Isotope Shifts in the Spectra of Mo and Ru†

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Isotope shifts in several lines showing shifts in the field-effect direction in the spectra of molybdenum and ruthenium have been studied with the aid of a Fabry-Perot interferometer.

The variations in the shifts are quite similar in the two elements. A distinct minimum shift between the even-even nuclei occurs at neutron number 56. Extreme even-odd staggering inverts the expected order of the atomic levels belonging to nuclei with neutron numbers 54 and 55. The variations in the shifts were qualitatively predicted by the nuclear deformations as measured by Coulomb excitation, particularily in the case of molybdenum.

I. INTRODUCTION

MOLYBDENUM and ruthenium are elements worthy of isotope shift studies particularly because both have a large number of stable isotopes, five even and two odd.

In this mass region there is a certain amount of competition between the mass effects (the normal mass effect and the specific mass effect) and the field effect which results from the spatial nuclear charge distribution.

The field effect in isotope shifts has been analyzed in terms of nuclear deformations with considerable success by Wilets *et al.*[1]

TABLE I. Isotopic concentration of molybdenum samples in percentages.

Isotope \ Sample	92	94	95	96	97	98	100
92	95.5	2.5	0.1	1.3	0.1	0.4	0.7
94	0.8	84.95	0.5	0.6	0.2	0.3	0.4
95	0.8	4.2	97.2	1.5	0.4	0.5	0.8
96	0.8	2.8	1.7	90.6	1.4	0.9	0.9
97	0.4	1.5	0.04	1.8	93.8	0.6	0.5
98	1.3	3.0	0.4	3.8	3.9	96.3	3.6
100	0.5	1.2	0.1	0.6	0.2	1.0	93.0

II. EXPERIMENTAL APPARATUS

Spectra from enriched isotopes[2] were excited in liquid-air-cooled hollow-cathode discharge tubes. Six such tubes were clamped in a circle at 60° intervals and rotated about a vertical axis, permitting the isotopes to be speeded into and away from exposure position.

The necessary high resolution was obtained by crossing a Fabry-Perot interferometer, which was placed in a sealed constant-temperature chamber, with a Hilger E-458 Littrow quartz-glass spectrograph.

III. DATA AND DISCUSSION

Isotope shifts were determined for several transitions in the spectra of molybdenum and ruthenium. Some results have been reported previously.[3,4]

Isotopic concentrations of the molybdenum samples are presented in Table I.

Isotope-shift measurements for molybdenum are presented in Table II. Wave numbers are measured in kaysers [1 kayser (K)$=1$ cm^{-1}], and shifts are measured in millikaysers (mK). The isotopic concentrations of the samples have not been taken into account. It is felt that no appreciable error is introduced by neglecting the contribution of the isotopic impurities in the lines showing large shifts, since none of the lines was overexposed and no trace of isotopic impurities was observed. Estimated limit errors on these measurements are about ± 1.4 mK. Similar results have been reported by Arroe and Cornwall.[5]

Isotope shifts in the first spectrum of ruthenium for two transitions are presented in Table III. The isotopic concentrations of the samples used are noted in Table

TABLE II. Isotope shifts in the first spectrum of molybdenum.[a]

Transition	Wave number (K)	100–98	98–96	96–94	94–92	100–92	96–95	97–96
$4d^45s\ ^5D_2 - 4d^55p\ ^5P_1^\circ$	17 261	−25.5	−10.8	−17.6	−24.0	−77.9	−14.7	+5.5
$4d^45s^2\ ^5D_2 - 4d^55p\ ^5P_2^\circ$	17 382	−26.4	−11.2	−18.5	−24.5	−80.4		
$4d^45s^2\ ^5D_4 - 4d^55p\ ^5P_3^\circ$	16 577	−26.3	−12.0	−18.5	−25.3	−82.6		
$4d^55s\ ^5S_2 - 4d^55p\ ^5P_1^\circ$	17 947	− 6.5	− 3.0	− 5.3	− 6.7	−21.2		
$4d^55s\ ^5S_2 - 4d^55p\ ^5P_2^\circ$	18 068	− 7.2	− 3.0	− 5.7	− 7.2	−23.3		
$4d^55s\ ^5S_2 - 4d^55p\ ^5P_3^\circ$	18 155	− 7.7	− 3.6	− 6.4	− 8.3	−25.0		

[a] Minus sign indicates shift in the field-effect direction. Estimated limit errors are ±1.4 mK.

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[1] L. Wilets, D. L. Hill, and K. W. Ford, Phys. Rev. **91**, 1488 (1953).
[2] Obtained from the Y-12 plant, Oak Ridge National Laboratory.
[3] R. H. Hughes, Bull. Am. Phys. Soc. **2**, 200 (1957).
[4] R. H. Hughes, Bull. Am. Phys. Soc. **4**, 262 (1959).
[5] H. Arroe and J. Cornwall, Phys. Rev. **117**, 748 (1960).

TABLE III. Isotope shifts in the first spectrum of ruthenium.

