Zeeman Effect in the Arc Spectrum of Nickel

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Measurements of the Zeeman patterns for 113 lines between λ5500 and λ3000 are presented, from which g-factors for 61 terms are calculated. The g-sum rule holds for configuration d^9s and for $d^8s(^2F)\cdot 4p$, but not for $d^9\cdot 4p$ or $d^8s(^4F)\cdot 5s$. It does hold for $d^9\cdot 4p$ and the quintet terms of $d^8s(^4F)\cdot 4p$ taken together, indicating that these groups interact. It is surmised that $d^8s(^4F)\cdot 5s$ is perturbed by $d^9\cdot 4d$. The theory of two-electron systems fits d^9s very well. It works fairly well with d^8s^2, but breaks down when applied to $d^9\cdot 4p$, probably because of increased importance of the magnetic interactions which are neglected in the theory.

THE arc spectrum of nickel (Ni I) provides an excellent opportunity to study the Zeeman effect in electron coupling intermediate between the (LS) and (jj) types. Henry Norris Russell[1] has extended the analysis of the spectrum to include nearly all of the lines, and has assigned the terms to electron configurations. The energy level separations in the triplet and quintet multiplets deviate markedly from the simple interval rules. It is evident that electron coupling in all configurations is intermediate, and fairly remote from (LS) coupling.

Several configurations, such as d^9s, d^8s^2, $d^9\cdot 4p$ and $d^9\cdot 4d$, are of the two-electron type. The d^9 group, which lacks one electron of completion, plays the rôle of a single electron except that it causes multiplet terms to be inverted. The d^8 group is related likewise to a d^2 group. The theory of two-electron systems in intermediate coupling has been developed sufficiently so that it accounts quite well for the arrangement of terms in configurations such as d^9s; but it fails when applied to such configurations as $d^9\cdot 4p$, probably because of neglected magnetic interactions of the electrons. Knowledge of the Zeeman effect in such configurations will be useful as a guide in the extension of the theory.

The energy levels of the intermediate and the high configurations are intermingled sufficiently so that fairly strong perturbations may be expected. Zeeman effect data will be useful in the study of these interactions.

Not much experimental work has been done on the Zeeman effect in the nickel spectrum. Several observers[2] have made measurements on a few lines, which do not permit fixing values of g-factors. The patterns for λ3597 and λ3722 observed by Beals[3] are consistent with the classification of the lines. The only precise measurements are those of Bakker,[4] who has observed the patterns of twenty-five lines, by using a vacuum arc as the source, and has calculated the g-factors for twenty terms.

This communication is a record of the investigation of the Zeeman effect for 113 lines in the range λ5500 to λ3000. The g-factors for 61 terms are calculated, and the results are tested by the g-sum rule. The experimental values are compared with the theoretical g-factors in intermediate coupling in the two-electron configurations d^9s and d^8s^2.

EXPERIMENTAL PART

The spectrum was photographed in the second and third orders of an Anderson 21-foot concave grating on a Paschen mounting. A quartz lens and a calcite plate were used to form separate images on the slit of the components of vibration parallel and perpendicular to the magnetic field. Several spectrograms were made of each com-

[1] Henry Norris Russell, Phys. Rev. **34**, 821 (1929).

[2] Reese, Astrophys. J. **12**, 120 (1900); Kent, Astrophys. J. **13**, 289 (1900); Kent, Johns Hopkins Univ. Circular **20**, 82 (1901); Peterke, Halle Inaug. Diss. (1909); Graftdijk, Thesis, Amsterdam (1911); Lüttig, Ann. d. Physik **38**, 43 (1912); Takahashi, J. Coll. Sci. Tokyo **41**, Art. 8 (1921); Yamada, J. Coll. Sci. Tokyo **41**, Art. 870 (1921).

[3] Beals, Proc. Roy. Soc. **A109**, 369 (1925).

[4] Bakker, Proc. Akad. Amsterdam **35**, 82 (1932).

ponent, and the best three of each were measured. Realizing that most of the Zeeman patterns would be unresolved, we aimed at the best quality for these patterns rather than at the highest resolution. The pole-pieces of the magnet were about 12 mm in diameter and 6 mm apart. The field strength, about 26,000 gauss, was computed from the Zeeman patterns of the Ca II lines λ3968.47 and λ3933.67, which appeared on the spectrograms because of calcium present in the carbon electrode of the arc.

