Nuclear physics

Not-so-magic numbers

David Warner

When a nucleus has a ‘magic’ number of neutrons or protons, it is particularly stable. But it seems that for exotic nuclei, with large numbers of neutrons relative to protons, these magic numbers can change.

Most people are familiar with the concept of an atom as a mini Solar System, with electrons orbiting a central nucleus. Not so many realize that the neutrons and protons within the nucleus behave in the same way. Despite the lack of a central nuclear ‘Sun’, the complex forces between the constituents of the nucleus produce an average potential that is central and that results in well-defined orbits for the neutrons and protons. Moreover, just as certain atoms are chemically more stable than others because they correspond to the filling of major electron shells (the noble gases, for instance), so nuclei with particular ‘magic’ numbers of neutrons and/or protons —2, 8, 20, 28, 50, 82, and so on — have enhanced stability. These magic numbers have been known and understood[1,2] for more than 50 years — until recently, when studies of extremely exotic nuclear species began to indicate that the magic numbers can change. In *Physical Review Letters*, Schiffer and colleagues[3] report results that dramatically reveal the onset of this effect in isotopes of tin. They suggest that a decreasing nuclear ‘spin–orbit’ interaction is to blame.

The challenge to the basic assumption of the permanence of nuclear magic numbers has developed through studies of nuclei that, in terms of their numbers of protons and neutrons, are far from the region of stable, naturally occurring isotopes. It seems that the gaps in the sequence of nuclear energy levels that give rise to the extra stability of magic-number nuclei are actually quite fragile and shift with changing nucleon (proton or neutron) numbers. So far, the evidence has been indirect and limited to lighter elements with large neutron excesses. For such elements, the properties associated with enhanced stability (spherical shape, difficult to excite) that would be expected for nuclei with magic neutron numbers 20 or 28, for example, are not always observed; in some cases the shell effects have vanished, only to reappear at different neutron numbers.

One feature that produces very different magic numbers in stable nuclei and atoms is the strength of the spin–orbit interaction, a force that depends on the direction of the intrinsic spin of a particle (electron or nucleon) relative to that of its orbital motion. This interaction is much larger in the nucleus than it is for electrons, with the result that when the directions of spin and orbital angular momentum are aligned, the orbits are pushed down in energy relative to orbits for which spin and orbital angular momentum are opposed. Theoretical studies[4,5] attempting to solve the mean-field problem in nuclei (whereby the interactions between all the nucleons in the nucleus give rise to the average shell-model potential) have suggested that an increasing excess of neutrons may lead to a steady decrease in the strength of this spin–orbit interaction and that this may contribute to a radical change in the ordering of energy levels in the potential. The experiment carried out by Schiffer *et al.*[3], at the tandem Van de Graaff accelerator at Yale University, has provided the first empirical evidence that this is indeed the case.

Schiffer and colleagues attacked the problem by studying a range of tin isotopes undergoing a nuclear reaction that transferred a single proton into specific vacant orbits of a tin nucleus. They directed a beam of 40-MeV α-particles (helium nuclei, $^4_2$He) onto a target of a single isotope of tin, and detected the tritons (tritium nuclei, $^3_1$H) that emerged whenever a proton had been transferred from an α-particle to a tin nucleus. The momentum of the tritons was measured using a magnetic spectrograph so that the populations of different energy levels in the final nucleus — corresponding to the proton entering different orbits of the shell model — could be distinguished. Particular care was taken to ensure that the absolute probability, or cross-section, for populating each state was accurately determined; these cross-sections were also measured as a function of angle relative to the direction of the beam.

The orbits of interest are those with the highest values of the orbital angular momentum, *l*. These orbits have the largest spin–orbit interactions and can contain the largest number of nucleons, so changes in their position have a dramatic effect on the magic numbers. The ideal experiment would have been to locate and track the relative positions of both members of a spin–orbit doublet — that is, two states with total angular momentum corresponding to the parallel and anti-parallel coupling of the spin to a specific *l*-value. Unfortunately, in nuclei this is not possible for higher values of *l*, because the splitting between the two members of the doublet becomes so large that both states cannot be observed in the same nucleus. The experimenters decided instead to focus on comparing the upper member of the highest-*l* doublet in the shell (with anti-parallel spin) with the lower, spin-aligned member of the highest-*l* doublet from the shell above (which is pushed down by the spin–orbit interaction).

