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# CHANGES IN MEAN SQUARE NUCLEAR CHARGE RADII FROM OPTICAL ISOTOPE SHIFTS OF LONG CHAINS OF ISOTOPES

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Results of recent measurements on isotope shifts are compiled for 20 chains of isotopes, mostly concerning short-lived radioactives. Unpublished material is also included. The $\delta\langle r^2\rangle$ are re-evaluated by using an improved calculation of the electron density at the nucleus. Therefore, in some elements, minor changes occur as compared to results given in the literature.

## 1. Introduction

The following tables give a compilation of measured isotope shifts (Iss) and $\delta\langle r^2\rangle$-values for 20 chains of isotopes. Some of them are in a rather preliminary state of art. The intention is, however, to accumulate the new information on long isotope chains as soon as possible, even accepting a somewhat uncompleted status. A detailed evaluation is in preparation |AHS 85| treating all elements.

The references are restricted to those needed for the compilation. A bibliography of references on experimental isotope shifts is given in |He 77| and |He 82|, a compilation of $\delta\langle r^2\rangle$ as of 1974 is given in |HS 74|. Various publications concerning the isotope shift of stable isotopes cannot be mentioned here. In order to achieve completeness of Iss data of long isotopic chains, many preliminary results are quoted. They must not be used or cited without permission of the authors.

The precision of the observed isotope shifts presented here is frequently so high that the usual estimates for the specific mass shift (SME), e.g. |HS 74|, are no longer adequate. This problem shows up also in heavy elements where the volume shift clearly dominates. Even in radium (Z = 88) the normal mass shift (NME) amounts to five times the experimental errors of the observed shifts. In sodium – a very light element – the mass shifts (ME) account for 99.5 percent of the observed shift. It is unnecessary to say how weightily error limits originating from SME will be here for the accuracy of the evaluated $\delta\langle r^2\rangle$. Mass shifts deducted by combining isotope shifts in optical transitions with those in muonic atoms also often do not yield the needed accuracy. In order to avoid any loss of information, the observed isotope shifts and their errors are given in the tables.

Nevertheless, the quoted $\delta\langle r^2\rangle$ are quite reliable, as can be checked by the slope of $\delta\langle r^2\rangle$ values of neighbouring isotopic chains or by the (model-dependent) comparison with nuclear data obtained in completely different ways (e.g. nuclear deformation). This is due to the strong correlation between the ME in all isotopes of an element. For illustrative discussions see, for example, ref. (a) of Na or ref. (a) of K.

## 2. Formulae and abbreviations

The theory of isotope shifts is well developed and described in many publications. Here, only the most important equations are listed. For details see, for example, |HS 74| and |Ki 84|.

$$\delta\nu_{i,obs}^{A,A'} = F_i \cdot \lambda^{A,A'} + M_{i,ME} \cdot \frac{A'-A}{A'A} \quad \text{with}$$

$$\lambda^{A,A'} = \delta\langle r^2\rangle^{A,A'} + \frac{C_2}{C_1}\,\delta\langle r^4\rangle^{A,A'} + \ldots \approx \delta\langle r^2\rangle^{A,A'} \quad \text{and}$$

$$\lambda^{A,A'} = \frac{\delta\nu_{i,obs}^{A,A'} - \mathring{M}_{i,ME} \cdot \frac{A'-A}{A'A}}{F_i} = \frac{\delta\nu_{i,FE}^{A,A'}}{F_i}$$

$$F_i = E_i \cdot f(Z) = \beta \cdot E_{ns} \cdot f(Z)$$

$$M_{i,NME}\,[\mathrm{MHz}] = \nu_i\,[\mathrm{cm}^{-1}] \cdot 16.4501 = \nu_i\,[\mathrm{MHz}] \cdot 5.48717 \cdot 10^{-4}$$

$$\delta\nu_{ME}^{A,A'} = M_{i,ME} \cdot \frac{A'-A}{A'A} \qquad M_{i,ME} = M_{i,NME} + M_{i,SME}$$

$\delta\nu_{i,obs}$: experimentally observed isotope shift in transition i,

$\delta\nu_{ME}$: mass shift,

$\delta\nu_{FE}$: field (volume) shift,

$\nu_i$: wave number of transition i,

A, A′: masses in a.m.u. |WB 77|,

$E_{ns}$: electronic factor; for the sake of consistency, the $E_{ns}$ are evaluated in most cases by use of the Goudsmit–Fermi–Segrè formula (GFS) wherever feasible.

$$E_{ns} = \pi \cdot a_0^3 \cdot |\psi(0)|^2_{ns}/Z$$

$$\Delta|\psi(0)|^2_{ns\text{-}np} = \beta|\psi(0)|^2_{ns} \qquad \Delta|\psi(0)|^2_{ns^2\text{-}nsnp} = \gamma|\psi(0)|^2_{ns}$$

f(Z) calculated according to ref. |Ba 63| and |Zi 84a| by P. Aufmuth |Au 84|. Slightly changed values for $C_{unif}$ are in preparation by D. Zimmermann |Zi 84b|.

$\beta, \gamma$ screening factors, calculated by P. Aufmuth |Au 84|.

$E_{ns}$, $F_i$, f(Z), $\beta$, $\gamma$ behave as scaling factors for $\delta\langle r^2\rangle$, thus facilitating future calculations with improved factors.

## 3. Comparison with values of $\delta\langle r^2\rangle$ from literature

The values of $\delta\langle r^2\rangle$ in the tables are calculated with improved values of $\beta$ and $\gamma$ and f(Z), see last chapter. Therefore, in some elements the $\delta\langle r^2\rangle$ values of the table differ slightly from the values given in the literature. The ratios of $\delta\langle r^2\rangle$ for different isotope pairs are not affected hereby.

For the $M_i$ values, the estimates according to |HS 74| are used. Therefore, in a few elements, again minor changes will be found.

## 4. Limits of error

$\delta\nu_{obs}$: as given in the references. Long isotopic chains: frequently one standard deviation. Stable isotopes only: three standard deviations.

$M_i$: in most cases $M_i$ can only be estimated roughly (see head of tables and accompanying footnotes).

$F_i$: the accuracy of the $F_i$ can only be estimated. It should be about five percent by comparison to results of other calculations; see e.g. ref. (c) of gold or ref. (f) of barium.

$\beta, \gamma$: accuracy of calculations about five percent.

f(Z): estimated to be about five percent.

Policy: (a) the $\delta\langle r^2\rangle$ errors contain at least the experimental errors;
(b) where changes in $M_i$ heavily affect $\delta\langle r^2\rangle$, two chains of $\delta\langle r^2\rangle$ are given, each one for a fixed $M_i$; in cases where $M_i$ is of minor influence, the $\delta\langle r^2\rangle$ errors contain the experimental error and the error of $M_i$;
(c) with exception of Ca, all $\delta\langle r^2\rangle$ are calculated without taking into account the error limits of $E_i$, $F_i$, $\beta$, $\gamma$, and f(Z), even when these (scaling) factors are given in the heads of the tables with limits of error.

## 5. $\delta\langle r^2\rangle$ for isotope pairs not given in the tables

As $\delta\langle r^2\rangle^{A,A'} = \delta\langle r^2\rangle^{A,A''} - \delta\langle r^2\rangle^{A',A''}$, the value of $\delta\langle r^2\rangle$ for adjacent isotopes can immediately be calculated. But concerning the limits of error, this procedure would lead to values much too high. The reason lies in the well-known $1/A^2$ dependence of the ME. Therefore, in this case one has to start the calculation of the errors from the experimental errors and to use the errors of the $\delta\nu_{ME}^{A,A'}$ and not those of $\delta\nu_{ME}^{A,A''} - \delta\nu_{ME}^{A',A''}$. The head of each table gives the constants needed. The tables of Rb and Ba illustrate this procedure.

The ratio $\delta\langle r^2\rangle^{A,A''}/\delta\langle r^2\rangle^{A',A''}$ shows weaker dependence on mass shift and hence smaller limits of error. This is due to the strong correlation of ME in different isotope pairs. The limits of error decrease further, if here the experimental error is minimized by measuring all needed pairs AA″, A′A″, and so on directly. A good example is given in the lower part of the table of Sn.

