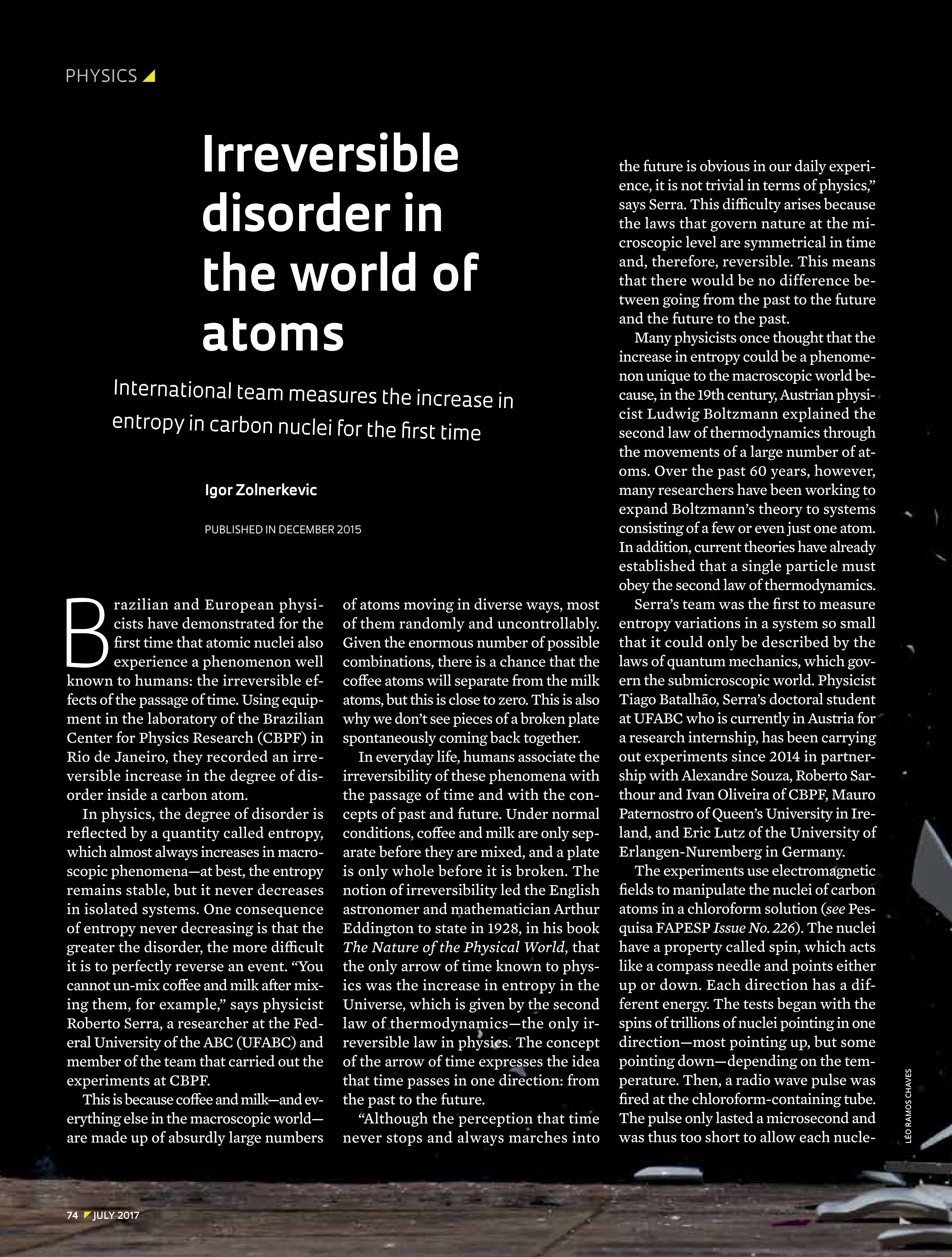

LÉO RAMOS CHAVES

Irreversible disorder in the world of atoms

International team measures the increase in entropy in carbon nuclei for the first time

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Brazilian and European physicists have demonstrated for the first time that atomic nuclei also experience a phenomenon well known to humans: the irreversible effects of the passage of time. Using equipment in the laboratory of the Brazilian Center for Physics Research (CBPF) in Rio de Janeiro, they recorded an irreversible increase in the degree of disorder inside a carbon atom.

