Original Article

Bulletin of Pure and Applied Sciences.
Vol.36 D (Physics), No.2, 2017: P.141-146
Print version ISSN 0970 6569
Online version ISSN 2320 3218
DOI 10.5958/2320-3218.2017.00019.7

REVIEW REGARDING DISCOVERY OF SUPER HEAVY NUCLEI (SHN) AND RELATED FUNDAMENTAL ASPECTS

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Received on 12.10.2017,
Accepted on 15.12.2017

Abstract

Discovery of super heavy nuclei (SHN), their properties, present status and other related aspects reported in the literature are presented in the article. A review of work done in the field of heavy and super heavy elements from early stages to present times has been mentioned. Also, the future prospective, brief overview of vast consequences of investigations as well as its outcome including numerous other possibilities relevant to this field is discussed. Investigations, till now, have confirmed the synthesis of nuclei with proton number Z = 118, along with a fair possibility of existence of nuclei beyond it.

Keywords: Super heavy nuclei (SHN), Heavy elements

INTRODUCTION

The search for the elements in the highest range of periodic table i.e, Z ≥ 104, has been of deep interest for the nuclear physics as well as astrophysical community since last few decades. There is a quest to understand the nature of super heavy elements (SHE's) or particularly the super heavy nuclei, about their existence, stability and other fundamental properties. Their isospin content, basic or distinct features, synthesis and decay mechanism has attracted both the theoreticians and experimentalists since the advent of 19th century.

The discovery of heavy elements, especially the super heavy nuclei (SHN) is pertinent to extract their fundamental characteristics, chemical properties and other exclusive features. It includes the existence of SHE's and the extension or existence of elements in the periodic table. One needs to know that how many elements actually exists in nature. What is their expected life time? On what parameters and factors their stability depends? How they are able to survive by overcoming the huge electrostatic repulsion. The next crucial question is the possibility of their synthesis in laboratory. This paper systematically provided the sequential information and investigations reported in the literature and the latest developments under the purview of heavy and super heavy elements.