## 6. Sign convention

If only NME is present, $\nu_i^{A'} - \nu_i^{A} = \delta\nu_i^{A,A'} > 0$, with $A' > A$.

$M_{i,NME}$, $\beta$, $\gamma$, and f(Z) are always positive.

If the radius increases upon addition of neutrons, $\langle r^2\rangle^{A'} - \langle r^2\rangle^{A} = \delta\langle r^2\rangle^{A,A'} > 0$. For unperturbed s-p transitions and the s-term below the p-term, $E_i < 0$ and $F_i < 0$ by convention and consequently $\delta\nu_{FE} < 0$.

## References

|Au 84| P. Aufmuth, private communication (1984).
|AHS 85| P. Aufmuth, K. Heilig, A. Steudel, in preparation (1985).

|Ba 63| J. Babushkin, J. Exp. Theor. Phys. USSR 44, 1661 (1963); Sov. Phys. JETP 17, 1118 (1963).

|He 77, 82| K. Heilig, Spectrochim. Acta 32B, 1–57 (1977) and 37B, 417–455 (1982); to be continued.

|HS 74| K. Heilig and A. Steudel, At. Data Nucl. Data Tables 14, 613–638 (1974).

|Ki 84| W.H. King, *Isotope Shifts in Atomic Spectra*, in: *Physics of Atoms and Molecules*, ed. P.G. Burke and H. Kleinpoppen (Plenum Press, New York and London, 1984).

|WB 77| A.H. Wapstra and K. Bos, At. Data Nucl. Data Tables 19, 177–214 (1977).

|Zi 84a| D. Zimmermann, Z. Phys. A315, 123–124 (1984).

|Zi 84b| D. Zimmermann, to be published (1984).

11 sodium

Investigated transition: Na I $\lambda$ = 589.59 nm $D_1$

$M_{i,ME}$ = 385.5 GHz  E = -0.225  $f(Z)^{20}$ = 203.3 MHz $fm^{-2}$

β = 1.11  $f(Z)^{31}$ = 201.8 MHz $fm^{-2}$

| A | $\delta\nu_{obs}$ / MHz ref. a) | ref. b) | ref. c), d) | $\delta\langle r^2\rangle$ / $fm^2$ $M_i$=385.5 GHz | $M_i$=386.7 GHz |
|---|---|---|---|---|---|
| 20 | | -2493.4(3.6) | | -0.13(7) | -0.29(7) |
| 21 | -1596.7(2.3) | -1595.2(2.9) | | +0.12(5) | +0.02(5) |
| 22 | -756.9(1.9) | -754.0(2.3) | -758.5(7) c) | -0.05(4) | -0.09(4) |
| 23 | 0 | 0 | 0 | 0 | 0 |
| 24 | 706.4(6.2) | 705.6(1.8) | | -0.12(4) | -0.07(4) |
| 24m | | | 1014(118) d) | -6.2(2.3) | -6.2(2.3) |
| 25 | 1347.2(1.3) | | | -0.10(3) | -0.02(3) |
| 26 | 1937.5(9) | | | -0.005(18) | +0.11(2) |
| 27 | 2481.3(2.0) | | | +0.12(4) | +0.27(4) |
| 28 | 2985.8(2.7) | | | +0.28(5) | +0.46(5) |
| 29 | 3446.2(3.8) | | | +0.60(8) | +0.81(8) |
| 30 | 3883.5(6.0) | | | +0.76(12) | +1.00(12) |
| 31 | 4286(16) | 4282.0(3.5) | | +1.09(7) | +1.36(7) |

$M_i$ = 385.5 GHz was fitted to the isotope pair 23,25 by arguments solely based on nuclear properties (see ref. a)). The field shift of this pair is only 0.4 per cent of the observed shift.

A very small change of 0.3 per cent of the mass-shift estimate drastically alters the quoted $\delta\langle r^2\rangle$ values. This is shown for comparison in the last column. Nevertheless, there is clear evidence for field shift. All quoted errors stem from $\delta\nu_{obs}$ errors.

The value of $\delta\langle r^2\rangle^{24m}$ is unreasonably large.

Ref. a) G. Huber et al., Phys. Rev. C 18, 2342-2354 (1978)
b) F. Touchard et al., Phys. Rev. C 25, 2756-2770 (1982)
c) K. Pescht et al., Z. Physik A 281, 199-204 (1978)
d) P. G. Pappas et al., Hyp. Int. 9, 187-192 (1981)

## 19 potassium

Investigated transitions: ref. a) K I $\lambda$ = 769.90 nm $D_1$
$\lambda$ = 766.49 nm $D_2$
ref. b) K I $D_1$

$M_{i,ME}$ = 200(4) GHz  $F_i^{41,39}$ = -128 MHz fm$^2$  $f(Z)^{38}$ = 658.3 MHz fm$^{-2}$
$\beta$ = 1.14  $f(Z)^{47}$ = 656.5 MHz fm$^{-2}$

| A | $\delta\nu_{obs}$ / MHz | | | $\delta\langle r^2\rangle$ / fm$^2$ |
|---|---|---|---|---|
| | $D_1$ ref. a) | $D_1$ ref. b) | $D_2$ ref. a) | |
| 38 | | -127.0(5.3) | | -0.059(41)(47) |
| 39 | 0 | 0 | 0 | 0 |
| 40 | 125.58(26) | | 126.43(30) | 0.023(2)(20) |
| 41 | 235.27(33) | 235.25(75) | 236.15(37) | 0.019(6)(40) |
| 42 | | 351.7(1.9) | | 0.118(15)(60) |
| 43 | | 459.0(1.2) | | 0.146(9)(76) |
| 44 | | 564.3(1.4) | | 0.152(11)(93) |
| 45 | | 661.7(1.6) | | 0.181(13)(109) |
| 46 | | 762.8(1.5) | | 0.147(12)(124) |
| 47 | | 857.5(1.7) | | 0.131(13)(138) |

$M_i$ was evaluated by use of $\delta\langle r^2\rangle^{41,39}_{\text{muonic K}\alpha}$ = 0.118(40); see ref. b) and c).
The calculation of the $\delta\langle r^2\rangle$ follows ref. a) and b). Two limits of error are quoted. The first column of errors was calculated considering the experimental limits of error only. When calculating the second column of errors, the limits of the $M_i$-estimates were also taken into account.

Ref. a) N. Bendali et al., J. Phys. B: At. Mol. Phys. 14, 4231-4240 (1981)
b) F. Touchard et al., Phys. Lett. 108 B, 169-171 (1982)
c) H. D. Wohlfahrt et al., Phys. Rev. C 23, 533-548 (1981)

## 20 calcium

Inv. tr.: Ca I

ref. a) and b) $\lambda$ = 422.67 nm $4s^2\ ^1S_0 - 4s4p\ ^1P_1$

$M_i$ = 362.54(44) GHz $F_i$ = -181(10) MHz $fm^{-2}$

ref. c) $\lambda$ = 657.28 nm $4s^2\ ^1S_0 - 4s4p\ ^3P_1$

$M_i$ = 461.6(5) GHz $F_i$ = -182(5) MHz $fm^{-2}$

| A | $\delta\langle r^2\rangle$ / $fm^2$ |
|---|---|
| 40 | 0 |
| 41 | 0.0012(25) |
| 42 | 0.2209(60) |
| 43 | 0.1221(45) |
| 44 | 0.2908(75) |
| 45 | 0.1272(89) |
| 46 | 0.1290(63) |
| 47 | 0.007(10) |
| 48 | 0.0032(67) |

The $\delta\langle r^2\rangle$ are the weighted mean values from ref. a), b) and c).

