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Compilation and Evaluation of Nuclear Charge Radii

Summary Report of the Technical Meeting

IAEA Headquarters, Vienna, Austria
27–30 January 2025

Prepared by

K. Flanagan
University of Manchester
Manchester, UK

H. Staiger
Clemson University
Clemson, SC, USA

E. Takacs
Clemson University
Clemson, SC, USA

P. Dimitriou
International Atomic Energy Agency
Vienna, Austria

June 2025

IAEA Nuclear Data Section
Vienna International Centre, P.O. Box 100, 1400 Vienna, Austria

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Nuclear Data Section

International Atomic Energy Agency

Vienna International Centre

PO Box 100

1400 Vienna

Austria

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Abstract
This report summarizes the proceedings of a Technical Meeting held to review the current status of measurements and theoretical developments in nuclear charge radii. Experts convened to discuss recent advancements, identify gaps in both existing data and theoretical approaches, and propose updates to the tables of compiled and recommended charge radii. The discussions also addressed evaluation methods and uncertainty quantification.

June 2025

Contents

1. INTRODUCTION

Knowledge of nuclear radii and other radii observables (neutron radius of nucleus) is important for fundamental nuclear and atomic physics. Nuclear charge radii are an input of nuclear models, used to benchmark *ab initio* theories, and required for an investigation of nuclear structure and nuclear matter properties. They are needed for precision tests of the Standard Model with nuclear, hadronic, and electroweak probes or with precision atomic physics measurements (non-linearity of king plots). They are input parameters for precision calculations in atomic and molecular spectroscopy, in nuclear astrophysics, and in direct and indirect searches for dark matter. As such, they impact the development of sound and reliable nuclear models to support nuclear data for a wide range of nuclear technologies and applications. Providing access to a continuously updated database of recommended values of nuclear charge radii is, therefore, beneficial for advancements in both fundamental and applied research.

The Nuclear Data Section of the International Atomic Energy Agency organized a Technical Meeting on Compilation and Evaluation of Nuclear Charge Radii, at the IAEA Headquarters, 27 to 30 January 2025. The purpose of the meeting was to discuss the revision of the table of recommended nuclear charge radii published by Angeli and Marinova in 2013, in ADNDT 99 (2013) 69-95. This table is accessible from the Nuclear Data Services webpage: https://nds.iaea.org/radii/.

Since 2013, there have been significant developments in both experimental techniques and theoretical calculations, improving the quality of the data and our knowledge of nuclear charge radii for a growing number of nuclei. It is, therefore, timely to capture those developments and improvements in the tables of recommended charge radii.

The meeting covered the following topics:

- New experimental techniques and measurements
- Evaluation methods and uncertainty quantification
- The role of nuclear theory
- Emerging needs and priorities
- Revision and future maintenance of the nuclear charge radii tables

The meeting was attended by eighteen participants from nine member states and staff from the International Atomic Energy Agency (IAEA). The Director of the Division of Physical and Chemical Sciences, Tzanka Kokalova Wheldon, opened the meeting by highlighting the significance of the topic and expressing the IAEA's gratitude to the participants for attending this meeting and offering their valuable contributions. The Technical Officer of the meeting, Paraskevi Dimitriou, provided a brief introduction outlining the meeting's purpose and objectives. Participants subsequently elected Endre Takacs (Clemson University) as the chair of the meeting. Additionally, Kieran Flanagan (University of Manchester) and Hunter Staiger (Clemson University) were appointed as rapporteurs. Prof. Istvan Angeli (University of Debrecen, ATOMKI) was able to attend and contribute to the meeting in person, providing historical background and details of the framework of the previous evaluation.

Summaries of the presentations are given in Section 2, while the technical discussions and recommendations are summarized in Section 3. Conclusions are provided in Section 4. The meeting agenda and participants' list are given in Annexes I and II, respectively. The presentations are accessible from https://conferences.iaea.org/event/401/.

2. SUMMARIES OF PRESENTATIONS

2.1. From total neutron cross sections to nuclear charge radii: tables and systematics, István Angeli (University of Debrecen, ATOMKI)

Measurements of total neutron cross sections ($E_n \approx 14$ MeV) lead to results characterizing nuclear matter radii: the Z, N = 6 non-traditional magic nucleon numbers [1], correlation of matter radii with binding energy [2], r_0 matter radius parameter and to surface thickness [3]. Looking for systematics in nuclear charge radii found in [4] (and references therein), resulted in the perception of shell effects, deformation effects and odd-even effects along isotopic series [5]. The same effects along isotonic, isobaric and iso-symmetric series were also studied in Ref. [6]; therein, the radius data used is attached as an Appendix in Table 1: this was our first charge radius table. A comparison to theoretical calculation followed [7] with the mass number dependence of neutron skin thickness for spherical nuclei. Collecting the ($r_{el} - r_{mu}$) differences for 85 nuclei, the mean value -9.3(1.5) fm shows that the deviations between radii – measured by the two methods – need an explanation [8]. The effect of valence nucleons on rms charge radii and surface thickness was also investigated [9]. In the early 90's, the "best method" of data evaluation was searched for with the conclusion that "The final results are less sensitive to the actual procedure of evaluation than to the selection of input data." [10]. The result of these searches was Table II of the same reference. In 1998, owing to a Research Contract with the IAEA(NDS), new tables have been produced: Table III. [11] comparing the results of a complicated method to those of a simple one. Soon, a new table followed with updates, background information, chapter with easy-to-use formulae; this was edited by the Agency: Table IV. [12]. Realizing that the application of constraints, the redundancy improves the accuracy and helps to find outliers by investigating χ^2 values, lead to Table V. [13]. For background works the moments of the two-parameter Fermi charge distribution was necessary; therefore, $<r^m>$ and differences $\delta<r^m>$ were calculated; in addition, $\delta<r^m>$ for even m are also given in terms of $\delta <r^2>$ [14]. Fermi parameters from charge moments were calculated in [15]. A common work with Krassimira Marinova resulted in the last Table VI. [16]. We also investigated the correlation of charge radii with other nuclear observables in [17]. The "proton radius puzzle" [18] has important consequences on the evaluation of normalized radii measured by electron scattering.

