Revealing secrets of atomic nuclei

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Individual proton or neutron in outermost shell of large atomic nucleus turns out not to behave according to the predictions made by existing theoretical models. This surprising conclusion was reached by an international team of physicists including staff members from the Faculty of Physics at the University of Warsaw. Credit: ©Faculty of Physics, University of Warsaw

Individual protons and neutrons in atomic nuclei turn out not to behave according to the predictions made by existing theoretical models. This surprising conclusion, reached by an international team of physicists including staff members from the Faculty of Physics at the University of Warsaw (UW), forces us to reconsider how we have been describing large atomic nuclei for the past several decades.

Atomic nuclei shape the nature of our reality: around 99.9% of the mass of all matter is contained within them. Yet in spite of their ubiquity and significance, they still remain relatively poorly understood by contemporary physics. The main barrier to formulating a consistent theoretical description of atomic nuclei is the complexity of the interactions between their component particles, namely protons and neutrons. The situation becomes even more complicated when the nucleus contains a high number of particles. Writing in the prestigious physics journal *Physical Review Letters*, a team of scientists from Poland (UW Faculty of Physics), Finland and Sweden have demonstrated that we have to modify the existing model of atomic nuclei containing a significant and almost magic number of both protons and neutrons.

"We have shown that one of the two main physical factors taken into consideration in our models of certain large atomic nuclei is not actually all that significant. In practice, this means that the physics of such nuclei operate in a slightly different way than previously thought," says Prof. Jacek Dobaczewski from the Institute of Theoretical Physics at the UW Faculty of Physics.

When physicists describe the motion of electrons in atoms, they generally assume that they move in an electrostatic field originating from the neighbouring electrons and from the distant atomic nucleus. The model predicts the formation of distinct electron shells with different capacities: the first can fit the maximum of 2 electrons, with 8 on the second, 18 on the third, and so on. Physicists also apply a similar model to the atomic nuclei themselves; however, this is made more difficult by the complex interactions between subatomic particles within the nucleus.

"In atoms, each electron is located at a great distance from other electrons and the atomic nucleus. As such, we can safely assume that distinct electrons move in a single, averaged field of interactions originating from the remaining atomic components. However, protons and neutrons in atomic nuclei are very close together, and they all exist in a field which they also actively shape," explains Dr. Dimitar Tarpanov (University of Warsaw).

As is the case with electrons, the averaged-field model predicts the existence of shells within the nucleus - shells with the greatest probability of a proton or a neutron being found there. Subsequent nuclear shells are complete when they contain 2, 8, 20, 28, 50, 82, and 126 protons (the same numbers apply to neutron shells). Additional filled shells appear at levels 114, 120 and 126 for protons, and 184 for neutrons. These are known as "magic" numbers; an atomic nucleus is dubbed as being "double magic" when it contains a magic number of protons alongside a magic number of neutrons.

The researchers were especially interested in situations where an atomic nucleus is in an almost double magic state: one of the shells is complete, whereas the next, outermost shell contains just a single proton or neutron. The question was, what interactions will determine the motion of this "lonely" particle?

For several decades now, in order to remain consistent with measurements taken in physics laboratories around the globe, in addition to the averaged field the existing model of large atomic nuclei has taken account of additional effects: the vibrations and motions of nucleons caused by quantum effects. In certain cases, such vibrations may even affect the appearance of a nucleus by flattening it slightly or rendering it pear-shaped. Such modifications would also have to affect the field of motion of a solitary proton or neutron moving in the outermost shell of the atomic nucleus.

Physicists have used experimental data available for double magic nuclei of oxygen 16O, calcium 40Ca and 48Ca, nickel 56Ni, tin 132Sn and lead 208Pb, as well as for nearly double magic nuclei such as 207Pb and 209Pb. The data were used to precisely fit various parameters used in the existing model. Theoretical analysis leaves no doubt: quantum effects and the vibrations that go with them turn out to have a significantly lower effect on the motion of individual particles in the nuclear shell than previously thought.

"This is a fascinating result. Since quantum effects in a nucleus as large as 209Pb are not terribly significant, that means that the existing model of the average field itself does not fully reflect reality. There is something we are failing to take into account. I wonder what that is...?" adds Prof. Dobaczewski.

Such work on devising a precise and consistent description of phenomena occurring in light, heavy and superheavy atomic nuclei has significant practical applications. Our understanding of the physics of atomic nuclei is used in the construction of nuclear power plants, the design of future thermonuclear power plants, the military, nuclear medicine, tissue imaging, and in diagnostics and cancer therapies. Furthermore, nuclear processes and interactions are fundamental to the way we describe stars in the Universe. Theoretical methods developed to describe the interactions of many particles in atomic nuclei also have numerous applications in nuclear physics and condensed matter physics, and also in quantum chemistry, in the spectral analysis of excited states of atomic nuclei, atoms and molecules.

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Physics and Astronomy first appeared at the University of Warsaw in 1816, under the then Faculty of Philosophy. In 1825 the Astronomical Observatory was established. Currently, the Faculty of Physics' Institutes include Experimental Physics, Theoretical Physics, Geophysics, Department of Mathematical Methods and an Astronomical Observatory. Research covers almost all areas of modern physics, on scales from the quantum to the cosmological. The Faculty's research and teaching staff includes ca. 200 university teachers, of which 88 are employees with the title of professor. The Faculty of Physics, University of Warsaw, is attended by ca. 1000 students and more than 170 doctoral students.

More information: "Spectroscopic properties of nuclear Skyrme energy density functionals"; D. Tarpanov, J. Dobaczewski, J. Toivanen, B.G. Carlsson; *Physical Review Letters* 113, 252501 (2014); DOI: dx.doi.org/10.1103/PhysRevLett.113.252501

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