Ref. a) H.-W. Brandt et al., Z. Physik A 288, 241-246 (1978)
b) A. Andl et al., Phys. Rev. C 26, 2194-2202 (1982)
c) E. Bergmann et al., Z. Physik A 294, 319-322 (1980)

## 37 rubidium

Inv. tr.: ref. a) Rb I $\lambda$ = 780.02 nm $D_2$

$M_{i,ME}$= 210.8(1.3 + 0.9) GHz E = -0.1838 $f(Z)^{76}$=348.6 MHz $fm^{-2}$

$\beta$ = 1.14 $f(Z)^{98}$=346.1 MHz $fm^{-2}$

ref. b) Rb I $\lambda$ = 420.19 nm $5s\ ^2S_{1/2} - 6p\ ^2P_{3/2}$

$M_{i,ME}$= 331(1.3 + 0.9) GHz $F_i^{87,85}$= -650.2 MHz $fm^2$ $\beta$ = 1.14

| A | $\delta\nu_{obs}$ / MHz | | $\delta\langle r^2\rangle$ / $fm^2$ ref.a) | | $\delta\langle r^2\rangle$ ref.b) |
|---|---|---|---|---|---|
| | ref. a) | ref. b) | $M_i$=274.0 GHz | $M_i$= 84.3 GHz | $M_i$= 331.1 GHz |
| 76 | -494(17) | | 0.053(23) | 0.486(23) | |
| 77 | -498.6(4.5) | | 0.123(6) | 0.511(6) | |
| 78 | -478.4(1.5) | | 0.158(2) | 0.503 | |
| 78m | -403.8(1.7) | | 0.056(2) | 0.401 | |
| 79 | -391.6(1.5) | | 0.100(2) | 0.402 | |

37 rubidium (continued)

| A | $\delta\nu_{obs}$ / MHz ref. a) | ref. b) | $\delta<r^2>$ / $fm^2$ ref.a) $M_i$= 274.0 GHz | $M_i$= 84.3 GHz | $\delta<r^2>$ ref.b) $M_i$= 331.1 GHz |
|---|---|---|---|---|---|
| 80 | -352.8(4.4) | | 0.106(6) | 0.368 | |
| 81 | -289.9(1.4) | | 0.078(2) | 0.299 | |
| 81m | -270.4(1.4) | | 0.051(2) | 0.273 | |
| 82 | -233.7(4.2) | | 0.057(6) | 0.240 | |
| 82m | -233.5(3.8) | | 0.057(5) | 0.240 | |
| 83 | -150.1(1.0) | | -0.002(1) | 0.142 | |
| 84 | -91.6(2.1) | | -0.029(3) | 0.078 | |
| 84m | -84(10) | | -0.039(14) | 0.068 | |
| 85 | -80.1(1.4) | -124.2(7)* | 0.008(2) | 0.079 | 0.054(1) |
| 86 | -45.8(2.0) | | 0.013(3) | 0.047 | |
| 86m | -32.1(2.3) | | -0.006(3) | 0.029 | |
| 87 | 0 | 0 | 0 | 0 | |
| 88 | -61.0(5.1) | | 0.133(7) | 0.099 | |
| 89 | -143.7(2.0) | -102(8) | 0.294(3) | 0.227 | 0.288(12) |
| 90 | -197.7(5.2) | -121(8) | 0.417(7) | 0.316 | 0.382(12) |
| 90m | -188.6(2.0) | | 0.404(3) | 0.304 | |
| 91 | -255.8(2.3) | -168(8) | 0.543(3) | 0.412 | 0.517(12) |
| 92 | -320.4(5.2) | -200(8) | 0.677(7) | 0.514 | 0.627(13) |
| 93 | -371.5(2.1) | -227(8) | 0.792(3) | 0.598 | 0.728(12) |
| 94 | -414.7(2.3) | | 0.895(3) | 0.670 | |
| 95 | -495.9(3.8) | | 1.049(5) | 0.795 | |
| 96 | -528.3(4.8) | | 1.135(7) | 0.853 | |
| 97 | -879.7(4.0) | | 1.660(6) | 1.349 | |
| 98 | -910(10) | | 1.741(14) | 1.403 | |

The limits of error of $M_i$ are neglected. The dependence of $\delta<r^2>$ from $M_i$ can be seen by comparing the 4th and 5th column. Concerning ref. b) $F_i$ is taken from the reference, but $\beta$ = 1.1 is replaced by 1.14 and the ratio $m_p/m_e$ by 1822.43.

*) value taken from ref. c)

Ref. a) C. Thibault et al., Phys. Rev. C 23, 2720-2729 (1981)
b) W. Klempt et al., Phys. Lett. 82 B, 47-50 (1979)
c) P. Grundevik et al., Z. Physik A 283, 127-132 (1977)

## 48 cadmium

Inv. tr.: Cd I ref. a),b),f)-i) $\lambda$ = 326.1 nm $5s^2\ ^1S_0 - 5s5p\ ^3P_1$

$M_i$ = 504(252) GHz $f(Z)^{102}$ = 7841 MHz $fm^{-2}$

$\gamma \cdot E_{5s}$ = -0.512 $f(Z)^{120}$ = 7784 MHz $fm^{-2}$

ref. c) and d) $\lambda$ = 467.8 nm $5s5p\ ^3P_0 - 5s6s\ ^3S_1$

$M_i$ = 253(126) GHz $\beta \cdot E_i$ = 0.156(8)

Cd II ref. e) $\lambda$ = 226.5 nm $4d^{10}5s\ ^2S_{1/2} - 4d^{10}5p\ ^2P_{3/2}$

$M_i$ = 944(653) GHz $E_{5s}$ = -0.800 $\beta$ = 1.11

| A | $\delta\nu_{obs}$ / MHz | | | $\delta\langle r^2\rangle$ / $fm^2$ | |
|---|---|---|---|---|---|
| | $\lambda$=326.1nm | $\lambda$=467.8nm | $\lambda$=226.5nm | ref. a),b),f)-i) | ref. c),d),e) |
| 102 | 3454(170)g | | | -0.992(42)(78) | |
| 103 | 3075(160)g | | | -0.886(40)(71) | |
| 104 | 2595(184)g | | | -0.755(46)(70) | |
| 105 | 2349(131)g | | | -0.682(33)(58) | |
| 106 | 1955(54)f | -796.8(4.5)c | 2912.1(3.8)e | -0.572(14)(44) | -0.511(5)(67) |
| 107 | 1666(115)g | | | -0.489(29)(46) | |
| 108 | 1387(54)h | -588.8(3.4)c | 2134.2(3.6)e | -0.408(14)(34) | -0.377(6)(49) |
| 109 | 1322(156)i | | | -0.381(39)(47) | |
| 110 | 893(18)f | -382.8(1.6)c | 1390.7(3.4)e | -0.264(5)(21) | -0.245(3)(32) |
| 111 | 839(51)f | -314(6)d | 1308.8(4.1)e | -0.240(13)(20) | -0.219(7)(25) |
| 111m | 871(390)g | | | -0.248(98)(99) | |
| 112 | 405(12)f | -182.0(1.0)c | 653.2(3.4)e | -0.121(3)(10) | -0.116(1)(16) |
| 113 | 333(42)f | -123(6)d | 562.7(4.3)e | -0.093(11)(12) | -0.090(3)(90) |
| 113m | 360(266)g | | | -0.100(67)(67) | |
| 114 | 0 | 0 | 0 | 0 | 0 |
| 115 | -63(174)g | | | 0.025(44)(44) | |
| 115m | -87(48)b | | | 0.031(12)(13) | |
| 116 | -279(9)f | 151.9(1.0)c | -494.1(2.4)e | 0.089(2)(10) | 0.092(1)(15) |
| 118 | -378(85)g | | | 0.132(21)(28) | |
| 120 | -497(164)g | | | 0.180(41)(50) | |

The influence of the estimated SMS on $\delta\langle r^2\rangle$ is quite different in the distinct lines. Therefore, two groups of $\delta\langle r^2\rangle$ values are given.

Two limits of error are quoted. The first column of errors was calculated considering the experimental limits of error only. When calculating the second

48 cadmium (continued)

column of errors, the limits of the $M_i$-estimates were also taken into account.

