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A consistent set of nuclear rms charge radii: properties of the radius surface $R(N,Z)$☆

I. Angeli*

Institute of Experimental Physics, University of Debrecen, H-4010 Debrecen, Pf. 81, Hungary

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Abstract

A set of 799 ground state nuclear charge radii is presented. Experimental data from elastic electron scattering, muonic atom X-rays, K_α isotope shifts, and optical isotope shifts have been taken into account that were available up to January 2004. Wherever possible, connections and constraints between the data were applied to make the data system consistent. Based on the resulting data set, the smooth global structure of the radius surface $R(N,Z)$ was investigated by fitting simple empirical functions to the intersections with constant Z and N as well as with constant A plains. The simple behavior of the surface rendered it possible to apply a simple model, the two-liquid drop model to reproduce the main tendencies, and to predict the existence of a indentation along the line of stability on the radius surface. This indentation suggests a decrease of average nucleon density away from stability. The fine structure in the mass number dependence of rms charge radii is briefly presented.

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* Fax: +36-52-315-087.

E-mail address: angeli@tigris.unideb.hu.

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Contents

Tables

1. Introduction

The rms charge radius $\langle r^2\rangle^{1/2}$ is a fundamental property of the atomic nucleus. It can be measured by two experimental methods: electron scattering (e^-) and muonic atom X-rays (μ^-), while the difference $\delta_{1,2}\langle r^2\rangle \equiv \langle r^2\rangle_{A2} - \langle r^2\rangle_{A1}$ between two isotopes of the same element is determined by the K_α isotope shift ($K_\alpha IS$) and by the isotope shift of optical spectrum lines (*OIS*). Early compilations [1–8] contained separate tables of results from the four different methods. It is of importance to derive radius values using the results of all experimental methods. This is also for the benefit of data users, who generally prefer a single, unified data set to several separate tables.

In 1994, a compilation of rms charge radii was published [9] comprising 523 ground state and 75 isomer radius data for isotopes of 42 elements. It was followed by another compilation [10], where the main emphasis was laid on the simultaneous evaluation of two experimental methods: $e^- + \mu^-$. Moreover, for nine elements results from three methods were taken into account: $e^- + \mu^- + OIS$. In addition, this compilation contained an updated table of radius differences from $K_\alpha IS$. Since then, several experimental results have been published mainly containing $\delta\langle r^2\rangle$ values from *OIS* along isotopic series.

Table 1 of the present paper contains rms radius data for 799 isotopes of 91 elements making use of results from the four methods: $e^- + \mu^- + K_\alpha IS + OIS$. Wherever possible, advantage was taken of constraints between directly measured radii and differences. Often, easy-to-use radius formulae with limited number of parameters are required, for example, for the extrapolation of the radius surface $R(N,Z)$ or $R(A,I)$ to unknown regions. In order to facilitate the global description of the smooth surface, simple empirical formulae were fitted to the resulting radius data (see Section 3 and Tables 2 and 3). These formulae may be useful to estimate the values of unmeasured radii, and especially in extrapolating charge radius values for nuclei far from the valley of stability or to perform analytic calculations with the continuous function $R(N,Z)$. A simple two-component liquid-drop model is applied for the interpretation of the empirical results. Finally, in Section 4 a short survey on the fine structure is given.

2. Sources and treatment of data

First, $\langle r^2\rangle^{1/2}$ data were obtained from e^- and μ^- measurements (from now on, the shorthand notation $R \equiv \langle r^2\rangle^{1/2}$ is used). Then, differences δR between non-isotope pairs were taken into account. These improve

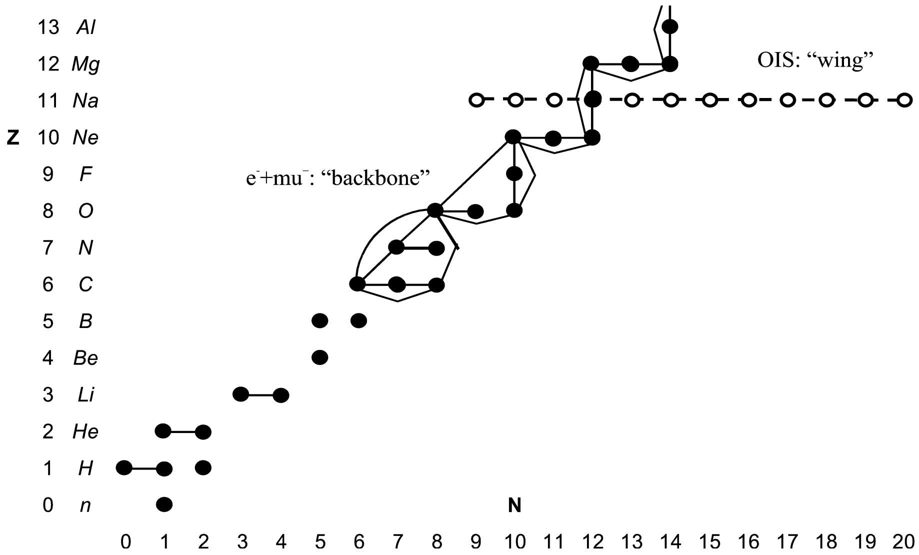

Fig. 1. Illustration of measured quantities and the links between them. Filled circles denote experimental rms radius data, continuous lines mark radius differences measured by electron scattering or muonic atom X-rays. These links are used as constraints to improve the input data and to search for inconsistencies (see Section 2). Broken lines denote differences from optical isotope shifts.

the links between different isotopic series, helping the study of isotonic and isobaric behavior. Then isotopic differences δR measured by e^- and μ^- were taken into account, followed by δR from $K_\alpha IS$. Finally, δR values from *OIS* are included in two steps: (1) differences between isotopes for which there exist data from the previous steps; these altogether form a backbone for the data system in the (N, Z) plot, Fig. 1, and (2) the remaining differences δR constitute the wings that are adjusted to the backbone. Some details of this multi-step task have been published in previous papers, which will be cited in the respective sections (Table 4).

2.1. rms radii from e^- and μ^-

In addition to the compilations, original papers and personal communications have also been taken into account up to January 2004. Of outstanding importance is the compilation [10]. It contains precise rms radius data evaluated model independently by combining e^-, μ^-, and *OIS*. The sources and treatment of data have been described in [11,12] together with a list of the references, e^-: 316, μ^-: 145. Therefore, this pre-1999 reference list for e^-, μ^- is not repeated here.

At this point, some remarks on the radius data for the proton and deuteron are appropriate. Worldwide data on elastic (el) electron–proton scattering have been re-analyzed taking into account corrections for Coulomb distortion and higher moments, resulting in an rms charge radius $R_{\mathrm{p,el}} = 0.895(18)$ fm [13]. The evaluation of high accuracy data of the *1S* Lamb shift (LS) in hydrogen yielded $R_{p,LS} = 0.883(14)$ fm [14]. The weighted average (av) of these two independent data is $R_{\mathrm{p,av}} = 0.887(11)$ fm. For the deuteron, the analysis of world data on electron scattering resulted in $R_{\mathrm{d,el}} = 2.130(12)$ fm [15]. From the measurement of the hydrogen–deuterium isotope shift, the difference of deuteron–proton rms charge radii have been derived: $R_{\mathrm{d}}^2 - R_{\mathrm{p}}^2 = 3.8212(15)\,\mathrm{fm}^2$ [16]. Using this as a constraint between $R_{\mathrm{p,av}}$ and $R_{\mathrm{d,el}}$ in a weighted least-squares adjustment procedure, we have $R_{\mathrm{p}} = 0.8791(88)$ fm and $R_{\mathrm{d}} = 2.1402(91)$ fm as listed in Table 1.

The final database selected contains 460 radius values (from the 1367 data published) for 285 nuclides. In some cases, the error estimates did not contain all components of uncertainty, e.g., model dependence, nuclear polarization correction, etc. In these cases a further error component was added, estimated after reading the respective literature. Quite often, there are several measured radius values for the same nucleus. To find the average value R_{av} and its uncertainty ΔR_{av} of a data group, two different methods were used, an iteration procedure and a single-step one [11]. The results are more sensitive to the decision of which data are included in the procedure, and less sensitive to the way in which the individual data are weighted to form an average. The resulting data system contains 285 isotopes of 85 elements.

2.2. Differences of rms radii from e^- and μ^- (not isotopes)

There are 94 data for 91 pairs of nuclei [7,10,17–20]; some data are from e^-, others from μ^-, while most of them result from a simultaneous evaluation $e^- + \mu^-$. Results of μ^- measurements are often published as Barrett moment [21] differences δR_{B}. Then the relationship [22]

$$\delta R = v(Z)\sqrt{\frac{3}{5}}\delta R_{\mathrm{B}}, \quad v(Z) = 1 + 0.0035 \times \ln(0.22 \times Z + 1) \tag{1}$$

was applied to derive the rms radius difference δR, where $Z = (Z_1 + Z_2)/2$. In the deformed region the coefficient $v(Z)$ is somewhat modified: $v(Z)_{\mathrm{def}} = v(Z) + 0.00054 \times \min(Z - 60, 77 - Z)$.

2.3. Application of constraints

In several cases, there are redundant, independently measured differences in a group of δR data, that is, in addition to $\delta R_{12}(\pm\Delta\delta R_{12})$ and $\delta R_{23}(\pm\Delta\delta R_{23})$ the radius difference $\delta R_{13}(\pm\Delta\delta R_{13})$ is also measured, e.g., ^{12}C–^{14}N, ^{14}N–^{16}O, and ^{12}C–^{16}O. In these cases the relation $\delta R^0_{13} = \delta R^0_{12} + \delta R^0_{23}$ between the true values δR^0_{ik} can be exploited to improve the accuracy. To do this, the method of weighted least-squares was used. This also made it possible to check the internal consistency of the data group by a χ^2/n' test. The new errors are less than the original ones, being always the least precise measurement that benefits most of the constraint. Some μ^- data groups have already been conditioned during the evaluation of the experiment and so published. Naturally, for these groups the above procedure was not applied. Constraints of the type $R^0_2 = R^0_1 + \delta R^0_{12}$ were also applied.

2.4. Radius differences between isotopes from e^- and μ^-

The main source for δR data between isotopes from electron scattering was the compilation [7], but original papers were also taken into account. There are altogether 88 δR values for 66 isotope pairs. From multiple data a weighted average was formed. For δR values from muonic X-rays the main source was [10], but results from original papers were also included. Resulting in altogether 195 data for 184 isotope pairs. Most of these data are Barrett differences, so they had to be transformed to rms differences making use of Eq. (1).

2.5. Radius differences between isotopes from K_α isotope shifts

Most of the 89 $K_\alpha IS$ data are from Table II of [10], which is an extended version of [2]. Original papers have also been taken into account [23–25]. Two modifications were performed in Table II of [10]: (1) for uranium the correct mass interval is $^{233-238}$U instead of $^{235-238}$U, see [26] and (2) regarding the results of a χ^2/n' test [27], the shift for $^{121-123}$Sb [28] was omitted and some error estimates increased. In the tables energy shifts δE_{Coul} are given, which can be expressed in terms of even moments of the charge distribution: $\delta E_{\mathrm{Coul}} = C_1\lambda$, where the nuclear parameter

$$\lambda = \delta\langle r^2\rangle + \frac{C_2}{C_1}\delta\langle r^4\rangle + \frac{C_3}{C_1}\delta\langle r^6\rangle + \cdots \tag{2}$$

contains information on the size of the nucleus. Seltzer [29] calculated the coefficients C_1, C_2, and C_3. The ratios C_2/C_1 and C_3/C_1 have also been calculated by [30,31]. Dividing the measured energy shift δE_{Coul} by C_1, one arrives at λ that contains the rms radius difference. Although a plot of λ_{KIS} from $K_\alpha IS$ against $\lambda_{e\mu}$ values formed from e^- and μ^- shows a linear correlation for three isotope pairs of Pb (Fig. 1 of [10]), the validity of $C_1(Z)$ has not been tested experimentally for a wide range of atomic numbers. By 2000, the wealth of δR data from e^- and μ^- experiments made it possible to compare the C_1 value to experiment. In [27] 54 energy shifts δE_{Coul} of 18 elements and the respective radius differences δR from e^- and μ^- are used to determine the experimental coefficients $C_{1,\mathrm{exp}} = \delta E_{\mathrm{Coul}}/\lambda_{e\mu}$ in the atomic number interval $Z = 42$–92. These experimental coefficients were then compared to the theoretically calculated C_1 values by a $\chi^2(f)$ minimization analysis, where $C_{1,\mathrm{exp}} = f \times C_1$. The result is $f = 0.965(14)$, i.e., the experimental $C_{1,\mathrm{exp}}$ values are, on the average, 3.5% lower than those calculated by Seltzer. It would be most desirable to have a new, more recent calculation of the momentum coefficients C_1, C_2, and C_3 with up-to-date theoretical methods.

