

## FORUM Theoretical physics

# Sizing up atoms

Niels Bohr's model of the structure of the atom raised the question of how large an atom can be. One hundred years on, the issue is still unresolved. Two physicists discuss the theoretical limits of atomic and nuclear size.

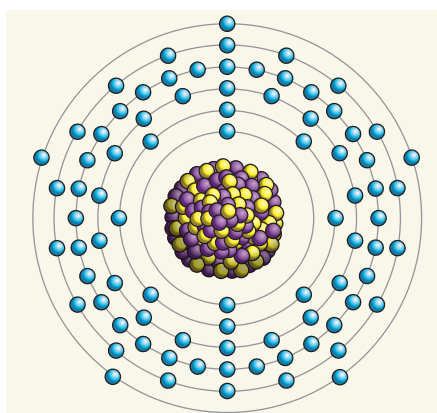
## Orbital arguments

PAUL INDELICATO

Bohr's model of the atom<sup>1</sup> (Fig. 1) provided a new way of thinking about atomic size. For example, it predicted that the radius of the smallest atom, hydrogen, in its ground state was  $0.5 \times 10^{-10}$  metres, 100,000 times larger than the size of the nucleus. This value, known as the Bohr radius ( $a_0$ ), was remarkably accurate and is now one of the fundamental constants of atomic physics. The model also proposed that the speed of an electron in the inner orbital of an atom was approximately  $Zc\alpha$  (where  $Z$  is the proton number,  $c$  is the speed of light and  $\alpha$  is the fine-structure constant, approximately  $1/137$ ). Intriguingly, this limits  $Z$  to a maximum of about 137, because, above this value, the electron's speed would be greater than the speed of light.

Nowadays, atomic models are based on the Dirac equation, which combines relativity and quantum mechanics in a theory called quantum electrodynamics (QED). The Dirac equation for a point nucleus leads to the same limit: the electron-binding energy becomes complex when  $Z$  is greater than or equal to  $1/\alpha$ . But for an extended nucleus, the limit is around  $Z = 173$ . Above that value, the electron-binding energy is more than twice the electron's rest mass, a condition that allows the formation of electron-antielelectron pairs, which would render the atom unstable.

The size of an atom can be defined in different ways<sup>2</sup>. If the mean spherical radius of the whole atom is considered, based on the total electron density, then the possible range of sizes is small: from  $1.06a_0$  to  $1.5a_0$ . But if the size of the outermost orbital is considered, then atomic size ranges from  $a_0$  at  $Z = 1$  to  $8a_0$  at  $Z = 172$  (refs 2,3). What happens above  $Z = 172$  is still being investigated<sup>4</sup> to study how



**Figure 1 | Atomic structure.** This cartoon of a bismuth-209 atom exemplifies the features of Niels Bohr's model of the atom: a nucleus, composed of protons (purple) and neutrons (yellow) is orbited by electrons (blue), which occupy distinct shells. The relative size of the nucleus and the electron shells are not shown to scale. Bismuth-209 can decay by emitting  $\alpha$ -radiation, but the measured half-life<sup>13</sup> for this process is  $1.9 \pm 0.2 \times 10^{19}$  years, a billion times longer than the estimated age of the Universe. It is, therefore, essentially the heaviest naturally occurring stable atom.

the emission of real electron-antielelectron pairs causes the breakdown of the quantum vacuum — a mysterious state predicted by QED, consisting of empty space in which virtual particles such as photons and electron-antielelectron pairs are constantly created and annihilated.

The heaviest nucleus to have been identified<sup>5</sup> has  $Z = 118$ . Nuclei with higher numbers of protons can be studied only by creating them temporarily during collisions of two lower-charged nuclei. This was attempted in the 1980s, but the accelerators of the time could not produce bare nuclei (or nuclei with single electrons) that had large enough  $Z$  to succeed. Today, high-quality beams of bare nuclei of heavy elements can be produced at energies that could allow binary nuclear systems to be prepared for approximately  $10^{-21}$  seconds. Projects to study the quasi-molecular state created in such collisions, and to investigate the properties of the resulting quasi-atoms, have been proposed.

But it is not only large atoms that can be

made — smaller, exotic atoms can also be created by replacing electrons with heavier particles, such as muons, pions or antiprotons. The resulting systems are 207 to 1,836 times smaller than the corresponding 'normal' atoms, and are thus close to the size of a nucleus. Such atoms have been used to study nuclear properties, such as the size of a proton<sup>6</sup>.