Ref. a) F. Buchinger et al., Hyp. Int. 9, 165-168 (1981)
b) P. A. Moskowitz et al., Z. Physik A 275, 203-208 (1975)
c) R. Wenz et al., Z. Physik A 303, 87-95 (1981)
d) J. M. Gagné et al., J. Opt. Soc. Am. 65, 962-963 (1975)
e) M. S. W. M. Brimicombe et al., Proc. Roy. Soc. London A 352, 141-152 (1976)
f) F. M. Kelly et al., Proc. Phys. Soc. 74, 689-692 (1959)
g) F. Buchinger, Thesis Mainz 1981
h) private communication R. Wenz in ref. g)
i) R. J. Hull et al., J. Opt. Soc. Am. 53, 1147 (1963)

## 49 indium

Investigated transition: In I λ = 451.13 nm 6s $^2S_{1/2}$ - 5p $^2P_{3/2}$

$M_i$ = 426.5 GHz * $F_i$ = -2.070 GHz $fm^{-2}$ *

| A | $\delta\nu_{obs}$ / MHz | | $\delta\langle r^2\rangle$ / $fm^2$ |
|---|---|---|---|
| | ref. a) | ref. b) | ref. a) |
| 107 | -1150(21) | | -0.590(10) |
| 108 | -1011(19) | | -0.518(9) |
| 109 | -819(14) | | -0.421(7) |
| 110m | -722(17) | | -0.371(8) |
| 111 | -517(20) | | -0.266(10) |
| 113 | | -255.4(5) | -0.131(3) |
| 115 | 0 | 0 | 0 |

* The evaluation of $M_i$, $F_i$, $\delta\langle r^2\rangle$ follows ref. a), namely: $\delta\langle r^2\rangle^{115,113}$ was chosen as a mean between $\delta\langle r^2\rangle$ in neighbouring Cd and Sn isotones. Because of the unknown uncertainties resulting from this procedure no limits of error were estimated. Therefore, the quoted errors of $\delta\langle r^2\rangle$ make allowance for the experimental errors only.

Ref. a) G. Ulm, Thesis Mainz 1984; GSI-84-8 Report
b) G. J. Zaal et al., J. Phys. B 11, 2821-2823 (1984)

## 50 tin

Investigated transition: Sn I; ref. a) and b) $\lambda$ = 286.3 nm $5p^2\ {}^3P_0$ - $5p6s\ {}^3P_1$
ref. c) $\lambda$ = 452.5 nm $5p^2\ {}^1S_0$ - $5p6s\ {}^1P_1$

$M_{i,286.3}$ = 98(70) MHz
$F_{286.3}$ = 3.3(5) GHz fm$^{-2}$

| A | $\delta\nu_{obs}$ / MHz, $\lambda$ = 286.3 nm, ref. a) | ref. b) | $\lambda$ = 452.5 nm, ref. c) | $\delta\langle r^2\rangle^{120,A}$ / fm$^2$ | |
|---|---|---|---|---|---|
| 108 | | | 1835 | | -0.782 |
| 109 | | | 1643 | | -0.699 |
| 110 | -1569.2(7.0) | | 1501 | -0.639(29) | -0.632 |
| 112 | -1218.3(3) | -1214.4(1.1) | | -0.497(24) | |
| 113 | -1079.8(1.3) | | | -0.439(22) | |
| 114 | -900.9(5) | -894.9(1.4) | | -0.367(18) | |
| 115 | -805.6(3) | -801.7(1.2) | | -0.322(15) | |
| 116 | -575.6(3) | -574.4(8) | | -0.236(11) | |
| 117 | -469.7(7) | -467.6(9) | | -0.188(8) | |
| 117m | -494(12) | | | -0.196(9) | |
| 118 | -270.2(8) | -269.2(9) | | -0.112(8) | |
| 119 | -180.4(3) | -175.1(1.2) | | -0.070(4) | |
| 120 | 0 | 0 | 0 | 0 | 0 |
| 121 | 87.9(7.4) | | | 0.042(3) | |
| 121m | 70.5(30) | | | 0.036(3) | |
| 122 | 235.3(3) | 234.1(9) | | 0.101(5) | |
| 123 | 298.9(8) | | | 0.135(6) | |
| 124 | 441.2(8) | 441.6(9) | | 0.192(8) | |
| 125 | 505.6(6.8) | | | 0.225(10) | |

| A - A' | $\delta\langle r^2\rangle^{A',A} / \delta\langle r^2\rangle^{124,116}$ | A - A' | $\delta\langle r^2\rangle^{A',A} / \delta\langle r^2\rangle^{124,116}$ | A - A' | $\delta\langle r^2\rangle^{A',A} / \delta\langle r^2\rangle^{124,116}$ |
|---|---|---|---|---|---|
| 109 - 108 | 0.194 | 116 - 114 | 0.304(7) | 121 - 120 | 0.100(11) |
| 110 - 108 | 0.350 | 117 - 116 | 0.122(4) | 121m- 121 | 0.012(1) |
| 112 - 110 | 0.329(10) | 117m- 117 | -0.019(1) | 122 - 120 | 0.234(3) |
| 113 - 112 | 0.138(8) | 118 - 116 | 0.290(6) | 123 - 122 | 0.079(5) |
| 114 - 112 | 0.306(6) | 119 - 118 | 0.102(6) | 124 - 122 | 0.213(5) |
| 115 - 114 | 0.104(8) | 120 - 118 | 0.262(3) | 125 - 124 | 0.077(7) |

50 tin (continued)

The evaluation follows ref. b). The contribution of systematic errors is minimized when ratios of $\delta<r^2>$ are evaluated directly from the observed shifts. Therefore, the lower part of the table is included (values taken from or evaluated following ref. b)).

Ref. a) M. Anselment et al., Ann. Rep. on Nucl. Phys. Act., Karlsruhe KfK 3621, p. 67-69 (1983); K. Bekk, private comm.; preliminary results (1984)

b) P. E. G. Baird et al., J. Phys. B: At. Mol. Phys. 16, 2485-2497 (1983)

c) G. Huber, private communication (H. Lochmann et al. 1984); preliminary results

## 55 cesium

Investigated transitions: Cs I ref. a) and b) $\lambda$ = 852.1 nm $D_2$
ref. c) $\lambda$ = 459.3 nm $6s\ ^2S_{1/2} - 7p\ ^2P_{1/2}$
ref. d) $\lambda$ = 455.5 nm $6s\ ^2S_{1/2} - 7p\ ^2P_{3/2}$

$M_{D2,ME}$ = 251(174) GHz $E_{6s}$ = -0.1686 $f(Z)^{118}$ = 12.747 GHz $fm^{-2}$
$\beta$ = 1.14 $f(Z)^{145}$ = 12.594 GHz $fm^{-2}$

| A | $\delta\nu_{obs}$ / MHz | | | | $\delta<r^2>$ / $fm^2$ | |
|---|---|---|---|---|---|---|
| | ref. a) | ref. b) | ref. c) | ref. d) | ref. a)* | ref. d)† |
| 118 | 984(13) | | | | -0.501(5)(68) | |
| 119 | 144.3(6.0) | | | | -0.150(3)(63) | |
| 119m | 602.6(8.7) | | | | -0.338(4)(63) | |
| 120 | 116.9(3.2) | | | | -0.132(1)(58) | |
| 121 | 447.1(2.2) | | | | -0.260(1)(53) | |
| 121m | 18.5(1.8) | | | | -0.084(1)(53) | |
| 122 | 453.0(3.4) | | | | -0.256(1)(48) | |
| 122m | 26.7(4.1) | | | | -0.081(2)(48) | |
| 123 | 362.6(1.4) | | 259(12) | | -0.212(1)(43) | |
| 124 | 359.2(2.8) | | 261(6) | | -0.204(1)(39) | |
| 125 | 258.0(1.3) | | 152(11) | | -0.155(1)(34) | |
| 126 | 286.1(2.0) | | 208(7) | | -0.161(1)(30) | |

