On the shores of the island of stability

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The study of the structure of the atomic nucleus is not an entirely new field – it is just over one hundred years since the nucleus was discovered in the famous experiment carried out by Rutherford's students Geiger and Marsden. This discovery led to a revised model of the atom, with the positively charged nucleus surrounded by a cloud of atomic electrons. Since these days at the dawn of the quantum era, we have learned a great deal about the atomic nucleus. Modern experiments generally work along similar lines to that devised by Rutherford, whereby an energetic probe (photon, electron, heavy ion) is used to interact with and excite a "target" nucleus and the outgoing radiation after the reaction is detected. The pattern of the detected radiation (energy, intensity, angular distribution, etc) can give us information about the nucleus, such as its size and shape. Contrary to common wisdom, nuclei take on a variety of non-spherical shapes. Nuclei can be oblate deformed (like a pancake), prolate deformed (like a rugby ball) or even pear-shaped (see Gaffney et al.[1]). The properties of the nucleus result from the subtle interplay between the attractive binding effect of the strong nuclear force between nucleons (protons and neutrons) and the replusive Coulomb effects due to the electromagnetic interaction acting between the positively charged protons. With the advent of particle accelerators, it became possible to produce ion beams of different species and with ever increasing energies. Eventually it became possible to accelerate heavy ions to energies high enough to overcome the Coulomb repulsion between the positively charged beam and target nuclei, allowing fusion reactions to be made. The ultimate legacy of these accelerator developments can now be seen as the Large Hadron Collider in CERN.

Taking a few steps back, the possibility to perform fusion reactions meant that a much wider range of nuclei (in terms of proton number, Z, and neutron number, N) could be produced in the laboratory. This leads to the question of "how many nuclei are there?" or alternatively "What are limits of nuclear stability in terms of proton and neutron number?". By changing the ratio of the proton number to neutron number, eventually we come to a situation where there are either so many neutrons that no more can be bound (neutron drip line) or too few neutrons so that all the protons can no longer be bound (proton drip line). At these limits the decay half-lives become so short that the nuclei cannot be observed in the laboratory. The nuclei that we observe in nature have a proton to neutron ratio which corresponds to "the valley of stability", with correspondingly long decay half-lives. There are 288 nuclei which we call "stable" – that is that they are stable against radioactive decay with a decay half-life longer than the age of the solar system (4.6 billion years). At the end of 2011, a total of 3104 nuclei with proton number up to 118 had been observed in the laboratory. Despite having studied the properties of this large number of nuclei, we paradoxically still do not have a good understanding of the form of the strong nuclear interaction between the nucleons in the nucleus. When we try to predict the limits of nuclear stability with state-of-the-art models of the nucleus, the answer obtained is very sensitive to the form of the interaction used in the calculation. This leads to an uncertainty in the exact proton or neutron numbers predicted to mark the limits of existence of the chart of the nuclides. A recent theoretical study suggested that a total of 6900±500 nuclei should be bound to proton or neutron emission (see Erler et al.[2]).

An additional factor affecting the stability of atomic nuclei arises from the fact that the nucleus is not simply a macroscopic "liquid drop", but is a quantum object. The nucleons in the nucleus are confined by the strong force to move in a potential generated by the nucleons themselves, and as a result the nucleons can only occupy quantum levels with certain allowed energies. The spacing between these quantum levels is not uniform, and for certain numbers of nucleons there can be a large gap or "jump" in energy to the next unoccupied level. Nuclei with nucleon numbers at these gaps are more stable than the subsequent nuclei where the next level above the gap is occupied. Such so-called "shell effects" are well known from the study of the atom, where certain numbers of electrons correspond to more stable (or unreactive) atoms. For example, the noble gases (helium, neon, argon, krypton, xenon and radon) have relatively high first electron ionisation energies due to similar gaps in the allowed energy levels for the electrons bound in the atom. The numbers of electrons where these gaps occur are the "magic numbers" – in the atomic case these are 2, 10, 18, 36, 54 and 86. In the nuclear case, we have magic numbers for both protons and neutrons. In both cases, we have magic numbers of 2, 8, 20, 28, 50 and 82. In the case of neutrons, there is an additional magic number of 126. A theoretical description of the nucleus which correctly predicted these experimentally known magic numbers was the great success of the shell model of the nucleus, for which Wigner, Goeppert-Mayer and Jensen shared the Nobel Prize in Physics in 1963.

Soon after the development of the shell model, the question arose "What are the next magic numbers beyond 82 for protons and 126 for neutrons?". This question is still an open one in the field of nuclear physics. As discussed above, the uncertainty in our knowledge of the nuclear interaction leads to subtle differences in the predictions made with our best models of the nucleus. As a result of this, the next magic numbers are predicted to be at a proton number of either 114, 120 or 126 and a neutron number of 172 or 184. These predictions lead to the concept of an "Island of Stability" inhabited by nuclei with proton and neutron number close to these magic numbers. The stabilising effect of the gaps in the level energies of these nuclei mean that they can survive against the destructive forces of Coulomb repulsion due to the very large number of protons. Indeed, all nuclei with a proton number beyond around 104 only exist due to the stabilising influence of the quantum shell effects.

