The Magic of Star Dust - Exploring Exotic Nuclei

by Rituparna Kanungo

Seeking clues to the origin of our existence

Our universe is made up of planets, galaxies, and stars. Seeking the clues to the origin of our existence, we look back at how the creation and evolution of the universe occurred. Our present understanding is the universe started with a big bang that created a soup of objects, among which were the massive ones called nucleons. The soup contained both positively charged nucleons called 'protons' and electrically neutral ones called 'neutrons'. As the universe cooled and expanded the hadrons coalesced together to form more complex objects, that we refer to as nuclei. Nuclei form the core of all matter around us and constitute more than 99% of the weight of any object. They are the driving fuel for the stars. The stars, including our sun shine due to the energy released by nuclear reactions.

Only a small handful of all the nuclei found in our universe exist on earth. Most of these are known as 'stable nuclei' because they are not radioactive. Ever since the discovery of the nucleus by Ernst Rutherford in 1911, the popular picture of the atom has been compared to the solar system, where electrons orbit a nucleus in the same way planets orbit the Sun. Since then we have learned that the nucleons in nuclei, also travel in "orbits". The difference is that, rather than orbiting around a massive central point like planets around the Sun, the nucleons orbit amongst each other. Also, the nuclei of atoms are small enough that their behaviour is governed by an underlying wave function, as postulated by quantum mechanics. We can never know where a nucleon is at any given time, only where it is likely to be. (The same is true for electrons in atoms.) Finally, there is not a sharp edge to a nucleus; the density is mostly constant, but as one moves out from the nucleus, it decreases smoothly to zero. However, this transition region is typically smaller than a nucleon itself.

Magic numbers

Scientists have also learned that the electrons in atoms and the nucleons in nuclei occupy different orbits (or shells), where the lowest energy orbits are filled first. For both atoms and nuclei a special set of numbers have been found, called 'magic numbers', where the electrons in atoms and nucleons in nuclei completely fill certain groups of orbits (see Fig 1). It is interesting to note that while magic numbers in atoms are 2,10,18,36,54, and 86, those in nuclei are slightly different: 2,8,16,20,28,50,82, and 126. Elements with magic atomic numbers tend to be chemically inert and undergo few if any chemical reactions. On the other hand, elements with magic nucleon numbers have extra strong binding and are often highly abundant. E.g., species like oxygen (*with proton number 8*), and calcium (*with proton number 20*) needed for our survival are abundant in nature and have the ability to react, a feature exploited by life. Since their discovery, the magic numbers have formed the basic pillars of nuclear science and were believed to be immutable. This belief was based on studying nuclei that are found naturally on earth. Today it appears this gave us a restricted view of the nucleus.

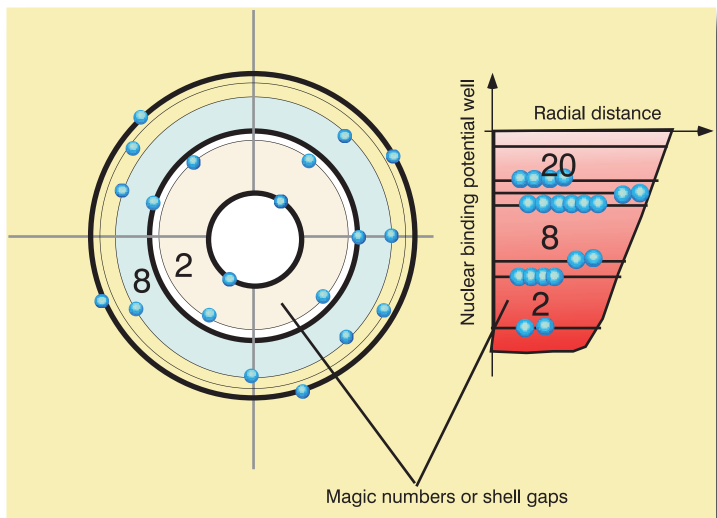

Fig.1: Schematic view of the planetary model of the nucleus. The blue balls are the nucleons (i.e. neutrons or protons). Each nucleon resides in a specific orbit that is shown on the left hand side by the black circles. The sketch on the right hand side shows the energies of the different orbits are energetically places inside the potential well that binds all these nucleons to form the nucleus. The innner most orbit (L.H.S.) is the same as the lowest orbit (R.H.S.). It is the most strongly bound orbit. The magic numbers appear as large energy gaps between clusters of orbits. They are shown in the figure as 2, 8, and 20.

