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HAL Id: jpa-00213649
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NUCLEAR VOLUME AND MASS EFFECT IN THE OPTICAL ISOPE SHIFT OF LIGHT ELEMENTS

R. BRUCH, K. HEILIG, D. KALETTA, A. STEUDEL, and D. WENDLANDT
Institut für Experimentalphysik A der Technischen Universität, Hannover, Germany

Résumé. — Nous avons étudié le déplacement isotopique optique dans les spectres de Ca, Ti, Cr, Fe et Sr en utilisant des spectromètres Fabry-Perot à détection photoélectrique avec digitalisation des résultats et des sources lumineuses à cathode creuse remplis d’isotopes séparés. Nous interprétons les résultats de déplacements isotopiques optiques en utilisant les mesures de déplacements isotopiques dans les spectres de rayons X électroniques ou muoniques. En utilisant les déplacements isotopiques optiques observés dans les éléments Ca, Ti, Cr, Fe, Ni, Sr, Zr et Mo, nous déterminons l’effet de volume nucléaire et l’effet de masse et nous présentons les rapports $\beta_{\text{exp}}/C_{\text{th}}$ dans un graphique de Brix-Kopfermann.

Abstract. — The optical isotope shift in Ca, Ti, Cr, Fe, and Sr was investigated using photoelectric recording Fabry-Pérot spectrometers with digital data output and hollow cathode light sources filled with separated isotopes. The normalization of the optical isotope shift data using isotope shift measurements in muonic or electronic X-ray spectra is discussed. From the optical isotope shift observed in the elements Ca, Ti, Cr, Fe, Ni, Sr, Zr, and Mo the nuclear volume shift and mass dependent shift are determined, and the ratios $\beta_{\text{exp}}/C_{\text{th}}$ are presented in a Brix-Kopfermann diagram.

We have measured the isotope shift in Ca, Ti, Cr, Fe and Sr using photoelectric recording Fabry-Pérot spectrometers with digital data output and hollow cathode light sources filled with separated isotopes. The point of our investigation was to obtain information on the mass dependent shift and on the nuclear volume shift in these elements.

The detailed results of the measurements will be published elsewhere [1] [2]. In the present paper we report only on the evaluation of volume and mass shift using non-optical measurements (mainly isotope shift measurements in muonic atoms) for normalizing the optical data. Also earlier optical measurements on Ni [3], Zr [4] and Mo [5] [6] will be discussed.

The isotope shift observed in atomic spectra is the sum of volume shift and mass shift. The observed shift $\Delta v$ between two isotopes with the mass numbers $A_i$ and $A_{i+1}$ in a particular line (index $a$) is given by

$$\Delta v_a(A_i, A_{i+1}) = E_a C(A_i, A_{i+1}) + K_a \frac{A_{i+1} - A_i}{A_i A_{i+1}}.$$  \hspace{1cm} (1)

$E_a C$ represents the volume shift. $E_a$ depends only on electronic properties and is proportional to the change of the electronic charge density at the nucleus in the particular electronic transition $a$. $C$ is the isotope shift constant which depends on nuclear properties only and is proportional to the change of the mean square nuclear charge radius $\delta \langle r^2 \rangle$ on the addition of neutrons. The second term gives the mass
shift. \( K_a \) includes the normal and the specific mass shift \([7]\). In another spectral line (index \( b \)) one has in general another factor \( E_b \) and another \( K_b \):

\[
\Delta \nu_b(A_i, A_{i+1}) = E_b C(A_i, A_{i+1}) + K_b \frac{A_{i+1} - A_i}{A_i A_{i+1}}. \tag{2}
\]

If \( E_a/K_a \neq E_b/K_b \) the relative isotope position in the two lines \( a \) and \( b \) is different as is often observed.

As is well known, the system of equations indicated above (1), (2), ... does not permit the separation of mass dependent and volume shift, even if measurements have been made for a large number of lines and isotopes. For the independent determination of mass and volume shift additional information is needed. For instance, it would be sufficient to calculate \( K \) for one line for which the volume shift does not vanish. Then, for all other lines mass and volume shift could be derived. There is, however, no hope of doing such a calculation with an accuracy comparable to that of the measurements at present.