55 cesium (continued)

| A | $\delta\nu_{obs}$ / MHz ref. a) | ref. b) | ref. c) | ref. d) | $\delta<r^2>$ / $fm^2$ ref. a)* | ref. d)$^{\dagger}$ |
|---|---|---|---|---|---|---|
| 127 | 159.2(1.5) | | 94(13) | | -0.102(1)(25) | |
| 128 | 204.9(9) | | 155(6) | | -0.114(1)(21) | |
| 129 | 84.7(2.6) | | 53(9) | | -0.059(1)(17) | |
| 130 | 74.0(2.2) | | 56(8) | | -0.048(1)(12) | |
| 130m | 111.7(3.3) | | 83(12) | | -0.064(1)(12) | |
| 131 | 10.4(1.6) | | -9(6) | | -0.016(1)(8) | |
| 132 | 74.3(1.3) | | 60(15) | | -0.036(1)(4) | |
| 133 | 0 | 0 | 0 | | 0 | |
| 134 | 33.1(2.5) | 37.5(1.8) | | | -0.008(1)(4) | |
| 134m | 2.4(3.7) | | | | 0.005(2)(4) | |
| 135 | -36.4(2.0) | -36.3(4.5) | | | 0.027(1)(8) | |
| 135m | -17.6(2.4) | | | | 0.019(1)(8) | |
| 136 | -6.8(3.3) | | | | 0.020(1)(12) | |
| 136m | -139.7(3.4) | | | | 0.075(1)(12) | |
| 137 | -147.4(2.5) | -142.7(3.0) | -104(6) | 0 | 0.083(1)(16) | 0 |
| 138 | -415.3(1.8) | | | -255(9) | 0.199(1)(20) | 0.119(10) |
| 138m | -415.1(1.6) | | | | 0.199(1)(20) | |
| 139 | -770.7(2.8) | | | -597(10) | 0.351(1)(21) | 0.275(20) |
| 140 | -1053.4(2.9) | | | -969(9) | 0.473(1)(27) | 0.401(29) |
| 141 | -1342.0(3.3) | | | -1093(20) | 0.597(1)(31) | 0.506(40) |
| 142 | -1631.8(1.5) | | | -1420(20) | 0.721(1)(34) | 0.655(50) |
| 143 | -1933.3(1.2) | | | | 0.851(1)(38) | |
| 144 | -2125.2(1.6) | | | | 0.935(1)(41) | |
| 145 | -2412.9(2.3) | | | | 1.059(1)(45) | |

*The $\delta<r^2>$ were re-evaluated using $M_{ME} = M_{NME}$ (1.3 ± 0.9), $E_{6s}$ and $\beta$ as given in the heading of the table. They differ only slightly from the values in ref. a).

Two limits of error are quoted. The first column of errors was calculated considering the experimental limits of error only. When calculating the second column of errors, the limits of the $M_i$-estimates were also taken into account.

The $\delta<r^2>$ values calculated from the observed shifts of ref. b) differ less than 4 % from the quoted $\delta<r^2>$ with exception of the isotope 125.

$^{\dagger}$These values are taken from ref. d). They are related to the isotope 137!

55 cesium (continued)

Ref. a) C. Thibault et al., Nucl. Phys. A 367, 1-12 (1981)
b) H. Hühnermann et al., Z. Physik 199, 239-243 (1967)
c) G. Huber et al., Phys. Rev. Lett. 41, 459-462 (1978)
d) J. Bonn et al., Z. Physik A 289, 227-228 (1979)

## 56 barium

Investigated transition: ref. a)...d) Ba I $\lambda$ = 553.6 nm $6s^2\ ^1S_0 - 6s6p\ ^1P_1$

$M_{ME}$ = 84.5(84.5)† GHz $F_i$ = 3125† MHz fm$^2$ $f(Z)^{122}$ = 13.65 GHz fm$^{-2}$
$f(Z)^{146}$ = 13.50 GHz fm$^{-2}$

ref. g), h), k) Ba II $\lambda$ = 493.4 nm $D_1$
$\lambda$ = 455.4 nm $D_2$

$M_{D2,ME}$ = 469(325) GHz $E_{6s}$ = -0.345
$\beta$ = 1.13

| A | $\delta\nu_{obs}$ / MHz Ba I | Ba II $D_1$ | Ba II $D_2$ | $\delta\langle r^2\rangle$ / fm$^2$ Ba I | Ba II $D_2$ |
|---|---|---|---|---|---|
| 122 | 521(7)a | | | -0.192(2)(26) | |
| 123 | 603(9)a | | | -0.216(3)(24) | |
| 124 | 447.0(1.0)c | | | -0.165(1)(22) | |
| 125 | 491(6)a | | | -0.177(2)(20) | |
| 126 | 355.8(6)d | | | -0.132(1)(19) | |
| 127 | 436(5)a | | | -0.156(2)(17) | |
| 128 | 271.1(8)b | | | -0.102(1)(15) | |
| 129 | 312.3(2.0)d | | | -0.113(1)(14) | |
| 129m | 362.7(1.5)d | | | -0.129(1)(14) | |
| 130 | 207.3(7)b | 355.3(4.4)g | 372.3(4.9)g | -0.078(1)(12) | -0.110(1)(30) |
| 131 | 249.2(2.1)b | | | -0.090(1)(10) | |
| 131m | 264(3)a | | | -0.095(1)(11) | |
| 132 | 167.9(5)b | 278.9(4.0)g | 294.9(4.2)g | -0.063(1)(9) | -0.085(1)(20) |
| 133 | 250.0(9)b | | | -0.088(1)(7) | |
| 133m | 202.0(1.0)b | | | -0.072(1)(7) | |
| 134 | 143.0(5)b | 222.6(3.0)g | 233.9(3.7)g | -0.052(1)(6) | -0.063(1)(13) |
| 135 | 260.9(7)b | 348.6(2.1)g | 360.7(2.2)g | -0.088(1)(4) | -0.083(1)(10) |
| 135m | 161.7(6)d | | | -0.056(1)(4) | |
| 136 | 128.9(5)b | 179.4(1.8)g | 186.9(2.1)g | -0.044(1)(3) | -0.045(1)(7) |

56 barium (continued)

| A | $\delta\nu_{obs}$ / MHz | | | $\delta<r^2>$ / fm$^2$ | |
|---|---|---|---|---|---|
| | Ba I | Ba II $D_1$ | Ba II $D_2$ | Ba I | Ba II $D_2$ |
| 137 | 215.0(7)b | 271.1(1.7)g | 279.0(2.6)g | -0.070(1)(1) | -0.058(1)(3) |
| 137m | -31(2)a | | | 0.008(1)(2) | |
| 138 | 0 | 0 | 0 | 0 | 0 |
| 139 | -473(3)a | | * | 0.153(1)(2) | |
| 140 | -1075(3)a | -1180(100)h | * | 0.347(1)(3) | 0.232(19)(20) |
| 141 | -1505(5)a | | * | 0.486(2)(4) | |
| 142 | -2019(4)a | | * | 0.652(1)(6) | |
| 143 | -2494(8)a | | * | 0.805(3)(7) | |
| 144 | -3025(10)a | | * | 0.977(3)(9) | |
| 145 | -3407(9)a | | * | 1.101(3)(10) | |
| 146 | -3887(11)a | | * | 1.256(4)(11) | |
| 148 | | | * | | |

†These values were taken from the very extensive study of Ba-iss given in ref. f). From A = 122 until 137 the $\delta<r^2>$ are nearly the same as calculated in ref. e), but for A > 138 the $\delta<r^2>$ become about 20 % greater than in ref. e). There is another 20 % discrepancy between results from optical and from muonic shifts; see ref. f).

For comparison recent results for Ba II, $D_1$ and $D_2$ are evaluated following GFS. Using Iss in myonic atoms gives $\beta \cdot E = -0.28$, thus yielding still larger $\delta<r^2>$ values, see ref. i).

*The Iss of these isotopes have been measured, but the analysis of the data is not yet completed; ref. k).

Limits of error: the first column of errors was calculated considering the experimental limits of error only. When calculating the second column of errors, the limits of the $M_i$-estimates were also taken into account.