Transition	Wave number (K)	Observed shifts in millikaysers 104–102	102–100	100–98	98–96	104–96	99–98	101–100
$4d^6 5s^2\ {}^5D_3 - 4d^7 5p\ {}^5F_3^\circ$	24 690	−25.1	−22.7	−15.2[a]	−36.2[a]	− 99.4	+1.6[a]	−4.3
$4d^6 5s^2\ {}^5D_4 - 4d^7 5p\ {}^5F_3^\circ$	25 782	−26.5	−23.6	−14.7	−40.3	−103.5	+2.5	−4.4

[a] The shifts relative to Ru^{98} in this transition are considered more reliable with an estimated limit error of ±4 mK. The estimated limit error involving shifts not relative to Ru^{98} is ±1.5 mK.

IV. The isotopic impurity of the Ru^{98} sample causes great difficulty. The more reliable data relative to Ru^{98} are obtained by very weak exposures of this sample, as indicated in the table.

Interesting variations in the shifts for Mo and Ru are seen in Tables II and III. Since the mass effects are constant for a given mass-number difference, these variations result from the nuclear-field effects. For instance, one would expect a relatively large shift between isotopes having neutron numbers 52 and the magic number 50, because the addition of two neutrons to the magic number results in a large increase in the nuclear deformation. This expectation is borne out by the size of the 94–92 shift in molybdenum.

It is interesting to note the strong even-odd staggering shown in these isotopes. A clear indication exists in molybdenum that the neutron number 55 isotope level lies lower than that of neutron number 54 isotope, a reversal of the expected relative position. There is evidence that this occurs in Ru also, but the error is too large to say so with too much certainty.

A graphic representation showing the variations in the even-even isotope shifts in molybdenum and ruthenium is included in Fig. 1. Normal mass effects have been removed. Shifts between neutron numbers 58 and 56 have been defined as unity. Unit shifts for the two cases have been displaced for schematic clarity.

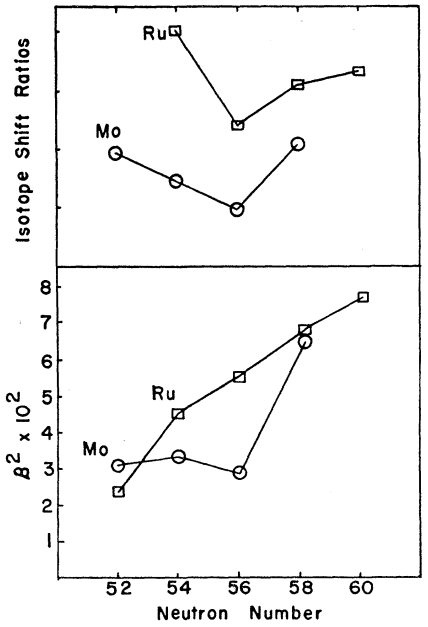

FIG. 1. Plot of isotope shift ratios vs neutron number and a plot of the square of the nuclear deformation parameter as measured by Coulomb excitation vs neutron number.

One of the sharpest variations is shown in the region of 56 neutrons. In both Mo and Ru the 56–54 shift represents a minimum shift. It is interesting to speculate on the cause of such a variation. Regardless of how one looks at the present isotope-shift theory, the explanation ultimately ends in a discussion of shell theory. It is to be noted that if the neutron $4d_{\frac{5}{2}}$ subshell is filled after the closure of the shell at 50, then a minimum deformation would be expected at neutron number 56. The closing of this subshell might explain the behavior of the Mo and Ru shifts at this number.

Also shown in Fig. 1 is a plot of the square of the "nuclear deformation" as measured by Coulomb excitation.[6] The slopes of the connecting lines in this plot should be a measure of the isotope shifts. As can be seen the correlation appears to be quite striking for molybdenum but much less so in the case of ruthenium although the direction of the isotope shift variations can still be predicted but with much less certainty.

TABLE IV. Isotopic concentration of ruthenium samples in percentages.

Isotope \ Sample	96	98	99	100	101	102	104
96	95.5	3.2	0.2	0.1	0.1	...	...
98	0.4	34.2	0.5	0.1	0.1	...	...
99	1.1	35.5	91.2	3.1	0.4	0.1	0.1
100	0.7	8.0	4.3	88.9	2.3	0.3	0.1
101	0.7	5.9	1.6	4.8	91.1	1.8	0.3
102	1.1	8.7	1.3	2.6	5.7	97.2	1.3
104	0.5	4.6	1.0	0.5	0.4	0.5	98.2

Appealing to the Nilsson plot[7] for possible qualitative information on deformations with its limitations in this mass region, one finds it predicts large oblate deformations in the initial filling of the $4d_{\frac{5}{2}}$ subshell. It is somewhat difficult, however, to relate the magnitude and variation of these deformations with the magnitude of the isotope shift variations even qualitatively.

Lastly, it is of some interest to note the shifts in the $4d^5 s\ {}^5S_2 - 4d^5 5p\ {}^5P_{1,2,3}$ lines of molybdenum. As the quantum number J of upper level increases, the isotope shifts increase which is an indication of level mixing in these upper levels.

[6] P. H. Stelson and F. K. McGowan, Phys. Rev. **110**, 489 (1958).

[7] S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **29**, No. 16 (1955).