In physics, the degree of disorder is reflected by a quantity called entropy, which almost always increases in macroscopic phenomena—at best, the entropy remains stable, but it never decreases in isolated systems. One consequence of entropy never decreasing is that the greater the disorder, the more difficult it is to perfectly reverse an event. “You cannot un-mix coffee and milk after mixing them, for example,” says physicist Roberto Serra, a researcher at the Federal University of the ABC (UFABC) and member of the team that carried out the experiments at CBPF.

This is because coffee and milk—and everything else in the macroscopic world—are made up of absurdly large numbers of atoms moving in diverse ways, most of them randomly and uncontrollably. Given the enormous number of possible combinations, there is a chance that the coffee atoms will separate from the milk atoms, but this is close to zero. This is also why we don’t see pieces of a broken plate spontaneously coming back together.

In everyday life, humans associate the irreversibility of these phenomena with the passage of time and with the concepts of past and future. Under normal conditions, coffee and milk are only separate before they are mixed, and a plate is only whole before it is broken. The notion of irreversibility led the English astronomer and mathematician Arthur Eddington to state in 1928, in his book *The Nature of the Physical World*, that the only arrow of time known to physics was the increase in entropy in the Universe, which is given by the second law of thermodynamics—the only irreversible law in physics. The concept of the arrow of time expresses the idea that time passes in one direction: from the past to the future.

“Although the perception that time never stops and always marches into the future is obvious in our daily experience, it is not trivial in terms of physics,” says Serra. This difficulty arises because the laws that govern nature at the microscopic level are symmetrical in time and, therefore, reversible. This means that there would be no difference between going from the past to the future and the future to the past.

Many physicists once thought that the increase in entropy could be a phenomenon unique to the macroscopic world because, in the 19th century, Austrian physicist Ludwig Boltzmann explained the second law of thermodynamics through the movements of a large number of atoms. Over the past 60 years, however, many researchers have been working to expand Boltzmann’s theory to systems consisting of a few or even just one atom. In addition, current theories have already established that a single particle must obey the second law of thermodynamics.

Serra’s team was the first to measure entropy variations in a system so small that it could only be described by the laws of quantum mechanics, which govern the submicroscopic world. Physicist Tiago Batalhão, Serra’s doctoral student at UFABC who is currently in Austria for a research internship, has been carrying out experiments since 2014 in partnership with Alexandre Souza, Roberto Sarthour and Ivan Oliveira of CBPF, Mauro Paternostro of Queen’s University in Ireland, and Eric Lutz of the University of Erlangen-Nuremberg in Germany.

The experiments use electromagnetic fields to manipulate the nuclei of carbon atoms in a chloroform solution (*see* Pesquisa FAPESP *Issue No. 226*). The nuclei have a property called spin, which acts like a compass needle and points either up or down. Each direction has a different energy. The tests began with the spins of trillions of nuclei pointing in one direction—most pointing up, but some pointing down—depending on the temperature. Then, a radio wave pulse was fired at the chloroform-containing tube. The pulse only lasted a microsecond and was thus too short to allow each nucleus to interact with its neighbors or the environment. Thus, the pulse affected each nucleus separately. “It’s as if each of them were isolated from the rest of the universe,” explains Serra.

The first pulse was made up of waves whose amplitude increased over time, this pulse disturbed the spins of each nucleus, which vibrated quickly and changed direction. Afterwards, the researchers fired a second pulse that was identical to the first one in almost all respects, except that the amplitude of the waves decreased over time, making this pulse a time-inverted version of the first. With the second pulse, they expected that the spin of each nucleus would return to its original state. In fact, the spins returned to a state very close to the initial one. But precise measurements showed that the initial and final states were not equal. There was a discrepancy resulting from transitions between the different energy states of the spins associated with the entropy produced during the process of increasing and decreasing the amplitude of the waves, according to the researchers’ article published in *Physical Review Letters*.

Vlatko Vedral, a physicist at the University of Oxford in the United Kingdom who performs similar experiments using lasers, considers the work a beautiful demonstration of quantum thermodynamics predictions. “But it’s not surprising,” he says. He says he would like to know if the entropy measured on the subatomic scale is produced by phenomena described by the laws of physics or if it is due to some unknown phenomenon acting on the arrow of time. ■

An increase in the degree of disorder in systems makes phenomena irreversible, which is associated with the idea of the passage of time

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Project

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Scientific article

BATALHÃO, T. B. *et al.* Irreversibility and the Arrow of Time in a Quenched Quantum System. **Physical Review Letters**. Nov. 6, 2015

Example of an increase in entropy: one cannot fully, spontaneously reverse the breaking of a plate