Ref. a) A. C. Müller et al., Nucl. Phys. A 403, 234-262 (1983)
b) G. Nowicki et al., Phys. Rev. C 18, 2369-2379 (1978)
c) H. Rebel et al., Nukleonika 25, 145-163 (1980)
d) K. Bekk et al., Z. Physik A 291, 219-230 (1979)
e) R. Neugart et al., Hyp. Int. 9, 151-158 (1981)
f) W. H. King "Iss in Atomic Spectra", Physics of Atoms and Molecules (P. G. Burke, H. Kleinpoppen eds.) Plenum Press New York and London 1984)

g) K. Wendt et al., submitted to Z. Physik 1984
h) W. Fischer et al., Z. Physik 267, 209 (1974)
i) B. Fricke et al., Phys. Lett. 97 A, 183 (1983)
k) R. Neugart, private communication 1984

## 62 samarium

Investigated transition: Sm I ref. a) $\lambda$ = 570.68 nm $4f^6 6s^2\ ^7F_1 - 4f^6 6s6p\ ^7F_0$
and 14 other lines
ref. b) $\lambda$ = 570.68 nm

| A | $\delta\nu_{obs}$ / MHz<br>$\lambda$ = 570.68 nm<br>ref. a) | <br><br>ref. b) | $\delta\langle r^2\rangle$ / fm$^2$ |
|---|---|---|---|
| 144 | 2222.8(1.9) | | -0.517(27) |
| 146 | | 1047.8(5.3) | -0.251(29) |
| 147 | 651.4(1.1) | | -0.152(8) |
| 148 | 0 | 0 | 0 * |
| 149 | -400.7(0.6) | | 0.092(5) |
| 150 | -1296.0(2,0) | | 0.303(16)* |
| 151 | | -1960.7(5.8) | 0.464(29)* |
| 152 | -3096.7(2.9) | | 0.726(27) |
| 154 | -4087.6(3.1) | | 0.956(30) |

In both references pairs of adjacent isotopes were investigated.

For a detailed discussion of $M_i$ and $E_i$ see ref. a). The $\delta\langle r^2\rangle$ errors include an error of 17 % for $M_i$ and 4 % for $E_i$.

*The effect of nuclear polarizability on the shift of isotopes 148, 150, and 152 was calculated to be 2, 7, and 6 % respectively, see ref. c).

Ref. a) H. Brand et al., Z. Physik A 296, 281-286 (1980)
b) D. A. Eastham et al., Z. Physik A 318, 243-244 (1984)
c) B. Hoffmann et al., Z. Physik A 315, 57-63 (1984)

63 europium

Inv. tr.: Eu I ref. a) $\lambda$ = 462.72 nm $6s^2\ a\ ^8S_{7/2}$ - $6s6p\ y\ ^8P_{7/2}$

$M_{ME}$ = 355.4(177.7) GHz $\gamma \cdot E$ = -0.2287

$f(Z)^{140}$ = 22.06 GHz $fm^{-2}$

$f(Z)^{153}$ = 21.91 GHz $fm^{-2}$

$\lambda$ = 459.40 nm $6s^2\ a\ ^8S_{7/2}$ - $6s6p\ y\ ^8P_{9/2}$

Eu II ref. b) $\lambda$ = 604.95 nm $6p_{3/2}$ $(7/2,3/2)_4$ - 5d $^9D_4$

| A | $\delta\nu_{obs}$/MHz preliminary values | ref. a) | ref. b) | $\delta\langle r^2\rangle$ fm$^2$ preliminary values | | |
|---|---|---|---|---|---|---|
| | $\lambda$= 462.7nm | $\lambda$= 459.4nm | $\lambda$= 604.9nm | $\lambda$= 462.7nm | $\lambda$= 462.7nm | $\lambda$= 604.9nm |
| 140 | -235(11) | | | 0.029(9) | | |
| 141 | -231(6) | | | 0.032(7) | | |
| 142 | 230(14) | 229(19) | | -0.056(6) | | |
| 142m | -56(7) | -64(9) | | 0.001(5) | | |
| 143 | 101(5) | 92(7) | | -0.027(4) | | |
| 144 | 238(8) | 239(8) | | -0.051(2) | | |
| 145 | 0 | 0 | | 0 | | |
| 146 | -607(10) | -620(8) | | 0.124(3) | | |
| 147 | -1325(5) | -1384(6) | -1231(14) | 0.270(4) | -0.579(11) | -0.529(36) |
| 148 | -1843(9) | -1902(8) | | 0.376(5) | | |
| 149 | -2602(5) | -2708(7) | -698(10) | 0.531(7) | -0.318(12) | -0.294(21) |
| 150 | -3056(7) | -3177(7) | | 0.624(8) | | |
| 150m | -3100(10) | -3225(10) | | 0.633(8) | | |
| 151 | -4170(6) | -4343(9) | 0 | 0.849(10) | 0 | 0 |
| 152 | -6879(18) | | +1399(10) | 1.392(12) | | 0.529(42) |
| 152m | | | +657(10) | | | 0.261(15) |
| 153 | -7146(9) | -7446(9) | +1465(10) | 1.448(13) | -0.599(16) | 0.577(25) |
| 154 | | | +1727(10) | | | 0.689(39) |
| 155 | | | +1642(10) | | | 0.677(33) |
| 156 | | | +1698(10) | | | 0.714(38) |

The measured iss in $\lambda$ = 462.7 nm and the evaluation of $\delta\langle r^2\rangle$ from the iss are preliminary. A detailed discussion will be given in ref. a)

$\delta\nu_{obs}$ and $\delta\langle r^2\rangle$ from $\lambda$ = 604.9 were taken from ref. b). For convenience the last column but one was added. The only variation as compared to the column before is the change of the reference isotop from 145 to 151.

Ref. a) S. A. Ahmad et al., to be published in Z. Physik;

63 europium (continued)

R. Neugart, private communication 1984
b) K. Dörschel et al., Z. Physik A 317, 233-234 (1984)

## 64 gadolinium

Investigated transition: Gd I $\lambda$ = 422.6 nm $5d6s^2\ ^9D_6$ - 5d6s6p

Measured isotopes: 142, 144, ... 154, and 145m
Measurements on the remaining stable isotopes are in progress, the data analysis is not yet completed:

Ref. S. A. Ahmad et al.; R. Neugart, private communication 1984

## 66 dysprosium

Investigated transition: Dy I $\lambda$ = 421.17 nm $4f^{10}6s^2\ ^5I_8$ - $4f^{10}6s6p$

| A | $\delta\nu_{obs}^{156,A}$ | $\delta\nu_{obs}^{A,A+2}$ / MHz |
|---|---|---|
| 146 | 8540(11) | 81(8) |
| 148 | 8459(8) | 1809(8) |
| 150 | 6650(7) | 1759(6) |
| 152 | 4891(5) | 2124(4) |
| 154 | 2767(3) | 2767(3) |
| 156 | 0 | 1433(3) |
| 158 | -1433(3) | 973(3) |
| 160 | -2406(4) | 985(4) |
| 162 | -3391(5) | 912(4) |
| 164 | -4303(6) | |

Isotopes measured in addition: 147, $147^m$, 149, 151, 153, 155, 157, 159, 161, 163.
The data analysis is in progress.

Ref. a) W. Klempt et al., R. Neugart, private communication 1984
b) AHS 85

68 erbium preliminary values

Investigated transition: Er I $\lambda$ = 415.1 nm
$\lambda$ = 440.9 nm
$\lambda$ = 582.7 nm

| A | $\delta\nu_{obs}$ / MHz $\lambda$ = 440.9 nm | $\delta\nu_{obs}$ / MHz $\lambda$ = 582.7 nm |
|---|---|---|
| 150 | -18066(8) | |
| 152 | -14997(6) | |
| 154 | -11990(6) | 7787(9) |
| 156 | -8762(5) | 5704(9) |
| 158 | -5107(5) | 3388(5) |
| 160 | -2040(3) | 1405(4) |
| 162 | 0 | 0 |
| 164 | 1653(2) | |

The measurements in the sequence of stable isotopes Er 162, 164, 166, 167, 168, 170 are not yet completed.