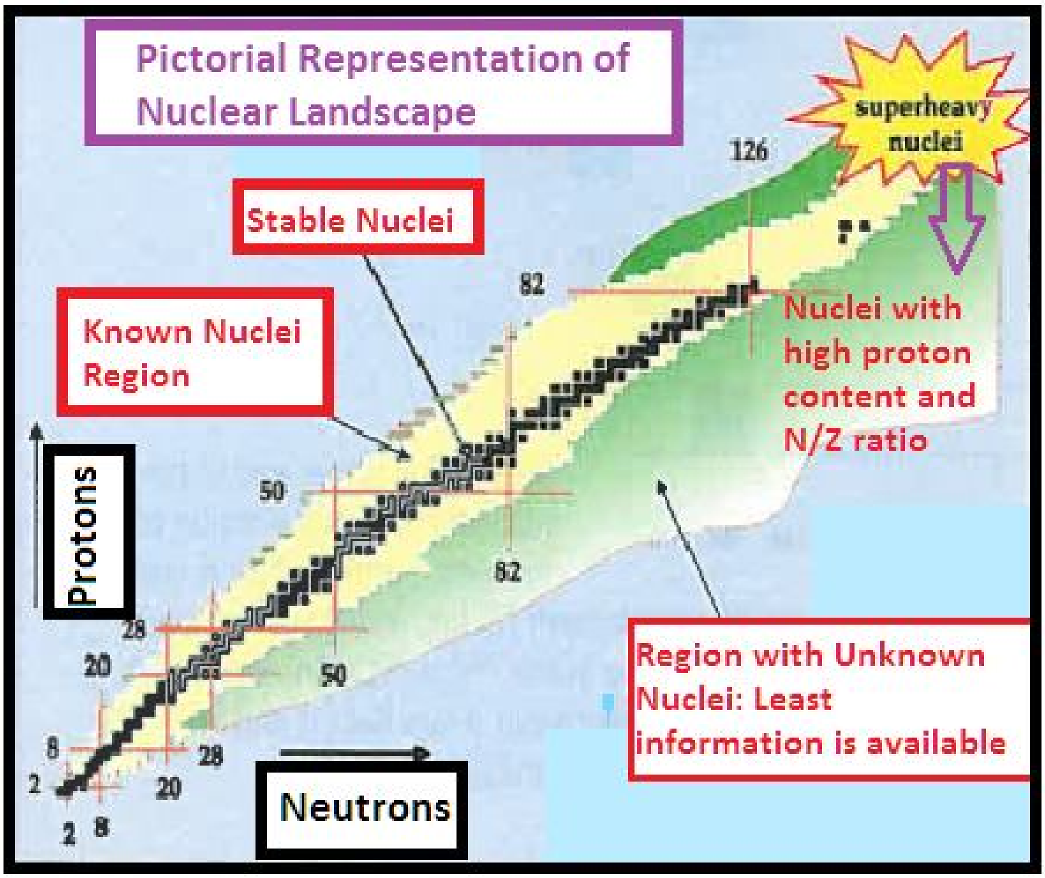

Fig. 1: The pictorial representation of the nuclear landscape with neutrons (along horizontal) and protons (along vertical side). The range of super heavy nuclei is depicted on the upper right side.

With the advent of liquid drop model [1], the stability of nuclei has been supposed to be a function of various attractive interactions and repulsive electric/coulomb forces. The interactive surface nucleonic interactions and mean field tends to enhance the stability of the nuclei. The Coulomb force tends to oppose the attractive forces which holds or binds the nucleons together in a nucleus. It interprets the binding energy as the major deciding factor for the stability of the nuclei. Under this approach, the binding energy is considerably affected by the symmetry energy (energy which represents the neutron-proton asymmetry in an isospin-asymmetric nuclei, i.e., N/Z ratio), odd-even arrangement, and coulomb forces. It assumes the nucleus to be a drop of charged liquid, without any specific structure. The repulsive Coulomb force depends directly on the proton content of the nuclei. Large proton content will lead to repulsion between like charges and hence will destabilize the nuclei. In super heavy elements, the greater proton content will make the coulomb interaction a dominant force to establish the stability and properties. The super heavy region is depicted in the Figure 1. The neutron content in heavy elements will stabilize the nuclei by countering the Coulomb force but will lead to larger N/Z ratio. The enhanced N/Z ratio will thus imply stronger symmetry energy interplay and will significantly influence the stability of nuclei and reaction dynamics, in addition to the coulomb interactions. Super-heavy elements can acknowledge the coulomb and symmetry energy role in a much better way. Hence, the heavy and super heavy elements are of the extreme interest to explore the role of isospin (symmetry energy and coulomb forces) in structure of nuclei, reaction dynamics and astrophysical phenomena such as giant dipole resonances (GDR), pygmy dipole resonances(PDR), nuclear magnetic resonances (NMR), formation of neutron stars and supernova explosions [2]. In other words, an exact knowledge of the stability, properties and structure of nuclei (either heavy or super heavy) is important to extract the information about symmetry energy as well as its density dependence part [3]. Investigations associated to the structure of super heavy nuclides, termed the existence of nuclei with atomic number more than 102 due the shell effects prescribed by the quantum theory. The classical interpretation of Liquid drop theory describes that the shape of a nucleus is governed by interplay between surface tension (which stabilizes the nuclei) and Coulomb repulsion. Large value of proton number Z inhibits strong Coulomb force and the nuclear liquid drop becomes unstable to surface distortions and it fissions spontaneously.

EARLY WORK DONE

The nuclear reactions with slow moving projectile and relatively much larger target does not always result in forming a super heavy nuclei. There are four main possible outcomes of nuclear reactions carried out at low excitation energies. The four prominent possibilities are listed below.

1. Compound Nucleus formation (and decay of compound nucleus).
2. Fusion.
3. Fusion-Fission.
4. Inelastic scattering (and Deep inelastic scattering).

The compound nucleus formation is one of the most interesting and unique phenomena. The decay process of compound nucleus is completely independent of the entrance channel (target-projectile combination and colliding geometry) as well as excitation energy. The nuclear reaction takes place in two distinct and independent stages. The stages are described below;

1. Formation of compound nucleus after the collision between target and nucleus: The compound nucleus has the energy of projectile shared among all nucleons, which survives a relatively long time ($\approx 10^{-16}$ seconds) compared to a usual small time ($\approx 10^{-22}$ seconds). The compound nucleus so formed remains in a highly excited and unstable state. At this point, the statistical equilibrium is reached and the compound nucleus retains no memory of its mode of formation.
2. In next stage, the disintegration of the compound nucleus into the products of the reaction occurs. The emission takes place through statistical fluctuations from the so called exit channels.