Another possibility of separating mass and volume shift exists when the ratio of the volume shifts of at least two isotope pairs is known from other than optical measurements. Muonic and electronic X-ray measurements give such information \((1)\), and can, therefore, be used to normalize optical isotope shift measurements, as was already pointed out by Hansen, Steudel and Walther \((8)\).

When measurements on at least four isotopes are available, the consistency of optical with muonic or electronic X-ray measurements or the results on \( \delta < r^2 > \) derived from electron scattering experiments can be checked. To do this we consider the quantities

\[
\zeta = \Delta \nu_b(A_i, A_{i+1}) \frac{A_i A_{i+1}}{A_{i+1} - A_i}
\]

and

\[
\xi = \Delta \nu_b(A_i, A_{i+1}) \frac{A_i A_{i+1}}{A_{i+1} - A_i}
\]

which are connected by (see ref. 8)

\[
\zeta = \frac{E_a}{E_b} \xi + K_a - \frac{E_a}{E_b} K_b.
\]

\((1)\) By taking the ratio of the volume shifts derived from muonic X-ray measurements the possible influence of higher moments of the nuclear charge distribution than \( < r^2 > \) cancels to good approximation. This was pointed out by C. S. Wu on the Symposium on the Physics of the One-and Two-Electron-Atoms, Munich 1968 \([15]\).
The optical isotope shift measurements in the two Nd lines used in figures 1 and 2 are consistent as can be seen when the optical shifts are plotted in a $\xi$, $\zeta$ diagram (see Fig. 7 in ref. [8]). Thus from figure 1, 2 and 3 we must conclude that at least the odd isotope Nd 143 shows a peculiar behaviour, when optical and X-ray measurements are compared. Further theoretical and experimental studies are required to settle this point.

In Sn the optical measurements are not consistent

**Table I**

Elements for which optical and non-optical isotope shift measurements are available for at least four isotopes

<table>
<thead>
<tr>
<th>Element</th>
<th>Z</th>
<th>Method</th>
<th>Isotopes</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca</td>
<td>20</td>
<td>optical, muon. X-ray, el. scatt.</td>
<td>40, 42, 44, 48</td>
<td>[10]</td>
</tr>
<tr>
<td>Cr</td>
<td>24</td>
<td>optical, muon. X-ray</td>
<td>50, 52, 53, 54</td>
<td>[12] [13] [14]</td>
</tr>
<tr>
<td>Ni</td>
<td>28</td>
<td>optical, muon. X-ray</td>
<td>58, 60, 61, 62, 64</td>
<td>[3]</td>
</tr>
<tr>
<td>Mo</td>
<td>42</td>
<td>optical, muon. X-ray</td>
<td>92, 94, 95, 96, 97, 98, 100</td>
<td>[5] [6]</td>
</tr>
<tr>
<td>Sn</td>
<td>50</td>
<td>optical, muon. X-ray</td>
<td>112, 114, 116, 117, 118, 119, 120, 122, 124</td>
<td>[17] [18]</td>
</tr>
<tr>
<td>Nd</td>
<td>60</td>
<td>optical, muon. X-ray, el. X-ray</td>
<td>142, 143, 144, 145, 146, 148, 150</td>
<td>[8] [15] [19]</td>
</tr>
</tbody>
</table>
with the muonic X-ray results obtained by the Chicago group [11]. However, concerning the even isotopes, recent muonic X-ray measurements made by the group at Columbia University indicate a good agreement with the optical data [21].

In Ni and Mo only earlier optical measurements are available in which the error of the measurements is of the order of ± 1 or 2 mK. Within these limits of error, in a ξ, ζ plot made with the muonic measurements, all points lie on a straight line. Figures 4 and 5 show the situation in Ni and Mo. Concerning Mo a King plot [9] was already made by C. S. Wu [15].

Very accurate measurements have been made in Cr. Figure 6 shows a ξ, ζ diagram of optical versus muonic X-ray measurements. Again the point including the odd isotope Cr 53 shows a slight but distinct deviation from the straight line defined by the pairs of even isotopes.

In Ca only measurements on even isotopes are available. Figure 7 gives a comparison between the results of muonic, electron scattering, and optical measurements in form of a ξ, ζ plot. The results of muonic and optical measurements are in good agreement. However, recent results obtained by electron scattering [14] seem to indicate a discrepancy concerning the isotope pair 44, 42.

