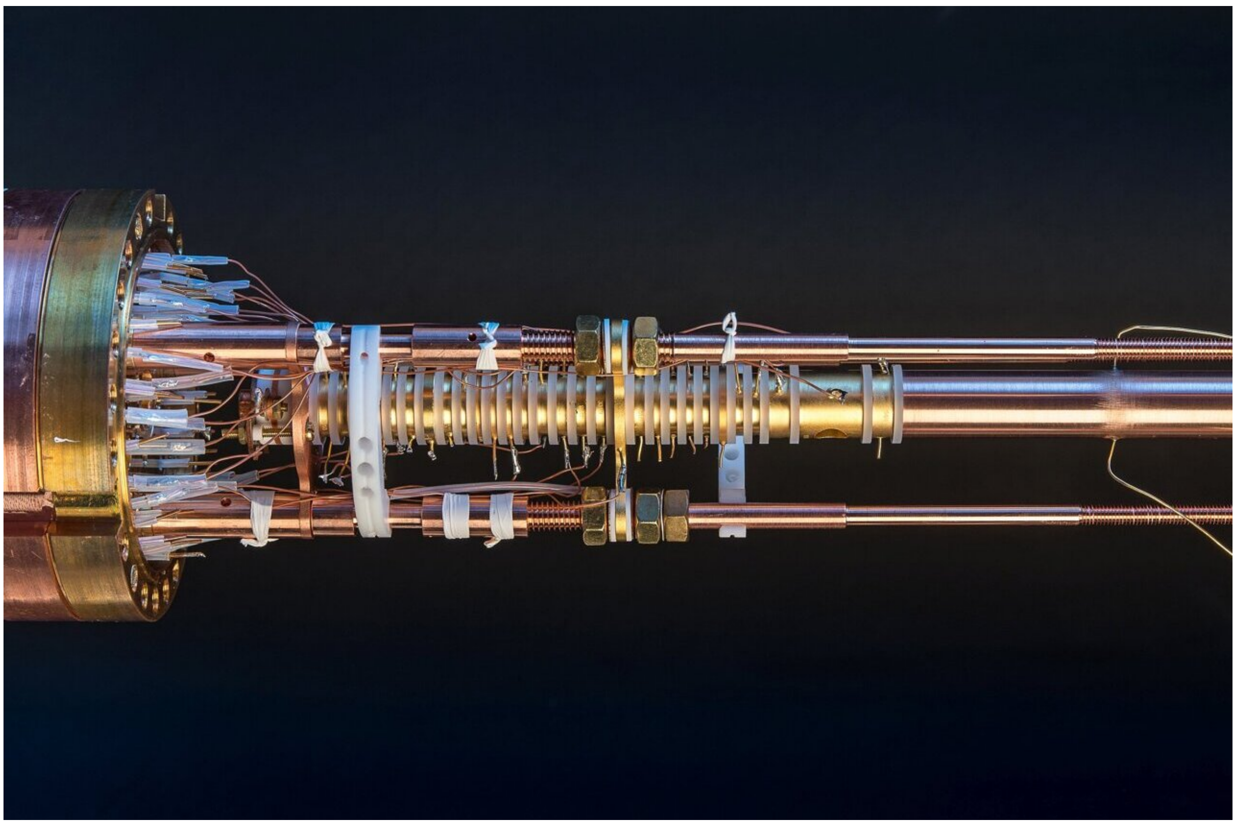
Researchers precisely measure effect of electromagnetic shielding in beryllium atoms

August 19 2024



Penning ion trap used for determining the nuclear magnetic properties of ^{9}Be. Credit: MPIK

The electron shell of atoms acts as an "electromagnetic shield," preventing direct access to the nucleus and its properties. A team in the group of Klaus Blaum, director at the Max Planck Institute for Nuclear Physics in Heidelberg, has now succeeded in precisely measuring the effect of this shielding in beryllium atoms. The study is published in the journal *Nature*.

The magnetic moment of beryllium-9 was determined with 40 times better precision than before. Such precision measurements are not only relevant to fundamental physics, they also help us gain insight into certain applications of nuclear magnetic resonance, which are applied in chemistry and for the highly accurate measurements of magnetic fields.

"Shields up!": This command is familiar to fans of "Star Trek." Something similar is known to natural science researchers—the electromagnetic shell serves as a protective shield that typically hinders access to its nucleus. This has consequences in chemistry, for example, where chemical properties are investigated by nuclear magnetic resonance.

This method is akin to magnetic resonance imaging. However, instead of producing images of a living body, it provides a highly precise chemical fingerprint of the material being studied. Both methods use strong magnetic fields and base on the fact that some nuclei are small magnets—like tiny compass needles.