At present, the main problems are: i) the estimation of the dispersion effect on charge radii measured by electron scattering; ii) the procedure with "H-normalized" data mentioned above.

Nuclear physicists would need also the radii of neutron distribution. Research activities in this direction may deserve attention in the future.

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Discussion

- Systematic differences have been observed between radii derived from muonic atom spectroscopy and electron scattering experiments. These differences have changed over time as the data and evaluation procedures have evolved.
- The dispersion correction to electron scattering data is a serious problem that remains to be solved. Different papers can even disagree on the sign of the correction.
- Nuclear polarization is a significant component of the uncertainty in muonic atom experiments.
- The possible use of electron scattering with polarized targets and or beams at facilities such as JLAB was discussed. In particular, that the polarization asymmetry is more sensitive to the weak charge form factor.
- The capability of a new/upgraded accelerator at Mainz with very high intensity for electron scattering was mentioned with emphasis on the proton radius and PREX type measurements.

2.2. Charge radii of light isotopes from laser spectroscopy of He-like atomic systems, Wilfried Nörterhäuser (TU Darmstadt & Helmholtz Research Academy Hesse for FAIR)

Light nuclei exhibit many facets of nuclear structure, like halos and clustering, and are accessible for ab-initio nuclear structure calculations [1]. This makes their radii important benchmarks for nuclear structure physics. Moreover, the extraction of differential charge radii of light few-electron systems is not affected by uncertainties in the mass-shift and field-shift coefficients as are heavier systems [1]. This is due to the availability of high-accuracy ab initio calculations applying non-relativistic quantum electrodynamics (NRQED). Up to five-electron systems, these have sufficient accuracy to extract precise changes in ms nuclear charge radii $\delta\langle r^2\rangle$ from the isotope shifts [2]. Further theoretical developments are ongoing for He-like systems in order to allow for an extraction of the total charge radius direct from the transition frequency without relying on any reference radius [3]. We have thus started to measure the transition frequencies of the laser accessible 1s2s 3S1 → 1s2p 3PJ transitions in He-like systems to determine absolute and differential charge radii, R_c and $\delta\langle r^2\rangle$ of the light elements from Be to N using collinear laser spectroscopy. In the first step, we have addressed these transitions in $^{12,13,14}C^{4+}$ [4] using the Collinear Apparatus for Laser Spectroscopy and Applied Science (COALA) [5] at the Technical University of Darmstadt. In order to reach the required accuracy of the order of 1 MHz in the transition frequency, quasi-simultaneous collinear and anticollinear laser spectroscopy was performed [4] to become independent from the ion velocity. The laser frequencies were measured with a frequency comb. The measurements are the first optical charge radius determinations in the carbon isotope chain. The total "all-optical" charge radius of ^{12}C – extracted from the transition frequency measurement and the calculated transition energy for a point-like nucleus – has still a too large uncertainty to be competitive with muonic atom or elastic electron-scattering results due to uncalculated mα^8 contributions to the transition energy [3,4]. This requires further efforts on the theoretical side, while the experimental accuracy is already sufficient to extract the charge radius with a similar accuracy as reached with muonic atoms. Until such calculations are available, the mass-shift approach is used to extract improved charge radii, for ^{13,14}C [5]. Therefore, the precise nuclear radius of ^{12}C from muonic atom or electron scattering experiments is used as a reference, which can later be replaced by an all-optical charge radius of ^{12}C. The work will be extended towards the stable isotopes of Be, B, and N and an activity towards an implementation of the technique on-line has been initiated at ISOLDE/CERN.

With respect to the measurements on B, Be, and N, it is very important to get improved charge radii for at least one of the isotopes of these elements. While muonic-atom spectroscopy using metallic microcalorimeter are ongoing in the QURATET collaboration at PSI, similar initiatives to either have improved electron scattering experiments on these nuclei or a reanalysis of existing data are very important to get a conclusive picture of the charge radii in this region of the nuclear chart. Additional charge radius information from new techniques, e.g., electron *g*-factor measurements in hydrogen-like ^{12,14}C, would be highly appreciated. The carbon isotopes ^{12,14}C are ideal candidates for calibrations of these techniques since they are the only even-even isotopes in this region from ^{4}He up to ^{16}O.

Note: The presenter maintains a webpage with a reference list of laser spectroscopy work that has been performed online, which may be helpful in the update and improvement of the current charge radii database. This is publicly available at: https://www.ikp.tu-darmstadt.de/laser_nuclear_chart

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Discussion:

- He-like laser spectroscopy requires several hundred pA up to a few nA of HCI, depending on the hyperfine splitting.
- The hope was that spectroscopy of He-like C would determine higher order theoretical contributions, which could then be used to improve the determination of fine-structure from He spectroscopy. However, the disagreement between theory and experiment in the total transition frequency was too large for this to be done.
- Future improvements must come from the theoretical side. While improvements in energy resolution are possible, they would not provide a decrease in the resulting uncertainty until theory can handle the higher order contributions.
- Nitrogen is the heaviest element with a laser accessible transition (194 nm) in the He-like charge state. It is challenging, but there is interest in the measurement.
- Request for a muonic atom measurement of the boron charge radius. Improvements in the charge radii of the other light elements would also be helpful to provide references for the differential charge radii approach.

2.3. Precise nuclear charge radii via bound electron *g* factor measurements, Fabian Heisse (MPIK Heidelberg)

The gyromagnetic *g* factor of bound electrons in highly charged ions is ideal for testing quantum electrodynamics (QED) in the strongest electric fields. In heavy highly charged ions (HCI) the innermost electrons experience electric fields exceeding 10^{15} V/cm that are otherwise unreachable in laboratories. Additionally, these systems are still simple enough to enable precise theory calculations [1, 2].