Applying now the modified Seltzer coefficients $C'_1 = f \cdot C_1$ $(f = 0.965)$, we have the modified nuclear parameter $\lambda' = \lambda/f$, from which the difference of mean square radii can be determined by a rapidly converging iteration procedure. Starting with $\delta\langle r^2\rangle_0 = \lambda'$,

$$\begin{aligned}\delta\langle r^2\rangle_{i+1} = \lambda' &- \frac{C_2}{C_1}\left[a_4\left(\delta\langle r^2\rangle_i\right)^2 + b_4\delta\langle r^2\rangle_i\right] \\ &- \frac{C_3}{C_1}\left[a_6\left(\delta\langle r^2\rangle_i\right)^3 + b_6\left(\delta\langle r^2\rangle_i\right)^2 + c_6\delta\langle r^2\rangle_i\right],\end{aligned} \tag{3}$$

where

$$a_4 \equiv \frac{25}{14}\left(\frac{A_2 + A_1}{A_2 - A_1}\right), \quad b_4 \equiv \frac{30}{7}(\pi a)^2,$$

$$a_6 \equiv \frac{125}{48}\left(\frac{A_2 + A_1}{A_2 - A_1}\right)^2, \quad b_6 \equiv \frac{275}{18}(\pi a)^2\left(\frac{A_2 + A_1}{A_2 - A_1}\right),$$

$$c_6 \equiv \frac{239}{9}(\pi a)^4$$

refer to a Fermi distribution with a constant surface diffuseness $a = t/(4\ln 3)$ and a mass number dependence $c = r_0 A^{1/3}$ for the half-density radius c. Note that the value of c and r_0 does not appear in the expressions.

2.6. Radius differences from optical isotope shifts

The sources of λ or $\delta\langle r^2\rangle$ data published before 1989 are the compilations [6,8]. More recent results are taken from original papers, they are listed among the references. Not all of the data are included in the table. Preference was given to long, recently measured isotopic series. Sometimes, however, results from two different measurements had to be merged. Wherever possible, relative (experimental) and total (experimental + systematic) errors were separately treated. This is because the main motivation of the present work was the investigation of the radius surface $R(N,Z)$. This necessitates the knowledge of absolute radii R. The procedure for the determination of λ and $\delta\langle r^2\rangle$ values from the measured $\delta\nu$ frequency shifts is described in detail in [6,10,32], together with the limitations of the procedure. Here only the main steps will be recalled. The isotope shift consists of a mass shift and a field (or volume) shift: $\delta\nu = \delta\nu_{MS} + \delta\nu_{FS}$. The latter term can be written in the form $\delta\nu_{FS} = F\lambda$, where the nuclear parameter λ has the same form as in the case of $K_\alpha IS$ (Eq. (2)). Although the values of $C_{i,\mathrm{Opt}}$ for optical transitions are an order of magnitude less than those $C_{i,K}$ for K_α, the corresponding ratios are practically equal: $C_{2,\mathrm{Opt}}/C_{1,\mathrm{Opt}} \approx C_{2,K}/C_{1,K}$ and $C_{3,\mathrm{Opt}}/C_{1,\mathrm{Opt}} \approx C_{3,K}/C_{1,K}$. Therefore, the iteration procedure described above can be utilized for those *OIS* results, where only λ values are given. In [8] and in some recent papers the measurements have already been evaluated by the so-called two-parameter model [33,34]. These $\delta\langle r^2\rangle$ values were accepted without changes. A comparison of the two procedures (Table I of [35]) shows that the results are close to each other, the difference being an order of magnitude less than the total error. Radius differences $\delta R \equiv \delta\langle r^2\rangle^{1/2}$ were calculated from $\delta\langle r^2\rangle$ by the relation $\delta R = \delta\langle r^2\rangle/(R_1 + R_2)$. For nuclei where no data for R_1 and R_2 existed, but there were R values for the neighbors on both sides, linear interpolation was used to estimate the missing radius. In the case of isotopic chains, the relation [36,37]

$$R(A) = R(A_0) \times \left(\frac{A}{A_0}\right)^{1/5} \tag{4}$$

was applied for extrapolation from the stable nucleus with mass number A_0. For the elements Re, Po, Rn, Fr, Ra, and Cm there are no measured R values. In these cases, $R(A_0)$ was estimated by the expression [38]

$$R(A_0) = \left(r_0 + \frac{r_1}{A_0^{2/3}} + \frac{r_2}{A_0^{4/3}}\right) \times A_0^{1/3} \tag{5}$$

with $r_0 = 0.891(2)\,\mathrm{fm}$, $r_1 = 1.52(3)\,\mathrm{fm}$, and $r_2 = -2.8(1)\,\mathrm{fm}$. Note that these elements are used in Section 3 only for the investigation of relative $R_Z(N)$ dependence, but they were omitted while investigating the $R_\mathrm{N}(Z)$ and $R_A(I)$ dependence, which necessitated the knowledge of absolute R values.

2.7. Adjusting OIS to $e^- + \mu^- + K_\alpha IS$

The systematic errors arising from specific mass shift and electron factors can be reduced if δR values from other experimental methods are also available. Therefore, weighted averages $\delta R_{e\mu KO}$ were formed. In doing this, total errors $\Delta\delta R_{O,\mathrm{tot}}$ were used. The uncertainty $\Delta\delta R_{e\mu KO}$ is significantly less than the original $\Delta\delta R_{O,\mathrm{tot}}$. The reduction varies from element to element between 0.2 and 0.6. Using these improved rms differences $\delta R_{e\mu KO}$ and the respective absolute $R_{e\mu}$ radii, 32 data triplets $(2R, 1\delta R)$ and 63 quintets $(3R, 2\delta R)$ could be formed, and the respective constraints applied. This further improved the accuracy and rendered it possible to correct three inconsistencies. As a result, we have R and δR values that contain in a consistent way all of the experimental information from the four methods. These nuclei constitute the backbone along the valley of stability, onto which the wings, the isotopic series of δR values from *OIS*, will be fitted.

2.8. Fitting δR_{OIS} series to the backbone

As described in the foregoing, $\delta R_{e\mu KO}$ values were formed for those isotope pairs for which at least two of the four methods were available. Relating the $\delta R_{e\mu KO}$ differences to those measured by *OIS*, correction factors $\delta R_{e\mu KO}/\delta R_{OIS}$ were formed, their values varied between 0.9 and 1.3. These factors were used to correct those δR_{OIS} differences for which only *OIS* measurements were available, thus correcting for the eventual common systematic error factor. The corrected δR_{OIS} differences, i.e., the wings were added to the respective backbone R values obtained in the previous paragraph. In this way a set of rms charge radii was obtained, displayed in Table 1. As the correction factor has the same value for the element, this correction does not change the relative trend of $R_Z(N)$ isotopic dependence. However, it improves the absolute R values, which are important for the investigation of the radius surface $R(N,Z)$.

3. Properties of the radius surface $R(N,Z)$

The set of data in Table 1 allows one to investigate the properties of the radius surface $R(N,Z)$ or $R(A,I)$. It is practical to consider this complicated set of points as the superposition of two structures: a smooth, slowly varying surface describing the global or rough structure, and a fine structure having valleys near magic nucleon numbers and mountains at deformations; odd–even staggering is also observed. The shell and deformation dependence has long been investigated [9,37,39–42]. On the other hand, the slow variations almost escaped attention, in spite of the fact that it may be a useful tool for extrapolation of R values to the limits of nucleon stability.

3.1. Global behavior of the radius surface along the valley of stability

First, following tradition, the mass number dependence along the valley of stability is examined using 299 isotopes of 74 elements. The radius parameter r_{LD} of the well-known liquid-drop (LD) model [43]

$$R_{\mathrm{LD}} = r_{\mathrm{LD}} A^{1/3} \tag{6}$$

was determined by a minimum-χ^2 procedure. The result is shown in Table 2 together with the standard deviation and the reduced χ^2 value χ^2/n'. It is interesting to see that the purely empirical function

$$R_e = r_e A^e \tag{7}$$

has its best fit with an exponent value $e = 0.294(1)$, which significantly differs from 1/3. Taking into account the finite surface thickness, Elton [44] derived a three-parameter formula

$$R_s = \left(r_0 + \frac{r_1}{A^{2/3}} + \frac{r_2}{A^{4/3}}\right) \times A^{1/3}, \tag{8}$$

which yields a better fit to the data. During the work it was found that the parameters r_1 and r_2 are strongly anticorrelated, which can be described by the simple linear relation $r_2 \approx -(1.4r_1 - 1)$. Hence, there remain only two free parameters in Eq. (8).

3.2. Intersections of the radius surface

The properties of the radius surface can be investigated by studying its different intersections by planes perpendicular to the (N, Z) plane, namely the $R_Z(N)$, $R_{\mathrm{N}}(Z)$, and $R_A(I)$ dependencies. As the latter is redundant information, its result can be used to apply a constraint with the former two. Finally, the direction $\Delta Z/\Delta N$, for which $R(N, Z) \approx$ constant, is determined. For isotopic chains the radius formula

$$R_Z(N) = R_0\left(\frac{A}{A_0}\right)^{k_Z}, \quad A = A_0 + \Delta N \tag{9}$$

was applied, where R_0 is the rms charge radius of the reference isotope (Z, A_0). Results of a weighted least-squares fit (k_Z, standard deviation (SD) and χ^2/n') are indicated in Table 3 under the column "From experiment." The procedure was also performed separately for proton-rich and neutron-rich nuclei. The Z-dependence along isotonic series was investigated by fitting the formula

$$R_{\mathrm{N}}(Z) = R_0\left(\frac{A}{A_0}\right)^{k_{\mathrm{N}}}, \quad A = A_0 + \Delta Z. \tag{10}$$

The resulting value of the parameter k_{N} is shown in Table 3. The simplified neutron and proton number dependence is illustrated schematically in Fig. 2, using rounded values of the exponents. It follows that the smooth component of the radius surface, around the nuclid $A_0 = Z_0 + N_0$, can be described by

$$R(N, Z) = R_0\left(\frac{Z_0 + N}{A_0}\right)^{k_Z}\left(\frac{Z + N}{Z_0 + N}\right)^{k_{\mathrm{N}}} \approx R_0\left(1 + \frac{\Delta N}{A_0}\right)^{k_Z}\left(1 + \frac{\Delta Z}{A_0}\right)^{k_{\mathrm{N}}}, \tag{11}$$

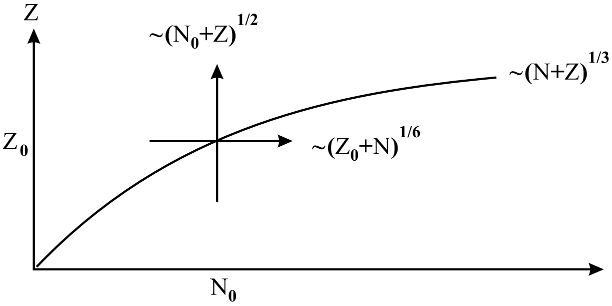

Fig. 2. Schematic illustration of the smooth radius surface $R(N, Z)$ around a reference nuclide $R(N_0, Z_0)$ (see Eqs. (9) and (10)). The exponents are rounded values of the empirical parameters shown in Table 3.

where $R_0 \equiv R(N_0, Z_0)$, $\Delta Z \equiv Z - Z_0$, and $\Delta N \equiv N - N_0 \ll N$.

Next, referring to Fig. 3, the surface $R(N, Z)$ can be represented by the level lines corresponding to rms radii with intervals $\Delta R = 0.5$ fm (Fig. 3B). For comparison, contour lines of the liquid-drop formula, Eq. (6) are plotted in Fig. 3A.

Along isobaric series the dependence of rms radii on the symmetry parameter $I \equiv (N - Z)/A$ was studied by

$$R_A(I) = R_0[1 + f(I - I_0)], \quad I_0 \equiv (N_0 - Z_0)/A. \tag{12}$$

The results for f are also shown in Table 3. They are close to those published earlier [45,46]. The search for the level lines $R(N, Z) =$ constant was performed considering a formula similar to those above

$$R_L(\Delta N, \Delta Z) = R_0\left(\frac{A}{A_0}\right)^{k_{\mathrm{CR}}} \tag{13}$$

(k_{CR} is the parameter for constant radius) but it was used in a different way; during the fits the $|k_{\mathrm{CR}}| \approx 0$ value was sought by choosing different directions in the (N, Z) plane. A direction can be characterized by the slope $\Delta Z/\Delta N$, and also by the value of the invariant L. For example, nuclei on the line with slope $(\Delta Z/\Delta N) = -(1/3)$ are characterized by $L = 3Z + N =$ constant as ${}^{20}_{11}\mathrm{N}$–${}^{22}_{10}\mathrm{Ne}$. This means that, on the average, a decrease of rms charge radius caused by picking out a proton from the nucleus can be compensated by adding three neutrons to it.

3.3. Application of constraints between the empirical parameters

Having these experimental parameters, their values can be improved by using the relations between them.