Paul Indelicato is at the Kastler Brossel Laboratory, ENS, CNRS, Université Pierre et Marie Curie, 75005 Paris, France.  
e-mail: paul.indelicato@lkb.upmc.fr

## The nuclear question

ALEXANDER KARPOV

The maximum size of an atomic nucleus is determined by its stability towards decay. In general, only a few isotopes of each element are stable, the heaviest of which is bismuth-209 (83 protons and 126 neutrons; Fig. 1). All elements heavier than this are radioactive, although two of them (thorium and uranium) have tremendously long half-lives and are found in large amounts in nature. In some respects, such long-lived radioactive elements can be thought of as 'stable'.

If we enlarged a nucleus by adding neutrons, then it would become increasingly short-lived, eventually reaching the border of neutron stability. Beyond this border, the nuclear system is unbound and spontaneously emits neutrons. The number of neutrons that can be added to a stable nucleus depends mainly on  $Z$ : the larger  $Z$  is, the further away is the border of neutron stability. The border has already been reached experimentally in elements up to oxygen (and probably up to aluminium, although some dispute this). But for heavy elements, only theoretical estimates of the border's position are available. For example, the heaviest uranium atom is predicted to bind 92 protons and about 208 neutrons, a total mass number of around 300; by comparison, the heaviest naturally occurring uranium



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nucleus has a mass number of 238.

If we added protons to uranium, the heaviest naturally occurring element, then we would produce new elements. (In fact, we would need to add protons and neutrons, to avoid reaching the border of proton stability). The resulting nuclei would be progressively less stable to spontaneous fission because of Coulomb repulsion in their interiors. Nuclei become totally unstable towards fission at about  $Z = 106$ , in the absence of quantum effects.

But nuclei consisting of certain 'magic' numbers of protons and neutrons are especially stable by comparison with their neighbours. Superheavy nuclei that have nearly magic numbers of protons and neutrons form islands of relatively long-lived nuclei surrounded by a sea of short-lived nuclei. A pair of magic numbers in the superheavy region (114 protons and 184 neutrons) was predicted<sup>7–10</sup> in the 1960s. The centre of this island has not been reached experimentally, and the ways to reach it are debated<sup>11</sup>. However, elements up to  $Z = 118$  have

been synthesized<sup>15,12</sup>. The existence of the island unambiguously follows from these results, but the data do not indicate where the top of the island is, nor how long-lived the nuclei at the top would be. No consensus on this topic has been reached from theoretical considerations.

Are there other islands of stability? Probably, yes. But different theories of nuclear stability diverge from each other when extrapolated into remote domains of nuclei, so the opposite answer cannot be excluded. One hypothesis proposes that very heavy nuclei do not have a 'normal', nearly uniform distribution of nuclear matter, but a bubble-like distribution. This should substantially suppress the Coulomb forces and increase nuclear stability. Some theories predict bubble-like structures in the vicinity of the first island of stability of superheavy nuclei — in which case, massive, long-lived nuclei might have rather exotic structures. ■

Alexander Karpov is at the Flerov Laboratory of Nuclear Reactions, Joint Institute for

Nuclear Research, 141980 Dubna, Moscow region, Russian Federation.  
e-mail: karpov@jinr.ru

1. Bohr, N. *Phil. Mag.* **26**, 1–25 (1913).
2. Indelicato, P., Santos, J. P., Boucard, S. & Desclaux, J.-P. *Eur. Phys. J. D* **45**, 155–170 (2007).
3. Indelicato, P., Bieroń, J. & Jönsson, P. *Theor. Chem. Acc.* **129**, 495–505 (2011).
4. Ackad, E. & Horbatsch, M. *Phys. Rev. A* **78**, 062711 (2008).
5. Oganessian, Y. T. *et al. Phys. Rev. C* **74**, 044602 (2006).
6. Pohl, R. *et al. Nature* **466**, 213–216 (2010).
7. Mosel, U., Fink, B. & Greiner, W. in *Memorandum zur Errichtung eines gemeinsamen Ausbildungszentrums fuer Kernphysik der Hessischen Hochschulen* (1966).
8. Mosel, U. & Greiner, W. *Z. Phys.* **222**, 261–282 (1969).
9. Meldner, H. *Ark. Fys.* **36**, 593 (1967).
10. Sobiczewski, A., Gareev, F. A. & Kalinkin, B. N. *Phys. Lett.* **22**, 500–502 (1966).
11. Zagrebaev, V. I., Karpov, A. V., Greiner, W. *J. Phys. Conf. Ser.* **420**, 012001 (2013).
12. Oganessian, Y. T. *et al. Phys. Rev. Lett.* **104**, 142502 (2010).
13. de Marcillac, P., Coron, N., Dambier, G., Leblanc, J. & Moalic, J.-P. *Nature* **422**, 876–878 (2003).

