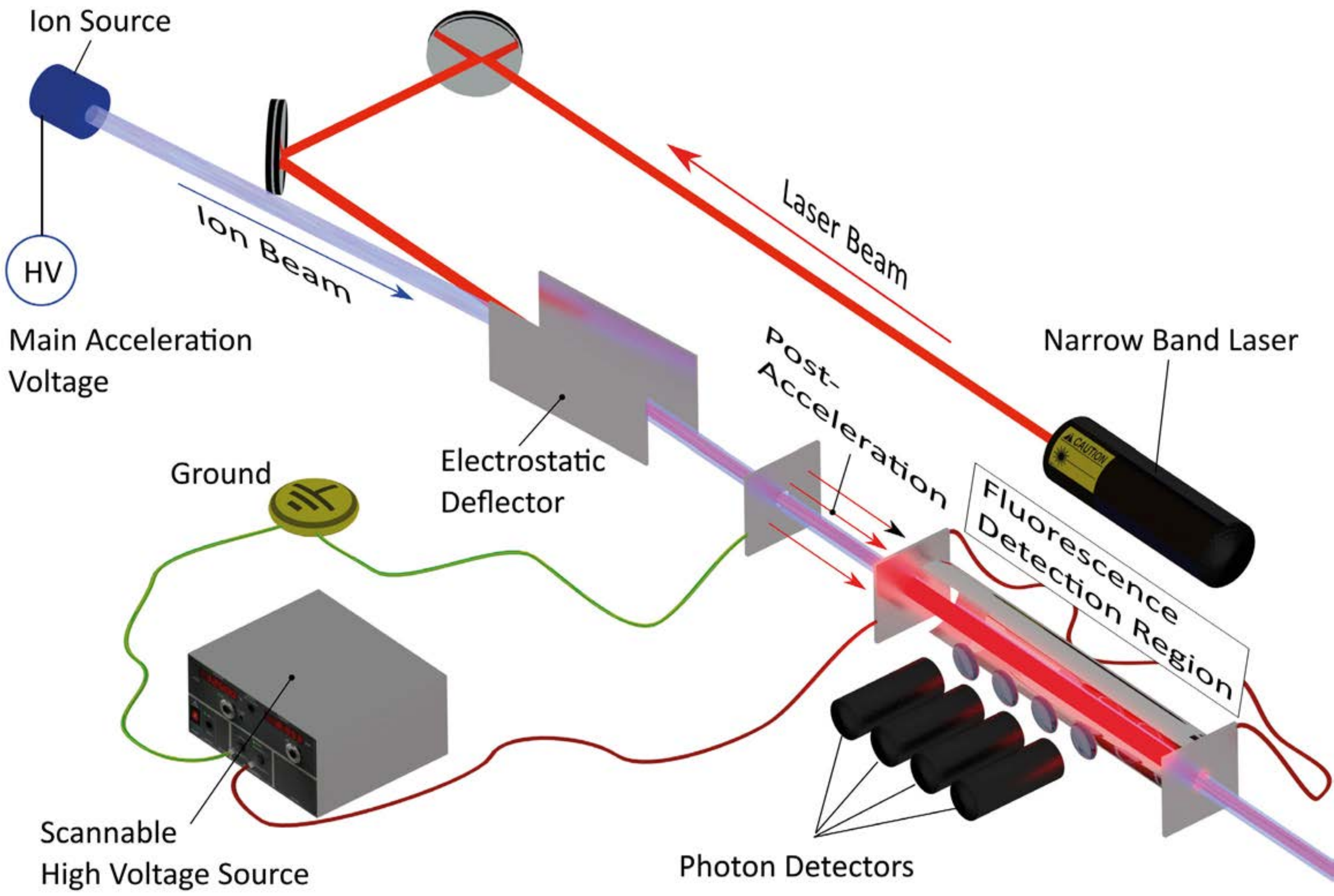
PROPERTIES OF NUCLEI PROBED BY LASER LIGHT

Rainer Neugart – DOI: https://doi.org/10.1051/epn/2017201
Institut für Kernchemie, Universität Mainz, D-55128 Mainz, and Max-Planck-Institut für Kernphysik – D-69117 Heidelberg, Germany