1. Starting from $A_0 = N_0 + Z_0$ one can arrive at the isobar $A = N + Z = A_0$ by the isotopic chain of element Z_0 through $A_1(N, Z_0)$ followed by the isotonic series containing N neutrons. Alternatively, one can step directly from (N_0, Z_0) to (N, Z) by varying the symmetry

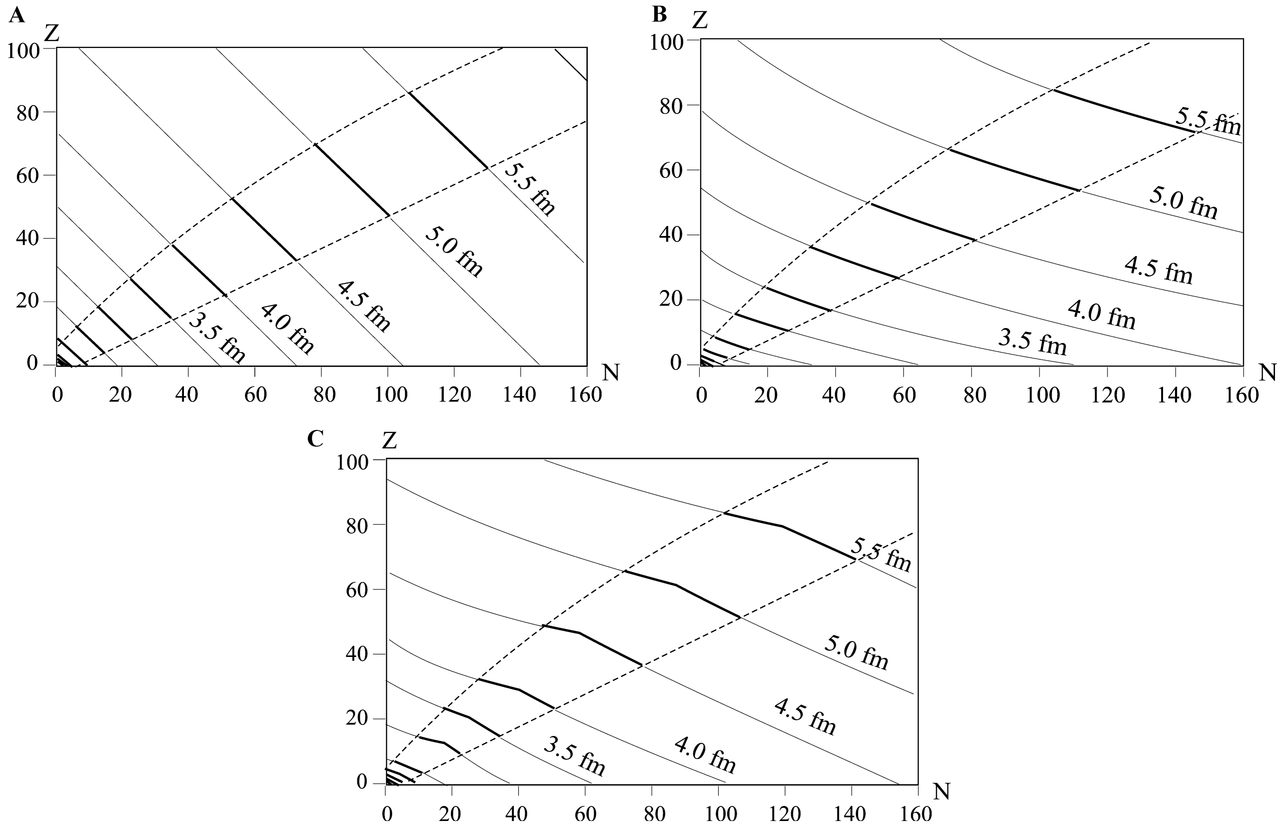

Fig. 3. (A) Level lines of the surface described by the liquid-drop model, Eq. (6) of Section 3. Broken lines show the region of nucleon stability. (B) Level lines of the surface described by the empirical formulae Eqs. (9) and (10) in Section 3. The slope −0.33 means that a decrease in R caused by removing a proton from the nucleus can be compensated by adding three neutrons to it. Broken lines show the region of nucleon stability. (C) Same as (B) but with separate parameter values for proton-rich and for neutron-rich nuclei (see Table 3). The indentation on the radius surface along the line of stability is clearly seen (see also Section 3).

parameter I. It can be shown that the relation for the true values of the parameters

$$f^0 \approx \frac{1}{2}(k_Z^0 - k_N^0) \tag{14}$$

is valid to a good approximation. The systematic error of this approximation ($\leqslant 1\%$) is much less than the experimental uncertainties of the parameters. The results for k_Z, k_N, and f derived by this constraint are shown in the last column of Table 3.

2. It can also be shown that for nuclei along iso-radius series ($R \approx$ constant) the ratio $-k_Z/k_N$ is close to the slope $\Delta Z/\Delta N$. Therefore, this ratio can be regarded as an independent estimation of the slope. Here, the systematic error of the approximation ($\sim 10\%$) is about the same size as the experimental one. This is taken into account by choosing the weights accordingly. Then the weighted average of $-k_Z/k_N$ and $\Delta Z/\Delta N$ was formed. These are shown for $\Delta Z/\Delta N$ in the last column of Table 3.

3.4. The two-liquid drop model

The smooth behavior of the radius surface renders its interpretation possible by a simple model, which is a simple extension of the traditional liquid-drop approach. Here only the main characteristics and results are described and details will be published elsewhere. The model works with uniform density distributions (by sections) for protons and neutrons separately. Their sum $\rho_0 = \rho_P + \rho_N$ is assumed constant within a radius $R_0 = (3A/4\pi\rho_0)^{1/3}$. In the calculations an average nucleon density $\rho_0 = 0.128\,\mathrm{n/fm^{-3}}$ was used, as obtained from fitting the liquid-drop formula (6) to stable nuclei. (The value $\rho_{0,F} \approx 0.17\,\mathrm{n/fm^{-3}}$, as often found in the literature, refers to the maximum density of a Fermi-like distribution fitted to measurements on the heaviest nuclei [44, p. 50].) It is assumed that in stable nuclei $\rho_{P,st}$ and $\rho_{N,st}$ both extend to R_0. Away from stability the extension and ratio of ρ_P and ρ_N are different. In proton-rich nuclei there is a proton skin from R_N to R_0; in neutron-rich nuclei there is a neutron skin from R_p to R_0. In the case of tin isotopes, rms radius values calculated by the model and by Eq. (9) are close to each other, the standard deviation being SD $= 0.004$ fm. The skin thickness formed by the majority nucleons depends almost linearly on $\mathrm{d}A \equiv A - A_{\mathrm{stab}}$: $\mathrm{d}R = 0.008 \times \mathrm{d}A$. Here the skin thickness $\mathrm{d}R$ is defined naturally as the difference between the radius parameters of the model, while most experiments generally yield the difference of rms neutron and proton radii. For uniform density distributions with radius difference dR_{np} the simple relation holds: $d\langle r^2\rangle_{np}^{1/2} = \sqrt{3/5}\,dR_{np}$. It should be noted that in the present simple form of the model it was postulated that at the line of stability the proton and neutron densities have the same radius, the skin thickness vanishes. This may not be true. There is evidence for a finite neutron skin, e.g. [47].

Small differences between the model and the empirical formula (9) suggested that different values for the empirical parameters should be used for proton-rich and neutron-rich nuclei, respectively. Results of these parameter searches are shown in Table 3. The level lines of the surface $R(N,Z)$ calculated with these parameters are plotted in Fig. 3C. It seems that there is an indentation in the radius surface along the stability line.

A possible interpretation for the indentation may be a decrease in ρ_0 as one moves away from the line of stability. Assuming a linear dependence on $|I - I_{st}|$, the nuclear density $\rho_0 = \rho_{0,st}(1 + g|I - I_{st}|)$ was introduced into the model by varying the value of the parameter g, so that the minimum SD was searched. In the case of the $Z = 50$ isotopic series the result is $g = -0.12$ (SD = 0.0021). That is, going away from the line of stability to $|I - I_{st}| = 0.1$, e.g., from $A = 118$ to 105, the density ρ_0 decreases by 1%.

4. Fine structure in the charge radii

Along the valley of stability radii of nuclei near or at magic nucleon numbers are significantly less than the average trend, while they deviate upwards in between. These deviations can be described by the nucleonic promiscuity factor [48] $P \equiv N_p N_n/(N_p + N_n)$ in the formula [45]

$$\begin{aligned} R_P &= R_{0,P} + dR_P \\ &= \left(r_{0,P} + \frac{r_{1,P}}{A^{2/3}} + \frac{r_{2,P}}{A^{4/3}}\right) \times A^{1/3} + a\frac{P}{R_{0,P}} \qquad (15) \end{aligned}$$

where $R_{0,P}$ is the radius for closed-shell nuclei, while N_p and N_n are numbers of valence protons and neutrons (or holes), respectively. Values of the parameters $r_{0,P}$, $r_{1,P}$, $r_{2,P}$, and a are shown in Table 2. For the calculation of the factor P the following magic numbers produced the best fit: $Z_M = 2, 6, 14, 28, 50, 82, (114)$, and $N_M = 2, 8, 14, 28, 50, 82, 126, (184)$. It should be noted that in other investigations [42,49,50], too, the irregular magic numbers 6 and 14 proved to be present. Other semi-magic proton and neutron numbers at $Z_M = 40$, 64 and $N_M = 56$ [51] were also tested in several combinations but without positive result. The parameters of the formula vary somewhat with mass number; therefore, the parameter set for light nuclei ^{9}Be–^{27}Al is separately given in Table 2.

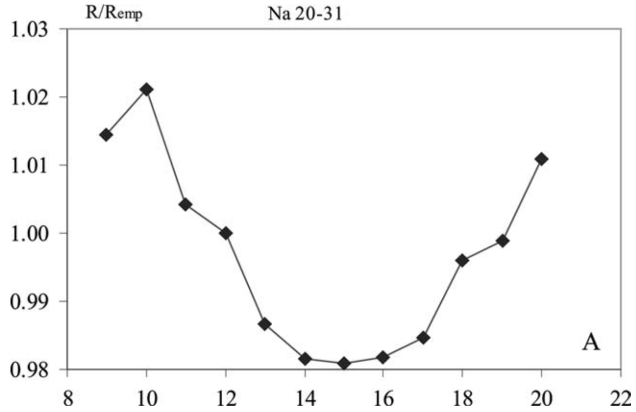

Fig. 4. R/R_{emp} values for sodium isotopes. R, Experimental rms charge radii from [52]; R_{emp}, radii calculated by the empirical formula Eq. (9) in Section 3.

Along isotopic series the smooth function $R(N,Z)$ may be used to divide the individual experimental R values. The resulting R/R_{emp} values (where R_{emp} is the value of the smooth empirical function for the given nucleus) along isotopic series follow nearly the same systematics as observed earlier [9,37,39–42], showing pronounced shell effects for neutron numbers $N = 28$, 50, 82, and 126. In the case of light nuclei $N \sim 14$–16 they seem to have magic character (see Fig. 4 regarding experimental data from [52]). (Figures for other elements can be obtained from the author.) A sudden increase at the transitional region $N \sim 88$–90 can also be clearly observed. Isotonic series are less accurate, but the main shell effects at $Z = 28$, 50, and 82 are clearly noticeable.

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Explanation of Tables

Table 1. Nuclear rms charge radii

Z	Atomic (proton) number of the element
El	Chemical symbol of the element
(El)	For six elements, designated by parentheses (El) there are only δR measurements; the reference R_0 values were estimated by Eq. (5)
A	Mass number of the isotope
R (fm)	$\equiv \langle r^2 \rangle^{1/2}$. Experimental root-mean-square charge radius in $\mathrm{fm} = 10^{-15}$ m. For the neutron $\langle r^2 \rangle$ is given in fm^2. For the proton, see also paragraph 3 in Section 2.
$\Delta_{\mathrm{tot}}R$ (fm)	Total error of R, including both experimental and systematic errors, in $\mathrm{fm} = 10^{-15}$ m. See Section 2
$\Delta_{\mathrm{rel}}R$ (fm)	Relative error of R with respect to the radius of the reference isotope; in $\mathrm{fm} = 10^{-15}$ m. See Section 2

Table 2. Parameters of radius formulae for nuclei near the stability line

Model	Model underlying the radius formula
Equation	Number of the equation of the radius formula in Section 1
Parameters	Best-fit parameter values of the formula
St. Dev. (fm)	Standard deviation of the experimental data from the formula
χ^2/n'	Reduced χ^2 value

Table 3. Empirical parameters characterizing the radius surface $R(N, Z)$

Equation	Number of the empirical formula
Parameter	Parameter of the formula
Region	Region of nuclei where the fit was performed
From experiment	Result of the best-fit procedure to the experimental data
St. Dev. (fm)	Standard deviation of the experimental data from the formula
χ^2/n'	Reduced χ^2 value
With constraint	Parameter values improved by the constraints, see Eq. (14) in Section 3.