The arc electrodes were strips of carbon and pure nickel which crossed each other at right angles between the magnet poles. The nickel electrode was fixed in position, and insulated from the pole by a fused quartz disk. The carbon electrode vibrated to produce an intermittent arc. Current from a 220 volt d.c. source was adjusted by a variable resistance to keep the nickel as cool as possible—in general, at a cherry-red heat. Operation of the arc in vacuum was unbearably tedious because magnetic debris had to be removed frequently from the pole-pieces. Fortunately, it could be operated in the open air without serious detrimental effect upon the quality of the spectrograms. The time of exposure was 4 to 8 hours.

The spectrograms were measured with a Gaertner comparator, the eyepiece of which was provided with several pairs of index lines ruled on glass. The comparator, in a darkened room, was illuminated by a 75 watt lamp through a green gelatin filter. Additional screens of thin white paper were used at the discretion of the operator. Zeeman patterns of weak lines, which were all but invisible by daylight illumination, were brought out clearly. The magnification was adjusted so that a pair of index lines spanned a component of the pattern, with the lines at the positions of sharp contrast on opposite sides of the center of intensity.

The unresolved Zeeman patterns of lines due to transitions between terms with nearly equal g-factors were easily measured. The observer had only to guard against errors of judgment in case of unequal shading off on opposite sides of the center of intensity. The patterns of lines due to transitions between terms with widely differing g-factors, which were nearly resolved, were troublesome because their centers of intensity were ill-defined. Reliance was placed, in these instances, upon the average of a large number of measurements made at different times, in order to eliminate personal errors; nevertheless, the measurements of these patterns are relatively inaccurate.

Many lines due to transitions from intermediate to deep configurations were reversed in the no-field exposures, and tended to be reversed in the field exposures. In some instances, notably λ3619, λ3524, λ3492, λ3458 and λ3414, reversal was clean-cut and complete. The separation of the parts of a reversed Zeeman component was nearly equal to the split of the reversed no-field line. We believe that this tendency toward reversal has given the arc in air an evil reputation which it does not deserve as a source for the study of the Zeeman effect. We were able to measure reversed and partially reversed unresolved patterns about as precisely as those which were not reversed.

The patterns of nearly all lines between λ5500 and λ3380 were measured on two or three spectrograms. Below λ3380 only one spectrogram was secured, for the perpendicular component. The number of measurements ranged from about 20 on patterns easy to measure consistently to more than 70 on those which were most difficult. The self-consistency of the g-factor values calculated from the measurements indicates that this procedure was effective in reducing error due to width and fuzziness of the components.

The g-factors were calculated from resolved patterns by the method of Landé, and from unresolved patterns by formulae given by Shenstone and Blair.[5] The combinations of intermediate terms with the deep terms a^3D, a^1D, a^1S and a^3F were considered first. In most instances, two to five combinations appeared on the spectrograms. The computed g-factor values were weighted in accord with our judgment of the relative precision of the measurements of the patterns, and weighted mean values were computed. The g-factors of the high terms were calculated in the same manner, from their combinations with intermediate terms. Finally, the g-factors of a few intermediate terms, which had no combinations with deep terms on the spectro-

[5] Shenstone and Blair, Phil. Mag. 8, 765 (1929).

