36 in one fell swoop: researchers observe 'impossible' ionization

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World’s most powerful X-ray laser kicks record number of electrons out of an atom

Using the world's most powerful X-ray laser in California, an international research team discovered a surprising behaviour of atoms: with a single X-ray flash, the group led by Daniel Rolles from the Center for Free-Electron Laser Science (CFEL) in Hamburg (Germany) was able to kick a record number of 36 electrons at once out of a xenon atom. According to theoretical calculations, these are significantly more than should be possible at this energy of the X-ray radiation. The team present their unexpected observations in the journal "Nature Photonics". CFEL is a collaboration of DESY, the Max Planck Society and the University of Hamburg.

When an atom loses electrons, it acquires a positive electric charge – it becomes ionized. This ionization is stronger the more electrons are torn from the atom. The researchers led by Rolles, who is working in the Max Planck Advanced Study Group at CFEL, had fired intense X-ray laser flashes from the Linac Coherent Light Source (LCLS) at the US National Accelerator Laboratory SLAC in California at atoms of the noble gas xenon. With 1.5 kiloelectronvolts (1.5 keV), the particles of light (photons) of the X-ray radiation had around a thousand times more energy than visible light. When such a high-energy photon hits an electron in the xenon atomic shell, its energy is transferred to the electron. Through this collision, the electron can be ejected from the atomic shell – depending on how strongly it is bound.

According to calculations, up to 26 of the 54 electrons of the noble gas could be kicked out at the energy employed, the remaining are too strongly bound. In fact, however, the researchers found that up to 36 electrons flew from the atoms. "To our knowledge, this is the highest ionization that has ever been achieved in an atom using a single electromagnetic pulse," says Rolles, who will lead a Helmholtz Young Investigators group at DESY in the future. "Our observation shows that the existing theoretical approaches have to be modified."

What causes the "impossible" ionization is a so-called resonance: in the energy range used, xenon electrons can absorb a lot of X-ray radiation. Some are thus directly ejected from the atom, while others go into an excited, i.e. more energetic, state, but are still bound to the atom. When one of the excited electrons returns to its initial state, in turn energy is released, which can give another excited electron the necessary extra nudge to kick it out of the atom. In rare cases, the already excited electron is hit by a second photon from the X-ray flash, and so ejected from the atomic shell.

"The LCLS experiment produced an unexpected and unprecedented charge state by ejecting dozens of electrons from an atom," says graduate student and co-author Benedikt Rudek from the Max Planck Advanced Study Group and the Max Planck institute for nuclear physics in Heidelberg, who analysed the data. "The absorbed energy per atom was more than twice as high as expected." This resonance effect is particularly strong for xenon at an energy of 1.5 keV. Consequently, even at a higher energy of 2 keV, the researchers observed only less strongly ionized atoms. Based on the measurements, the CFEL researchers refined a computational model that allows them to calculate such resonances in heavy atoms. In subsequent experiments, scientists used the LCLS to examine, among others, krypton and molecules that contain heavy atoms, as co-author Artem Rudenko from Kansas State University says, who headed one of these follow-up experiments.

The observations also have practical significance for research: "Our results give a recipe for maximizing the loss of electrons in a sample," says Rolles. This can be desirable or undesirable. "For instance, researchers can use our results if they're interested in creating a very highly charged plasma." When investigating biological samples, however, most researchers should avoid the resonance regions of such heavy atoms. "Most biological samples have some heavy atoms embedded," says Rolles. In the resonance region, such samples can be damaged very quickly in these places, which may affect the image quality.

For their precision measurements the team used a special experimental station that was built by the Max Planck Advanced Study Group (ASG) at CFEL together with the Max Planck institutes for nuclear physics, for medical research and semiconductor laboratory. The CFEL-ASG Multi-Purpose chamber (CAMP) was shipped to SLAC in 40 crates weighing a total of 11 tons and was installed at the LCLS for three years. It was used in more than 20 experiments.

Along with researchers from the Center for Free-Electron Laser Science, several Max Planck institutes, DESY and the US National Accelerator Laboratory SLAC, the study involved scientists from about a dozen institutions in Germany, France, Japan and the USA.

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