Table 4. Annotated references for the Introduction and for the Tables

Table 1
Nuclear rms charge radii. (For the neutron the entry is $\langle r^2 \rangle$ (fm^2) and for the proton and deuteron, see Section 2.) See page 194 for Explanation of Tables

Z	El	A	R (fm)	$\Delta_{\rm tot}R$ (fm)	$\Delta_{\rm rel}R$ (fm)
0	n	1	−0.1149	.0024	
1	H	1	0.8791	.0088	
		2	2.1402	.0091	
		3	1.7591	.0356	
2	He	3	1.9448	.0137	
		4	1.6757	.0026	
3	Li	6	2.5385	.0267	
		7	2.4312	.0281	
4	Be	9	2.5180	.0114	
5	B	10	2.4278	.0492	
		11	2.4059	.0291	
6	C	12	2.4703	.0022	
		13	2.4614	.0033	
		14	2.5037	.0081	
7	N	14	2.5579	.0068	
		15	2.6061	.0074	
8	O	16	2.7013	.0055	
		17	2.6953	.0073	
		18	2.7745	.0058	
9	F	19	2.8976	.0024	
10	Ne	17	3.0428	.0188	.0135
		18	2.9719	.0084	.0048
		19	3.0081	.0053	.0033
		20	3.0053	.0021	
		21	2.9672	.0026	
		22	2.9541	.0019	
		23	2.9126	.0105	.0057
		24	2.9032	.0104	.0044
		25	2.9305	.0133	.0069
		26	2.9268	.0153	.0081
		28	2.9632	.0245	.0159
11	Na	20	2.9716	.0424	.0119
		21	3.0138	.0287	.0084
		22	2.9852	.0169	.0067
		23	2.9936	.0021	
		24	2.9736	.0168	.0067
		25	2.9770	.0249	.0050
		26	2.9928	.0327	.0030
		27	3.0133	.0461	.0066
		28	3.0394	.0573	.0082
		29	3.0915	.0718	.0131
		30	3.1172	.0878	.0195
		31	3.1702	.0891	.0113
12	Mg	24	3.0568	.0017	
		25	3.0280	.0021	
		26	3.0334	.0020	
13	Al	27	3.0605	.0040	
14	Si	28	3.1223	.0024	
		29	3.1168	.0050	
		30	3.1332	.0040	
15	P	31	3.1888	.0018	
16	S	32	3.2608	.0018	
		34	3.2845	.0021	
		36	3.2982	.0021	
17	Cl	35	3.3652	.0145	
		37	3.3840	.0170	
18	Ar	32	3.3462	.0103	.0057
		33	3.3434	.0076	.0031
		34	3.3649	.0043	.0009
		35	3.3632	.0066	.0039
		36	3.3902	.0020	.0006
		37	3.3901	.0028	.0013
		38	3.4020	.0017	
		39	3.4085	.0105	.0099
		40	3.4269	.0017	.0006
		46	3.4363	.0068	.0032
19	K	38	3.4262	.0067	.0057
		39	3.4346	.0017	
		40	3.4378	.0027	.0003
		41	3.4514	.0030	.0004
		42	3.4512	.0074	.0020
		43	3.4551	.0089	.0013
		44	3.4558	.0104	.0014
		45	3.4599	.0121	.0017
		46	3.4552	.0129	.0016
		47	3.4529	.0141	.0017
20	Ca	**40**	3.4764	.0010	
		41	3.4768	.0011	.0004
		42	3.5063	.0010	.0007
		43	3.4928	.0008	.0005
		44	3.5155	.0009	.0009
		45	3.4931	.0015	.0008
		46	3.4925	.0009	.0007
		47	3.4771	.0022	.0019
		48	3.4738	.0009	.0009
		50	3.5145	.0072	.0049
21	Sc	45	3.5443	.0023	
22	Ti	46	3.6052	.0016	.0008
		47	3.5944	.0018	.0009
		48	3.5912	.0017	
		49	3.5735	.0018	
		50	3.5704	.0016	
23	V	51	3.5994	.0022	
24	Cr	50	3.6604	.0022	
		52	3.6424	.0021	
		53	3.6588	.0021	
		54	3.6866	.0017	
25	Mn	55	3.7057	.0022	
26	Fe	54	3.6931	.0018	
		56	3.7371	.0015	
		57	3.7534	.0017	
		58	3.7748	.0014	
27	Co	59	3.7875	.0021	
28	Ni	58	3.7748	.0014	
		60	3.8119	.0014	
		61	3.8221	.0017	
		62	3.8406	.0016	
		64	3.8587	.0017	
29	Cu	63	3.8823	.0017	
		65	3.9022	.0017	
30	Zn	64	3.9286	.0014	
		66	3.9496	.0013	
		68	3.9665	.0014	
		70	3.9845	.0019	
31	Ga	69	3.9973	.0017	
		71	4.0118	.0018	
32	Ge	70	4.0414	.0012	
		72	4.0577	.0012	
		73	4.0634	.0014	
		74	4.0744	.0012	
		76	4.0812	.0012	
33	As	75	4.0969	.0019	
34	Se	74	4.0700	.0200	
		76	4.1397	.0016	
		77	4.1397	.0017	

Table 1 (*continued*)

Z	El	A	R (fm)	$\Delta_{tot}R$ (fm)	$\Delta_{rel}R$ (fm)
		78	4.1407	.0018	
		80	4.1399	.0019	
		82	4.1399	.0020	
35	Br	79	4.1630	.0021	
		81	4.1599	.0021	
36	Kr	72	4.1635	.0071	.0022
		74	4.1871	.0040	.0006
		75	4.2097	.0041	.0008
		76	4.2020	.0034	.0005
		77	4.2082	.0035	.0006
		78	4.2032	.0016	.0004
		79	4.2034	.0029	.0005
		80	4.1976	.0013	.0008
		81	4.1953	.0021	.0005
		82	4.1922	.0015	.0004
		83	4.1860	.0018	.0004
		84	4.1882	.0014	.0001
		85	4.1846	.0014	.0005
		86	4.1836	.0012	
		87	4.1986	.0021	.0004
		88	4.2174	.0040	.0005
		89	4.2290	.0052	.0005
		90	4.2428	.0070	.0012
		91	4.2549	.0080	.0007
		92	4.2732	.0099	.0006
		93	4.2802	.0106	.0005
		94	4.3014	.0128	.0005
		95	4.3078	.0135	.0004
		96	4.3282	.0160	.0012
37	Rb	76	4.2289	.0092	.0033
		77	4.2380	.0084	.0008
		78	4.2410	.0084	.0004
		79	4.2303	.0066	.0003
		80	4.2287	.0065	.0008
		81	4.2225	.0051	.0003
		82	4.2164	.0044	.0008
		83	4.2057	.0026	.0002
		84	4.1992	.0022	.0004
		85	4.2031	.0018	.0003
		86	4.2019	.0020	.0004
		87	4.1981	.0017	
		88	4.2178	.0039	.0010
		89	4.2419	.0073	.0004
		90	4.2599	.0103	.0010
		91	4.2783	.0132	.0007
		92	4.2983	.0164	.0010
		93	4.3135	.0189	.0010
		94	4.3287	.0214	.0011
		95	4.3517	.0251	.0013
		96	4.3637	.0271	.0014
		97	4.4458	.0404	.0021
		98	4.4577	.0424	.0022
38	Sr	78	4.2550	.0040	.0010
		79	4.2577	.0052	.0007
		80	4.2550	.0048	.0008
		81	4.2534	.0041	.0007
		82	4.2457	.0037	.0007
		83	4.2432	.0030	.0005
		84	4.2364	.0017	.0004
		85	4.2267	.0015	.0004
		86	4.2263	.0011	.0002
		87	4.2197	.0009	.0002
		88	4.2198	.0010	
		89	4.2380	.0017	.0001

Table 1 (*continued*)

Z	El	A	R (fm)	$\Delta_{tot}R$ (fm)	$\Delta_{rel}R$ (fm)
		90	4.2606	.0034	.0005
		91	4.2747	.0043	.0004
		92	4.2949	.0059	.0006
		93	4.3062	.0067	.0005
		94	4.3244	.0081	.0007
		95	4.3370	.0090	.0006
		96	4.3612	.0108	.0007
		97	4.3725	.0117	.0009
		98	4.4578	.0178	.0008
		99	4.4710	.0189	.0010
		100	4.4874	.0206	.0019
39	Y	89	4.2417	.0020	
40	Zr	87	4.2820	.0014	.0005
		88	4.2812	.0013	.0005
		89	4.2715	.0011	.0006
		90	4.2696	.0008	
		91	4.2844	.0010	
		92	4.3057	.0009	
		94	4.3312	.0009	
		96	4.3498	.0011	
		97	4.3933	.0091	.0006
		98	4.4185	.0109	.0006
		99	4.4349	.0121	.0006
		100	4.5220	.0184	.0005
		101	4.5487	.0203	.0006
		102	4.5690	.0218	.0006
41	Nb	93	4.3241	.0015	
42	Mo	92	4.3156	.0011	
		94	4.3518	.0009	
		95	4.3617	.0009	
		96	4.3841	.0008	
		97	4.3877	.0008	
		98	4.4088	.0011	
		100	4.4458	.0013	
44	Ru	96	4.3927	.0047	
		98	4.4232	.0055	
		99	4.4346	.0042	
		100	4.4536	.0031	
		101	4.4616	.0020	
		102	4.4818	.0018	
		104	4.5104	.0020	
45	Rh	103	4.4942	.0023	
46	Pd	102	4.4839	.0044	
		104	4.5086	.0025	
		105	4.5158	.0025	
		106	4.5322	.0028	
		108	4.5563	.0028	
		110	4.5776	.0031	
47	Ag	101	4.4712	.0093	.0003
		103	4.4976	.0070	.0002
		104	4.5069	.0062	.0002
		105	4.5237	.0049	.0002
		107	4.5442	.0035	.0001
		109	4.5647	.0029	
48	Cd	102	4.4704	.0095	.0047
		103	4.4860	.0088	.0045
		104	4.5052	.0088	.0051
		105	4.5157	.0071	.0037
		106	4.5340	.0045	.00004
		107	4.5438	.0057	.0032
		108	4.5538	.0045	.00003
		109	4.5590	.0063	.0044
		110	4.5743	.0025	.00002
		111	4.5798	.0022	.00002

Table 1 (*continued*)

Z	El	*A*	*R* (fm)	$\Delta_{tot}R$ (fm)	$\Delta_{rel}R$ (fm)
		112	4.5950	.0020	
		113	4.6006	.0020	.00002
		114	4.6137	.0019	
		115	4.6170	.0054	.0049
		116	4.6284	.0021	.00002
		118	4.6316	.0037	.0024
		120	4.6379	.0059	.0045
49	In	104	4.5168	.0119	.0016
		105	4.5298	.0105	.0015
		106	4.5364	.0096	.0013
		107	4.5487	.0082	.0011
		108	4.5566	.0071	.0005
		109	4.5684	.0061	.0008
		110	4.5742	.0056	.0009
		111	4.5859	.0043	.0005
		112	4.5911	.0039	.0007
		113	4.6018	.0025	.00003
		114	4.6066	.0027	.0002
		115	4.6169	.0024	
		116	4.6225	.0024	.0001
		117	4.6308	.0030	.0004
		118	4.6353	.0031	.0002
		119	4.6427	.0038	.0004
		120	4.6464	.0040	.0002
		121	4.6527	.0046	.0003
		122	4.6557	.0050	.0004
		123	4.6619	.0055	.0003
		124	4.6650	.0060	.0006
		125	4.6696	.0063	.0005
		126	4.6728	.0068	.0008
		127	4.6761	.0071	.0008
50	Sn	108	4.5607	.0027	.0004
		109	4.5690	.0025	.0004
		110	4.5807	.0064	.0003
		111	4.5859	.0061	.0003
		112	4.5943	.0018	.0002
		113	4.6038	.0047	.0001
		114	4.6103	.0017	.0003
		115	4.6167	.0038	.0001
		116	4.6266	.0015	
		117	4.6318	.0012	.0001
		118	4.6413	.0011	.0001
		119	4.6450	.0010	.0001
		120	4.6543	.0009	.0002
		121	4.6589	.0013	.0001
		122	4.6657	.0010	.0003
		123	4.6684	.0020	.0001
		124	4.6759	.0012	.0004
		125	4.6779	.0027	.0003
51	Sb	121	4.6802	.0023	
		123	4.6879	.0021	
52	Te	122	4.7084	.0021	
		123	4.7111	.0023	
		124	4.7178	.0017	
		125	4.7198	.0018	
		126	4.7269	.0021	
		128	4.7353	.0025	
		130	4.7426	.0025	
53	I	127	4.7500	.0038	
54	Xe	116	4.7113	.0084	.0010
		118	4.7318	.0073	.0007
		120	4.7461	.0066	.0007
		122	4.7555	.0061	.0006
		124	4.7621	.0046	.0005

Table 1 (*continued*)

