Atomic Structure – Essay

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Introduction

Ever since its discovery, the atom, which is the basic unit of matter, has captured the interest and fascination of scientists for over a hundred years. The purpose of this essay is to conduct a full exploration of atomic structure, investigating the fundamental components of subatomic particles, their organisation within atoms, and the intricate quantum mechanical principles that regulate their behaviour. This essay has investigated the essential differences that exist between protons, neutrons, and electrons, addressed isotopes, looked into atomic orbitals, and explored ionisation energies, all with references to pertinent scientific studies and discoveries.

Atomic Structure

At the heart of atomic structure are three primary subatomic particles: protons, neutrons, and electrons. Fundamentally disparate in relation to their weight and charge, these particles determine their conduct and position inside the atom. Ernest Rutherford found protons in 1919; they carry a positive charge and have a mass of roughly 1.67 × 10^-27 kg (Yasuoka, 2020). James Chadwick discovered neutrons in 1932, and they are electrically neutral while having a mass nearly the same as protons (Nesvizhevsky and Villain, 2017). First noted by J.J. Thomson in 1897, electrons are the lightest of the three subatomic particles and hold a negative charge, with a mass of around 9.11 × 10^-31 kg, approximately 1/1836 the weight of a proton (Kuehn and Kuehn, 2016).

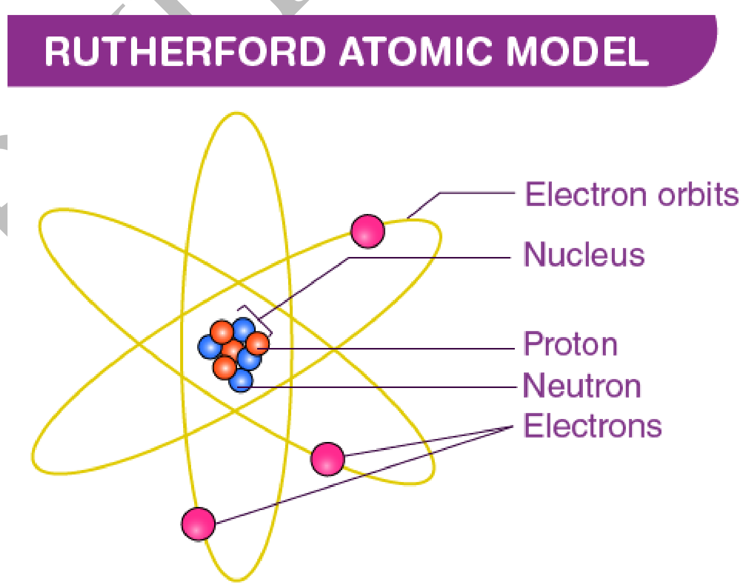

Figure 1: Rutherford atomic model

The mass and charge within an atom are not uniformly distributed, highlighting important implications for how atoms conduct themselves and how they behave chemically. In excess of 99% of the atoms' mass is densely situated in its nucleus, which is a dense core containing protons and neutrons. Approximately 10^(-15) of the total volume is occupied by this nucleus, yet it represents almost all the atom's mass (Arnould and Goriely, 2020). Orbiting this nucleus is a cloud of electrons that are responsible for the majority of the atom's volume yet contribute almost nothing to its mass. Typically, the equilibrium between the positive charge of protons in the nucleus and the negative charge of the electron produces electrically neutral atoms.

To demonstrate the construction of atomic nuclei and the number of electrons in atoms and ions, think about the instance of carbon. A carbon atom that is neutral (^{12}C) has 6 protons in its nucleus, which means it is defined as carbon, and it also has 6 neutrons, increased its mass number to 12. It also has 6 electrons orbiting the nucleus, balancing the positive charge of the protons. However, carbon can exist in different forms. For instance, the carbon-13 isotope (^{13}C) has 7 neutrons instead of 6, while still maintaining 6 protons and 6 electrons. In ionic forms, such as the carbonate ion (CO_3^{2-}), the carbon atom has lost 4 electrons, resulting in a total of 10 electrons shared among the carbon and oxygen atoms in the ion (Ellsworth and Cousins, 2016).

