 (4d,4d;4d,5d)	18262 (fix)	21484	0.850	18935 (fix)	22276	0.850
R^4 (4d,4d;4d,5d)	14175 (fix)	16676	0.850	14701 (fix)	17295	0.850
R^2 (4d,5s;4d,5d)	45306 (fix)	53301	0.850	48076 (fix)	56560	0.850
R^2 (4d,5s;5d,4d)	13248 (fix)	15586	0.850	14092 (fix)	16579	0.850
Standard Deviation[c]	116 cm^{-1}			143 cm^{-1}		
Eav (4f)	963568 (41)	969187		1012980 (45)	1018824	
ζ (4d)	12309 (51)	12143	1.014	13904 (54)	13657	1.018
ζ (4f)	1198 (34)	1262	0.949	1502 (37)	1515	0.991
F^2 (4d,4f)	117916 (453)	137069	0.860	125081 (491)	143828	0.870
F^4 (4d,4f)	86086 (784)	89296	0.964	90675 (865)	93826	0.966
G^1 (4d,4f)	134154 (107)	160862	0.834	139830 (130)	167652	0.834
G^3 (4d,4f)	90591 (685)	103436	0.876	92629 (754)	108390	0.855
G^5 (4d,4f)	68642 (1226)	73873	0.929	72566 (1332)	77582	0.935
Eav (5p)	1124333 (53)	1131905		1243723 (58)	1252056	
ζ (4d)	12734 (46)	12392	1.028	14404 (49)	13934	1.034
ζ (5p)	31299 (84)	29868	1.048	35740 (89)	34367	1.040
F^2 (4d,5p)	52910 (567)	60671	0.872	56599 (619)	63624	0.890
G^1 (4d,5p)	15812 (214)	17370	0.910	17234 (257)	18120	0.951
G^3 (4d,5p)	17691 (965)	17653	1.002	19687 (1046)	18476	1.066
Eav (5f)	1757601 (54)	1768033		1925818 (61)	1935390	
ζ (4d)	12455 (46)	12418	1.003	14266 (45)	13960	1.022
ζ (5f)	413 (fix)	413	1.000	500 (fix)	500	1.000
F^2 (4d,5f)	38346 (656)	40336	0.951	40310 (664)	43437	0.928
F^4 (4d,5f)	19460 (fix)	19460	1.000	20893 (fix)	20893	1.000
G^1 (4d,5f)	8445 (fix)	14075	0.600	8258 (fix)	13763	0.600
G^3 (4d,5f)	9248 (1348)	12799	0.723	9114 (846)	13029	0.700
G^5 (4d,5f) r	7455 (1087)	10317	0.723	7441 (691)	10637	0.700
R^2 (4d,4f;4d,5p)	− 2485 (fix)	−2924	0.850	− 880 (fix)	−1035	0.850
R^4 (4d,4f;4d,5p)	1880 (fix)	2212	0.850	2954 (fix)	3475	0.850
R^1 (4d,4f;5p,4d)	1764 (fix)	2075	0.850	2861 (fix)	3366	0.850
R^3 (4d,4f;5p,4d)	3710 (fix)	4365	0.850	4650 (fix)	5470	0.850
R^2 (4d,4f;4d,5f)	27387 (fix)	32220	0.850	27392 (fix)	32226	0.850
R^4 (4d,4f;4d,5f)	19873 (fix)	23380	0.850	19809 (fix)	23305	0.850
R^1 (4d,4f;5f,4d)	30999 (fix)	36470	0.850	29500 (fix)	34707	0.850
R^3 (4d,4f;5f,4d)	23051 (fix)	27119	0.850	22541 (fix)	26518	0.850
R^5 (4d,4f;5f,4d)	17381 (fix)	20448	0.850	17159 (fix)	20188	0.850
R^2 (4d,5p;4d,5f)	33078 (fix)	38916	0.850	36382 (fix)	42803	0.850
R^4 (4d,5p;4d,5f)	16433 (fix)	19333	0.850	18211 (fix)	21425	0.850
R^1 (4d,5p;5f,4d)	8365 (fix)	9841	0.850	9228 (fix)	10857	0.850
R^3 (4d,5p;5f,4d)	8973 (fix)	10557	0.850	9887 (fix)	11632	0.850
Standard Deviation[c]	174 cm^{-1}			189 cm^{-1}		

(a) r = this parameter has been linked by a fixed ratio of HFR integrals to the parameter in the previous row.
(b) The uncertainties of the fitted parameter are given in parentheses.
(c) Standard deviation $=[\Sigma(E_{\text{obs}} - E_{\text{calc}})^2/(n-p)]^{1/2}$, where n is the number of known levels, p is the number of free parameters.