Z	El	*A*	*R* (fm)	$\Delta_{tot}R$ (fm)	$\Delta_{rel}R$ (fm)
		126	4.7703	.0048	.0007
		128	4.7755	.0048	.0004
		129	4.7762	.0047	.0001
		130	4.7832	.0046	.0003
		131	4.7812	.0046	.0001
		132	4.7866	.0047	.0002
		134	4.7921	.0047	.0001
		136	4.7991	.0047	
		137	4.8143	.0048	.0003
		138	4.8359	.0054	.0003
		139	4.8511	.0060	.0006
		140	4.8694	.0067	.0002
		141	4.8845	.0075	.0004
		142	4.9016	.0086	.0009
		143	4.9137	.0092	.0004
		144	4.9300	.0102	.0005
		146	4.9575	.0119	.0005
55	Cs	118	4.7834	.0092	.0002
		119	4.7898	.0090	.0006
		120	4.7916	.0076	.0001
		121	4.7773	.0078	.0001
		122	4.7776	.0070	.0002
		123	4.7823	.0070	.0001
		124	4.7831	.0062	.0001
		125	4.7882	.0062	.0001
		126	4.7875	.0056	.0001
		127	4.7938	.0055	.0001
		128	4.7923	.0052	.00004
		129	4.7982	.0051	.0001
		130	4.7993	.0049	.0001
		131	4.8026	.0047	.0001
		132	4.8003	.0046	.0001
		133	4.8041	.0046	
		134	4.8031	.0046	.0001
		135	4.8067	.0047	.0001
		136	4.8058	.0052	.0001
		137	4.8126	.0050	.0001
		138	4.8251	.0050	.0001
		139	4.8414	.0069	.0001
		140	4.8545	.0088	.0001
		141	4.8678	.0109	.0002
		142	4.8812	.0132	.0001
		143	4.8950	.0151	.0002
		144	4.9039	.0162	.0002
		145	4.9171	.0191	.0002
		146	4.9263	.0193	.0003
56	Ba	120	4.8088	.0057	.0002
		121	4.8176	.0052	.0002
		122	4.8154	.0053	.0003
		123	4.8136	.0055	.0003
		124	4.8187	.0051	.0002
		125	4.8179	.0052	.0002
		126	4.8225	.0049	.0002
		127	4.8207	.0050	.0002
		128	4.8260	.0047	.0001
		129	4.8252	.0048	.0001
		130	4.8288	.0047	.0001
		131	4.8281	.0047	.0001
		132	4.8309	.0046	.0001
		133	4.8291	.0046	.0001
		134	4.8298	.0048	.0001
		135	4.8273	.0048	.0001
		136	4.8327	.0048	.0001
		137	4.8326	.0048	.0001

Table 1 (*continued*)

Z	El	A	R (fm)	$\Delta_{\text{tot}}R$ (fm)	$\Delta_{\text{rel}}R$ (fm)
		138	4.8385	.0045	
		139	4.8523	.0048	.0001
		140	4.8697	.0058	.0001
		141	4.8823	.0068	.0001
		142	4.8973	.0082	.0002
		143	4.9110	.0096	.0002
		144	4.9264	.0112	.0002
		145	4.9375	.0124	.0002
		146	4.9513	.0139	.0002
		148	4.9773	.0168	.0004
57	La	137	4.8492	.0060	.0029
		138	4.8464	.0053	.0011
		139	4.8549	.0049	
58	Ce	136	4.8737	.0017	.0002
		138	4.8735	.0017	.0002
		140	4.8770	.0017	
		142	4.9065	.0017	
		144	4.9308	.0024	.0002
		146	4.9602	.0028	.0002
		148	4.9911	.0035	.0002
59	Pr	141	4.8919	.0050	
60	Nd	132	4.9168	.0038	.0029
		134	4.9123	.0031	.0020
		135	4.9080	.0040	.0032
		136	4.9106	.0035	.0026
		137	4.9075	.0029	.0015
		138	4.9124	.0031	.0020
		139	4.9071	.0028	.0013
		140	4.9095	.0035	.0025
		141	4.9052	.0028	.0013
		142	4.9118	.0024	
		143	4.9231	.0024	.0005
		144	4.9409	.0029	.0003
		145	4.9536	.0054	.0005
		146	4.9686	.0027	.0004
		148	4.9986	.0019	.0004
		150	5.0415	.0021	.0005
62	Sm	138	4.9528	.0063	.0011
		139	4.9480	.0063	.0011
		140	4.9491	.0063	.0011
		141	4.9396	.0065	.0018
		142	4.9438	.0063	.0009
		143	4.9396	.0063	.0011
		144	4.9445	.0062	
		145	4.9584	.0063	.0007
		146	4.9746	.0065	.0010
		147	4.9839	.0010	
		148	5.0009	.0016	
		149	5.0108	.0010	
		150	5.0400	.0011	
		151	5.0544	.0093	
		152	5.0842	.0055	
		153	5.0940	.0084	
		154	5.1112	.0058	
63	Eu	138	4.9850	.0175	.0057
		139	4.9792	.0167	.0033
		140	4.9716	.0163	.0012
		141	4.9718	.0162	.0009
		142	4.9628	.0163	.0010
		143	4.9656	.0162	.0005
		144	4.9632	.0162	.0006
		145	4.9682	.0162	—
		146	4.9807	.0164	.0009
		147	4.9954	.0170	.0017

Table 1 (*continued*)

Z	El	A	R (fm)	$\Delta_{\text{tot}}R$ (fm)	$\Delta_{\text{rel}}R$ (fm)
		148	5.0059	.0176	.0024
		149	5.0215	.0190	.0033
		150	5.0308	.0199	.0039
		151	5.0534	.0041	
		152	5.1075	.0302	.0080
		153	5.1127	.0037	
		154	5.1213	.0317	.0063
		155	5.1200	.0314	.0060
		156	5.1236	.0320	.0063
		157	5.1348	.0146	.0006
		158	5.1408	.0155	.0006
		159	5.1493	.0169	.0007
64	Gd	146	4.9760	.0134	
		152	5.0819	.0030	.0001
		154	5.1253	.0017	
		155	5.1346	.0016	.00003
		156	5.1458	.0014	.0001
		157	5.1492	.0014	.0001
		158	5.1617	.0018	.0001
		160	5.1776	.0020	.0001
65	Tb	147	4.9211	.1508	.0033
		148	4.9299	.1507	.0030
		149	4.9429	.1506	.0027
		150	4.9502	.1505	.0026
		151	4.9633	.1504	.0023
		152	4.9691	.1504	.0021
		153	4.9950	.1502	.0016
		154	5.0336	.1501	.0019
		155	5.0391	.1500	.0010
		157	5.0487	.1500	.0009
		159	5.0600	.1500	
66	Dy	146	5.0522	.2030	.0002
		148	5.0538	.2030	—
		149	5.0642	.2035	.0012
		150	5.0772	.2057	.0024
		151	5.0860	.2081	.0034
		152	5.1000	.2133	.0049
		153	5.1079	.2171	.0058
		154	5.1272	.2283	.0078
		155	5.1475	.2428	.0097
		156	5.1630	.2556	.0117
		157	5.1712	.2628	.0126
		158	5.1812	.2720	.0136
		159	5.1820	.2728	.0136
		160	5.1938	.2843	.0146
		161	5.1965	.0061	
		162	5.2068	.0027	
		163	5.2091	.0025	
		164	5.2207	.0024	
67	Ho	151	5.0454	.0349	.0011
		152	5.0660	.0339	.0009
		153	5.0791	.0334	.0009
		154	5.0893	.0329	.0006
		155	5.1104	.0322	.0005
		156	5.1145	.0322	.0006
		157	5.1549	.0312	.0003
		158	5.1584	.0312	.0004
		159	5.1684	.0310	.0002
		160	5.1672	.0310	.0003
		161	5.1791	.0309	.0002
		162	5.1823	.0309	.0007
		163	5.1909	.0308	.0006
		165	5.2022	.0308	
68	Er	**150**	5.0388	.0287	—

Table 1 (*continued*)

Z	El	*A*	*R* (fm)	$\Delta_{\mathrm{tot}}R$ (fm)	$\Delta_{\mathrm{rel}}R$ (fm)
		152	5.0707	.0291	.0024
		154	5.1016	.0303	.0048
		156	5.1344	.0322	.0074
		158	5.1707	.0353	.0106
		160	5.2019	.0380	.0126
		162	5.2242	.0042	
		164	5.2375	.0037	
		166	5.2505	.0031	
		167	5.2547	.0031	
		168	5.2673	.0037	
		170	5.2857	.0043	
69	Tm	156	5.1018	.0134	.0006
		157	5.1146	.0074	.0009
		158	5.1239	.0069	.0007
		159	5.1396	.0060	.0004
		160	5.1507	.0055	.0004
		161	5.1619	.0050	.0003
		162	5.1715	.0048	.0005
		163	5.1851	.0042	.0002
		164	5.1908	.0042	.0006
		165	5.2006	.0038	.0002
		166	5.2047	.0038	.0003
		167	5.2130	.0036	.0003
		168	5.2171	.0036	.0004
		169	5.2256	.0035	
		170	5.2304	.0036	.0005
		171	5.2387	.0037	.0006
		172	5.2408	.0052	.0030
70	Yb	152	5.0303	.0136	.0058
		154	5.0790	.0132	.0056
		156	5.1158	.0130	.0055
		158	5.1427	.0091	.0006
		160	5.1721	.0079	.0004
		161	5.1832	.0075	.0003
		162	5.2005	.0069	.0003
		163	5.2112	.0066	.0002
		164	5.2269	.0063	.0003
		165	5.2364	.0061	.0002
		166	5.2496	.0059	.0001
		167	5.2595	.0059	.00005
		168	5.2678	.0059	—
		170	5.2830	.0058	.0001
		171	5.2891	.0060	.0001
		172	5.2978	.0053	.0002
		173	5.3041	.0046	.0002
		174	5.3115	.0057	.0003
		176	5.3228	.0069	.0003
71	Lu	161	5.2313	.0112	.0006
		162	5.2416	.0102	.0005
		163	5.2582	.0087	.0004
		164	5.2690	.0077	.0004
		165	5.2841	.0064	.0003
		166	5.2981	.0053	.0002
		167	5.3115	.0044	.0002
		168	5.3233	.0038	.0001
		169	5.3294	.0036	.0001
		170	5.3368	.0302	—
		171	5.3439	.0302	.0001
		172	5.3488	.0302	.0001
		173	5.3578	.0303	.0001
		174	5.3635	.0303	.0001
		175	5.3700	.0300	.0002
		176	5.3738	.0304	.0002
		177	5.3812	.0305	.0002

Table 1 (*continued*)

Z	El	*A*	*R* (fm)	$\Delta_{\mathrm{tot}}R$ (fm)	$\Delta_{\mathrm{rel}}R$ (fm)
		178	5.3855	.0306	.0002
		179	5.3914	.0307	.0003
72	Hf	170	5.2876	.0056	.0007
		172	5.3047	.0043	.0005
		173	5.3123	.0039	.0004
		174	5.3185	.0035	.0003
		175	5.3175	.0037	.0011
		176	5.3305	.0037	.0002
		177	5.3331	.0038	.0001
		178	5.3356	.0031	
		179	5.3358	.0024	.0001
		180	5.3422	.0024	.0002
		182	5.3481	.0037	.0011
73	Ta	181	5.3507	.0034	
74	W	180	5.3493	.0023	.0008
		182	5.3566	.0017	
		183	5.3300	.1500	.0005
		184	5.3670	.0017	.0008
		186	5.3759	.0019	.0007
75	Re	**185**	5.3286	.0126	
		187	5.3386	.0127	.0009
76	Os	184	5.3820	.0023	.0010
		186	5.3908	.0016	
		187	5.3934	.0017	.0005
		188	5.3994	.0011	.0009
		189	5.3600	.1500	.0010
		190	5.4061	.0009	
		192	5.4127	.0011	
77	Ir	182	5.3809	.1061	.0006
		183	5.3857	.1061	.0005
		184	5.3881	.1061	.0005
		185	5.3899	.1061	.0005
		186	5.3943	.1061	.0005
		187	5.3881	.1061	.0005
		188	5.3890	.1061	.0005
		189	5.3938	.1061	.0005
		191	5.3981	.1061	
		193	5.4019	.1061	.0005
78	Pt	178	5.3721	.0070	.0015
		179	5.3915	.0055	.0020
		180	5.3890	.0051	.0010
		181	5.3998	.0044	.0014
		182	5.3971	.0043	.0009
		183	5.4033	.0037	.0007
		184	5.4028	.0037	.0006
		185	5.4155	.0029	.0006
		186	5.4046	.0039	.0011
		187	5.4074	.0041	.0019
		188	5.4059	.0035	.0007
		189	5.4068	.0037	.0012
		190	5.4117	.0032	.0007
		191	5.4110	.0032	.0007
		192	5.4181	.0029	.0009
		193	5.4201	.0027	.0006
		194	5.4247	.0025	
		195	5.4278	.0026	.0004
		196	5.4315	.0032	.0004
		198	5.4403	.0063	.0007
79	Au	183	5.3877	.0062	.0012
		184	5.4298	.0041	.0011
		185	5.4288	.0040	.0008
		186	5.4345	.0038	.0007
		187	5.4002	.0058	.0008
		188	5.4037	.0055	.0008

Table 1 (*continued*)