The iss in the Er I line 415.1 nm for the isotopes Er 150, 152, 167 (including the odd-A isotopes) have been also measured. The data analysis is in progress:

Ref. S. A. Ahmad et al.; R. Neugart, private communication 1984

70 ytterbium

Investigated transitions: Yb I

ref. a), b) and c): $\lambda$ = 555.6 nm $6s^2\ ^1S_0 - 6s6p\ ^3P_1$

ref. a) $\lambda$ = 769.9 nm $6s6p\ ^3P_2 - 6s7s\ ^3S_1$

$M_{i,555.6}$ = 295.9(147.9) GHz $E_i(6s)$ = -0.457 $f(Z)^{156}$ = 35.75 GHz fm$^{-2}$

$\gamma$ = 0.73 $f(Z)^{176}$ = 35.34 GHz fm$^{-2}$

70 ytterbium (continued)

| A | $\delta\nu_{obs}$ / MHz $\lambda$ = 769.9 nm | $\lambda$ = 555.6 nm | $\delta\langle r^2\rangle$ / $fm^2$ $\lambda$ = 555.6 nm |
|---|---|---|---|
| 156 | -5794(10) | | -1.00(2)$^{\dagger}$ |
| 158 | -4696(6) | 11220(12) a | -0.9554(58) |
| 159 | | * | |
| 160 | -3605(6) | 8601(10) a | -0.7319(38) |
| 161 | | 7605(8) a | -0.6472(32) |
| 162 | -2538(5) | 6053(8) a | -0.5157(28) |
| 163 | | 5094(7) a | -0.4340(23) |
| 164 | -1548(5) | 3675(6) a | -0.3135(27) |
| 165 | | 2823(3) a | -0.2409(16) |
| 166 | -691.2(1.5) | 1634(4) a | -0.1397(10) |
| 167 | | 752(3) a | -0.0640(5) |
| 168 | 0 | 0 | 0 |
| 169 | 582.4(1.3) | -602(16) b | 0.0517(14) |
| 169m | | * | |
| 170 | | -1367.9(8) c | 0.1173(12) |
| 171 | | -1830.2(8) c | 0.1573(14) |
| 172 | | -2654.6(8) c | 0.2279(19) |
| 173 | | -3100.1(8) c | 0.2664(23) |
| 174 | | -3655.9(6) c | 0.3144(27) |
| 176 | | -4610.4(8) c | 0.3968(34) |

The evaluation of $\delta\langle r^2\rangle$ follows HS 74. For a discussion of more recent calculations see ref. c) and e).

$^{\dagger}$This value deduced from $\lambda$ = 769.9 nm

*These isotope shifts have been measured, too, the data still to be analysed, ref. d).

Ref. a) F. Buchinger et al., Nucl. Instr. Meth. 202, 159-165 (1982)
b) R. J. Champeau et al., J. Phys. B 7, L262-265 (1974)
c) D. L. Clark et al., Phys. Rev. A 20, 239-252 (1979)
d) R. Neugart, private communication 1984
e) W. H. King "ISS in Atomic Spectra", Physics of Atoms and Molecules (P. G. Burke, H. Kleinpoppen eds.) Plenum Press New York and London 1984

## 79 gold

Investigated transition: Au I $\lambda$ = 267.60 nm $D_1$

$M_i$ = 614(1.3 $\pm$ 0.9) GHz  $F_i^{197,195}$ = -47.5(5.0) GHz  $\lambda^{195,197}$ = 0.936 $\delta\langle r^2\rangle^{195,197}$

$\beta$ = 1.14

| A | $\delta\nu_{obs}$ / GHz<br>ref. a) | $\delta\langle r^2\rangle$ / fm$^2$ |
|---|---|---|
| 190 | -11.12(39) | 0.247(11) |
| 191 | -9.67(12) | 0.215(5) |
| 192 | -8.32(15) | 0.185(5) |
| 193 | -6.29(11) | 0.139(4) |
| 195 | -3.05(22) | 0.067(6) |
| 197 | 0 | 0 |

The evaluation of $F_i$ follows ref. b), $\beta$ taken from |Au 84|.

Recent MCDF-calculations give $F_i$ = -43 GHz, see ref. c).

Ref. a) J. Streib, Thesis, Mainz 1984
b) H. J. Kluge, Z. Physik A 309, 187-192 (1983)
c) A. Rosén, Z. Physik A 316, 157-160 (1984)

## 80 mercury

Investigated transitions: Hg I $\lambda$ = 253.65 nm $6s^2\ {}^1S_0$ - $6s6p\ {}^3P_1$

Hg I $\lambda$ = 546.07 nm $6s6p\ {}^3P_2$ - $6s7s\ {}^3S_1$

$M_{253.7,ME}$ = 648.3(1 ± 0.5)  $\gamma \cdot E_i$ = -0.7020  $f(Z)^{181}$ = 72.08 GHz fm$^{-2}$

$f(Z)^{206}$ = 70.91 GHz fm$^{-2}$

80 mercury (continued)

| A | $\delta\nu_{obs}$ / MHz ; ref. λ = 253.7 nm | | | average | $\delta\nu_{obs}$ / MHz λ = 546.1 nm |
|---|---|---|---|---|---|
| 181 | 5560(200)l | | | | |
| 182 | | | | | 5890(17)p* |
| 183 | 3310(100)l | | | | |
| 184 | 27720(90)m | | | | 4932(14)p |
| 185 | 3710(30)m | | | | |
| 185m | 27770(110)m | | | | |
| 186 | 24060(70)m | | | | 4285(11)p |
| 187 | 22420(200)m | | | | |
| 187m | 23970(120)n | | | | |
| 188 | 20420(80)m | | | | 3629(10)p |
| 189 | 19620(120)m | | | | |
| 189m | 20050(60)n | | | | |
| 190 | 16560(80)m | | | | 2925(7)p |
| 191 | 15710(70)m | | | | |
| 191m | 15690(60)n | | | | |
| 192 | 12400(300)j | 13220(600)f | 12620(150)g | 12610(220) | 2203(7)p |
| 193 | 11480(210)i | 12350(150)g | | 12060(580) | |
| 193m | 11090(120)n | 11030(180)f | 11630(240)g | 11150(120) | |
| 194 | 8400(380)c | 8510(210)f | | 8480(180) | 1471(5)p |
| 195 | 6420(190)c | 6420(240)f | 6330(150)g | 6370(110) | |
| 195m | 6670(110)n | 6560(150)f | 7110(150)g | 6760(270) | |
| 196 | 4110(120)b | | | | 740(4)p |
| 197 | 2730(150)b | | | | |
| 197m | 2200(110)n | 2100(210)a | | 2180(100) | |
| 198 | 0 | 0 | 0 | 0 | 0 |
| 199 | -651.4(6.3)d | | | | -90(30)r |
| 199m | -3190(150)n | | | | |
| 200 | -4805.3(4.5)d | | | | -840(30)r |
| 201 | -6409.5(5.7)d | | | | -1110(30)r |
| 202 | -10101.7(4.5)d | | | | -1769(30)r |
| 203 | -11750(180)q | | | | |
| 204 | -15312.4(12.9)d | | | | -2671(30)r |
| 205 | -17090(100)l | | | | |
| 206 | -20420(80)m | | | | |

80 mercury (continued)

| A | $\lambda^{198,A}$ 253.7 nm | A | $\lambda^{198,A}$ 253.7 nm | A | $\lambda^{198,A}$ 253.7 nm |
|---|---|---|---|---|---|
| 181 | -0.1166(50) | 190 | -0.3329(21) | 197m | -0.0443(22) |
| 183 | -0.0712(33) | 191 | -0.3157(18) | 198 | 0 |
| 184 | -0.5565(31) | 191m | -0.3153(17) | 199 | 0.0134(2) |
| 185 | -0.0784(24) | 192 | -0.2494(61) | 199m | 0.0641(30) |
| 185m | -0.5573(32) | 193 | -0.2308(43) | 200 | 0.0968(3) |
| 186 | -0.4832(25) | 193m | -0.2230(25) | 201 | 0.1292(5) |
| 187 | -0.4504(44) | 194 | -0.1690(76) | 202 | 0.2034(7) |
| 187m | -0.4812(31) | 195 | -0.1292(38) | 203 | 0.2369(37) |
| 188 | -0.4103(24) | 195m | -0.1342(23) | 204 | 0.3086(10) |
| 189 | -0.3941(29) | 196 | -0.0828(24) | 205 | 0.3446(23) |
| 189m | -0.4027(20) | 197 | -0.0549(30) | 206 | 0.4117(20) |

Much work on iss in the intercombination line has been done, in stable isotopes as well as in radioactives. That is why many slightly different factors for the calculation of the nuclear parameter λ can be found in literature. For a detailed discussion see ref. t). The values used for the table (given in the heading) are similar to those in ref. t) with the exception of f(Z).