Additionally, the bound electron g factor is significantly influenced by the nuclear properties due to the close vicinity of the electrons to the nucleus. Especially, the *g* factors of hydrogen-like ions are ideal probes for the nuclear charge radius. Hydrogen-like ions consist only of the innermost 1s electron and the nucleus resulting in a very high probability density of the electron being at the position of the nucleus. Such an effective two-body system can be calculated extraordinarily precise [3]. This allows to extract the absolute charge radius as well as charge radius differences to similar or even higher precision compared to the current literature values. Therefore, nuclear charge radii extracted from bound electron *g* factors are complementary to charge radii obtained from elastic electron scattering and muonic atom x-ray spectroscopy studies. Such *g* factor experiments inherently have different uncertainties compared to the two main traditional methods. Therefore, these represent a very important independent method for precise nuclear charge radii determination.

Importantly, the *g* factor of various hydrogen-like ions is between ≈ 2.0 (for $^{4}He^{+}$) and ≈ 1.6 (for $^{238}U^{91+}$). Consequently, the Zeeman splitting for all spinless nuclides from Z=2 to Z=92 varies only by 20% for a given magnetic field. It is possible to determine *g* factors of various elements over a very large Z range with the same detection and measurement scheme. The ALPHATRAP experiment is a dedicated cryogenic Penning-trap setup to measure these bound electron *g*-factor of single HCIs [4]. By co-trapping two hydrogen-like neon ions ($^{20}Ne^{9+}$ and $^{20}Ne^{9+}$) we have determined their isotope *g*-factor shift with 13 digits precision in respect to g [5]. This allows to test the QED recoil contribution to highest precision and to improve the mean square nuclear charge radius difference by about an order of magnitude compared to the literature value. This enabled us to set limits on hypothetical new physics beyond the standard model. Recently, we measured the *g* factor of hydrogen-like tin ($^{118}Sn^{49+}$) [6]. Given agreement with the latest theory calculation this allows the extraction of the tin nuclear charge radius with a precision which is only a factor of four less precise compared to the current literature value. A more precise extraction of the charge radius is possible with an improved theory.

In the future we will expand the *g* factor measurements towards $^{208}Pb^{81+}$ and beyond. For these high Z nuclides, the electron is even closer bound to the nucleus, leading to an increased sensitivity regarding the nuclear charge radius. Currently, the production of these hydrogen-like ions remains most challenging. For this purpose, we construct a new electron beam ion trap (EBIT) with electron beam energies of 300 keV and beam currents up to 0.5 A at the MPIK. The determination of *g* factors of elements with similar Z will allow to experimentally enhance the theory precision and therewith link the nuclear charge radii of nuclei with different Z with high precision. Eventually, it will also be possible to expand the bound electron *g* factor determination to nuclei with spin via additional hyperfine interaction spectroscopy. Finally, there is a new experimental set up at MPIK called LSYM, which will be capable to determine nuclear charge radii of light nuclei by co-trapping them with a single positron [7].

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Discussion:

- Both *g*-factor and muonic atom measurements are limited by the precision of nuclear polarization calculations.
- For nuclei with non-zero spin, the calculations become much more challenging, as they have to be calculated with QCD. In all nuclides, the effect of QED in the *g* factor remains, but it is mostly removed by taking the difference in *g*-factor between two isotopes.
- Determining any nuclear parameter to the same precision of a bound electron *g* factor is of huge assistance to nuclear theorists.
- It is possible to extract the nucleon's *g* factor to high precision via the determination of the *g* factor in the ground and excited hyperfine state.
- Future theoretical work enhancements will yield immediate improvements in charge radii derived from *g* factor measurements.

2.4. Nuclear polarization in muonic atoms, Mikhail Gorshteyn (University of Mainz)

Precise nuclear radii play an important role in low-energy tests of the Standard Model in the quark sector. The extraction of Cabibbo's 2-flavor quark-mixing angle ϑ_C, $V_{ud}=\cos\vartheta_C$, from superallowed nuclear beta decays at the 0.01% level crucially depends upon precise charge radii of the participating nuclei. They enter through Coulomb corrections to the statistical rate function f, and via the isospin-breaking correction ΔC which can be benchmarked with combinations of nuclear radii across the superallowed isotriplet. Nuclear radii enter the calculations of these quantities as external input, and their uncertainties directly affect the uncertainties of f, ΔC and hence V_{ud}. The impact of a precise charge radius on the V_{ud} extraction is illustrated by the recent 0.5% determination of the radius of the ^{26m}Al isomer resulting in a 1−2σ shift in ΔC and in V_{ud} extracted from the ^{26m}Al to ^{26}Mg decay. The radius of the ^{26m}Al isomer was determined with respect to that of the stable ^{27}Al isotope, obtained from muonic x-ray spectra. This reference radius requires a precise calculation of the nuclear polarization (NP) correction. In the past few decades, a great amount of theoretical work has been dedicated to NP in the lightest hydrogen-like muonic systems motivated by a technological leap in the laser spectroscopy of muonic H, D, $^{3,4}He^+$ where modern ab initio nuclear theory methods are applicable. For heavier muonic atoms, the estimates of NP stem from the 1970's work by Rinker and Speth and are routinely used to extract the nuclear radii. The main difference lies in the Z_α-expansion being used for lightest nuclei, and no such expansion for heavier systems. Until now, it is not entirely clear how the two approaches are related. I propose a hybrid approach that uses the Z_α expansion as the starting point and incorporates higher-order corrections in a transparent and straightforward way. I show that this approach gives results that are close to those of Rinker and Speth for nuclei from for $4\leq Z\leq 41$. On the other hand, by construction the approach is easily relatable to the Z_α-expansion. I discuss how future works may provide us with a detailed understanding of the nuclear polarization correction across the entire nuclear chart for nuclear charge radii with a robust theoretical uncertainty.

