Isotope Shifts in Palladium*

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Isotope shifts in the $4d^95s\ ^1D_2-4d^95p\ ^3F_3{}^\circ$ transition at λ4212 A in the first spectrum of Pd has been studied with the use of enriched isotopes. The shifts are similar to those found by Kuhn and Warner in the $4d^95s\ ^3D_3-4d^95p\ ^3F_4{}^\circ$ transition at λ3405 A. The most interesting feature is the maximum in the isotope shift which appears at the neutron number pair 60–58.

I. APPARATUS

SPECTRA from enriched samples of Pd isotopes[1] were produced in liquid-air-cooled hollow-cathode discharge tubes. Six such tubes were arranged in a circle at 60° intervals allowing motion into and away from the exposure position. High resolution was accomplished by crossing a Fabry-Perot interferometer with a Hilger *E*-458 Littrow quartz-glass spectrograph.

II. TREATMENT OF DATA

Table I shows the isotopic concentrations of the Pd samples used. As can be seen, the isotopic impurities in the samples must be taken into account. The odd isotope, Pd^{105}, represents an important impurity. Spectrograms were taken of the 105 sample. Within the spectral range where even isotopes appear, the 105 hfs components seemed to contribute a uniform background. It therefore seemed reasonable to disregard the presence of impurities of Pd^{105} in our corrections.

Table II includes shifts corrected for isotopic impurities, neglecting the contribution of Pd^{105} impurities. Excluding the 104–102 shift, the shift corrections were merely center-of-gravity corrections for the presence of only the immediately adjacent even-mass-number isotopic impurities. A glance at Table I shows that this is indeed a reasonable procedure.

The 104–102 shift is extremely difficult to correct, however. The simple center-of-gravity correction breaks down for the 102 spectrogram The fringe pattern for this sample was spread over a relatively large distance on the photographic plate because of the several isotopic impurities, and thus the fringe separations became larger compared with a single isotope fringe width. Because the photographic emulsion response is nonlinear near threshold exposure, the weaker isotopic components toward the fringe edge away from the stronger isotopic components affect the plate blackening somewhat less than their isotopic abundance would indicate. As in this case, where the fringe overlap is small and the isotopic abundances are considerably different, there is a tendency to overcorrect in using a simple center-of-gravity correction. The corrected 104–102 shift in Table II represents some application of subjective judgement.

TABLE I. Isotopic concentration of the palladium samples in percentages.

	Sample					
Isotope	102	104	105	106	108	110
102	50.9	0.1	0.04	0.06	0.03	...
104	20.7	78.3	3.76	1.24	0.20	0.10
105	13.2	16.5	78.16	11.25	0.63	0.35
106	8.4	3.9	16.04	82.33	2.84	0.86
108	4.8	1.0	1.75	4.56	94.19	7.28
110	2.0	0.1	0.23	0.42	2.08	91.42

III. DISCUSSION

Included in Table II are the data in Kuhn and Warner.[2] Our uncorrected shifts correspond quite closely with their uncorrected shifts, despite a suspected different mass effect shift and the fact that our 102 and 104 samples were different and considerably better enriched (50.9% enrichment compared with 35.2% for 102 and 78.3% enrichment compared with 63.2% for 104). Kuhn and Warner obtained the 104–102 shift by a trial-and-error method of reproducing the intensity profile from profiles of the various components, intensities of which were known from the mass analysis. This is an excellent procedure, assuming that the nonlinearity of emulsion response is taken into account.

As pointed out by Kuhn and Warner, the isotope shift ratios do not correspond well with the isotope shift ratios obtained for Cd where the neutron numbers overlap. Our data represent a worse correspondence. However, it should be pointed out that the isotope shift ratio probably should be used only for qualitative comparison between elements, particularly in this mass region, because the specific mass effects may not be negligible. The isotope shift for a given mass number difference then represents the sum of a mass effect constant plus the field effect which will vary from isotope to isotope. However, the variations (differences) in the shifts will give a measure of the field effects alone.

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[1] Obtained from the *Y*-12 plant, Oak Ridge National Laboratory, Oak Ridge, Tennessee.
[2] H. G. Kuhn and A. G. Warner, Proc. Roy. Soc. (London) **A245**, 330 (1958). Note: Apparently Kuhn and Warner made an error in determining the isotope shift ratio for the neutron pair 60-58 in the case of Cd. They quote a value of 1.07 for this ratio.

TABLE II. Isotope shifts in the first spectrum of palladium in units of 10^{-3} cm^{-1}. Negative sign indicates shift in the field effect direction.

	Shifts in the λ4212 A line[a]			Shifts in the λ3405 A line[b]		
Shift	Plate shift[c]	Corrected shift[c]	Isotope shift ratio[d]	Plate shift	Corrected shift	Isotope shift ratio[d]
110–108	−13.3±1.5	−14.4±1.6	1.00	−13.3	−14.36±0.3	1.00
108–106	−15.6±1.5	−16.2±1.6	1.11	−14.8	−15.46±0.5	1.07
106–104	−16.1±1.0	−16.2±1.2	1.11	−15.9	−17.40±0.6	1.19
104–102	−7.1±1.5	-13.0 ± 3.0	0.90	−7.2	−11.35±1.0	0.84

[a] Present work.
[b] Kuhn and Warner (reference 2).
[c] Errors are limit errors (high confidence).
[d] Normal mass effects have been subtracted.

Isotope shift ratios are calculated for our data and can be compared with the values of Kuhn and Warner. Although it appears that our accuracy suffers in comparison with theirs, we believe that for the most part this reflects our conservativism in estimating errors.

A weighted isotope shift ratio is shown for Pd in Table III. Considerably more effort was made on the part of Kuhn and Warner in establishing their measurements. For this reason we weighted their shift ratio between neutron numbers 62–60 heavily but allowed our measurements associated with neutron numbers 60–58 and 58–56 to carry equal weight because of the greater purity of our 102 and 104 samples.

TABLE III. Comparison of isotope shift ratios for Pd with those for neighboring elements.

	Neutron number pair							
Element	54–52	56–54	58–56	60–58	62–60	64–62	66–64	68–66
Ru	1.61	0.74	1.05	1.15[a]				
Pd			0.87	1.15	1.08	1.00[a]		
Cd				1.15	0.97	1.00[a]	0.87	0.65

[a] Arbitrary basis for comparison.

Table III gives a comparison of the isotope shift ratios for ruthenium,[3] palladium, and cadmium.[4] As can be seen, the isotope shift ratios apparently reach a maximum for the neutron pair 60–58 after a minimum in the isotope shift ratio at 56–54 neutron pair. An analysis in terms of nuclear deformations is difficult, since there is little information on nuclear deformation in this region. It may be worthwhile to point out, however, that in terms of the simple independent-shell deformation theory a minimum deformation would be expected at $N=56$ if the $4d_{5/2}$ neutron subshell is closed at that number, and that following this shell closure a maximum deformation would be expected at $N=60$ where the $5g_{7/2}$ shell is half filled. Such a scheme would qualitatively fit the isotope shift data.

[3] R. H. Hughes, Phys. Rev. **121**, 499 (1961).
[4] Mean values from several investigations are taken from W. M. Cloud, in *Summaries of Doctoral Dissertations* (University of Wisconsin Press, Madison, Wisconsin, 1956), p. 360.