In a strong magnetic field, they can start to spin in a circular motion. Like in a class room experiment with an induction coil through which a magnet is moved, this movement of the atom interacts with the surrounding electron shell. As the electrons make up the chemical bonds, the signal of the precessing atomic nuclei gives very precise information on their chemical surroundings.

The three-body problem

Now, one might think that in modern physics, the magnetic moment of a nucleus and the shielding effect of the electron shell could be calculated accurately. However, this is not the case, confirms Zoltan Harman, who is responsible for such theoretical calculations at the institute in Heidelberg. The reason—as is often the case—is the fundamental problem that calculations for systems consisting of more than two bodies can not be performed exactly.

This applies to planetary orbits in stellar systems as well as to atoms, whose electrons can only be in certain quantized energy orbitals around the nucleus. In addition, an atomic nucleus itself cannot be calculated exactly. Even the simplest nucleus, the single proton in hydrogen, consists of three quarks that interact with each other in complex ways.

"Theoreticians can therefore only calculate such a nuclear moment to an uncertainty of about one per thousand," says Stefan Dickopf. For applications in nuclear magnetic resonance and fundamental physics, high-precision experiments are therefore important in order to measure such properties much more accurately than calculations can.

Klaus Blaum's team has developed a method with world-class performance using so-called Penning traps. It makes it possible to measure the magnetic properties of an atomic nucleus very precisely. Stefan Dickopf, the lead doctoral student in the team headed by Andreas Mooser, has now carried out such measurements on the isotope beryllium-9.

Why beryllium-9 is so interesting

But why beryllium, the number four element in the periodic table? There are several reasons for this, explains Dickopf, one of which is: "It has a small atomic nucleus, which is why certain corrections that are required for larger atomic nuclei are not necessary." Above all, however, it is close to element number two, helium. This plays an important role with regard to applications in nuclear magnetic resonance.

If one wants to carry out precision measurements there, first the magnetic field needs to be accurately measured inside the apparatus. This accuracy plays a decisive role in the subsequent analysis.

A suitable "probe" for these magnetic field measurements is the helium isotope helium-3. Blaum's team has already been able to measure its magnetic moment very precisely in a Penning trap, which *Nature* published in 2022. However, they had to remove an electron from the helium-3.

This is because a Penning trap can only work with an electrically charged ion that is trapped for months with a combination of a complex-shaped electric field and a strong magnetic field. Nuclear magnetic resonance methods, on the other hand, work with neutral helium-3 as a probe, which poses a problem. Says Dickopf, "The shielding by two electrons is not well understood."

This motivated the Heidelberg team to carry out a similar measurement with beryllium-9. To do this, the team removed three electrons from it, leaving only one electron. The cross-comparison with already established measurements of the nuclear magnetic moment on beryllium, from which fewer electrons were removed, provided key data on the exact shielding effect of the electrons. This in turn allows conclusions to be drawn about the shielding in neutral helium-3.

The beryllium-9 ion with only one "residual electron" was also the focus of attention because it is a "hydrogen-like" system, explain Dickopf and Harman. As the atomic nucleus is small, it can be considered a good approximation as a single unit, in effect like a tiny compass needle. Together with the only remaining electron, it almost forms a theoretically exactly calculable two-body system.

According to Haman, the electron can now be used as an antenna to measure the magnetic moment of the beryllium-9 nucleus. "This is roughly 26 orders of magnitude, i.e., one hundred millionth of a billionth of a billionth, weaker than a compass needle," says Dickopf, outlining the challenge.

Second most accurate measurement of a nuclear magnetic moment

Like all precision measurements, the measurement in a Penning trap is based on the fact that a repetitive movement can be counted precisely—just as a clock counts the pendulum swings via its movement. The ion rotates on a circular orbit in the strong magnetic field of the trap, and this "cyclotron frequency" allows the counting electronics to measure the magnetic field of the trap itself very precisely. This is essential for a precise measurement of the magnetic moment.

Now the orientation of the nuclear moment must be measured as a tiny compass needle in the magnetic field. The decisive factor here is how the energy of the nuclear moment changes in the magnetic field between two different orientations permitted by quantum physics. This information is provided by other frequencies that occur within this measurement method. However, this signal is extremely weak. The electron as a small antenna close to the nucleus amplifies it and thus makes these frequency measurements possible in the first place.

"In this way, we succeeded in performing the second-most precise measurement, after the proton, of a nuclear magnetic moment with beryllium-9," says Dickopf. The experiment also provided the first precise data on the shielding effect of several electrons, which can now be transferred to helium-3. This will help to make certain nuclear resonance applications even more precise.

The results from Heidelberg are therefore a double win, both for fundamental physics and for applications in the precise measurement of magnetic fields.

More information: Stefan Dickopf et al, Precision spectroscopy on ^{9}Be overcomes limitations from nuclear structure, *Nature* (2024). DOI: 10.1038/s41586-024-07795-1

Provided by Max Planck Society