TABLE I. *Zeeman patterns and g-factors for lines of the Ni I spectrum.*

λ	Combination $x-y$	Zeeman Effect Patterns Observed	Zeeman Effect Patterns Calculated	*g*-factors g_x	*g*-factors g_y
5476.91	$a^1S_0-z^1P_1^0$	(0), 0.997 (a)	(0), 0.997	0/0	0.997
5081.12	$z^1F_3^0-e^1G_4$	(0), 1.025 (d)	(0), 1.025	1.019	1.021*
5080.53	$z^3F_4^0-e^3G_5$	(0), 1.066	(0), 1.021	1.282	1.195
5035.36	$z^3F_3^0-e^3G_4$	(0), 1.014	(0), 1.014	1.078	1.055
5017.61	$z^5F_5^0-e^5F_5$	(0), 1.398	(0), 1.395	1.395	1.395
4984.12	$z^3F_2^0-e^3G_3$	(0), 0.821	(0), 0.821	0.718	0.770
4980.17	$z^5F_4^0-e^3G_5$	(0), 1.009	(0), 1.019	1.283	1.195
4918.37	$z^3G_4^0-f^3F_3$	(0), 0.996	(0), 0.996	1.046	1.079
4904.40	$z^3P_2^0-e^3S_1$	(0), (0.514), 1.253 (b)	(0), (0.463), 1.228	1.459	1.922
4873.45	$z^5F_3^0-e^5F_2$	(0), 1.500	(0), 1.497	1.225	0.953
4866.28	$z^5F_5^0-e^5F_4$	(0), 1.510 (e)	(0), 1.527	1.395	1.329
4855.42	$z^3P_2^0-e^3P_2$	(0), 1.445	(0.050), 1.445	1.459	1.431
4831.19	$z^5F_4^0-e^5F_3$	(0), 1.426 (e)	(0), 1.370	1.283	1.225
4829.04	$z^3P_2^0-f^3D_3$	(−), 1.172	(−), 1.172	1.459	1.316
4806.99	$z^3D_3^0-f^3F_4$	(−), 1.250	(−), 1.205	1.310	1.268
4786.54	$z^5G_5^0-e^5F_5$	(0.537), 1.329	(0.524), 1.331	1.267	1.395
4763.95	$z^3F_4^0-f^3F_4$	(0), 1.266	(0.053), 1.275	1.282	1.268
4756.52	$z^5G_4^0-e^5F_4$	(0.635), 1.241	(0.573), 1.243	1.157	1.329
4715.76	$z^5G_3^0-e^5F_3$	(0.807), 1.083	(0.774), 1.080	0.935	1.225
4714.42	$z^5G_6^0-e^5F_5$	(0), 1.147	(0), 1.147	1.324	1.395
4686.21	$z^5G_2^0-e^5F_2$	(0.622), (1.203), − (b)	(0.618), (1.236), −	0.335	0.953
4648.66	$z^5G_5^0-e^5F_4$	(0), 1.167	(0), 1.143	1.267	1.329
4604.99	$z^5G_4^0-e^5F_3$	(0), 1.058	(0), 1.055	1.157	1.225
4600.36	$z^5G_2^0-e^5F_1$	(0), (0.277), 0.453 (b)	(0), (0.265), 0.467	0.335	0.070
4592.53	$z^5G_3^0-e^5F_2$	(0), 0.914	(0), 0.917	0.935	0.953
4470.49	$z^5D_2^0-e^5F_3$	(0), 0.852	(0), 0.837	1.613	1.225
4462.46	$z^5D_1^0-e^5F_2$	(0), (0.575), 0.666 (b)	(0), (0.574), 0.666	1.527	0.953
4459.05	$z^5D_3^0-e^5F_4$	(0), 1.057	(0), 1.047	1.517	1.329