*The $\delta\nu_{obs}$-values from ref. p) (λ = 546.1 nm) are preliminary.

Ref. a) A. C. Melissinos et al., Phys. Rev. 115, 130-137 (1959)
b) A. C. Melissinos, Phys. Rev. 115, 126-129 (1959)
c) H. Kleiman et al., J. Opt. Soc. Am. 53, 822-827 (1963)
d) W. G. Schweitzer jr., J. Opt. Soc. Am. 53, 1055-1072 (1963)
e) O. Redi et al., Phys. Lett. 8, 257-259 (1964)
f) W. J. Tomlinson III et al., Nucl. Phys. 60, 614-633 (1964)
g) S. P. Davis et al., Phys. Rev. 147, 861-866 (1966)
h) J. Bonn et al., J. Phys. Soc. Jap. Suppl. 34, 317-323 (1973)
i) G. F. Fülöp et al., Phys. Rev. A 9, 593-605 (1974)
j) G. Huber et al., Z. Physik A 272, 381-385 (1975)
k) J. M. Rodriquez et al., Z. Physik A 272, 369-374 (1975)
l) J. Bonn et al., Z. Physik A 276, 203 (1976)
m) P. Dabkiewicz et al., J. Phys. Soc. Jap. Suppl. 44, 503-508 (1978); P. Dabkiewicz, Thesis Mainz 1980
n) P. Dabkiewicz et al., Phys. Lett. B 82, 199-203 (1979)

80 mercury (continued)

p) R. Neugart, private communication 1984; preliminary values

q) O. Redi et al., Phys. Rev. A 9, 1776 (1974) and J. Opt. Soc. Am. 65, 1-5 (1975)

r) J. Blaise et al., J. Phys. Rad. 18, 193-200 (1957)

t) W. H. King "Iss in Atomic Spectra", Physics of Atoms and Molecules (P. G. Burke, H. Kleinpoppen eds.) Plenum Press New York and London 1984

## 82 lead

Investigated transition: Pb I $\lambda$ = 283.3 nm $6p^2\ ^3P_0 - 6p^7s\ ^3P_1$

$M_i$ = 576(5760) GHz $F_i$ = 22.1(3.3) GHz $fm^{-2}$ $\lambda = 0.93\ \delta\langle r^2\rangle$

| A | $\delta\nu_{obs}$ / MHz ref. a) | ref. b) | ref. c) | $\delta\langle r^2\rangle$ / $fm^2$ |
|---|---|---|---|---|
| 196 | | | -11441(30) | -0.572(17) |
| 197 | | | -11402(19) | -0.609(10) |
| 197m | | | -10827(17) | -0.555(2) |
| 198 | | -9848.4(5.0) | | -0.527(12) |
| 199 | | -9748.0(9.0) | | -0.5175(54) |
| 200 | | -8094.1(3.5) | | -0.4320(72) |
| 201 | | -7727.6(5.0) | | -0.4094(41) |
| 202 | | -6193.7(3.5) | | -0.3298(44) |
| 202m | | -6230.4(5.0) | | -0.3316(42) |
| 203 | | -5749.0(5.0) | | -0.3033(35) |
| 204 | -4257(9) | -4212.0(2.5) | | -0.2237(25) |
| 205 | | -3712.6(3.0) | | -0.1946(40) |
| 206 | -2233(18) | -2226.6(2.5) | | -0.1176(13) |
| 207 | -1397(18) | -1390.9(2.5) | | -0.0723(25) |
| 208 | 0 | 0 | 0 | 0 |
| 209 | | 1767(10) | | 0.0905(52) |
| 210 | | 3973.7(3.5) | | 0.202(14) |
| 212 | | 7815(30) | | 0.399(27) |
| 214 | | | 11500(99) | 0.586(39) |

82 lead (continued)

The evaluation follows the very detailed discussion (including results from combined analyses of electron scattering and muonic x-ray transitions) in ref. b).

Ref. a) F. A. Moscatelli et al., J. Opt. Soc. Am. 72, 918-922 (1982)
b) R. C. Thompson et al., J. Phys. G 9, 443-458 (1983)
c) M. Anselment et al., Ann. Rep. Nucl. Phys. Act. KfK 3621, p. 63 (1983)

## 87 francium

Investigated transitions: Fr I ref. a) $\lambda$ = 717.9716(1) nm $D_2$
ref. b) $\lambda$ = 816.9418(1) nm $D_1$
$\lambda$ = 422.5656(1) nm 7s $^2S_{1/2}$-8p $^2P_{3/2}$

| A | $\delta\nu_{obs}$ / MHz | | |
|---|---|---|---|
| | $D_2$ | $D_1$ | $\lambda$ = 422.6 nm |
| 208 | 6645.2(9.2) | | |
| 209 | 4771.4(7.5) | | |
| 210 | 4243.1(8.0) | 2449.0(20.1) | |
| 211 | 2533.7(8.0) | | |
| 212 | 1628.3(7.5) | 0 | 0 |
| 213 | 0 | | -1614.4(4.0) |
| 220 | | | -23751.0(6.2) |
| 221 | | | -23298.7(4.4) |

Isotopes measured recently: 207, 222, ..., 228. The data analysis is in progress.

Ref. a) S. Liberman et al., Phys. Rev. A 22, 2732-2737 (1980)
b) F. Touchard et al., 7th Int. Conf. At. Mass. and Fund. Const., Darmstadt-Seeheim, FRG, Sept. 1984

88 radium preliminary values

Investigated transition: Ra I $\lambda$ = 482.59 nm $7s^2\ ^1S_0$ - $7s7p\ ^1P_1$
Ra II $\lambda$ = 468.22 nm $D_1$

$M_{D1,ME}$ = 456.6 GHz $E_i\ (D_1)$ = -0.3591 $f(Z)^{208}$ = 126.67 GHz $fm^{-2}$
$\beta\ (D_1)$ = 1.13 $f(Z)^{232}$ = 124.51 GHz $fm^{-2}$

| A | $\delta\nu_{obs}$ / MHz Ra II | Ra I $D_1$ | $\lambda^{214,A}$ from $D_1$ |
|---|---|---|---|
| 208 | 8485(8) | 11950(9) | -0.2342(8) |
| 210 | 6003(6) | 8449(7) | -0.1657(6) |
| 211 | 5522(4) | 7770(4) | -0.1523(4) |
| 212 | 3256(3) | 4583(4) | -0.0899(3) |
| 213 | 2167(3) | 3049(4) | -0.0598(2) |
| 214 | 0 | 0 | 0 |
| 220 | -21904(8) | -30808(14) | 0.6045(8) |
| 221 | -25945(8) | -36496(14) | 0.7164(10) |
| 222 | -28827(8) | -40552(14) | 0.7963(11) |
| 223 | -32453(9) | -45657(16) | 0.8969(12) |
| 224 | -35123(9) | -49411(17) | 0.9710(13) |
| 225 | -38888(10) | -54710(18) | 1.0755(15) |
| 226 | -41124(11) | -57852(18) | 1.1377(16) |
| 227 | -43937(13) | -61811(19) | 1.2160(17) |
| 228 | -46950(12) | -66050(10) | 1.2998(18) |
| 229 | -50066(15) | -70432(22) | 1.3865(20) |
| 230 | -53634(15) | -75456(25) | 1.4859(21) |
| 232 | -59585(19) | | 1.6519(26)* |

*This value was interpolated from $\delta\nu_{obs,Ra\ II}$. $\lambda$ or $\delta\langle r^2\rangle$ are not yet finally evaluated; see ref. a).

Ref. a) R. Neugart, private communication 1984; S. A. Ahmad et al., to be published in Nucl. Phys.
b) S. A. Ahmad et al., Phys. Lett. 133 B, 47-52 (1983)

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