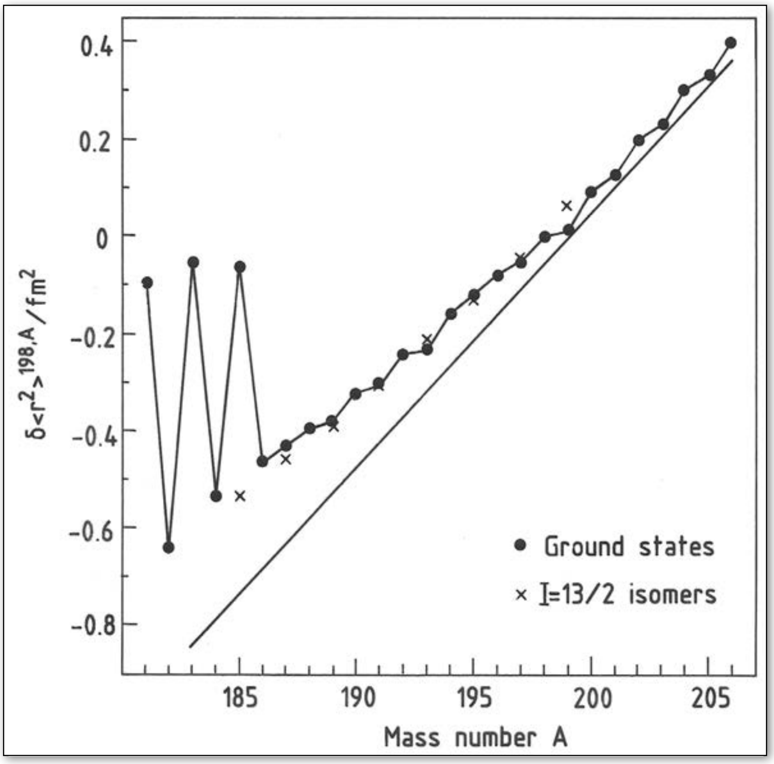
Viewing objects as small as atomic nuclei by visible light sounds quite unrealistic. However, nuclei usually appear as constituents of atoms whose excitations are indeed associated with the absorption and emission of light. Nuclei can thus interact with light via the atomic system as a whole.



Early in the past century it was discovered that basic properties of nuclei influence the atomic spectra. Energy levels of atoms with an odd number of protons or neutrons exhibit hyperfine structure [1]. This was found to arise from a nuclear magnetic moment interacting with the magnetic field produced by the shell electrons. The magnetic moment is associated with a characteristic angular momentum quantum number, called nuclear spin. Both these quantities characterize a nucleus and are related to the orbital of an unpaired nucleon.

Improved spectroscopic resolution even revealed the tiny effect of a nuclear quadrupole moment interacting with the electric-field gradient from the electrons. Quadrupole moments reflect a non-spherical nuclear shape. The so-called deformation occurs by the influence of the shell structure on the collective behaviour of the nucleons. For symmetry reasons, nuclei with spin 0 or 1/2 have vanishing quadrupole moments, independent of intrinsic deformation.

Finally it was found that the wavelengths of spectral lines are slightly shifted between different isotopes. For light elements, this effect arises mainly from differences in nuclear mass. But an additional shift dominates in heavier nuclei, caused by different sizes of the nuclei influencing the Coulomb interaction between the nucleus and the electrons. More precisely, isotope shifts probe differences in the mean square nuclear charge radius $\delta\langle r^2\rangle$, a quantity which is sensitive to deformation, independently of the spin. It thus provides information complementary to the quadrupole moments.



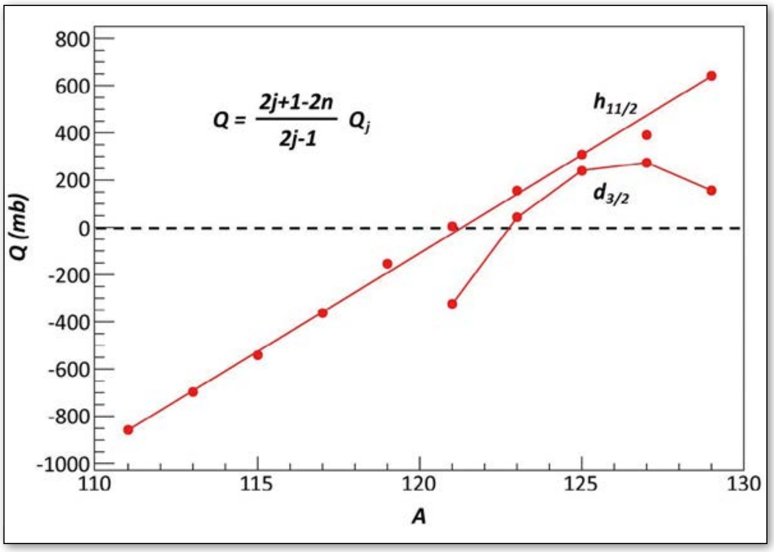
▲ **FIG. 1: Development of mean square nuclear charge radii of neutron-deficient mercury isotopes (from [3]). Plotted is the difference in $\langle r^2\rangle$ between isotopes with mass number *A* and the stable ^{198}Hg.**