Discussion:

- A relatively simple model of nuclear polarization gives uncertainties of ~10-20%, better than the 30% estimated in Fricke and Heilig 2004. It is unclear how accurate the uncertainties of nuclear polarization are, and further corrections are needed for current models.
- Nuclear polarizability was assumed to have a 10% uncertainty. Spread between experimental values and a two-parameter fit was large. Additional measurements on nuclear polarizability are needed for atomic and nuclear physics.
- There is often a several month delay between experiment and theoretical calculations. Future work should seek to involve theorists as early as possible to minimize this delay.

2.5. Recent improvements in the theory of heavy muonic atoms and their influence on nuclear radii, Natalia S. Oreshkina (MPIK Heidelberg)

Muonic atom spectroscopy is one of the two well-established techniques to measure nuclear charge root-mean-square (rms) radii. Most of the experiments were conducted 40-50 years ago for almost all stable isotopes. Later, the values obtained from muonic atoms were combined [1] with scattering data via Barrett radii [2], and this combined value is now used as an input parameter for nuclear, atomic, molecular, and quantum electrodynamics (QED) calculations.

Interest in muonic atoms was recently renewed with new measurements of the proton radius, also known as the "proton size puzzle" [3]. The value obtained from muonic hydrogen was significantly more precise and in striking disagreement with the established values from hydrogen spectroscopy and scattering experiments. Later, the value based on muonic measurements was accepted as the CODATA value, whereas the uncertainties of other methods turned out to be underestimated [4].

Motivated by the proton radius puzzle and a new series of measurements on heavy muonic atoms with microtargets, we started theoretical efforts to extract the rms radii. A literature study revealed the existence of another puzzle, the muonic fine structure anomaly, discovered about 50 years ago and forgotten since then [5-8]. This puzzle originated from an extremely poor fit between experimental data and theoretical predictions, and the disagreement was attributed to the least understood and most complicated of all QED effects, namely nuclear polarization effects. This led to significant improvement in the fit quality. However, our rigorous QED calculations of the nuclear polarization effect have shown that it is most likely not responsible for the anomaly [9]. This implies that the fit quality should return to its original state, and the uncertainty of the nuclear radius of double-magic 208Pb should be significantly underestimated. The same situation applies to other medium and heavy muonic atoms, as the methods used for evaluation have been the same.

Together with my group at MPIK (Heidelberg), we have performed a full re-evaluation of all QED effects contributing at the 10% level from the experimental accuracy and obtained preliminary results for the ^{208}Pb rms radius. Additionally, we examined the details of the muonic-scattering combination procedure and studied the Barrett radii. Preliminary results showed that, although Barrett radii are indeed model-independent, as previously claimed, they are extremely sensitive to the chosen fitting region, which also influences the final value of the extracted rms. Therefore, we recommend focusing more on the procedure to realistically evaluate the uncertainties that arise at each step of the commonly used method.

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Discussion:

- Nuclear excitation modes calculated using Skyrme codes. Once these are known, the contributions can be calculated in a straightforward way.
- Two parameter Fermi model is reproducible, and many QED effects are not affected by nuclear shape. However, uncertainties due to nuclear model dependence are difficult to evaluate. Electron scattering data can introduce a bend in the pdf of Fermi model parameters.
- The timescale of redoing a muonic calculation should be a few days. Nuclear polarization and self-energy are the most challenging to calculate.
- Benchmarking nuclear polarization calculations is challenging as models depend on input nuclear radius. However, it is important to constrain calculations by these comparisons. New methods of measuring nuclear radii are critical to checking consistency of existing methods.
- Nuclear model dependence in highly charged atoms is quite small. This has been seen in spectroscopy of Na-like HCI as well.
- V2 parameters must have QED contributions subtracted for accurate comparisons. Authors should make it clear what has been subtracted when determining rms radii, Barrett radii, etc.

2.6. Isomeric mean-square charge radii changes, Deyan Yordanov (CERN)

Nuclear isomeric states are associated with individual spins, electromagnetic moments, and mean-square charge radii. The latter cause shifts between fine-structure energy levels in the atom, which albeit being small are detectable by high-resolution measurements. These "isomer shifts" are essentially free of the mass effect, since the difference in mass between states in the same nucleus is negligible, and as such are proportional to the isomeric charge-radius change in the nucleus. Systematic uncertainties may still arise from experimentation and the field-shift coefficient of proportionality.

The relevance of the charge radius to nuclear-structure studies over isotopic chains has been questioned. In principle, a change in the number of neutrons brings no charge in charge. Any deviation of the charge radius should thus be considered an indirect phenomenon. Nevertheless, it has been shown that the charge radius may be sensitive to details of the neutron shell structure. The isotopes of magnesium in the *sd*-shell have been presented as an example. They follow a radial increase with the removal of neutrons owed to nuclear clustering, a strongly pronounced kink at a subshell closure, and another kink associated with excitations to the next major neutron shell. Therefore, it may be argued that an empirical link exists between the charge radius and the neutron shell structure in nuclei.

Isomer shifts in the region of tin have been presented. These are specific to the unique-parity $h_{11/2}$ orbital whose mean-square charge radius appears to change quadratically with respect to the common-parity state. It has been argued that this quadratic trend is related to the linear increase of the corresponding quadrupole moment. Cadmium stands as the key example in this region. Preliminary data suggest similar effects along the $i_{13/2}$ orbital in lead and neighboring isotopic chains.

The need for accurate charge radii derived from electron scattering and muonic atoms has been pointed out. These enter as an ingredient in the geometrical procedure for determining charge radii from laser spectroscopy. Hence, any future improvement of the radii database may be considered a two-stage process.

Finally, a point has been made that the radii database may deprive original works of citations. One should present it to the community as a freely accessible platform for finding the original work and its impact on evaluated values. Both should be cited.

Discussion:

- To what extent ground state charge radius is constant as neutron number changes, even without deformation. Rough assumption is that the nucleus cannot be compressed, so the charge radius is constant.
- Magnetic moments are generally easier to measure and can be improved by improving experimental precision. Analysis of hyperfine splitting is complicated by quadrupole interactions.
- Measured intensities of hyperfine levels do not affect the charge radii, as simple relations between hyperfine level populations are used.