Barring the problem with the odd isotopes, we believe that muonic or electronic X-ray isotope shift measurements on even isotopes can be used to normalize optical isotope shift data in a reliable way.

In the present work volume and mass shift in the elements Ca, Cr, Ni, Sr and Mo were evaluated using

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**Fig. 4.** — ξ, ζ plot in Ni; optical isotope shifts measured in two lines [3] plotted against muonic results [11].

**Fig. 5.** — ξ, ζ plot in Mo; optical isotope shifts measured in two lines [5] [6] plotted against muonic results [15] [16].

a ξ, ζ diagram and muonic isotope shift data. Results are given in tables II and III.
Chromium
Relative isotope shifts due solely to nuclear volume effect (a positive sign stands for an increase of $<r^2>$).

<table>
<thead>
<tr>
<th>Isotope Pair</th>
<th>Relative Shift</th>
<th>Isotope Pair</th>
<th>Relative Shift</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cr 52, 50</td>
<td>-0.40</td>
<td>Zr 92, 90</td>
<td>+1.00</td>
</tr>
<tr>
<td>Cr 54, 52</td>
<td>+1.00</td>
<td>Mo 94, 92</td>
<td>+1.4</td>
</tr>
<tr>
<td>Cr 55, 52</td>
<td>-0.47</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

There are, however, many cases in which muonic or electronic X-ray measurements are available for two isotopes only. In these cases we consider the

**Table II**

Relative isotope shifts due solely to nuclear volume effect (a positive sign stands for an increase of $<r^2>$).

<table>
<thead>
<tr>
<th>Element</th>
<th>Isotopes</th>
<th>Relative Shift</th>
<th>Element</th>
<th>Isotopes</th>
<th>Relative Shift</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca</td>
<td>42, 40</td>
<td>+1.0</td>
<td>Sr</td>
<td>86, 84</td>
<td>-0.21</td>
</tr>
<tr>
<td>Cr</td>
<td>52, 50</td>
<td>-0.40</td>
<td>Zr</td>
<td>92, 90</td>
<td>+1.00</td>
</tr>
<tr>
<td>Cr 54, 52</td>
<td>+1.00</td>
<td>Zr 92, 90</td>
<td>+1.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cr 55, 52</td>
<td>-0.47</td>
<td>Mo 94, 92</td>
<td>+1.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cr 56, 58</td>
<td>-1.0</td>
<td>100, 98</td>
<td>+1.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe</td>
<td>56, 58</td>
<td>-1.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe 57, 56</td>
<td>+0.9</td>
<td>Mo 94, 92</td>
<td>+1.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ni</td>
<td>60, 58</td>
<td>-1.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ni 61, 60</td>
<td>+0.3</td>
<td>97, 96</td>
<td>+0.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table III**

Volume shift $\Delta v_v$ and mass shift $\Delta v_m$ in some lines ($\Delta v_{obs}$ observed shift; $\Delta v_n$ normal mass shift, calculated according to [7]; $\Delta v_{sp}$ specific mass shift; $\Delta v_m = \Delta v_n + \Delta v_{sp}$). All shifts in mK. The last column gives the ratio $\Delta v_{sp}/\Delta v_n$ for alkali-like $s - p$ transitions (see text).