Exotic nuclei

For about three decades, up to the seventies, a variety of magnetic-resonance experiments yielded rich data on nuclear moments of stable and some long-lived radioactive nuclei [1]. These played an important role for the development of nuclear models, in particular the shell model. Radioactive nuclei with unusual neutron-to-proton ratio came into view with the issue of stability of nuclear systems. Such nuclei also play a key role for the synthesis of elements in stellar atmospheres. The question arises whether established nuclear models are still valid for nuclei far off stability. These nuclei – sometimes called exotic nuclei – have short half-lives down to seconds or even milliseconds and can be produced only in tiny quantities. Measuring their properties requires very high sensitivity and this is where optical spectroscopy reappears on the scene, soon in combination with the new tool of tunable laser light sources.

First experiments on short-lived radioactive nuclides were performed at the ISOLDE (CERN) on-line isotope separator facility, still using conventional light sources (see [2]). The spectacular results of this work on the neutron-deficient mercury isotopes (Fig. 1) boosted all further efforts enormously. From the isotope shifts in the famous 253.7 nm line, the charge radii were found to decrease gradually as expected, from the stable isotopes (like, *e.g.*, ^{202}Hg) down to ^{186}Hg. This trend continues for the even isotopes, but ^{185}Hg, ^{183}Hg, and ^{181}Hg exhibit much larger radii, comparable with the stable isotopes which have about 15 more neutrons. Theoretical considerations suggested a sudden shape change to be responsible for this effect: Depending on the even or odd number of neutrons, the nuclei are nearly spherical or strongly deformed. Both shapes even coexist in the same nucleus: ^{185}Hg has a strongly deformed spin-1/2 ground state, but a spherical spin-13/2 isomer. Very recent measurements on more neutron-deficient isotopes used the laser ion source at ISOLDE as an extremely sensitive spectroscopic tool. They show a disappearance of the strong odd-even effect beyond ^{181}Hg, confirming theoretical expectations.

The early work on mercury took advantage of large hyperfine structure and isotope shift effects. It was still based on methods of classical optical spectroscopy, limited in resolution by the Doppler broadening of spectral lines. However, most elements require much better resolution for accurate measurements of hyperfine structure and isotope shift. With tunable narrow-band cw lasers, new laser spectroscopy methods reached natural linewidth resolution in the 10 MHz range for strong optical transitions, typically two orders of magnitude below the Doppler width. On top of this comes the unbeatable sensitivity due to a high cross-section of optical resonance, given by just the wavelength: $\sigma = \lambda^2/(2\pi)$. Transitions are easily saturated with the laser power available and detection is readily achieved by counting photons from the decay of excited states. Today, the accessible spectral range covers all relevant wavelengths, from about 200 nm to 1 μm, for hyperfine spectroscopy on the isotopes of most chemical elements.



▲ **FIG. 2:** Quadrupole moments of cadmium isotopes (isomers) in the $h_{11/2}$ and $d_{3/2}$ neutron shells [9].

Nuclide production and Laser spectroscopy

A modern version of the chart of nuclides shows the enormous progress made in the exploration of the nuclear landscape and the production of nuclei far from stability. In addition to about 300 stable isotopes more than 3000 radioactive nuclei have been produced and are being investigated. Of the different production schemes we only discuss here the on-line isotope separator (ISOL) approach that has decisively influenced the implementation of laser spectroscopy techniques, in particular the ISOLDE facility [4] at CERN. Such facilities use unspecific high-energy (~ 1 GeV) nuclear reactions in a thick heated target from which the products are released and ionized. Low-energy (~ 50 keV) beams of individual isotopes are selected by magnetic mass separation and guided to different experimental stations. Using this principle ISOLDE has been an outstanding installation for nearly 50 years.

The concept of collinear laser spectroscopy [5] emerged from discussions about a suitable method to be used with ISOL beams. Such beams, obtained by acceleration in a static electric field and merged with a laser beam, naturally provide narrow Doppler width comparable to typical natural linewidths [6]. This is a consequence of the energy being proportional to the square of the velocity: Increasing all ion energies by the same amount conserves the energy spread and thus compresses the velocity distribution in the beam. The Doppler shift can be used to tune the (rest-frame) laser frequency across a resonance structure by slightly changing the velocity of the ions. The requirement of high sensitivity is met by the Doppler width matching the natural linewidth, meaning that optical resonance occurs simultaneously for all ions. Sensitivity is finally limited by the efficiency of fluorescence photon detection in the presence of background from scattered laser light. If neutral atoms offer more favourable spectroscopic conditions than singly-charged ions, the beam may be neutralized by charge exchange with alkali atoms in a vapour cell. Due to a high cross-section this process hardly affects the beam quality.