TRIUMF's ISAC: exploring nuclei not found on earth

At TRIUMF, Canada's National Laboratory for subatomic physics in Vancouver, B.C., we are now capable of producing and studying the nuclei that exist in various environments in the universe but not on earth. This opens the possibility to go beyond the nuclei on earth and look into what exists in a supernova explosion, or in other cosmic objects like novae and X-ray bursters. These nuclei, called unstable nuclei (because they decay naturally), have ratios of protons and neutrons different from stable nuclei. The creation of the majority of elements on earth took place in such explosive by Rituparna Kanungo

stellar environments, involving the unstable nuclei. Exploring and understanding unstable nuclei is a quest to unravel the variation of nature's principles and forces that bind the nucleons together to form the large variety of nuclei in our universe.

The nuclear halo: an unexpected and exotic nucleus

An unexpected exotic type of nucleus was discovered in 1985 by Isao Tanihata and his colleagues at Lawrence Berkeley National Laboratory when experiments revealed that the most neutron-rich unstable isotope of lithium, with only 11 nucleons, has an unusually large size similar to a very heavy nucleus like gold, with 197 nucleons. This remarkable deviation from the previous finding that the radius of a nucleus depends only on the total number of nucleons clearly showed a phenomenon beyond the conventional concept. ^{11}Li has two extremely weakly bound neutrons that have a large probability of being located at distances very far from the rest of the nucleus, called the 'core', thereby forming a thin neutron halo around the core. A schematic visualization of this is shown in Fig 2.

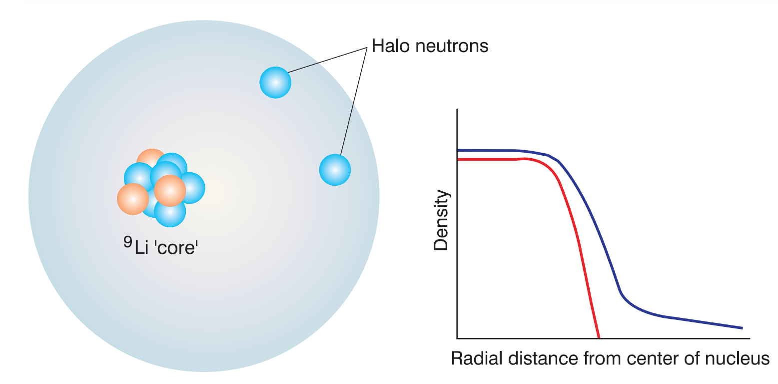

Fig.2: Schematic view of a two-neutron halo, e.g.^{11}Li. The two halo neutrons are located vary far away from the rest of the nucleus called the 'core' which is ^{9}Li in this case. A normal stable nucleus looks like ^{9}Li. The right hand side figure shows a view on the distribution of protons (red) and neutrons (blue) in such a nucleus.

An important question is how these two neutrons are arranged relative to the core and with respect to each other. It is also possible that the interaction felt by these two neutrons may differ from the general interaction between nucleons, because these two neutrons are much further away from the charged protons in the core nucleus.

ISAC-II's first experiment: a first in the world

The first experiment at the newly launched ISAC-II facility at TRIUMF, in December 2006, was also the first one in the world to investigate these halo neutron correlations through the most sensitive reaction probe. In this reaction of an ^{11}Li radioactive beam with a proton (p) target, two halo neutrons were transferred from ^{11}Li to the proton target. The resultant nuclei ^{9}Li(=^{11}Li-2n) and triton(=p+2n) were scattered in different directions. The probability distribution of this process to occur for different scattering angles carries information on the correlation between the two halo neutrons. This experiment was led by two visiting scientists Isao Tanihata and Herve Savajols using an active target detector system called 'MAYA' (Fig 3) which was brought from the French laboratory GANIL [see Davids, *ISAC-II Science with MAYA and EMMA,* Annual Financial Report 2006-07 for details].