## HIGH-TEMPERATURE SUPERCONDUCTIVITY

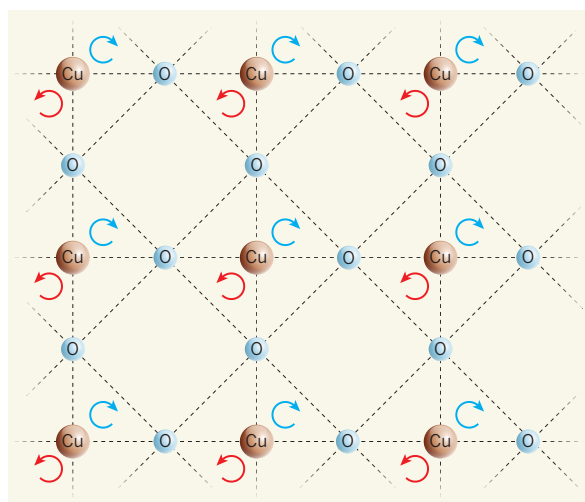
# The sound of a hidden order

Ultrasound measurements in a copper oxide superconductor have revealed an exotic phase of matter, composed of loops of spontaneous quantum currents, that has hitherto excelled at evading observation. [SEE LETTER P.75](#)

JAN ZAAENEN

Rigid things are obvious in the human world, but nature allows for circumstances in which hardness gets a quantum-physics twist. The electron systems formed in copper oxide compounds became famous with the discovery in 1986 that these materials become superconductors at high temperature. But this turned out to be only the tip of the iceberg: the intensive research that ensued revealed surprise after surprise. It became clear that the strongly interacting electrons of these systems form the building blocks of a plethora of exotic phases of matter that are shaped by the weirdness of quantum mechanics<sup>1</sup>. On page 75 of this issue, Shekhter *et al.*<sup>2</sup> present conclusive evidence for the existence of one such phase — one that breaks 'quantum-spookiness' records. Driven by a quantum effect known as zero-point motion, the electrons in this phase organize themselves into patterns formed from spontaneous current

loops, and the phase transition in which this electronic order sets in leaves an unambiguous mark on the sound waves travelling through the copper oxide lattice.



**Figure 1 | Electronic order.** Shekhter *et al.*<sup>2</sup> demonstrate an electronic order in a copper oxide compound (Cu, copper; O, oxygen) which consists of counter-circulating currents (arrows) within the unit cells of the compound's atomic lattice.

The discovery of a phase of matter formed from spontaneous quantum currents is stunning in itself: this 'hidden order' has been playing hide-and-seek for a long time<sup>1</sup>. The first indications of it came from neutron-scattering experiments<sup>3,4</sup>. However, to qualify as a phase of matter, such an electronic order must set in suddenly at a critical temperature. Measuring thermodynamic quantities such as the specific heat is the standard way to detect such phase transitions, because at the critical temperature these quantities should show singularities — sharp cusps in their temperature dependence. These singularities have not been detected, but it was argued<sup>4</sup> that, given its special symmetry, this order could conceal itself completely even in this regard.

Much like the vibrating strings of a violin produce sound waves, the vibrations of the ions in copper oxide compounds also generate sound waves. At high (ultrasound) frequencies, such 'phonons' lose their energy to the electron system, and when the electrons undergo a phase transition, their 'boiling' markedly increases their capacity to damp the phonons. This is precisely what Shekhter *et al.* observe in their ultrasound measurements of the copper oxide compound  $\text{YBa}_2\text{Cu}_3\text{O}_{6+x}$ : at the critical temperature, the onset of the current-loop order in this material causes sharp changes in both the speed and the lifetime of the phonons. These changes reveal the thermodynamic singularities demonstrating that the currents form a macroscopic phase of matter.

What is the origin of this form of spontaneous-current order? Although details remain to be settled, theorists