<table>
<thead>
<tr>
<th>Element Isotope Pair</th>
<th>Line</th>
<th>Transition</th>
<th>$\Delta v_{obs}$</th>
<th>$\Delta v_n$</th>
<th>$\Delta v_{sp}$</th>
<th>$m_v$</th>
<th>$\Delta v_{sp}/\Delta v_n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca 42, 40</td>
<td>3 933</td>
<td>$4 s^2 S_{1/2}$ $- 4 p^2 P_{1/2}$</td>
<td>+13.4 ± 0.1</td>
<td>+16.4</td>
<td>-0.8</td>
<td>-2.2</td>
<td>-0.05</td>
</tr>
<tr>
<td>Ti 48, 46</td>
<td>4 533</td>
<td>$3 d^3 4 s^2 F_5$ $- 3 d^3 4 p^2 F_{5/2}$</td>
<td>+17.9 ± 0.4</td>
<td>+10.9</td>
<td>+7.0</td>
<td>0</td>
<td>+0.64</td>
</tr>
<tr>
<td>Cr 52, 50</td>
<td>4 254</td>
<td>$3 d^3 4 s^2 P_{3/2}$ $- 3 d^3 4 p^2 P_{3/2}$</td>
<td>+4.4 ± 0.07</td>
<td>+9.8</td>
<td>-6.6</td>
<td>+1.2</td>
<td>-0.67</td>
</tr>
<tr>
<td>Fe 58, 56</td>
<td>4 045</td>
<td>$3 d^7 4 s^2 F_{4/2}$ $- 3 d^7 4 p^2 F_{4/2}$</td>
<td>+9.9 ± 0.1</td>
<td>+8.3</td>
<td>+6.8</td>
<td>-5.2</td>
<td>+0.81</td>
</tr>
<tr>
<td>Ni 60, 58</td>
<td>3 510</td>
<td>$3 d^9 4 s^2 D_{5/2}$ $- 3 d^9 4 p^2 P_{1/2}$</td>
<td>+15.3 ± 1.0</td>
<td>+8.9</td>
<td>+19.6</td>
<td>-13.2</td>
<td>—</td>
</tr>
<tr>
<td>Sr 90, 88</td>
<td>4 077</td>
<td>$5 s^2 5 p^2 P_{1/2}$ $- 5 p^2 P_{3/2}$</td>
<td>-11.1 ± 0.5</td>
<td>+3.4</td>
<td>-0.1</td>
<td>-14.4</td>
<td>-0.03</td>
</tr>
<tr>
<td>Zr 92, 90</td>
<td>4 687</td>
<td>$4 d^3 5 s^2 F_5$ $- 4 d^3 5 p^5 G_{9/2}$</td>
<td>-12.0 ± 0.2</td>
<td>+2.8</td>
<td>+3.7</td>
<td>-18.5</td>
<td>+1.32</td>
</tr>
<tr>
<td>Mo 98, 96</td>
<td>6 031</td>
<td>$4 d^4 5 s^2 D_{4}$ $- 4 d^5 5 p^5 P_{3}$</td>
<td>-10.8 ± 1.4</td>
<td>+1.9</td>
<td>-37.0</td>
<td>+24.3</td>
<td>—</td>
</tr>
</tbody>
</table>
ratio \( \frac{\delta(AE_{\text{exp}})}{\delta(AE_{\text{th}})} \) derived from X-ray measurements. \( \delta(AE_{\text{exp}}) \) is the measured volume shift in the 1s level and \( \delta(AE_{\text{th}}) \) is the corresponding shift calculated for a uniformly charged incompressible spherical nucleus, whose radius changes according to the \( A^{1/3} \) law. This ratio must be equal to the ratio \( C_{\text{exp}}/C_{\text{th}} \), where \( C_{\text{exp}} \) is the experimental isotope shift constant \(^1\) [7], which describes the nuclear volume effect in the optical spectrum, and \( C_{\text{th}} \) is the theoretical isotope shift constant calculated for the same nuclear model as used with the X-ray measurements. If for a particular isotope pair the ratio \( \frac{\delta(AE_{\text{exp}})}{\delta(AE_{\text{th}})} \) is known, and the optical isotope shift has been measured in a line for which the electronic factor \( E \) can be calculated, then the volume shift for this isotope pair is obtained by \( \Delta v_{v} = E C_{\text{exp}} \). The difference between the observed shift and the volume shift gives the mass shift \( \Delta v_{m} \). This information is sufficient to derive mass and volume shift for all other isotope pairs and all other optical lines. In this way the volume shifts in the elements Fe and Zr were determined. The results are included in tables II and III. In contrast to the evaluation of mass and volume shift using a \( \xi, \zeta \) plot the method just described for the normalization of optical isotope shift data suffers, of course, from the influence of higher moments of the nuclear charge distribution observed in the muonic X-ray spectra. The results are, therefore, supposed to have an uncertainty of about 20 % [15].

We now want to compare and to check against each other the different methods of evaluating volume shifts and experimental isotope shift constants. As an example we take the measurements in the Cr I resonance line \( \lambda \ 4.254 \ \text{Å} \) \((3 \ d^{4}s \ 4 \ s \ 7S_{3} - 4 \ p \ 7P_{4})\) shown in figure 8, and we restrict the discussion on the even isotopes.