4401.55	$z^5D_4^0-e^5F_5$	(0), 1.162	(0), 1.162	1.512	1.395
4359.59	$z^5D_2^0-e^5F_2$	(−), 1.297	(−), 1.283	1.613	0.953
4331.64	$b^1D_2-y^1D_2^0$	(−), 0.997	(−), 0.997	1.141	0.853
4325.61	$z^5D_3^0-e^5F_3$	(−), 1.378	(−), 1.371	1.517	1.225
4288.01	$z^3G_5^0-g^3F_4$	(0), 1.078	(0), 1.078	1.205	1.268
3973.55	$a^1D_2-z^3P_2^0$	(0.838), 1.213	(0.799), 1.237	1.015	1.459
3944.10	$z^3F_3^0-f^3G_4$	(−), 0.950	(−), 0.950	1.078	1.027
3858.28	$a^1D_2-z^3F_3^0$	(0), 1.152	(0), 1.141	1.015	1.078
3807.14	$a^1D_2-z^3D_3^0$	(0), (0.302), (−), 1.647 (b)	(0), (0.295), (−), 1.605	1.015	1.310
3783.52	$a^1D_2-z^5F_3^0$	(0), 1.455	(0), 1.435	1.015	1.225
3775.56	$a^1D_2-z^3D_2^0$	(0), 1.026	(0.040), 1.026	1.015	1.037
3749.04	$a^3F_3-z^5D_3^0$	(−), 1.301	(−), 1.300	1.083	1.517
3739.23	$a^3F_3-z^5G_4^0$	(0), 1.332	(0), 1.268	1.083	1.157
3736.81	$a^1D_2-z^5F_2^0$	(0), 0.996	(0.075), 0.994	1.015	0.972
3722.48	$a^3D_1-z^3P_2^0$	(0), (0.929), 0.474, 1.445, 2.403 (a)	(0), (0.959), 0.500, 1.459, 2.418	0.500	1.459
3688.41	$a^3F_2-z^3F_3^0$	(0), 1.562	(0), 1.488	0.668	1.078
3674.11	$a^1D_2-z^3F_2^0$	(0.586), 0.826 (e)	(0.555), 0.866	1.015	0.718
3670.42	$a^3F_3-z^3P_2^0$	(0), 0.661	(0), 0.707	1.083	1.459
3669.23	$a^3F_3-z^5G_3^0$	(0.451), 1.008	(0.381), 1.009	1.083	.0935
3664.09	$a^3F_2-z^3P_1^0$	(0), (.811), 0, − (a)	(0), (0.783), 0, 0.668	0.668	1.451
3624.73	$a^3F_4-z^5G_5^0$	(0), 1.314 (e)	(0), 1.301	1.250	1.267
3619.39	$a^1D_2-z^1F_3^0$	(0), 1.039	(0), 1.023	1.015	1.019
3612.73	$a^3F_2-z^3D_2^0$	(0.686), 0.840	(0.664), 0.852	0.668	1.037
3610.45	$a^3D_2-z^3P_2^0$	(0.588), 1.295	(0.553), 1.305	1.152	1.459
3609.31	$a^3D_2-z^5G_3^0$	(0), 0.729	(0), 0.718	1.152	0.935
3602.28	$a^3F_3-z^5F_4^0$	(0), 1.613	(0), 1.583	1.083	1.283
3597.70	$a^3D_1-z^3P_1^0$	(0.956), 0.511, 1.425 (a)	(0.951), 0.500, 1.451	0.500	1.451
3587.93	$a^3D_3-z^5G_4^0$	(0), 0.890	(0), 0.893	1.333	1.157
3571.87	$a^3F_3-z^3F_3^0$	(0), 1.077	(0), 1.081	1.083	1.078
3566.37	$a^1D_2-z^1D_2^0$	(0), 1.020	(0), 1.017	1.015	1.018
3561.75	$a^3F_4-z^5G_4^0$	(−), 1.192	(−), 1.203	1.250	1.157