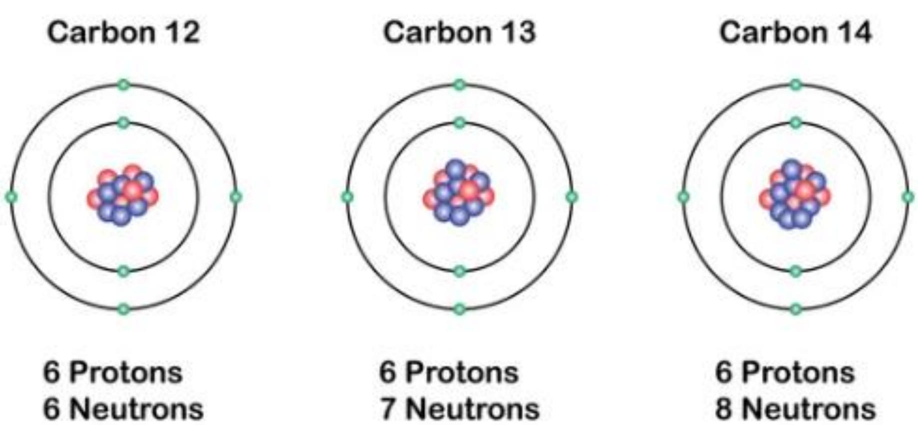

Figure 2: Carbon isotopes

Isotopes, atoms of the same element with different numbers of neutrons, provide a fascinating insight into the variability of atomic structure. While isotopes of an element share the same number of protons and electrons (in their neutral state), the differing number of neutrons leads to variations in mass and, in some cases, stability. For example, hydrogen has three naturally occurring isotopes: protium (^1H) with no neutrons, deuterium (^2H) with one neutron, and tritium (^3H) with two neutrons

(Lozada-Hidalgo et al., 2016). These isotopes exhibit different physical properties, such as boiling points and reaction rates, due to their mass differences. Moreover, some isotopes, like tritium, are radioactive, decaying over time due to their unstable neutron-to-proton ratio (Momoshima, 2022).

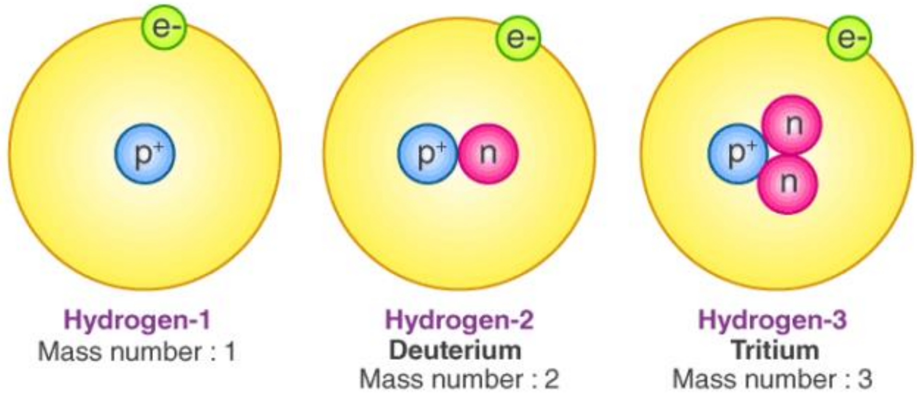

Figure 3: Hydrogen isotopes

Atoms and subatomic matter are controlled at their fundamental level by quantum mechanics, which is a theory that explains the essence of matter and energy. In accordance with quantum theory, electrons reside in unique energy levels, often called shells, which surround the nucleus, and within these shells, they occupy areas known as orbitals that indicate the regions where they are most likely found. The quanta mechanical model of the atom offers four quantum numbers that articulate the influence of energy, angular momentum, magnetic moment, and electron spin.

For the principal quantum numbers 1, 2, and 3, the number and relative energies of the s, p, and d orbitals are as follows:

1. Principal quantum number n = 1:
    - One s orbital (1s)
    - Lowest energy level
2. Principal quantum number n = 2:
    - One s orbital (2s)
    - Three p orbitals (2p)
    - Higher energy than n = 1, with 2p higher in energy than 2s

3. Principal quantum number n = 3:
   - One s orbital (3s)
   - Three p orbitals (3p)
   - Five d orbitals (3d)
   - Higher energy than n = 2, typically with the order 3s < 3p < 3d

