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Atomic physics

Positronic lithium and the many-body problem

J.-P. Connerade

At one level, physics is simply about interactions between particles. In a sense, then, it fails miserably, because if more than two particles or bodies are involved, no general solution can be found to their equations of motion — only partial solutions for special cases. The many-body problem troubled such celebrated scientists as Newton and Poincaré, and as the world we live in is dominated by many-body interactions, it is a highly relevant problem. A surprising new tool to explore the many-body problem has been found in atomic physics: G. G. Ryzhikh and J. Mitroy, of the Northern Territory University, Australia, have shown[1] that it should be possible to attach a positron to a neutral lithium atom. Why is this useful? To explain that, a brief excursion into chaos and quantum mechanics is required.

By considering the three-body problem, Poincaré grasped the significance of chaos in classical mechanics — that the behaviour of even simple systems can be exponentially sensitive to initial conditions, making it impossible to predict beyond a certain timescale. In other words, although all classical many-body systems are deterministic, many have no tractable solutions.

In quantum physics, the many-body problem emerges again. But true chaos is excluded from quantum mechanics because of the Uncertainty Principle: the very existence of chaos requires infinite divisibility of space, which only occurs in classical physics. At first sight, this is very promising — one might hope to make better progress with the many-body problem in quantum physics. Also, the Pauli exclusion principle, which tells us how to construct a wavefunction for several identical particles, seems designed to assist. In reality, the situation is much more complicated: the many-body problem persists at the quantum level, and the role of chaos remains mysterious[2]. Although useful approximations are found, the problem is fundamentally unsolved.

There are several approaches to solving it. Many physicists take the view that the 'best' systems in which to study many-body effects are those where the forces between the constituents are completely known. From this standpoint, atoms are ideal. The force involved is the Coulomb force, arguably the best documented in the whole of physics. But a complexity of quantum systems stems from the Pauli principle. When several electrons are present, one must include not only the direct interaction between them, but also a quantum-mechanical force — the exchange interaction — whose origin is the indistinguishability of particles.

Fortunately, nature provides a tool to probe this exchange force. This tool consists in substituting a positron for an electron. Because these are distinguishable, the exchange force disappears. Other differences emerge, as the charge of the positron is also of opposite sign, but many-body theories can be tested more thoroughly in this way than just by comparing theory with experiment for a given atom.

In principle, there are two ways for a positron to cling to an atom. A positron and an electron together form bound states of a 'pseudo-atom' called positronium (Ps). This is neutral, but one can attach it to an atom, forming a new kind of molecule. Several such molecules are stable. For example, positronium hydride (PsH) was predicted, and has been observed[3]. This is less surprising than seems: removing the positron leaves behind a negatively charged ion, so one can understand how the positron becomes bound.

The second is less obvious. One can also attach a charged particle to a neutral system, provided the latter possesses an electric dipole moment of its own, or can be distorted (polarized), in which case a dipole is induced by the particle that attaches to it. Atoms do not possess an intrinsic dipole moment, so the second mechanism must act. Negative ions occur for many atoms, of course — even positronium forms a negative ion[4].

But can one attach a positron to the neutral atom, to produce an exotic positive ion (a positronic ion, to distinguish it from normal positive ions)? It could then be compared with the corresponding negative ion. This strategy depends on whether a bound state exists for any atom, which is by no means obvious. All depends on whether the induced dipole is sufficient to bind a charged particle; that is, on whether the polarizability of the original system is large enough. That depends on many-body interactions, so it is of great interest to enquire whether a neutral atom is able to form negative or positronic ions when bombarded by electrons or positrons respectively. This question can be addressed either experimentally or theoretically.

In general, as one removes electrons from an atom to form the more usual positive ions, screening of the Coulomb force between the nucleus and the external electrons is reduced, and the central force experienced by the electrons is strengthened in comparison with the many-body forces between the electrons. We say that the many-body forces, or correlations, are reduced. On the other hand, the correlations in a neutral system or (even better) an ion produced by attaching an additional charged particle are much larger. For this reason, such ions are among the most suitable objects in which to study many-body effects.

Already, the suggestion had been made on the basis of theoretical estimates that magnesium, zinc, cadmium and mercury should possess positronic ions. However, these elements have closed outer subshells, which are less extended in space than the outer shells of the corresponding alkali elements, and therefore less polarizable.

The latest step is more decisive. The new theoretical paper[1] describes a fully *ab initio* calculation showing that lithium, the lightest of the alkalis, can bind a positron, to form a stable positronic ion. The binding energy is 0.059 eV. To discover anything new about many-body interactions in this system, actual positronic lithium will have to be produced and its spectrum measured.

More exhaustive tests could be carried out if we could also compare ions in other systems. Unfortunately, it is not yet clear how to extend the new theory to incorporate the additional closed shells of heavier alkali elements. Another route might be to make much larger spherical objects[5] — spherical metallic clusters. By virtue of their size, clusters are even more readily polarized than atoms, and can also form negative ions[6]. Various models have been developed to represent them, and are in general similar to self-consistent field theories of the atom. So there seems to be no reason why positronic ions of metallic clusters should not eventually form a new test-bed for our theories of many-body physics. □

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