Listening to electrons 'talk': Lithium-like tin's g-factor measured with 0.5 parts per billion experimental accuracy

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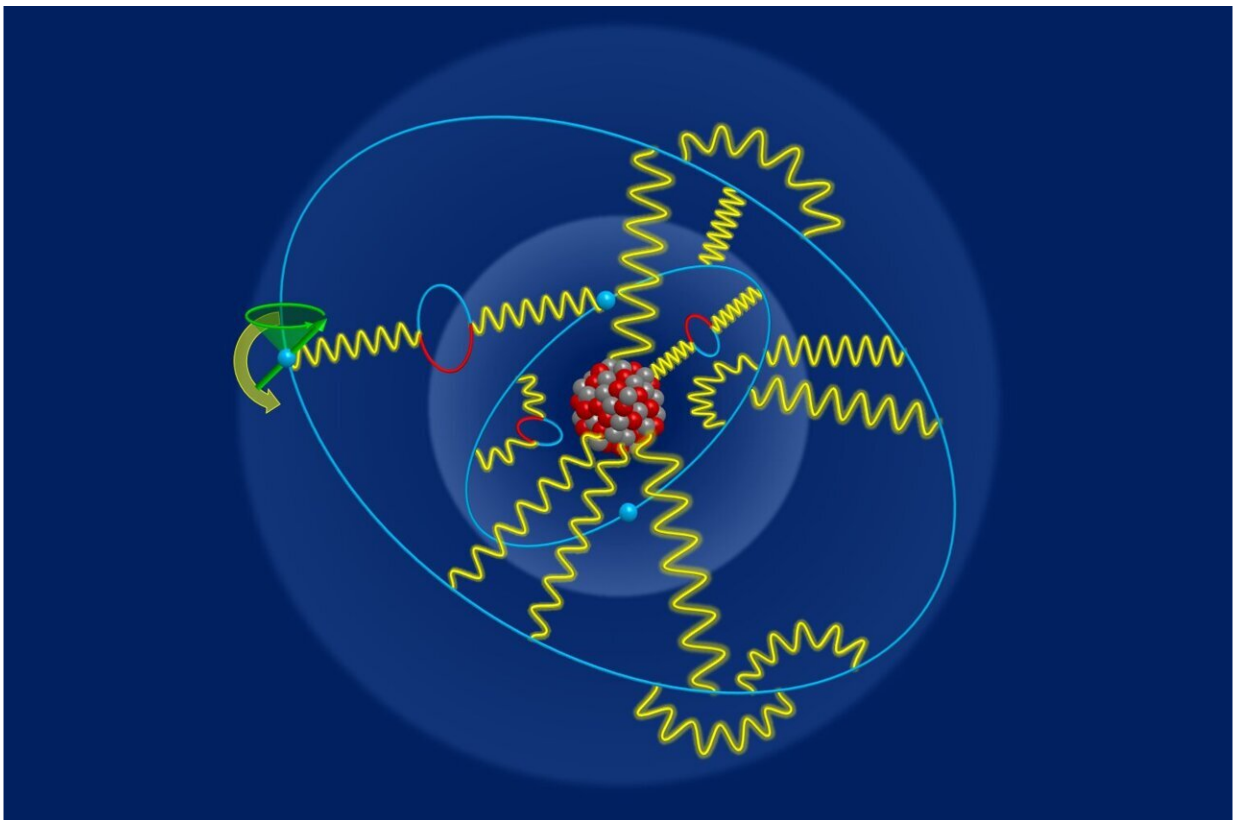


Schematic illustration of the QED interactions in lithium-like tin ions. Credit: MPIK

Researchers from the Max-Planck-Institut fuer Kernphysik present new experimental and theoretical results for the bound electron g-factor in lithium-like tin, which has a much higher nuclear charge than any previous measurement. The paper is published in the journal *Science*.

The experimental accuracy reached a level of 0.5 parts per billion. Using an enhanced interelectronic QED method, the theoretical prediction for the g-factor reached a precision of 6 parts per billion.

Quantum electrodynamics—a competition area for precision

Quantum electrodynamics (QED) is the fundamental theory describing all electromagnetic phenomena including light (photons). At the same time, it is the most precisely tested theory in physics at all.

It has been stringently tested in various ways up to 0.1 parts per billion. But it is just the very strength of this theory that drives physicists to test it even more rigorously and to explore its possible limits. Any significant deviation would be a hint for new physics.

QED understands the electromagnetic interaction among charged particles as the exchange of "virtual" photons—the way electrons in an atom "talk" to each other and to the nucleus—and with themselves via emission and reabsorption of a photon, a QED effect called "self energy."

Furthermore, it turned out that the physical vacuum is not empty but filled with virtual particles such as electron-positron pairs, which appear all the time "out of nothing" but have to disappear within the limits set by the uncertainty principle of quantum physics.

Though this might sound spooky, it is just the way to explain the underlying physics of experiments performed in atomic physics already in the 1940s.

A state-of-the-art access to QED phenomena is the so-called g-factor of the electron, which describes the relation of its mechanic (intrinsic angular momentum: spin) and magnetic properties. According to Dirac's theory (relativistic quantum mechanics), the g-factor of the free electron should be exactly 2.