2.7. Vision and Precision in Charge Radii determination, Ben Ohayon (Technion, Israel Institute of Technology)

Part I

There is a balance to be struck between having the most robust, reliable and precise charge radii (‘precision’), and providing the community with simple, pragmatic and timely values (‘vision’).

Recently, the nuclear physics community is putting pressure on the accuracy with which we can provide absolute charge radii, thus giving motivation to revisit prior extractions.

Moreover, there are “new kids on the block”: experiments in H-like, He-like and Na-like ions which are sensitive to absolute radii (and various differences) at a level which again puts pressure on the value from muonic atoms.

There is a revival in muonic atom experiments and theory, so it is a good time to move forward.

Finally, laser spectroscopy is going from strength to strength. More data is becoming available, but we need to collect it better (“big data”). In the long term, this may motivate a living breathing compilation (like “AME” or even one with more theory like “CODATA”)

A radius of an unstable nucleus is a combination of a reference radius and an isotopic difference. Differential radii predominantly come from a combination of electron scattering and X-ray spectroscopy. I revisited this combination and found that above Z=10, the main uncertainty comes from the scattering experiment and how sensitive they are to the nuclear shape [1]. In other words, the “V2-factors” have an uncertainty of few parts per thousand which translate directly to the radii. Except for the lightest nuclei, I have a hard time imagining a radius with better than 0.1% uncertainty. This is larger than an order of magnitude compared to the literature. So, although nuclear polarization must be revisited, it may be that the effect is negligible compared with the V2 factors.

Part II
For nuclei between Z=2 and Z=11, the experimental uncertainty dominates, so there is opportunity for new experiments in muonic atoms. Measuring these light nuclei is now possible with an emerging technology: cryogenic microcalorimeters [2]. The QUARTET experiment at PSI will do just that [3]. We have taken data with muonic Li, Be and B and the analysis is ongoing. Next year we are looking to do Carbon (to compare with W. Nörtehäuser's measurements), Nitrogen, and Oxygen.

Pushing to higher Z requires improvements in the theory so our experimental goals are tied with the theoretical calculation.

Part III
I discussed our project to reanalyze isotope shift data with improved atomic calculations [4]. There has been great advancement in the last few years (discussed by Prof. Sahoo) so that old (and new) experimental data may be reinterpreted with in some cases an order of magnitude higher accuracy [5]. I emphasized the role of accurate, reliable, transparent, and well-tabulated F and K factors relating isotope shifts to differential radii [6]. The uncertainties in these factors usually dominate the differential radii and must be tabulated in a future compilation!

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Discussion:

- Discussion on common systematic errors between different experiments.
- Radiative corrections for scattering experiments are often not clearly presented in the literature. To better understand the data, the process of calculating the radiative corrections needs to be reviewed. Coulomb corrections should also be included. Although such corrections would change the cross section and introduce additional bias, they are important to produce a realistic form factor.
- Question on the performance of the cryogenic microcalorimeters: A few keV to 100 keV provides best resolution a detector with 100 um thickness will have eV resolution.
- There is a comment on the ^{20}Ne work which was measured to 6 eV with statistical and systematic errors included.
- There is a recent focus on muon atoms, however, electron scattering data have also been used in some of the cases considered by Ohayon.

2.8. Radbase and correlations, Hunter Staiger (Clemson University)

There are three significant steps to a nuclear radius evaluation:

1. measurement, compiling and critically evaluating all nuclear radius-related experiments;
2. conversion, transforming measured values into nuclear radius data;
3. optimization, combining all nuclear radius data into a consistent set of radii.

Optimization of the nuclear radius network is challenging due to the higher number of radii (>800) to optimize and the tight coupling of radii from relative measurements. Care must be taken to make a completely accurate non-linear approach feasible. radbase, an open-source set of Python codes, analyzes the network formed by nuclear radius data and breaks the minimization into computationally simple steps. Additionally, radbase supports including correlations between different pieces of data, an aspect missing from previous evaluations. radbase is currently under active development and hosted at the GitHub repository:

https://github.com/hstaige/radbase

The challenge of computing the correlations between different data points was discussed. Particular emphasis was placed on correlations between muonic atom spectroscopy radii due to the conversion to the rms radius from the Barrett moment and a reformulation of the King Plot in terms of correlations. A potential tool to address these correlations automatically is the uncertainties package developed by Matt Newville.

Future features of radbase include the ability to determine correlations automatically and integration with a planned nuclear radius database. Care will also be taken to make these calculations transparent and reproducible.

Discussion:

- There is a discussion on the use of Seltzer coefficients and lambda and if sufficient detail is included.
- Questions on the optical isotope shifts and how they are encoded into the covariance matrix.
- Discussion on the use of modern AI tools. Staiger's response is that general least square fitting is better than AI although AI is good at looking for trends from the radii or identifying outliers.
- There is a comment on extrapolation from the database, which is different to extending the database.
- Use of the software for single isotope analysis should be possible.
- The use of Bayesian inference techniques is discussed but implementing them will be challenging due to the complexity of the data set. The current code runs in 5 minutes with the existing dataset.
- There is a comment if nuclear reaction data should be included into the charge radius data. Charge radii from these sources have not been considered.
- OIS data from different sources: how will this effect be accounted for using this correlation method.

Discussion moved onto the uncertainties and improving clarity compared to previous tables. There is consensus that:

- The tables should include measurements and references as well as evaluation of the numbers which gives the recommended final numbers. Potentially a database of the data that can be accessed.
- The discussion moves to what should be included (X-ray energy or Barrett Radii).
- Mistakes do occur in the tables (entry errors) and these need to be rooted out by means of a careful review process.
- Dispersion effects in elastic scattering from ^{12}C raise the question of measuring neutron radii via the neutron weak charge [1, 2]. There is significant motivation to measure neutron skins in super allowed daughters, as that allows one to look at the isospin symmetry by considering the neutron skin in two systems. There is also possibility to perform reasonable calculations.
- Dispersive corrections are going to be studied extensively in the US. A positron beam is key to this type of measurement [3]. Letter of intent has been submitted and a dedicated experiment is now planned.