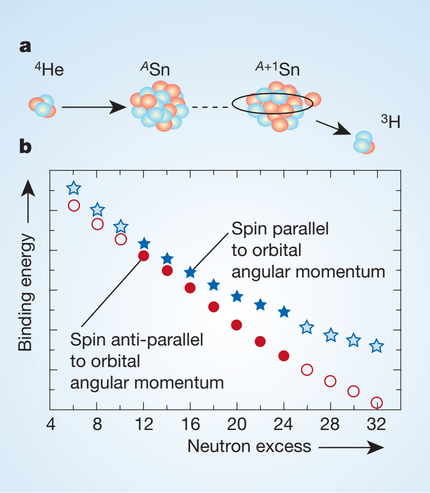

Figure 1 **Neutron excess and the energy of states.** a, **Firing a beam of α-particles (^{4}He) at a tin target causes the transfer of a proton to a tin nucleus of mass *A* (^{A}Sn), and a triton (^{3}H) emerges. The proton can enter one of two nuclear orbits with high angular momentum: one in which the proton’s spin is parallel to its orbital angular momentum, the other in which the spin is opposed to its orbital motion.** b, **Schiffer *et al.*[3] have measured the binding energies of these two orbits as a function of the neutron excess — that is, the number by which neutrons exceed the 50 protons in a tin nucleus. The separation of the states increases with increasing neutron excess, suggesting that the magnitude of the spin–orbit interaction is changing. (Filled symbols are Schiffer and colleagues’ data, open symbols represent data not yet confirmed by transfer reactions;** b **derived from ref. 3.)**

The results are shown in Figure 1, and the steadily increasing separation of the two states is obvious. The accurate experimental determination of the cross-sections means that these states can be associated unambiguously with particular proton orbits, and hence this is the first direct evidence in heavy nuclei of the changing relative energy of these high-*l* proton orbits with increasing neutron excess. Moreover, this association can now be extended with confidence to analogous states in the most exotic tin nuclei. The authors present a similar analysis of nuclei with one neutron outside the 82-neutron closed shell — albeit with less quantitative backing — that suggests a similar trend exists for two higher-energy spin-opposed and spin-parallel neutron states, again consistent with a decreasing spin–orbit interaction with increasing neutron excess.

Understanding the origin of the shifting nuclear shell structure is not just a challenge for nuclear physicists. The nuclei that make up our world have been manufactured in nuclear interactions in the stars. Many of these processes of nucleosynthesis take place far from conditions of stability, on timescales short enough to prevent an unstable nucleus decaying before it is involved in another reaction. Thus, the properties of highly exotic nuclear species are central to the problem, and changes in the nuclear magic numbers will have a profound impact on the reaction rates that determine the formation of elements in the stars. ■

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Self-assembly

Towards precision micelles

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Detailed imaging reveals the structure of a spherical 'micelle', self-assembled from cone-shaped molecules, and marks progress towards mimicking the natural assembly skills of biological systems.

Cells synthesize and assemble molecules, even complex machines, of exacting but non-symmetric structure. The precision of the building-blocks and the checks and rechecks of assembly ultimately establish the variety and complexity of cellular function, replication and division. Could man-made molecules mimic those in the cell and also form precision materials? Apparently so. In *Angewandte Chemie International Edition*, Kellermann *et al.*[1] provide a convincing demonstration in their work on amphiphilic dendro-calixarenes.

Calixarenes are cone-shaped molecules; 'amphiphilic' describes their tendency to self-assemble into aggregates. The dendrocalixarenes in Kellermann and colleagues' study have T-shaped dendrimer, or branching, heads, and these coordinate the self-assembly of exactly seven molecules into a micelle with a non-polar core and a hydrophilic exterior (Fig. 1). This is the first structural characterization of a micelle on the molecular scale, made possible by high-resolution imaging techniques that include reconstructions from cryogenic transmission electron microscopy (or 'cryo-TEM'). Such techniques will clearly soon be playing a major role in the characterization and synthesis of ordered soft materials.

The symmetry of these calixarene micelles is remarkable: two pairs of T-shapes bind through specific lock-and-key interactions, and another three molecules complete the ensemble (Fig. 1c). What emerges is a near-spherical micelle with C_2 symmetry — that is, the micelle is symmetric under rotation through an angle of π radians. The micelles are also surprisingly stable and persist even after removal of the solvent; such behaviour is consistent with the existence of strong interactions that dictate order beyond assembly. Coordination between the heads of the calixarenes seemingly opposes disassembly and reorganization.