We first assume that only optical measurements are available. In this case only the difference of the volume shifts \( \delta(\Delta v_{v}) \) of two isotope pairs can be determined

\[
\delta(\Delta v_{v}) = \Delta v_{v}(54, 52) - \Delta v_{v}(52, 50) = \Delta v_{\text{obs}}(54, 52) - \Delta v_{\text{obs}}(52, 50) + \frac{4}{54} \Delta v_{m}(52, 50).
\]

Here the mass shift \( \Delta v_{m} \) enters only with the small factor \( 4/54 \), thus reducing considerably the influence of the uncertainty in an estimate of \( \Delta v_{m} \). As \( \lambda \ 4.254 \ \text{Å} \) is an alkali-like \( s-p \) transition, we can calculate the electronic factor \( E \) from fine structure data and use the estimate on \( \Delta v_{m} \) mentioned below. Then the difference of the experimental isotope shift constants results in

\[
\delta(C_{\text{exp}}) = C_{\text{exp}}(54, 52) - C_{\text{exp}}(52, 50) = (11 \pm 6) \text{ mK}.
\]

The large error is due mainly to the uncertainty in the estimate on the mass shift. The screening factor \( \beta \) is assumed to be approximately \( 1 \) [7].

Secondly we use a \( \xi, \zeta \) plot made with the muonic measurements on the even isotopes (Fig. 6). Mass and volume shift derived in this way are shown in the figure 8. From the volume shifts we obtain with the electronic factor \( E \) the experimental isotope shift constants

\[
\beta C_{\text{exp}}(52, 50) = (-2.9 \pm 0.7) \text{ mK}
\]

and

\[
\beta C_{\text{exp}}(54, 52) = (7.1 \pm 0.7) \text{ mK}.
\]

\( \Delta v_{\text{obs}} \) observed shift, \( \Delta v_{m} \) mass shift, \( \Delta v_{v} \) volume shift.

The difference of the two values

\[
\delta(\beta C_{\text{exp}}) = (10 \pm 1) \text{ mK}
\]

is in good agreement with the result of the first method. The error is, of course, now much smaller. Using the theoretical isotope shift constant calculated for an incompressible homogeneously charged spherical nucleus with radius \( R = 1.20 A^{1/3} \) fm we find

\[
\frac{\beta C_{\text{exp}}}{C_{\text{th}}} (52, 50) = -0.29 \pm 0.07
\]

and

\[
\frac{\beta C_{\text{exp}}}{C_{\text{th}}} (54, 52) = +0.72 \pm 0.07.
\]

\(^2\) The isotope shift constant from equation (1) is usually called \( C_{\text{exp}} \) when determined from experimental data.
Thirdly we assume that muonic isotope shift measurements would be available only for the isotope pair 52, 50. Then we take

$$\left[ \frac{\delta(AE_{\exp})}{\delta(E_{\text{th}})} \right]_{52,50} = -0.31 \pm 0.03$$

derived from the muonic investigation, equate this ratio to $C_{\text{exp}}/C_{\text{th}}$ for the isotope pair 52, 50, and obtain in the way described above

$$\frac{C_{\text{exp}}}{C_{\text{th}}} (54, 52) = 0.77 \pm 0.08.$$  

This result is in very good agreement with the value 0.72 ± 0.07 obtained by the second method. The muonic measurement gives for the isotope pair 54, 52 the value

$$\left[ \frac{\delta(AE_{\exp})}{\delta(E_{\text{th}})} \right]_{54,52} = 0.85 \pm 0.08.$$  

This result lies still in the uncertainty of 20% mentioned above.

In figure 9 are shown the ratios $\beta C_{\text{exp}}/C_{\text{th}}$ plotted against the neutron number. As usual only values for $\Delta N = 2$ are given. For comparison also the values are nearly the same.

The main trend of the values in the diagram is the same as is known from investigations in heavier elements: the ratio $\beta C_{\text{exp}}/C_{\text{th}}$ is about 1 or greater, if the heavier isotope of a pair contains two more neutrons than a closed neutron shell, and the values decrease slowly but irregularly, if further neutrons are added.