Ag II to Ce XIII for $4d^95s$, $4d^95p$, $4d^95d$ and $4d^95f$ configurations [5]. In the present work, the data on Pr XIV and Nd XV have been included into the fit and resulted in minor changes in the coefficients of Z_c expansion of [5]. Therefore the revised values for fitted parameters and scaling factors SF of the HFR integrals are not given here. The present GLS fit for $4d^95d$ comprises two hundred twenty eight $E_{\rm exp}$ values (all with equal weight in the fit) for thirty nine free parameters. The *r.m.s.* deviation of $76.5\,{\rm cm}^{-1}$ is obtained provided that a few levels are discarded: the $^3P_0$ levels in La XII, Ce XIII and Pr XIV, which are about $440\,{\rm cm}^{-1}$ above the GLS predictions $E_{\rm GLS}$. Furthermore, the $4d^95d\,^1S_0$ level of laser interest, does not fit accurately the isoelectronic trends in Pr XIV ($E_{\rm exp} = 1\,505\,085\,{\rm cm}^{-1}$, $E_{\rm GLS} = 1\,505\,460\,{\rm cm}^{-1}$) and in Nd XV ($E_{\rm exp} = 1\,653\,432\,{\rm cm}^{-1}$, $E_{\rm GLS} = 1\,652\,895\,{\rm cm}^{-1}$). In order to describe the configuration mixing of $4d^95p$ and $4d^94f$ in the Xe IX - Nd XV sequence, a GLS fit of both configurations together was attempted to yield the interaction parameters. The Z_c-expansion was then applied to the scaling factors SF of all the radial integrals (except $E_{\rm av}$) which have a smoother Z_c dependence than the integrals themselves so that the number of adjustable coefficients could be reduced. The fit included one hundred seventy six experimental energies $E_{\rm exp}$. In order to take into account the decreasing accuracy of experimental energies with increasing Z_c, the $E_{\rm exp}$ values were weighted by $1/Z_c$ in the fit. The configuration interaction mostly affects the $J = 1$ levels of both configurations in the few spectra where they are close and the R^k(4d5p,4d4f) ($k = 2, 4$), R^k(4d5p,4f4d) (k =1, 3) interaction parameters cannot be fitted independently. By linking the variation of R^2 and R^4 (respectively R^1 and R^3) through a common scaling factor, a value of 0.48 ± 0.18 is obtained for R^2 and R^4 and respectively of 0.92 ± 0.08 for R^1 and R^3. However these values of the scaling factors are to be taken with caution because of the small number of mixed levels involved in their determinations. The average of deviations $|E_{\rm exp}$- $E_{\rm GLS}|$ in this study increases with Z_c ($118\,{\rm cm}^{-1}$ in La XII, $166\,{\rm cm}^{-1}$ in Ce XIII, $228\,{\rm cm}^{-1}$ in Pr XIV and $313\,{\rm cm}^{-1}$ in Nd XV). Although the application of the GLS method to the Pd I sequence results in sufficiently good results to support revisions and new analyses [5, 6], the presence of strong configuration interactions makes it less conclusive than in the Ni I and Zn I isoelectronic sequences [13].

4. Conclusion

The complete energy structures of the $4d^95s$, $4d^94f$, $4d^95p$ and $4d^95d$ configurations in Pr XIV and Nd XV and of the $4d^96s$ configuration in Pr XIV have been experimentally established in our analysis. Concerning the $4d^95f$ configuration, the energies of most levels with $J < 3$ could not be determined since the corresponding transitions from these levels have relatively low transition probabilities and were not observed in the spectra. It should be also mentioned that a number of $4d^94f$ and $4d^95f$ level energies were determined each through one transition only. However these transitions were strong enough and appeared as the unique possible solution for identifications in their spectral regions.

Beyond Nd XV and the gap of the radioactive promethium (Pm XVI), our attempt in exciting the Pd-like Sm XVII spectrum has been unsuccessful up to now. However the present GLS determination of the scaling factors for HFR integrals may be useful for further predictions of wavelengths and transition probabilities.

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