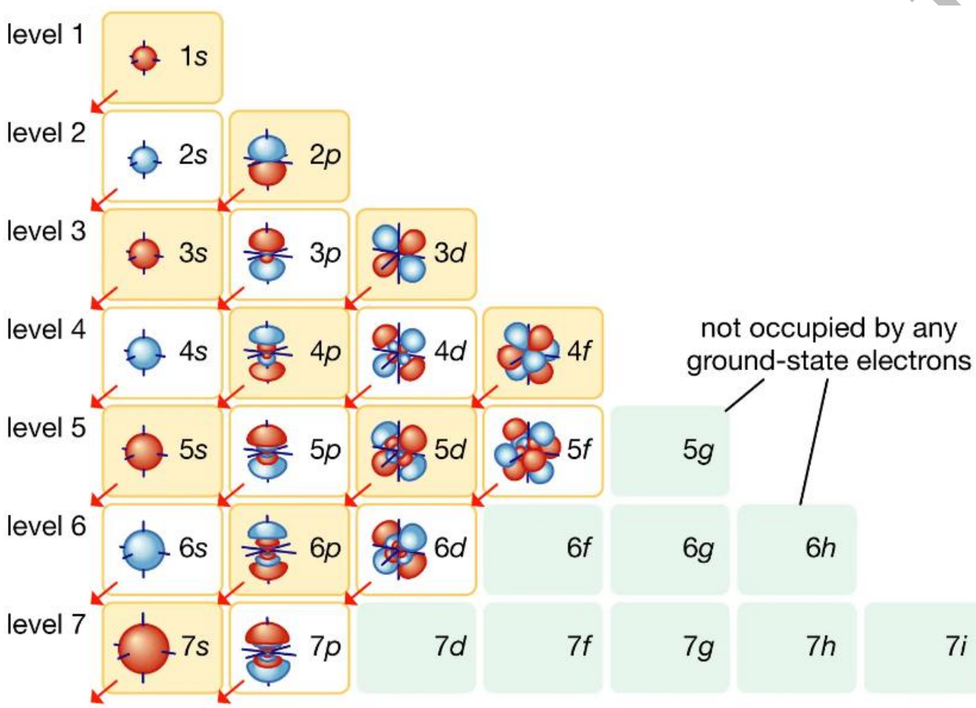

Figure 4: Electronic configuration and orbitals

The configurations of these orbitals are individual and indicate the likely distribution of an electron in three-dimensional space. Within s orbitals, the electron density is uniformly spread in a spherical pattern around the nucleus. The p orbitals are marked by a characteristic dumbbell shape with two lobes extended along each axis (x, y, and z). The d orb rounds are characterised by more intricate shapes, such as clover-like four-lobed patterns and donut-shaped bands (Azizi, 2021).

To recognize atomic behaviour and chemical reactivity, it's important to understand the amount of energy required to separate electrons from atoms. The energy needed to transform one mole of electrons from a gaseous state in which they are in their fundamental state to a mole of gaseous ions with a charge of +1 equals the first molar ionisation energy of an element. The principle is fundamental in understanding an element's chemical behaviour and its positioning within the periodic table.

The electronic blueprints shown by elements are distinguishable from the information about continual ionisations, which disclose vital details about the structure of electron shells. Think about the element magnesium (Mg) for an example. Its successive ionisation energies (in kJ/mol) are:

- 1st: 737.7
- 2nd: 1450.7
- 3rd: 7732.7
- 4th: 10542.5

The abrupt change between the second and third ionisation energies reveals the transition from detaching valence electrons to taking electrons from a lower, steadier shell. This data reflects that magnesium has two valence electrons, in keeping with its grouping in Group 2 of the periodic table and an electron configuration of [Ne]3s² (Housecroft, 2012).

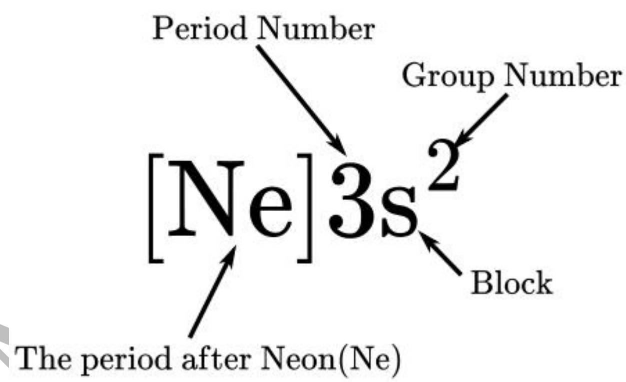

Figure 5: Electron configuration of Ne

Successive ionisation data collected regarding a particular element can reveal essential insights into its placement in the periodic table. Corresponding to similar valence electron configurations, members of the same group have ionisation energies that follow similar patterns. For instance, let's examine the first few ionisation energies of sodium (Na), another element:

- 1st: 495.8 kJ/mol
- 2nd: 4562 kJ/mol
- 3rd: 6910 kJ/mol

The dramatic increase between the first and second ionisation energies indicates that sodium has one valence electron, consistent with its position in Group 1 of the periodic table. Such action is a representation of alkali metals that easily release their one valence electron to form +1 ions.

Conversely, elements across different periods but within the same group may exhibit similar trends in their ionisation energies, typically showing increasing values as one moves downward in the group. This change has occurred because of the growing atomic radius together with the consequent decrease in the strength of the nucleus-to-electron attraction at the edges (Shaw, 2022).

Knowledge about atomic structure leads to important outcomes in multiple fields of science. Recognising atomic structure in chemistry enables a better understanding of chemical activity, bonding behaviours, and reactivity. The arrangement of the periodic table is determined by the assumption of electron configuration, which stems from our knowledge of atomic orbitals, hence helping to illustrate the periodic variations in elemental characteristics.