TABLE I—*Continued*

λ	Combination $x-y$	Zeeman Effect Patterns Observed	Zeeman Effect Patterns Calculated	g-factors g_x	g-factors g_y
3548.19	$a^3D_1-z^3D_2^0$	(0), −, 1.066, 1.586 (c) (e)	(0), 0.500, 1.037, 1.574	0.500	1.037
3527.99	$a^3F_3-z^3D_3^0$	(−), 1.201	(−), 1.197	1.083	1.310
3524.54	$a^3D_3-z^3P_2^0$	(0), 1.204	(0), 1.207	1.333	1.459
3523.45	$a^3D_3-z^5G_3^0$	(1.009), 1.134 (e)	(1.023), 1.134	1.333	0.935
3519.78	$a^3F_2-z^3F_2^0$	(0), 0.707	(0), 0.693	0.668	0.718
3515.06	$a^3D_2-z^3F_3^0$	(0), 0.998	(0), 1.004	1.152	1.078
3513.95	$a^3D_1-z^5F_2^0$	(0), (−),	(0), (0.472)		
		−, 0.950, 1.477 (a)	0.500, 0.972, 1.444	0.500	0.972
3510.34	$a^3D_1-z^3P_0^0$	(0), 0.498 (a)	(0), 0.500	0.500	0/0
3500.85	$a^3F_3-z^3D_2^0$	(0), 1.122	(0), 1.129	1.083	1.037
3492.97	$a^3D_2-z^3P_1^0$	(0), 1.005	(0), 1.003	1.152	1.451
3483.78	$a^3F_2-z^3D_1^0$	(0), 0.710	(0), 0.732	0.668	0.540
3472.55	$a^3D_2-z^3D_3^0$	(0), 1.418	(0), 1.468	1.152	1.310
3469.48	$a^3F_2-z^1F_3^0$	(0), 1.355	(0), 1.370	0.668	1.019
3467.51	$a^3F_3-z^5F_2^0$	(0), 1.206	(0), 1.194	1.083	0.972
3461.66	$a^3D_3-z^5F_4^0$	(0), 1.167	(0), 1.208	1.333	1.283
3458.47	$a^3D_1-z^3F_2^0$	(0), 0.815	(0), 0.827	0.500	0.718
3452.89	$a^3D_2-z^5F_3^0$	(0), 1.275	(0), 1.298	1.152	1.225
3446.26	$a^3D_2-z^3D_2^0$	(0), 1.081	(0.207), 1.094	1.152	1.037
3437.28	$a^3F_4-z^5F_4^0$	(0), 1.270	(0.110), 1.262	1.250	1.283
3433.57	$a^3D_3-z^3F_3^0$	(0.670), 1.180 (e)	(0.656), 1.205	1.333	1.078
3423.71	$a^3D_1-z^3D_1^0$	(0), 0.509	(0.020), 0.520	0.500	0.540
3414.77	$a^3D_3-z^3F_4^0$	(0), 1.183	(0), 1.205	1.333	1.282
3413.94	$a^3D_2-z^5F_2^0$	(−), 1.072 (d)	(−), 1.062	1.152	0.972
3413.48	$a^3F_3-z^3F_2^0$	(−), 1.499	(−), 1.448	1.083	0.718
3392.99	$a^3D_3-z^3D_3^0$	(0), 1.321	(0.059), 1.322	1.333	1.310
3391.05	$a^3F_4-z^3F_4^0$	(−), 1.278	(−), 1.266	1.250	1.282
3380.89	$a^3F_2-z^3G_3^0$	(0), 0.814 (d)	(0), 0.814	0.668	0.741*
3380.58	$a^1D_2-z^1P_1^0$	(0), 1.017	(0), 1.024	1.015	0.997
3374.64	$z^5G_6^0-e^5H_7^0$	(−), 1.101 (d)	(−), 1.101	1.324	1.264*
3374.23	$a^3D_3-z^5F_3^0$	(−), 1.197	(−), 1.279	1.333	1.225
3372.00	$a^3F_3-z^3G_4^0$	(−), 0.981	(−), 0.990	1.083	1.046
3369.58	$a^3F_4-z^3D_3^0$	(−), 1.158	(−), 1.160	1.250	1.310
3366.17	$a^3F_3-z^1F_3^0$	(−), 1.067 (d)	(−), 1.051	1.083	1.019
3365.77	$a^1D_2-y^3F_3^0$	(−), 1.317	(−), 1.285	1.015	1.150
3361.56	$a^3D_2-z^3F_2^0$	(−), 0.938	(−), 0.935	1.152	0.718
3322.32	$a^1D_2-y^3D_3^0$	(−), 1.442	(−), 1.442	1.015	1.229
3320.26	$a^3F_3-z^1D_2^0$	(−), 1.170	(−), 1.148	1.083	1.018
3315.67	$a^3D_2-z^1F_3^0$	(−), 0.923	(−), 0.888	1.152	1.019
3250.75	$a^1D_2-y^3D_2^0$	(−), 1.086	(−), 1.100	1.015	1.185
3248.44	$a^3D_3-z^3G_4^0$	(−), 0.664	(−), 0.616	1.333	1.046
3243.06	$a^3D_3-z^1F_3^0$	(−), 1.173	(−), 1.176	1.333	1.019
3234.66	$a^3D_2-z^3G_3^0$	(−), 0	(−), 0**	1.152	0.741*
3232.95	$a^3F_4-z^3G_5^0$	(−), 1.115	(−), 1.115	1.250	1.205
3225.03	$a^1D_2-y^3D_1^0$	(−), 1.276	(−), 1.262	1.015	0.522
3221.66	$a^3F_4-z^1F_3^0$	(−), 1.617	(−), 1.597	1.250	1.019
3134.11	$a^3D_1-y^3F_2^0$	(−), 0.948	(−), 0.934	0.500	0.789
3101.88	$a^1D_2-y^1F_3^0$	(−), 1.021	(−), 1.021	1.015	1.018
3101.56	$a^3D_2-y^3F_3^0$	(−), 1.149	(−), 1.148	1.152	1.150
3080.76	$a^3D_1-y^3D_2^0$	(−), 1.570	(−), 1.528	0.500	1.185
3057.65	$a^3D_1-y^3D_1^0$	(−), 0.540	(−), 0.511	0.500	0.522
3054.32	$a^3D_2-y^3F_2^0$	(−), 0.966	(−), 0.971	1.152	0.789
3037.94	$a^3D_3-y^3F_3^0$	(−), 1.241	(−), 1.242	1.333	1.150
3012.01	$a^1D_2-y^1D_2^0$	(−), 0.934	(−), 0.934	1.015	0.853
2994.46	$a^3D_3-z^1G_4^0$	(−), 0 (e)	(−), −	1.333	−

(a) Resolved pattern.
(b) Parallel component pattern resolved.
(c) Perpendicular component pattern resolved.
(d) Perpendicular components of adjacent lines overlap slightly.
(e) Decides classification of the line.
* g_y not less than value given.
** Strongest perpendicular components in the Landé pattern are at −0.08.

grams, were determined from their high term combinations; and the g-factor for b^1D_2 was calculated from its single combination with an intermediate term. A critical survey of the whole array of g-factor values indicated that the self-consistency of the results could not be improved by altering arbitrarily the g-factors of the deep terms which were first considered.