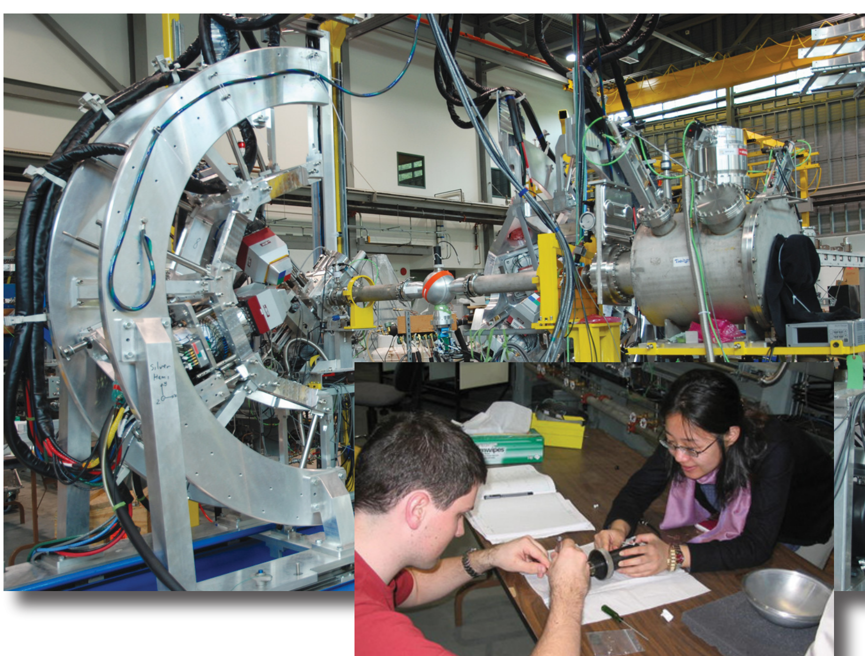

Fig.3: The TIGRESS facility where the ^{11}Be(d,p)^{12}Be reaction was performed. The inset shows students from Saint Mary's University setting up the target ladder for the experiment.

The measured distribution is now being compared to theoretical calculations based on different models of ^{11}Li. The data seem to suggest that the two neutrons often remain close to each other, being located on the same side of the ^{9}Li core. In the conventional picture of nuclear orbits the two halo neutrons should occupy only the p-orbit. The data

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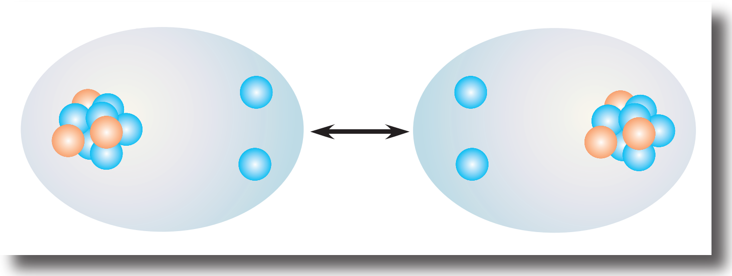

Fig.4: Schematic view of the two halo neutrons in ^{11}Li oscillating against the core to give rise to a new mode of excitation known as a 'soft dipole resonance'.

however suggests that these neutrons also occupy the *s*-orbit. Because of the weak binding and this abnormal occupation of the *s*-orbit, (which does not have a centrifugal barrier), the neutrons can extend to large distances, creating the halo.

The unusual character of the halo neutrons raises the question of whether they can affect the proton or charge distribution in ^{11}Li. Previously, a pioneering experiment led by Wilfred Nörterhäuser from Germany was carried out at ISAC to study this effect by observing the atomic transitions from the various lithium isotopes. The observations showed that the neutral halo has the effect of extending the proton distribution [see Hackman, *Experiments with ^{11}Li Beams at TRIUMF-ISAC,* Annual Financial Report 2004-2005 for details]. The proton (or charge) radius of ^{11}Li and the matter radius of ^{11}Li taken together require the halo neutrons to be located on the same side of the ^{9}Li core, consistent with the observations from the two-neutron transfer reaction.