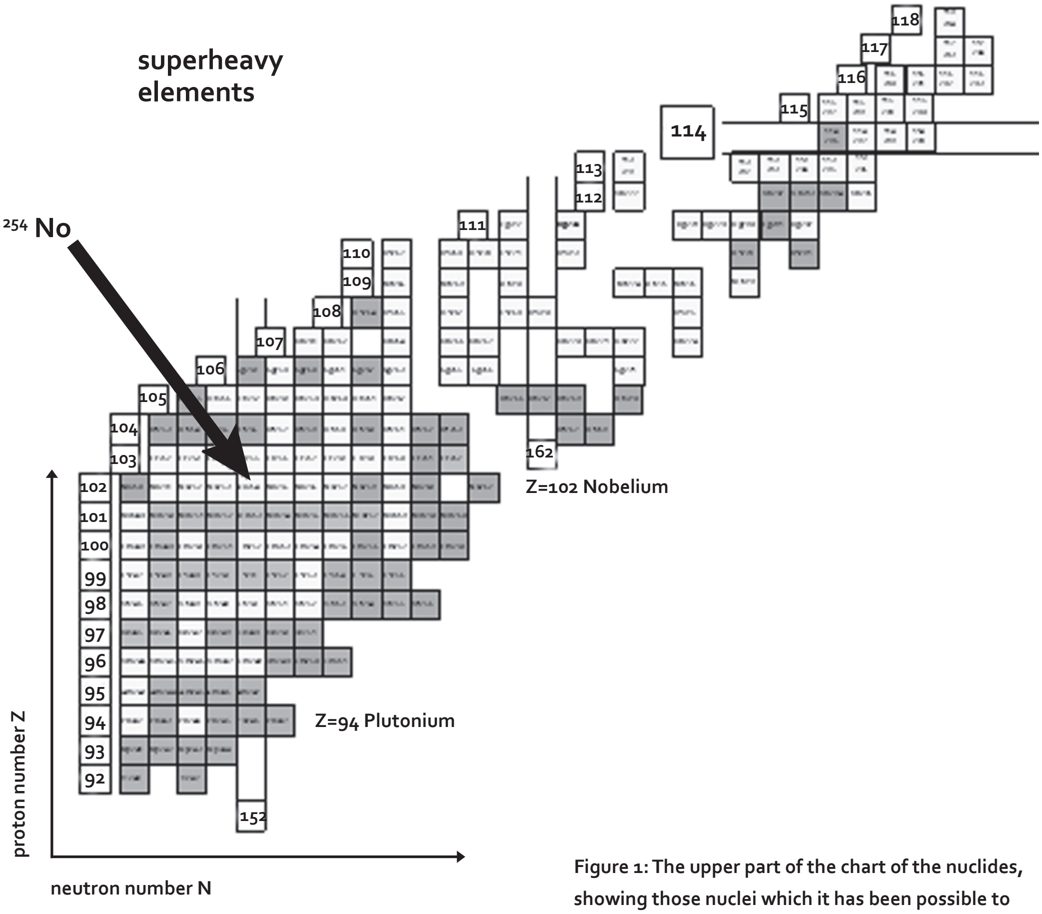

Figure 1: The upper part of the chart of the nuclides, showing those nuclei which it has been possible to produce in the laboratory.

In order to test the theoretical predictions, and ultimately to improve our understanding of the strong nuclear force, it is necessary to produce and study these "superheavy" nuclei in the laboratory. In order to have more stringent tests, it is preferable to also determine the spins and parities of the energy levels. As stated above, to date the heaviest nucleus we have observed in the laboratory has a proton number of 118 and has a mass of 294, meaning that the nucleus contains 176 neutrons (see Oganessian et al. [3]). A diagram showing the currently known nuclei in this region of the chart of the nuclides is shown in figure 1.

The traditional way in which experimentalists have tried to locate the island of stability and to study the properties of the nuclei found there is to try to synthesise them directly in the laboratory. The cross-section, or probability to produce nuclei with proton number of around 114 is extremely small. Thus, it is very difficult to produce these nuclei in large numbers. An extreme example of such synthesis experiments is the study of element 113 carried out in Japan. In a period from 2003 to 2012, a total of 553 days were dedicated to producing element 113. Over this period a total of *three* atoms of element 113 were observed (see Morita et al.[4]). Whilst experiments of this type prove that such elements exist, and provide information on decay modes and half-lives, it is impossible with current experimental techniques to determine the spins and parities of the energy levels with so few atoms.

An alternative approach is to produce nuclei with lower proton number, such as isotopes of nobelium, with 102 protons. These nuclei can be produced in much greater numbers (of the order of hundreds or thousands per week). With this number of nuclei, our experimental techniques allow a much wider range of nuclear properties to be determined, including the important spins and parities of the occupied levels. The results of these experiments can then be used as a stringent test for the latest theoretical models of the nucleus. If the structure of these nuclei with around 100 protons can be described correctly, then one can have greater confidence that the predictions for the properties of the superheavy elements will be more accurate. At the Accelerator Laboratory of the Department of Physics, University of Jyväskylä, experimental studies of this type have formed one of the main research topics for the past decade or so. The experiments employ extremely sensitive equipment, which is capable of isolating a single atom of interest from a background of about 10 billion other atoms (see Greenlees et al.[5]).

In collaboration with theoretical physicists also working in Jyväskylä, it has been possible to compare the experimental results with the predictions of state-of-the-art nuclear models. The models have found to be lacking, and moves to improve the theoretical predictions have begun (see Shi [6]). These investigations, both experimental and theoretical, should help us to improve our description of the atomic nucleus and to better locate and define exactly where the shores of the island of stability lie.

References:

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