- Work at JLAB is ongoing on studying data (on Carbon, Iron and Aluminium) for charge radii extraction using two photon exchange mechanism (Coulomb correction is already taken account).
- The Japanese ultra-low Q^2 and SCRIT facilities, and charge radii measurements using electron scattering is also mentioned.
- At FRIB there will be a range of angular correlation measurements that allows model dependent charge radii determination on exotic nuclei (very short-lived nuclei). Other measurements will help with the dispersive corrections.

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2.9. Roles of atomic many-body methods for accurate determination of isotope shift constants, Bijaya Kumar Sahoo (Physical Research Laboratory (PRL) - Ahmedabad)

With the advent of new techniques, it is possible to carry out very high-precision measurements of isotope shifts in various atoms and ions these days [1-3]. The primary objective of isotope shift measurements has been to extract nuclear charge radii by combining these measurements with the atomic calculations. Recently these studies have been extended to probe the existence of a new vector boson by exploring the non-linearity behavior in the King's plot for which atomic calculations of the second-order isotope shift parameters are crucial. In order to determine the corresponding atomic factors, it is imperative to use a suitable many-body method and an appropriate approach to evaluate the isotope shift constants very reliably [4,5]. By employing finite-field and analytical response approaches in the relativistic coupled-cluster methods [6,7], we have determined isotope shift parameters for many atomic systems in the last few years, but these approaches suffer large numerical errors. We aim at developing more accurate approaches in the relativistic coupled-cluster method to provide very precise calculations of isotope shift constants; particularly by developing biorthogonal relativistic coupled-cluster method [8,9].

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Discussion:

- QED corrections improved the energy values, which were then used to adjust the wavefunction. QED corrections also affect the isotope shift operators. It was debated whether this approach is appropriate for hyperfine structure calculations.
- Three different kinds of distributions were tested, although it was pointed out that clustering effects in light ions could make the charge distribution significantly different from a Fermi distribution.
- Generally, it is assumed that the model dependence is small for light ions. Estimations for Yb show the model dependence is also ten times smaller than current experimental uncertainties.
- It was noted that the GRASP codes appear to sometimes underestimate uncertainties.

2.10. Nuclear charge radii vs. other experimental observables, Georgi Georgiev (IJCLab CNRS/IN2P3)

We discussed the relations between the charge radii and several nuclear experimental observables. This included a possible interpretation of the charge radii as a zeroth order nuclear moment, which is defined even for a spin zero nuclear state. The correlations between charge-radii change and the nuclear deformation and shape coexistence have been discussed. A question which has been put forward is whether the charge radii could be regarded as (another) experimental indicator for shell closures. The overall conclusions were that the charge radii can provide complementary information, and that a variety of experimental observables need to be considered in order to get an insight into the nuclear structure and its modifications.

Discussion:

- Interpreting global trends is challenging due to high correlations between data from optical isotope shifts. The effect of a large uncertainty in F and M is not always intuitive. It is critical that uncertainties are provided not only for absolute radii but also for isotopic shifts.
- Users of nuclear charge radius data must have the covariance matrix of all charge radii.
- It was debated how much information should be incorporated from assumed global trends. For example, should an evaluation be constrained to prevent crossing of radii for different elements?
- Correlations from nuclear model dependence should be carefully considered and clearly presented. Potential model dependence in isotonic differences should be transparently evaluated.
- Key idea: nuclear charge radii are one observable, but all observables should be considered in tandem to gain insight in the structure properties of the nucleus.

2.11. Isotope Shift and charge radii measurements with the CRIS experiment at ISOLDE, Kieran Flanagan (University of Manchester)

Over the last decade the CRIS experiment has utilized a high-resolution resonance ionization spectroscopy technique (CRIS) to measure charge radii in exotic nuclei. The low background and high efficiency have allowed the technique to measure short-lived exotic systems with production yields down ~10 atoms/second. In this presentation we summarized the technical developments, challenges and results from the last 10 years of activity.

Discussion:

- Random shifts in the accelerating voltages increase uncertainties, while systematic drifts can change the value. Voltage data is stored and used for a correction. It is important to take enough voltage measurements to track the slowly varying voltage function.
- Systematic errors from voltage shifts over time can be eliminated using a King Plot with muonic data. Authors of collinear spectroscopy should clearly communicate/disseminate any systematic corrections that have been done.

- Field should move towards multi-messenger nuclear physics - combining charge radii, B(E2) values, and other observables to better understand nuclear structure.

2.12. Nuclear charge radii of neutron-rich scandium and zinc isotopes, Xiaofei Yang (Peking University)

The isotope shifts of neutron-rich Sc and Zn isotopes have been measured in recent years using high-resolution laser spectroscopy techniques. By taking advantage of advanced atomic theory calculations, the nuclear charge radii of these two isotopic chains have been determined or re-evaluated, providing valuable insights into their nuclear structure. This contribution presented the measured isotope shifts, as well as the extracted or re-evaluated charge radii for both isotopic chains.

Discussion:

- The accuracy of uncertainties from various theoretical frameworks was discussed. It was recommended that multiple lines in multiple charge states be measured per isotope pair as consistency checks.
- If a King Plot is used to account for any voltage shifts, then that must be taken into account when comparing the mass shift coefficient to theory.
- Theorists should be involved in the analysis as early as possible to decrease the time to results and to help identify appropriate transitions. However, experimental limitations often make it difficult to have these discussions years before the experiment begins.