The wave-lengths and classifications of the spectrum lines, the observed Zeeman patterns, the weighted g-factors and the Zeeman patterns calculated from these for comparison with the observed patterns are given in Table I. Parallel components are lacking for lines below $\lambda3380$, and for a few other weak lines. This is of little moment, for the perpendicular components are more useful in determining g-factors. The perpendicular components of adjacent lines overlapped slightly, in a few instances, so that it was impossible to resolve them cleanly. Zero weight was given to these measurements when the g-factors could be calculated from other lines. In three instances in which the g-factor is calculated from one of these questionable patterns alone, the value is indicated as a lower limit. Several instances are noted in which the observed Zeeman pattern decides the classification of the line, where Russell gives an alternative.

The g-factors are compared with their theoretical values for (LS) coupling in Table II. Bakker's values are given for comparison. The agreement of the two sets of experimental values is excellent. In three instances only is the discrepancy greater than we would expect from the estimates of ex-

TABLE II. *Comparison of observed g-factors with their theoretical values for (LS) coupling.*

Configuration	Term	g-factors (LS) coupling	Observed	Bakker
d^{10}	a^1S_0	0/0	0/0	0/0
d^9s	a^3D_3	1.333	1.333	1.33
	a^3D_2	1.167	1.152	1.15
	a^3D_1	0.500	0.500	0.50
	a^1D_2	1.000	1.015	1.01
d^8s^2	a^3F_4	1.250	1.250	1.25
	a^3F_3	1.083	1.083	1.08
	a^3F_2	0.667	0.668	0.67
	b^1D_2	1.000	1.14	—
$d^9\cdot 4p$	$z^3F_4^0$	1.250	1.28	1.25
	$z^3F_3^0$	1.083	1.08	1.08
	$z^3F_2^0$	0.667	0.72	0.74
	$z^3D_3^0$	1.333	1.31	1.29
	$z^3D_2^0$	1.167	1.04	1.03
	$z^3D_1^0$	0.500	0.54	0.55
	$z^3P_2^0$	1.500	1.46	1.49
	$z^3P_1^0$	1.500	1.45	1.43
	$z^3P_0^0$	0/0	0/0	0/0
	$z^1F_3^0$	1.000	1.02	1.04
	$z^1D_2^0$	1.000	1.02	1.06
	$z^1P_1^0$	1.000	1.00	1.02
$d^8s\cdot 4p$ (^4F)	$z^5G_6^0$	1.333	1.32	
	$z^5G_5^0$	1.267	1.27	
	$z^5G_4^0$	1.150	1.16	
	$z^5G_3^0$	0.917	0.93	
	$z^5G_2^0$	0.333	0.33	
	$z^5F_5^0$	1.400	1.40	
	$z^5F_4^0$	1.350	1.28	
	$z^5F_3^0$	1.250	1.23	
	$z^5F_2^0$	1.000	0.97	
	$z^5D_4^0$	1.500	1.51	
	$z^5D_3^0$	1.500	1.52	
	$z^5D_2^0$	1.500	1.61	
	$z^5D_1^0$	1.500	1.53	

Configuration	Term	g-factors (LS) coupling	Observed
$d^8s\cdot 4p$ (^2F)	$z^3G_5^0$	1.200	1.20
	$z^3G_4^0$	1.050	1.05
	$z^3G_3^0$	0.750	0.74*
	$y^3F_3^0$	1.083	1.15
	$y^3F_2^0$	0.667	0.79
	$y^3D_3^0$	1.333	1.23
	$y^3D_2^0$	1.167	1.19
	$y^3D_1^0$	0.500	0.52
	$y^1F_3^0$	1.000	1.02
	$y^1D_2^0$	1.000	0.85
$d^9\cdot 4d$	e^3G_5	1.200	1.20
	e^3G_4	1.050	1.05
	e^3G_3	0.750	0.77
	f^3D_3	1.333	1.32
	e^3P_2	1.500	1.43
	e^3S_1	2.000	1.92
	e^1G_4	1.000	1.02*
$d^9\cdot 5d$	f^3G_4	1.050	1.03
$d^8s\cdot 5s$ (^4F)	e^5F_5	1.400	1.40
	e^5F_4	1.350	1.33
	e^5F_3	1.250	1.23
	e^5F_2	1.000	0.95
	e^5F_1	0.000	0.07
	f^3F_4	1.250	1.27
	f^3F_3	1.083	1.08
$d^8s\cdot 4d$ (^4F)	e^5H_7	1.286	1.26*
$d^8s\cdot 5s$ (^2F)	g^3F_4	1.250	1.27

* Value not less than that given.

perimental error. Bakker states that his values are reliable to about 0.01. We estimate that our values for the deep multiplets a^3D, a^1D and a^3F are reliable to about 0.003 and those for the configurations $d^9 \cdot 4p$, $d^8s(^4F) \cdot 4p$ and $d^8s(^4F) \cdot 5s$ to about 0.01, while others may be uncertain by as much as 0.02 in instances where the term appears in but one line on our spectrograms.