The structure of atoms is vital in physics when tracking events like spectroscopy, in which the special energy levels of electrons cause emission and absorption spectra to be detectable. The range of applications extends from astrophysics, where spectral analysis enables us to identify the composition of distant stars, to materials science, where it promotes the creation of new materials with intended electronic characteristics.

The study of atomic nuclei is the focus of nuclear physics, and it has advanced technology by making available nuclear power generation as well as diagnostic techniques such as Positron Emission Tomography (PET) (Gallamini et al., 2014). The characteristics of isotopes are relevant to several topic areas, including archaeological dating (for example, using carbon-14 dating), and environmental tracing (using ratios of isotopes to trace climate patterns or pollutants).

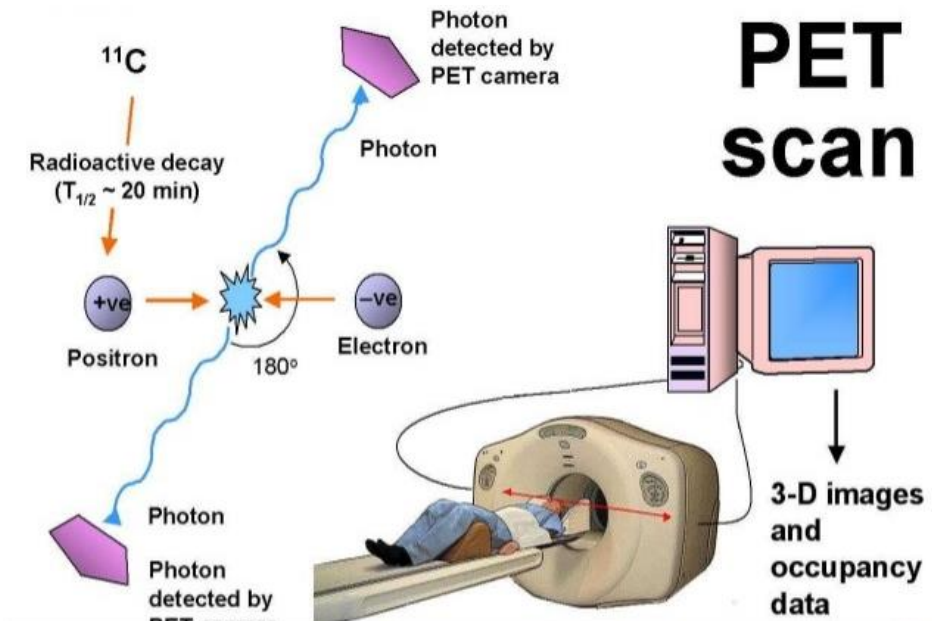

Figure 6: Positron Emission Tomography (PET) scan

In this field of study, our understanding of atomic structure and quantum mechanics has created chances for domains such as quantum computing and quantum cryptography. These technologies take advantage of the distinctive qualities of atoms and subatomic particles, allowing calculations or information transfer that are exclusive to conventional methods.

The considerable achievements in the field of atomic structure has noticeably enhanced the foundations for a variety of Nobel Prizes that have been presented. In the year 1922, the Nobel Prize for Physics went to Niels Bohr for his atom model, which introduced the notion of electron shells. In the field of atomic structure, Heisenberg, Dirac, and Schrödinger conducted critical work in quantum mechanics that continues to be critical today and brought them all the accolades of a Nobel Prize.

Recently, the 2005 Nobel Prize in Physics was given to Theodoro W. Hänsch and John L. Hall for their revolutionary work in laser-based precision spectroscopy (Chiao, 2011). Serge Haroche and David J. Wineland received the Nobel Prize in Physics in 2012 for their role in developing techniques that allowed the control and understanding of individual quantum systems (Mompart, 2013). Their contributions have considerably evolved the ways to detect and influence atomic behaviour.

The study of the characteristics of rare atoms, like positronium (an electron and positron combination) and muonic atoms (featuring a muon rather than an electron), is providing new revelations into the cornerstones of physics. The study of attosecond science, whereby events of 10^-18 seconds are examined, is permitting us to track electron dynamics within atoms in real-time, which is expanding our capacity to understand atomic behaviour better than ever before (Frugiuele et al., 2019).

Conclusion

In conclusion, it is obvious that the present essay looking into atomic structures is undeniably one of great importance. By examining the characteristics of protons, neutrons, and electrons, coupled with an analysis of complex quantum orbitals and ionisation energies, there has been progress in our appreciation of the physical constitution of the universe. This ability is at the nucleus of a sizable segment of chemistry, physics, and the science of materials, and keeps pushing technological advancements forward. It is clear that the study of the universe, which encompasses phenomena at small scales and over short periods, highlights the relevance of the atom in giving explanations.

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