2.13. Charge radii of nuclei by EUV and X-ray Spectroscopy of highly charged ions, Endre Takacs (Clemson University)

Electron beam ion traps (EBITs) have proven to be a valuable tool for the spectroscopy of highly charged ions (HCIs) over the past few decades. Variations on the typical EBIT size (ranging from "compact" to "hyper") are being created in several labs as the potential of HCIs for precision measurements is being realized. The NIST EBIT group has developed techniques to take advantage of HCIs to provide nuclear charge radius information in the understudied high Z region. Na-like and Mg-like ions are especially interesting in the context of nuclear charge radii sensitivity due to the enhanced overlap of their ground-state wave functions with the nucleus. The energy of their strong 3s–3p emission can be measured experimentally with high precision in the extreme ultraviolet and x-ray spectral ranges. The simplicity of the Na-like and Mg-like systems also allows for precise calculation of transition energies for a given nuclear model.

At medium to high Z, the smooth Z-scaling of transition energies means differences in transition energies can be calculated to a higher precision than the energies themselves due to a partial cancellation of terms. Experimental uncertainties are also reduced when taking energy differences due to a reduction in calibration uncertainties. Comparing the theoretical and experimental energy differences results in the difference in nuclear charge radii between the two nuclides. Crucially, this method can be applied to two nuclides from different elements, providing powerful constraints on the nuclear radius landscape. Previous work has determined the isotopic difference in radius between Xe isotopes, as well as the difference between Ir and Os radii.

The measurement utilizes only a few million ions stored in an ion trap, which is advantageous for measurements involving small quantities of sample nuclei. Preparations are underway to apply the technique to radioactive nuclei extracted from a beamline at TRIUMF. Extensions to this method involving Li-like / Be-like ions are currently being explored with several planned measurements for $Z > 60$.

This work is funded by a NIST grant (Award Number 70NANB20H87) and by a National Science Foundation grant (Award Number 2309273).

Discussion:

- Due to the smooth scaling with Z of many terms, it is expected theoretical energies for different elements are highly correlated with each other at high Z.
- It was recommended Li-like transitions be investigated as a consistency check on the method.
- Second order hyperfine effects were estimated using a Monte Carlo simulation.
- Deformation parameter taken from IAEA database. Uncertainty on this parameter was very large in an attempt at a model independent evaluation.

3. TECHNICAL DISCUSSION

Participants addressed the main issues related to measurements, theory, and data evaluation of nuclear charge radii summarized below.

3.1. Evaluated charge radii tables

The current evaluation is widely used and has been published online as a pdf; the previous evaluation 12 years ago had 1800+ citations. Since 2013, the field has expanded significantly. The number of facilities that produce such data has increased significantly in the last ten years. Experimental techniques have improved, new methodologies have been developed, and theoretical methods have changed. As these approaches mature, they should be included in a new, modern evaluation. *Therefore, a critical evaluation of the current database is needed based on the experimental and theoretical updates.* A new evaluation also has potential for improvement in the dissemination via digital means: e.g. enhanced navigation, visualization, interactivity, transparency, clarity, and completeness of data stored. There is also a demand for more reactive updates of the evaluations. Additionally, the multidisciplinary usage of these evaluations implies different levels of expertise; future dissemination should provide multiple layers of access and functionality so that all users are served according to their needs. The development of the present nuclear charge radii database can profit from its relations with existing complementary developments of other nuclear databases e.g. nuclear moments and transition probabilities.

3.2. Experimental techniques

There are two main techniques, electron scattering and muonic atom spectroscopy, for determining absolute charge radii. New methods for determining absolute charge radii, including ion trap measurements (g-factors) and spectroscopy of highly charged ions, are being developed. Relative radii measurements currently use mostly laser spectroscopy, but the analysis also relies on muonic spectroscopy, electron scattering, and K-alpha measurements as well as theoretical inputs. We encourage the design of complementary absolute and relative measurement techniques to provide additional constraints on reference radii. In all cases, there is a need for additional details in published experimental and theoretical procedures. There is also a need for authors to specify correlations and separate statistical and systematic uncertainties in their final values.

3.3. Theoretical developments

Theoretical developments in optical isotope shifts over the last five years are already changing the field. We are also seeing advancements in the theory of muonic atoms and highly charged ions, and we expect significant improvements in data interpretation in these areas as well. Theoretical input plays a large role in the interpretation of experimental data.

4. RECOMMENDATIONS

Based on the presentations and subsequent discussions, participants formulated the following list of recommendations, which they considered crucial for creating a new table of recommended nuclear charge radii that is both functional and easy to maintain:

- We recommend regular updates and maintenance of the database with all data and enhancing dissemination using modern web interfaces and database technologies.
- We recommend creating a working group that will regularly meet to advise on developments, updates, and dissemination of the database. It should contain data producers, evaluators, and user representatives.
- There is a need for a white paper with detailed recommendations describing the visions and future directions of the field and the future evaluation.
- We encourage the reanalysis of existing data using modern theoretical and statistical techniques, *(for example dispersion correction in electron scattering, nuclear polarization in muonic atoms, and others)*.
- There is a need for additional support from stakeholders for experimental and theoretical groups in acquiring new data as well as developing new and improving existing theoretical frameworks.
- We recommend training the next generation of experts in nuclear charge radii and evaluation.
- Since this database is complementary to the nuclear moments and transition's probability databases, we recommend the results of this effort are communicated to the nuclear structure and decay data network.

5. CONCLUSIONS

The meeting was highly appreciated and deemed extremely useful.

Participants recognized the IAEA's coordinating role and recommended that it continue providing coordination and supporting their efforts in creating and maintaining tables of recommended nuclear charge radii.