Z	El	A	R (fm)	$\Delta_{\mathrm{tot}}R$ (fm)	$\Delta_{\mathrm{rel}}R$ (fm)
		189	5.4072	.0051	.0006
		190	5.4095	.0049	.0006
		191	5.4134	.0046	.0005
		192	5.4166	.0044	.0005
		193	5.4213	.0042	.0004
		194	5.4239	.0040	.0002
		195	5.4284	.0040	.0006
		196	5.4318	.0038	.0004
		197	5.4358	.0037	
		198	5.4386	.0038	.0002
		199	5.4440	.0039	.0001
80	Hg	181	5.4373	.0032	.0003
		182	5.3844	.0053	.0003
		183	5.4415	.0031	.0003
		184	5.3946	.0047	.0003
		185	5.4406	.0031	.0003
		186	5.4014	.0044	.0003
		187	5.4046	.0043	.0003
		188	5.4083	.0041	.0003
		189	5.4098	.0040	.0003
		190	5.4157	.0038	.0003
		191	5.4171	.0037	.0003
		192	5.4233	.0035	.0003
		193	5.4239	.0035	.0003
		194	5.4311	.0033	.0003
		195	5.4347	.0032	.0003
		196	5.4388	.0032	.0003
		197	5.4415	.0031	.0003
		198	5.4466	.0031	
		199	5.4484	.0031	.0003
		200	5.4549	.0023	.0003
		201	5.4583	.0025	.0003
		202	5.4633	.0015	.0003
		203	5.4687	.0035	.0003
		204	5.4742	.0013	.0003
		205	5.4788	.0031	.0003
		206	5.4851	.0031	.0003
81	Tl	188	5.3985	.0092	.0015
		189	5.4235	.0063	.0007
		190	5.4088	.0081	.0013
		191	5.4138	.0070	.0003
		192	5.4161	.0073	.0012
		193	5.4302	.0058	.0008
		194	5.4233	.0065	.0010
		195	5.4303	.0055	.0003
		196	5.4304	.0058	.0009
		197	5.4370	.0048	.0002
		198	5.4376	.0048	.0001
		199	5.4466	.0040	.0001
		200	5.4477	.0039	.0001
		201	5.4564	.0034	.0003
		202	5.4587	.0033	.0003
		203	5.4664	.0026	.0002
		205	5.4763	.0026	
		207	5.4862	.0028	.0002
		208	5.4963	.0031	.0006
82	Pb	190	5.4210	.0026	.0011
		191	5.4217	.0026	.0011
		192	5.4287	.0025	.0011
		193	5.4298	.0022	.0007
		194	5.4359	.0022	.0009
		196	5.442	.0105	.0014
		197	5.4420	.0105	.0014
		198	5.4500	.0085	.0012

Table 1 (*continued*)

Z	El	A	R (fm)	$\Delta_{\mathrm{tot}}R$ (fm)	$\Delta_{\mathrm{rel}}R$ (fm)
		199	5.4500	.0085	.0012
		200	5.4590	.0075	.0010
		201	5.4610	.0075	.0009
		202	5.4690	.0055	.0007
		203	5.4710	.0055	.0007
		204	5.4794	.0008	.0005
		205	5.4820	.0035	.0005
		206	5.4897	.0007	.0003
		207	5.4942	.0013	.0002
		208	5.5010	.0009	
		209	5.5110	.0025	.0002
		210	5.5230	.0035	.0005
		211	5.5330	.0055	.0007
		212	5.5450	.0075	.0010
		214	5.5650	.0105	.0014
83	Bi	209	5.5211	.0026	
84	Po	200	5.4861	.0133	.0007
		202	5.4936	.0131	.0003
		204	5.5025	.0130	.0002
		205	5.5044	.0130	.0006
		206	5.5123	.0129	.0001
		207	5.5147	.0129	.0005
		208	5.5222	.0129	
		209	5.5264	.0129	.0004
		210	5.5336	.0129	.0003
86	Rn	202	5.5150	.0136	.0001
		204	5.5197	.0134	.00009
		205	5.5198	.0134	.00009
		206	5.5270	.0132	.00007
		207	5.5282	.0132	.00007
		208	5.5354	.0131	.00005
		209	5.5373	.0131	.00004
		210	5.5442	.0130	.00002
		211	5.5479	.0130	.00002
		212	5.5545	.0130	
		218	5.6172	.0144	.0001
		219	5.6280	.0149	.0001
		220	5.6363	.0153	.0001
		221	5.6467	.0159	.0002
		222	5.6549	.0164	.0002
87	Fr	207	5.5349	.0130	.00005
		208	5.5358	.0130	.00005
		209	5.5428	.0130	.00003
		210	5.5448	.0130	.00002
		211	5.5511	.0130	.00001
		212	5.5545	.0130	
		213	5.5606	.0130	.00002
		220	5.6320	.0130	.0001
		221	5.6422	.0131	.0002
		222	5.6523	.0131	.0002
		223	5.6584	.0131	.0002
		224	5.6695	.0132	.0002
		225	5.6747	.0132	.0003
		226	5.6825	.0132	.0003
		227	5.6972	.0133	.0003
		228	5.7036	.0133	.0003
88	Ra	208	5.5475	.0138	.0024
		209	5.5478	.0137	.0022
		210	5.5542	.0134	.0017
		211	5.5554	.0133	.0015
		212	5.5616	.0131	.0009
		213	5.5646	.0130	.0006
		214	5.5705	.0130	
		220	5.6311	.0178	.0062

Table 1 (*continued*)

Z	El	A	R (fm)	$\Delta_{tot}R$ (fm)	$\Delta_{rel}R$ (fm)
		221	5.6423	.0195	.0073
		222	5.6502	.0207	.0081
		223	5.6602	.0222	.0091
		224	5.6676	.0234	.0098
		225	5.6781	.0252	.0109
		226	5.6841	.0263	.0115
		227	5.6911	.0276	.0123
		228	5.7002	.0292	.0132
		229	5.7088	.0308	.0140
		230	5.7186	.0325	.0150
		232	5.7351	.0356	.0167
90	Th	227	5.6654	.0516	.0061
		228	5.6738	.0512	.0049
		229	5.6807	.0509	.0040
		230	5.6920	.0506	.0025
		232	5.7100	.0504	
92	U	233	5.8138	.0074	.0043
		234	5.8289	.0062	.0033
		235	5.8287	.0073	.0027
		236	5.8366	.0074	.0016
		238	5.8507	.0072	
94	Pu	238	5.8248	.0378	.0012
		239	5.8311	.0378	
		240	5.8407	.0379	.0016
		241	5.8451	.0379	.0019
		242	5.8523	.0380	.0024
		244	5.8643	.0382	.0032
95	Am	241	5.8929	.0035	
		243	5.9047	.0035	
96	Cm	242	5.7851	.0149	.0049
		244	5.7995	.0134	
		245	5.8040	.0135	.0010
		246	5.8127	.0138	.0020
		248	5.8252	.0149	.0040

Table 2
Parameters of radius formulae for nuclei near the stability line. See page 194 for Explanation of Tables

Model	Equation	Parameters	St. Dev. (fm)	χ^2/n'
Liquid drop	(6)	$r_{\mathrm{LD}} = 0.9542(13)$ fm	0.106	2894
Empirical exponent	(7)	$r_{\mathrm{e}} = 1.153(7)$ fm $e = 0.2938(12)$	0.05	669
Finite surface	(8)	$r_0 = 0.9071(13)$ fm $r_1 = 1.105(25)$ fm $[r_2 = -0.548(34)$ fm$]$	0.04	467
Finite surface + P	(15)	$r_{0,\mathrm{P}} = 0.8966(20)$ fm $r_{1,\mathrm{P}} = 1.128(35)$ fm $[r_{2,\mathrm{P}} = -0.58(05)$ fm$]$ $a = 0.0809(19)$ fm^2	0.023	167
Finite surface + P (light nuclei)	(15)	$r_{0,\mathrm{P}} = 0.982(10)$ fm $r_{1,\mathrm{P}} = 0.32(10)$ fm $[r_{2,\mathrm{P}} = +0.55(14)$ fm$]$ $a = 3.93(42)$ fm^2	0.034	93

Table 3
Empirical parameters characterizing the radius surface $R(N,Z)$. See page 194 for Explanation of Tables

Equation	Parameter	Region	From experiment	St. Dev. (fm)	χ^2/n'	With constraint
(9)	k_Z	All nuclids	0.149(15)	0.036	64	0.156(14)
		Proton-rich	0.131(25)	0.027	27	0.128(23)
		Neutron-rich	0.219(30)	0.025	35	0.240(27)
(10)	k_{N}	All nuclids	0.484(15)	0.027	29	0.478(14)
		Proton-rich	0.482(25)	0.027	23	0.485(23)
		Neutron-rich	0.484(30)	0.017	20	0.463(27)
(12)	f	All nuclids	−0.148(15)	0.032	38	−0.161(9)
		Proton-rich	−0.185(25)	0.027	17	−0.179(14)
		Neutron-rich	−0.070(30)	0.019	16	−0.112(17)
(13)	$\Delta Z/\Delta N$	All nuclids	−0.33(4)	0.035	34	−0.33(4)
		Proton-rich	−0.25(6)	0.029	18	−0.25(5)
		Neutron-rich	−0.67(10)	0.027	19	−0.62(8)

Table 4
Annotated references for the Introduction and for the Tables. See page 194 for Explanation of Tables