The first attempt to synthesize the super heavy elements in laboratory has been listed in the literature in 1930 by Fermi and his co-workers [4]. Soon after this, investigations regarding neutron induced reactions indicated towards the previously known elements provided the masses approximately that of the original system. Investigations for Rutherfordium (Z = 104), bring forth various reaction mechanisms which provided identifications of a spontaneously fissioning (SF) nuclide with a half life of few seconds [5]. Later, the efforts signify the existence of neptunium, plutonium and related information [6]. Investigations for the heavy elements in 1982, mark the discovery of element with N = 266 and Z = 109, and was denoted as most proton rich nuclei at that time [7]. Initially, the Neptunium with Z = 93, was synthesized with bombardment of Uranium with slow moving neutrons. Neptunium is marked as the first element among the actinide series to be discovered and first trans-uranium element to be produced synthetically. ^{237}Np was established as the most stable isotope with half life of 2.14 million years. Plutonium with Z = 94, was characterized in the mass number from 228 to 247. The nest element Americium (Z = 95) was discovered in 1944. After this the Curium (Z = 96), Berkelium (Z = 97), and Californium (Z = 98) were discovered in 1944, 1949 and 1950 respectively. The last element of actinide series Lawrencium (Z = 103) was synthesized in 1961. Further investigations revealed the existence of transuranic elements and Z = 118 has been the last possible trans-actinide discovered. Nevertheless, there exists a stern possibility for the existence and synthesis of elements beyond atomic number Z = 118. In this article, the heavy elements are specified as with atomic number greater than 92, and super heavy elements with atomic number greater than 104. Much basic details about SHN are available in Ref. [8].

After many exhaustive discoveries pertaining to heavy/super heavy nuclides, the focus shifted towards their stability and decay mechanism. The stability, decay mechanism, and other distinct features of SHN were the major topics of interest. Many questions are still answered in the super-heavy nuclear physics research which poses a challenge to the experimental researchers.

METHODOLOGY (Experimental Facilities/Techniques)

It is imperative to mention that all the heavy and super heavy nuclides are produced by artificial methods using accelerators in laboratories at low excitation energies. The super heavy nuclides generally decay by two modes, i.e.

1. Spontaneous alpha decay
2. Spontaneous fission.

The interpretation of the possibility that the nucleus might divide into two nuclei was given in 1939 and the term fission was coined for the process [9]. The sustainability or life time of superheavy nuclei is determined by considering spontaneous emission of alpha, beta particles and/or spontaneous fission. Calculations based on the strutinsky method [10] yielded important facts (associated to calculations of fission barriers and ground state masses) about the super-heavy nuclei [11]. An important conclusion, of half lives of about 10^9 years for the most stable nuclei was obtained in many investigations [12]. These developments motivated many researchers. Meantime, various theoretical models with extensive improvements from years 1960 to 1980 yielded much interesting facts about the properties of elements in the super heavy range. Improvements in models, inclusion of necessary facts and overcoming the deficiencies of previous investigations yielded much precise information. The stability and decay of elements at the end of periodic system was also studied [13]. The understanding for the existence of super heavy nuclei got enhanced and hence the element with atomic number Z = 118 was revealed in 1999 in LBNL, Berkeley [14, 15].

Heavy elements (transuraniums) were produced using heavy-ion accelerators by fusing heavy actinide targets [16]. Nobelium (Z =102), rutherfordium (Z = 104), lawrencium (Z = 103), dubnium (Z = 105), seaborgium (Z = 106), were synthesized in 1958, 1969, 1961, 1967, and 1974 respectively by bombarding light ions at heavy actinide targets. Einstenium and fermium were found to exist in the debris from thermonuclear explosions. Fermium nucleus was synthesized by the reaction involving capture of 17 neutrons by ^{238}U followed by the subsequent beta decays. Performing "Cold fusion" reactions in accelerators and using medium mass projectiles with $Z \geq 24$, with lead or bismuth targets, the discovery of bohrium (Z =107), hassium (Z =108), meitnerium (Z = 109), ununnilium (Z = 110), ununinium (Z = 111), and ununbium (Z = 112), was made in years 1976, 1984, 1982, 1994, 1994 and 1996 respectively. Most of the experiments regarding the synthesis of heavy/super heavy nuclides are performed at three prominent accelerator facilities available at Lawrence Berkeley laboratory in Berkeley (USA), Joint Institute of Nuclear Research in Dubna (Russia), and GSI at Darmstadt (Germany). These prominent accelerator facilities are also termed as "heavy element factories".