Theoretical Part

The g-sum rule holds for a configuration unless it is perturbed. Perturbations are usually small unless the energy levels of the configurations concerned are actually interspersed. There is considerable opportunity in the nickel spectrum for perturbations, especially among the intermediate and high configurations. The data presented in the preceding section enable conclusions to be drawn concerning interactions among a few configurations, by applying the g-sum rule and the theory of two-electron systems.

The d^9s configuration is not perturbed. Laporte and Inglis[6] have shown that Houston's theory[7] of the two-electron system with one electron in an s state fits this configuration. Table III shows

Table III. d^9s *configuration.*

Term	Level Exp.	Level Theor.	g-factor Exp.	g-factor Theor.
a^3D_3	205	205	1.333	1.333
a^3D_2	880	872	1.152	1.152
a^3D_1	1713	1713	0.500	0.500
a^1D_2	3411	3402	1.015	1.015

how accurately Houston's formulae give the energy levels and the g-factors. The constants which appear in the formulae have the values $X = -7.809$ and $\gamma = -301.6hc$. The experimental g-factors obey the g-sum rule.

The g-sum rule cannot be applied to the d^8s^2 configuration, since only four g-factors are known. Johnson's formulae[8] for the d^2 configuration were adjusted to fit as well as possible, and theoretical values for the g-factors were calculated by the formulae of Inglis and Johnson.[9] The empirical and theoretical energy levels, and the experimental and theoretical g-factors are shown in Table IV. The constants in Johnson's

Table IV. d^8s^2 *configuration.*

Term	Level Exp.	Level Theor.	g-factor Exp.	g-factor Theor.
a^3F_4	0	0	1.250	1.250
a^3F_3	1332	1332	1.083	1.083
a^3F_2	2216	2260	0.668	0.668
a^3P_2	15610	16685	—	1.388
a^3P_1	15734	16832	—	1.500
a^3P_0	16017	17091	—	0/0
a^1G_4	22102	22102	—	1.000
b^1D_2	13521	14417	1.14	1.112
$^1S_0$	—	54179	—	0/0

formulae were adjusted to bring the levels of a^1G and a^3F into good agreement with their empirical values, and to leave the multiplet a^3P undistorted. The values assigned to the constants are $\alpha = 53106hc$, $\beta = 15500hc$, $\gamma = 13845hc$, $\delta = 21078hc$ and $a = -655.8hc$. The calculated values for a^3P and b^1D are about 1080 and 800, respectively, above their empirical values. The displacement is probably a consequence of the insufficiency of the theory of the two-electron system which, at present, takes account of the interactions of the electrons only to the zeroth order approximation. It is probable that the electrostatic interaction needs to be worked out to a higher order, in this instance. The fact that the calculated values for a^3P and b^1D are pushed apart may be due to perturbation by the configuration d^{10}, since its a^1S level lies between a^3P and b^1D and near to both of them. The magnitude of the perturbation, if any, cannot be determined until the theory of the two-electron system is extended to higher order approximations.

The term ^1S, which has not been found, is far above a^1G. It should be sought between 50,000 and 56,000.

The theoretical g-factors are very near to the values for (LS) coupling, except for those terms for which $J = 2$. The values for these terms are very sensitive to changes in the values assigned to the constants in the formulae. Since the theory of the two-electron system fits this configuration imperfectly, the g-factors calculated for the terms a^3P_2 and b^1D_2 are relatively uncertain. The experimental g-factors for the multiplet a^3F agree very well with the theoretical

[6] Laporte and Inglis, Phys. Rev. **35**, 1340 (1930).
[7] Houston, Phys. Rev. **33**, 297 (1929).
[8] Johnson, Phys. Rev. **38**, 1628 (1931).
[9] Inglis and Johnson, Phys. Rev. **38**, 1642 (1931).