Over 30 years, collinear laser spectroscopy has provided rich information on the electromagnetic properties, radii and shapes of unstable nuclei. It is virtually impossible to show a representative choice of experimental approaches [7] and results [8]. Spins provide basic information for the classification of nuclei, while magnetic moments serve as a probe of the nuclear wave functions within a particular model. Quadrupole moments have often been interpreted qualitatively in terms of collective deformation. Nowadays, multi-configuration shell-model descriptions have succeeded to explain them on a microscopic basis, at least up to the mid-mass region approaching Z = 50.

Two recent examples

Recent measurements on the cadmium isotopes shed light on an early prediction of quadrupole moments across a complete nucleon shell. ISOLDE provides viable cadmium yields up to the "magic" neutron number N = 82, representing an excess of 16 neutrons over stable ^{114}Cd. Laser spectroscopy was performed in the Cd^+ ion [9] for the isotopic chain from ^{106}Cd to ^{130}Cd. The required laser wavelength of 214.5 nm was obtained by quadrupling the output frequency of a titanium sapphire laser.

Favourably it turns out that all odd-A nuclei from N = 63 to 81 have a spin-11/2 isomeric state. This offers the possibility of studying the unpaired neutron while gradually filling the complete $h_{11/2}$ shell. The measured quadrupole moments are shown in Fig. 2. Most striking is their perfect linear increase with neutron number, from negative to positive values. Such behaviour,

> **The question arises how well we understand the properties of nuclei far off stability, which have half-lives down to seconds or even milliseconds. Are established nuclear models still valid for nuclei with a large neutron or proton excess?**

predicted by a simple shell model, was suggested by experimental data, but never observed as beautifully. Theory will have to explain how a simple linear relationship can describe complex nuclei and why it spans 10 odd isotopes instead of 6 as would be expected for the sequential filling of the shell.

For a long time nuclear radii were interpreted in terms of phenomenological models of a deformed liquid drop of nuclear matter. These usually failed to explain details of the measured radii variations. Only for the lightest nuclei with nucleons in the lowest s and p shells microscopic approaches have now succeeded to predict the measured radii impressively well. These are based on realistic two- and three-nucleon interactions between individual nucleons.

Disclosing the tiny effect of charge radii in the isotope shifts of beryllium required a dedicated experimental approach, because the voltage measurements of Doppler shifts are not sufficiently accurate. The problem can be circumvented by precisely measuring resonance frequencies ν_c for a collinear and ν_α for an anti-collinear laser beam applied simultaneously. Relativistic formulas then yield the rest-frame atomic transition frequency $\nu_0 = \sqrt{\nu_c \nu_\alpha}$. In this way the absolute transition frequencies as well as the isotope shifts for ^{7}Be to ^{12}Be were measured to about 0.1 MHz [10]. The determination of radii changes from the total isotope shifts then depends on accurate mass shift calculations for the atomic 3-electron system of Be+ [11].

The results of Figure 3 show decreasing charge radii from ^{7}Be to ^{10}Be and a marked increase towards ^{11}Be [10] and ^{12}Be [12]. The observed trends are well reproduced by several advanced theoretical models. The results from "Fermionic Molecular Dynamics (FMD)" calculations even provide a descriptive explanation of the effects seen in the radii and illustrated in the lower part of the figure. The essence is a cluster structure with ^{7}Be built of ^{3}He and ^{4}He (α particle), and the remaining isotopes of two α particles and additional neutrons. While two α particles (corresponding to ^{8}Be) do not form a bound system, additional neutrons act as glue which is stronger for ^{10}Be than for ^{9}Be. The increased charge radius for ^{11}Be is explained by the influence of a weakly bound halo neutron whose wave function extends far beyond the nuclear core [13], thus widening the proton distribution by the centre-of-mass motion. For ^{12}Be the further increase is related to a quenched N = 8 neutron shell effect.

We have shown how laser light has become an invaluable tool of nuclear structure physics. With newly developed atomic spectroscopy techniques it revived the traditional access to nuclear spins, moments and charge radii for wide ranges of nuclei, from heaviest to lightest and from stable to short-lived isotopes far from stability. ■

About the author

Rainer Neugart was teaching experimental physics at the University of Mainz. He introduced collinear laser spectroscopy at ISOLDE (CERN) and for many years he has carried out experiments exploring the properties and the structure of unstable nuclei.

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▾ **FIG. 3:** Beryllium nuclear charge radii and underlying cluster structure from FMD calculations. Protons are shown in red, neutrons in blue (Courtesy R. Sánchez).