PRESENT STATUS

Till now super-heavy elements have been synthesized artificially, and currently serve very less practical purpose, because their short half-lives cause them to decay after a very short time. Except Dubnium (half life of about a day) other elements are extremely hard to study **[16].** However, some transuranic elements have practically potential applications. They can be utilized in devices such as spectrometers and smoke detectors.

The synthesis of nuclei with Z =118 element has been reported to be an absolute possibility [15]. It has been established that the possibility of the existence of super-heavy elements with Z =118, and higher atomic numbers cannot be ruled out [17]. Over the last 15 years, multiple experiments have been performed to produce elements with proton numbers, Z = 113–118 [18] and to study their properties [19]. A quantum of exhaustive information regarding the discovery of the heaviest elements (Z = 107 – 112), their ground state properties, and detail of research performed in this domain is available in Ref. [8]. A theoretical approach based on the formation of neutron rich super-heavy nuclei in laboratory via. Radioactive Ion beams (RIB's) can be used to study the nuclear astrophysical phenomenon and nuclear structure properties [20]. This theoretical investigation [20] of formation of super heavy elements (SHE's), via. RIB's under the ambit of Glauber's approach [21] using reaction and fusion cross-sections revealed that the stability of neutron rich SHE's against spontaneous fission arises due to widening of the fission barriers because of excess number of neutrons. The formation of elements in the super heavy region in laboratory probably confirms its presence in nature anywhere in the universe or astrophysical environment. A comprehensive review of the prominent properties of super heavy nuclei pertaining to their ground state binding energies and deformations is available in [8]. Also the mechanism of decay of SHN is reported in detail. It mentioned the synthesis of SHE's with respect to their excitation functions and process of fusion by transfer.

The formation, presence and decay mechanism of super heavy elements has attracted the scientific community to a large extent. Availability of much efficient RIB facilities instilled hope to study the nuclear structure and astrophysical phenomena's. Radioactive Ion beam facilities can be used as an optimum tool for the intensive research and formation of SHE's. Such facilities can probably reveal the mysteries of many astrophysical events and activities taking place at distant universe.

CONCLUSIVE DISCUSSION AND FUTURE PROSPECTIVES

This paper provided a general overview of the investigations for the synthesis of super heavy nuclei and discovery of the related aspects. Initial research work comprising the discovery or formation of heavy/super heavy elements and their critical properties are reported. No doubt, heavy and super heavy elements are a topic of extreme interest for the researchers in the present times with respect to their structure and understanding of reaction physics. Further advancements in the production of super heavy nuclei and attempts to explore their properties will surely help in gathering in-depth understanding of many aspects related to structure of nuclei and dynamics of nucleonic (inter-nucleon) interactions. The study will enhance the knowledge of symmetry energy as well as its density dependent and momentum dependent part. The experimental work pertaining to last few decades corresponds to almost continuous decrease in cross-sections for the synthesis of heaviest elements, except few cases. The probability of synthesis of much heavy elements decreases with an increase in atomic number. However, in case of synthesis of nuclei with Z = 114 and Z = 118, similar trend was not observed. Investigations have confirmed the existence of SHN upto Z =118. Indeed, there is always an utmost possibility for the existence of nuclei with Z more than 118.

The study of super heavy nuclei within theoretical domain is facing critical challenges. Outside the region of known elements the theoretical predictions of phenomenological models ceases to justify the data. On the experimental front, the construction of new detectors with latest techniques and facilities is under progress. Such new facilities may make it possible to perform experiments aimed at synthesizing nuclei with high atomic number in reasonable measuring times. It will also facilitate and support the other investigations such as reaction physics, astrophysics, and spectrometry.

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