References for the Introduction		
Compilations		
An99	I.Angeli: *Table of Nuclear Root Mean Square Charge Radii,* INDC(HUN)-033, September 1999 (IAEA Nuclear Data Section, Vienna) Web: http://www-nds.iaea.or.at/indc-sel.html.	$e^- + \mu^-$, $e^- + \mu^- + OIS$,
Au87	P.Aufmuth, et al.: *At. Data Nucl. Data Tables*, **37** (1987) 455	OIS
Bo74	F.Boehm, and P.L.Lee: *At. Data Nucl. Data Tables*, **14** (1974) 605	$K_\alpha IS$
En74	R.Engfer, et al.: *At. Data Nucl. Data Tables*, **14** (1974) 509	μ^-
Fr95	G.Fricke, et al.: *At. Data Nucl. Data Tables*, **60** (1995) 177, Table V	Many; compilation.
He74	K.Heilig, and A.Steudel: *At. Data Nucl. Data Tables*, **14** (1974) 613	OIS
Ho67	R.Hofstadter, and H.R.Collard: *Landolt-Börnstein, New series, Group I.: Nuclear Physics and Technology*, **vol. 2**, Nuclear Radii, ed. H.Schopper, Springer-Verlag, Berlin (1967)	e^-, μ^-, $K_\alpha IS$, OIS
Ja74	C.W. deJager, et al: *At. Data Nucl. Data Tables*, **14** (1974) 479	e^-
Na94	E.G.Nadjakov, et al: *At. Data Nucl. Data Tables*, **56** (1994) 133	$e^- + \mu^- + OIS$
Ot89	E.W.Otten: in: *Treatise in Heavy-Ion Physics*, **Vol. 8** (1989) 604	OIS
Vr87	H.deVries, et al: *At. Data Nucl. Data Tables*, **36** (1987) 495	e^-
Other papers		
Ah85	S.A.Ahmad, et al.: *Z. Physik*, **A321** (1985) 35	Eu
Ah88	S.A.Ahmad, et al.: *Nucl. Phys.*, **A483** (1988) 244	Ra
An77	I.Angeli, and M.Csatlós: *Nucl. Phys.*, **A288** (1977) 480	Isotopic dependence $R_Z(N)$
An78	I.Angeli, and M.Csatlós: *ATOMKI Közlemények*, **20** (1978) 1	Isotonic, isobaric dep.
An91	I.Angeli: *J.Phys. G.: Nucl. Part. Phys.*, 17 (1991) 439	Fine structure in $R(A)$
An91a	I.Angeli: *Acta Phys. Hung.*, **69** (1991) 233	Compilation
An92	I.Angeli: *AMCO-9, 9th Conf. on Atomic Masses and Fundamental Constants*; July 19–24, 1992, Bernkastel-Kues	Mass number dependence $R(A_0)$
An00	I.Angeli: *Acta Phys. Hung. New Series: Heavy Ion Physics*, **13** (2001) 149	I-dependence
An01	I.Angeli: *Hyperfine Interactions*, **136** (2001) 17	$K_\alpha IS$: C_1
An02	I.Angeli: *Acta Phys. Hung. New Series: Heavy Ion Physics*, **15** (2002) 87	μ^-: Barrett mom.
An03	I.Angeli: *Acta Phys. Hung. New Series: Heavy Ion Physics*, **17** (2003) 3	OIS: eval.
Ba70	R.C.Barrett: *Physics Letters*, **B33** (1970) 388	Theory
Bl87	S.A.Blundell, et al: *J. Phys.*, **B20** (1987) 3663	$K_\alpha IS$, theory
Ca87	R.F.Casten, et al: *Phys. Rev. Lett.*, **58** (1987) 658	P-factor
El61	L.R.B.Elton: *Nuclear Sizes* (Oxford University Press, 1961)	Formula $R(A)$
Ga30	G.Gamow: *Proc. Roy. Soc. London*, **A216** (1930) 632	Formula $R(A)$
He87	K.Heilig: *Hyperfine Interactions*, **38** (1987) 803	Evaluation
He89	J.Herberz: *Ph.D. thesis*, *Univ. Mainz*, **KPH 6/89** (1989)	O, F, Na, Ne, Mg, Al, Si
Hu98	A.Huber, et al.: *Phys. Rev. Letters*, **80** (1998) 468	D
Kr99	A.Krasznahorkay, et al.: *Phys. Rev. Letters*, **82** (1999) 3216	Neutron skin
Me00	K.Melnikov, and T. van Ritbergen: *Phys. Rev. Lett.*, **84** (2002) 1673	H
My83	W.D.Myers, and K.H.Schmidt: Nucl. Phys., A410 (1983) 61	Formulae $R(N, Z)$
Sc69	J.P.Schiffer: *Physics Letters*, **29B** (1969) 399	Isotopic dependence $R_Z(N)$
Se69	E.C.Seltzer: *Phys. Rev.* **188** (1969) 1916	Theory: $C_{1,2,3}$ coeffs.
Si98	I.Sick, and D.Trautmann: *Nucl. Phys.*, **A637** (1998) 559	D
Si03	I.Sick: *Physics Letters*, **B576** (2003) 62	H
St66	D.N.Stacey: *Rep. Prog. Phys.*, **29** (1966) 171	Fine structure in $R_Z(N)$
To85	G.Torbohm, et al: *Phys. Rev.*, **A31** (1985) 2038	$K_\alpha IS$, theory
Un75	M.Uno, and M.Yamada: *Progr. Theor. Phys.*, **53** (1975) 987	Fine structure in E
Un81	M.Uno, and M.Yamada: *Progr. Theor. Phys.*, **65** (1981)1322	Fine structure in E
We85	E.Wesolowski: *J. Phys. G.: Nuc. Part.Phys.*, **11** (1985) 909	Formulae $R(NZ)$
Ze81	N.Zeldes: *Proc. 4th Int. Conf. on Nuclei Far From Stability*, Helsingor, Denmark, Eds. P.G.Hansen, and O.B.Nielsen, **Vol. I** (Geneva, CERN, 1981) p.93	
References for the Tables		
Differences between radii of neighboring nuclei (not isotopes) from electron scattering and muonic atom X-rays		
Fr92	G.Fricke, et al.: *Phys. Rev.* **C45** (1992) 80, Table III	O, F, Ne, Na, Mg, Al, Si
Fr95	G.Fricke, et al.: *At. Data Nucl. Data Tables*, **60** (1995) 177, Table VII	Many; compilation
He89	J.Herberz: *Ph.D. thesis*, *Univ. Mainz*, KPH **6/89** (1989)	O, F, Na, Ne, Mg, Al, Si
Vr87	H.de Vries, et al.: *At. Data Nucl. Data Tables*, **36** (1987) 495, Table III	Many; compilation.
Wo80	H.D.Wohlfahrt, et al.: *Phys. Rev.* **C22** (1980) 264	Ti, Cu Zn
Wo81	H.D.Wohlfahrt, et al.: *Phys. Rev.* **C23** (1981) 533, Table VI	K,Ca,Sc,Ti,V,Cr,Mn,Fe
Differences between radii of isotopes, from electron scattering		
Ja74	C.W.de Jager, et al.: *At. Data Nucl. Data Tables*, **14** (1974) 479, Table II	Many; compilation.
Ro76	H.Rothhaas, *Ph.D. Thesis*, *Univ. Mainz* (1976). **KPH 18/76**	Zr
Vr87	H.de Vries, et al.: *At. Data Nucl. Data Tables*, **36** (1987) 495, Table II	Many; compilation.

Table 4 (*continued*)

Differences between radii of isotopes, from muonic atom X-rays		
Ba80	G.Backenstoss, et al.: *Physics Letters*, **95B** (1980) 212	O
En74	R.Engfer, et al.: *At. Data Nucl. Data Tables*, **14** (1974) 509, Table IV	Many; compilation.
Fr92	G.Fricke, et al.: *Phys. Rev.* **C45** (1992) 80. Table III	O, Ne, Mg, Al, Si
Fr95	G.Fricke, et al.: *At. Data Nucl. Data Tables*, **60** (1995) 177, Table V	Many; compilation.
He89	J.Herberz: *Ph.D. thesis, Univ. Mainz*, **KPH 6/89** (1989)	O, F, Na, Ne, Mg, Al, Si
Ho81	M.V.Hoehn, et al.: *Phys. Rev.* **C24** (1981) 1667	Os
La83	D.B.Laubacher, et al.: *Phys. Rev.* **C27** (1983) 1772	Gd
Ma89	P.Mazanek: *Dipl. Th., Inst. f. Kernph.* **PKH 11/89**, U. Mainz 1989	Zr, Mo
Ma92a	P.Mazanek, *Ph.D. Th. Inst. f. Kernph.* **PKH 5/92**, U. Mainz 1992	Pb
Po79	R.J.Powers, et al.: *Nucl. Phys.* **A316** (1979) 295, Table 18	Sm
Sc80	L.Schellenberg, et al.: *Nucl. Phys.* **A333** (1980) 333	Mo
Sc82	L.A.Schaller, et al.: *Nucl. Phys.* **A379** (1982) 523	C
Sc85	L.A.Schaller, et al.: *Phys. Rev.* **C31** (1985) 1007	S
Sh82	E.B.Shera, et al.: *Physics Letters*, **112B** (1982) 124	Ba
Ta84	Y.Tanaka, et al.: *Phys. Rev.* **C29** (1984) 1897	Eu
Ta84a	Y.Tanaka, et al.: *Phys. Rev.* **C30** (1984) 350	Hf
Wo80	H.D.Wohlfahrt, et al.: *Phys. Rev.* **C22** (1980) 264	Ti, Cu Zn
Wo81	H.D.Wohlfahrt, et al.: *Phys. Rev.* **C23** (1981) 533, Table VI	Ca, Ti, Cr
Differences between radii of isotopes, from atomic K_α isotope shifts		
Bh68	S.K.Bhattacherjee, et al.: *Phys. Rev. Letters*, **20** (1968) 1295	Nd
Bh69	S.K.Bhattacherjee, et al.: *Phys. Rev.*, **188** (1969) 1919	Gd, Dy, Er, Hf + prev.: Sn, Nd, Sm, W, Hg, Pb, U
Bl87	S.A.Blundell, et al.: *J. Phys.*, **B20** (1987) 3663	Theory: S_4, S_6 calc.
Bo81	G.L.Borchert et al: 4th *I. C. Nucl. far from Stab.* L.O.Skolen, 1981, **I.** p.56	Pb
Bo83	G.L.Borchert, et al.: *Nuovo Cimento*, **A73** (1983) 273	Pb
Br65	R.T.Brockmeier, et al.: *Phys. Rev. Lett.*, **15** (1965) 132	U
Ch67	R.B.Chesler, et al.: *Phys. Rev. Letters*, **18** (1967) 953	Sn, Sm, W
Ch68	R.B.Chesler, and F.Boehm: *Phys. Rev.* **166** (1968) 1206	Sn,Nd,Sm,Gd,W,Hg,Pb
Ei70	C.W.E. van Eijk, and F.Schutte: *Nucl. Phys*, **A151** (1970) 459	Dy
Ei70a	C.W.E. van Eijk, and M.J.C.Visscher: *Phys. Lett.*, **34B** (1970) 349	Ce
Ei79	C.W.E.Eijk, et al.: *Journ. Phys.* **G5** (1979) 315	Cd
El96	S.R.Elliott, et al.: *Phys. Rev. Lett.*, **76** (1996) 1031	U, see El96 er
El96er	S.R.Elliott, et al.: *Phys. Rev. Lett.*, **77** (1996) 4278 (erratum)	U corrected.
Le73	P.L.Lee, and F.Boehm: *Phys. Rev.* **C8** (1973) 819	Nd, Sm, Dy, Yb, Pb
Le78	P.L.Lee, F.Boehm, and A.A.Hahn: *Phys. Rev.* **C17** (1978) 1859	Hg
Ry72	A.S.Rylnikov, et al.: *Journ. Exp. Theor. Phys.* **63** (1972) 53	Sb, Eu
Su65	O.I.Sumbaev, and A.F.Mezentsev: *Journ. Exp. Theor. Phys.* **49**(1965)459	Mo
Su67	O.I.Sumbaev, et al.: *Yadernaya Fizika*, **5** (1967) 544	Nd, Sm
Su68	O.I.Sumbaev, *"Nuclear Structure"*, IAEA Vienna, 1968, p.527	Mo,Ba,Nd,Sm
Su69	O.I.Sumbaev: *Int. C. Prop. Nucl. St. Montreal*, Aug. 25-30 1969. Contr. 2.67	Te
Su69a	O.I.Sumbaev, et al.: *Yadernaya Fizika*, **9** (1969) 906	Ba
To85	G.Torbohm, et al.: *Phys. Rev.*, **A31** (1985) 2038	Theory: C_i/C_1 calc.
Special case: H-D isotope shift		
Hu98	A.Huber, et al.: Phys. Rev. Letters, **80** (1998) 468	H-D Isotope Shift
Pa94	K.Pachucki, et al.: Phys. Rev. **A49** (1994) 2255	H-D IS theory
Sc93	F.Schmidt-Kaler, et al.: Phys. Rev. Letters, **70** (1993) 2261	Re-anal in Pa94, We95
We92	M.Weitz: Ph.D. Thesis, Max-Planck-Institut für Quantenoptik (1992)	Re-anal in Pa94, We95
We95	M.Weitz, et al.: Phys. Rev. **A52** (1995) 2664	H-D Lamb-shift, IS.
Differences between isotopes from optical isotope shifts		
Ah85	S.A.Ahmad, et al.: *Z. Physik*, **A321** (1985) 35	Eu
Ah88	S.A.Ahmad, et al.: *Nucl. Phys.*, **A483** (1988) 244	Ra
Al79	E.Alvarez, et al.: *Physica Scripta*, **20** (1979) 141	Xe
Al83	G.D.Alhazov, et al.: *Zhurn.Exp.Teor. Fiz. Letters*, **37** (1983) 231	Eu
Al85	G.D.Alhazov, et al.: *Izv. Ak. Nauk SSSR, Ser. Fiz.*, **49** (1985) 24	Sm, Eu
Al85a	G.D.Alhazov, et al.: *Tez. Dok. XXXV. Sov. Leningrad* (1985)	Tm
Al86a	G.D.Alhazov, et al.: *Yadernaya Fizika*, **44** (1986) 1134	Sm, Eu
Al87	G.D.Alhazov, et al.: *Tez. Dokl. XXXVII. Soveshch.* (1987) 96	Nd, Sm
Al88	G.D.Alkhazov, et al.: *Nucl. Phys.*, **A477** (1988) 37	Tm
Al88a	G.D.Alkhazov, et al.: *Pisma v Zs.E.T.F.*, **48** (1988) 373	Gd
Al89	G.D.Alkhazov, et al.: *Nucl. Phys.*, **A504** (1989) 549	Ho
Al90	G.D.Alkhazov, et al.: *Z. Phys.*, **A337** (1990) 367	Tb
Al90a	G.D.Alkhazov, et al.: *Z. Phys.*, **A337** (1990) 257	Eu
An82	A.Andl, et al.: *Phys. Rev.*, **C26** (1982) 2194	Ca

Table 4 (*continued*)