However, various QED interactions change the g-factor and lead to a small but precisely measurable deviation from the value 2. QED effects depend in a strong nonlinear way on external fields.

Electrons experience the extremely high electric field due to the high nuclear charge in heavy elements. The simplest systems are hydrogen-like highly charged ions, which have been investigated both theoretically and experimentally with great success.

In a joint collaborative experimental-theoretical work, researchers at the Max Planck Institute for Nuclear Physics in Heidelberg have now investigated the g-factor of the outermost bound electron in lithium-like tin. This system is similar to hydrogen but adds the interaction with the two tightly-bound electrons of the inner atomic shell.

Theory: ab initio QED calculations

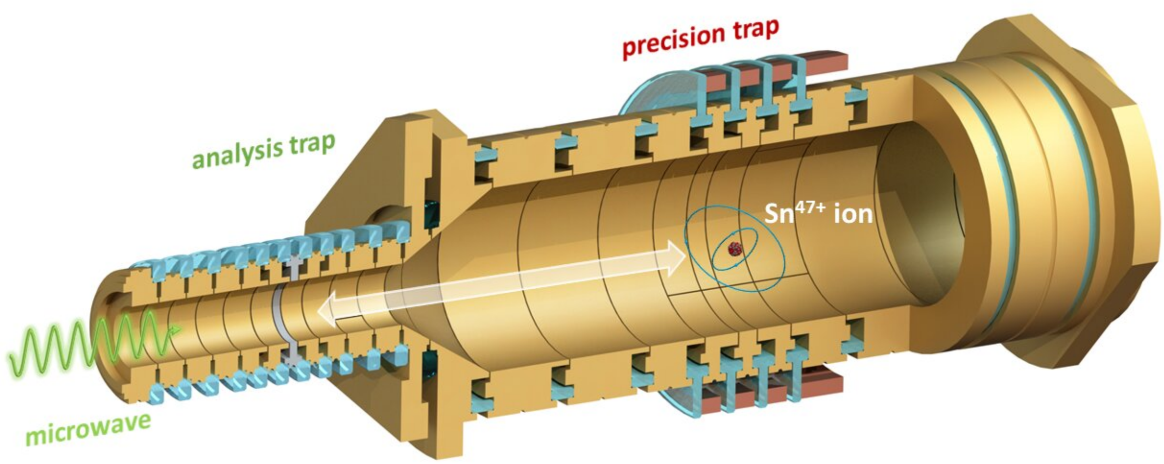
An ab initio calculation takes into account all electromagnetic interactions among the constituents—here of a lithium-like ion—on a fundamental level, including QED effects up to a certain degree.

Electron structure effects where the electrons exchange photons are incorporated into the calculations, as well as QED screening effects, where the electron interacts both with the other electrons and with itself or with the vacuum.

The ab initio prediction has been further improved by using the two-loop QED contribution extracted from the recent measurement in hydrogen-like tin [33] scaled to the lithium-like electron case. This yields an "experimentally enhanced" theoretical prediction of

g_{th} = 1.980 354 797(12)

with the uncertainty given in parentheses. Compared to the hydrogen-like case, this is overall a 25-fold improvement.



Sketch of the ALPHATRAP Penning ion trap with the precision trap for the measurement of the ion motion frequencies and the analysis trap for spin detection. Credit: MPIK

Experiment: Counting spin flips

The measurement of the g factor of the bound electron was performed using the cryogenic Penning trap ALPHATRAP at MPIK. The strong magnetic field inside the trap leads to a characteristic motion of the ion confined by the field as well as to a precession of the spin of the outer electron like a tiny magnetic spinning top.

The g factor can be extracted from the ratio of the ion's motional frequency and the precession frequency while the magnetic field is eliminated from this calculation. The ion motion can be detected directly from small induced electric signals in the trap electrodes of the "precision trap."

To determine the precession frequency, microwave radiation is sent into the trap which can induce a spin flip, a change of the orientation of the spin (due to quantization there are only two measurable spin states, "up" and "down"). The rate of spin flips reaches a maximum when the microwave matches resonantly the precession frequency.

Results and outlook

The experimental value for the g factor of the lithium-like tin ion is

$$g_{exp} = 1.980\ 354\ 799\ 750(84)_{stat}(54)_{sys}(944)_{ext}$$

with the statistical, systematic and external uncertainties given in parentheses. The external uncertainties are dominated by the ion mass uncertainty, currently limiting the experimental accuracy.

The overall accuracy is 0.5 parts per billion. The experimental result agrees well with the theoretical prediction given above within the uncertainty of the calculation.

On the experimental side, it is feasible to improve the precision of the mass value by more than an order of magnitude and consequently enhance the precision of the g factor if motivated by advancements in theory.

In the future, measurements of heavier lithium-like systems such as $^{208}Pb^{79+}$ and the expected progress in two-loop QED calculations will provide even better tests in the strong electric field regime using highly charged ions.

The advanced theoretical methods developed here for interelectronic QED effects can be applied to g-factor calculations of more complex ions (boron- or carbon-like), parity non-conserving transitions in neutral atoms and other effects.

More information: Jonathan Morgner et al, Testing inter-electronic interaction in lithium-like tin, *Science* (2025). DOI: 10.1126/science.adn5981.
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