Although this appears to be the first and most highly ordered example of a persistent spherical micelle, a large family of structures with extended and highly stable cylindrical morphologies has been generated using amphiphilic peptides, or short stretches of amino acids; the peptides contribute to β-sheet structures along the length of a cylinder[2]. These nanofibres are showing promise as self-assembled scaffolds for cells in various contexts. Another example[3] is based on amphiphilic block copolymers (composed of covalently linked polymer units). These, through metal-coordinating monomers, seem to crystallize within their cylindrical core[4]. Self-assembled nanowires for molecular electronics are a possibility with such linear architectures[5].

However, to obtain spheres as Kellermann *et al.*[1] have done, the coordinating interactions must not be linear. In the T-calixarene micelles, the unique arrangement of seven amphiphiles not only breaks the symmetry of the micelle but also suggests that the entire structure should be polar. This in turn should make it possible to align the micelles in fields (magnetic or electric) for more accurate characterization and possibly for use as macromolecular ferrofluids or electrorheological fluids. It might also allow higher-order assembly, although probably under different solution conditions, to give chains that are akin to biofilaments such as actin, which is integral to the structure of the cell[6].

What sort of interactions could create the highly asymmetric structure within the T-calixarene micelle? When seven spheres are brought together by a surrounding interface, they tend to form an arrangement that has a different symmetry[7] from the C_2 symmetry of these micelles. This suggests that simple packing of the T-calixarenes is

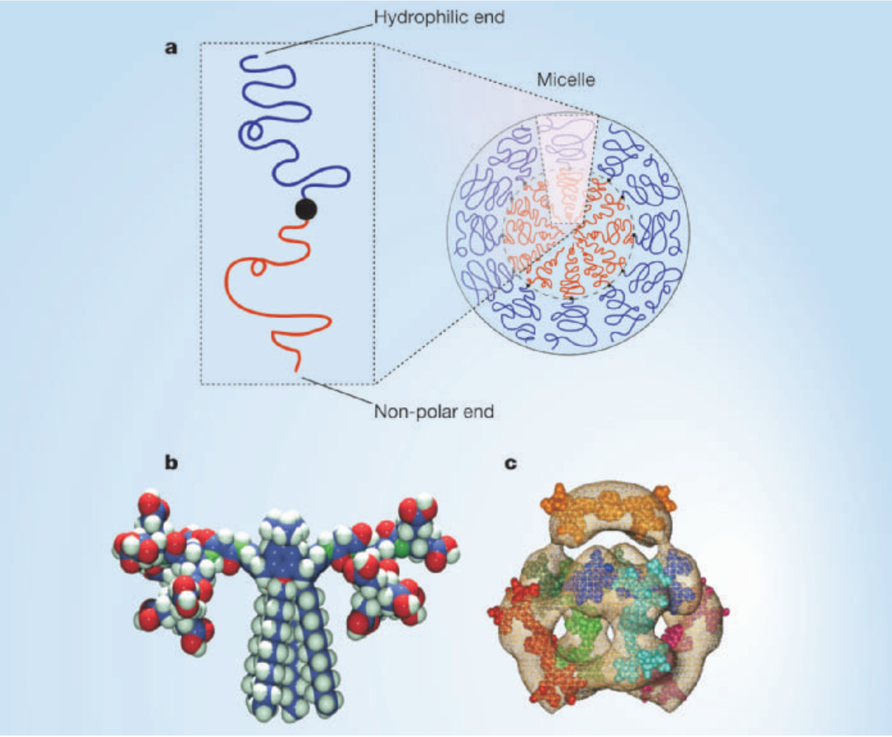

Figure 1 **The seven-molecule spherical micelle.** a, **Amphiphilic molecules, which have a hydrophilic end and a non-polar end, can arrange themselves into a micelle, with all the hydrophilic ends at the outermost edge.** b, **Kellermann *et al.*[1] have created micelles from T-shaped molecules composed of cone-like calixarene molecules with dendritic heads. The low-energy conformer is shown here.** c, **High-resolution imaging reveals a curious structure of two pairs of intercalated T-calixarenes, with three additional molecules 'clipped' around them.** (b and c **reproduced, with permission, from ref. 1.)**