An86	M.Anselment, et al.: *Phys. Rev.*, **C34** (1986) 1052	Sn
An86b	M.Anselment: *Nucl. Phys.* **A451**(1986)471 [Corrected in: KFK 4159 p.63.]	Pb
An87	M.Anselment, et al.: *Z. Phys.*, **A326** (1987) 493	Sr
An92	A.Anastassov, et al.: *Hyperfine Interactions*, **74** (1992) 31	Hf, U
An94	A.Yu.Anastassov, et al.: *Zhurn.Exp.Teor. Fiz.* **105** (1994) 250	Hf
An94a	A.Anastassov, et al.: *Z. Phys.*, **D30** (1994) 275	Ti
Au78	P.Aufmuth, et al.: *Z. Physik*, **A285** (1978) 357	Mo
Au83	P.Aufmuth, and M.Haunert: *Physica*, **123C** (1983) 109	Zr
Ba76	P.E.G.Baird: *Proc. Roy. Soc. London*, **A351** (1976) 267	Pd
Ba79	P.E.G.Baird, et al.: *Proc. Roy. Soc. London*, **A365** (1979) 567	Ba
Ba83	P.E.G.Baird, et al.: *J. Phys.*, **B16** (1983) 2485	Sn
Ba85	J.Bauche, et al.: *Z. Physik*, **A320** (1985) 157	Cd; eval. of Br76
Ba98	A.E.Barzakh, et al.: *Eur. Phys. J.*, **A_1** (1998) 3	Yb
Ba00	A.E.Barzakh, et al.: *Phys. Rev.*, **C61** (2000) 034304	Tm
Be79	K.Bekk, et al.: *Z. Physik*, **A291** (1979) 219	Ba
Be80	E.Bergmann, et al.: *Z. Physik*, **A294** (1980) 319	Ca
Be84	D.Bender, et al.: *Z. Physik*, **A318** (1984) 291	Sr
Be85	A.Bernard, et al.: *Z. Physik*, **A322** (1985) 1	Er
Bl87	S.A.Blundell, et al.: *J. Phys.* **B20** (1987) 3663	Theory: S_4, S_6 calc.
Bo76	J.Bonn, et al.: *Z. Physik*, **A27**6 (1976) 203	Hg
Bo79	J.Bonn, et al.: *Z. Physik*, **A289** (1979) 227	Cs
Bo81	G.Borghs, et al.: *Z. Physik*, **A299** (1981) 11	Xe
Bo84	G.Bollen, et al.: *Proc. AMCO-7*, *Darmstadt* (1984) p. 347	Au
Bo87a	S.K.Borisov, et al.: *Zhurn.Exp.Teor. Fiz.* **93** (1987) 1545	Nd, Sm, Gd
Br58	G.Breit: *Rev. Mod. Phys.*, **30** (1958) 507	Basic OIS
Br58a	P.Brix: *Rev. Mod. Phys.*, **30** (1958) 517	Basic OIS
Br76	M.S.W.M.Brimicombe, et al.: *Proc. R. Soc. Lond.*, **A352** (1976) 141	Cd; eval in Ba85
Br78	H.-W.Brandt, et al.: *Z. Physik*, **A288** (1978) 241	Ca
Br79	H.-W.Brandt, et al.: *Z. Physik*, **A291** (1979) 97	Sm
Br80	H.Brand, et al.: *Z. Physik*, **A296** (1980) 281	Sm
Br81	H.Brand, et al.: *Z. Physik*, **A302** (1981) 291	Eu
Bu85	F.Buchinger, et al.: *Phys. Rev.*, **C32** (1985) 2058	Sr
Bu87	F.Buchinger, et al.: *Nucl. Phys.*, **A462** (1987) 305	Cd
Bu90	F.Buchinger, et al.: *Phys. Rev.*, **C41** (1990)	Sr
Bu03	B.A.Bushaw, et al.: *Phys. Rev. Letters*, **91** (2003) 043004	Li
Ca95	P.Campbell, et al.: *Physics Letters*, **B346** (1995) 21	Bi
Ca02	P.Campbell, et al.: *Phys. Rev. Letters*, **89** (2002) 082501	Zr
Cl79	D.L.Clark, et al.: *Phys. Rev.*, **A20** (1979) 239	Yb
Cl82	D.L.Clark, and D.W.Greenlees: *Phys. Rev.*, **C26** (1982) 1636	Dy
Co85	A.Coc, et al.: *Physics Letters*, **B163** (1985) 66	Fr
Co87	A.Coc, et al.: *Nucl. Phys.*, **A468** (1987) 1	Cs, Fr
Di87	U.Dinger, et al.: *Z. Physik*, **A328** (1987) 253	Pb
Dö84	K.Dörschel, et al.: *Z. Physik*, **A317** (1984) 233	Eu
Du89	H.T.Duong, et al.: *Physics Letters*, **B217** (1989) 401	Pt
Du90	S.B.Dutta, et al.: *Phys. Rev.*, **C42** (1990) 1911	Gd
Du91	S.B.Dutta, et al.: *Z. Phys.*, **A341** (1991) 39	Pb
Ea84	D.A.Eastham, et al.: *J. Phys.*, **G10** (1984) *L* 271	Sm
Ea84a	D.A.Eastham, et al.: *Z. Physik*, **A318** (1984) 243	Sm
Ea86	D.A.Eastham, et al.: *J. Phys.*, **G12** (1986) L205	Sr
Ea87	D.A.Eastham, et al.: *Phys. Rev.*, **C36** (1987) 1583	Sr
Eb87	J.Eberz, et al.: *Z. Physik*, **A326** (1987) 121	Sn
Eb87a	J.Eberz, et al.: *Nucl. Phys.*, **A464** (1987) 9	In
Fi75	W.Fischer, et al.: *Z. Physik*, **A274** (1975) 79	Ag
Fo02	D.H.Forest, et al.: *J. Phys. G:Nucl. Part. Phys.*, **28** (2002) L63	Zr
Ga87	Yu.P.Gangrsky, et al.: *Tez. Dokl. XXXVII. Soveshch.* (1987) 103	Sm, Gd
Ga88a	Yu.P.Gangrsky, et al.: *Zhurn.Exp.Teor. Fiz.*, **94** (1988) 9	Zr
Ga89c	Yu.P.Gangrsky, et al.: *Yadernaya Fizika*, **50** (1989) 1217	Ce
Ge79	H.Gerhardt, et al.: *Z. Physik*, **A292** (1979) 7	Kr
Ge81	H.Gerhardt, et al.: *Hyperfine Interactions*, **9** (1981) 175	Kr, Xe
Ge98	U.Georg, et al.: *Eur. Phys. J.*, **A_3** (1998) 225	Lu
Ge02	R.W.Geithner, CERN-Thesis, 2002-030	Ne
Go85	A.T.Goble, and C.W.P.Palmers: *J. Phys.*, **B18** (1985) 2181	Mo
Gr82	P.Grundevik, et al.: *Z. Physik*, **A306** (1982) 195	Ba
He85	K.Heilig: *Hyperfine Interactions*, **24** (1985) 349	Many. Review.
He87	K.Heilig: *Hyperfine Interactions*, **38** (1987) 803	Evaluation
Hi92	Th.Hilberath, et al.: *Z. Phys.*, **A342** (1992) 342	Pt

Table 4 (*continued*)

Ho84	B.Hoffmann, et al.: *Z. Physik*, **A315** (1984) 57	Polarisation
Hö76	C.Höhle, et al.: *Physics Letters*, **B62** (1976) 390	Ba
Hu78	G.Huber, et al.: *Phys. Rev.*, **C18** (1978) 2342	Na
Hü78	H.Hühnermann, et al.: *Z. Physik*, **A285** (1978) 229	Xe
Is97	Y.Ishida, et al.: *J. Phys.* **B30** (1997) 2569	Ce
Ji90	Wei Guo Jin, et al.: *Journ. Phys. Soc. Jap.*, **59** (1990) 3148	Er
Ji91	Wei Guo Jin, et al.: *Journ. Phys. Soc. Jap.*, **60** (1991) 2896	Yb
Ji97	W.G.Jin, et al.: *Phys. Rev.*, **C55** (1997) 1545	Hf
Kä89	W.Kälber: *Ph.D. Thesis*, *Univ. Heidelberg*, *KfK-4513* (Februar 1989)	Th
Ke95	M.Keim, et a.: *Nucl. Phys.*, **A586** (1995) 219	Kr
Ki84	W.H.King:*Isotope Shifts in Atomic Spectra* (Plenum Press, New York, 1984)	Review
Kl79	W.Klempt, et al.: *Physics Letters*, **B82** (1979) 47	Rb
Kl96	A.Klein, et al.: *Nucl. Phys.*, **A607** (1996) 1	Ar
Ko58	H.Kopfermann: *Nuclear Moments* (Academic Press Inc., New York, 1958)	Basic OIS
Ko91	D.Kowalewska, et al.: *Phys. Rev.*, **A44** (1991) $R_1$442	Po
Kr88	U.Krönert, et al.: *Z. Physik*, **A331** (1988) 521	Au
Kü77	T.Kühl, et al.: *Phys. Rev. Letters*, **39** (1977) 181	Hg
La92	W.Lauth, et al.: *Phys. Rev. Letters*, **68** (1992) 1675	Tl
LB97	F.LeBlanc, et al.: *Rapport d'activité IPN Orsay*, *1996-97*, p. 33	Au
LB99	F.LeBlanc, et al.: *Phys. Rev.*, **C60** (1999) 054310	Pt
Le88	J.K.P.Lee, et al.: *Phys. Rev.*, **C38** (1988) 2985	Pt
Le99	J.M.G.Levins, et al.: *Phys. Rev. Letters*, **82** (1999) 2476	Hf
Li91	P.Lievens, et al.: *Physics Letters*, **B256** (1991) 141	Sr
Li92a	P.Lievens, et a.:*Europhysics Letters*, Submitted, Personal Communication	Kr
Lo85	H.Lochmann, et al.: *Z. Physik*, **A322** (1985) 703	In
Lu94	P.Luc, et al.: *Z. Phys.*, **D31** (1994) 145	Ti
Me89	R.Menges: *Ph.D. Thesis*, *Univ. Mainz GSI-89-06* (Februar 1989)	Tl, Pb
Me92	R.Menges, et al.: *Z. Phys.*, **A341** (1992) 475	Tl
MH97	Ma Hongliang, et al.: *J. Phys.* **B30** (1997) 3355	Nd
Mu83	A.C.Mueller, et al.: *Nuclear Physics*, **A403** (1983) 234	Ba
No77	G.Novicki, et al.: *Phys. Rev. Letters*, **39** (1977) 332	Ba
No78	G.Novicki, et al.: *Phys. Rev.*, **C18** (1978) 2369	Ba
Ok87	H.Okamura, and S.Matsuki: *Phys. Rev.*, **C35** (1987) 1574	Er
Pa84	C.W.P.Palmer, et al.: *Journ. Phys.*, **B17** (1984) 2197	Ca
Pa94	G.Passler, et al.: *Nucl. Phys.*, **A580** (1994) 173	Au
Re80	H.Rebel, et al.: *Nukleonika*, **25** (1980) 145	Ba
Ri92	J.Rink: *Dissertation*, *Univ. Heidelberg*, *KfK 4993* (Februar 1992)	Hf
Ri94	E.Riis, et al.: *Phys. Rev.*, **A49** (1994) 207	(From Bu03) Li
Sa90	G.Savard, et al.: *Nucl. Phys.*, **A512** (1990) 241	Au
Sa95	C.J.Sansonetti, et al.: *Phys. Rev.*, **A52** (1995) 2682	(From Bu03) Li
Sa00	J.Sauvage, et al.: *Hyperfine Interactions*, **129** (2000) 303	Rev: Ir, Pt, Au
Sc90	H.A.Schuessler, et al.: *Phys. Rev. Letters*, **65** (1990) 1332	Kr
Sc96	W.Scherf, et al.: *Z. Phys.*, **D36** (1996) 31	(From Bu03) Li
Si88	S.E.Silverans, et al.: *Phys. Rev. Letters*, **60** (1988) 2607	Sr
Sp89	G.D.Sprouse, et al.: *Phys. Rev. Letters*, **63** (1989) 1463	Yb
St80	A.Steudel, et al.: *Z. Physik*, **A296** (1980) 189	Ni
St85	J.Streib, et al.: *Z. Physik*, **A321** (1985) 537	Au
Th81	C.Thibault, et al.: *Phys. Rev.*, **C23** (1981) 2720	Rb
Th81b	C.Thibault, et al.: *Nucl. Phys.*, **A367** (1981) 1	Cs
Th83	R.C.Thompson, et al.:*J. Phys.*, **G9** (1983) 445 [KFK 3455 (Dez. 1982)]	Pb
To82	F.Touchard, et al.: *Phys. Rev.*, **C25** (1982) 2756	Na
To82b	F.Touchard, et al.: *Physics Letters*, **B108** (1982) 169	K
To85	G.Torbohm, et al.: *Phys. Rev.* **A31** (1985) 2038	Theory: C_i/C_1 calc.
Ul75	S.Ullrich, and E.W.Otten: *Nucl. Phys.*, **A248** (1975) 173	Cs
Ul85	G.Ulm, et al.: *Z. Physik*, **A321** (1985) 395	In
Ul86	G.Ulm, et al.: *Z. Physik*, **A325** (1986) 247	Hg
Ve92	L.Vermeeren, et al.: *Phys. Rev. Letters*, **68** (1992) 1679	Ca
Ve99	D.Verney, et al.: *Rapport d'activité IPN Orsay*, *1998-99*, p. 43	Ir
Wa87	K.Wallmeroth, et al.: *Phys. Rev. Letters*, **58** (1987) 1516	Au
Wa89	K.Wallmeroth, et al.: *Nucl. Phys.*, **A493** (1989) 224	Au
Wa90	M.Wakasugi, et al.: *Journ. Phys. Soc. Jap.*, **59** (1990) 2700	Nd, Sm, Gd, Dy
Wa03	J.Walls, et al.: *Eur. Phys. J.*, **D22** (2003) 159	(From Bu03) Li
We88	K.Wendt, et al.:*Z. Physik*, **A329** (1988) 407	Ba
Wi58	L.Wilets: *Handbook of Physics*, **38/1** (1958) 96	Basic OIS
Zi80	D.Zimmermann, et al.: *Z. Physik*, **A295** (1980) 307	Lu
Zi94	D.Zimmermann, et al.: *Phys. Rev.*, **A50** (1994) 1112	Hf