IAEA Technical Meeting Technical Meeting on Compilation and Evaluation of Nuclear Charge Radii

27 – 30 January 2025
IAEA, Vienna
Room: C0343 (Hybrid)

ADOPTED AGENDA

Monday, 27 January

10:00 **Welcoming and Introduction**
Tzanka Wheldon, NAPC-Director
Vivian Dimitriou, NAPC-Nuclear Data Section, Technical Officer

10:15 **Election of Chairman and Rapporteur, Adoption of the Agenda**

10:20 **Participants' Presentations** *(45' unless indicated otherwise)*
- Introduction to the Nuclear Data Section (15')
  Vivian Dimitriou, IAEA
- From total neutron cross sections to nuclear charge radii - Part 1
  Istvan Angeli, Debrecen
- Charge Radii of Light Isotopes from Laser Spectroscopy of He-Like Atomic Systems
  Wilfred Nörterhäuser, GSI/FAIR - TU Darmstadt
- Precise nuclear charge radii via bound electron g factor measurements
  Fabian Heisse, MPI Heidelberg

13:00 **Lunch Break**

14:15 **Participants' Presentations** cont'd *(45' unless indicated otherwise)*
- Nuclear polarization in muonic atoms
  Mikhail Gorshteyn, University of Mainz
- Recent improvements in the theory of heavy muonic atoms and their influence on nuclear radii
  Natalia Oreshkina, MPI Heidelberg
- Isomeric mean-square charge radii changes
  Deyan Yordanov, ISOLDE-CERN

Coffee breaks as needed

Tuesday, 28 January

09:00 **Participants' Presentations** cont'd *(45' unless indicated otherwise)*
- From total neutron cross sections to nuclear charge radii - Part 2
  Istvan Angeli, Debrecen
- Vision and precision in radii estimations
  Ben Ohayon, Technion
- Radbase: codes for non-linear least-squares analysis of the nuclear radius network - towards next generation recommended values of nuclear charge radii
  Hunter Staiger, Clemson University
- Nuclear databases and webtools at the IAEA (30')
  Vivian Dimitriou, IAEA

12:30 **Lunch Break**

14:00 **Roundtable discussion:**

Topics for discussion:

- Current experimental techniques and measurements – status, what is measured, what is needed as input to derive charge radii
- Evaluation methods and uncertainty quantification
- The role of nuclear theory
- Emerging needs and priorities
- Revision and future maintenance of the nuclear charge radii tables

Coffee breaks as needed

Wednesday, 29 January

09:00 **Participants' Presentations** cont'd *(45' unless indicated otherwise)*

- Roles of atomic many-body methods for accurate determination of isotope shift constants
  Bijaya Sahoo, PRL Gujarat University
- Nuclear charge radii vs. other experimental observables (30')
  Georgi Georgiev, IJC Lab Orsay
- Isotope Shift and Charge Radii Measurements with the CRIS experiment at ISOLDE
  Kieran Flanagan, University of Manchester
- Nuclear charge radii of neutron-rich scandium and zinc isotopes (30')
  Xiaofei Yang, Peking University
- Charge Radii of Nuclei by EUV and X-ray Spectroscopy of Highly Charged Ions
  Endre Takacs, Clemson University

Lunch Break

14:00 **Roundtable** cont'd**:**

Topics for discussion:

- New experimental techniques and measurements
- Evaluation methods and uncertainty quantification
- The role of nuclear theory
- Emerging needs and priorities
- Revision and future maintenance of the nuclear charge radii tables.

Coffee breaks as needed

18:30 **Social Dinner**

Thursday, 30 January

09:00 **Drafting of the meeting summary report**

12:30 Closing of the meeting

Coffee break as needed

Annex II

Technical Meeting on the Compilation and Evaluation of Nuclear Charge Radii

27 – 30 January 2025

Vienna, Austria (Hybrid)

PARTICIPANTS

Country / Organization	Name	Surname	Affiliation	Email
IAEA	Paraskevi	DIMITRIOU	International Atomic Energy Agency	p.dimitriou@iaea.org
China	Xiaofei	YANG	Peking University	xiaofei.yang@pku.edu.cn
France	Georgi	GEORGIEV	IJC Lab, Orsay	Georgi.Georgiev@csnsm.in2p3.fr
Germany	Misha	GORSHTEYN	University of Mainz	gorshtey@uni-mainz.de
	Fabian	HEISSE	Max-Planck-Institut für Kernphysik, Heidelberg	fabian.heisse@mpi-hd.mpg.de
	Wilfried	NÖRTERSHAUSER	GSI/FAIR – Institute for Nuclear Physics TU Darmstadt	wnoertershaeuser@ikp.tu-darmstadt.de
	Natalia	ORESHKINA	Max-Planck-Institut für Kernphysik, Heidelberg	natalia.oreshkina@mpi-hd.mpg.de
Hungary	Istvan	ANGELI	Retired	angeli@science.unideb.hu
India	Bijaya Kumar	SAHOO	Physical Research Laboratory (PRL), Gujarat University	bijaya@prl.res.in
Israel	Ben	OHAYON	Technion - Israel Institute of Technology	benohayon@gmail.com
Romania	Dimiter	BALABANSKI	Extreme Light Infrastructure, Nuclear Physics (ELI-NP)	dimiter.balabanski@eli-np.ro
Switzerland	Deyan	YORDANOV	Isotope Separator On Line Device (ISOLDE) - CERN	deyan.yordanov@cern.ch
UK	Kieran	FLANAGAN	University of Manchester	kieran.flanagan-2@manchester.ac.uk
USA	Dipti	DIPTI	Clemson University	dipti@clemson.edu
	Paul	GUEYE	Facility for Rare Isotope Beams, Michigan State University	gueye@frib.msu.edu
	Kei	MINAMISONO	Facility for Rare Isotope Beams, Michigan State University	minamiso@frib.msu.edu
	Filip	KONDEV	Argonne National Laboratory	kondev@anl.gov
	Hunter	STAIGER	Clemson University	hstaige@g.clemson.edu
	Endre	TAKACS	Clemson University	etakacs@clemson.edu

Nuclear Data Section	E-mail: nds.contact-point@iaea.org
International Atomic Energy Agency	Fax: (43-1) 26007
Vienna International Centre, P.O. Box 100	Telephone: (43-1) 2600 21725
A-1400 Vienna, Austria	Web: https://nds.iaea.org