By the methods described above volume and mass shift can be determined separately. As the normal mass shift $\Delta \nu_n$ can be calculated exactly [7], the specific mass shift $\Delta \nu_{sp}$ is easily derived. In table III the ratio $\Delta \nu_{sp}/\Delta \nu_n$ is given for alkali-like $s$-$p$ transitions. The absolute value of this ratio is found to be always smaller than 1.4. This result was already obtained earlier by considering the ratio $\Delta \nu_{sp}/\Delta \nu_n$ in very light elements in which the influence of the volume shift can be neglected. It now seems to be more justified to use the estimate $|\Delta \nu_{sp}| \leqslant 1.4 \Delta \nu_n$ for alkali-like $s$-$p$ transitions also in heavier elements. This is of importance for the calculation of the experimental isotope shift constant from the shift observed in such transitions, when no muonic or electronic X-ray measurements for normalization are available. In Ni we don’t give the ratio $\Delta \nu_{sp}/\Delta \nu_n$ as the investigated $s$-$p$ transitions are certainly influenced by configuration mixing.

Table IV summarizes the specific shifts in transitions of the type $3d^n 4s - 3d^{n-1} 4s 4p$. In these lines the volume shift is zero within the limits of error and the observed isotope position is given solely by the mass shift. As can be seen from the last column of table IV the specific shifts are two to five times larger than the normal shifts and all have the opposite sign than the normal shifts. The results are presented in figure 10. They may be valuable for checking theoretical calculations as were done by Bauche [22].

We want to express our gratitude to Professor C. S. Wu for providing us with the results of her muonic measurements prior to publication.
TABLE IV

<table>
<thead>
<tr>
<th>Element</th>
<th>Line</th>
<th>Transition</th>
<th>Isot.</th>
<th>( \Delta v_n )</th>
<th>( \Delta v_{sp} )</th>
<th>( \Delta v_{sp} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti</td>
<td>3.414</td>
<td>( 3d^3 \ 4s \ \bar{5}F_4 - 3d^2 \ 4s \ 4p \ \bar{3}D_3 )</td>
<td>48, 46</td>
<td>+11.8</td>
<td>-29.3</td>
<td>-2.53</td>
</tr>
<tr>
<td>Cr</td>
<td>3.578</td>
<td>( 3d^2 \ 4s \ \bar{7}S_3 - 3d^4 \ 6s \ 4p \ \bar{7}P_4 )</td>
<td>52, 50</td>
<td>+11.6</td>
<td>-38.8</td>
<td>-3.27</td>
</tr>
<tr>
<td>Fe</td>
<td>5.167</td>
<td>( 3d^3 \ 4s \ \bar{3}F_4 - 3d^6 \ 4s \ 4p \ \bar{3}D_3 )</td>
<td>56, 54</td>
<td>+6.9</td>
<td>-39.1 (*)</td>
<td>-5.66</td>
</tr>
<tr>
<td>Ni</td>
<td>3.674</td>
<td>( 3d^8 \ 4s \ \bar{3}D_3 - 3d^8 \ 4s \ 4p \ \bar{5}D_2 )</td>
<td>60, 58</td>
<td>+8.5</td>
<td>-47.8</td>
<td>-5.56</td>
</tr>
<tr>
<td>Cu</td>
<td>2.492</td>
<td>( 3d^{10} \ 4s \ 2S_{1/2} - 3d^{10} \ 4s \ 4p \ \bar{2}P_{3/2} )</td>
<td>65, 63</td>
<td>+10.6</td>
<td>-36.6</td>
<td>-3.48</td>
</tr>
</tbody>
</table>

(*) Preliminary result.

FIG. 10. — Measured specific shifts for elements of the iron group.

The support of the Deutsche Forschungsgemeinschaft is gratefully acknowledged.

References

[1] HEILIG (K.), to be published.
[2] Part of the results on Cr have been published in HEILIG (K.) and WENDLANDT (D.), Phys. Letters, 1967, 25 A, 277.

[10] Present work.
[14] VAN OOSTRUM (K. J.), HOFSATDTER (R.), NOELDEKE (G. K.), YEARIAN (H. R.), CLARK (B. C.), HERMAN (R.), and RAVENHALL (D. G.), to be published. NOELDEKE (G. K.), private communication.