Measuring the mass of halo nuclei with ISAC's TITAN

As mentioned earlier, the halo is strongly dictated by the weak binding of ^{11}Li. A measure of this weak binding is obtained by measuring the mass of ^{11}Li and the mass of ^{9}Li. The TITAN facility at TRIUMF has recently succeeded in measuring the mass of ^{11}Li with a precision of better than 1 part in 10 million. This measurement, part of the Ph.D. thesis of Mathew Smith, was 30 times more precise than the previous best measurements. It also showed that the energy required to knock the last two neutrons out of ^{11}Li is 20% more than previously determined.

Another interesting consequence of the halo could be a unique mode of excitation of ^{11}Li. In a pictorial view, the nucleus when perturbed could set the halo to oscillate against the core (Fig 4). This kind of oscillation can give rise to low-lying dipole resonances in the nucleus. Experiments to confirm the existence of such excitation modes are also planned at TRIUMF.

Halo features in other nuclei

^{11}Li is not the only nucleus exhibiting the halo feature. Halos can occur when nuclei tend to have very weak binding for a few nucleons located in the outermost orbits. Halos can therefore be formed with one or more nucleons. Observations so far have disclosed the existence of several one and two-nucleon halo nuclei. Most of these findings have been confined to very light nuclei. It remains an open question, whether giant multi-nucleon halos exist and how the scenario appears for heavy nuclei.

To elucidate halo features in other nuclei, and thereby aid in a complete understanding of why nuclear halos appear in nature, investigations are underway at TRIUMF of other neutron-rich nuclei such as ^{12}Be, which has the same number of neutrons as ^{11}Li but one extra proton. The presence of this extra proton seems to alter the binding of this nucleus significantly, making the neutron almost 10 times more strongly bound than that in ^{11}Li. It is interesting to determine, therefore, how the two outermost neutrons in ^{12}Be are arranged compared to ^{11}Li.

In a recent experiment led by Saint Mary's University, ^{11}Be ions from ISAC/TRILIS were accelerated through ISAC-II and reacted with deuterium atoms, whose nuclei contain one neutron and one proton. In some of the nuclear collision events, the ^{11}Be picks up the neutron from the deuterium to form ^{12}Be. In some of these events, energy from the reaction is released as a gamma ray. This experiment was performed using the TRIUMF-ISAC Gamma-Ray Escape Suppressed Spectrometer (TIGRESS) to isolate specific reaction channels. The collected data is currently under analysis.

The neutron skin: important consequences for fusion probability

A more general feature in neutron-rich nuclei is the formation of a thick layer of neutrons outside the layer of protons. This is termed as the neutron skin. The distinction between nuclear halo and nuclear skin is determined by the distribution of matter inside the nucleus. A neutron halo nucleus has a neutron distribution having a very low-density tail, whose slope is different from the proton density at the surface. On the other hand, formation of a thick neutron skin occurs when the bulk of the neutrons push outwards compared to the protons. This gives rise to a neutron distribution whose half-density radius is larger than that of the proton distribution. Neutron skins can also give rise to low-lying dipole resonance modes. The presence of such excitation modes might have important consequences for enhancing the fusion probability in these nuclei. Interestingly, the fusion of ^{9}Li with a moderately heavy nucleus ^{70}Zn measured at ISAC by a group from Oregon State University showed an abnormally large fusion probability that is yet to be fully understood, but is conjectured to be the effect of a neutron skin. The effect of exotic structures on fusion may have a strong impact on our understanding of synthesis of heavy elements in nature. It is important to search for the existence of such resonances and investigate the fusion of heavy neutron-rich nuclei.