TABLE V. *Application of g-sum rule to quintet terms.*

Configuration	Multiplet	$J=6$	$J=5$	$J=4$	$J=3$	$J=2$	$J=1$	$J=0$
$d^9\cdot 4p$	z^3F^0			1.28	1.08	0.72		
	z^3D^0				1.31	1.04	0.54	
	z^3P^0					1.46	1.45	0/0
	z^1F^0				1.02			
	z^1D^0					1.02		
	z^1P^0						1.00	
g-sum, observed				1.28	3.41	4.24	2.99	0/0
g-sum, (LS)				1.250	3.417	4.333	3.000	0/0
$d^8s\cdot 4p$ (^4F)	z^5G^0	1.32	1.27	1.16	0.93	0.33		
quintets only.	z^5F^0		1.40	1.28	1.23	0.97	—*	
	z^5D^0			1.51	1.52	1.61	1.53	—
g-sum, observed		1.32	2.67	3.95	3.68	2.91	1.53	—
g-sum, (LS)		1.333	2.667	4.000	3.667	2.833	1.500	0/0
Sum of g-sums, observed		1.32	2.67	5.23	7.09	7.15	4.52	—
Same, (LS)		1.333	2.667	5.250	7.083	7.167	4.500	0/0

* g-factor for $z^5F_1{}^0$ is not known. Its value is 0.000 for (LS) coupling.

values. The agreement for the term b^1D_2 is satisfactory, considering that both values are relatively uncertain.

The configuration $d^9\cdot 4p$ overlaps the quintet levels of $d^8s(^4F)\cdot 4p$, while the triplet levels of the latter are far higher. It seems possible that these quintet terms may be practically independent of all other terms of $d^8s\cdot 4p$, on account of their isolation from them. It seems probable that they interact with $d^9\cdot 4p$. This point is tested by applying the g-sum rule, in Table V. The rule does not hold for either group of terms alone. The deviations of the sums in the column $J=2$, particularly, from the sums for (LS) coupling are too large to be accounted for as due to errors of measurement. The rule does hold, however, for both groups taken together. This indicates fairly strong interaction. It is unfortunate that no combination of the term $z^5F_1{}^0$ appeared on our spectrograms. The g-sum in the column $J=1$ is uncertain, for this reason; but it appears that a g-factor for $z^5F_1{}^0$ close to 0.000, the (LS) value, would bring this sum into line.

Bakker concluded that the g-sum rule holds for $d^9\cdot 4p$. If all of his Zeeman patterns are given equal weights in the calculation of g-factors, however, a deviation from the g-sum rule is found in the same direction as in Table V, though not so large.

TABLE VI. *Application of g-sum rule to* $d^8s(^2F)\cdot 4p$.

Configuration	Multiplet	$J=5$	$J=4$	$J=3$	$J=2$	$J=1$
$d^8s\cdot 4p$ (^2F)	z^3G^0	1.20	1.05	0.74*		
	y^3F^0		—	1.15	0.79	
	y^3D^0			1.23	1.19	0.52
	z^1G^0		—			
	y^1F^0			1.02		
	y^1D^0				0.85	
g-sum, obs.		1.20	—	4.14	2.83	0.52
g-sum, (LS)		1.200	2.883	4.167	2.833	0.500

* Value not less than that given.

TABLE VII. *Failure of g-sum rule for* $d^8s(^4F)\cdot 5s$.

Configuration	Multiplet	$J=5$	$J=4$	$J=3$	$J=2$	$J=1$
$d^8s\cdot 5s$ (^4F)	e^5F	1.40	1.33	1.23	0.95	0.07
	f^3F		1.27	1.08	—	
g-sum, obs.		1.40	2.60	2.31	—	0.07
g-sum, (LS)		1.400	2.600	2.333	1.667	0.000

Inglis and Ginsburg[10] have pointed out that the theory of two-electron systems, in its present incomplete form, does not yield exact results when the outer electron is in a p state because of neglected magnetic interactions. This is the case with the $d^9\cdot 4p$ configuration. Johnson's formulae for the $d\cdot p$ system distort the multiplets seriously, and displace them considerably. The g-factors computed by the method of Inglis and Johnson exhibit deviations from the observed values about as great as those found by Inglis and Ginsburg in the $2p^5\cdot 3p$ configuration of neon.

The g-sum rule is applied to $d^8s(^2F)\cdot 4p$ in Table VI. The triplets of this configuration are so close to the singlets of $d^9\cdot 4p$ that interaction is possible. It is evident, from the table, that the interaction is very small if it exists at all.

Table VII indicates that the g-sum rule does not hold for $d^8s(^4F)\cdot 5s$. The levels of this configuration are so intermingled with those of $d^9\cdot 4d$ that interaction may be expected. Indeed, the evidences of interaction found are surprisingly small. The strong perturbation of the g-factor of the term e^5F_1 may be caused by f^3D_1, which is very close beside it.

[10] Inglis and Ginsburg, Phys. Rev. **43**, 194 (1933).