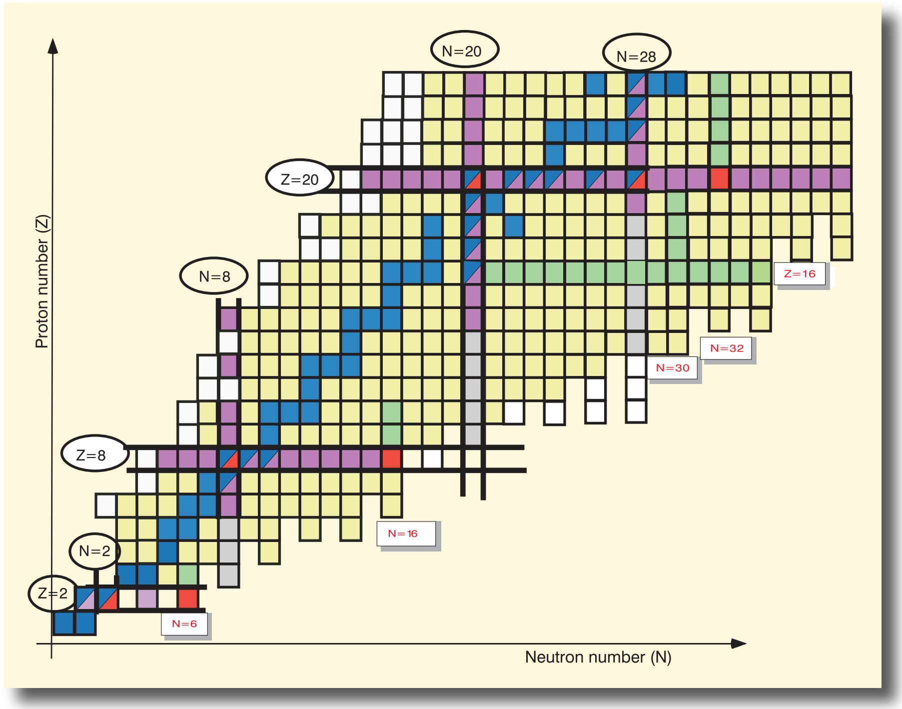

Fig.5: A section of the nuclear chart for light nuclei. The blue squares are stable nuclei. The yellow squares are unstable nuclei. The conventional magic numbers for protons and neutrons are denoted in circles and are shown by pink squares. The red filled squares are nuclei that have both magic proton and neutron numbers. These are called doubly magic. in regions of grey squares the conventional magic numbers are found to disappear in unstable nuclei. Instead, for unstable nuclei the green squares show new magic numbers appearing. They are showen in red.

New magic numbers for exotic nuclei

The golden set of numbers that formed the planetary model of the nucleus appears to undergo mutation when we are in the region of exotic nuclei that have highly unbalanced numbers of neutrons and protons. The fact that the halo neutrons in the nucleus ^{11}Li occupy the s-orbit tells us that this orbit is lowered in energy, making it possible for neutrons to reside in it. Such a change in the location of this orbit causes the conventional nucleon magic number to disappear. At some point scientists pondered whether this meant that the planetary model of the nucleus was completely washed out for exotic nuclei. It was exciting however to find the signature of new magic numbers, from recent measurements of the masses of these exotic nuclei (Fig 5). In the near future, the TITAN trap at ISAC holds excellent promise to provide clues on new magic numbers for heavier neutron-rich nuclei.

Experiments at TRIUMF, ISAC have already started to help build a detailed understanding of how and why the magic numbers change. This is associated with understanding the occupation of nucleons in different orbits. At the lowest end of the nuclear map, an experiment led by the Saint Mary's University group at the ISAC TUDA facility has shown that in very neutron-rich nuclei, the neutron number N=6 exhibits new magic number-like behavior. This is not due to the gap between orbits being further increased as we go more neutron-rich, but appears to be due to the fact that the neighboring N=8 gap disappears. Therefore, N=6 neutron-rich nuclei are more strongly bound and less prone to being deformed.

An international impact

The last few years have seen a significant growth in the amount and quality of data available on halo and neutron-skin nuclei. As evidenced by the Halo '08 International Workshop organized by Saint Mary's University and TRIUMF in March 2008, TRIUMF-ISAC beams and facilities have had a prominent and internationally recognized impact in this area of research. This leadership role is expected to continue as heavier neutron-rich isotopes produced using actinide targets will soon become available at ISAC.

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